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INTRODUCTION

Proba (Project for On-Board Autonomy) satellite was launched in October 2001 as a technology demonstrator for onboard operational autonomy, for new spacecraft technology both hardware and software, and to test Earth observation and space environment instruments in space. The instrument payload includes a Compact High Resolution Imaging Spectrometer (CHRIS), a radiation measurement sensor (SREM), a debris measurement sensor (DEBIE), high resolution and wide angle Earth pointing cameras, a star tracker and gyroscopes.

After the one-year of operations as technology demonstration mission Proba had its lifetime extended as an Earth Observation mission providing the scientific community with unprecedented and innovative satellite hyperspectral multi-angular CHRIS data. The CHRIS instrument provides Earth surface reflectance data in the visible/near infrared, at high spatial and spectral resolution, and by using Proba’s pointing capabilities collects Bi-directional Reflectance Distribution Function (BRDF) data for selected test sites on the Earth’s surface with a wide range of different viewing configurations.

Following the workshop in April 2003 and after a successful year of CHRIS/Proba exploitation in 2003, it has been decided to invite all principal investigators, selected through ESA’s announcement of opportunity, to a second workshop to present the results of their analysis of 2002 and 2003 acquisitions and their plans for 2004. The workshop is also open to all parties interested in the CHRIS/Proba achievements.

The CHRIS/Proba workshop represents a major opportunity for the user community to present scientific results obtained using CHRIS data for atmospheric, land and coastal studies. Contributions that discuss the performance of the satellite and the quality of its data products are also welcome. The workshop will be organised around a single stream of plenary sessions with oral presentations providing a forum for:

- Assessment of satellite performance and data quality;
- Scientific exchange on results achieved with CHRIS data in various application areas;
- Presentation of future CHRIS/Proba data exploitation projects;
- Review of individual projects for final definition of the 2004 CHRIS acquisition plan.
REVIEW OF ASPECTS ASSOCIATED WITH THE CHRIS CALIBRATION

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ABSTRACT
Following almost two years of CHRIS in-orbit operations, this paper reviews the procedure for calibration of the CHRIS instrument to assess whether changes could be implemented to improve the radiometric calibration. In particular the paper addresses: first, the variation of the dark signal data acquired over the period of the mission, from October 2001 to March 2004, secondly, the use of the generic dark-field data sets for correcting analogue electronic offsets and, thirdly, the influence of the platform temperature variations on instrument response and hence radiometric calibration.

1 INTRODUCTION
Sira Technology Ltd developed the Compact High Resolution Imaging Spectrometer (CHRIS). This instrument has been designed principally to provide remote sensing data for land applications and aerosol measurements; it is also used for coastal zone monitoring, although this was not a design driver. It is the main instrument payload on the European Space Agency (ESA) small satellite platform PROBA (Project for On-Board Autonomy). At perigee, CHRIS provides a ground sampling distance of 17m, over typical image areas 13km square. It has a spectral range from 400nm to 1050nm, at spectral resolution <11nm. The instrument provides sets of images of selected target areas, at different pointing angles, forming up to 5 images of each target in a single overpass.

The small platform offers limited scope for on-board calibration facilities. Consequently, calibration is provided by a mixture of on-ground and in-orbit measurements.

On-ground measurements included:

- full aperture radiometric calibration,
- stray light calibration,
- spatial resolution,
- spectral and spatial registration assessment,
- wavelength characterisation (with respect to temperature),
- linearity and saturation, and
- noise measurements.

In-flight measurements include:

- DC offset measurements,
- relative gain measurements,
- wavelength calibration,
- response calibration using sunlight,
- linearity and saturation, and
- noise measurements.

Vicarious calibration for response has also been undertaken by some PIs.

Data for absolute response measurement is gathered in flight by use of a solar calibration device (SCD). This device comprises a small reflecting prism, with one lens surface, which is located at the outer end of the instrument external baffle. When the platform is over the Antarctic region, on the dark side of the terminator, with the telescope pointing to nadir, the SCD receives direct sunlight. The platform is manoeuvred so that the device reflects sunlight into the field of the instrument, with spread provided by the lens power. The SCD fills the field of the instrument at a nominal radiance equivalent to albedo 0.25 in direct sunlight. The SCD is not moved; it is fixed in the main instrument aperture area, but occupies (and samples) only a small fraction of the instrument aperture area. The field of the device for receiving sunlight is limited to 2° x 4°. This field is fully sampled, in pre-flight calibration and in orbit, to check for non-uniformities in transmission of the device and instrument optics: this provides a check for local particulate contamination that would invalidate results.

Wavelength calibration is checked in flight using atmosphere absorption features, particularly the atmospheric oxygen absorption band at 762nm.

Aspects associated with the calibration procedure are reviewed in this paper. The main purpose of the review is to assess whether changes need to be implemented in the calibration procedure or instrument configuration.

2 CALIBRATION PROCESS
Each image acquired by CHRIS includes raw image data and DC offset data. Components of DC offset include electronic offsets, dark signal and “smear” generated during CCD frame transfer. Full-frame dark field data is acquired using images of dark Earth, with
the platform in eclipse. The current process of correcting CHRIS images involves subtracting dark signal and other offsets, and dividing the result by response data acquired from pre-launch measurements.

Adjustments are made at various stages during the processing to take account of the gain, integration time and number of CCD rows in each spectral band.

3 DARK SIGNAL VARIATIONS

As indicated above, one aspect of the calibration process is the measurement of the DC offsets and in particular the offset generated by CCD dark signal. The magnitude of the dark charge will typically increase with time due to space radiation. This variation in dark charge through the mission life was investigated to assess the impact on the calibration performance.

A number of dark charge measurements were made through the in-orbit mission life as well as during pre-launch tests. These measurements were compared using a selection of imaging CCD pixels assigned to wavelengths ranging from 400 to 1050nm.

The platform temperature changes through the year, affecting the operating temperature of the detector. The dark charge data was scaled to a nominal temperature of 5°C using the following formula:

\[
\text{Dark charge} = AT^{1.5} e^{-E/(2kT)}
\]

where \(E = 1.1557 - (7.021^4 T^2)/(1108 + T)\)

\(T\) is in Kelvin and \(k = 8.62 \times 10^{-5}\) eV/K

The dark files used were:

<table>
<thead>
<tr>
<th>File</th>
<th>Date</th>
<th>Temp. °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-flight</td>
<td>July 1999</td>
<td>20.0</td>
</tr>
<tr>
<td>2B4B</td>
<td>September 1st 2002</td>
<td>0.2</td>
</tr>
<tr>
<td>2B8B</td>
<td>September 1st 2003</td>
<td>3.2</td>
</tr>
<tr>
<td>2B8C</td>
<td>October 3rd 2003</td>
<td>4.4</td>
</tr>
<tr>
<td>2B8D</td>
<td>November 3rd 2003</td>
<td>5.6</td>
</tr>
<tr>
<td>2B8E</td>
<td>December 2nd 2003</td>
<td>6.6</td>
</tr>
<tr>
<td>2B8F</td>
<td>January 8th 2004</td>
<td>6.1</td>
</tr>
<tr>
<td>2B90</td>
<td>February 2nd 2004</td>
<td>8.5</td>
</tr>
<tr>
<td>2B91</td>
<td>March 4th 2004</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 1 Dark File Data

Figure 1 shows the corrected dark charge histogram.

4 ANALOGUE OFFSET ERRORS

Analogue offsets are present on all recorded pixels. These can be removed in the image processing procedure by subtracting the pixel data from a “specific” dark image data set. A “specific” dark image data set is a dark image, acquired in dark scene conditions, with the same spectral, spatial and gain configuration as the bright image that is being corrected. The dark image would typically be acquired in the eclipse period of the orbit.

In practice the use of specific dark image data for offset correction is quite cumbersome for the CHRIS operations for two reasons. First, the configuration gain is optimised with respect to target latitude to maximise the signal to noise ratio, leading to 46 different configurations for the 2004 Science Plan. Secondly, only one dark image can be acquired in a single download session and in practice we would wish to repeat the acquisition of dark image data each month. In practice acquisition of the 46 specific dark images would take several days and is not the preferred approach.

To minimise the number of configurations that need to be used, a “generic” dark image data set is acquired and...
used together with the average bright image offset data that is recorded at each end of a CCD row.

The “generic” dark image data is acquired by recording a dark image of all the bands that are within the total spectrum of interest, i.e. 400 to 1050nm, plus the smear band. This is in practice about 242 bands. This data can then be used to construct any band combination required to correct the dark signal offsets in the bright images.

The use of the generic dark image approach is convenient for the CHRIS operation. However, it provides the correct offset only if the offsets are constant across the CCD and in practice this is not the case and a small variation is expected. Assuming the analogue levels across the CCD stay within the offset pixel levels recorded at the ends of each recorded CCD row, which is probably a reasonable assumption, then the maximum offset error is half the difference between the averages of the offset levels recorded at the ends of each row.

Examples of the levels of maximum bias errors, as a proportion the scene signal, are shown in the figure below. In most cases the level of errors are probably acceptable, although mode 1 and 2 errors are higher than those of the other modes.

![Figure 2 Maximum Bias Errors](image)

In practice the higher errors seen above are due to low scene signals. The mode 2 image over Rame Head – an area mainly of water giving low signals – resulting in the high bias error for band 18.

There are two options that could be considered for reducing bias errors generated by the variation in the analogue offsets. The first option is to increase the analogue gain levels, if not already at maximum level. The second option is to use specific dark image data for those modes that consistently have low signal levels, such as the modes used for coastal applications (i.e. mode 2). It should be noted that the current analogue gains have been selected to avoid saturation on clouds, for which an albedo of 1.1 is assumed as an upper limit. Most natural targets will have albedos lower than 0.7 and scenes over water will typically be much lower. There is some scope for increasing the gains, if saturation of cloud images is accepted, when clouds are present.

The preference out of the above two options is to increase the gains where possible, although some specific dark image data may be acquired as a fall back solution for mode 2 acquisitions.

5 WAVELENGTH CALIBRATION

5.1 PRE-LAUNCH MEASUREMENTS

CHRIS was calibrated for wavelength and wavelength variation with temperature using a monochromator operating at 10 wavelength groups (405, 446, 496, 546, 648, 746, 846, 910, 1020, 1060nm) and with CHRIS at 3 temperatures (13.3°C, 20.2°C, 28.8°C).

Analysis of this data indicated that the location of the spectrum incident on the CCD varied with temperature according to:

$$\Delta N = 0.103\Delta T$$  

where $\Delta N$ is the change in row number (for any selected wavelength) produced by a change of temperature $\Delta T$. This shift with temperature is a consequence of the temperature dependent refractive index of the spectrometer prisms.

5.2 IN-ORBIT MEASUREMENTS

In orbit wavelength calibration measurements were made using the atmospheric oxygen absorption band at 762nm. Measurements were made over the ocean off the west coast of California.

The pre-launch calibration data from the SCD was measured at 23.5°C and this needed to be pixel shifted to compensate for a temperature-induced shift of 2.2 pixels. A first order comparison of the in-orbit SCD measurements with standard solar irradiance tables was undertaken by applying a temperature dependent pixel shift to the calibration data before correcting the in-orbit data. This gave a relatively close match as indicated in the Figure 3.

Measurements using the CHRIS solar calibration device (SCD), were intended principally to assess the CHRIS optical throughput. One particular surprise was that the spectrometer was able to resolve Fraunhofer structure on the SCD input near 430nm (probably the Fe and Ca lines). Having applied the pixel shift to the pre-launch SCD calibration data set, it was evident that there was a
very close correspondence within 1nm of the standard and in-orbit irradiance data providing confidence in the wavelength calibration procedure.

The preferred approach is to generate a 1-D function of the average spectral response across the CCD by averaging the data in the rows and applying a correction corresponding to the change in the response curve when the appropriate number of row shift is applied. The averaging process reduces the pixel-to-pixel response non-uniformity in the 1-D spectral response curve.

The average calibration curve of all CCD rows is shown in Figure 4.

5.3 IMAGE DATA CALIBRATION WRT TEMPERATURE

The temperature of the CHRIS instrument in-orbit varies due to seasonal variations and platform events. Temperature changes >8°C have been recorded, although within an imaging session the changes are <0.5°C.

The temperature variation of the CHRIS spectrometer produces two orthogonal shifts, first there is the shift of the slit across the CCD, which gives rise to banding seen in the images, and secondly, there is a shift of the spectrum along the CCD columns as indicated above.

The radiometric response curve for the CHRIS instrument can be considered to consist of two overlapping components. The first component is the 2-D map of pixel-to-pixel response of the CCD, which is relatively stable with temperature and time, although the dark charge will develop spikes due to proton damage. The second component is the “system response” of the optical system. This latter component is a 2-D function that shifts in two orthogonal directions due to the influence of temperature as indicated above. The ground calibration was undertaken at a different temperature to in-orbit measurements, therefore the associated pixel shifts need to be corrected. An ideal approach would be to separate out these two 2-D components, shift the system response function and recombine the two 2-D components before correcting the in-orbit data. In practice the process of separating the two components, shifting one, and recombining them is problematic. This is largely because the calibration data has low signal to noise at the two extremes of the spectrum, where the response of the system is low, resulting in significant noise artefacts in the separated data.

The blue curve indicates the row-by-row temperature correction factor, which at short wavelengths has high spectral resolution of the order of 2nm. In practice CHRIS is not used with such high resolution and thus the perturbations in the region between 400 and 500nm are smoothed, as indicated by the pink curve where the rows are integrated to represent bands of 10nm. The large temperature correction factor above 900nm is a consequence of the rapidly changing response function in this region.

It is planned to implement the temperature dependency into the software that is used to process images released to PIs, although some validation with ground data sets will be undertaken to improve confidence in the level of the precise temperature-induced pixel shifts.
6 CONCLUSIONS

This paper has reviewed the procedure for calibration of the CHRIS instrument, particularly addressing:
(a) the variation of the dark signal data acquired over the period of the mission,
(b) the use of the generic dark-field data for correcting analogue electronic offsets and,
(c) the influence of the CHRIS temperature variations on instrument radiometric calibration.

It is concluded, first, that the errors introduced by dark signal are small and can be neglected.

Secondly, the use of the generic dark image data for correcting analogue offsets is probably acceptable for most land applications, where the scene albedo is relatively high, but may be improved by increasing gain levels for coastal scenes, accepting that some images may experience saturation where clouds are present. Alternatively, in critical cases, specific dark image data can be used although it would be preferable to limit the number of acquired data sets.

Lastly, the temperature-induced pixel shifts do significantly affect radiometric calibration and this effect will need to be modelled within the image processing software.
**ABSTRACT**

An atmospheric correction algorithm for satellite/airborne data taken over land has been implemented. The algorithm is designed to obtain the main atmospheric parameters needed in the correction from the image itself, so an optimal characterization of the atmospheric state, in temporal and spatial resolution terms, is achieved. The results of the application to CHRIS/PROBA data from the ESA SPARC campaign is presented in this work, focusing on the validation of both the final surface reflectance and the intermediate atmospheric water vapor and aerosol products. A final step devoted to the recalibration of the obtained reflectances is needed, due to calibration problems in the near-infrared CHRIS bands. The comparison with coincident MERIS data provides a final validation of the surface reflectance image.

Key words: Atmospheric correction, Surface reflectance, CHRIS/PROBA, Radiative transfer, SPARC campaign.

**1. INTRODUCTION**

In Earth Observation, the atmospheric influence on the visible and infrared radiation is strong enough to modify the reflected electromagnetic signal, causing the loss or the corruption of part of the carried information about the observed target. Thus, any set of remote sensing data needs a previous removal of the atmospheric effects in the initial processing steps, to assert a maximal accuracy and reliability in the results inferred by the latter exploitation of the data. This is the fundamental basis of the atmospheric correction in optical remote sensing: the elimination of the atmospheric effects from the useful signal reflected by the observation target in the observer’s line of sight. A traditional statement of the problem can be found, for instance, in [1,2]

Generally speaking, the atmospheric correction procedure can be divided into two separated phases. The first one is devoted to the retrieval of the atmospheric parameters needed to quantify the atmospheric influence on the measured radiation. Once the atmospheric optical functions are known, the second phase deals with the decoupling of the surface and atmosphere radiative transfer effects, which leads to the evaluation of equations formulating the Top-of-Atmosphere (TOA) radiances as a combination of surface and atmosphere contributions. Depending on the degree of accuracy of the physical assumptions underneath these formulations, there is a wide range of equations to be solved, ranging from simple analytical equations to complex integro-differential ones that have to be solved using numerical techniques.

Concerning the first phase, the loadings and types of the atmospheric components, gases and aerosols, must be known in order to calculate their optical properties. For an accurate atmospheric correction, the ideal situation would be the availability of an atmospheric product containing the main atmospheric information simultaneous to the image acquisition and with the same spatial resolution. This can be accomplished if atmospheric retrievals are done from the data itself, by means of the inversion of the measured radiances in some selected wavelengths. Thanks to the hyperspectral and multiangular capabilities of the last generation of satellite sensors, the extraction of atmospheric information from the data themselves is becoming a real possibility.

In this framework, we have developed an atmospheric correction algorithm for high spectral resolution data over land surfaces. It is designed to obtain the main atmospheric parameters needed in the correction from the image itself, so an optimal characterization of the atmospheric state, in temporal and spatial resolution terms, is achieved. The use of the limiting concept of dark targets is avoided in the aerosol retrievals. Instead, the atmospheric parameters are estimated from every type of land surfaces, with the only restriction that the surface reflectance can be represented by a linear combination of two pure vegetation and bare soil endmembers.

The algorithm has already been applied to the recently launched ESA sensors CHRIS/PROBA [3] and ENVISAT/MERIS [4] with a high consistency in the results. In this paper we describe the particular implementation of the algorithm for CHRIS/PROBA data, as well as the results obtained in the estimation of atmospheric parameters and the subsequent surface reflectance retrieval. The validation of these results is achieved by means of simultaneous ground measurements made during the ESA Spectra-Barra Campaign (SPARC), which took place in Barrax (Spain) during 12-14th July, 2003.
2. CHRIS/PROBA DATA

The Project for On-Board Autonomy (PROBA) [3] small satellite mission launched on 22 October 2001 is a technology proving experiment to demonstrate the on-board autonomy of a generic platform suitable for small scientific or application missions. The instrument payload includes the Compact High Resolution Imaging Spectrometer (CHRIS).

The platform provides pointing in both across-track and along-track directions, as well as a fixed scanning speed on the ground during imaging in order to increase the CHRIS integration time. In this way, the system CHRIS/PROBA has multangular capabilities, acquiring five consecutive images at time when the zenith angle of the platform with respect to the “fly-by position” (position where the satellite projection in the surface is closest to the observation target), corresponding to a minimum observation zenith angle in the surface is closest to the observation target. The platform provides pointing in both across-track and along-track directions, acquiring five consecutive images at time when the zenith angle of the platform with respect to the “fly-by position” (position where the satellite projection in the surface is closest to the observation target), corresponding to a minimum observation zenith angle (MZA), is equal to a set of Fly-by Zenith Angle (FZA): 0°, ±36°, ±55°. Negative values correspond to target locations East of the ground track. CHRIS datasets from the SPARC campaign present an MZA = +20° on 12th July, and a MZA = −27° on 14 July. This means that the image closest to nadir, FZA = 0°, is acquired with a view zenith angle equals to 20°.

CHRIS operates over the visible/NIR bands from 400 nm to 1050 nm and can operate in 62 spectral bands at a spatial resolution of 34 m, or with 18 bands at 17 m, with a minimum spectral sampling interval ranging between 1.25 (at 400 nm) and 11 nm (at 1000 nm). There are several operation modes, with different combinations of band configuration (number, center location and width) and spatial resolution. The data we have worked with correspond to mode 1, consisting of 34 m pixel and 62 bands between 400 and 1000 nm.

3. ALGORITHM DESCRIPTION

3.1. Estimation of Atmospheric Parameters

In the spectral range covered by the algorithm, 0.4-1.0 µm, we consider three atmospheric contributors to be treated specifically: ozone, water vapor and aerosols. The resultant content values are used to calculate the corresponding spectral atmospheric reflectance and transmittance functions with the 6S radiative transfer code [5]. These functions are an input in the second algorithm step to finally obtain the surface reflectance.

The stratospheric ozone absorbs principally in the shorter wavelengths. Due to its low spatial and temporal variation, we do not make a particular treatment of this gas, as the total ozone column content can be provided with enough accuracy by any public database. For instance, the values provided by the ECMWF (European Center for Medium-Range Weather Forecasting) are attached to ENVISAT/MERIS images.

For water vapor and aerosols the situation is different, as they vary strongly in small spatial and temporal scales. So, the temporal and spatial coincidence of this atmospheric information and the image to be processed is needed. The most efficient way to achieve this is the retrieval of the atmospheric parameters from the image itself.

There are several methods to retrieve aerosols and water vapor from high spectral resolution data, but the general approach is to calculate them separately (see, e.g., [6–9] for aerosol retrieval and [10–13] for water vapor). However, due to the coexistence of aerosols and water vapor in the same low atmosphere layers (~ 2-3 km), the coupling can be important: aerosols radiative effects are noticeable in the near-infrared (NIR) bands if middle-big size aerosols are present, coupling to absorption in those wavelengths close to the water vapor absorption band centered around 0.94 µm.

So, we have implemented a procedure which retrieves aerosols and water vapor contents simultaneously. The retrieval is based on the assumption that the atmospheric state is invariant inside a 30 x 30 km window (or the whole image for sensors with swath less than 30 km, as CHRIS), while the surface reflectance varies from pixel to pixel. This one is given by a linear combination of two vegetation and soil spectra, which act as endmembers. Then, aerosol and water vapor contents are retrieved simultaneously from 5 pixels inside this window, by means of a multiparameter inversion of the TOA spectral radiances from a selected combination of bands, chosen depending on the particular band configuration of each sensor.

This inversion is performed by means of the minimization of a Merit Function δ2 specifically designed for this problem,

\[ \delta^2 = \sum_{pix=1}^{5} \sum_{\lambda_i} \frac{1}{\lambda_i} \left( \rho_{TOA|pix,\lambda_i} - \rho_{SIM|pix,\lambda_i} \right)^2 \] (1)

where \( \rho_{SIM} \) is the TOA reflectance simulated with the 6S code, \( \lambda_i \) corresponds to the center of the \( i \) band in the particular band configuration of the sensor, and \( \rho_{TOA} \) stands for the TOA apparent reflectance measured by the sensor, given in terms of the TOA radiance \( L_{TOA} \), the solar constant \( E_{sc} \) and the cosine of the solar zenith \( \mu_s \) angle by

\[ \rho_{TOA} = \frac{\pi L_{TOA}}{\mu_s E_{sc}}. \] (2)

The free parameters in the optimization are the water vapor column content, the aerosol loading and the percentage of basic types, and the proportions of vegetation and soil endmembers for each of the 5 reference pixels.
The particular selection of 5 as the number of pixels to serve as a reference for the atmospheric retrievals is a balance between the computation burden and the representative sampling in the 30 × 30 km window: a higher number would increase the number of free parameters in the inversion, without adding too much information to the sampling. The 5 reference pixels must have a spectral contrast as strong as possible (ranging from pixels with high vegetation content to high soil content) in order to improve the numerical stability in the inversion process. A perfect choice for the set of reference pixels would be a pure vegetation pixel, a pure bare soil pixel, and three intermediate ones, mixture of vegetation and soil.

The Merit Function in Eq. 1 is weighted by \( \lambda \) so the soil.

For aerosol characterization, the SRA types defined by the Radiation Commission of IAMAP [16] (dust-like, water soluble, oceanic and soot) are implemented in the 6S database. So, aerosols are specified by means of the visibility and the percentages of those basic types, resulting in 4 free parameters.

Regarding water vapor, the total column content is another free parameter to be inverted. The vertical profile is given by the U.S. Standard Atmosphere [17], also implemented in the 6S database. The ozone profile is set by this default atmosphere as well.

The surface spectral reflectance is given by the linear combination of two endmembers of typical vegetation (alfalfa) and soil spectra,

\[
\rho_s = C_v \rho_{\text{veg}} + C_s \rho_{\text{soil}} \quad C_v, C_s \in [0, 1.5] \tag{4}
\]

The proportions of vegetation and soil are allowed to be bigger than 1.0 in case spectra brighter than the endmembers are present. The ten coefficients \( C_{v,s} \), 2 for each of the 5 pixels, are also free parameters in the TOA reflectance simulation.

The minimization of the Merit Function in Eq. 1 is performed by the Powell’s Minimization Method [18], based on a 1-D minimization separately in each direction of the parameters space, without the need of the analytical expression of the function derivatives. An appropriate initialization of the Powell’s algorithm is needed in order to reduce the convergence time and to reach the best minimum. For the atmospheric parameters, common values are selected: visibility 23 km, a mixture of continental and maritime model for aerosol type and a water vapor column content of 2.0 g·cm\(^{-2}\). Concerning the vegetation and soil proportions, a strong correlation between the \( \text{Normalized Difference Vegetation Index} \) (NDVI) [19] and the coefficients \( C_{v,s} \) was found from several simulations.

### 3.2. Surface reflectance retrieval

**General Procedure: Lambertian assumption**

Once the atmospheric functions are calculated, they are used to retrieve the surface reflectance image from the TOA radiance image provided by the sensor. As starting point, a Lambertian reflectance for the surface is assumed, what leads to the analytical inversion of Eq. 3 to retrieve \( \rho_s \). So, an initial surface reflectance image is obtained with a little algebra.

This is an important justification for the Lambertian assumption. However, some authors have pointed out that this assumption may lead to noticeable errors in some particular combinations of geometry,
target reflectance and atmospheric state conditions [20, 21]. The problem is that multangular information is needed in order to characterize properly the BRDF effects in the target. In the case of platforms with multangular viewing capabilities, such as PROBA, accounting for the directional effects in the target reflectance is feasible. Then, although the general procedure is based on the Lambertian assumption also for CHRIS/PROBA, a further step involving directional effects has been done for some pixels in the image.

**BRDF/Atmosphere Coupling Correction**

In order to consider directional effects in the target, instead of Lambertian behavior, Eq. 3 can be extended to account for the BRDF coupling between atmosphere and surface reflectance [22]. However, the resultant formulation is not analytically invertible to retrieve $\rho_s$, because this is embedded in integrals accounting for the atmosphere/surface coupling terms (surface hemispherical-directional, directional-hemispherical and hemispherical-hemispherical reflectances, angular integrals of the downward radiance field and the surface BRDF). Then, for the evaluation of the coupling terms $\rho_s$ is, in turn, needed. We have then an integral equation, which may be solved by an iterative process.

Thus, there is a need for techniques that can provide some surface information, to be used in the calculations of the coupling terms. In practical considerations, there are several ways to get these initial estimates of the surface reflectance. Most of them depend on the availability of other surface products, but some authors [20, 23] have suggested surface BRDF information can be retrieved from an initial correction assuming a Lambertian surface, where coupling terms are not needed. The angular pattern retrieved by means of the Lambertian assumption is fitted to a BRDF model, which is used to perform the integrals in the coupling terms. Once the coupling terms are known, a newer set of $\rho_s$ values is obtained. This is again used to update the coupling terms and the subsequent $\rho_s$ values. The procedure continues in this fashion until convergence in two consecutive iterations is found.

The BRDF model we use to fit the angular pattern $\rho_s$ in each iteration is the RPV model [24], which offers a good balance between number of free parameters, three, and flexibility in the representation of distinct BRDF shapes. The retrieved angular pattern is fitted to RPV model by means of the Powell’s Minimization Method, and the angular integrals for the coupling terms are numerically calculated with the Gaussian quadratures method. The final output of this BRDF coupling correction is a second order correction of the surface reflectance obtained from the Lambertian assumption, more substantial in the larger observation angles. A detailed description of the procedure is given in [25].

From an operational point of view, the application of this procedure to a set of images, as it should be in the case of the CHRIS/PROBA 5 angles, is quite complex:

- The fit to the RPV model is computationally very expensive on a pixel by pixel basis (even if a linear kernel model was chosen instead). So, the time needed in each iteration would be prohibitive for practical applications.

- The geometric correction of the images has an associated error of around three pixels, what corresponds to around 100 m in the surface. As a result, it is not very rigorous to assume 5 viewing directions for every single point, because the value corresponding to one angle might be referred to a point in the neighborhood of the observation point for another angle. Particularly, this leads to important problems in the evaluation of the borders of different surfaces in the images, as different angles might be viewing different surfaces, in both sides of the boundaries.

- There is only a partial overlapping in the observed region for the 5 images, so an initial test of the number of angles needed to perform an adequate BRDF correction should be done for those areas not viewed from all of the angles.

For these reasons, the BRDF correction has only been made for some pixels in the CHRIS/PROBA images, taken visually from the center of uniform surfaces in the overlapped region, to avoid the problems with the geometric correction. Anyway, directional effects do not cause important modifications of the results obtained with the Lambertian assumption, as expected for a geometric configuration out of the principal plane, what reinforces the use of the Lambertian approach.

**Adjacency Correction**

The final step in our atmospheric correction algorithm is the removal of the image blurring caused by those photons reflected by the target environment and scattered by the atmosphere particles into the sensor’s line-of-sight. This effect is called adjacency effect because the apparent signal at the TOA of a pixel comes also from adjacent pixels.

The adjacency correction involves inverting the linear combination of reflectances to isolate the reflectance of the target pixel. The simple formulation proposed by Vermote et al. [20, 26], weighting the strength of the adjacency effect by the ratio of diffuse to direct ground-to-sensor transmittance, is used:

$$\rho_s = \rho_s^u + \frac{t_d(\mu_v)}{e^{-\tau/\mu_s}} [\rho_s^u - \bar{\rho}], \quad (5)$$

where $\rho_s^u$ is the surface reflectance before the adjacency treatment, $\rho_s$ the final surface reflectance,
output of the complete atmospheric correction algorithm, and $\bar{\rho}$ is the average of the environment reflectance. This average is calculated for a $1 \times 1 \, \text{km}^2$, which is in the same order of the aerosol coupling scale.

4. RESULTS

4.1. Atmospheric Retrievals

Once the algorithm has been properly implemented and tested with simulated data, it has been applied to real CHRIS/PROBA data. The ESA SPARC campaign (SPectra bArrax Campaign) \[^{[27, 28]}\] has been very important in the validation of the algorithm, as it offered a unique situation in which CHRIS/PROBA images were acquired simultaneously to atmospheric and ground in-situ measurements. The SPARC campaign took place in Barrax, La Mancha, Spain, from 12 to 14 of July 2003, under the umbrella of a formal ESA campaign as part of Phase-A Preparations for the SPECTRA mission.

We have two sets of CHRIS/PROBA images from that date (12th and 14th July 2003, acquired in mode 1, 62 bands and 34 m). The results obtained from the application of the algorithm to those images and the validation with in-situ measurements will be discussed next.

Starting with the atmospheric retrievals, 5 reference pixels have been selected according to the criterium of having a maximum spectral contrast: one pixel from a potato field, two from corn, one from alfalfa and the last one from bare soil. Concerning the inversion of the TOA radiances for the 5 reference pixels in order to estimate the atmospheric information, from a quick look to Fig. 1 it may be noted that some discrepancies happen between the TOA radiances spectra and the fitted ones. Dashed circles show the wavelengths with major deviations. The bands in the extremes of the spectral range are among them. This was a priori expected due to the detectors in the borders of focal plane arrays usually present problems, because the maximum performance for array detectors is chosen to be in the center of the array. Other wavelengths with possible calibration problems are around 0.5 and 0.85 $\mu$m: in the first case, either a binning problem, shifts in the spectral positions of the narrow bins which compose a band, or a bad implementation of the filter functions may explain the apparition of two peaks between 0.48 and 0.52 $\mu$m.

Despite these problems, the information in the rest of bands is enough to lead to reliable results. The water vapor column contents for 12 and 14 July are compared with the values provided by radiosoundings launched simultaneously to PROBA overpasses in Table 1. The errors are around 13% taking radiosoundings as a reference, what is a good result if the high spatial variability of water vapor and the CHRIS calibration problems mentioned are considered.

Concerning aerosols retrieval, the calculated parameters are displayed in Table 2. The visibility values are around those found in normal atmospheric conditions. However, we can state that the algorithm seems to not be very sensible to aerosol types, because the retrieved values are very close to the initialization values. Anyway, these values are not very different from those expected in Barrax (rural and possible Mediterranean maritime aerosols).
Ground solar irradiance spectra, global and direct radiation, have been used to validate the retrieved aerosol parameters. In Fig. 2 the ground measurements, taken simultaneously to the image acquisition by a LICOR detector\(^1\), are compared with runs of the 6S code under the same conditions, setting aerosol specification to the values in Table 2.

Figure 2. Comparison of 6S code simulated total and direct irradiances using the retrieved atmospheric parameters as input with ground measurements (12/07/03).

4.2. Surface Reflectance Retrieval

Surface reflectance spectra for 2 of the 5 reference pixels obtained from the retrieved atmospheric parameters and Eq. 3 are plotted in Fig. 3, as well as the TOA apparent reflectance.

It can be stated that not only several systematic small artifacts are present in the corrected spectra, but also the typical plateau shape for vegetation spectra is lost. From a close look at these artifacts in the 5 spectra, one can note that, despite looking like some random noise, they have a systematic fluctuation, with a similar spectral variation. Thus, a procedure eliminating these oscillations should provide a set of spectral multiplicative coefficients to be applied to every spectrum after the atmospheric correction. We have called this procedure *recalibration*, as it has similarity with in-flight calibration procedures to convert digital numbers to radiances [29,30].

4.3. Surface Reflectance Recalibration

To find a spectral recalibration curve, there is a need for reference patterns to be used in the calculation of the multiplicative coefficients. This is usually done by means of ground measured spectra, taken with a relative temporal coincidence with the image acquisition. However, these spectra are seldom available, except for data from ground campaigns.

As the requirement is to have some reference surface spectra free from artifacts and with the same reflectance levels, we can use the surface reflectance spectra constructed by the atmospheric retrieval module, avoiding the limiting use of ground measurements: the \( C_{v,s} \) coefficients calculated as a by-product in the atmospheric retrievals can be used with Eq. 4 to calculate a surface reflectance spectrum free from the spikes for each one of the 5 reference pixels. Then, thanks to the systematism in the oscillations, a correlation can be derived between spiky and smooth spectra, given the recalibration coefficients as a result. For each band, the recalibration coefficients are the slope of the linear fit of the 5 points (one for each reference pixel) corresponding to the comparison between the smooth and the spiky reflectances.

The resultant recalibration curves for the 5 angles are shown in Fig. 4. The curve obtained from the MODTRAN4 simulations is also plotted. Several conclusions can be extracted from Fig. 4:

- The recalibration not only removes little artifacts, but it also reconstructs the expected shape in the NIR wavelengths, with a recalibration reaching a factor 2. The correction in the first band is important as well. This confirms the

\(^1\)Data from the Solar Radiation Unit of the University of Valencia
a priori expectations, because the focal plane array is designed to have the best radiometric quality in the central wavelengths, getting worse as the wavelength approaches the extremes.

- The spikes in the corrected spectra are not due to intrinsic inaccuracies in the correction algorithm, because the spectral position and signs of the peaks in the recalibration curves are different in those from MODTRAN4 and CHRIS data. If there were a systematic miscalculation of the atmospheric functions, it would have been detected in both simulations and real data.

- The recalibration curve is nearly angle independent, as the different curves are almost overlapped. This reinforces the validity of the coefficients as universal coefficients to be applied in a vicarious calibration of the raw TOA data.

- Both the general shape and the levels of the recalibration curve are in very good agreement with the one provided by Sira Technology Ltd, the designers of the instrument (M. Cutter, personal communication), calculated from an engineering perspective.

The surface reflectance after the recalibration for the 5 reference pixels is shown in Fig. 5. The results are highly satisfactory, as the spikes have been completely removed, and the vegetation plateau in the NIR is also recovered. Only in the bands between 0.95 and 1 µm some artifacts are still visible, due to the perturbation caused by the influence of plants water content, as well as the mentioned high degradation of the detectors response. This results in an overestimation of the reflectance in these bands in the case of soil surfaces, what would be difficult to improve.

Each recalibration curve is applied to the corresponding image after the atmospheric correction. Fig. 6 displays a true color composition of the TOA and corrected images for FZA= 0° from 12 July. From a quick look at them, an important decrease of the blue level is found in the corrected image, due to the removal of molecular and particle scattering in the shorter wavelengths. An increase in the contrast is also appreciable thanks to the treatment of the adjacency effects.

The algorithm basis is general enough to be applied to different sensors with little modifications in the implementation. Thanks to this, it is being used to correct small windows from MERIS images. Even though the spatial resolution is completely different, some corrected spectra from CHRIS and MERIS have been compared in Fig. 7. To avoid problems with sub-pixel mixing, the spectra have been extracted from uniform zones in the image. The agreement in the results is high, even with the differences in calibration and technical capabilities of both sen-
sors, which demonstrates the algorithm’s reliability and consistency.

5. CONCLUSIONS

A new atmospheric correction algorithm for satellite data taken over land has been presented in this work. The fundamental basis lies on the estimation of the main atmospheric parameters from the data to be corrected, what provides an accurate characterization of the atmospheric state simultaneous to the image acquisition.

The strategy followed for the retrieval of the atmospheric information avoids the limiting use of dark targets, so the algorithm can be applied to a wide range of land surfaces, from dense forests to arid areas.

A polishing/recalibration curve for the smoothing of the retrieved surface reflectance is automatically calculated by the algorithm, without needing external ground measurements as a reference. This curve accounts for both small inaccuracies in radiative transfer calculations and calibration problems of the sensor.

Real CHRIS/PROBA data present important calibration problems, specially in NIR wavelengths. Radiiances are underestimated in such spectral range. Anyway, the information for atmospheric characterization seems to be enough, as stated by means of the comparison of the retrieved atmospheric products with ground measurements taken during the ESA SPARC campaign. The recalibration procedure fixes calibration problems, leading to smooth surface reflectance spectra with the typical flat plateau shape in NIR for pure vegetation pixels. A comparison with surface reflectance spectra derived from MERIS data provides a validation of the recalibration procedure and of the complete algorithm, as the surface reflectances retrieved from each sensor are quite similar and no recalibration is applied to MERIS data.

REFERENCES


QUASI-AUTOMATIC GEOMETRIC CORRECTION AND RELATED GEOMETRIC ISSUES IN THE EXPLOITATION OF CHRIS/PROBA DATA

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ABSTRACT

The multiangular and off-track pointing capabilities of CHRIS/PROBA introduce a strong distortion on the geometry on the resulting images. In order to make full scientific use of the data some information about the geometry of acquisition is needed. In particular, the viewing azimuth and zenith angles must be known, and the images must be geometrically corrected to make possible multi-angular and multi-temporal studies.

CHRIS/PROBA images are distributed with ancillary data related to its acquisition. The angles provided with the images, Minimum Zenith Angle (MZA) and Fly-by Zenith Angle (FZA), accurately determine the satellite-target geometry, but they are not the ones needed for atmospheric / angular corrections, and the information provided with the data is not enough to derive the required geometric information.

There is an urgent need of precise methods to obtain the CHRIS/PROBA data in a practical format. That means precise Azimuth and Zenith Observation Angles for each image, and accurate geometric correction of the images. Also, the great volume of images provided demands, in order to be practical, that these methods should be automatic with a minimum intervention for quality checks in the processing.

1. INTRODUCTION

Before scientific use of satellite images they need some preprocessing (e.g. geometric and atmospheric correction) to convert them to the physical values of interest for each study.

The objective for CHRIS is to provide Earth surface hyperspectral reflectance data with a wide range of different viewing configurations, and provide Bidirectional Reflectance Distribution Function (BRDF), for atmospheric, land and coastal studies [1].

Geometric correction transforms images, as they are acquired by the sensors, to match a certain cartographic projection, free of distortions; and each pixel is assigned with coordinates. Several methods exist to perform geometric correction, each one with pros and cons. Atmospheric correction removes effects of the atmosphere on the radiation from the surface that arrives to the sensor; it also converts the physical values of the image from radiance to ground reflectance. But it needs accurate observation and illumination angles for each pixel.

Other scientific studies also need observation and illumination angles; some examples are research of angular effects, retrieval of biophysical parameters from surface BRDF, or surface albedo determination.

1.1 Geometric Correction

After receiving the first CHRIS/PROBA image set we performed a ground control point (GCP) correction over a georeferenced Landsat image, to quickly produce geometrically corrected images. But this method is time consuming and the interpolation applied cannot correct all the distortions in an image, especially in areas where there are few features to set as GPC. This method becomes unpractical for coastal waters, and inapplicable for open sea scenes.

Each CHRIS/PROBA acquisition is a set of up to five images taken with different view angles [2]. Geometric correction must be applied independently to each image. In the case of extreme observations (FZA=+-55) GCP are very difficult to determine with precision, what introduces further distortions in the geometric correction using this method. GCP correction is very time consuming, and becomes unpractical for processing of a time series of acquisitions.

Also the correction of images with different view angles introduces a problem of resampling. Due to the different viewing geometry the pixel size is variable, but after coregistration they must have the same size, therefore interpolation is required. But standard methods are not always satisfactory.

At present the general method to correct CHRIS/PROBA images is using Ground Control Points [1]. More sophisticated alternatives are available: e.g. co-registration method, but they present other problems, as interpolation, or the lack of providing observation angles.

1.2 Knowledge of Observation Angles

The determination of the solar illumination angles can be easily obtained knowing the geographical coordinates of the target and the time of the acquisition. But the observation angles of each pixel cannot be obtained by direct methods without previous knowledge about the sensor design and operation, and the satellite position and orientation at acquisition time.
The angles provided with the images, Minimum Zenith Angle (MZA) and Fly-by Zenith Angle (FZA), accurately determine the mean satellite-target geometry [3]. But their definitions are based on engineering criteria and are very useful to operate the satellite, but they are not appropriate for scientific analysis. Therefore it is necessary to convert MZA and FZA to standard view azimuth and zenith angles.

PROBA is capable to manoeuvre pointing off-track to acquire images of sites even when the satellite does not pass directly above them.

In order to operate PROBA needs to know where to point to, that is, what rotations it has to perform so the programmed target falls within the field of view of CHRIS sensor. These rotations are more easily defined with respect to the position in the orbit of maximum approach to the target. At this moment the satellite is flying over a certain location that we designate sub-satellite position at maximum approach (SSMA), and the view zenith angle to the target is minimum for this orbit (MZA). The SSMA serves as reference point to define the Fly-by Zenith Angle (FZA). These angles are univocally related to the observation azimuth and zenith angles, as reflected in Fig. 1.

Fig. 1. Relationship between engineering and observation view angles

1.3 Parametric Method

A quasi-automatic parametric method (a mathematical orbit/attitude model) is desired, because it reproduces the acquisition process; thus it does not require GCPs except a few in order to correct for small deviations from nominal actuation of the satellite. It also provides accurate observation angles, and actual pixel sizes, allowing the use of better interpolation methods that take into account the point spread function (PSF) of the sensor.

The problem is that the ancillary data available with the images provided are not enough to apply parametric correction directly.

2. DETERMINATION OF OBSERVATION ANGLES

Scientific applications require the knowledge of observation angles. In order to calculate view azimuth and zenith angles from the MZA and FZA there are various possible approaches:

- Orbit propagation from TLEs
- Spherical geometry calculations
- As by-product of parametrical geometric correction.

The first, based on orbital mechanics, is more rigorous but its application is complex.

The second is based on geometrical relationships and makes some approximations. It is simple and fast.

The last provides an accurate calculation of the view angles, but it is currently under development, so we are using only the first two.

2.1 Orbit Propagation

The orbital elements of a satellite are a set of parameters that determine the orbit that the satellite is following at a given moment. Using these orbital elements with the appropriate orbital model it is possible to calculate the position and velocity in space of the satellite at any given time past or future; this is called orbit propagation. The model allows calculating the viewing angles of the satellite from a given point in the surface of the earth, among other parameters.

The CHRIS/PROBA team makes available the orbital elements for the satellite in a daily basis in the form of Two Line Elements (TLE) calculated by the EE.UU. NORAD surveillance system [4]. These TLEs must be used with the NORAD’s SGP4/SDP4 orbital model [5]. In particular we have used the TrackStar implementation of the orbital model developed by T. S. Kelso.

In case of very stable orbits the propagation from a given set of orbital elements can be very accurate for long periods of time. In the case of PROBA its orbit is low and suffers of atmospheric drag and other types of perturbations, because of that it is very unstable and the propagations are only accurate within a few weeks. Therefore, to calculate the observation angles of a given image set it is recommended to use the closest TLE available.

To calculate the observation angles from the known MZA and FZA the model must be run setting the observation point at target location (TGT), to determine the time of maximum approach (i.e. the moment when
MZA is reached), and the corresponding sub-satellite coordinates (SSMA).

Then, it is run again using the SSMA coordinates as target to get the times when Fly-by Zenith Angle (FZA) ±55 and ±36 occur. Finally, going back to the first run to obtain the observation angles at the proper time stamps.

The whole process is schematized in Fig. 2 as flow chart.

![Flow chart for determination of view angles by orbital propagation.](image)

This method is not practical because it requires several runs and the available models need code rewriting in order to automate the process; so simpler ones are needed.

### 2.2 Spherical Geometry

Due to the need of a simple method to know the actual view angles we have obtained the relationship between the engineering angles (FZA, MZA) and the observation zenith angles, by means of spherical geometry. At present the assumptions are spherical Earth and circular orbit, but the precision obtained is sufficient.

\[
\begin{align*}
A &= \text{FZA} - \arcsin\left(\frac{R_t}{R_t + H}\right) \cdot \sin(\text{FZA}) \\
B &= \text{MZA} - \arcsin\left(\frac{R_t}{R_t + H}\right) \cdot \sin(\text{MZA}) \\
C &= \arccos\left(\cos(A) \cdot \cos(B)\right) \\
\text{VZ} &= \arctan\left(\frac{\sin(C)}{\cos(C)}, \frac{R_t + H}{R_t - \cos(C)}\right) \\
\text{RVA} &= \arcsin\left(\frac{\sin(A)}{\sin(C)}\right)
\end{align*}
\]

Where \(R_t\) is mean Earth radius, \(H\) is the altitude of the satellite, \(\text{VZ}\) is the view zenith angle, and \(\text{RVA}\) is the relative azimuth angle. The function \(\arctan(x,y)\) returns the angle whose tangent is equal to \(x/y\) in the \([-\pi, \pi]\) range.

Azimuth observation angles obtained in this way are relative to the maximum approach direction, so a second relationship is found between the MZA and the inclination of the orbit to determine the actual Observation Azimuth Angle.

The MZA defines a circle of radius \(R\) around the target. The inclination \(i\) of the orbit limits the possible ground tracks to two solutions. The sign of the MZA determines which one of the two is the correct solution, as illustrated in Fig. 3.

![Fig. 3. Determination of the actual view azimuth angle.](image)

### 2.3 Comparison of Results

To test these two simpler methods we used the images corresponding to the SPARC RC campaign, which took place in Barrax (Spain) between the 12\(^{th}\) and the 14\(^{th}\) of July 2003. There were images available the first and last days, unfortunately the acquisition of the 13\(^{th}\) (nadir view pass) failed.

We used the following data with the spherical geometry approach and the orbit propagation model.

The coordinates of the site:

- 39.047N, -2.073E
- 700m ASL

The TLE from the 12\(^{th}\) of July:

\[
\begin{align*}
1 & \text{ 26958U 01049B 03193.84088317 .00001065} \\
& 00000-0 11503-3 0 243 \\
2 & \text{ 26958 97.8423 271.3000 0083543 329.7739 29.8652 14.88062739 93418}
\end{align*}
\]

The provided MZA in the HDF files were:

- MZA = 20\(^{\circ}\) on the 12\(^{th}\) of July
- MZA = -27\(^{\circ}\) on the 14\(^{th}\) of July

The inclination of the orbit is 97.8423\(^{\circ}\) (from the TLE).

Both methods provide similar results with the greatest difference being azimuth at maximum approach (the
fastest varying parameter), and it is less than 1 degree. Results are summarized in Fig. 4 and Tables 1 and 2.

Table 1. Calculated view angles for the image set of SPARC campaign using spherical geometry.

<table>
<thead>
<tr>
<th>FZA</th>
<th>+55</th>
<th>+36</th>
<th>0</th>
<th>-36</th>
<th>-55</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/07/2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth</td>
<td>26.11</td>
<td>37.98</td>
<td>102.40</td>
<td>165.44</td>
<td>177.06</td>
</tr>
<tr>
<td>Zenith</td>
<td>55.99</td>
<td>38.78</td>
<td>19.40</td>
<td>39.15</td>
<td>56.24</td>
</tr>
<tr>
<td>14/07/2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth</td>
<td>353.77</td>
<td>339.44</td>
<td>285.27</td>
<td>231.22</td>
<td>216.91</td>
</tr>
<tr>
<td>Zenith</td>
<td>57.29</td>
<td>42.44</td>
<td>27.60</td>
<td>42.53</td>
<td>57.40</td>
</tr>
</tbody>
</table>

Table 2. Calculated view angles by orbital propagation

<table>
<thead>
<tr>
<th>12/07/2003</th>
<th>Orbital Propagation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuth</td>
<td>26.093 37.654 101.568 165.412 176.946</td>
</tr>
<tr>
<td>Zenith</td>
<td>56.025 39.132 19.420 39.146 56.042</td>
</tr>
</tbody>
</table>

Fig. 4. Polar plot, showing the angular configuration for the SPARC campaign. Data corresponding to the 12th of July in blue diamonds, 14th of July in red squares.

2.4 Side Effects of Slow-down Factor

The previous methods provide easy solutions that do not need much effort to implement. They make some assumptions, that in general are appropriate, but there is one that can be problematic: the consideration that during the acquisition of an image the observation conditions do not change substantially.

In reality, the satellite uses the forward motion to perform the scanning process, and at the same time rotates slightly to keep the target pointed for a longer time in order to increase the signal to noise ratio [6]. This means that the distance covered by the satellite is longer than the surface scanned, and the effect is as if the satellite was travelling slower. The ratio between both distances is known as slow-down factor.

Due to the slow-down factor applied to increase integration time, the angles of observation of the first and last lines of the image are no longer equal. This difference is larger for larger slow-down factors. In the case of CHRIS/PROBA, its slow-down factor of 5 introduces noticeable variation in the observation angles throughout the image.

So the solutions provided by the simpler algorithms represent only the mean value of the observation angles. For most applications this is sufficient, but for some others, especially BRDF and angular effects studies, more precise values are necessary.

Fig. 5 illustrates how the slowdown factor increases the angles of observation within one image acquisition. It also shows that the scanning direction is reversed at ±36º from the forward advance of the satellite. This is designed so in order to reduce the rotation rate needed to operate the satellite.

We have calculated what would be the actual range of view angles within every image of the SPARC campaign, which includes large off-track pointing (MZA=-27) and almost nadir pointing (MZA=-4). We also calculated it for a theoretical case of nadir passing. The results are shown in Tables 3 and 4 and depicted in Fig. 6.

To calculate these ranges we have used the orbital propagation model, and we needed to make some assumptions as close to the real case as possible: The time that takes to acquire any image is always 10s and the acquisition begins 5s before reaching FZA (dashed red line in Fig. 5). Also we have considered, for simplicity, that the sensor is always pointing to the centre of the scene; this implies that we disregard the reverse scanning for FZA=±36, so our results in these cases would be slightly underestimated.
Table 3. Range of view angles at start, mid and end of image acquisition for close to nadir observation.

<table>
<thead>
<tr>
<th>FZA</th>
<th>MZA = -4</th>
<th>Time</th>
<th>Azimuth</th>
<th>Zenith</th>
</tr>
</thead>
<tbody>
<tr>
<td>+55</td>
<td>start: 11:18:11</td>
<td>9.5788</td>
<td>56.3865</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mean: 11:18:16</td>
<td>9.4395</td>
<td>55.0605</td>
<td></td>
</tr>
<tr>
<td></td>
<td>end: 11:18:21</td>
<td>9.2864</td>
<td>53.6715</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Δ=0.2924</td>
<td>Δ=2.7150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+36</td>
<td>start: 11:19:04</td>
<td>6.9338</td>
<td>38.3996</td>
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<td>Δ=0.2980</td>
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Table 4. Range of view angles at start, mid and end of image acquisition for extreme off-nadir observation.

<table>
<thead>
<tr>
<th>FZA</th>
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<th>Time</th>
<th>Azimuth</th>
<th>Zenith</th>
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<tr>
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<td>+36</td>
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<td>43.8842</td>
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</tr>
<tr>
<td></td>
<td>mean: 11:31:26</td>
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<td>42.2938</td>
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</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Δ=4.3541</td>
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<tr>
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<td></td>
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<tr>
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<td>40.7545</td>
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</tr>
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<td>mean: 11:33:32</td>
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<td></td>
<td>Δ=1.6461</td>
<td>Δ=3.2314</td>
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<td></td>
</tr>
</tbody>
</table>

If we look at the results, we see that the difference of angles at start and end of the image of the azimuth and zenith angles are very different depending on the FZA and MZA. For FZA=0 the effect is stronger in azimuth; even for a pass very close to nadir (MZA=-4) the zenith angle has only a variation of ~1º, but when it reaches MZA=0 the zenith angle has the greatest variation ~6.5º, and the azimuth angle has only a change in the direction (180º). At FZA=±36 the change affects both azimuth and zenith angles, and with exception of the nadir case, it has the greatest zenith variations. In the cases of FZA=±55 the variation is smaller and affects more the zenith angle.

Fig. 6. Polar representation of the calculated observation angles at start, mid and end of each image acquisition.

In order to represent with a single magnitude the range of the observation angles we have considered the azimuth and zenith angles as coordinates of a unitary vector in spherical coordinates. Then we have calculated the scalar product of the start and end vectors, which is related to the angle formed by both vectors. The resulting quantities, in Table 4, show that the absolute angle variation within the images is similar at each FZA independent of the MZA, being more important in the case of maximum approach (FZA=0). But the contribution of azimuth and zenith angles to this variation depends on how far is the overpass from nadir, as described previously.

Table 5. Absolute angle variation due to slowdown factor in SPARC images and a theoretical nadir case.

<table>
<thead>
<tr>
<th>FZA</th>
<th>MZA = -27</th>
<th>Time</th>
<th>Azimuth</th>
<th>Zenith</th>
</tr>
</thead>
<tbody>
<tr>
<td>+55</td>
<td>start: 11:30:28</td>
<td>354.5574</td>
<td>58.426</td>
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</tr>
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<td>mean: 11:30:33</td>
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<td></td>
<td>end: 11:30:38</td>
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<tr>
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<td>-36</td>
<td>start: 11:33:27</td>
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<td></td>
<td>Δ=1.6461</td>
<td>Δ=3.2314</td>
<td></td>
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</tr>
</tbody>
</table>

3. SIMPLE GEOMETRIC CORRECTION

A simple geometric correction is possible by using the zenith and azimuth viewing angles together with basic orbital information and making the assumption of instantaneous image acquisition. The image is then...
projected onto the surface of the Earth using the cross-track Field of View (FOV) and an effective along-track Field of View.

Because the sensor is “push-broom” type there is not a real FOV, just an Instant Field of View for each line, so an effective FOV for the whole scene must be used that can be estimated taking into account the duration of the acquisition, a reference pointing profile and the slowdown factor.

This method could be adequate for those orbits which overfly the target very close to nadir, and always using some GCP to adjust the correction. In the case of off-track pointing this approach might not very reliable.

We do not expect the method to be accurate enough to provide a satisfactory result by itself, but it is automatic and gives a better starting point for the application of GCP correction, reducing drastically the number of control points required (i.e. less time required) and improving results.

4. PARAMETRIC GEOMETRIC CORRECTION

A parametric correction method would be able to describe rigorously the acquisition process [7], and to provide accurate results needed for scientific purposes.

The idea is to reconstruct the position and orientation of the sensor at each instant of the acquisition process making possible to determine the actual geographical coordinates of each pixel. To do the orbit reconstruction it is necessary to combine all the available data from PROBA (TLE and telemetry data).

Taking into account that the acquisition of a single image takes 10s and it has 748 lines, this means that the time precision needed is 1/100 of a second in order to have the time reference assigned to a single line. Such precision is required to link GCP and orbital parameters that help to increase accuracy in the correction process.

Telemetry data available in the image headers is by far too coarse to be useful for a parametric approach to geometric correction, although some parameters (e.g. calculated image centre time) could be useful together with the corresponding TLE if no other telemetry data is available.

Fortunately the full telemetry data received at the PROBA control ground station has a time precision of 1/1000 of second , that greatly satisfies the precision required; but it is updated every 25s which is longer than the acquisition time of a single image [8]. The orbit is quite stable within that lapse of time, so interpolation is a satisfactory solution. In the case of attitude, the pointing manoeuvre takes place in a matter of few seconds, therefore the telemetry data is not enough precise for direct correction procedure, and an estimation of the attitude is necessary.

After orbit determination, one can reconstruct the attitude reference profiles in the satellite reference in the same way as the satellite computes the Guidance Profile Generation [9]. Since the method does not require the derivatives of such angles (the satellite needs the second derivative to compute forces) the computation is rather straightforward, and then a simple algorithm allows geolocation.

Initially all error is attributed to the fact that initial attitude data used by the satellite to compute the guidance profile can be slightly wrong due to the filtering of star-tracker data [1], and then GCPs are used to recompute the reference initial attitude for the same attitude guidance profile. If this is not enough the residuals can then be used to model polynomials in time for the deviations in attitude angles during the acquisition sequence (a second-degree polynomial in time during each one of the five acquisitions). We want to combine all these corrections with a very sophisticate resampling technique [10] to compensate the different ground spatial resolutions for each angular view, something possible if a detailed reconstruction of the observation geometry is available.

A general scheme of the whole process is synthesized in Fig. 7, where the dependencies between the different steps are reflected, and the role of GCPs as mean of error reduction.

Despite its complexity, this method is very convenient, in particular when a large amount of images must be processed. In the case of open coastal waters, where the number of available GCPs is small or even inexistent, this method becomes the only reasonable solution to corregistration of images.
5. CONCLUSIONS

In the present work we analyse the problems related to the geometry of a complex dataset as it is the multiangular image set from CHRIS/PROBA, namely:

- The calculation of the observation angles of each single image: the angles (MZA and FZA) provided with the images are related to the operation of the satellite, and only indirectly to the observation angles.

- The effect of the slowdown factor: due to the acquisition manoeuvres to increase the radiometric performance of the sensor, the view angles are not constant within each image. For precise BRDF studies the actual view angles should be calculated.

We propose a general method for the geometric correction of CHRIS/PROBA images based on the physical modelling of orbit and attitude parameters and such method will also provide accurate observation angles for every single pixel. This method provides almost automatic correction of the images, with the use of just a few GCP needed to assess the accuracy of the telemetry and attitude.

Some advantages of the proposed method are

- it can operate with minimum supervision, so it can handle large number or images in short time.

- it can work without GCPs (at the cost of accuracy) allowing the georectification of open water images.

- it provides accurate observation angles in per-pixel basis

- it solves the problem of resampling pixels of different sizes

Until full development of this geometric correction procedure, more simplistic approaches have been presented for immediate use:

- Spherical geometry relationships to obtain view angles from data available in the image header.

- An orbital propagation method that uses published TLE data, with similar results to the spherical geometry solution.

- A “photographic model” that could help to accelerate the geometric correction process by standard GCP procedure.
It is certain that many users are facing similar problems related to the geometric correction procedure, but it is also sure that most users cannot (or do not want) to enter into this kind of technical details.

The same is true for removal of noises, atmospheric corrections, etc. but it seems that the geometrical problem is particularly crude, and the current situation where users have even difficulties to compute elementary magnitudes such as view zenith and azimuth angles should be corrected. Some generic procedure, operational but accurate enough, would be quite useful for the CHRIS/PROBA community.

ACKNOWLEDGEMENT

This work has been supported by the ESA project SPARC RFQ/3-10824/03/NL/FF. We would like to thank the kind help of Mike Cutter and Jeff Settle.

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ABSTRACT

CHRIS/PROBA images are affected by two main noises, and for simplicity we will call them horizontal and vertical noises.

Horizontal noise consists in the random loss of partial data from some lines of the images. In the same image, the lost lines appear always in different bands and positions. When that noise appears, there is not a complete loss of the whole line, maintaining a correct value for the even pixels. Using that property of the noise, it is easy to detect the lines with horizontal noise because they always have a correct value followed by an incorrect value along all the line. Once we have detected the lost lines, even pixels for such lines are corrected using the average of the nearest pixels with a correct value.

On the one hand, vertical noise or vertical striping is due to errors in the alignment of the sensors in the construction of the instrument (we can consider these errors as a constant). On the other hand, thermal fluctuations during the orbit causes small variations in the alignment of the optical elements, making that this vertical noise does not stay constant during all the time [Settle, 2001]. In the literature we can find a couple of methods to obtain the factors to correct this type of noise, and they are always based in the application of a filter in some point of the methodology, so that they have an important dependence with the image content.

We have developed a new methodology to obtain the correction factors without the use of any filter, and we have demonstrated that these factors are constant during an orbit, using the same factors obtained in the nadir image to correct all the images of the same orbit.

That procedure for the removal of noises in CHRIS/PROBA images has been developed and used for the correction of all the images acquired during the SPARC campaign, but is general enough to be applicable to any other CHRIS data due to the no dependence on the image content. It has been tested in other core sites as Libian desert.

1. INTRODUCTION

Before doing geometric and atmospheric corrections in the CHRIS/PROBA images, it is convenient to apply some algorithms to reduce the noises of the images.

A CHRIS/PROBA image is affected basically by horizontal and vertical noises. This paper describes the new methodology developed by DIELMO 3D and the University of Valencia to detect and correct this two different noises in the images acquired during the SPARC campaign, but this methodology can be applicable to other study sites because there is not a dependence with the image content.

2. HORIZONTAL NOISE

Horizontal noise consists in the random loss of partial data from some lines of the images. In the same image, the lost lines appear always in different bands and positions. When that noise appears, there is not a complete loss of the whole line, maintaining a correct value for the even pixels, as we can see in Fig. 1.

Using that property of the noise, it is easy to detect the lines with horizontal noise because they always have a correct value followed by an incorrect value along all the line. To do that, we compare the horizontal profile of each file of the image with the next one. If two adjacent lines do not have this error, their profiles are very similar, but if one of the lines has this error, we obtain the result shown in Fig. 1, where even pixels are similar...
and there is a strong variation in the odd pixels.

Once we have detected the lost lines, we produce a text file with the locations of the errors (band and line), and even pixels for such lines are corrected using the average of the nearest pixels with a correct value (as shown in Fig. 2).

3. VERTICAL NOISE

Vertical noise or vertical striping consists in strong variations in the average value of each column of the image.

Fig. 3 shows an example of this noise:

In the literature we can find a couple of methods to obtain the factors to correct this type of noise. For example, [Settle, 2004] proposes:

• A) For each band, calculate an average radiance for each column of data.

• B) Calculate the logarithm of A (the use logarithms is because this striping is a multiplicative effect).

• C) Apply a low pass filter to B (in order to eliminate the high frequency variations).

• D) Subtract C from B to obtain only the high frequency variations, considered as the noise.

• E) Calculate the anti-logarithm of D. The resulting numbers should all be close to one.

At the end of this algorithm, we obtain the correction factors, that are applied to each column of the image to correct the vertical noise.

We have implemented an algorithm based in that procedure, and the results are shown in Fig. 4 and 5.

Fig. 4. Procedure for the estimation of the correction factors using the methodology developed by Settle.

Fig. 5 shows two original images (in the left) and the correction obtained with the factors of Fig. 4. We can see that part of the vertical noise has been removed, but not completely.

This type of algorithms are always based in the application of a filter in some point of the methodology, so that they have an important dependence with the image content, and they do not always work well if the image has large amounts of bright and dark targets (for example, some coastal images).
4. DIELMO – U.V. METHODOLOGY TO CORRECT THE VERTICAL NOISE.

We have developed a new methodology to estimate directly the correction factors without the use of any filter.

For example, in Fig. 6 we can appreciate that the central column has an important offset regarding the two adjacent columns. The idea is to obtain the mean factor that allows to reduce the offset of the central column, to place it in the theoretical point D between Columns A and C.

![Fig. 6. Correction factors calculation using the DIELMO - U.V. methodology.](image)

To do that, for each band and each column of the image we obtain the average of all the theoretical correction factors (X1) of each pixel of the column. X1 is defined as indicated in Fig. 6.

When we have an important offset over the nearest columns (as in column B of Fig. 6), the correction factor is well estimated using A and C columns, but it produces an underestimation in the correction factors of the previous and next column (as we can see in the right of Fig. 7). The same case appears if we have an important offset under the nearest columns, producing an overestimation in the correction factors of the previous and next columns.

![Fig. 7. Underestimation of the correction factors in columns A and C due to an important offset over the nearest columns.](image)

To solve that problem, we detect an important peak in the final correction factors (for example B in Fig. 7) followed by two peaks in the inverse direction (A and C in Fig. 7). As these two peaks in the inverse direction are incorrect, we put them to 1, apply the correction factors to the image and then we calculate the correct factors for the points that were put to 1 and apply the correction again only for that columns.

On the one hand, vertical striping is due to errors in the alignment of the sensors in the construction of the instrument (we can consider these errors as a constant). On the other hand, thermal fluctuations during the orbit causes small variations in the alignment of the optical elements, making that this vertical noise does not stay constant during all the time.

In any case, we can consider that the correction factors are constant during one orbit or more. We have demonstrated that we can use the nadir image to estimate the correction factors in each orbit and apply these factors to the rest of the images of the orbit [Barnsley, 2004] (see Fig. 8).

![Fig. 8. Viewing angles in a CHRIS/PROBA acquisition.](image)

We can do that because our estimation of the correction factors does not use any filter, and there is not a dependence with the image content. This is an important point in the correction of the vertical striping, because the correction is consistent for all the images of the same orbit, applying exactly the same correction factors.

Fig. 9 shows a zoom of the same part of the images for the 5 viewing angles. Of course in each image the content is different (because changes the angle of overestimation), but the vertical noise is constant because they correspond with the same columns of the image.
Fig. 9. Correction of the 5 angles of a CHRIS/PROBA image using the factors obtained from the nadir image.

We have observed that this methodology works well in the study area of Barrax, using CHRIS/PROBA images of the SPARC campaign. We also have tested it in other sites as the Libian desert (results are shown in Fig. 10).

Libian desert is a homogeneous area where it is more easy to study noises of the images because there is not a large dependence with the image content. The result shown in Fig. 10, indicates that we can correct the high frequency vertical noise, but in the left part of the zoom we appreciate that remains a low frequency vertical noise (several darker adjacent columns). In the future, we have to solve this problem.

Fig. 11. Correction factors comparison for Barrax and Libian desert study sites (band 10).

Fig. 12. Correction factors comparison for Barrax and Libian desert study sites (band 57).

5. COMPARISON OF THE VERTICAL STRIPING CORRECTION PARAMETERS.

Fig. 11 and 12 shows a comparison of the correction parameters of two different images and two different bands.
On the one hand, we can appreciate that there are bands with more noise than others. For example, band 10 is more noisy than band 57.

On the other hand, we also can appreciate, that factors are very similar although they differ in an interval of time of 45 days.

We have said before that vertical striping is due to two main factors: errors in the alignment of the sensors in the construction of the instrument (constant) and thermal fluctuations during the orbit that causes small variations in the alignment of the optical elements (variable).

Looking to the correction parameters for different images and bands (for example Fig. 11 and 12), we can say that the main influence in the vertical striping is due to the constant part of the noise, and that the thermal fluctuations are not very significative (at least in this case).

In the future, we have to study with more detail how the correction parameters change with time, in order to find the way to define standard correction factors for all the CHRIS/PROBA images during a determined period of time.

6. CONCLUSIONS

We have corrected the two main noises in CHRIS/PROBA images: loss of horizontal lines and vertical striping.

On one hand, horizontal lines are easy to detect and correct using the horizontal profile of each file and the average of the nearest pixels to correct the bad values.

On the other hand, we have developed a new methodology to correct the vertical striping that allows to obtain the correction factors without the use of any filter, and we have demonstrated that these factors are constant during an orbit, using the same factors obtained in the nadir image to correct all the images of the same orbit (the correction is consistent for all the 5 angles images).

After the noise correction, the images are ready for geometric and atmospheric corrections.

In the future we have to improve the low frecuency vertical striping, to study with more detail the variations of the correction parameters with time (to try to define standard correction during a determined period of time), and to test with more sites with different spatial properties.

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http://io.uv.es/projects/sparc

ABSTRACT

In the framework of preparatory activities for the SPECTRA (Surface Processes and Ecosystems Changes Through Response Analysis) ESA Earth Explorer Core Mission, CHRIS/PROBA acquisitions over the Barrax Core Site in Spain were used to compile a reference dataset for future in-depth studies. Taking advantage of the possibility of consecutive days of acquisitions, multiple-angular acquisitions finally included 10 different view angles from CHRIS, in Mode 1 with 62 spectral, and a ground resolution of about 34 m. Additional ROSIS and HYMAP sensors, flying simultaneously with CHRIS overpass, provided detailed images for validation of CHRIS data, particularly in the spectral domain. Moreover, up to 3
angles per sample from airborne HYMAP data were acquired, with high spectral and spatial resolution, and then both spectral and angular domains can be exploited with the combined CHRISS/HYMAP/ROSIS dataset. Detailed soil/vegetation and atmospheric measurements complete the SPARC data, and data from other satellites (MERIS, SEVIRI, SPOT, Landsat) were collected as well, to address scaling issues. Methods for data analysis and exploitation have been developed in the context of SPARC activities, and preliminary results about retrievals of biophysical information from multi-angular hyperspectral data are already available. The whole SPARC dataset represents a reference for the exploitation of CHRISS data, allowing the development of new processing and retrieval algorithms, and the validation of such algorithms by means of ground measurements and complementary airborne and satellite data. More details on several processing aspects of the CHRISS/PROBA data acquired within the SPARC campaign are presented in other papers in this conference [4] [6] [7] [8].

1. INTRODUCTION

The SPARC campaign took place on 12-14 July 2003 in coincidence of CHRISS/PROBA acquisitions over the agricultural site of Barrax, in Castilla-La Mancha, Spain. It was, in fact, a combination of different activities as part of the EC DEMETER project and other different EC, ESA and national projects, planned independently over the Barrax core site, that were coordinated to get a maximum benefit from all the combined activities. The campaign was organised around the possibility of getting three consecutive dates of CHRISS acquisitions, due to the particular orbit of PROBA, with 3 different minimum zenith angles, over the same Barrax core site. Different research teams (University of Valencia, University of Castilla-La Mancha, Institute of Regional Development of Albacete, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) of Madrid, University of Naples "Federico II", Italy, INRA-CSE, Avignon, France, Laboratoire du Télédétection et SIRS, Tunisia, Meteo-France-Toulouse, France) participated to the intensive field activities concentrated during the three-days of a multi-resolution imagery acquisition and field data collection.

2. CAMPAIGN OBJECTIVES

The main objective of the Spectra Barrax Campaign was to collect coincident in-situ data over the Barrax site, about 20 km west of Albacete, Spain, with CHRISS/PROBA multi-angular and multi-spectral in order to address the following critical issues in the Earth-Explorer SPECTRA Phase A study:

- Development and testing of atmospheric correction algorithms for multi-view images.
- Validation of multiple view image co-registration algorithms.

On the other hand, the SPARC campaign exploited:

- The availability of the CHRISS/PROBA spaceborne sensor during the July 2003 to collect representative multi-angular measurements over the Barrax test site.
- The opportunity provided by the presence of HYMAP/ROSIS hyperspectral imaging instrument operated by DLR in the vicinity of the test site.

Furthermore coincident in-situ data required to address the above objectives were also planned. In-situ activities included the following:

- The collection of soil and plant geo-physical parameters in selected test fields as required for the validation of current BRDF forward models and the assessment of BRDF and hyperspectral retrieval algorithms.
- The collection of geometric and cartographic data required to validate the geo-coding of multi-angular CHRISS image datasets.
- Atmospheric measurements required to establish and validate a multi-angular atmospheric correction algorithm for the CHRISS sensor.

The main objective of the campaign was to collect a SPECTRA reference dataset, consisting of:

- CHRISS / PROBA multitemporal dataset
- Ground measurements: soil/vegetation/atmosphere
- Complementary satellite data to address scaling issues

3. STUDY AREA

The selection of the Barrax site for the SPARC campaign was justified through a large experience in using this area as test site for many previous satellite and airborne remote sensing experiments [2] [3].

![Fig. 1. Location of the study area](image-url)
coordinates 30°3' N, 2° 6' W). The area around Barrax has been used for agricultural research for many years. The main test area has a rectangular form and an extent of 5 km x 10 km.

The Barrax test site is situated within La Mancha, a plateau 700 m above sea level. The area is characterised by a flat morphology and large, uniform land-use units. Differences in elevation range up to 5-10 m only. The regional water table is about 20-30 m below the land surface. The region consists of approximately 65% dry land and 35% irrigated land.

The climatic conditions accord the Mediterranean features: high precipitations in spring and autumn and the minimum in summer. The annual rainfall averages is about 400 mm. Furthermore, the region has high continentality with high thermal oscillations during all seasons. La Mancha represents one of the driest regions of Europe.

Major activities going on in the Barrax study area during 2003 were:

- CHRIS / PROBA time series acquisition (AO Barrax Core Site)
- DEMETER (DEMOnstration of Earth observation Technologies in Routine irrigation advisory services) European Commission project (2002-2005)
- SPECTRA Phase-A Preparatory Studies
- ASAR / MERIS / AATSR ENVISAT AO Projects
- ENVISAT / MERIS Biophysical Products Validation
- MSG / SEVIRI Biophysical Products Validation (as part of VALERI initiative)
- Canopy reflectance modelling studies (FLUORMOD)
- SMART-Spectra EC Project for developments in new spectral imaging technologies
- Spain-Tunisia bilateral scientific cooperation programme
- Some other national projects

By putting together activities initially disconnected, and under the umbrella of CHRIS acquisitions to derive a reference dataset for SPECTRA studies, was how the SPARC activities were organised.

4. CHRIS DATA ACQUISITIONS

A major aspect in the campaign was the possibility of having 3 days of consecutive CHRIS acquisitions, due to the peculiar orbit of the PROBA satellite. Such consecutive acquisitions are possible by using different across-track viewing angles: one close to nadir and two around with +20° and -27° zenith angles, respectively. Since for each across-track angle we have 5 along-track multi-angular acquisitions, in total we have 15 different viewing angles in this peculiar geometric configuration.

Since surface changes are minimal along 3 consecutive days, the multi-angular dataset in this way collected can be considered as a good characterisation of surface BRDF (by putting together all the 15 angles) with enough spectral information (62 spectral bands) for each view angle.

All acquisitions were selected to be in CHRIS Mode 1 (62 bands, full spectral information), with a spatial resolution of 34 m at nadir, compatible with the requirements for SPECTRA (50 m at nadir) and quite acceptable for the geometrical conditions of fields in Barrax, which are large enough to be perfectly resolved with a spatial resolution of 34 m.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Minimum Satellite Zenith Angle</th>
<th>Solar Zenith Angle</th>
<th>Satellite altitude (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 July</td>
<td>11:07</td>
<td>+20°</td>
<td>22</td>
<td>667</td>
</tr>
<tr>
<td>13 July</td>
<td>11:20</td>
<td>-4</td>
<td>21</td>
<td>668</td>
</tr>
<tr>
<td>14 July</td>
<td>11:32</td>
<td>-27°</td>
<td>20</td>
<td>668</td>
</tr>
</tbody>
</table>

Unfortunately, due to some technical failure in the spacecraft of some commanding problem, the fact was that only the first image on 12th July and the last image on 14th July from the 3 days expected sequence, were correctly acquired. The CHRIS image of 13th July was acquired, but apparently the satellite was pointing in a wrong way and the image does not correspond to our study area. The final angles available for our study area are illustrated in Figure 2.

![Figure 2](image_url)

Fig. 2. Polar plot corresponding to all CHRIS/PROBA multi-angular acquisitions in the SPARC campaign.

A key issue for us, especially after the loss of the image of 13th July, was to test the co-registration of the multiple angular view. This is critical because multi-
angular information can only be exploited over the area of overlap of all the CHRIS multi-angular data. If such overlap is too small, little information can be extracted. Moreover, another key issue was to test that the overlap area was just the area where field data were collected for validation purposes.

Fig. 3. Overlap of all 5 CHRIS multi-angular acquisitions on 12 July 2003 in Barrax, after geometric registration of each view over a background Landsat TM image.

As shown in Figure 3, the overlap among all the 5 multi-angular acquisitions is quite good, and the area where 5 angles are available for BRDF reconstruction is high enough for statistical analysis. Sub-areas covered by 4 or even 3 angles can also be considered as well. Moreover, the satellite was pointing almost exactly to the desired ground position.

5. AIRBORNE DATA ACQUISITIONS

Since the objective of SPARC was to validate data processing methods and retrieval algorithms for CHRIS/PROBA data, a particularly adequate way of addressing such validation was by means of high spatial resolution imagery, from airborne sensors, with similar or enhanced spectral capabilities as CHRIS. The availability of ROSIS was especially relevant, because it covers the same spectral range as CHRIS, but with enhanced spectral resolution and a spatial resolution of about 2 m. A mosaic of parallel flight lines with ROSIS would cover the same area as CHRIS images, and then would be extremely useful for validation purposes.

Since one of the objectives of the campaign was also to provide a reference dataset for SPECTRA studies, the availability of HYMAP was also particularly relevant, since it covers the part of the solar spectrum from 1000 to 2500 nm that is not available in CHRIS but would be available in SPECTRA.

On 12 July 2003 airborne HYMAP (126 bands, 6 m resolution) and ROSIS (115 bands, 1 m resolution) data were acquired simultaneously with CHRIS/PROBA overpass, to validate CHRIS data by means of very high spatial resolution data with similar spectral capabilities.

Fig. 4. Mosaic of the 4 lines of HYMAP data acquired simultaneously with CHRIS/PROBA overflight in SPARC (12 July 2003).

As indicated before, airborne high spatial resolution airborne data are mainly used as a validation tool. Algorithms used to retrieve biophysical variables from CHRIS can also be applied to ROSIS and HYMAP data. The derived biophysical maps in high spatial resolution can then be used to validate the retrievals done with lower resolution data such as CHRIS.

Fig. 5. Comparison of radiance spectra measured by HYMAP and ROSIS airborne sensors and simultaneous ground radiance measurements by means an ASD spectroradiometer.
On the other hand, high spatial resolution imagery allow precise geolocation of ground measurements, and the scaling from such ground measurements to CHRIS data, by using airborne high spatial resolution data as an intermediate step.

6. COMPLEMENTARY SATELLITE ACQUISITIONS

Apart from the successive CHRIS/PROBA acquisitions along three days, in the SPARC campaign MERIS data were acquired simultaneously with CHRIS data for intercomparison and intercalibration/validation of retrievals from both sensors. This was possible on 14th July 2003, when PROBA and ENVISAT overpasses over Barrax on the same day were used to collect such unique MERIS-CHRIS dataset.

MERIS data was of particular interest for SPARC because one of the objectives of the campaign was to serve in the validation of Level 2 algorithms used to derive MERIS vegetation products. The availability of CHRIS data (34 m resolution) was specially relevant in the scaling from ground measurements of such vegetation variables and MERIS FR data (300 m resolution).

Apart from the CHRIS/PROBA and MERIS acquisitions, data from other satellites were acquired simultaneously or in nearby dates: Landsat, SPOT, ASTER, MODIS. As part of the validation activities for Eumetsat LandSAF project, data from MSG/SEVIRI were also collected during the SPARC campaign.

Scaling effects can then be analysed from 1 m (ROSIS) data up to 3 km data (SEVIRI), with a number of intermediate steps: from ground to CHRIS (34 m) and from CHRIS to MERIS (300 m).

7. ATMOSPHERIC DATA

Detailed atmospheric characterisation was carried out by means of two radio-soundings per day, spectral radiance measurements with four different instruments (Licor 1800 and Optronic 754-O-PMT spectroradiometers, Cimel 318 and Microtops II sunphotometers). In addition, ground-based LIDAR mobile laboratory with autonomous power system was operated on site by CIEMAT (Madrid). This data set allowed for the validation of new atmospheric correction algorithms.

Soil and vegetation targets were selected for field spectral measurements carried out by means of two ASD Field Spec and one GER-3700. An inter-comparison of the different instruments was performed. Field spectral measurements were mainly used to validate the atmospheric correction procedures.

![Fig. 6. Solar direct /and diffuse spectral irradiance measurements during SPARC.]

![Fig. 7. MERIS FR image acquired on 14 July 2003 over the Barrax study area during the SPARC campaign.](image_url)
Fig. 8. Lidar profiles measured along the three days of campaign during SPARC, to characterise aerosols vertical structure for precise atmospheric correction of multi-angular data.

Fig. 9. Landuse map and vegetation sampling points.
7. SOIL / VEGETATION DATA

An intensive field data acquisition plan was established. Taking advantage of simultaneous availability of many instruments from the different participating teams, data were collected using different methods and techniques. Extensive ground truth data acquisitions included spectral calibration measurements and determination of main biophysical parameters, namely Leaf Area Index and leaf chlorophyll, water and dry matter contents. Leaf Area Index measurements were taken by four different teams equipped with canopy digital analyser Licor LAI-2000. In total 113 elementary units were sampled in 7 different types of crop (alfalfa, corn, sugarbeet, onions, garlic, potato, papaver). The determination of the LAI value in each elementary unit was resulting from the average of 24 point measurements. The centre of each elementary unit was georeferenced by using a portable GPS. This measurement strategy produced a LAI data-set of great accuracy and reliability, covering a range of values from 0.5 to 6.3, with a global average of 3.07 and standard deviation of 1.45. Chlorophyll measurements were performed with a CCM portable instrument, calibrated in-situ by means of laboratory chlorophyll measurements. Dry matter and water content were determined by weighting wet and dry samples by heating, after leaf area was determined for each leaf sample.

what represents an interesting case for testing different retrieval methodologies.

An special effort was put on the characterisation of chlorophyll values. Details of the procedures used and obtained results are given in [8].

Hemispherical photographs were used to characterise Vegetation Fractional Cover and other canopy geometry parameters, as illustrated in Figure 11.

Fig. 11. Hemispherical photographs over selected plots to determine LAI and Fractional Vegetation Cover.

It is important to point out that such range of LAI values corresponds to all the possible values that one can expect in an agricultural area. This is in fact one of the aspects that makes Barrax such an interesting site for validation purposes, because in a small area one can find simultaneously crops in all development stages (and thus all possible values of LAI) in different fields. Moreover, we have same crop fields but with different LAI values, and same LAI values for different crops,

what represents an interesting case for testing different retrieval methodologies.

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9. DATA PROCESSING AND FIRST RESULTS

A significant step in the processing of CHRIS/PROBA data acquired during the SPARC campaign has been the consistent geo-registration of the multiple angular views in order to exploit the information content of multi-angular data. Although geometrical corrections tend to be considered a well established procedure implemented in most commercial software packages, the traditional techniques are not accurate enough for the type of data such as CHRIS. Moreover, some peculiar aspects such
as the slow-down factor, used to increase radiometric quality in CHRIS data, introduce additional geometrical problems. Two additional aspects become essential in the geometric processing of CHRIS data:

(a) The need to get the view zenith and azimuth angles for every pixel in the image and for every angular view, in order to exploit BRDF information, requires geometrical methods that can explicitly compute such angles. Geometric processing methods based on polynomial approaches and ground control points —and even those methods based on image cross-correlation techniques— do not allow to compute the viewing angles for every pixel. Then, a specific method is needed for CHRIS data.

(b) The fact that BRDF reconstruction is made by using multiple angular views, and the fact that the ground spatial resolution of the images is different for each angular view, makes the resampling a critical element in the geometric processing of the data.

Such geometrical issues have been analysed in detail in the context of the processing of SPARC data [4].

Finally, the retrieval of vegetation biophysical properties has been of course the main focus. Due to the need of developing a number of procedures for geometric and atmospheric corrections as previous steps, the retrieval of biophysical parameters is still in an early stage of development, and in most cases the processing has consisted in applying to CHRIS data procedures that had been developed previously for other sensors [9] [10]. However, several results have been already obtained from CHRIS data in SPARC, and such results are reported in [7] and [8]. The efforts for the next months will focus on improving the methods used in such retrievals and develop methods more specifically adapted to CHRIS data. A problem encountered has been the effect on the retrievals of CHRIS radiometric noises. Although SPARC CHRIS data have been radiometrically corrected for noises [6] before application of retrieval methods, in the case of retrieval algorithms that make use of spectral derivatives, band ratios, band differences, or mathematical combination of bands (spectral indices) it turns out that the remaining noise effects appear in the resulting maps of biophysical parameters in the forms of stripping. Efforts should be put in eliminating such noises as much as possible, or to develop retrieval algorithms resistant to such noise effects.

Scaling issues, by using multiple resolution imagery, from ROSIS (2 m) up to MERIS RR (1 km) and using CHRIS data as intermediate step, have been also a focus of studies. More work will be carried out in the next months about this subject. Moreover, CHRIS data are being used for validation of retrieval algorithms applied to MERIS FR data.

Such scaling aspects are also quite relevant for the work to be done in the context of SPECTRA preparatory activities. One key element in SPECTRA is that it will not provide global coverage, but detailed information only over selected sites. Such information must later be integrated with other data from global coverage sensors to provide all necessary inputs to global models describing vegetation functioning and the role of vegetation in the global CO₂ cycle. Then, techniques for combination of local site information (CHRIS data

Fig. 13. Geometrically and atmospherically corrected CHRIS data collected on 12 July 2003 in SPARC for the Barrax test site.
over Barrax) and global type of information (MERIS for instance) are also aspects that can be analysed by using the SPARC dataset.

![Graph showing radiance and reflectance](image1.png)

**Fig. 14.** CHRIS original radiances (blue) and retrieved surface reflectance (red) by applying the atmospheric correction procedure developed in SPARC.

Although the processing of the whole SPARC dataset is still in an early stage, some interesting preliminary results have been already achieved. The methodology developed for the geometric processing of the data is of particular relevance, because a proper geometric processing is the initial requisite for a proper exploitation of the multiangular data. The removal of noises is another relevant aspect. Moreover, methods for atmospheric correction of CHRIS data have been developed to become almost automatic, without using any external information, and thus producing auto-consistent retrievals of surface reflectance from the multiangular radiances. Finally, the main objective of the SPARC campaign was to demonstrate the retrievals of vegetation parameters from CHRIS data, and the validation of such retrievals by means of field collected data.

![Graph showing reflectance vs wavelength](image2.png)

**Fig. 15.** Surface reflectance spectra derived for the 62 CHRIS spectral bands over several crops in the SPARC study area.

A significant achievement in SPARC has been the development of an algorithm for atmospheric correction of the data that can produce "smooth" (almost free of noise) spectra for all surface types and for all the 62 CHRIS spectral bands. Minor problems remain in the blue bands and in the near infrared near 1000 nm, due to poor performance of the sensor in such spectral regions. In any case, the derived surface reflectance spectra are usable in biophysical retrieval methods, including those more radiometrically demanding such as those based on model-inversion techniques.

**10. CONCLUSIONS AND PERSPECTIVES**

Taking advantage of the possibility to get an almost unique multiangular dataset due to the consecutive three-days acquisitions of CHRIS/PROBA data, a complete dataset was acquired in the SPARC campaign during July 2003 in Barrax, Spain. Procedures for geometric correction of multi-angular CHRIS data have been developed [4], as well as methods for the removal of the different noises present in the images [6], and several procedures for atmospheric correction have been tested. A new algorithm [5], especially adapted to CHRIS data have been developed, that uses information contained in the image itself to derive the necessary atmospheric information for precise correction of the data. Moreover, algorithms for the retrieval of biophysical information from CHRIS data have been developed and tested over the available field data collected for validation purposes. The particular features of CHRIS data for vegetation monitoring have been demonstrated, pointing out the interest of contiguous spectral coverage and multi-angular observations.

While the processing of the whole SPARC-2003 dataset will continue over the next months, a new campaign, SPARC-2004, is planned again for July 2004 in Barrax, increasing statistical data from previous campaigns and covering new aspects, by taking advantage of the continuity of the successful exploitation of the CHRIS/PROBA mission.

**ACKNOWLEDGEMENTS**

The SPARC-2003 activity has been supported by DEMETER (DEMonstration of Earth observation Technologies in Routine irrigation advisory services) European Commission contract EVG1-CT-2002-00078, 12/2002-11/2005 (Energy, Environment and Sustainable Development Programme) and by the ESA contract "Technical assistance for CHRIS/PROBA measurements during SPECTRA Barrax Campaign 2003 (SPARC)". ESA RFQ/3-10824/03/NL/FF. Some SPARC activities are also funded by Eumetsat (LandsAF programme), CNES (VALERI) and partially by other national and international projects.
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ABSTRACT

In the context of the SPARC campaign, a total of 10 different view angle images are available from CHRIS/PROBA data, all of them acquired in Mode 1 (62 spectral bands). These data make possible to test some of the algorithms developed to extract vegetation biophysical variables from high-spectral resolution data with multiangular capabilities, in the context of the SPECTRA mission. Validation of retrievals with the large dataset of ground measurements that is available in SPARC represents a unique opportunity to exploit the innovative CHRIS/PROBA data. Variability in ground measurements was evaluated by statistical techniques, according to the sampling used in the data collection. Two different approaches have been followed in the retrieval of vegetation biophysical variables. First, a large number of spectral indices have been tested with the available spectral information. The second method used is based on model inversion techniques. A combination of adapted versions of PROSPECT [1], and SAIL [2], models have been tested in forward mode, by using all available ground measurements to reproduce the top-of-canopy reflectance, and then compare these forward simulations with atmospherically corrected CHRIS data.

1. INTRODUCTION

A large amount of ground measurements were collected in the Barrax study area during the SPARC campaign, covering LAI, fCover, Leaf Chlorophyll a+b, Leaf water content and leaf biomass, together with other complementary data. All the SPARC CHRIS images have been radiometrically, geometrically and atmospherically corrected according to methods described in other papers in this conference. All the available ground measurements were cross-checked with GPS measurements. Then, for each available ground measurement, the corresponding point in each angular image was identified, and a database has been developed by putting together each ground measurement with the corresponding CHRIS measurements to facilitate the development and testing of different retrieval algorithms.

Although it was a large variability in some biophysical variables (particularly leaf chlorophyll and water contents) mean field values can be derived, and inter-fields variability is still larger than intra-field variability. The data was collected to make possible retrievals at the level of sampling unit, thus describing within field variability. Retrievals based on spectral indices are limited in accuracy, but they allow also checking the overall consistency in database content. Large discrepancies in model simulations versus CHRIS data must be understood before a model inversion strategy is applied. Moreover, multi-step techniques seem to be required to decouple the different information in a consistent manner and to determine simultaneously all the biophysical variables with reasonable values for all of them. Leaf structure and dry matter content seem to be critical factors when accounting for multiangular variations, due to the coupling of leaf reflectance and leaf transmittance at the canopy level.

2. VEGETATION MEASUREMENTS

During the SPARC-2003 campaign in Barrax (Spain), we have measured and studied different vegetation properties.

a. Leaf Area Index (LAI) from LAI-Licor
b. Fractional Vegetation Cover (FVC) from hemispherical photographs
c. Dry Matter content (DM)
d. Water Content (WC)
e. Chlorophyll Content (CC)

We have defined a strategy for the number of measurements from each crop that are statistically representative for biophysical parameters used in the characterisation of the different crops. We have focused our interest on the LAI, dry matter, water content and chlorophyll values, all of them inputs for PROSPECT and SAIL models to the forward simulations of the spectrum for the different crops.

2.1. Analysis of biomass and water content values

The measures of dry matter and water content were made in the traditional way. Typical range values for
dry matter and for water content lies in the intervals (19–165) g m\(^{-2}\) and (40–400) g m\(^{-2}\) respectively and almost all the measured values can be found in this range except values obtained for water content from onion and garlic crops. Table 1 shows this range of values and mean values (µ) with standard deviation obtained for dry matter and water content.

Table 1. Dry matter and water content range values for crops and mean values (µ) with standard deviation (σ).

<table>
<thead>
<tr>
<th>Crop</th>
<th>DM Range of values (g m(^{-2}))</th>
<th>DM µ±σ (g m(^{-2}))</th>
<th>WC Range of values (g m(^{-2}))</th>
<th>WC µ±σ (g m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>53.9 - 69.9</td>
<td>61 ± 6</td>
<td>165.9-189.5</td>
<td>180 ± 8</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>55.4-106.1</td>
<td>90 ± 20</td>
<td>110.9-160.3</td>
<td>140 ± 30</td>
</tr>
<tr>
<td>Alfalfa</td>
<td>47.1 - 90.4</td>
<td>65 ± 19</td>
<td>105.9-142.8</td>
<td>126 ± 16</td>
</tr>
<tr>
<td>Potato</td>
<td>39.7-46.1</td>
<td>43 ± 3</td>
<td>213.8-240.4</td>
<td>223 ± 15</td>
</tr>
<tr>
<td>Onion</td>
<td>71.4 - 81.4</td>
<td>83 ± 7</td>
<td>602.9-810.1</td>
<td>680 ± 70</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>50.5 - 81.8</td>
<td>72 ± 11</td>
<td>315.1-635.6</td>
<td>400 ± 100</td>
</tr>
<tr>
<td>Garlic</td>
<td>99.8 -189.5</td>
<td>130 ± 30</td>
<td>482.1-712.1</td>
<td>600 ± 90</td>
</tr>
</tbody>
</table>

2.2. Chlorophyll content measurements: calibration procedure for a CCM-200 meter and posterior analysis

A CCM-200 (Opti-Sciences, Inc.) meter was used for chlorophyll content measurements because of the practical difficulties found on apply the chemical method to analyse a large number of samples.

CCM-200 gives a relative measure in digital counts and this fact justify the calibration procedure to obtain chlorophyll values. For the selection of the samples in order to calibrate the CCM-200 meter we have considered the chlorophyll content variability in the samples from the crops selected for in-situ data measurements (see Table 2). We took more samples of alfalfa in order to assure a good mean value because of the difficulty of making the measure with the CCM-200 due to the small size of the leaves.

Table 2. Selected samples for CCM-200 calibration procedure

<table>
<thead>
<tr>
<th>Crop</th>
<th>Samples/Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>15</td>
</tr>
<tr>
<td>Corn</td>
<td>11</td>
</tr>
<tr>
<td>Sugar Beet</td>
<td>8</td>
</tr>
<tr>
<td>Wheat</td>
<td>4</td>
</tr>
<tr>
<td>Garlic</td>
<td>4</td>
</tr>
<tr>
<td>Onion</td>
<td>4</td>
</tr>
<tr>
<td>Potato</td>
<td>4</td>
</tr>
</tbody>
</table>

Chlorophyll content was analysed following the methodology described by Inskeep and Bloom [3], based on the determination of the extinction coefficients of chlorophyll a (Chl a), chlorophyll b (Chl b) and total chlorophyll (Chl total) dissolved on NN-dimethylformamide (DMF). The absorbity (A) for 647 nm and 664.5 nm wavelengths was measured, by means of a CARY-UV-Visible Spectrophotometer, what allows to calculate the contents of chlorophyll by using next equations:

\[
Chl a = 12.70 A_{664.5} - 2.79 A_{647} \text{ (mg/L)} \\
Chl b = 20.70 A_{647} - 4.62 A_{664.5} \text{ (mg/L)} \\
Chl total = 17.90 A_{647} + 8.08 A_{664.5} \text{ (mg/L)}
\]

where \( A \) is absorbance read at “i” nanometers and Chl is leaf chlorophyll content in mg/L.

We have checked the ratio Chl-b:Chl-a for all the calibration samples and we have found they lies, basically, in the typical expected range of values (between 0.2 and 0.38) and only on the case of corn crop results are outside this interval (Fig.1). This fact find justification in the particular structural characteristics observed for the corn plant compared to the rest of crops under study.

![Fig. 1. Ratio Chl-b:Chl-a values for all the CCM-200 calibration samples.](image)

By applying different calibration functions it was found best results for the logarithmic one. Next equation gives the total chlorophyll content (Chl\(_{ab}\)) from the CCM-200 Digital Counts (DC) values:

\[
Chl_{ab}(\mu g/cm^2) = -12 + 34.5*\log(DC)
\]

Fig.2 shows results of applying this function and chlorophyll content values obtained for the different crops.
2.3. Chlorophyll in-situ measurements: analysis of the variability

The methodology applied to get the in-situ chlorophyll data consisted on measuring around 50 samples with the CCM-200 meter to characterize each Elementary Sampling Unit (ESU) previously selected for the characterisation of LAI. The measurements were taken on the leaves on the top of the plant in order to get values that could be related with satellite data.

![Fig.2. Relationship between CCM-200 digital counts and Chlorophyll values by means of the logarithmic calibration function.](image)

Table 3 illustrates the different ESU’s taken for each crop, the number of sampling points per ESU, mean values obtained for each ESU and for each crop with the standard deviation error.

Table 3. Chlorophyll mean values for different crops

<table>
<thead>
<tr>
<th>Crop</th>
<th>ESU</th>
<th>Samples</th>
<th>Chlorophyll Mean Value (µg cm⁻²)</th>
<th>Crop Mean Values (µg cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>C1-A1</td>
<td>56</td>
<td>48.9 ± 0.5</td>
<td>50.3 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>C1-A2</td>
<td>53</td>
<td>51.6 ± 0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C1-A3</td>
<td>55</td>
<td>50.4 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>Sugar-beet</td>
<td>B1-T1</td>
<td>44</td>
<td>44.9 ± 1.0</td>
<td>44.3 ± 1.4</td>
</tr>
<tr>
<td></td>
<td>B1-T2</td>
<td>40</td>
<td>48.6 ± 0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T3</td>
<td>42</td>
<td>42.5 ± 1.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T4</td>
<td>45</td>
<td>43.4 ± 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T5</td>
<td>52</td>
<td>38.8 ± 1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T6</td>
<td>47</td>
<td>47.4 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>Onion</td>
<td>On1-B1</td>
<td>54</td>
<td>23 ± 3</td>
<td>18 ± 2</td>
</tr>
<tr>
<td></td>
<td>On1-B2</td>
<td>43</td>
<td>23 ± 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>On1-B3</td>
<td>54</td>
<td>20 ± 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>On1-B4</td>
<td>49</td>
<td>16 ± 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>On1-B5</td>
<td>50</td>
<td>18 ± 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>On2-A1</td>
<td>64</td>
<td>22 ± 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>On2-A2</td>
<td>44</td>
<td>6 ± 2</td>
<td></td>
</tr>
<tr>
<td>Garlic</td>
<td>G1-A7</td>
<td>53</td>
<td>20 ± 2</td>
<td>15 ± 2</td>
</tr>
<tr>
<td></td>
<td>G1-A8</td>
<td>50</td>
<td>15.0 ± 1.6</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3 shows the mean chlorophyll values for the crops selected in the experience.

![Fig. 3. Mean chlorophyll values for different crops](image)

3. BIOPHYSICAL PARAMETERS RETRIEVALS BASED ON SPECTRAL INDICES

The first approach followed in the retrieval of vegetation biophysical variables is based on spectral indices.

Several optical indices have been reported in the literature [4][5] and have been proved to be well correlated with various vegetation parameters such as LAI, dry matter, chlorophyll concentration and more. Exhaustive comparative studies have been already carried out to assess the prediction power of different optical indices and their sensitivity to various canopy parameters and external factors [6], [7].

Retrievals based on these spectral indices (combinations of different spectral channels) are limited in accuracy, but they allow also checking the overall consistency in database content. Most significance relationships between vegetation parameters values and reflectance have been obtained from the next spectral indices:

- **RVI = \frac{irc}{r}** Pearson & Miller 1972 (1)
- **NDVI = \frac{(irc - r)}{(irc + r)}** Rouse 1974 (2)
- **Ratio = \frac{R_{674}}{R_{553}}** Datt 1998 (3)
- **Ratio = \frac{(R_{682} - R_{553})}{(R_{682} + R_{553})}** (4)
- **Ratio = \frac{TCARI}{OSAVI}** Miller 2002 (5)
where

$$\text{TCARI} = 3 \times \left[ R_{670} - R_{670} \right] - 0.2 \times \left[ R_{700} - R_{550} \right] \frac{R_{700}}{R_{670}}$$

$$\text{OSAVI} = (1 + 0.16) \frac{R_{450} - R_{670}}{R_{700} - R_{670} + 0.16}$$

$$y = -30.194 \ln(x) - 18.363 \quad \text{Miller 2002 (6)}$$

In addition the Depth Index and the Area Index are well correlated to chlorophyll absorption. Fig. 4 illustrates the way to obtain the Depth Index: we have measured the depth at 674 nm from a linear function fitted to 471 and 553 nm.

![Fig. 4. Meaning of the Depth Index](image)

The area index relates the chlorophyll absorption to the area obtained as it shows at fig. 5.

![Fig. 5. Meaning of the Area Index](image)

All these indices have been checked with our data considering, on one hand, vegetation values that were measured at leaf level so we used the Chl*LAI, DM*LAI and WC*LAI products to apply the analysis at canopy level. On the other hand, mean values per crop for vegetation parameters were checked studying reflectance correlations with the Chl*LAI, Chl*FVC, LAI*FVC and Chl*FVC*LAI products. Figs. 6 and 7 show results obtained for indices (1) and (3) using different parameters vegetation products.

![Fig. 6. Relationship between Datt proposed index and Chlorophyll-cover product](image)

$$y = 1.52 - 0.0198 x \quad R = 0.86$$

![Fig. 7. Relationship between RVI index and Chlorophyll-cover-LAI product.](image)

$$y = 2.7 + 0.0256 x \quad R = 0.78$$

Correlations obtained for the different checked indices are indicated at next table where the $R^2$ values are reported.

<table>
<thead>
<tr>
<th>INDEX</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth index</td>
<td>0.56</td>
</tr>
<tr>
<td>Area index</td>
<td>0.56</td>
</tr>
<tr>
<td>Ratio (553, 682)</td>
<td>0.46</td>
</tr>
<tr>
<td>$(R_{684} - R_{553}) / (R_{684} + R_{553})$</td>
<td>0.64</td>
</tr>
<tr>
<td>Ratio (674, 553)</td>
<td>0.74</td>
</tr>
<tr>
<td>Ratio (694, 682)</td>
<td>0.42</td>
</tr>
<tr>
<td>RVI index</td>
<td>0.61</td>
</tr>
</tbody>
</table>
4. FORWARD MODELLING OF CANOPY REFLECTANCE

As second approach for the retrieval of vegetation biophysical variables our aim was to retrieve canopy variables by applying model-inversion techniques. But for the previous step it was necessary to test the forward modelling of canopy reflectance to compare the output data from applying the PROSPECT model at leaf level and the SAIL model at canopy level, both of them filtered for the CHRIS channels, to the acquired CHRIS spectral data from SPARC-2003 campaign (July 12th and 14th).

Figs. 8 and 9 show the CHRIS spectral mean values got, respectively, for garlic and potato and the standard deviation ($\sigma$).

Fig. 8. Reflectance mean values and standard deviation measured for garlic crop from CHRIS data. SPARC-2003.

Fig. 9. Reflectance mean values and standard deviation measured for potato crop from CHRIS data. SPARC-2003.

LAI, chlorophyll, dry matter and water content values introduced as inputs for the forward modelling of canopy reflectance can be found in Table 5.

The input considered necessary for PROSPECT-SAIL model, in addition to in-situ biophysical data, was the structure parameter, $N$, related to the number of leaf layers and we checked the sensibility of the model for $N$ values previously to start the forward modelling. Results for simulated and measured spectra from potato crop (ESU P1-T10) and for nadir view angle are illustrated at Fig. 12, where the simulated spectra with $N=1.5$, $N=2.5$ and $N=5$ (maximum value suggested for the structure parameter) are all lower than expected when they are compared to CHRIS spectrum, taking into account the interval error in the spectrum measured ($\sigma$).
Table 5. Biophysical parameters introduced as inputs to forward modelling of canopy reflectance

<table>
<thead>
<tr>
<th>Crop</th>
<th>ESU</th>
<th>LAI</th>
<th>Chlorophyll Mean Value (g cm(^{-2}))</th>
<th>Dry matter (g cm(^{-2}))</th>
<th>Water content (g cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>C1-A1</td>
<td>3.84</td>
<td>48.9</td>
<td>0.006119</td>
<td>0.017979</td>
</tr>
<tr>
<td></td>
<td>C1-A2</td>
<td>3.09</td>
<td>51.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C1-A3</td>
<td>3.02</td>
<td>50.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugar - beet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T1</td>
<td>3.85</td>
<td>44.9</td>
<td>0.007198</td>
<td>0.044815</td>
</tr>
<tr>
<td></td>
<td>B1-T2</td>
<td>3.47</td>
<td>48.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T3</td>
<td>4.15</td>
<td>42.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T4</td>
<td>3.78</td>
<td>43.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T5</td>
<td>3.52</td>
<td>38.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-T6</td>
<td>3.44</td>
<td>47.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onion</td>
<td>On1-B1</td>
<td>2.36</td>
<td>23</td>
<td>0.008278</td>
<td>0.068112</td>
</tr>
<tr>
<td></td>
<td>On1-A1</td>
<td>2.88</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>On1-B2</td>
<td>1.41</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>On1-B4</td>
<td>2.41</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>On1-B5</td>
<td>2.1</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>On2-A1</td>
<td>1.56</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>On2-A2</td>
<td>1.68</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garlic</td>
<td>G1-A7</td>
<td>0.65</td>
<td>20</td>
<td>0.012951</td>
<td>0.059354</td>
</tr>
<tr>
<td></td>
<td>G1-A8</td>
<td>0.62</td>
<td>15.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>G1-A9</td>
<td>0.55</td>
<td>12.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>G1-A10</td>
<td>0.4</td>
<td>11.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potato</td>
<td>P1-T12</td>
<td>6.2</td>
<td>36.7</td>
<td>0.004289</td>
<td>0.022302</td>
</tr>
<tr>
<td></td>
<td>P1-T11</td>
<td>5.54</td>
<td>36.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P1-T10</td>
<td>5.93</td>
<td>35.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P1-T9</td>
<td>5.39</td>
<td>34.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>A9-T0</td>
<td>3.84</td>
<td>48.5</td>
<td>0.006119</td>
<td>0.017979</td>
</tr>
</tbody>
</table>

Other parameter checked in order to reproduce the spectral measurements was the dry matter, which was considered as all kind of matter that remains in leaf when we dry it.

For this reason different values of dry matter were introduced in the PROSPECT + SAIL keeping the other biophysical parameters with their real values.

Fig. 12. Model simulations using different N values versus CHRIS data for the potato field.

Fig. 13 shows the PROSPECT + SAIL simulated spectra for garlic (ESU G1-A9) compared to CHRIS data for different view angles and their dependence with the structure parameter N. We can see that even with the largest value used of the structure parameter, we cannot reproduce the CHRIS spectrum for each view angle.

Fig. 13. Simulated spectra for garlic for different structure parameter values, N, compared to CHRIS spectrum got for different view angles.

Next figure shows the simulated and measured CHRIS spectral results for potato (ESU P1-T10) for different values of dry matter (in \( \mu g \) cm\(^{-2}\)) using N = 2.5 as structure parameter value.

Fig. 14. Simulated and measured CHRIS spectral values for potato crop and for different values of dry matter.
As we can see in this figure, the simulated spectrum increases when dry matter decreases, and it is justified by the low absorption found for low dry matter values, but, as it can be observed, even with a DM value so small and far from the measured one (4.3 µg cm$^{-2}$) as 0.5 µg cm$^{-2}$ we were not able to reproduce CHRIS spectrum.

For this reason, the next step was to check results changing LAI values. Fig. 15 and 16 show the CHRIS spectra for potato and garlic respectively for different view angles, together with:
- the simulated spectrum got from measured values of LAI and the rest of biophysical parameters and
- the simulated spectrum obtained by changing only the LAI value for one assigned value that reproduces the CHRIS spectrum.

For this reason, the next step was to check results changing LAI values. Fig. 15 and 16 show the CHRIS spectra for potato and garlic respectively for different view angles, together with:
- the simulated spectrum got from measured values of LAI and the rest of biophysical parameters and
- the simulated spectrum obtained by changing only the LAI value for one assigned value that reproduces the CHRIS spectrum.

As we can observe in both figures, in most of cases, a change in LAI values gives similar results for simulated and measured CHRIS spectral data in the infra-red spectral region. Nevertheless, for the visible range it was not possible to simulate the same spectrum with our PROSPECT+SAIL modelization.

Fig. 17 shows how the difference between measured and assigned LAI ($\Delta$LAI) is related to view angle, taking as example two measuring dates, (12$^{th}$ July and 14$^{th}$ July) and two different crops (potato and onion). It seems that, in almost all the cases, negative view angles correspond to negative values of $\Delta$LAI or, what is the same, measured LAI is smaller than the value of LAI necessary to reproduce CHRIS spectrum, while positive view angles correspond to positive values of $\Delta$LAI. What we mean is that it seems to be a dependence in the LAI values with the view angle.

Fig. 17. Relationship between $\Delta$LAI and view angle for two crops and two measuring dates. SPARC-03.

Fig. 16. Simulated spectra for onion (On1-B1) compared to CHRIS measured spectra for different view angles. SPARC-2003.

As we can observe in both figures, in most of cases, a change in LAI values gives similar results for simulated and measured CHRIS spectral data in the infra-red spectral region. Nevertheless, for the visible range it was not possible to simulate the same spectrum with our PROSPECT+SAIL modelization.
5. LAI AND CHLOROPHYLL RETRIEVALS

By using simple line-fitting techniques that allow to match the measured reflectance spectrum to a (simplified) reflectance model, that mostly exploit the spectral variability, some retrievals of chlorophyll and Leaf Area Index have been derived already from SPARC CHRIS data. Results are illustrated in Figures 18 and 19. First of all, it must be pointed out that the results have been derived by using individually single-angle images, with the idea of intercomparison of the results derived for each angles. Biochemicals such as chlorophyll and LAI values should be the same as derived from each angular image, and this variations in the retrievals for each angle allow to account for the angular effects. On the other hand, the overall results look quite satisfactory, taking into account the preliminary character of these retrievals.

In the case of chlorophyll retrievals, there is a significant dispersion in the scatterplot between the measured values and the retrieved ones, but there are no significant systematic effects with view angle. In the case of LAI retrievals, the dispersion in the scatterplot between the retrieved values and the measured ones is also significant, but the most significant effect is a kind of systematic dependence of LAI retrievals with viewing angle.

Finally, it must be noted that LAI and chlorophyll maps derived from CHRIS data show some artefacts due to the presence of noises in the data that have not been perfectly removed. Retrieval algorithms that make use of channel ratios, channel differences, spectral derivatives or other mathematical combinations of CHRIS bands turn out to be quite sensitive to such coherent noises, and then a proper radiometric filtering of the images is absolutely needed before application of sophisticate retrieval algorithms.
6. CONCLUSIONS

CHRIS/PROBA data from the SPARC campaign have shown again the difficulties in retrieving biophysical variables when constraining models in all (most significant) inputs variables: the accuracy in the retrieval of some particular variable should not be compromised at the expenses of wrong values for other key variables.

Retrieval of biochemical contents (i.e., chlorophyll) by model-inversion approaches is limited by the capability of the model to actually represent the observed spectrum reflectance. Use of multiple views to constraint LAI compromises retrievals of biochemicals: the role of fCover and gap functions in the coupling of biochemicals and canopy structure must be accounted for. Alternative formulations allow to retrieve LAI as a function of view angle and then use such function to derive structural properties.

Significant improvements in modelling hyperspectral/multiangular data still needed before effective inversion methods can be successfully used. Exploitation of multitemporal aspects in retrievals will be explored with the SPARC 2004 dataset.

ACKNOWLEDGMENTS

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REFERENCES


ANALYSES OF HYPERSPECTRAL AND DIRECTIONAL CHRIS DATA FOR AGRICULTURAL MONITORING USING A CANOPY REFLECTANCE MODEL

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ABSTRACT

Agricultural monitoring using a canopy reflectance model through analyses of hyperspectral and directional CHRIS data is targeted. CHRIS data of the Upper Rhine Valley test-site (Germany) were destriped and geometrically corrected, so that the 5 angular observations can be compared. An atmospheric correction was performed that uses the radiative transfer model MODTRAN 4. An extended version of the GeoSAIL canopy reflectance model (FourSAIL2) is adapted according to the spectral wavelength of CHRIS. Optical simulation results are compared with satellite measurements. Directional reflectance spectra are extracted and the directional variations compared to the model results.

1. INTRODUCTION

The additional test-site No. 55 of the CHRIS PROBA mission is located in the Upper Rhine Valley near Weisweil at 7.68° E and 48.19° N. Its average height is 150 m. Main subject for research is agriculture. Land use and field size vary between the German and the French Rhine side. One of the most important crops in the area is maize but other crops including specialised ones like tobacco are grown as well. Close to the riverside there are alluvial forests.

For the 2003 data acquisition mode 5 was selected in order to get the highest possible spectral, directional and spatial resolution. This means 18m spatial resolution at half swath width (approximately 7 km image width), 37 spectral bands and along track BRDF (5 angles) [1]. For the Upper Rhine Valley test-site five CHRIS acquisitions were successful in 2003, all of which covered the investigation area (this was not the case with the one acquisition in 2002). They span over the time period from March to August and thus give a good possibility to observe the vegetation development. Three of the acquisitions were completely cloudfree, three consisted of all angles (Tab. 1).

<table>
<thead>
<tr>
<th>Date</th>
<th>-55°</th>
<th>-36°</th>
<th>0°</th>
<th>36°</th>
<th>55°</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.03.</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>02.06.</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td>some clouds</td>
</tr>
<tr>
<td>18.07.</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>03.08.</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>11.09.</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>heavy clouds</td>
</tr>
</tbody>
</table>

The overlap of the angular observations is at least half of the covered ground area. Usually the overlap is better for ± 36° than for ± 55°. An overview on the nadir view data is presented in Fig. 1. Even though on Sep 11 2003 there are heavy clouds over the whole Upper Rhine area the test-fields themself are free of clouds and cloud shadows for all observation angles.

2. METHODOLOGY

For quantitative interpretation of the CHRIS data some radiometric and spatial corrections had to be applied. Radiometric destriping was performed to minimize sensor noise. The data were georeferenced to the Gauss-Krüger projection, so that different dates and angles could be combined. The radiometric calibration had to be adjusted as a sensitivity drop in the near infrared had become visible. An atmospheric correction was performed to extract reflectances from the radiances.

2.1. Radiometric Destriping

For the radiometric destriping a statistical approach for each column was chosen. Corrections use the moving averages of mean gray values for each column. The factor between the actual gray value and the moving average was used for coarse correction. The visual inspection of all bands after the first automatic destriping procedure revealed that some features could not be corrected sufficiently. These were corrected manually by optimisation of the gain factors of the destriping also spectrally variable and
successive visual control of success. A sample of how well the compensation of striping worked is shown in Fig. 2 and 3. Pixels 64 to 69 have the same landuse. Before destriping their radiances vary widely, afterwards they show close spectral signatures.

2.2. Geometric Corrections and Georeferencing

For georeferencing ground control points for all observation angles were located on a georectified IKONOS image (ground resolution: 4 m, Gauss-Krüger projection). All images were resampled to the nominal ground resolution of the nadir view, i.e. 18 m. For resampling the nearest-neighbour approach was chosen so that the values of the DNs were not changed. The results for the test-site area for the nadir images can be seen in Fig. 4. The Sep 11 2003 image could not be rectified as a whole due to the heavy cloud coverage.

The co-location of the five different angles (Fig. 5 and 6) for Aug 03 2003 shows that the images match spatially (the overlap is nearly total for nadir and ± 36°). Fig. 6 shows that the quality of the correction even for the ± 55° data is high.

2.3. Adjustments of Radiometric Calibration

The temperature dependent values for central wavelength and width of each spectral band stored in the header file were used to simulate the radiances at sensor for the CHRIS bands. A comparison with MODTRAN 4 high spectral resolution simulations showed that the central wavelengths were placed at the right positions but that the width of the individual bands was too small (e.g. clearly detectable from the shape and position of the O²-absorption band at 760 nm). So the spectral width was extended by 7.5 nm for all bands. As spectral response function for the sensor file the rectangular function was chosen as this represents the shape of the sensitivity function of each individual band most closely.

The radiometric calibration coefficients were adapted via vicarious calibration using the spectral signatures for bare soil. A sensitivity drop in the near infrared as well as the overcompensation in the blue band at 442 nm could thus be corrected. No change of calibration had to be applied to the middle part of the sensor spectrum (490 - 744 nm). The updated calibration coefficients can be seen in Fig. 7. The default value was 0.01 W/m² sr µm. The effects of the updated calibration coefficients on sample spectra of soil and maize are shown in Fig. 8.

2.4. Atmospheric Corrections

The atmospheric correction was based upon MODTRAN 4 radiative transfer simulations using the atmospheric correction scheme PULREF [2]. For example, as input parameters for the August 03 2003 image a visibility of 40 km and a water vapour factor of 1.1 were chosen. These values were estimated from the scene by stepwise modification and choose of the best results. For correct simulation of the pathway through the atmosphere for the angular observations the solar geometry was used as input to MODTRAN 4 (mode 12 [3]). For Aug 03 2003 the solar azimuth is 158,31°, the sensor azimuth 12° (forward looking) or 192° (backward looking), resulting in a relative azimuth of 146.31° (forward looking) and 33.70 ° (backward looking). As the minimum zenith angle is only 1° its influence on the path length and observation angles is negligible.

An adjacency effect [4] correction using the average
Figure 2. Radiances of one particular landuse before destriping (Aug 03 2003)

Figure 3. Radiances of one particular landuse after destriping (Aug 03 2003)

Figure 4. Overview on georeferenced nadir acquisitions (from left to right: Mar 25, Jun 02, Jul 18, Aug 03, bgr: 675nm, 713 nm, 781nm)
Figure 5. Color composite of observation angles $-36^\circ$, $0^\circ$, $+36^\circ$ (Aug 03 2003)

Figure 6. Color composite of observation angles $-55^\circ$, $0^\circ$, $+55^\circ$ (Aug 03 2003)

Figure 7. Derived calibration coefficients for the scene from Aug 03 2003 with a reference temperature of 3.43 K (mode 5)

Figure 8. Effect of updating the calibration coefficients for sample spectra of soil (triangles) and maize (diamonds) for Aug 03 2003 (blue: gain value 0.01 W/m$^2$ sr µm; red: derived values shown in Fig. 7)
value of image statistics has been included in the atmospheric correction procedure. The calculation of the contribution of radiation from adjacent surfaces is important for the later analyses as the adjacency effect influences the BRDF functions.

Samples of nadir spectra retrieved from the August 03 2003 image are shown in Fig. 9. The spectra represent one pixel only, no smoothing has been applied. The spectra are satisfactorily similar to the expected curves for water, bare soil and vegetation. For vegetation (maize, dense vegetation, forest) the differences in the position of the red edge as well as the different depths of the water absorption band at 960 nm can be seen clearly and can later be used for extraction and analyses of agricultural parameters.

Spatial variable water vapour retrieval was tested but the signal to noise ratio was found to be not adequate for this procedure.

3. RESULTS

After completion of the preprocessing, quantitative analyses of different features were started. BRDF functions were analysed visually and a comparison between calculated reflectances of CHRIS data and simulated reflectances of the canopy reflectance model FourSAIL2 has been performed.

3.1. BRDF Analysis

As a first step of analyses the BOA reflectances of all five angles were compared. In Fig. 10 the BOA reflectances for bare soil for Aug 03 2003 are shown. The nadir spectrum lies in the middle between the forward and backward looking angles. - 55° and - 36° are close to the “hot spot” and therefore brighter than the nadir spectrum. + 55° and + 36° look towards the sun and thus are darker. The difference between nadir and 36° is in both cases much larger than the difference between 36° and 55°.

Fig. 11 shows bottom of atmosphere (BOA) reflectances retrieved from the Aug 03 2003 CHRIS acquisition at a fixed wavelength (780 nm) for different landuses. The solar zenith was at 32°. The “hot spot” effect, which is an increase of reflectances since shadows disappear if the sun is situated in the back, can be seen clearly. Again the figure shows that the difference between nadir and 36° is bigger than the difference between 36° and 55°.

3.2. Canopy reflectance modelling with FourSAIL2

FourSAIL2 (or 4SAIL2) is a surface reflectance model that was evolved from the GeoSAIL model [5] through an extension with a non-lambertian soil BRDF model and the additional consideration of vegetation with ground or crown coverage below 1. These extensions allow the more realistic simulations of directional acquisitions and of forests. As shown in Fig. 12 FourSAIL2 follows a 4-stream concept, which divides the modeled fluxes in their direct and diffuse, upward and downward contributions.

The input parameters to 4SAIL2 are listed in Fig. 12. They describe structural and physiological information on the vegetation, soil properties and the observation geometry. 4SAIL2 incorporates a sub-model for the soil reflectance and its variation with moisture [6]. The canopy model is a two-layer version of the model SAILH [7]. The canopy is modeled in 2 layers to mimic the vertical leaf color gradient often seen in agricultural canopies. The structural properties in both layers (leaf angle distribution and leaf size) are assumed to be identical in both layers, but the LAIs for green and brown leaves may differ.
Figure 9. Sample nadir spectra CHRIS Aug 03 2003

Figure 12. Four stream canopy reflectance model 4SAIL2 and required input parameters
Figure 13. Simulated directional reflectances of bare soil (solar zenith: 32°, relative azimuth: 146.31° (forward looking), 33.70° (backward looking))

The leaf angle distribution is described by two parameters, a and b, of which a determines the average leaf slope, and b expresses the so-called bimodality of the distribution [8]. The division of the LAI (leaf area index) for both types of leaf over both layers is governed by the parameters fraction brown leaves fB and the so-called dissociation factor D. For the extreme values D = 1 (complete dissociation) and D = 0 (homogeneous mixture). The spectral information on the optical properties of the leaves (i.e. spectral reflectance and transmittance of green and brown leaves) is calculated using the PROSPECT model [9].

The application of 4SAIL2 under consideration of the spectral configuration of the CHRIS sensor allows the simulation of surface reflectances as seen with CHRIS from the PROBA satellite.

3.3. Comparison of CHRIS data with FourSAIL2 simulation results

The soil BRDF model is a parametric model using 4 coefficients (b, C, B0 and h) to describe the non-lambertian reflection of soils. The change of spectral reflectance of a soil for the 5 CHRIS observations are simulated and shown in Fig. 13. Without fine-tuning of the parametric model a good agreement between the simulations and the measurements shown in Fig. 10 can be observed so that we follow, that the soil background reflectance of a canopy is sufficiently represented in FourSAIL2.

Comparisons of the canopy reflectance of maize under varying observation angles are further started. Fig. 14 shows a simulation for maize. Observations using CHRIS are illustrated in Fig. 15. Again the simulations with 4SAIL2 were not optimized in order to check the quality of the simulation with the default input parameters assigned to maize. Here the agreements are good. The largest differences can be observed in the red spectral range, where the simulated chlorophyll absorption is too strong compared to the CHRIS measurements. Interesting is that the forward looking spectra of maize are almost identical in the CHRIS acquisitions. The simulation expects however a decrease in the NIR reflectances for forward looking observations.

These first analyses demonstrate how useful CHRIS data will be for checking the performance of canopy reflectance modeling and for the determination of input parameters to the models. After this understanding is improved, the reflectance model will then also be used for retrieval of canopy parameters.

4. CONCLUSIONS AND OUTLOOK

From our present experience with CHRIS data, we conclude that a careful processing of CHRIS data is required before any thematic analyses of the hyperspectral directional acquisitions. This includes im-
provements of the SNR through destriping, the control and optimization of the calibration of the sensor, and a high quality atmospheric correction. Our experiences showed that data with high spectral resolution is required for these tasks, so the acquisition of mode 1 or 5 is suggested to be selected.

The first analyses of CHRIS data and comparisons with canopy reflectance modeling with 4SAIL2 showed that CHRIS PROBA helps to identify BRDF parameters in surface reflectance models, allows the check of model performance and input parameter optimization. The coarser spatial resolutions of the observation at 36° and 55° must however be considered in these BRDF analyses. In order to avoid misinterpretation, it is suggested that spatial homogenous pixels must be selected for these tasks.

Future activities will include the continuation of the spectral and directional analyses of the 2003 data of the Upper Rhine Valley test-site. Plant parameters like LAI, chlorophyll and water content will be extracted from the hyperspectral directional CHRIS data using the canopy reflectance model 4SAIL2.

Multitemporal and multispectral remote sensing data have already proven their potential for the determination of land surface information like biomass production through their combination with plant growth models [10, 11]. The optical data are interpreted using canopy reflectance models in order to retrieve plant parameters that allow the spatially update of plant production simulations. The retrieved agricultural variables are assimilated in plant production and management models (e.g. the crop growth model PROMET) [12]. This methodology shall be further tested and extended using hyperspectral, directional CHRIS data.

ACKNOWLEDGMENTS

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REFERENCES

RETRIEVAL OF LEAF AREA INDEX BY INVERTING HYPER-SPECTRAL, MULTI-ANGULAR CHRIS/PROBA DATA FROM SPARC 2003

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ABSTRACT

The SPARC campaign has been organized in coincidence of CHRIS/Proba multi-angular and hyper-spectral acquisition over the agricultural test site of Barrax in Spain. Radiometric and biophysical vegetation parameters measurements have been carried out for different crops in both field and laboratory. The aim of this preliminary study is to assess the capability to estimate Leaf Area Index (LAI) from CHRIS/Proba data by inverting the coupled radiative transfer models PROSPECT+SAILH. Two different approaches have been used to invert canopy reflectance observed in 5 directions and 62 spectral bands: Look Up Tables and Pest ASP Tool. Results show that the use of a priori knowledge is of great importance for the estimation of LAI. In this way we have been able to estimate this parameter with an accuracy of around 15%÷20% for Alfalfa, Potatoes, and Sugar Beet samples.

1. INTRODUCTION

Over the past decade, there has been a great interest in the application of Earth Observation techniques in the field of hydrology, water management and precision farming [1]. More in particular, hydrological models for the simulation of water flow in the soil-vegetation-atmosphere system require the estimation of canopy parameters such as LAI, surface albedo, and crop height [2].

D’Urso et al.[3] have exploited remote sensing data to estimate these canopy characteristics by using empirical approaches based on spectral indices. These approaches are based on simplified assumptions on the reflective behavior of vegetation thus limiting the resulting accuracy in absence of a proper calibration of the empirical relationship adopted. On the other hand, it has been shown that the estimation of canopy characteristics can be improved and generalized if spectral directional information is available [4], [5].

The Compact High Resolution Imaging Spectrometer on board the Proba platform (http://www.chris-proba.org.uk/) has made available hyper-spectral and multi-angular high resolution observations from space on selected sites during 2003. This mission was considered as an unique opportunity to validate radiative transfer models of vegetation from satellite, in order to assess the accuracy of these models in the estimation of the canopy characteristics of our interests.

In this preliminary research work, we have used CHRIS/Proba data acquired over the agricultural site of Barrax (Spain) in conjunction with the radiative transfer models PROSPECT (leaf level) [13] and SAILH (canopy model) [9]. The reflectance models were applied in the inverse mode to retrieve the value of Leaf Area Index for different crops in the test-site.

Two inversion techniques were applied, the first based on LookUp tables and the second on a non-linear parameter estimation software.

2. DATA AND METHODOLOGY

2.1 Study Area

The SPARC campaign was carried out in Barrax (N30°3’, W2°6’), an agriculture test area situated within La Mancha region in the south of Spain, from 12 to 14 July 2003.

The area has been analysed for agricultural research for many years thanks to its flat topography (differences in elevation range up to 2 m only) and its large, uniform stands of Alfalfa, Corn, Sugar Beet, Onions, Garlic and Potatoes. Around 35% of the area is irrigated while the remaining 65% is dry land (Fig. 1).

Fig. 1. Agricultural land use in Barrax test site
During the SPARC campaign, different sensors were flown in this time interval, with resolution ranging from 1 m (airborne Rosis operated by DLR) to 300 m (MERIS on Envisat).

2.2 CHRIS Data Acquisitions

CHRIS/Proba hyper-spectral, multi-angular imagery was collected on 12 and 14 July 2003 with overpass times 11:07 and 11:32 (UT) respectively (Table 1).

Five images with different nominal view angles (-55°, -36°, 0°, +36°, +55° along-track zenith angles) and 62 spectral bands (from 410 nm to 1050 nm) per angle were acquired for each pass. The covered image area is 14 km x 14 km (748 X 748 pixels) with a spatial resolution of 36 m (Table 2).

Table 1. Acquisition geometry for SPARC2003

<table>
<thead>
<tr>
<th>F.Z.A.</th>
<th>+55</th>
<th>+36</th>
<th>0</th>
<th>-36</th>
<th>-55</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/07/2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth</td>
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<td>102.40</td>
<td>165.44</td>
<td>177.06</td>
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<td>19.40</td>
<td>39.15</td>
<td>56.24</td>
</tr>
<tr>
<td>14/07/2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Azimuth</td>
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<td>339.44</td>
<td>285.27</td>
<td>231.22</td>
<td>216.91</td>
</tr>
<tr>
<td>Zenith</td>
<td>57.29</td>
<td>42.44</td>
<td>27.6</td>
<td>42.53</td>
<td>57.40</td>
</tr>
</tbody>
</table>

Fig. 2 shows the angular sampling of CHRIS/Proba image acquisition over Barrax site. The images were atmospherically corrected at the University of Valencia by mean of an improved algorithm based on Vermote et al. scheme for MODIS atmospheric correction [6].

2.3 Field and Lab Measurements

Extensive and systematic in situ measurements included spectral calibration data and determination of main biophysical parameters [7].

Field non-destructive measurements of Leaf Area Index (LAI) and Mean Tilt Angle (MTA) were made by means of the digital analyser Licor LAI-2000; leaf chlorophyll content was measured with the CCM-200 Chlorophyll Content Meter. A set of 39 out of 113 LAI measurements was included on the overlap area of multi-angular CHRIS/Proba images and this set was used for this preliminary study. Measurements of LAI and leaf chlorophyll content were carried out again in the laboratory from destructive samples in order to validate those taken in situ by the CCM-200 showing a good correlation between the two data sets [8]. Additional measurements on leaf water content and leaf dry matter were also taken.

In addition to the LAI and chlorophyll, radiometric measurements were performed by means of two ASD FieldSpec in coincidence of CHRIS/Proba data acquisitions. Two bare soil surfaces representing bright and dark soil conditions and one alfalfa field were selected for the spectral profile measurements.

2.4 Radiative transfer models

In order to compare CHRIS/Proba BRDF data with simulated BRDF from a radiative transfer model we have chosen SAILH (with the Hotspot effect) [9] [10] [11] for the description of the canopy radiation fluxes and PROSPECT [12] [13] for the simulation of the leaf optical properties (Fig. 3).

Two fundamental criteria have led us to choose PROSPECT+SAILH model: i) simplicity, i.e. the possibility to have a rather good representation of the radiative transfer of the canopy using a relatively small amount of input parameters as well as limited computational requirements, and ii) reliability since the SAILH model has been successfully tested for a large set of crops, among which corn [14] and sugar beet [15], which were present in our study-area.

In order to simulate top of the canopy reflectance by PROSPECT and SAILH models, 7 vegetation
<table>
<thead>
<tr>
<th>Spatial sampling</th>
<th>18 m on ground at nadir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image area</td>
<td>14 km X 14 km (748 X 748 pixels)</td>
</tr>
<tr>
<td>Spectral range</td>
<td>410nm to 1050 nm</td>
</tr>
<tr>
<td>Number of spectral bands</td>
<td>63 bands at a spatial resolution of 36m</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>1.3 nm @ 410nm to 12 nm @ 1050nm (i.e it varies across the spectrum)</td>
</tr>
</tbody>
</table>

**Fig. 3. Basic flow-chart of the combined used of PROSPECT + SAILH models.**

Parameters, 3 sun-sensor geometric parameters and 1 visibility parameter are needed to calculate the BRF for each wavelength and for each view angle for a given sun-sensor geometry. Thus:

\[
\rho(\lambda, \theta_v) = f(N, C_{ab}, C_w, C_m, \text{LAI}, \text{HOT}, \text{LIDF}, \theta_s, \psi, \text{Esky})
\]  

(1)

where:

- \( \rho(\lambda, \theta_v) \) = canopy reflectance at wavelength \( \lambda \) and view zenith angle \( \theta_v \).
- \( N \) = Leaf mesophyll parameter
- \( C_{ab} \) = Chlorophyll a and b content
- \( C_w \) = Water content
- \( \text{LAI} \) = Leaf area index
- \( \text{HOT} \) = Hot spot parameter
- \( \text{LIDF} \) = Leaf inclination density function
- \( \theta_s \) = Sun zenith angle
- \( \psi \) = Relative sun-object azimuth angle
- \( \text{Esky} \) = Diffuse part of the incoming radiation

The hot spot parameter \( \text{HOT} \) is defined as the ratio between the average size of the leaf and the canopy height [10].

A first validation of the PROSPECT and SAILH models on the test-site was performed by using the spectral measurements done on the alfalfa field with the ASD FieldSpec instrument. The following input parameters were considered: nadir view, \( C_{ab}=50 \text{ mg/cm}^2 \), \( C_w=0.011 \text{ g/cm}^2 \) \( C_m=0.0055 \text{ g/cm}^2 \), LAI=2.7, \( \text{HOT}=0.057 \) and \( \text{Esky}=0.13 \), as from ground measurements, while we have assumed \( N=1.8 \) [19] and Spherical LIDF (average leaf angle 57°). The PROSPECT+SAILH models were then run with 9 different background measured spectra, ranging from very bright to very dark. The maximum radiometric discrepancy due to the soil background effect was evaluated around 13.7% (VIS=14.4%; NIR=12.9%). Fig. 4 shows that the best fit between simulated and measured alfalfa canopy reflectance spectrum, which was obtained by choosing a wet (dark) soil. The value of RMSE = 2.298 over all wavelengths was considered satisfactory.

**3. INVERSION ALGORITHMS**

Two algorithms were considered to solve the inverse problem: i) the construction of LookUp Table (LUT) and subsequent best-fit procedure, and ii) the PEST-ASP software tool [16], based on the Gauss-Marquardt-Levenberg algorithm.

**3.1 LookUp Table**

The LUT is a very easy to implement method consisting in the following steps:

- sampling the parameters space of canopy for a given sun-sensor geometry;
- for each combination of canopy parameters, computing and storing the spectral profile generated by means of PROSPECT and SAILH models;
- finding which set of canopy parameters corresponds to the best fit between observed and simulated spectral profile, according to the minimum RRMSE defined as:

![Fig. 4. ASD FieldSpec- measured vs. simulated spectra for a Alfalfa field](image-url)
The main advantage of the LUT is that the forwarding modelling process is disjointed by the inversion procedure. Hence, the simulated spectral firms have to be computed only once.

In this study, no particular distribution function for the vegetation parameters was assumed in order to sample the parameters space. They were sampled uniformly according to Table 3. $C_w$ was fixed since the leaf water content doesn’t affect the spectrum in the 400-1000 nm range and 5 different leaf inclination distribution, corresponding to 5 different plant architecture (Planophile, Plagiophile, Extremophile, Erectophile, Spherical) were taken into consideration. Finally, the sun-sensor geometric parameters were set according to CHRIS/Proba pass 12/7 (Table 1). The Esky parameter was retrieved through the atmospheric measures.

A total of 585000 simulated spectra were thus computed.

### 3.2 PEST- ASP© tool

The model independent Parameter Estimation program PEST [16] is used to determine the optimised parameters accordingly to a pre-defined cost-function. PEST is a nonlinear parameter estimation program, which can be easily linked by templates to any model. It runs the specific model, compares the model results with the observed (measured) values and adjusts selected parameters using Marquardt-Levenberg optimisation algorithm [17], [18]. The procedure is iteratively repeated until the optimal set of adjustable parameters (Fig. 5).

### 4. RESULTS AND DISCUSSION

The multi-angular surface reflectance data were extracted from the atmospherically corrected image acquired by CHRIS/Proba on July 12th. The overlay area for the images on all five angles (-55º, -36º, 0º, +36º, +55º) included 39 fields were LAI measurements were taken on 5 different types of crop (Alfalfa, Potatoes, Sugar Beet, Corn, Onion).

The BRDF of these 39 plots were extracted from the CHRIS/Proba images by taking the mean reflectance value at each angle in a window of 3x3 pixels.

In order to characterise the average soil surface reflectance, we extracted 50 different bare soil spectra from the nadir image and we calculated the average. In Fig 6, the mean and the extreme spectral values for the bare soil surfaces observed in the nadir image are shown. We may notice that the average soil spectrum resulted similar to one collected at ground by means of ASD FieldSpec, which was finally chosen to represent the soil reflectance in the application of SAILH model. To this end, we considered the soil background contribution as a constant within the whole image, beside the assumption of Lambertian reflection.

In a first step of the inversion process based on the LUT approach, we tried to retrieve LAI for all 5 crops without applying any a-priori knowledge, i.e. no restrictions were considered in the range of variability.

### Table 3. LUT parameters and space

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Increments</th>
<th># of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>[1.5,2.5]</td>
<td>0.2</td>
<td>6</td>
</tr>
<tr>
<td>$C_{ab}$</td>
<td>[10,70]</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>$C_w$</td>
<td>0.011</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>$C_m$</td>
<td>[0.002,0.02]</td>
<td>0.002</td>
<td>10</td>
</tr>
<tr>
<td>LAI</td>
<td>[1.6,8]</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>LIDF</td>
<td>5</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Esky</td>
<td>0.13</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

![Fig. 5. ASP-PEST routine](image-url)
Fig. 6. Different reflectance spectra from CHRIS/Proba and ASD FieldSpec measures

of input parameters. In such case, the total RMSE between estimated and measured LAI values was found to be equal to 2.1. Considering a crop-by-crop analysis, the RMSE value for Alfalfa dropped to 0.26, probably due, in this case, to a better correspondence to the turbid medium assumption of the SAILH model; the worst results were obtained for the potatoes, which LAI values resulted to be constantly underestimated by around 40%. Rather poor estimations results were obtained for the other crop types. In this inversion procedure based on the PEST-ASP tool on the same fields of the LUT approach, we could achieve a better RMSE=1.56. Then, we focused on the three main crops of our study area: alfalfa, potatoes and sugar beet. In order to increase the accuracy of the inversion procedure, we applied some restrictions to the parameter variability, based on the knowledge of the crop type. At first instance, we limited the range of variability of input parameters; successively, we fixed one or more parameters values. This a-priori knowledge can be easily introduced in the inversion process performed by means of PEST-ASP tool. For all the inversions we fixed, beyond sun-sensor geometrical parameters, the water content, since its effect on the overall reflectance in the range of frequencies 400÷1000 nm should be negligible, Esky as given by the atmospheric measures, and the LIDF as closest as possible to the geometrical canopy structure. In the case of alfalfa, the remaining five parameters were bounded to the following ranges: 1<N<2, 10<Cab<110, 0.001<Cm<0.02, 0.0001<HOT<1, and 0.3<LAI<8. This strategy proved to be very effective, resulting in a RMSE of 0.3 in the retrieval of LAI. Similar procedure was followed in the case of potatoes fields, by limiting the range of N to the interval 1+1.6. The valued of RMSE=0.4 was obtained in this latter case.

Finally, we tried the inversion procedure on sugar beet fields. The leaf structure parameter N was fixed to 1.5, as it was found in literature [15], and the mean leaf inclination fixed to 65° [20]. Although the canopy of this crop strongly departs from the turbid medium hypothesis of SAILH, the strategy of applying a-priori knowledge produced a good agreement between LAI field measurements and LAI estimated, with a RMSE = 0.49. On all the three crop types considered, the overall RMSE in the estimation of LAI parameter was thus 0.42 (Fig. 7).

5. CONCLUSIONS

A preliminary analysis on CHRIS/Proba data has been carried out in this study with the purpose of LAI estimation for agricultural crops. The spectral and spatial information content of the satellite data was exploited to validate canopy reflectance models. It has been demonstrated the effectiveness of the combined use of PROSPECT and SAILH models to simulate canopy BRDF of alfalfa and potatoes crops with a good accuracy (RMSE of 0.3 and 0.4 respectively).

A first attempt of inversion has been carried out using all the information available from hyper-spectral and multi-angular CHRIS/Proba data. The retrieved LAI parameter was estimated with an accuracy of around 15%÷20% for most of the samples.

The investigation has also shown the importance of the soil component in the overall image reflectance. Therefore a better vegetation parameters estimation can be achieved using either a soil spectral map of the image or, more reasonably, a soil BRDF model which takes into account chemical, physical and geometrical soil parameters removing, thus, the Lambertian surface hypothesis.

The results obtained for the crops under investigation encourage to the use of canopy reflectance models in the inverse mode in order to retrieve also other vegetation parameters such as chlorophyll content, dry matter and canopy geometrical characteristics like mean leaf inclination angle. Further steps in the inversion process of hyper-spectral and multi-angular data will be the use of semi empirical models for a first attempt of vegetation parameter estimation to better solve the ill posed problem adding more a priori knowledge. An analysis of the redundancy of information in both the spectral and angular domain will be also performed.
6. REFERENCES


SAN ROSSORE (ITALY) FORESTRY TEST SITE: METHODOLOGY FOR CALIBRATION AND VALIDATION OF CHRIS-PROBA DATA

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ABSTRACT

Following the general trend to better understand the directional reflection properties of a surface, we present some results from CHRIS-PROBA images acquired during last year over the San Rossore (Italy) forestry test site. Particular attention is devoted to the description of the adopted methodology for calibrating and validating CHRIS-PROBA data and for obtaining images of spectral reflectance taking into account the atmospheric effects. Anisotropy Factor are estimated from experimental data and they are used in conjunction of literature data to study the spectral behaviour of multangle remotely sensed data.

1. INTRODUCTION

A large amount of laboratory and in-field measurements has been collected in order to assess the geometrical properties of reflection from a surface in terms of Bidirectional Reflectance Distribution Function (BRDF). This quantity, which takes into account both the illumination and the viewing geometry [1], describes the directional reflectance by relating the incident irradiance from a given pencil of directions to its contribution to the reflected radiance in another propagation direction. To this aim various systems have been developed such as the European GO niometric Facility (EGO) by the Joint Research Centre (Ispra, Italy) [2], the LABor-GONiometer System (LAGOS) and Field-GONiometer System (FIGOS) by the University of Zurich [3], the Portable Apparatus for Rapid Acquisition of Bidirectional Observation of Land and Atmosphere (PARABOLA) instrument by NASA – GSFC [4], and an instrument manufactured at Miami University (Florida, USA), which is able to perform simultaneously multiple viewing-angle measurements [5].

Moreover, recent satellite missions such as the Multi-angle Imaging Spectro Radiometer (MISR) on the Earth Observation Science (EOS AM-1) Terra platform [6] and the Compact High Resolution Imaging Spectrometer (CHIRS) on board of European Space Agency (ESA) PRoject On Board Autonomy 1 (PROBA-1) platform [7] supply experimenters with their off-nadir viewing capability.

Following this general trend aimed to improve the current understanding of directional properties of reflection from natural surfaces, we present a large CHRIS-PROBA data set acquired over the San Rossore (Italy) forestry test site during the last year. This sample area is included within the Regional Natural Park of Migliarino-San Rossore- Massaccicuoli and it is characterised by a land cover mainly dominated by the presence of Pinus pinaster Ait., and Pinus pinea L. This Park is close to the shoreline and it includes the Arno and Serchio river’s estuary.

Inside the San Rossore area many groups are involved in different research activities dealing with agronomy, climatology, eco-physiology and they often utilise remote sensing techniques. For this aim many efforts are devoted to the calibration and validation of aerospace hyperspectral data. In order to obtain level 2 products by correcting remote sensing data for atmospheric effects San Rossore area has been permanently equipped with scientific instruments which measure total and diffuse solar irradiance in the visible and infrared spectral range, ground temperature, pressure, relative humidity.

After introducing some details about CHRIS spectrometer in Section 2, the description of the calibration and validation procedure is reported in Section 3 together with a preliminary data quality assessment of CHRIS-PROBA data. Section 4 is devoted to the presentation of early results obtained correcting the experimental data for the atmospheric effects. In Section 5 conclusion and open problem are drawn with the discussion of future activities to be carried out in order to better assess BRDF effects from multangle remotely sensed data.

2. CHRIS SPECTROMETER

CHRIS is a “push-broom” imaging spectrometer that was designed by SIRA Electro-Optics Ltd. (U.K.) to collect data for land investigation and aerosol measurement. CHRIS is the main instrument payload on ESA small satellite platform PROBA-1 launched on October 22, 2001.

The mission is being used as a demonstrator in order to evaluate the performance of compact design technology. The knowledge derived from CHRIS-PROBA will guide the design of hyperspectral imaging systems for future missions, such as the ESA Earth Explorer Mission SPECTRA.

The main scientific CHRIS-PROBA goal is the measurement of Earth surface directional reflectance in the visible and near-infrared spectral bands using the platform pointing capability.
To this aim in the along-track and across-track directions CHRIS acquires a set of five images of the same scene during the same sun-synchronous polar orbit. Each image set has an associated “fly-by position” on the ground (roughly the image center) that corresponds to the Minimum Zenith Angle (MZA), defined as the off-nadir inclination of the sensor viewing direction in the plane perpendicular to the satellite orbit. The line of sight inclination in the along track direction (held in the orbit plane) is indicated by the Fly-by Zenith Angle (FZA). The geometrical composition of the aforementioned angles gives the true zenith angle of the sensor viewing direction.

CHRIS acquires images of the same scene at FZA of +55°, +36°, 0°, -36°, and -55° during the same orbit with different configurations. In fact, CHRIS collects 18, 37 or 63 spectral bands if operated at spatial resolution of 18 or 36 m with a spectral coverage ranging from 405 nm until 1050 nm. The main characteristics of CHRIS spectrometer are listed in Table I.

Table 1. Main characteristics of CHRIS-PROBA.

<table>
<thead>
<tr>
<th>Instrument:</th>
<th>push-broom imaging spectrometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of view:</td>
<td>1.3°</td>
</tr>
<tr>
<td>Ground swath:</td>
<td>13.5 km</td>
</tr>
<tr>
<td>Altitude:</td>
<td>Apogee: 688 km, perigee: 556 km</td>
</tr>
<tr>
<td>Orbit inclination:</td>
<td>97.8°</td>
</tr>
<tr>
<td>Descending node:</td>
<td>12:10 local time</td>
</tr>
<tr>
<td>Across track pixel size:</td>
<td>18m or 36m</td>
</tr>
<tr>
<td>Along track pixel size:</td>
<td>Finest resolution is 18m</td>
</tr>
<tr>
<td>Number of images:</td>
<td>5 acquisitions of the same area at +55°, +36°, 0°, -36°, -55° view angles during the same orbit</td>
</tr>
<tr>
<td>Spectral range:</td>
<td>410 nm to 1050 nm</td>
</tr>
<tr>
<td>Spectral resolution:</td>
<td>From 1.25 nm @ 400 nm to 11 nm @ 1050 nm and binning possibility</td>
</tr>
<tr>
<td>Number of spectral bands</td>
<td>From 18 bands at a spatial resolution of 18 m, to 63 at 36 m</td>
</tr>
<tr>
<td>Digitalization:</td>
<td>12 bits</td>
</tr>
<tr>
<td>Signal-to-noise ratio</td>
<td>max. 250 @ target albedo = 0.2, λ = 800 nm, gain = 8.583</td>
</tr>
</tbody>
</table>

Since June 2002 up to now many hyperspectral images were collected over San Rossore forestry test site (latitude: 43.73°N, longitude: 10.30°E, altitude 5 meters a.s.l.) by CHRIS utilizing different spectral configuration (MODE) and for various angular geometries. Table II lists the complete set of images acquired so far.

Table 2. Complete list of CHRIS images acquired so far over the San Rossore forestry test site.

<table>
<thead>
<tr>
<th>DATE and TIME (GMT)</th>
<th>MZA</th>
<th>MODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 June 19, 2002</td>
<td>- 6°</td>
<td>4</td>
</tr>
<tr>
<td>2 April 16, 2003</td>
<td>- 19°</td>
<td>4</td>
</tr>
<tr>
<td>3 June 16, 2003</td>
<td>0°</td>
<td>4</td>
</tr>
<tr>
<td>4 July 1, 2003</td>
<td>+ 13°</td>
<td>4</td>
</tr>
</tbody>
</table>

3. CALIBRATION AND VALIDATION METHODOLOGY OF CHRIS-PROBA DATA

3.1 Physical background

The geometrical properties of a reflecting surface are readily described by its BRDF, denoted symbolically as \( \rho_{BRDF} (\lambda, \vartheta_0, \varphi_0, \vartheta_r, \varphi_r, E_i) \), which is defined [1] as the ratio of the radiance \( dL_{out} (\lambda, \vartheta_0, \varphi_0, \vartheta_r, \varphi_r; E_i) \) scattered into the direction \((\vartheta_r, \varphi_r)\) to the irradiance \( dE_i (\lambda, \vartheta_0, \varphi_0) \) impinging at angle \((\vartheta_0, \varphi_0)\) on a unitary surface area:

\[
\rho_{BRDF} (\lambda, \vartheta_0, \varphi_0, \vartheta_r, \varphi_r, E_i) = \frac{dL_{out} (\lambda, \vartheta_0, \varphi_0, \vartheta_r, \varphi_r; E_i)}{dE_i (\lambda, \vartheta_0, \varphi_0)} \tag{1}
\]

As indicated in Eq. 1 BRDF is a density of reflectance \([sr^{-1}]\) ranging from zero to infinity. Let us note that the BRDF, defined as ratio of infinitesimals (vanishing quantities), is a derivative with instantaneous values that can not be directly measured, since real measurements involve finite extension intervals (resolution) of the concerned geometrical parameters.

Although the BRDF is an important parameter for describing the surface reflectance, its measurement is hindered even for simple surfaces from the impossibility of yielding Field-Of-View (FOV) having a vanishing width. Moreover, because this function varies versus both illumination and viewing angle, many measurements are required for laboratory reflectance measurements.

A common simplification of the BRDF is to assume the concerned reflector as a Lambertian (perfectly diffuser) surface, i.e. an infinite ideal surface for which the upward radiance is isotropic with the same value for all concerned geometrical parameters. Therefore, Lambertian surfaces constitute a restricted ensemble of reflectors, which are included in the more general class of natural surfaces. For Earth remote sensing purpose, spectral reflectance is generally retrieved considering the observed target as a Lambertian and homogeneous diffuser for which the upward radiance can explicitly be expressed as a function of surface reflectance [8], [9].

In the visible and near-infrared spectral range, the reflectance of an observed Lambertian surface is retrieved using the well-known Eq. 2:
\[
\rho(\lambda) = \frac{\pi [L_{1B}(\lambda, \vartheta) - L_{\text{path}}(\lambda, \vartheta) - \frac{1}{T(\lambda, \vartheta) E_{\text{tot}}(\lambda, \zeta) \cos \vartheta}]}{2 \pi v \cos \vartheta \cos \vartheta \cos \vartheta \cos \vartheta \cos \vartheta}
\]

where \( \vartheta \) is the zenith angle of the viewing direction, \( \zeta \) the Sun's zenith distance, \( L_{1B}(\lambda, \vartheta) \) the spectral radiance reaching the sensor, \( E_{\text{tot}}(\lambda, \zeta) \) the total (direct plus diffuse) irradiance impinging on the target, \( L_{\text{path}}(\lambda, \vartheta) \) the atmospheric up-welling “path radiance”, and \( T(\lambda, \vartheta) \) the atmospheric transmittance from ground to the sensor. Each spectral term in the right side of Eq. 2 is intended to be averaged over the spectral channel bandwidth, while the geometrical factor \( \cos \vartheta \) only accounts for the push-broom imaging spectrometer sampling.

Although many surfaces behave similarity to an ideal diffuser, the above assumption will fail in two areas. The first obvious failure is that many flat surfaces have a not negligible specular component (for instance oceanic water in the visible spectral range and high-reflecting soil), i.e. an increase in the observed reflectance when the illumination and viewing zenith angles are the same and the relative azimuth angle is 180°.

Many rough surfaces (like vegetation) also show a reflectance increase in the “hot spot” direction when the illumination and viewing zenith angles are the same but the relative azimuth angle is null. Moreover, the error resulting from assuming Lambertian reflection for a natural target can be large for off-nadir views in remote sensing observations [10], [11].

However, it is possible to define another class of reflectors whose bi-directional reflectance distribution function \( \rho_{BRDF}(\lambda, \vartheta_1, \varphi_1, \vartheta, \varphi) \) is assumed to be a separable function in spectral and geometrical factors as shown in Eq. 3:

\[
\rho_{BRDF}(\lambda, \vartheta_1, \varphi_1, \vartheta, \varphi) = \rho_0(\lambda) h(\vartheta_1, \varphi_1, \vartheta, \varphi)
\]

If we impose according to the definition of reflected irradiance [1] that:

\[
\int h(\vartheta_1, \varphi_1, \vartheta, \varphi) \cos \vartheta \cos \vartheta \cos \vartheta \cos \vartheta \cos \vartheta = \pi
\]

then, we obtain an additional definition of albedo \( \rho_0(\lambda) \):

\[
\rho_0(\lambda) = \frac{2 \pi \cos \vartheta \cos \vartheta \cos \vartheta \cos \vartheta \cos \vartheta}{\pi}
\]

being \( \cos \vartheta \cos \vartheta \cos \vartheta \cos \vartheta \cos \vartheta \) the so called projected solid angle.

3.2 Data quality assessment

Every “push-broom” imaging spectrometer is affected by along-track stripes changing with wavelength, and the response corrected images, as provided by SIRA, have to be corrected for this kind of disturbance. In absence of any flat-field calibration measurement, an empirical correction algorithm has been adopted to remove this effect [12]. This algorithm is able to separate contributions due to scene texture from those originated by the noise pattern utilizing information from the acquired image data alone (average image horizontal line).

A statistical data quality assessment of at-sensor radiance spectra has also been performed analyzing image minimum, maximum and mean values as well as its standard deviation, skewness, energy and entropy. Particular attention has been devoted to the calculation of radiometric levels (histograms) for each image in order to establish the effective dynamic range of the sensor.

4. PRELIMINARY RESULTS

4.1 Noise removal and statistical computation

In Fig.1 at-sensor radiance image acquired by CHRIS over San Rossore on September 18, 2003 is shown. The viewing geometry is specified by MZA = -8° and FZA = 0° with a solar zenith angle (SZA) of 43°. As can be seen, this image is affected by the so called “stripe-noise” which appears as vertical lines superimposed to the observed scene.

Fig. 2 shows the same image corrected for this coherent noise applying. The average image brightness has not been changed but the noise pattern has been strongly reduced.

![Image](image332x176to506x346)

Fig. 1. at-sensor radiance image acquired by CHRIS over San Rossore on September 18, 2003 with MZA = -8° and FZA = 0°. The image is displayed in “true colors”: Red channel (6st band, 631 nm), Green channel (3rd band, 530 nm) and Blue channel (1st band, 442 nm).
Simulations of at-sensor radiance have been performed utilizing MODTRAN 4 in order to compare the obtained spectra with those extracted from various CHRIS images. Fig. 3 shows the comparison among these spectra from beach sand surface (located south, near the Gombo residence) whose reflectance spectrum was measured in laboratory and used to run MODTRAN 4. As can be seen the agreement between simulations and measurements appears to be fair even if the experimental data are systematically lower than those simulated, and some degradation of the sensor response is detected especially at both ends of the observed spectral range.

Table 2. Statistical values related to the CHRIS image acquired at FZA = 0° on June 16, 2003 over San Rosore forestry test site.

<table>
<thead>
<tr>
<th>Band</th>
<th>Nlev</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>St.Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33914</td>
<td>47625</td>
<td>157623</td>
<td>64745.58</td>
<td>6820.558</td>
</tr>
<tr>
<td>2</td>
<td>45644</td>
<td>39583</td>
<td>179964</td>
<td>58979.36</td>
<td>11526.70</td>
</tr>
<tr>
<td>3</td>
<td>58192</td>
<td>23050</td>
<td>176374</td>
<td>40849.03</td>
<td>15269.64</td>
</tr>
<tr>
<td>4</td>
<td>60928</td>
<td>19971</td>
<td>178412</td>
<td>36184.67</td>
<td>16561.83</td>
</tr>
<tr>
<td>5</td>
<td>56327</td>
<td>15188</td>
<td>150080</td>
<td>31252.90</td>
<td>14543.23</td>
</tr>
<tr>
<td>6</td>
<td>55844</td>
<td>15063</td>
<td>142770</td>
<td>30818.22</td>
<td>14365.86</td>
</tr>
<tr>
<td>7</td>
<td>57841</td>
<td>14799</td>
<td>143724</td>
<td>32671.80</td>
<td>15549.19</td>
</tr>
<tr>
<td>8</td>
<td>59844</td>
<td>14994</td>
<td>151241</td>
<td>36168.03</td>
<td>17792.08</td>
</tr>
<tr>
<td>9</td>
<td>60624</td>
<td>14515</td>
<td>154872</td>
<td>39015.17</td>
<td>19950.56</td>
</tr>
<tr>
<td>10</td>
<td>51903</td>
<td>-3839</td>
<td>393653</td>
<td>35602.87</td>
<td>19186.81</td>
</tr>
<tr>
<td>11</td>
<td>63882</td>
<td>-15241</td>
<td>162835</td>
<td>47098.83</td>
<td>29008.73</td>
</tr>
<tr>
<td>12</td>
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<td>-3279</td>
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<td>57008.36</td>
<td>37962.56</td>
</tr>
<tr>
<td>13</td>
<td>81974</td>
<td>-4265</td>
<td>381573</td>
<td>57837.91</td>
<td>39565.20</td>
</tr>
<tr>
<td>14</td>
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<td>-4112</td>
<td>141037</td>
<td>45126.86</td>
<td>31089.23</td>
</tr>
<tr>
<td>15</td>
<td>84749</td>
<td>-12606</td>
<td>162835</td>
<td>58304.07</td>
<td>41541.18</td>
</tr>
<tr>
<td>16</td>
<td>82771</td>
<td>-3933</td>
<td>299149</td>
<td>55747.09</td>
<td>40088.34</td>
</tr>
<tr>
<td>17</td>
<td>78379</td>
<td>-3705</td>
<td>397534</td>
<td>51731.65</td>
<td>37375.24</td>
</tr>
</tbody>
</table>

As can be seen, some spectral channels have negative minima and a too high number of radiometric levels with respect to the sensor dynamic range (12 bit).

### 4.2 Atmospheric effects correction

Fig. 3 shows an example of reflectance map retrieved from CHRIS images after the atmospheric correction depicted in Eq. 2 including restoration from trapping effect. The image was acquired by CHRIS over San Rosore on July 25, 2003 at 10 34 GTM, with a spatial resolution of 18 m and gathered at MZA = -2° and FZA = +36°. The Solar Zenith Angle (SZA) was 26° and the Solar Azimuth Angle (SAA) was 152°.
Fig. 3. Reflectance image displayed in “true color”, like in Fig.1, as result of data acquired July 25, 2003 at MZA = -2° and FZA = +36°.

In Fig.s 4(a)-(c) we show spectra of reflectance obtained at different viewing geometries for the same ground location. Sand, vegetation and sea surface data have been extracted from the five images set of 25 July and plotted in separate pictures.

In Fig.4(a) sand reflectance is compared with reflectance measurement carried out in laboratory over the same sample. Let us note the good agreement between the laboratory measurement and the nadir spectrum with a residual relative difference which is lower than 15 % at the both ends of the digitised spectral range. The spectral region of worst agreement (around 0.760 µm) is characterised for inherent difficulty in atmospheric modelling that may involve inaccuracy in the adopted O₂ absorption band model. Another trouble that may affect spectral matching between the two reflectance estimates is due to poor radiometric calibration of CHRIS sensor especially at both ends of the observed spectral range. In order to elucidate spectral behaviour of multiangle remotely sensed data in Fig.s 5(a)-(c) we have reported reflectance normalized to that obtained at nadir viewing geometry (with FZA = 0°).

The anisotropy factor (ANIF) resulting from this normalization technique, which is applicable when a low angular resolution of directional data is available like in CHRIS data set, is a tool to separate directional effects from spectral signature of the involved surface according to the following definition:

\[
\rho_{ANIF}(\lambda, \theta_0, \phi_0, \delta_\tau, \phi_\tau) = \frac{\rho(\lambda, \theta_0, \phi_0, \delta_\tau, \phi_\tau)}{\rho(\lambda, \theta_0, \phi_0, 0)}
\]  

(6)
Fig. 6. Anisotropy factors versus viewing zenith angles are shown for six different wavelengths (0.491 µm, 0.552 µm, 0.631 µm, 0.712 µm, and 0.893 µm) related to the July acquisition for the same ground location (a) sand pixel, (b) vegetation pixel and (c) sea pixel (about two km far from the coast line). The forward (backward) direction is indicated by positive (negative) values for viewing zenith angles.

As can be seen the estimated reflectance factors show a distinct spectral behaviour for different targets. Over sand all six wavelengths show a fairly symmetrical bowl shape. Over vegetation the bowl shape is particularly well developed in the near-infrared wavelengths while in the blue and red chlorophyll absorption band directional effects are more pronounced.

The observed spectral dependence of directional reflectance may be explained considering the relationship

Anisotropy factors are plotted versus viewing zenith angles in Fig.s 6(a)-(c) for six different wavelengths related to the July acquisition for the same natural targets (sand, vegetation and sea).

Fig. 5. Examples of reflectance normalized to that obtained at nadir viewing geometry (with FZA = 0°) for data shown in Fig. 4 for (a) sand, (b) vegetation and (c) sea pixel (about two km far from the coast line).

Anisotropy factors are plotted versus viewing zenith angles in Fig.s 6(a)-(c) for six different wavelengths related to the July acquisition for the same natural targets (sand, vegetation and sea).
between vegetation canopy optical properties and multiple scattering effects [13], [14].

In the high absorbing (low reflecting) wavelengths located at 0.491 µm and 0.631 µm, multiple scattering effects are reduced due to a low amount of radiation travelling inside the vegetation canopy. Therefore, the contrast between shadowed and illuminated canopy components, and consequently the BRDF effects are enhanced.

In the green wavelength at 0.551 µm and, particularly, in the near-infrared wavelengths at 0.751 µm and 0.893 µm, multiple scattering effects are strong since the corresponding average single-scattering albedo is relatively high and, therefore, directional effects are dimmed. As a consequence, BRDF effects are rather small in the low-absorbing (high reflecting) wavelengths.

As shown in Fig. 6(b) in the backward direction (negative values of FZA) it is evident the “hot spot” phenomenon, which is caused by the absence of shadow in the radiation scattered back toward the source. As observed this effect is more pronounced at blue (0.491 µm) and red wavelengths (0.631 µm). In the near-infrared wavelengths (0.751 µm and 0.893 µm) the larger amount of multiple scattering reduces “hot spot” but increases reflectance at high view zenith angles.

Over sea surface, see Fig. 6(c), the anisotropy factor is dominated by specular reflection in the forward directions (positive values of FZA) as it also evident from Fig. 3.

As can be seen, the “hot spot” peak is more pronounced for small solar zenith angles (at SZA=23°, and SZA=26°). The reason for this behaviour may be connected to the circumstance that for small solar zenith angles the optical path is relatively small and the probability to collect radiation back-scattered toward the source without encountering any other scatterer is large. Conversely, for high zenith solar angles most of contribution to at-sensor radiance comes from multiple scattering that in turns reduce the hot-spot effect.

Monochromatic ANIF images have been computed starting from the CHRIS data set of July 25, and an example of this processing has been shown in Fig.8 for the 2nd CHRIS spectral channel (0.491 µm). The image has been obtained as the ratio between two target reflectances estimated from images at FZA=+36° and FZA=0°. To this aim the off-nadir (FZA=+36°) image was precisely geo-located with respect to the nadir (FZA=0°) acquisition, using the ENVI second-degree polynomial co-registration procedure based on 40 ground control points (GCP). The r.m.s. error for the considered GCPs as estimated from the procedure was about 0.8 pixel, a circumstance that confirms the high accuracy of the performed geo-location.

Fig. 8. Monochromatic ANIF images computed from CHRIS data set acquired on July 25, and displayed utilising the 2nd CHRIS spectral channel (0.491 µm).

We point out that the outcome of ANIF calculation is a flat image in which the difference among different targets is subtle. The picture in Fig. 8, in fact, reminds typical thermal infrared images where one can only observe small signal variations along the scene. It can be seen that homogeneous areas of the original data of Fig. 3 give rise to grey regions in Fig.8, and that different kinds of vegetation coverage are no longer detectable in the ANIF domain. We have verified that the ANIF maps computed at different wavelengths originate roughly the same image shown in Fig. 8, confirming that the ANIF signal has high spectral correlation.

5. CONCLUSIONS

In this paper some results, obtained from multiangle images acquired by CHRIS over the San Rossore (Italy) site during the last year, have been presented. A deep investigation about reflectance dependence on optical
properties of the surface, illumination and viewing geometry has been performed by estimating anisotropy factor from the available multiangle data sets. From the analysis of this great amount of data the spectral variability of the retrieved factors has been assessed versus viewing zenith angles. Physical mechanism have been proposed in conjunction with already existing scientific works to explain the observed spectral behaviour of remotely sensed data.

The need to improve the modelling of BRDF of natural surface has arisen from the analysis of preliminary results and future investigations will regard the effects of atmosphere on the retrieval of reflectance from multiangle remote sensing data.

6. ACKNOWLEDGMENTS

We would like to thank all the scientists from different institutions that are involved in remote sensing activities carried out in San Rossore test site. Moreover, we would like to thank people from SIRA and RSAC in particular M. Cutter and P. Fletcher for planning the acquisitions and providing CHRIS data, and for useful discussions.

7. REFERENCES


FOREST TYPE DISCRIMINATION USING MULTI-ANGLE HYPERSONSPECTRAL DATA

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ABSTRACT

The directional anisotropy of vegetation remote sensing data has been seen as a valuable information source to characterize the vegetation canopy structure. Several studies were devoted to the relationship between the structural characteristics of vegetation canopy and the bidirectional reflectance measured from ground, from airborne and coarse spatial resolution spaceborne sensors. The CHRIS sensor onboard the PROBA satellite has been the first high spatial resolution spaceborne sensor dedicated to the acquisition of nearly simultaneous multiple view angle images. In this study, the potential of the such data for temperate forest types discrimination was assessed with the accent on the stand structure. The results showed that the most forest types could be discriminated on the basis of near-nadir spectral data alone. However, two deciduous forest types differing essentially by their tree density were discriminable only thanks to off-nadir images. The directional data were therefore a useful complement to the spectral information provided by single view angle images.

Key words: Vegetation; Forest canopy structure; BRDF; Hyperspectral; PROBA; CHRIS.

1. INTRODUCTION

The directional anisotropic behaviour of remotely sensed earth’s surface objects has been largely demonstrated. This anisotropy is regarded either as noise to remove from data or as a valuable source of information on the structural features of the sensed objects. Correcting for the directional effects often consists in normalizing the multi-angle reflectances to the nadir view or to a constant "off-nadir" view angle. It is currently applied in the multi-temporal compositing of coarse spatial resolution images acquired by sensors with a large field of view (Leroy & Hautecoeur, 1999; Huete et al., 2002; Duchemin & Maisongrande, 2002). The analysis of spectral data without taking into account the geometric properties of the image acquisition could lead to erroneous conclusions. For example, Deering et al. (1999) showed that the Normalized Difference Vegetation Index (NDVI) values of coniferous stands in a boreal forest might vary considerably (from 0.36 to 0.54) when the view zenith angle (VZA) changed.

On the other hand, structure information of the land cover, e.g. vegetation canopy structure, can be derived from the directional properties of multi-angle images, namely through the bidirectional reflectance distribution function (BRDF) parameters (Gao et al., 2003; Chopping et al., 2003). A review of the application of BRDF models to infer land cover parameters at regional and global scales has been proposed by Roberts (2001). At local scale, e.g. at agricultural parcel or forest stand level, the directional reflectance effects may be a source of valuable information in addition to the spectral and temporal signal (Goel & Reynolds, 1989).

Barnsley et al. (1997) assessed the relative contribution of the directional and spectral components to the statistical variance of aerial multiple view angle images taken over an agricultural area. They showed that the spectral component tended to dominate in all wavebands while the directional component explained 3% to 21% of the total statistical variance in the near-infrared (NIR) and red wavelengths, respectively. Even if the investigated landcover classes were quite separable on the basis of the spectral content alone in the NIR band, the directional component was still important in discriminating between two classes which exhibited similar spectral signatures in the nadir-viewing image.

The contribution of the directional component was also investigated by Sandmeier & Deering (1999) in deriving forest canopy structure parameters and classifying boreal forests on the basis of airborne hypersonspectral BRDF data. They found that the integration of the BRDF information, through an anisotropy index, substantially increased the overall classification accuracy (from 37.8% to 44.7%), but the improvement was not consistent for all classes. For some classes, the producer’s accuracy diminished dramatically (from 53.5% to 22.9%, and from
47.0% to 26.1%) when the BRDF data were included. This raises the question of the usefulness of the anisotropy index used in this study since the class which contributed significantly to the overall accuracy improvement (from 55.4% to 86.4%) was the clear muskeg.

Most of the studies on multiple view angles data have been carried out using either ground measurements or airborne sensors data. Only few studies were devoted to near-simultaneous multi-angle data acquired by spaceborne sensors. Indeed, apart from the POLDER-1 sensor (Polarization and Directionality of the Earth’s Reflectance), on board ADEOS-1 (Advanced Earth Observing Satellite), which operated for 8 months in 1996-1997, the three other really multi-view spaceborne sensors, i.e. POLDER-2, the CHRIS-PROBA system described in section 2 and the Multispectral Imaging Spectroradiometer (MISR) on board the Terra satellite, are relatively recent. Furthermore, CHRIS-PROBA is the first spaceborne sensor to acquire high spatial resolution and near-simultaneous multiple view angle images allowing local studies like forest stands characterization. The IKONOS-2 and QuickBird satellites could also deliver near-simultaneous multiple view angle images thanks to their great agility but the cost of such image sets is prohibitive.

This study aims therefore to investigate the information content in multiple view angle data from a high spatial resolution spaceborne sensor for forest type characterization with emphasis on directional effect contribution compared to spectral effect. The used data were acquired in the framework of the European Space Agency (ESA) scientific programme of the CHRIS-PROBA mission.

2. CHRIS-PROBA SYSTEM CHARACTERISTICS

The PROBA (PRoject for On Board Autonomy) spacecraft is a mini-satellite (94 Kg) operated by the European Space Agency to explore the feasibility and benefits of autonomy in space. It was launched on October 22nd, 2001. The satellite is capable of along and across-track pointing. The main payload of PROBA is the CHRIS (Compact High Resolution Imaging Spectrometer) sensor which can acquire up to 63 spectral bands (400 nm - 1050 nm) with nominal spatial resolutions of 17 m or 34 m at nadir. The CHRIS sensor can be commissioned from ground station allowing different acquisition modes according to the number and location of spectral bands, the spatial resolution and the width of the swath. However, only five principal modes are actually used. They have been selected according to the requirements for four major application fields: aerosol, land cover, vegetation and coastal zones. Thus, the CHRIS-PROBA system allows to acquire hyperspectral images of the same scene with five different view angles during a single overpass. Additional ten images (five image on each side of the principal track) can be captured within a 3 days thanks to the across-track pointing capabilities.

The system acquires the images at times when its zenith angle is equal to a set of so-called fly-by zenith angles (FZA): +55°, +36°, 0°, −36° and −55°. When the satellite is pointing along-track, the FZA is in that case equivalent to the platform zenith angle. But when the satellite is pointing laterally, the real zenith angle is calculated by considering the FZA with respect to the so-called fly-by position. That is the position on the ground track when the platform zenith angle, as seen from the target, is a minimum. This angle, hereafter called minimum zenith angle (MZA), is equivalent to the roll angle of the 0°−FZA image.

In order to minimize the platform movement in pointing manoeuvres, the first image, i.e. the +55°−FZA image, is acquired in synchronous scanning mode (north-south direction) while the second image, i.e. the +36°−FZA image, is acquired in asynchronous scanning mode (south-north direction). Thus, three scans (+55°, 0° and −55°) are executed in north-south direction while the two others (+36° and −36°) are executed in south-north direction. For more details on CHRIS-PROBA, the reader may look at the dedicated website (http://www.chris-proba.org.uk).

3. TEST SITE AND REMOTE SENSING DATA

The study site is located in the Nismes forest, southern Belgium (50°00’N, 4°34’E). It is characterized by a slightly hilly relief with an altitude varying from 200 m to 350 m above the sea level. The main species are oak (Quercus spp.) and Norway spruce (Picea abies (L.) Karst), representing more than 90% of the forested area. The oak stands are usually made of a dominant stage (high forest) of oak trees and an understorey of different deciduous species, namely the hawthorn (Crataegus sp.), the hornbeam (Carpinus betulus L.) and the hazel (Corylus avellana L.). On the other hand, the spruce stands are even-aged without understorey vegetation excepted the young stand in which shrubs of deciduous species are well developed competing with the spruce plantation. At the time of the CHRIS data acquisition, all the deciduous species were leafless. The crown coverage in the middle-aged and mature spruce stands was always over 90% while in one selected oak stand it was about 70%. The main characteristics of the selected forest stands are reported in table 1. The figure 1 shows an aerial photograph (at a scale of 1:6600) of oak and spruce stands similar to ones of the studied area.

The remote sensing data consisted in a set of five hyperspectral images acquired by the CHRIS sensor on April 09th, 2003. The site was imaged by laterally pointing with a minimum zenith angle of 22°. Thus, the five images were off-nadir. The exact satellite position (azimuth and zenith angles as well as altitude)
Table 1. Description of the studied forest types.

<table>
<thead>
<tr>
<th>Code</th>
<th>Main species</th>
<th>Age (years)</th>
<th>Basal area (m².ha⁻¹)</th>
<th>Density (N.ha⁻¹)</th>
<th>Height (m)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CYO</td>
<td>Spruce</td>
<td>10</td>
<td>-</td>
<td>2860</td>
<td>5</td>
<td>Young plantation with open canopy</td>
</tr>
<tr>
<td>CME</td>
<td>Spruce</td>
<td>26</td>
<td>42</td>
<td>2140</td>
<td>15</td>
<td>Middle-aged plantation with closed canopy</td>
</tr>
<tr>
<td>CMA</td>
<td>Spruce</td>
<td>90</td>
<td>40</td>
<td>360</td>
<td>25</td>
<td>Mature stand with closed canopy</td>
</tr>
<tr>
<td>BME</td>
<td>Oak, Birch</td>
<td>-</td>
<td>18</td>
<td>540</td>
<td>20</td>
<td>Middle-aged stand with a regular structure and a closed canopy</td>
</tr>
<tr>
<td>BMA</td>
<td>Oak</td>
<td>-</td>
<td>22</td>
<td>250</td>
<td>25</td>
<td>Mature stand with closed canopy, one stage, herbaceous understorey</td>
</tr>
<tr>
<td>BMA2</td>
<td>Oak, Birch, Cheesnut</td>
<td>-</td>
<td>15</td>
<td>160</td>
<td>25</td>
<td>Mature stand with open canopy in the upper stage, and understorey made of birch and cheesnut</td>
</tr>
</tbody>
</table>

Figure 1. An aerial infrared false colour photograph of forest stands similar to ones of the study area. The coniferous appear in red, the deciduous tree crown in grey. Note that the photograph was taken during winter.

Figure 2. Polar plot showing the positions of the satellite (•) and the Sun (⋆) at the images acquisition moment. The circular axis represents the azimuth angle and the radial axis represents the zenith angle.

when the target was imaged was estimated using the WXtrack package (http://www.satsignal.net). Detailed information about the acquisition configuration are reported in table 2. The figure 2 shows, on a polar plot, the relative position of the satellite and the Sun. It appears that the −36° and −55°–FZA images are on close to the hotspot configuration. The images were acquired in the so-called 'chlorophyll' mode, i.e. with the highest spatial resolution, full swath and 18 spectral bands suited to vegetation applications. The location and resolution of the spectral bands are given in table 3. The images were delivered at 1A-processing level; that is they have been corrected for radiometric calibration.
Table 2. Acquisition configuration parameters of the five CHRIS images.

<table>
<thead>
<tr>
<th>Time (hh:mm:ss)</th>
<th>Satellite altitude (km)</th>
<th>Solar zenith angle (SZA, deg)</th>
<th>Solar azimuth angle (SA, deg)</th>
<th>Viewing azimuth angle (VAA, deg)</th>
<th>Viewing zenith angle (VZA, deg)</th>
<th>Fly-by zenith angle (FZA, deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:46:54</td>
<td>667</td>
<td>45.8</td>
<td>159</td>
<td>51.4</td>
<td>742</td>
<td>+55</td>
</tr>
<tr>
<td>10:47:44</td>
<td>665</td>
<td>45.9</td>
<td>160</td>
<td>34.6</td>
<td>785</td>
<td>0</td>
</tr>
<tr>
<td>10:48:33</td>
<td>663</td>
<td>46.0</td>
<td>160</td>
<td>22.9</td>
<td>755</td>
<td>−36</td>
</tr>
<tr>
<td>10:49:23</td>
<td>661</td>
<td>46.0</td>
<td>160</td>
<td>36.8</td>
<td>757</td>
<td>−55</td>
</tr>
<tr>
<td>10:50:12</td>
<td>658</td>
<td>46.1</td>
<td>161</td>
<td>53.0</td>
<td>757</td>
<td>−36</td>
</tr>
</tbody>
</table>

Table 3. Spectral bands of the CHRIS images acquired in the so-called chlorophyll mode.

<table>
<thead>
<tr>
<th>Band number</th>
<th>Centre (nm)</th>
<th>Width (nm)</th>
<th>Band number</th>
<th>Centre (nm)</th>
<th>Width (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>489</td>
<td>9</td>
<td>C10</td>
<td>709</td>
<td>6</td>
</tr>
<tr>
<td>C2</td>
<td>551</td>
<td>10</td>
<td>C11</td>
<td>716</td>
<td>6</td>
</tr>
<tr>
<td>C3</td>
<td>631</td>
<td>9</td>
<td>C12</td>
<td>735</td>
<td>7</td>
</tr>
<tr>
<td>C4</td>
<td>672</td>
<td>11</td>
<td>C13</td>
<td>742</td>
<td>7</td>
</tr>
<tr>
<td>C5</td>
<td>680</td>
<td>6</td>
<td>C14</td>
<td>748</td>
<td>7</td>
</tr>
<tr>
<td>C6</td>
<td>686</td>
<td>6</td>
<td>C15</td>
<td>755</td>
<td>7</td>
</tr>
<tr>
<td>C7</td>
<td>691</td>
<td>6</td>
<td>C16</td>
<td>777</td>
<td>7</td>
</tr>
<tr>
<td>C8</td>
<td>697</td>
<td>6</td>
<td>C17</td>
<td>785</td>
<td>8</td>
</tr>
<tr>
<td>C9</td>
<td>703</td>
<td>6</td>
<td>C18</td>
<td>792</td>
<td>8</td>
</tr>
</tbody>
</table>

In this mode, the nominal nadir spatial resolution was 17 m at an altitude of 556 km, and the width swath was 34 km.

4. METHOD

4.1. Data processing

The first step of the data processing was to co-register the five images so that to deliver angular profiles. As the 2nd and 4th images in the five image series, i.e. the +36° and −36°–FZA images, were got in asynchronous scanning mode, they were firstly flipped in order to put them in the same orientation as the three others. Secondly, co-registration of the four far off-nadir images to the nearest-nadir image was performed using a 1st order polynomial model adjusted from 15 tie points collected on the nearest-nadir image (reference image) and on each of the other four images. Finally, the nearest-nadir image was geometrically corrected using a 2nd order polynomial model adjusted from 16 ground control points. The ground control points were collected from digital colour orthophotographs having a spatial resolution of 0.40 m. The same model was subsequently applied to the four co-registered images. The application of successive models may result in lower spatial accuracy of the geocoded images due to the propagation of errors from one model to another. It should have been better to georeference each image independently. However, this required in any case the use of tie points to estimate the pixel size of the off-nadir images as this information was not available in the images metadata. Therefore, we were in the same situation as for successive models application with, in addition, errors due to ground control points collection.

4.2. Angular and spectral signatures analysis

The angular and spectral signatures analysis was carried out on basis of samples taken from six different forest types (table 1). The forest stands were selected on flat terrain to avoid topographic effects as we were dealing with multiangular images. The stands had also to be large enough (at least 2 ha) in order to have homogeneous pixels within the stand. A set of five pixels were selected randomly in each stand and constituted the basis of subsequent analysis. The angular and spectral profiles of the six forest types were compared and the effect of the viewing angle was tested by the means of the analysis of variance of the top-of-atmosphere radiance. No atmospheric correction was applied to the remote sensing data as the five images were acquired within a very short time interval (less than 4 minutes). However, the atmosphere path length have influenced the at-sensor recorded radiance by increasing the diffusion and signal attenuation, namely in the visible domain.

In order to separate the directional effects from the spectral signature of a target, Sandmeier & Itten (1999) proposed an anisotropy factor calculated by normalizing the reflectance $R$ in a specific view direction to nadir reflectance $R_0$ for a given incident irradiance direction (equation 1):

$$ANIF(\theta_r, \phi_r; \lambda) = \frac{R(\theta_r, \phi_r; \lambda)}{R_0(\lambda)}, \quad (1)$$

where $\theta_r$ and $\phi_r$ are the zenith and azimuth angles of the viewing direction, and $\lambda$ refers to the wavelength. Since this index is based on the nadir reflectance, its use with spaceborne sensor data is constrained by the fact that the required nadir views are not necessarily available from a multiple view angle satellite, such as PROBA. Strub et al. (2002) proposed to normalize the directional reflectance data by the hemispherical reflectance:

$$ANIF_{BHR}(\theta_r, \phi_r; \lambda) = \frac{1}{\frac{1}{2} \int_0^{2\pi} \int_0^{\pi/2} R(\theta_r, \phi_r; \lambda) \cos \theta_r \sin \theta_r \, d\theta_r \, d\phi_r} \int_0^{2\pi} \int_0^{\pi/2} R(\theta_r, \phi_r; \lambda) \, d\theta_r \, d\phi_r, \quad (2)$$
However, the angular sampling remains poor. The integral in equation 2 should therefore be replaced by a discrete approximation. Furthermore, for spaceborne sensor data, the view direction sampling is never regular so that the discrete approximation of the integral in equation 2 should be replaced by the sum of reflectances over all sampled view directions. Thus, we propose a directional reflectance index (DRI) computed as following:

$$DRI(\theta_r, \phi_r; \lambda) = \frac{R(\theta_r, \phi_r; \lambda)}{\sum_{\theta_r} \sum_{\phi_r} R(\theta_r, \phi_r; \lambda)}.$$  \hfill (3)

In this study we used the top-of-atmosphere radiances instead of reflectances in equation 3. This should not influence the main conclusions since further analysis were done on different spectral bands separately.

5. RESULTS

5.1. Image registration

Automated processing of multi-angle images requires accurate co-registration, namely an error of less than 1 pixel. In this study, the co-registration of the five images resulted in root mean square residual errors (RMSE) of 0.71, 0.73, 0.82 and 1.18 pixels for respectively the $+36^\circ$, $-36^\circ$, $+55^\circ$ and $-55^\circ$-FZA images. The geocoding model gave an RMSE of 0.63 pixels, or approximately 13 m as the pixel size of the nearest-nadir image was 20 m. However, in spite of the RMSE of less than 1 pixel for the first three images, visual checking revealed that the corrected images were not well co-registered. These results also showed that only the co-registration quality diminishes with increasing view zenith angle, but also the images acquired in backward configuration were less accurately co-registered than ones acquired in forward configuration. That is, apart from the ground sampling distance effect, there may be an effect of lower contrast due to higher levels of reflected radiances in the backward direction than in the forward direction. Thus tiny ground elements which are usually used as ground control points are less easy to locate in backward configuration.

5.2. Angular and spectral signature analysis

The figures 3 and 4 show the average radiances of three deciduous stands and three coniferous stands as a function of the FZA and the wavelength. The data have been interpolated for visualization purposes. The classical spectral signatures of vegetation were well observed for the coniferous stands while the deciduous stands showed, as expected, low radiance in the near-infrared bands since the images were acquired during winter. For almost all spectral bands, the radiance decreases slightly from the FZA of $+55^\circ$ to $0^\circ$ and increases significantly when the viewing configuration tends towards the hot spot point which is located somewhere between the $-36^\circ$ and $-55^\circ$-FZA configurations. That is also illustrated on figure 5 where the six forest types are compared for some selected spectral bands. In the blue (489 nm) and green (551 nm) bands, the radiance increase between $-36^\circ$ and $-55^\circ$ keeps high rate while in the red-edge (716 nm) and near-infrared regions (785 nm) there is either a slight increase or even a decrease. The behaviour in the red-edge and near-infrared regions agrees with the fact that the maximum radiance should be observed in the hot spot configuration (figure 2). In the visible region, this trend was hidden by the atmospheric effect. The figures illustrate also that the BRDF effect is spectral dependent.

When looking close to the directional signature of the six forest types as revealed by the anisotropy index on figure 6, it appears that the spectral bands in the visible region, and specially the blue and green bands (489 nm and 551 nm), cannot help discriminating the studied forest types. The directional reflectance index computed in the red bands (631 nm and 672 nm) shows clear different trends between the deciduous stands on one hand and the mature and middle-aged coniferous stands on the other hand. But the young coniferous stand has the same signature as the deciduous stands. In the red-edge and near-infrared regions (figure 7), it becomes possible to make a distinction between the three deciduous stand types, namely thanks to the $-55^\circ$ and $+36^\circ$-FZA images. The two mature deciduous stands with different stand density could be discriminated using the $+36^\circ$-FZA data in the NIR bands. A such discrimination was not possible with the near-nadir data alone.

The directional anisotropy due to stand structure was more pronounced in the NIR bands than in the visible region bands, perhaps because the visible wavelengths were more affected by the atmospheric diffusion which tends to mask the directional reflection. Nevertheless, the same findings have been reported by de Wasseige & Defourny (2002) on the basis of tropical forest images recorded by the SPOT-HRV sensor. It is worth noting also that in the near-infrared bands the anisotropy indices of the mature deciduous stand with high tree density and the young coniferous stand were equivalent for all view angles (figure 7) while the top-of-atmosphere radiances of these stands were very different (figure 5). This is an illustration that the directional reflectance index used in this study was well suited for isolating the directional component of the signal related to the stand structure.

5.3. Statistical investigation of the contribution of the multi-angle data

In order to investigate real contribution of multi-angle data for forest types discrimination, an analysis of variance was carried out to test the view angle
Figure 5. Top-of-atmosphere radiance as function of the fly-by zenith angle for different forest stands at four key spectral bands. The forest types acronyms are explained in table 1.
Figure 6. Directional radiance index – blue, green, and red bands. The forest types acronyms are explained in table 1.

Figure 7. Directional radiance index – red-edge and near-infrared bands. The forest types acronyms are explained in table 1.
Figure 3. Top-of-atmosphere radiance as function of the spectral band wavelength and the fly-by zenith angle for a mature deciduous stand with high density (top), a mature deciduous stand with low density (middle) and a middle-aged deciduous stand (bottom).

Figure 4. Top-of-atmosphere radiance as function of the spectral band wavelength and the fly-by zenith angle for a mature coniferous stand (top), a middle-aged coniferous stand (middle) and a young coniferous stand (bottom).
effect on radiance recorded at sensor level. The results for selected spectral bands are reported in table 4. For all spectral bands, there is a significant effect of the forest types and of the view angle, either for coniferous stands or deciduous ones. This was obviously expected. In some spectral bands (489 nm, 551 nm and 742 nm), the interaction between the forest type and the view angle was not significant for deciduous stands. That is, for those spectral bands, the different deciduous stands do not show differentiated spectral behaviour depending on the view angle. This fact corroborates what was observed on figures 6 and 7 that the anisotropy index in those spectral bands could not allow discriminating the forest types.

When the global effects are found significant, it is necessary to check which means are really significantly different since there were three or more means to compare. This analysis had been carried out by comparing all pairs of means of the interaction effect. We were indeed interested in the interaction effect which allowed to assess the contribution of the multi-angle data in discriminating forest types. This contribution becomes critical for forest types which are not separable with one-angle data, namely the near-nadir image. Thus, the results reported in tables 5 and 6 concern comparison between mean radiance measured with the same viewing angle for the deciduous and the coniferous forest stands, respectively. There were 15 means to compare per spectral band for either deciduous stands or coniferous stands. In order to control the type error rate, the Tukey method (Duncan, 1955) was used.

For the coniferous forest types (table 6), the results show that the pairwise comparisons of radiance means involving the red-edge and near infra-red bands (716 to 785 nm) were highly significant in most of the cases. In two cases, i.e. comparison between the mature and middle-aged stand in the -55° image at 716 nm wavelength, and between the mature and young stand in the -36° image at 742 nm wavelength, the test was not significant at 5% level. It should be underlined that on the basis of single view data, say the near-nadir image, the radiance means were significantly different for several spectral bands. That is the directional information provided by the multiple view angle data was not absolutely necessary in discriminating the studied coniferous forest types.

On the other hand, when we consider the deciduous forest types (table 5), no one single view image at any wavelength showed significantly different radiance means for all pairwise forest types comparison. In many cases, the radiance means of the mature and the middle-aged stands were found significantly different, for example in the near-nadir image at the red, red-edge and near-infrared wavelengths. However, the comparison test of the radiance means between the low density and the high density mature stands was significant only in the +36° image at the red-edge and near-infrared wavelengths. The multiple view angle data were therefore essential in order to discriminate those forest types.

6. DISCUSSION

In the precedent section, it has been shown that the distinction between two deciduous stands with different tree densities was possible only in the image acquired with a FZA of +36°. How can we explain this phenomenon?

Considering the figure 2, we can see that the +36°–FZA image configuration was the closest to the plane perpendicular to the principal plane. As the images were taken in the winter, the tree shadows casted to the understory alternated with shined zones of the understory (figure 1). Thus the proportion of shadowed understory sensed by the satellite explained the difference in the reflected radiance of the two forest types. The stand with low density had more proportion of shadowed understory than the high density stand due to the presence of shrubs in the sub-stage of the stand with low density. This conclusion is supported by the fact that in almost all wavelengths and all view angles, the reflected radiance of the young deciduous stand is higher than the radiance of the mature high density stands which is also higher than or equal to the radiance of the mature low density stand (figure 5). The understory contributed significantly to the total radiance of the stand. That is why for example the leafless stands and the young coniferous stand showed less pronounced BRDF effects than the other coniferous stands. According to Sandmeier et al. (1998), if the soil/background influences are negligible, the BRDF effects are most pronounced in erectophile canopies and are reduced in planophile canopies. In the case of this study, the deciduous stands and the young coniferous stands had an erectophile architecture while the other two coniferous stands had a rather planophile architecture.

The shadowing effect discussed in the previous paragraph is the main cause of the directional anisotropy of reflected radiance over vegetation canopies where scattering elements are much larger than the wavelength as shown by Hapke et al. (1996) in studying the cause of the hot spot in vegetation canopies. The directional anisotropy of the reflected radiance was found more pronounced in the forest stand with closed canopies, namely the mature and middle-aged coniferous stands (figure 7). There are two sources of that effect.

Firstly, the shadow-hiding mechanism responsible of the hot spot effect was more evident in the coniferous stands whose canopies were well closed than in the deciduous stands whose canopies were made only with boles without leaves and in the young coniferous stand whose canopy was not yet closed (figures 6 and 7). Indeed, in the two last cases, there were a major contribution of the background to the total radiance. The forward scattering is more likely to
Table 4. Table of the analysis of variance. Figure in bold means that the effect is not significant at $\alpha = 0.01$ level. The acronym FT stands for “Forest type” and VA for "View angle".

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Effect</th>
<th>Coniferous</th>
<th>Deciduous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>F-value</td>
<td>p-value</td>
</tr>
<tr>
<td>489</td>
<td>FT</td>
<td>74.76</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>VA</td>
<td>8528.21</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>FT × VA</td>
<td>9.00</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>551</td>
<td>FT</td>
<td>187.38</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>VA</td>
<td>6623.47</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>FT × VA</td>
<td>8.14</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>631</td>
<td>FT</td>
<td>478.81</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>VA</td>
<td>2664.01</td>
<td>&lt;0.0001</td>
</tr>
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<td></td>
<td>FT × VA</td>
<td>7.41</td>
<td>&lt;0.001</td>
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<tr>
<td>672</td>
<td>FT</td>
<td>493.37</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>VA</td>
<td>1456.55</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>FT × VA</td>
<td>7.22</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>716</td>
<td>FT</td>
<td>1120.77</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>VA</td>
<td>4396.20</td>
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</tr>
<tr>
<td></td>
<td>FT × VA</td>
<td>4.84</td>
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</tr>
<tr>
<td>742</td>
<td>FT</td>
<td>856.35</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>VA</td>
<td>3981.63</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>FT × VA</td>
<td>21.04</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>755</td>
<td>FT</td>
<td>765.55</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>VA</td>
<td>4233.43</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>FT × VA</td>
<td>25.46</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>785</td>
<td>FT</td>
<td>1261.97</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>VA</td>
<td>5567.10</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>FT × VA</td>
<td>30.53</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Table 5. Pairwise comparison of the mean radiance to assess the view angle effect. Results (p-values) of the Tukey’s test for the deciduous forest stands. The forest types acronyms are explained in table 1.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Forest types</th>
<th>Fly-by zenith angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>−55°</td>
</tr>
<tr>
<td>489</td>
<td>BMA-BMA2</td>
<td>0.0752</td>
</tr>
<tr>
<td></td>
<td>BMA-BME</td>
<td>1.0000</td>
</tr>
<tr>
<td></td>
<td>BMA2-BME</td>
<td>0.1114</td>
</tr>
<tr>
<td>551</td>
<td>BMA-BMA2</td>
<td>0.7191</td>
</tr>
<tr>
<td></td>
<td>BMA-BME</td>
<td>1.0000</td>
</tr>
<tr>
<td></td>
<td>BMA2-BME</td>
<td>0.9166</td>
</tr>
<tr>
<td>631</td>
<td>BMA-BMA2</td>
<td>0.1563</td>
</tr>
<tr>
<td></td>
<td>BMA-BME</td>
<td>0.9953 &lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>BMA2-BME</td>
<td>0.0051 &lt;0.0001</td>
</tr>
<tr>
<td>672</td>
<td>BMA-BMA2</td>
<td>0.1655</td>
</tr>
<tr>
<td></td>
<td>BMA-BME</td>
<td>0.7863 &lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>BMA2-BME</td>
<td>0.0004 &lt;0.0001</td>
</tr>
<tr>
<td>716</td>
<td>BMA-BMA2</td>
<td>0.6246</td>
</tr>
<tr>
<td></td>
<td>BMA-BME</td>
<td>0.9990 &lt;0.0001</td>
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<tr>
<td></td>
<td>BMA2-BME</td>
<td>0.0881 &lt;0.0001</td>
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<tr>
<td>742</td>
<td>BMA-BMA2</td>
<td>1.0000</td>
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<tr>
<td></td>
<td>BMA-BME</td>
<td>0.8087</td>
</tr>
<tr>
<td></td>
<td>BMA2-BME</td>
<td>0.5080 &lt;0.0001</td>
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<td>BMA-BMA2</td>
<td>1.0000</td>
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<td>BMA-BME</td>
<td>0.9816</td>
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<tr>
<td></td>
<td>BMA2-BME</td>
<td>0.7954 &lt;0.0001</td>
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<tr>
<td>785</td>
<td>BMA-BMA2</td>
<td>1.0000</td>
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<td></td>
<td>BMA-BME</td>
<td>0.9868 &lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>BMA2-BME</td>
<td>0.9989 &lt;0.0001</td>
</tr>
</tbody>
</table>
Table 6. Pairwise comparison of the mean radiance to assess the view angle effect. Results (p-values) of the Tukey’s test for the coniferous forest stands. The forest types acronyms are explained in table 1.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Forest types</th>
<th>Fly-by zenith angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>−55°</td>
</tr>
<tr>
<td>489</td>
<td>CMA-CME</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>CMA-CYO</td>
<td>0.0257</td>
</tr>
<tr>
<td></td>
<td>CME-CYO</td>
<td>0.2586</td>
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<td>551</td>
<td>CMA-CME</td>
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<td></td>
<td>CME-CYO</td>
<td>0.9815</td>
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<tr>
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<td>CMA-CME</td>
<td>0.0303</td>
</tr>
<tr>
<td></td>
<td>CMA-CYO</td>
<td>&lt;0.0001</td>
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<tr>
<td></td>
<td>CME-CYO</td>
<td>&lt;0.0001</td>
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<tr>
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<td>CMA-CME</td>
<td>0.2146</td>
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<td>CMA-CME</td>
<td>0.1669</td>
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<tr>
<td></td>
<td>CME-CYO</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>742</td>
<td>CMA-CME</td>
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</tr>
<tr>
<td></td>
<td>CMA-CYO</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>CME-CYO</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>755</td>
<td>CMA-CME</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>CMA-CYO</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>CME-CYO</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>785</td>
<td>CMA-CME</td>
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<tr>
<td></td>
<td>CMA-CYO</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>CME-CYO</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>
occur on a such background raising the radiance in the forward direction.

Secondly, multiple scattering of the radiation by the sunlit background and also by the canopy elements (boles and needles) is more important in open canopies than in closed canopies. There are more diffuse radiance in the “shadow” side when there is a big part of sunlit background.

The fact that the directional reflectance index of a young coniferous stand was found equivalent to the one of a mature deciduous stand brings a new information in the understanding of the relationship between physical characteristics of a forest and its BRDF captured by a medium spatial resolution sensor like CHRIS (10-30m/pixel). It appears that the horizontal arrangement of the trees and the stand density influence more the directional component of the radiance than the tree height and diameter.

7. CONCLUSION

The contribution of the multiple view angle remote sensing data has been investigated with emphasis to a better understanding of the mechanism of the directional anisotropy and to separation of the spectral and directional effects in the reflected radiance measured at 18 wavelengths. In this study, we used images acquired during the winter while, traditionally, the forest remote sensing studies used images taken during the growing season. The images of deciduous stands acquired during the winter have been found particularly interesting to understand the mechanism of the directional anisotropy. The proportion of sensed shadow, casted to the background, was found to be the main cause of the anisotropy in such images. It was therefore possible to make distinction between two mature deciduous forest stands having different tree densities.

The six forest types studied here showed different directional signatures (revealed namely by the anisotropy index) but most of them could be discriminated on the basis of the near-nadir spectral signature alone. The means of reflected radiances of this near-nadir image at the red-edge and near infrared wavelengths were found significantly different for all pairwise comparisons of the forest types, excepted the comparison between the mature deciduous stands. Their mean radiances were significantly different in the images acquired with a FZA of +36°, i.e. when the sensor was close to the plane perpendicular to the principal plane. It appeared therefore that, on one hand, the contribution of the multiple view angle is important in differentiating some particular forest types in relation to their structural characteristics, and on the other hand, that the spectral effects are the main driving factor in discriminating the most forest types.

8. ACKNOWLEDGEMENTS

This work was carried out in the framework of the PRODEX programme funded by the European Space Agency (arrangement no 90070). The authors are grateful to the staff of the Cantonement of Couvin for their help during the field campaign.

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A MULTI-TEMPORAL & MULTI-ANGULAR STUDY OF HYPERSPECTRAL DATA RELATED TO THE BIOPHYSICAL PROPERTIES OF COTTON CROPS & SOIL CHARACTERISTICS, NSW, AUSTRALIA.

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**Minerals Mapping Technologies Group,
CSIRO - Exploration and Mining, Sydney, AUSTRALIA.

ABSTRACT

This interim research report is intended to highlight key elements of the larger CHRIS-based experiment in the absence of reliable field-based cotton targets resulting from widespread drought across Eastern Australia. The results primarily reflect a predominance of glasshouse trial results in addition to elements of early CHRIS, HyMap, and field-related results.

Keywords: ESA, CHRIS, hyperspectral, cotton, multi-temporal, multi-scale, vegetation indices, vegetation mapping.

1. INTRODUCTION

Growers are challenged to access current and precise information about their crops in the field. Therefore, information about crop conditions and landscape variability during the growing season is a crucial factor. Remote sensing has become one of main tools for agricultural applications, especially for crop monitoring during the growth cycle applying vegetation specific indices as indicators (Clevers and Jongschaap, 2003). Remote sensing techniques mostly applies reflectance data obtained either by satellite or aircraft to provide relatively low cost spatially distributed data on plant growth at large scales. Improving the spectral information of vegetation through remote sensing platforms was perceived as the key to a more direct means of identifying surface cover types (Goetz, 1992; Merton and Cochrane, 1995). In order to detect plant growth condition and vigour, the underlying principle is that plant canopy with varying nutrient levels reflect differently in specific wavelength (Mutanga et al. 2003). Therefore, remote sensing data, especially high spectral resolution data, can be used to detect canopy reflectance in specific wavelength in which represent the plant ‘stress’ status.

Therefore this study aims to monitor the spectral variations in agricultural practices as a function of multi-scale changes over time. Scale-dependency will be assessed at leaf, canopy, and landscape scales. Like most hyperspectral studies, the irregularly spaced intervals between image and field dataset acquisition (coincident or not) adds to the complexity of any undertaking of this magnitude. Furthermore, this study aims to investigate selected aspects of
the relationship between the BRDF of the various lab, field, aerial, and orbital spectrometers, particularly between pointable devices such as CHRIS and the lab/field goniometer spectrometer (Figure 3).

This study focuses on the hyperspectral imaging and mapping of a single species across a large homogeneous area. The aim of this study is the use of high spectral resolution data to discriminate of spectral variation of single crop at leaf, canopy, and orbital scales. Through this analysis, two main goals will be assessed; 1) the variation spectra can be used to predict vegetation health and vigour, 2) the possibility the use spectral variation relate to nutrient deficiency in the field.

Advanced technology in remote sensing enables to discriminate crop condition such as vigour, stress, health, maturity and yield by analysing vegetation indices in small range of spectral reflectance captured by the sensor, change detection, crop and sensor geometry and other aspects of analysis. The calculation of multi-temporal hysteresis data from even a single vegetation species can provide an opportunity to examine the suitability of measuring temporal spectral trajectories as ecologically meaningful data associated with changing vegetation growth, phenology, stress, and productivity.

This interim research report is intended to highlight key elements of the larger CHRIS-based experiment in the absence of reliable field-based cotton targets resulting from widespread drought across Eastern Australia.

2. STUDY SITES

The main study site located at “Colly” Central, forms a remote hub of an agricultural business owned by Iffley Cotton Field, Tywnam Pty. Ltd. who regionally operate large commercial cropping stations predominantly growing cotton, sunflowers, and winter wheat. The Colly farm is centred at 29°36’South, 148°51’East, and is located about 40 kilometres east of the remote small town of Collarenebri in the North West region of New South Wales, Australia (Figure 1). The research site is a large commercial enterprise with a history of remote sensing research, an existing multispectral-based yield prediction model, and excellent records of past yields and other agronomic measures. Five fields were selected in the Colly area ranging between 42 to 257ha. Agronomic data was made available across the time period of our research, and included records of plantings, irrigation rates, fertilisation history, and crop yields.
3. **DATASETS**

The following schematic (Figure 2) shows the three core areas of data; 1. remotely sensed imagery, 2. lab/glasshouse BRDF experiments, and 3. field derived soil and goniometer measurements. As this is an interim CHRIS report, aspects of relevant image and lab-based analysis will be emphasised.

![Figure 2. Schematic Diagram of Image, Lab, and Field Site Datasets.](image)

*Note: The primary cotton research site is Colly Cotton (29.66°S, 148.85°E), with AusCott (lat/long ??) as the secondary site.*
Field and remotely sensed datasets (refer Figure 3) include 1. & 2. Lab/Field ASD HH spectrometer (512 bands; 281 – 1088nm) mounted to the hemispherical goniometer, 3. HyMap (Cocks et al., 1998) aerial hyperspectral imaging system (126 bands; 400 – 2500nm), 4. CHRIS (Mode 1; 62 bands; 405 – 1035nm), 5. Landsat (std. mode; 7 bands). HyMap imagery of this study site area was acquired in 5 Feb 2000 (maturity), 11 Sept 2000 (emergent growth), 5 Apr 2001 (late maturity/senescence). Accurate field spectral data was not obtained coincident with HyMap data scans all runs were collected as opportunistic acquisitions prior to the formation of this CHRIS research initiative, however ancillary data related to cotton growth and yield and other agronomic variables were recorded.

Figure 3 Multi-scale Research Datasets.

Note: Spectra/imagery obtained at the: leaf-scale(1), field-scale(2), aerial-scale(3), & orbital scale(4 & 5).

To gain an estimate of cotton growth variability and yields (Table 1) versus remotely sensed spectral measures, a laboratory trial based on fertility rate was conducted in a series of glasshouse experiments across the same growing period in the 2002/2003 season.

Table 1. Total cotton selected field area of subset image of Iffley farm, ROI and yield for 1999/2000 Growing season

<table>
<thead>
<tr>
<th>Fields No.</th>
<th>Area (ha)</th>
<th>Area (%)</th>
<th>ROI Calc (ha)</th>
<th>Yield (bales/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>302</td>
<td>240</td>
<td>(28.17)</td>
<td>215.92</td>
<td>10.403</td>
</tr>
<tr>
<td>303</td>
<td>252</td>
<td>(29.58)</td>
<td>235.92</td>
<td>11.243</td>
</tr>
<tr>
<td>307</td>
<td>237</td>
<td>(27.82)</td>
<td>217.59</td>
<td>12.182</td>
</tr>
<tr>
<td>323</td>
<td>81</td>
<td>(9.51)</td>
<td>72.14</td>
<td>8.303</td>
</tr>
<tr>
<td>325</td>
<td>42</td>
<td>(4.93)</td>
<td>37.31</td>
<td>7.907</td>
</tr>
<tr>
<td>Total Area</td>
<td>852</td>
<td>(100.01)</td>
<td>778.88</td>
<td></td>
</tr>
</tbody>
</table>

Only selected fields were planted with cotton during 1999/2000 growing season (early phase of drought event), therefore, only five cotton fields were selected as focus of analysis. Field numbers included 302, 303, 307, 323, and 325, with total area 852ha (refer Figure 4). Region Of Interest (ROI) where defined within each of these fields, representing 90.8% of the original area (refer Table 1).

**Figure 4. Colly Cotton Field Study Sites.**

*Note: Field numbers 302, 303, 307, 323, and 325 where used to define spectral ROI’s.*

### 3.1 CHRIS DATASET CHARACTERISTICS

A common point in each look angle image (+55°, +36°, 0°, -36, -55°) is useful to assess the degree of pointing accuracy that the CHRIS sensor achieves across the acquisition. Figure 5 (Colly site) and Figure 6 (AusCott site) show strong pointing error drift across the look angle datasets. In one acquisition (Colly +55°) the exact location fell somewhere off the study site area. This pointing drift creates difficulties when mapping across the datasets effectively reducing the spatial extent of coincident coverage. The derivation of ROI’s from these spatially reduced datasets in this instance becomes problematic, especially when only 5% of pixels are common to all the 5 view angle datasets.
Figure 5. CHRIS Colly Dataset Look Angles (November 2003).
Note: Common reference points are marked as yellow circles.

Figure 6. CHRIS AusCott Dataset Look Angles (March 2004).
Note: Common reference points are marked as yellow circles.

Figure 7. CHRIS multi-angle spectral plots of cotton.
Note: Spectra (A) and stacked spectra (B) are derived from the 25 March 2004 CHRIS dataset.
4. **Glasshouse Experiment**

Glasshouse trials growing five varieties of cotton were carried out during September 2002 until April 2003. The five varieties of cotton plant (Sicot 189, Siokra V16, Delta Diamond, Delta Pearl, and Delta Opal) were grown under four types of soil fertilization. The standard watering rate during this trial was at rate of 455mm/growing season, equivalent to rainfall rate at Colly Cotton research site. Soils substrate consist of three components; river sand, organic-rich soil, and clay-rich soil were used in this experiment. Cotton grown in Australia is dominated by cracking self-mulching clay, sandy soil, found mostly on flood plains (Cotton Australia, 2001). Clay soil also contains many of the nutrients required by cotton plants. The specific soil structure of a blend of rich-organic matter and clay was designed to replicate the analogous soil structure of Colly Cotton site research site. Potted glasshouse soils were also mixed with varying quantities of standard agricultural fertilizer specifically for productivity trials (Table 2).

<table>
<thead>
<tr>
<th>Soil Name</th>
<th>Symbol</th>
<th>Sand:Black Soil:Clay Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>S0</td>
<td>60:20:20</td>
</tr>
<tr>
<td>Moderate</td>
<td>S1</td>
<td>40:30:30</td>
</tr>
<tr>
<td>Fertile</td>
<td>S2</td>
<td>20:40:40 + standard fertilizer</td>
</tr>
<tr>
<td>Very fertile</td>
<td>S3</td>
<td>20:40:40 + standard fertilizer + micronutrient</td>
</tr>
</tbody>
</table>

*Note: Standard fertilizer = 1 gram/pot, Micronutrient = 20 mg/pot. Replicating std. field agricultural application rates.*

Table 2. Category and Composition of Soils.

A randomized block design was applied for the cotton growing experiments. However, the result of analysis of variance for each single treatment is not presented here. The ASD FieldSpec HandHeld spectroradiometer (ASD, 1999) was used to collect the spectral data to detect the spectral differences among different fertilization and watering rates from the 5 different cotton crop varieties. The ASD HH has a wavelength range of 325 to 1075nm with a Full Width Half Maximum (FWHM) of 1.6nm, acquiring 512 contiguous channel bands with a selectable foreoptic viewing angle of 1, 10, or 25 degrees.

A goniometer was constructed to measure plant hemispherical reflectance as a function of Bidirectional Reflectance Distribution Function (BRDF) (Figure 8B). The goniometer comprises a horizontal azimuth hemisphere bisected by a vertical zenith track along which the spectrometer is moved at angular increments. The construction was designed measure azimuth and zenith spectra of the plant or soil as a complete 3-D hemisphere.

The spectroradiometer was elevated one meter above the foliage to acquire of cotton spectra. A $10^\circ$ spectroradiometer foreoptic was used to create a Field of View (FOV) area 240.46cm² *(refer Equation 1 & Equation 2).*

$$r = h \cdot \tan \left( \frac{\alpha}{2} \right) \cdot \frac{\pi}{180}$$

*Equation 1. Radius Calculation*
\[ A = \pi \cdot r^2 \]

Equation 2. FOV Area Calculation

where: \( r \) is the radius of field of view, \( h \) height of equipment to the target, \( \alpha \) is angle of view of the spectroradiometer, and \( A \) is total area field of view to the target.

Spectral measurements of cotton were replicated 10 times per plot, and the spectroradiometer was configured to average 25 samples per single spectrum. Samples were acquired throughout the growing season.

Figure 8 Site location and glasshouse experiment.

Note: A. Ploughed Colly cotton field with remnant cotton lint, B. lab/field goniometer C. cotton grown at different watering rates, D. cotton grown at different soil fertility rates.

5. Vegetation Indices

Derived broad-band vegetation indices (VIs) have been widely used to quantify crop variables such as wet biomass, leaf area index, plant height, and productivity (Thenkabail, Smith and De Pauw, 2004). Variation of these crop variables may occur due to climate, soils, cultivars, management practices as well as technological input. Studies (e.g., Blackburn, 1998; Sibayama and Akiyama, 1991; Elvidge and Mouat, 1989) has shown that narrow waveband
(hyperspectral) indices could provide additional information in quantifying biophysical characteristic of agricultural crops.

This paper present the derived spectrally dataset limited to representative spectra curve of the four classes; very fertile, fertile, medium and low nutrient content of soil to calculate VI’s of cotton. Calculation of spectral values were focused on six aspects of indices; red-edge ratio (Gitelson and Merzylak, 1996), CAI index (Oppelt and Mauser, 2001a and b), NDVI (Tucker, 1979), and NVI values (Takebe et al., 1990, Bausch and Duke, 1996). The index of Gitelson and Merzylak (1996) shown in Equation 3 was modified using 752nm and 690nm instead of 750nm and 700nm originally defined. 752nm is the maximum reflectance at near infrared region and 690nm is the maximum absorption of red spectrum region. The red-edge productivity of a plant can be assessed as the ratio between 752nm and 690nm can show:

\[ \text{Red\_edge\ ratio} = \frac{R_{752}}{R_{690}} \]

Equation 3.

where: \( R_{752} \) reflectance (%) value at 752nm, \( R_{690} \) reflectance (%) value at 690nm.

The Chlorophyll Absorptions Integral (CAI) index derives the chlorophyll content by measuring the area between a straight line connecting two points of the red-edge and the curve of the red-edge itself. Therefore, it is an approach based on a spectral envelope (continuum) measurement (Oppelt and Mauser, 2001a & b). To conform to the spectral bands of the ASD spectroradiometer, the CAI was modified in the following equation (see Equation 4 and 5)

\[ mCAI = A - \int_{R_{552}}^{R_{752}} f \]  

Equation 4

where: \( A = \) area of the trapeze between \( R_{552} \) and \( R_{752} \), \( f = \) reflectance curve.

Therefore, the \( mCAI \) value can be calculated as follow:

\[ mCAI = \frac{(R_{552} + R_{752})}{2} * (752 - 552) \right) - \sum_{R_{552}}^{R_{752}} \sum R * 1.579 \]

Equation 5

The modified CAI (mCAI) calculates the area above the spectral curve between 552nm (green peak) and 752nm and the index, with 1.579nm is the FWHM of the spectroradiometer. The mathematic approach is to calculate the area of the trapezoid (A) between 552nm and 752nm and subtract it with the integral of the spectral curve between the same spectral values. This calculated index also can be used to estimate the vigour and health of cotton plant under different fertilization rates.
The ratio of to be constant at the level regardless of the differences in chlorophyll concentrations, and defined a chlorophyll absorption ratio index (CARI, Kim et al 1994). To estimate the variation within the 550nm and 770nm reflectance range, the chlorophyll absorption band at 670 nm can be used to predict the Chlorophyll Absorption Ratio Index (CARI) ratio variations, therefore:

\[
\text{CARI} = \text{CAR} \frac{R_{700}}{R_{670}}
\]

\[
\text{CAR} = \left| (a \times 670 + R_{670} + b) / (a^2 + 1)^{0.5} \right|
\]

\[
a = \frac{(R_{700} - R_{550})}{150} \quad \text{and} \quad b = R_{550} - (a \times 550)
\]

Equation 6

The Photochemical Reflectance Index is calculated based on the normalised ratio of reflectance between $R_{528}$ and $R_{567}$. These two wavelengths define regions of biochemical absorption and therefore capable of measuring photosynthetic down-regulation (Gamon, et al. 1995)

\[
\text{PRI} = \frac{R_{528} - R_{567}}{R_{528} + R_{567}}
\]

Equation 7

6. INTERIM RESULTS AND DISCUSSION

Table 5. Calculated values of Red_edge, CAI, NDVI, NDI, CARI and PRI. shows the fertile and very fertile soil condition gives the higher value for all indices calculated, except for PRI value. Low soil fertility produces lower values for given indices calculated, while the red-edge, CAI and the CARI of healthy plants show high index values. Interestingly, in this vegetation index calculation the values on NDVI and PRI among the soil fertility conditions give almost the same values; 0.99 to 1.00 and -0.08 to -0.11, respectively. It is assumed that the NDVI value calculated is not appreciably different amongst soil conditions due in part to plant “greenness” in emergent growth.

Generally, reflectance curves highlight a significant difference among cotton growth conditions. High fertility plants exhibit higher reflectance especially in the NIR compare to that of low fertility samples. Additionally, the “green peak” at 552nm is clearly more apparent compared to those of lower fertility. These trends were highlighted when applying the four vegetation indices; red-edge, CAI, NDI and CARI. Higher values at the red-edge, CAI and CARI indicate higher plant vigour for both fertile and very fertile soil conditions. Interestingly, Red-edge, CAI, NDI, and CARI all exhibit lower values for lower fertility trials, however NDVI and PRI are exceptions to this trend. The cotton trials generated valuable spectral library data for application to lab, field, and satellite data.
Variation in VIs has shown that soil condition influences the crop biophysical performance during growing season in addition to the spectral characteristics. Similar trends were reported by Thenkabail et al. (2004) as cotton leaves changed visible spectral properties from green to light green due to some soil backgrounds that effect the reflectance such as soil moisture (Dabrowska-Zeilinska, Inoue, Gruszczynska, Kowalik, and Stankiewicz, 2001), particle size (Dathe, Eins, Niemeyer, and Gerold, 2001), and nutrient content (Palacios-Orueta, Pinzón Ustin, and Roberts 1999).

**Table 3. Leaf Scale Mean & Std. Deviation of Indices**

<table>
<thead>
<tr>
<th></th>
<th>So (low)</th>
<th>S1 (medium)</th>
<th>S2 (fertile)</th>
<th>S3 (very Fertile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVI</td>
<td>-2.253</td>
<td>-3.753</td>
<td>-5.013</td>
<td>-6.943</td>
</tr>
<tr>
<td>Red_edge Ratio</td>
<td>3.057</td>
<td>4.294</td>
<td>5.065</td>
<td>6.042</td>
</tr>
<tr>
<td>NDVI</td>
<td>0.471</td>
<td>0.614</td>
<td>0.649</td>
<td>0.695</td>
</tr>
<tr>
<td>RNVI</td>
<td>2.116</td>
<td>2.219</td>
<td>2.472</td>
<td>2.940</td>
</tr>
<tr>
<td>CARI</td>
<td>28.381</td>
<td>43.124</td>
<td>55.982</td>
<td>52.090</td>
</tr>
<tr>
<td>PRI</td>
<td>-0.203</td>
<td>-0.214</td>
<td>-0.058</td>
<td>-0.102</td>
</tr>
<tr>
<td>WI</td>
<td>1.017</td>
<td>0.981</td>
<td>0.956</td>
<td>0.953</td>
</tr>
<tr>
<td>NPCI</td>
<td>0.104</td>
<td>0.064</td>
<td>0.051</td>
<td>0.006</td>
</tr>
</tbody>
</table>

**Table 4. Variation in Vegetation Index Values CHRIS Dataset (Nov’03)**

<table>
<thead>
<tr>
<th></th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
<th>Site 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVI</td>
<td>-0.02379</td>
<td>-0.04801</td>
<td>-0.02607</td>
<td>-0.01619</td>
<td>-0.02502</td>
<td>-0.02124</td>
</tr>
<tr>
<td>SR</td>
<td>1.855329</td>
<td>2.778927</td>
<td>1.897708</td>
<td>1.559155</td>
<td>1.730547</td>
<td>1.839076</td>
</tr>
<tr>
<td>NDVI</td>
<td>0.299555</td>
<td>0.470749</td>
<td>0.309799</td>
<td>0.218942</td>
<td>0.267546</td>
<td>0.295546</td>
</tr>
<tr>
<td>RNVI</td>
<td>1.694012</td>
<td>2.038898</td>
<td>1.660468</td>
<td>1.471129</td>
<td>1.649593</td>
<td>1.735462</td>
</tr>
<tr>
<td>PRI</td>
<td>-0.01198</td>
<td>-0.03166</td>
<td>-0.00027</td>
<td>-0.00619</td>
<td>-0.01172</td>
<td>-0.02025</td>
</tr>
<tr>
<td>WI</td>
<td>0.949135</td>
<td>0.945022</td>
<td>0.972169</td>
<td>0.971461</td>
<td>0.999029</td>
<td>0.978073</td>
</tr>
<tr>
<td>NPCI</td>
<td>-0.03289</td>
<td>-0.12663</td>
<td>-0.08576</td>
<td>-0.04171</td>
<td>-0.02451</td>
<td>-0.01708</td>
</tr>
</tbody>
</table>
Table 5. Calculated values of Red_edge, CAI, NDVI, NDI, CARI and PRI.

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Medium</th>
<th>Fertile</th>
<th>Very Fertile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red-edge</td>
<td>1.59</td>
<td>2.95</td>
<td>6.33</td>
<td>6.20</td>
</tr>
<tr>
<td>CAI/1000</td>
<td>0.51</td>
<td>2.15</td>
<td>4.47</td>
<td>4.60</td>
</tr>
<tr>
<td>NDVI</td>
<td>0.99</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>NVI</td>
<td>2.04</td>
<td>2.38</td>
<td>3.52</td>
<td>2.69</td>
</tr>
<tr>
<td>CARI</td>
<td>6.89</td>
<td>28.20</td>
<td>65.49</td>
<td>84.88</td>
</tr>
<tr>
<td>PRI</td>
<td>-0.09</td>
<td>-0.11</td>
<td>-0.08</td>
<td>-0.10</td>
</tr>
</tbody>
</table>

Figure 9. Graph of Spectral Vegetation Indices (Red-edge, CAI, NDVI, and NVI) as a Function of Soil Fertility.

The measured production and estimated production per hectare of cotton is shown in table 3. It shows that variation in soil fertility give significant in production.

Table 6. Production of Cotton at Varying Soil Condition

<table>
<thead>
<tr>
<th></th>
<th>Yield (g/pot)</th>
<th>Estimated yield (kg/ha)</th>
<th>Bale/ha</th>
<th>Bale/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9 pl/m</td>
<td>12 pl/m</td>
<td>9 pl/m</td>
<td>70% est.</td>
</tr>
<tr>
<td>Low</td>
<td>10.68</td>
<td>865.08</td>
<td>1537.92</td>
<td>3.81</td>
</tr>
<tr>
<td>Medium</td>
<td>15.59</td>
<td>1262.79</td>
<td>2244.96</td>
<td>5.56</td>
</tr>
<tr>
<td>Fertile</td>
<td>43.35</td>
<td>3511.35</td>
<td>6242.40</td>
<td>15.47</td>
</tr>
<tr>
<td>Very Fert.</td>
<td>52.20</td>
<td>4228.20</td>
<td>7516.80</td>
<td>18.63</td>
</tr>
</tbody>
</table>

*Note: Pl = plants.*
Considering the presented results of the first data in the laboratory, the authors will intensify the field experiments in the field during 2003/2004 growing season. Additionally, multi-temporal air borne; HyMap and space borne; CHRIS/PROBA hyperspectral data analysis will be evaluated against the laboratory and the field measurements. The results will be used to develop a method of spatial variation of soil fertility in the field based on spectral indices calculation.

7. REFERENCES


ABSTRACT

The CHRIS core site Gilching is located in the Bavarian Alpine foothills, 25 km south-west of Munich. The activities in this area are coordinated by the University of Munich – chair for geography and geographical remote sensing together with the GTCO (Ground Truth Center Oberbayern).

In 2003, four CHRIS images were acquired. Airborne and field based hyperspectral measurements were also conducted during the vegetation period of that year. Also, four airborne data sets were acquired using AVIS-2 (Airborne Visible / near Infrared imaging Spectrometer) and three sets of GVIS (Ground based Visible and near Infrared imaging Spectrometer) measurements were acquired.

Besides the discussion of the acquired data, problems that occurred during the campaign in 2003 will be addressed.

For 2004, a more intensive field campaign is planned. The field measurements will be carried out at weekly intervals, AVIS and GVIS measurements are planned as often as possible, depending on the weather conditions. A list of planned activities provides a basis for the discussion and coordination of desired CHRIS acquisition dates in the test site Gilching.

1. INTRODUCTION

The core site “Gilching” is located in the Bavarian Alpine foothills, 25km south-west of Munich. This area is a test site for several research projects providing various measurements, both from the ground and remotely sensed. The main research topics in this area are the retrieval of biophysical parameters (biomass, chlorophyll, nitrogen) using optical remote sensing as well as retrieval of soil moisture using radar. These parameters serve as input and validation for hydrological and vegetation modelling approaches.

The optical remote sensing activities are conducted at various scales. To achieve this, various optical sensors (field spectrometer (GVIS), airborne (AVIS-2) and satellite based (CHRIS) sensors) are used to investigate scaling issues between different spatial resolutions.

2. TEST SITE

Within the test site Gilching (48°6’ N, 11° 17’ S), one field with silage maize (Zea mays L.), one with rape (Brassica napus L.), one with triticale (X Triticosecale Wittmack) and one with winter wheat (Triticum aestivum L.) were chosen as test fields for 2003.

Most of the farmers are under contract to the local office for water management. This enables access to detailed field management data including information about crop rotation, cultivars, dates of sowing and harvest, the application of fertiliser, herbicides and fungicides and the quantity applied.

A weather station of the Bavarian network of agrometeorological stations enables access to local weather monitoring. Station No. 72 (Gut Hülß), located at the north-eastern edge of the test site, provides meteorological data such as precipitation, soil and air temperature, total radiation and air humidity. An eddy covariance flux station and a permanent soil moisture station were installed on the rape field to obtain data at hourly intervals.

A biweekly field campaign was conducted, where plant parameters such as wet/dry biomass, height, phenological stage, leaf chlorophyll and nitrogen content were measured.

3. INSTRUMENTATION

Figure 1 presents the remotely sensed data that was collected for Gilching in 2003.

Figure 1: Available remotely sensed data from 2003 (top = CHRIS; centre = AVIS-2; bottom = GVIS). The number of rays indicates the number of acquired angles.

During 2003, four CHRIS data sets were acquired (May 24, July 27, August 2 and September 17); airborne and field-based hyperspectral measurements were also...
conducted during that year’s vegetation period; four airborne data sets (April 14 and 16, May 16 and 24) were acquired using AVIS-2 and three GVIS (Ground based Visible and near Infrared imaging Spectrometer) measurements were acquired (May 16 and 24, June 4).

3.1 CHRIS

Four CHRIS data sets are available for 2003; these are shown in Figure 2.

The CHRIS data is dark current corrected using the mean value of the masked pixels for each line. After dark current correction the images have been destriped using a multiplicative approach, where the pixels of a column were aligned to their adjacent pixels.

The atmospheric correction and reflectance calibration was conducted using PAAK [1], which is based on the radiation transfer model RSTAR. Although Lidar measurements are available, the cloudy or dusty weather hampered a correct atmospheric correction, as presented in section 4.1.

The geometric pre-processing was carried out using ground control points.

3.2 AVIS-2

AVIS-2 is a pushbroom imaging spectrometer that operates with 64 spectral bands in the visible/near infrared domain (400-850nm). The sensor AVIS was built at the University of Munich, chair for geography and remote sensing in 1998 [2, 3, 4]. The second generation – AVIS-2 – offers the possibility of along-track pointing [5]. Its specifications are as follows:

Spectral Coverage: 400 - 850 nm
Data Acquisition: digital B/W camera
640x64 pixels, 16 bit
Spectral Resolution: 7 nm, 64 bands
IFOV: 2.2 mrad, 640 pixels per scan line
Along-track pointing: ±55°, 7 angles selectable

An example for an AVIS-2 image stripe, which was acquired on May 24, is presented in Figure 3. Angular data sets were collected on both May 16 and 24 and will be described in more detail in section 4.2.

All data was dark current and flat field corrected. Atmospheric correction and reflectance calibration was conducted using PAAK [1]. Geometric processing was carried out using the GPS and INS data recorded in the header of each image line.

3.3 GVIS

GVIS is a tractor-mounted version of AVIS using 16 optical fibres, installed on a cantilever arm, instead of a lens. The movement of the tractor offers the possibility of two-dimensional ground measurements at a spatial scale below 1m. The specification of GVIS is as follows:

- Spectral Coverage: 530 - 1020 nm
- Data Acquisition: digital B/W camera 512x120 pixels, 16 bit
- Spectral Resolution: 6 nm, 119 bands
- FOV/Fibre: 0.44 rad
- FOV Total: 12 m

![ GVIS Schematic Design](image)

Figure 4: Schematic design of GVIS [6]

The GVIS data was dark current and flat field corrected. The reflectance calibration was conducted using both measurements of reference panels and diffuse skylight.

Geometric pre-processing is conducted using the GPS data stored in the header of each image line.

4. ANGULAR MEASUREMENTS

A direct comparison of angular measurements of AVIS-2 and CHRIS is not possible for 2003 because of the different acquisition dates (see also Figure 1). Therefore CHRIS angular acquisitions of September 17 will be described in more detail. AVIS-2 angles will discussed on the basis of measurements conducted on May 24.

4.1 CHRIS

Figure 5 provides five CHRIS angular images acquired on September 17 in a false colour composite. The data was pre-processed as described in section 3.1. The sun azimuth angle is 145°.

![ CHRIS Angular Data](image)

At this time of the year, crops such as wheat, triticale or rape are harvested. Maize plants begin to wither. Therefore the angular reflectances of two meadows will be discussed: the reflectance spectra represent mean field spectra of permanent grassland sites in Gilching. The reflectance shapes of the different observation angles are very similar, but the levels vary. For both
sites, the highest reflectance levels occur at the backward-looking –35° angle. The reflectance level decreases at higher or lower angles. Therefore the –35° angle appears to be the measurement nearest the hot spot. The lowest reflectance level can be observed at the forward-looking +35° angle in the VIS, in the NIR at the forward-looking +55°.

A problem occurred in the VIS, where the reflectances of all angles (12 to 28 %) are far too high. This is caused by the mist that can be observed in large parts of the CHRIS image from that day. Although Lidar measurements were carried out on that day, the partial coverage prohibited a correct atmospheric correction.

The reflectance spectra in Figure 5 also display a strong decrease at wavelengths above 800nm. This is due to the decreasing sensitivity of CHRIS in the NIR. A recalibration could not be conducted because of the existing problems with the atmospheric correction of this data set.

4.2 AVIS-2

AVIS-2 angular measurements were conducted on May 24, which are shown in Figure 6. The data was pre-processed as described in section 3.1.

The reflectance levels of the different observation angles show behaviour similar to those of CHRIS that are presented in Figure 5. The near hot spot observation can be observed at the backward –45° angle. The forward +45° angle shows the lowest level in the VIS while the nadir angle is the lowest in the NIR part of the spectrum.

5. SENSOR COMPARISON

A major issue in the test site Gilching is the comparison of hyperspectral data acquired with different sensors at different spatial scales. Simultaneous measurements of CHRIS, AVIS-2 and GVIS could only be conducted on May 24. Unfortunately, the CHRIS image does not cover the test fields that were measured with GVIS. Therefore a direct comparison of all sensors is not possible. A comparison of GVIS to AVIS-2 on the one hand and AVIS-2 to CHRIS on the other hand will be presented instead.

5.1 AVIS-2 and GVIS

An AVIS-2 image stripe acquired on May 24 is shown in Figure 7. In its northern part the flight stripe covers a field of triticale, where GVIS measurements were carried out simultaneously to the AVIS-2 acquisition. The data was pre-processed as described in section 3.1.

Although the GVIS image illustrates the heterogeneity within the field much better than the AVIS-2 image does, the mean field spectra of AVIS-2 and GVIS are quite similar; slight differences can be observed in the RED and NIR part of the spectra (680-720nm and >770nm).

5.2 AVIS-2 and CHRIS

When comparing the mean field spectra of a meadow and a forest site of CHRIS and AVIS-2, there appear to
be many more differences than when comparing AVIS-2 to GVIS. This is caused by difficulties with the atmospheric correction of the CHRIS image. The weather conditions are comparable to those described in section 4.1 for the September acquisition. A layer of mist covers parts of the CHRIS image leading to problems with an accurate atmospheric correction. As a result the reflectances in the VIS are too high for both sites that were observed. A recalibration to eliminate the decrease of CHRIS sensitivity in the NIR could not be carried out. Therefore the reflectance spectra cannot be compared.

5. AIMS FOR 2004

For 2004, an intensive field campaign is carried out with weekly ground sampling intervals. Hyperspectral measurements using GVIS and AVIS-2 are planned to be carried out in a weekly or biweekly time interval (depending on the weather conditions). In addition, plant parameters will be measured simultaneously to CHRIS, AVBIS-2 and GVIS acquisitions as often as possible.

To enhance the possibility of comparison between the sensors the CHRIS mode should be changed from mode 3 (land mode, 18 bands, full swath) to mode 5 (land mode, 37 bands, half swath). This leads to new centre coordinates for the test site Gilching, which are given in Table 1.

Table 1: New centre coordinates the test site Gilching for 2004

<table>
<thead>
<tr>
<th>New Centre Coordinates</th>
<th>Geogr. (WGS 84)</th>
<th>UTM (WGS 84)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Centre</td>
<td>48.0587 N</td>
<td>32 5325859 N</td>
</tr>
<tr>
<td></td>
<td>11.3079 E</td>
<td>671982 E</td>
</tr>
</tbody>
</table>

Ground Elevation 580m

6. REFERENCES


ABSTRACT

This study reports on work to assess the utility of multi-angle data in providing measures of the physical structure and composition of desert grasslands. The target is in the United State Department of Agriculture (USDA), Agricultural Research Service (ARS) Jornada Experimental Range (JER) near Las Cruces, New Mexico, USA. The JER is a CHRIS/Proba Core Site. The approaches followed include multi-angle image ratios, bi-directional reflectance distribution function (BRDF) model inversion – Li-Ross kernel-driven and the non-linear simple geometric model (SGM) – and the structural scattering index (SSI). The data used are from the Compact High Resolution Imaging Spectrometer (CHRIS) flown on the European Space Agency's Project for On-Board Autonomy (Proba) satellite launched on October 22, 2001 into a sun-synchronous elliptical low Earth orbit. The results indicate that there is canopy structure information in angular ratio images, where spatial variation corresponds with mean plant size. The SSI did not behave as expected with high values corresponding to sparsely vegetated areas. SGM fits to data were good (mode RMSE < 0.01) and produced mostly reasonable parameter values with meaningful spatial distributions.

1. INTRODUCTION

1.1 CHRIS Data Description

The CHRIS sensor developed by Sira Electro-Optics Ltd. produces imagery in up to 62 spectral channels in the range 415 - 1050 nm with a spectral resolution of 5 - 12 nm and is highly configurable in terms of both spectral channels and spatial resolution [1]. For the CHRIS/Proba Jornada Experiment the formal mode was chosen to be Mode 3 (Land Channels), providing a nominal ground sampling distance of 17 m and 18 spectral channels with a full swath. The selected CHRIS spatial resolution is highly appropriate for studies of the reflectance anisotropy of the land surface in desert grasslands since a sensor footprint of between 15 and 100 m most effectively captures the BRDF; smaller footprints risk a non-representative sampling of elements contributing to the BRDF and larger footprints risk losing information on spatial variability. 

1.2 The Jornada CHRIS/Proba Core Site

The USDA, ARS, Jornada Experimental Range lies 37 km north of Las Cruces, New Mexico and is one of the 22 core sites worldwide selected for studying the exploitation of data from the CHRIS instrument on Proba [2] (Fig. 1). It is located in the northern part of the Chihuahuan Desert between the Rio Grande floodplain (elevation 1,186 m) on the west and the crest of the San Andres mountains (2,833 m) on the east. Vegetation on the JER is classified as desert grassland but shrub density has increased dramatically since the 1880’s and is continuing to do so [3]. Honey mesquite (Prosopis glandulosa) is now a major dominant on sandy soils where broom snakeweed (Gutierrezia sarothrae), and soaptree yucca (Yucca elata) are also abundant.

Fig. 1. (a) The location of the JER, New Mexico, USA (b) CHRIS false colour composite, 5th August 2002.

At one diffuse boundary where remnant grassland is giving way to shrub domination there is a transition
zone which is of great ecological interest and the site of several remote sensing research campaigns [4-6], including efforts directed at furthering exploitation of CHRIS data as part of the JORNada EXperiment. The areas imaged by CHRIS encompass a variety of plant communities and topoedaphic conditions, including black grama grassland, grass-shrub transition, mesquite- and creosotebush-dominated shrubland, areas infested with broom snakeweed, areas of sand entrainment and deposition, experimental plots and swales.

1.3 Preparatory Work

Prior to distribution of full CHRIS data sets to investigators in late 2002, a number of activities had been performed in preparation for research with CHRIS data over the JER. These included the acquisition of multi-angle observations from the air using a tilting DuncanTech digital multi-spectral camera; collection of detailed plant measurements and spectroscopy; and cross-validation between radiosity, BRDF model and multi-angle observations [7-8]. Previous modeling efforts used canopy measurements over several 25 m² plots in conjunction with the RGM radiosity model [5] and a simplified geometric model (SGM) based on geometric optics. This was tested against the RGM [6], inverted for canopy structure parameters using the DuncanTech data set [7], and used to simulate 650 nm scenes at the landscape scale for the intensively studied transition site (inputs based on overstorey and understory plant density simulated using a relation between IKONOS panchromatic imagery and field measured parameters) [9]. The SGM was driven with detailed field measurements and tested against dual view angle data from a CHRIS acquisition in August 2002, with mean differences between modeled and measured red reflectance < 0.04 [10].

2. METHOD

2.1 Data Extraction and Navigation

Calibrated spectral radiance images in 18 bands from 442 nm – 1019 nm (CHRIS Mode 3 – Land Channels) have been obtained over desert grasslands in the JER since 2001, providing up to five angular looks in the space of a few minutes via tilting and nodding of the satellite. The launch did not provide the intended orbit and data sets with more than three looks with adequate ground overlap were not available until 2003. CHRIS image sets from 2003 and early 2004 were examined for overlap extent, cloud cover, quality and angular sampling and sets from June 30, August 22 and December 28, 2003 were selected. The images were extracted from the distribution files and co-located using sets of >30 ground control points based on features such as road intersections, pits, and swales. They were then resampled to a 25 m grid on a UTM map projection using a low-order polynomial transform with a nearest-neighbour rule and using a 1 m IKONOS panchromatic image as reference. This grid corresponds precisely with that used previously for BRDF modeling studies and ground data collection in the transition zone [7-8]. The absolute root mean square error (RMSE) at the control points was at all times < 3 m and the match between transformed and reference images was carefully checked across the images and not just at control point locations.

2.2 Data Set Angular Sampling and Selection

Image acquisition times were used with orbital ephemeris to obtain the satellite zenith and azimuth angles for each of the image sets. The angular sampling for several CHRIS overpasses is shown in Fig. 2. The June 30 data set provides only four overlapping images at a low solar zenith angle and at an angular sampling configuration far from the principal plane for high viewing zenith angles, which is less than optimal for characterizing the BRDF or BRDF model inversion. Further investigation therefore focused on the other two image sets. The August 22 set was acquired with a 26° solar zenith angle and provides one look close to the solar principal plane and three close to the perpendicular plane. The immediate utility of these data was considered likely to be restricted to calculation of simple angular ratio images, using the images providing the maximum angular separation (one image in the backscattering and one in the forward-scattering hemisphere).

Fig. 2. CHRIS angular sampling.

The December 28, 2003 data set provides an angular sampling which is considerably better than the other two, closer to the principal plane. It also provides a large overlap region with five looks. This data set was selected for BRDF model inversion experiments.
2.3 Surface Bidirectional Reflectance Assessment

Surface spectral reflectance estimates were calculated using 6S v4.2 [11] for all Mode 3 bands and assuming a desert aerosol type. Meteorological data indicated a visibility of 16.1 km for August and December overpasses, from which an optical thickness at 550 nm of 0.3 was estimated. The resulting reflectance spectra were examined by plotting against wavelength and normalized to the image viewing closest to nadir (Fig. 3). The estimates are reasonable – with the exception of the shorter, blue wavelengths which are affected importantly by scattering in the atmosphere – and demonstrate the large variability possible as a result of surface anisotropy. As expected, forward-scattering reflectance values are considerably lower than nadir values for all wavelengths as a result of the increased visibility of shadows cast by vegetation and soil roughness elements. Similarly, back-scattering reflectance values are higher than those close to nadir since a greater degree of shadow-hiding is in effect.

Fig. 3. Example CHRIS spectra for a bright target in the Jornada Experimental Range (a) as a function of wavelength, (b) normalized to the image viewing closest to nadir. The legend in (a) shows the scene code, viewing in the (F)orward or (B)ack-scattering hemisphere, and view zenith angle (°).

The surface reflectance estimates were also assessed against previous measurements on the ground and from the air. The comparisons for band 6 indicate that the instrument calibration and atmospheric correction procedures did not introduce error of an important magnitude into the data set (Fig. 4).

Fig. 4. CHRIS Band 6 (631 nm) for sparse and dense plots in the JORNEX transition site for Solar Zenith Angles (SZA) of 26° and 57°. The ground measure was taken over sand from an SE590 radiometer [5]. The air measure was acquired by a calibrated DuncanTech multispectral digital camera [8].

2.4 BRDF Model Inversions

Multi-angle images from the December 28, 2003 data set were used to adjust the isotropic-LiSparse-RossThin and isotropic-LiSparse-RossThick kernel-driven models [12] for the red and near-infrared wavelength regions using the 631 nm and 742 nm bands (separately). Inversions were effected on a location-by-location basis using proprietary code together with a version of the AMBRALS algorithm used for the MODIS BRDF/Albedo product. Only the sub-region where at least four angular observations were available was considered: this corresponds to 125,928 inversion problems. The retrieved red channel geometric and near-infrared volume scattering kernel weights were used to calculate a structural scattering index after [13].

The non-linear simple geometric model (SGM) [7-10] was inverted for various combinations of structural parameters – mean plant density, radius and height; and leaf area – by means of an iterative direct search optimization code [14]. As with kernel-driven models, the SGM assumes potential contributions from both geometric-optical and volume scattering phenomena and is formulated as (Eq. 1):
The inversion scheme allows for retrieval of one or more adjustable parameters simultaneously and the inversions can be either unconstrained or constrained so that solutions tend to avoid setting negative mean plant height or width or (model-calculated) fractional cover to obtain a good fit. Inversions can also be interactive: in this scheme the model is inverted for the most reliably-retrieved parameter and the retrieved values are used on the second run to obtain the second most reliably-retrieved parameter, and so on for subsequent parameters. This paper reports only on the results of inversions where simultaneous retrievals were effected with constraints imposed by dramatically raising RMSE if height > 4 m, LAI < 0, fractional cover > 0.9, plant density <= 0 or plant width <= 0. In addition inversions were restricted to using only the 631 nm band images to adjust the SGM. This is because in these wavelengths absorption by plant photosynthetic materials and pigments is maximal (and so contrast between soil and vegetation is maximal) and the single scattering approximation is more valid than in the near infra-red. This is corroborated in [18] which asserts that the wavelength should be chosen to maximize the reflectance / absorption contrast between vertically clumped elements and the background. Furthermore, [6] points out that the linear mixture assumption underlying geometric-optical models is more valid for the red than near infra-red wavelengths. Note that other research groups looking at inversion of BRDF models using CHRIS reflectance data (CLASSIC/University of Swansea/University College London) have opted for a sparse lookup table (LUT) inversion approach [19]; the use of a more traditional numerical optimization code here will provide results valuable for comparative purposes.

3. RESULTS AND DISCUSSION

3.1 Angular Ratio Images

The image of the ratio of forward- to back-scattering images from the August 22 data set highlights regions with very distinctive canopy architectures and community types. This scene was acquired in the middle of the wet season, with green leaves on most shrubs and some green-up of grasses and forbs. Fig. 5 (a) is a false colour composite showing areas of remnant grama grass in dark tones and aeolian deposition in blue-white tones. Comparisons with 1 m panchromatic IKONOS imagery show that in general, areas with smaller shrubs and a greater vegetation understory cover appear darker in the ratio image, while bright areas in the ratio image correspond to large plant structures such as honey mesquite over brighter backgrounds (i.e., more sparsely vegetated understory). In these circumstances the geometric angular signal is greatest as bright exposed soil – rather than covered understory – is shaded by the larger plant overstorey. The angular ratio image appears to show a greater response to plant size than to understory cover, since mean plant size is determined by the number of smaller plants: in swales (depressions which collect run-off, allowing greater vegetation development, usually including both shrubs and a relatively dense understory – is shaded by the larger plant overstorey. The angular ratio image appears to show a greater response to plant size than to understory cover, since mean plant size is determined by the number of smaller plants: in swales (depressions which collect run-off, allowing greater vegetation development, usually including both shrubs and a relatively dense understory – is shaded by the larger plant overstorey. The angular ratio image appears to show a greater response to plant size than to understory cover, since mean plant size is determined by the number of smaller plants: in swales (depressions which collect run-off, allowing greater vegetation development, usually including both shrubs and a relatively dense understory – is shaded by the larger plant overstorey.

\[
R = G_{\text{Walthall}}(i, v, j) \cdot k_G(i, v, j) + C_{\text{Ross}}(i, v, j) \cdot k_C(i, v, j)
\]
A closer examination of the data for the brightest feature in the image at the centre (Fig. 5 (b)) shows that this corresponds to large mesquite plants on a sparse, bright background just to the south-east of a swale with a more dense understorey and a smaller mean plant size (Fig. 6 (a)). Several large swales of > 50 m in extent are clearly visible in the IKONOS image in Fig. 6 (b), although the area of larger shrubs on a more sparse understorey is less obvious. Careful inspection of the images shows that the relationship holds although it has not yet been quantified.

3.2 Linear BRDF Model Inversion and SSI

The results of the Li-Ross model inversions were similar for both models (using Ross-Thick and Ross-Thin kernels) and for both wavelengths: for the vast majority of inversions, the RMSE values obtained were < 0.025. As usual with these models, the retrieved isotropic and geometric kernel weights are less noisy than the volume scattering kernel weight.

Recent research using MODIS data reported in [13] found a good relationship between a structural scattering index (SSI), defined as the logarithm of the ratio of the near-infrared (NIR) wavelength volume scattering kernel weight to the red wavelength geometric scattering kernel weight. Although this relationship is based partly on theoretical considerations and partly on observations of the relation with the Normalized Difference Vegetation Index (NDVI) for a very broad range of land cover classes, it is worth investigating its applicability with CHRIS data over desert grasslands in the JER.
The SSI map for this CHRIS scene is shown in Fig. 8 (a). A strong relation is seen between cover and the index, with very high values (in red) corresponding to very bright surfaces with a very high proportion of exposed soil (Fig. 8 (b)). Areas which appear darker in the false colour composite have higher vegetation cover but have a lower SSI value. Inspection of isolated clusters of non-negative SSI values such as that seen in Fig. 8 (c) with the high resolution panchromatic imagery again shows the inverse relation between SSI and vegetation abundance. The relation holds across the scene and the SSI is also affected rather strongly by the angular sampling and the calibration artifacts (striping) apparent in this CHRIS data set. This result was unanticipated; it is possible that in this arid environment with such sparse vegetation and NIR-bright soils, there is insufficient information available from the estimate of volume scattering in the NIR provided by the kernel weight, which is also generally considered to be more noisy than the geometric-optical kernel weight.

3.3 Inversion Experiments with the SGM

The main foci of interest with respect to the inversion of the non-linear SGM are the model fits to observations, the (absolute) value distributions of the retrieved parameters, and the spatial distributions of these parameters. The major questions surround whether the retrieved values are reasonable and whether their spatial distributions are meaningful.

SGM fits to observations were very good for all inversion attempts, with modal values of RMSE of $< 0.01$ and effective maxima of $< 0.03$, at histogram tails, $n = 125,928$. The retrieved parameter value distributions differed somewhat according to the number of free parameters but mean canopy plant density, plant width...
and leaf area index were generally estimated in ranges of values which are reasonable in terms of magnitude (Table I). Note that the leaf area index is an effective parameter and that these statistics are for the entire imaged area where at least four and a maximum of five angular looks were available.

Table 1. SGM Inversion Statistics

<table>
<thead>
<tr>
<th>Run</th>
<th>Parameter</th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>Mode</th>
<th>Std. Dev.</th>
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<td>0.00</td>
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<tr>
<td>1</td>
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<td>0.27</td>
<td>0.30</td>
<td>0.16</td>
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<tr>
<td>1</td>
<td>RMSE</td>
<td>0.10</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>2</td>
<td>GLAI</td>
<td>8.79</td>
<td>0.00</td>
<td>4.03</td>
<td>0.00</td>
<td>3.10</td>
</tr>
<tr>
<td>2</td>
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</tr>
<tr>
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<td>0.01</td>
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<tr>
<td>3</td>
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<td>-0.03</td>
<td>4.10</td>
<td>-0.03</td>
<td>3.14</td>
</tr>
<tr>
<td>3</td>
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<tr>
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<tr>
<td>3</td>
<td>RMSE</td>
<td>0.08</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Note: values shown as zero are > 0.0. GLAI is green leaf area index. Density is the number of plants per m² of a given mean size, crown oblateness and height.

Negative values were retrieved for all three parameters in spite of the dissuasion provided by spikes in the error hyper-surface. There is a tendency for density and width to both be retrieved as negative – and unphysical – values for areas where vegetation is extremely sparse. Width was retrieved less reliably than density. Green leaf area index showed the greatest variability with a standard deviation of > 3.0; this is probably owing to the minimal importance of this parameter in these desert grasslands, particularly in December (the middle of the dry season).

The spatial distributions of retrieved parameters are interesting because they do not match that of NDVI from a wet season IKONOS acquisition (Fig. 9(d)). The NDVI image shows broad trends in vegetation cover, with higher values corresponding to the black grama grassland in the SW quadrant, towards the shrub-dominated areas in the NE (an area down-slope which receives greater runoff), and for isolated swales and small playas. The retrieved plant density and width distributions correspond well to what is observed in high resolution IKONOS 1 m and Quickbird 0.6 m panchromatic images: lower density and width are associated with brighter soil areas, while higher density and width is associated with denser grass areas. The relationship is better for lower density sites with bright soil; it does not hold as well for dark swale sites where mesquite is dense, but the soil is not very bright. However, these are isolated communities. The different angular regimes – with either four or five looks – are not apparent in the inversion results for plant density and width but become more obvious where leaf area index is left as a free parameter (Fig. 9(b) and (c)).

Fig. 9. (a) December 28, 2003 spatial SGM model inversion results (unconstrained) as RGB image composites: (a) for density and width (b) LAI (R) and density (G and B), (c) LAI (R), density (G) and width (B) (d) IKONOS 4m NDVI image (July 2000; white = high). See also Fig. 8(b).
4. CONCLUSIONS

This paper has reported on a variety of efforts to determine the physical structure and composition of desert grasslands by exploiting the angular signature from CHRIS on Proba. The simplest metric, a ratio of forward- to back-scattering spectral reflectance, was shown to bear an important relation to mean plant size, although this was not quantified in this study and further efforts will be necessary to see whether the relation can be well calibrated. The structural scattering index developed in [13] and which has shown promise for determination of canopy structure for a wide range of broad cover types produced ambiguous results for these desert grasslands. This may be because of the high proportion of exposed soil and / or variations in understorey density in this arid environment, or because differences in canopy structure are more subtle. It could also be owing to the fixed viewing angles of CHRIS on Proba and the very small range of solar zenith angles; the linear, semi-empirical, kernel-driven BRDF models are known to be sensitive to angular sampling, and in particular the range of solar as well as viewing zenith angles. The SGM inversion experiments resulted in low RMSE values and meaningful spatial distributions, although parameter values were not always reasonable (i.e., sometimes negative). This may again be in part because the number and distribution of the angular samples is limited for BRDF model inversions: the view azimuth angles are not always close to the solar principal plane – where reflectance anisotropy is at a maximum for most wavelengths in the visible and near-infrared – in both forward and backscattering directions. Furthermore, there is only a single solar zenith angle for each set of four or five multi-angle images. This is important because the BRDF is a three-space, depending on view and solar zenith and relative azimuth angles. It is hoped that this may be mitigated in the future by exploiting the cross-track pointing ability of the Proba satellite and by using data acquired within one to two weeks on different overpasses. The initial plans for the exploitation of CHRIS on Proba included use of the platform’s agility to provide cross-track sampling [20]. Future work will be aimed at quantifying the relations found here, comparing these results with other approaches to derive useful multi-angle metrics [21], examining the utility of CHRIS data in differentiating variations in canopy structure and composition within the transition site, extending the SGM to include CHRIS reflectance data in several wavelength regions; and inversion of other BRDF models.

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FIELD GONIOMETER SYSTEM FOR ACCOMPANYING DIRECTIONAL MEASUREMENTS

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ABSTRACT

Field measurements with the “Mobile Unit for Field Spectroradiometric Measurements” (MUFSPEM) accompanying the CHRIS/Proba data have been planned for 2002 at the core test site Gilching. The experiment was cancelled as while the instability of parameter extraction in the daily cycle by applying ProSail inversion algorithms did not satisfy our expectations. To eliminate as much error sources as possible a new system was designed and constructed in 2003, working according to the goniometer principle, but allowing the measurements from 10m above the canopy in the 400 – 2200 nm range. Mounted on the top of a 4WD vehicle the change of position is very fast. Delays in construction progress but component delivery prohibited the introduction of the system during the 2003 vegetation period. The system will be finished and free for application during the 2004 measurement season. Existing angular measurement systems are briefly reviewed, the developed new mobile field goniometer construction is presented and moot under discussion.

Keywords: field spectroscopy, field goniometer, BRDF, physical modeling, ProSail inversion.

1. BACKGROUND AND MOTIVATION

At the time, we handed in our proposals we have been involved in precision farming research activities [1]. The general research concept matches very well the flow chart showed by the ESA AO 1-3381 in 1998 [2] (Fig. 1). Light blue lines mark areas and relations under present investigation. For the specific PF needs we are speaking about the integration of growth-, physical backscatter as well as inverted physical backscatter models.

There is a general consent about the necessity of radiometric calibration of airborne scanner data to normalize for sensor, atmospheric, topographic and cross track effects. Less investigated are diurnal effects due to changing illumination to stand structure geometries which are superimposing the before mentioned alterations. The presentation reports from a study conducted to quantify reflection changes for predefined view directions over the day and over the vegetation period of maize by the help of multidirectional field spectroscopic measurements. Morning, midday and afternoon measurement series are used to approximate the BRDF at different phenologic stages during the vegetation period 2000 and 2001 [3]. By the help of ProSail canopy parameters are calculated for five particular times of the day. The results show significant differences in parameter retrieval leading to the conclusion that both complexes, the phase angle related correction approaches as well as the adaptation of physical models to the specific crop structure should further be improved.

The modern agriculture allows the application of knowledge based interpretation rules. Grouped in
Remote sensing data are inverted, the calculated stand parameters are compared with the predictions of the growth models, application maps are delivered. “Real time” sensors are performing the “fine tuning” during application (“operational loop”, top of flow chart).

growing regions, which are defined by soil condition, microclimate, topographic units, seeding is distributed by regional seed centers (in Bavaria for example the BayWa or Raiffeisen companies). Sort variety for market production is restricted on some few for each crop type and growing region. The specific properties of these sorts are well known. About plots, managed with precision farming methods, a comprehensive database is established with information about the topographic parameters slope and aspect, soil parameter, yield of the last few years, calamity and management history, microclimate parameter, etc. (database of the mapping approach).

For the combined approach this information base needs to be extended by incorporating additional data layers. Two groups of unknown variables can be distinguished:

(i) the precipitation, temperature and fPAR history of the respective vegetation period, defined by parameters which are easy to sample by permanent meteorological ground stations, and

(ii) the distribution, magnitude and reason of growth differences on subplots. The second group of variables is not as easy to be parameterized, especially when fast and cost effective methods are demanded. It is a general consent that only remote sensing is appropriate to provide such information.

The problem to be solved at this point is that at least optical remote sensing data takes are dependent on cloud conditions. In Central Europe this is a severe restriction especially during the vegetative stage of crop development, from April to June, the most important period for fertilization. It can not been foreseen at which growth stage remotely sensed data are available. This situation leads to the need to introduce vegetation growth models into the evaluation chain. The precondition is that the basic variables and parameters for running the growth models are available in the plot related databases. Implemented in crop and variety adopted growth models, the expectations on the phenologic stage and physiologic status needed for the detailed management plan can be calculated taking into account growth differences on subplots. The requirements on a specific data take period are now less strict. Each remote sensing data set registered during the ongoing vegetation period can be used to calibrate the growth models.

So far the theory!

For developing the operational chain first the adapted growth models have to be related to “physical models of canopy reflectance” of the respective crop. For the envisaged precision farming application especially the inversion of the physical models is of relevance. On behalf of the inversion results, bio-geo-physical parameters of the crop under investigation can be derived from remote sensing data for each observation to illumination situation at any time of the growing period. In the final step, the retrieved parameters are used to calibrate the growth models according to the present growth situation. This is the key step for the elaboration of the application maps needed for fertilizer distribution or irrigation control.

Implemented on the bulldog mounted field computer this “a priori” information can directly be used for fertilization or irrigation (improving the “mapping approach”). Further developed to the “real-time approach with map overlay” the application maps should be fine tuned by the signal received by the real-time sensors, taking into account the recent progresses in canopy development and the site specific conditions. The abusive application of fertilizer on subplots with a limited field capacity and a reduced growth potential is expected to be avoided, preventing the environment and especially the ground water from pollution by fertilizers or pesticides. In case of irrigation application the control loop should identify areas with drought stress and restrict the irrigation on these areas. The combined approach is expected to gain essential improvements in front of the traditional precision farming practices.

The general evaluation chain of the combined approach is very close to the scheme proposed by ESA [2]. At the present nearby each of the described steps needs to be improved before an operational evaluation becomes possible. The approach is especially dependent on the accurate evaluation of remotely sensed data. To be successful, the evaluation chain must be able to detect small growth differences, compare them with the site specific stand conditions, and relate them with the phenologic and/or physiologic status of the crop or, in general with each other vegetated surface.
A basic need in the frame of this concept is the adaptation of backscatter models to the specific crops under investigation. For this purpose a spectral database should be established and based on high resolution field spectroradiometric data. In order to be prepared for all possible sun and observer positions, a calibration database should ideally be based on bidirectional reflection distribution functions (BRDFs) [4][5] covering all phenologic and physiologic stages of a crop.

There are two basic principles for angular measurements for BRDF approximation:

(i) the “goniometer” principle, where always the same section of a surface is observed by moving the measuring unit (European GOniometer facility (EGO) in Ispra at the Joint Research Center (JRC) [6] and the Field GOniometer System (FIGOS) of the Remote Sensing Laboratories (RSL) of the University of Zurich, Swiss [7]) and

(ii) a principle which is based on the assumption that the observed surface is homogeneous and it is sufficient to change the look angle observing different sections of the surface while the instrument is at the same place (PARABOLA (Portable Apparatus for Rapid Acquisition of Bidirectional Observations of Land and Atmosphere [8]), operated from NASA, GSFC, WAAC instrument (Wide Angle Airborne Camera), DLR Berlin [9]).

Evaluating these systems we came to the following conclusions:

- FIGOS is the perfect system for physical measurements but with restricted mobility and with an insufficient distance between instrument and surface so there are doubts weather the surface section is representative in case of high growing crops
- Parabola system is working very fast, the measurement height is sufficient but the instrument is restricted on some few spectral bands (650-670nm, 810-840nm, 1620-1690nm) [8]
- WAAC very fast, narrow spectral bands, measurement height sufficient but restricted on VIS/NIR [9]

To accomplish our objectives we decided to develop a platform according to our requirements: the Mobile Unit for Field Spectroradiometric Measurements (MUFSPEM) [10] was constructed and a special measurement strategy was developed.

The results presented in this paper focus on a detail of the evaluation chain: diurnal effects due to changing illumination to stand structure geometries which are superimposing the before mentioned alterations. A data set of maize at the phenologic stadium EC 67 is used to demonstrate the MUFSPEM data collection capability, to discuss the limitations of BRDF approximation from morning, midday and afternoon measurements and finally the retrieval of canopy parameter by the help of the ProSail physical model [11].

The evaluation of the results finally led to the decision to skip the CHRIS/Proba measurement campaign with MUFSPEM and to start the development of a new system.

For understanding the limitations of the solution a detailed description of MUFSPEM and the measurement strategy is given in the next chapter.

2. MATERIAL AND METHODS

6.1 Testsite

The core testsite covers the area of the research farm „Dürnast“ of the Agricultural Faculty of the TU of Munich in Freising /Weihenstephan at an average altitude of about 450 m above sea level. It lies between 11°37’30.4”E and 11°43’55.4”E longitude and 48°22’39.4”N and 48°25’58.9”N latitude. The main part of the test and surrounding area belongs to tertiary aged hills, formed from clastic sediments of the upper molassic series. Common soils in this area are sandy loams and loam with soilpoints from 34 to 67 on a scale from 0 (for an unproductive soil) to 100 (excellent productive soil).

6.2 Mobile Unit for Field Spectroradiometric Measurements (MUFSPEM)

The Mobile Unit for Field Spectroradiometric Measurements (MUFSPEM) (Fig. 3), presented during the outdoor exhibition session of the IWMMM-2 workshop in Ispra, 1999, has been used over the last three years to create a data base for BRDF approximation throughout the
Fig. 3: Scheme of min. measurement height required for a measurement section representative for the surface at an aperture of 10°

vegetation period of winter wheat, winter barley and maize (74, 51 & 67 available BRDF-hemispheres respectively).

The concept for the measurement arrangement was to be high, mobile and fast. The MUFSPEM allows registering in situ the multispectral and multiangular radiation from the vegetation canopy from a height of about 10 meters above the surface. The fibre optic of a GER 3700 instrument with 10° field of view is mounted on a computer controlled motor driven tripod head performing the measurements following the predefined sequence of look directions from an ASCII file. [11]

The set up of the whole construction lasts about 20 minutes for the two men team.

**Measurement strategy**

Angular backscattered reflectance measurements are time sensitive and time consuming. The measurement sequence suggested and adopted for the multiangular mode is described by the Fig. 4 and 5. One measurement cycle consists of about 25 measurements including the reference measurements and lasts about 17 minutes. The measurement sequence begins by placing MUFSPEM’s vehicle long axis parallel to the sun principal plane. Measurements take place every 45° in the azimuth direction (0°, 45°, 90°, 135° and 180°) and 15° in the zenith one (0°, 15°, 30°, 45° and 60°). For time saving reasons reference measurements are registered at the beginning and the end of a measurement sequence. The drawback of this measurement concept is that at every registration position the measurement covered a different section in the selected sub area (Fig. 4).

High and low useful water storage capacity (UWSC) sites were depicted in order to compare differing canopy vitality situations. Sub areas of these sites are considered to be homogeneous and are taken into account as a unity. Each of them was covered by a semi-hemisphere of measurements (including the sun principal plane). The two different UWSC sites in a plot

Fig. 4: Measurement sequence for BRDF approximation. Starting from the nadir looking position (reference and object measurement) the five azimuth directions for each of the four zenith angles are measured. The series is finished by a second nadir measurement pair.

Fig 5: measurement scheme for BRDF approximation showing the measurement positions over the daytime which are controlled by the principal plane.
are measured within an hour, so the comparability of the registered data is assured at an acceptable degree of reliability.

Due to the BRDF database requirements [12] the reflectance of the same plot site was registered at three different times in a day. The first measurement series was taken as early in the morning as sun position allows (<65° zenith angle) the second one as close to the highest sun position at noon as possible and the last one late in the afternoon.

Ancillary data, such as direct and diffuse light flux, and temperature are simultaneously registered by two neighboring meteorological stations. Soil and plant water potential data and samples for wet and dry biomass laboratory estimation are acquired at selected dates during the vegetative period. Furthermore, target pictures of the field of view are taken for laboratory evaluation of stereo stand parameters by photogrammetric methods. All this information should be used together with soil, crop yield, height, and topographic maps for the final evaluations.

The growth stage of crops are determined on behalf of the eucarpia scale (EC) used by the German Biological State Foundation for Agriculture and Forestry (Biologische Bundesanstalt fuer Land- und Forstwirtschaft, [13]). In this case a data set of maize at EC stage 67 is evaluated. During the measurements the sky was clear (direct to diffuse irradiation ratio: 2 - 3.5), and the visibility was extended up to 25km, the air temperature between 21.2°C and 23.8°C, and the wind velocity at the canopy height was low (< 1 m/sec).

Software
GER 3700 original software is used for the guidance of the spectroradiometer. The pan-tilt head is being driven by the prototype developer’s software [14]. Further data assessment is being carried out with a specific series of program routines (Hemispheric Reflectance Viewer, Parametric Goniometric Viewer), written for IDL5.0, by S. Sandmeier (NASA), U. Beisl (DLR) and Martin Habermayer(DLR). Statistic and logistic platforms, such as SPSS and Ms Excel, are also involved in the data assessment procedure.

Data processing
Registered data are sorted out in conjunction with the field protocol in a database. Calibration of the data is carried out using the Spectralon white panel reference measurements and interpolating between the beginning and end references of the hemispherical measurement sequence according to the registration times of each measurement file. Diagrams and plots, as well as statistics are used to establish the fluctuation of the reflectance over the day according to the sun versus registration geometry. The whole spectrum is assessed. However, preference and priority is given to wavelengths that are related better to canopy characteristics.

From the three measurement series taken over the daytime an approximation function is calculated for each look direction [15][16]. On base of this function each other look direction at sun positions between the morning and the afternoon measurement series can be simulated. For ProSail adaptation and inversion simulated data sets for five daytimes have been calculated (see Fig. 6).

3. RESULTS

The measurement arrangement proofed to be high, mobile and fast enough to measure from 10 m above the maize canopy and to change position as fast that the two different UWSC subplots could be measured within one hour.

The GER 3700 worked well in the VIS, NIR and SWIR 1 wavelength region. In the SWIR 2 region from about 2200nm to 2500 nm the SNR of the GER 3700 instrument was not satisfying, so we cannot trust this data. The reflectance differences with changing azimuth and zenith angle are in the range of 100 to 150%, the distribution show a strong wavelength (Fig. 6) and development stage dependency. All over this results confirm the results reported from other investigations [17][18][19][20].

The new aspects investigated in the frame of the IKB Dürnast project are...
the differences between high and low UWSC sub plots over the vegetation period and the diurnal changes due to changing illumination conditions. In both cases the data analysis indicated significant differences. For demonstration the diagrams in Fig. 7 are restricted on three wavelengths, at 550, 805 and 2185 nm in the NIR, and the principal plane, where the highest differences can be observed (y-axis). The values are calculated as difference of the nadir reference normalized reflection of the corresponding view direction from high and low UWSC sub plots. Changes over the day are shown in the three 3D diagrams of the morning, midday and afternoon series, the development due to phenologic changes from EC 30 to EC 70 is displayed along the x-axis. Green to dark blue colors indicate the reflectance of high UWSC subplot to be higher, brown to dark red the reflectance of the low UWSC. The smallest differences occur during the midday measurements. With increasing sun zenith angle the differences become more and more pronounced. Furthermore it is to be pointed out that at each daytime and throughout the vegetation period there are view directions where the lower UWSC and other where the higher UWSC subplot show higher reflectance values!

The next step was to run ProSail with these data sets. As described above five distinct sun zenith angle situations have been simulated dependent on the daytime of the first and last registered measurement series. In case of the maize example discussed in this paper the high UWSC subplot was first measured at a sun zenith angle of more than 57° and the last series was measured at around 48°, the low UWSC started at 46° and the last series was taken at a sun zenith angle of around 58°. The approximated BRDF from this measurement series allowed to deliver data for 55°, 45°, 35°, 35° and 45° for the high UWSC sub plot and for 45°, 35°, 35°, 45° and 55° for the low UWSC site. The two data sets at 35° sun zenith angle represent the situation before and after the highest sun position at midday. Soil, leaf mesophyll and leaf area to canopy height variables are assumed to be constant.

Fig. 8 is displaying the results of ProSail inversions. The Root Mean Square Error (RMSE) is giving an estimate about the reliability of the inversion process from the statistical/mathematical point of view. Values between 0.017 and 0.04 are good, between 0.04 and 0.07 still acceptable. As lower the sun elevation as higher the RMSE. Best results are retrieved for the midday measurement series at the highest sun elevation. According to the RMSE indicator the calculation for sun zenith angles higher 45° should not be used for parameter retrieval. Despite this fact the retrieved parameter show a clear trend which is similar for subplots with high and low UWSC. This let us decide to present and discuss these results as well.

Leaf area inclination (LAD) meaning the mean inclination angle of all leaves is calculated with values from 64° to 69° for the high UWSC site and from 43° to 77° for the low UWSC site. For the leaf area index (LAI) values from 1 to 6 (high UWSC) and 2 to 4 (low UWSC) are retrieved. LAI values increase from the morning to the afternoon. The parameter Chlorophyll (a+b) content (Cab), Canopy dry matter (Cm), Canopy water content (Cw) decrease from the morning to the afternoon calculations. At the low UWSC site Chlorophyll (a+b) content (Cab) from 97 to 23 [µg/cm²], Canopy dry matter (Cm) from 0,012 to 0,002 [g/cm²] and Canopy water content (Cw) from 0,037 to 0,008 [g/cm²] and at the high UWSC site Chlorophyll (a+b) content (Cab) from 101 to 47 [µg/cm²], Canopy dry matter (Cm) from 0,03 to 0,003 [g/cm²] and Canopy water content (Cw) from 0,045 to 0,017 [g/cm²].
4. INTERIM DISCUSSION

The results proved:
- the well known fact, that directional reflection is dependent on wavelength, illumination and observation direction (Fig. 6, 7)
- the highest differences occur in the wavelength region of absorbing pigments in the VIS (fig. 6)
- field capacity differences are displayed in the data and change over the vegetation period (fig. 7)
- that ProSail inversion results do not accurately retrieve the B-G-C-P parameter in case data are registered under different illumination and observation conditions! (fig.8)

Especially the last result has drawbacks on our general concept of growth and physical backscatter model driven vegetation assessments. All measurements representing one development stage are expected to deliver the same or nearly the same parameter values. One may concede some slight differences in some of the parameters which are explained by diurnal physiological cycles of the canopy, e.g. Cw or LAD, but these differences should not exceed the 5% limit. The reason for the observed differences of up to the factor 10 (Cm for the high UWSC site) have to be of other origin. Under discussion is the measurement strategy but the ProSail model as well.

Measurement strategy: The applied measurement strategy was developed to unravel the anisotropy behaviour of crops using field spectroradiometric measurements. Time saving reasons, the mobility requirement, hardware, and budget limitations force to compromises which led inevitably to simplify the measurement scheme taking some assumptions:

- The Helmholtz reciprocity theorem is supposed to be valid for the undertaken measurements, since neither fluorescence nor the light polarisation plane is under investigation [21].
- The arrangement is delivering measurements which are acceptable from the physical point of view, but the assumption is not absolutely true. Compared to the other error sources the errors due to this assumption are small.
- The backscatter characteristic right and left of the principal plane is treated as symmetrical.
- Measurements can be restricted on one part of the hemisphere which is a time saving assumption and allowed to simplify the ladder construction. In reality such a situation is only exceptionally to be found and may lead to significant errors, especially in case special conditions occur, like wind aligned ears [23], with heliotrope vegetation, etc.
- The whole measurement area is homogeneous. In such case not the observation position (FIGOS measurement strategy [7]), but the measured spot of the sub area is changed (Parabola, WAAC concept [8][9]). Taking into account that the area, which is supposed to be homogeneous has a magnitude of 240-485m² (crop and observation height depended), it could be criticised that this area is most possibly including heterogeneities due to differences in plant physiology or the local geomorphology. On the other hand, taking into consideration that the fertiliser application raster cell has a minimum of 225m² at the present or that the average spatial satellite image resolution of the Landsat generation (Landsat TM and ETM+, Spot, IRS, etc.) lies at about 400m², it could be conceded that the error
potential is kept under acceptable proportions. Nevertheless the occurring errors may be of a magnitude, which do not allow deriving general valuable rules as required for optimizing physical models.

Another often asked question is why we decided to measure first the different azimuth directions at constant zenith angles and not one azimuth plane at the established zenith angles like it is done from systems like Chris/Proba or MISR. The reason was that stereo data sets of satellite systems like MOMS-02, Spot 6 or ALOS, of airborne systems like the HRSC camera but of the Hydro-N [23] sensor as well are operating with predefined zenith angles. For normalizing such data sets it was considered more important in a disturbed measurement sequence to have at least complete hemispherical values for one zenith angle than to have a complete zenith sequence for an azimuth angle.

A next weak point of the measurement arrangement was that it was not possible to measure the different sort, variety and management type sample plots installed by the partners of the IKB Dürnast project for phenologic/physiologic experiments [1]. These plots have been systematically measured by traditional laboratory methods. The sample plots, being of a size of 5 * 2.5m can only be measured by a goniometer like measurement arrangement.

On the other hand, the measurement series performed and the inversion results retrieved show a logical trend. The values for the low UWSC sub plot are indicating a reduced vitality compared to the high UWSC test site, the trend is constant increasing or decreasing and similar for both subplots. This results are similar to the results of [3] obtained by analyzing the behaviors of two wheat subplots of high and low UWSC over the vegetation periods 2000 and 2001.

ProSail inversion requires a set of additional external information and is based on functions, which relate the measured reflection to the canopy parameters to be retrieved. Error sources may be the accuracy of the input variables, e.g. the BRDF of the soil which is dependent on the micro surface, the mineral composition but on the wetness stage and under story vegetation as well, changing atmospheric conditions, etc.. The other, and regarding the magnitude of the observed errors in the diurnal comparison probably most sever, error source is the insufficient adaptation of the functions and look up tables needed to relate the registered signal and the canopy parameters. A major problem in this case is the accuracy of traditional sampling methods. Experiences in the frame of the IKB Dürnast project with state of the art sampling methods proofed, that the variability is in the range of 20%!! The variability of the same parameter retrieved from field spectroscopy was in the range of less than 10% [24].

5. RESULTING CONCLUSIONS
The working hypothesis is basically verified:
- There exist differences in the anisotropy behaviour of the canopy reflectance at different UWSC sites in a plot.
- The fluctuation of this behaviour between the high and low UWSC sites in a plot for the investigated crops and growth stages can be registered and sampled in BRDF databases.
- Variables that influence the registered reflectance, such as the sun zenith and azimuth angle, the registration geometry, the row alignment, the topography, as well as the atmosphere interference need to be further investigated and the degree of their contribution to the angular spectral response of the canopy to be estimated. Correlations should be established.

The major conclusion from the four year research work are that it is inevitably to continue, more, to increase the efforts for adaptation of physical models by field measurements. For this task it is necessary to improve ground sampling techniques and the measurement arrangement as well. The development of more precise ground sampling techniques (measurement accuracy, sampling design, etc.) is in the duty of the respective specialists. Our contribution to advances in field spectroscopy for BRDF approximation and physical model adaptation is the development of an improved measurement arrangement which is taking into account the experiences made in the IKB Dürnast project.

The drawback for the planned CHRIS/Proba supporting campaign was that it makes no sense to work with a system which we can not explain.

That for the campaign was cancelled and we started to construct a new system working according the goniometer principle.

6. THE “NEW” GONIOMETER SYSTEM

6.1 Goniometer like unit
The scheme of the “goniometer like” solution proposed to be developed is shown in Fig. 9. The same section of the surface is observed. Changes in area at increasing view zenith angle, which occur with “pure” goniometer systems, are partially compensated by the rotating arm with the entrance object optic and are of less than 20%. At the same time the distance from the optic to the surface is changing and is around 50% closer than in the nadir looking position.

The ASD Field Spec Pro FR instrument purchased proofed to be too heavy for the already developed system so the construction had to be changed.
Large sun zenith angle

A second head fixed at the upper bar for reference measurements

Fig. 9: Scheme of the measurement construction allowing registering multidirectional measurements following the goniometer principle. Changing the azimuth angle is possible by rotating around the vertical axis. Object and reference measurements are taken quasi simultaneously.

Different from this scheme the realized solution is using bifurcated fiber optic cables attached to the ASD Field Spec Pro FR instrument to take the measurements. The negative consequence of this compromise is the reduction of transmissivity for about 50% and the complete loss of signal at wavelength higher 2200nm. The positive one is the fact that both, the reference and the object are measured with the same detector set, facilitating the radiometric calibration of the system.

Fig. 10 shows the system at the 2nd assembly test in Iffeldorf, on the 1th of October 2003. The Goniometer system works with a Field Spec FR field spectroradiometer from ASD company covering the wavelength region from 400 to 2500 nm combined with a broadband (8 – 12.5 µm) thermal sensor (KT 15D) of the Heitronics company. The goniometer unit will be used to approximate the BRDF from an altitude of about 10m above the top of the canopy. In Tab. 1 the technical details are specified.

In the frame of the ongoing projects this system shall be used for BRDF approximations of grasslands (pasture and meadows), reed and different crops of the Waging Tachinger lake catchment, for supporting CHRIS/Proba sensor calibration by simultaneous measurements.

Fig. 11: Movements of the object measurement positioning arm of the goniometer-like field device for BRDF approximation. The slides show five positions from nadir view to 60° view zenith angle. The subsection of the canopy to be measured can be additional changed by rotating the device on the roof.

**Tab. 1: Technical specifications of the device**

<table>
<thead>
<tr>
<th>goniometer device:</th>
<th>height above canopy: 10m (ground: 10-12.5m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>azimuth/zenith positioning accuracy +/- 3° resp. +/- 2° (worst case)</td>
<td></td>
</tr>
<tr>
<td>azimuth angle range: 270°</td>
<td></td>
</tr>
<tr>
<td>zenith angle range: 0° to 70°</td>
<td></td>
</tr>
<tr>
<td>rotating assembly on the roof rack: 360°</td>
<td></td>
</tr>
<tr>
<td>mounting time 2 persons: appr. 1h</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Photogrammetric stereo device:</th>
<th>2 Canon G2 digital cameras</th>
</tr>
</thead>
<tbody>
<tr>
<td>base distance: 1m</td>
<td></td>
</tr>
<tr>
<td>height above canopy: 5m</td>
<td></td>
</tr>
<tr>
<td>software by Wilfried Linder based on BLUH and LISA</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detectors:</th>
<th>ASD Field Spec FR (350 – 2500nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bifurcated fiber cable for alternate object/ reference measurement</td>
<td></td>
</tr>
<tr>
<td>Heitronics KT 15D 8-14µm</td>
<td></td>
</tr>
</tbody>
</table>
Not finally solved is the problem of the shutter, needed to alternatively close the object or the reference optic end of the fiber cable. A mechanical solution is under development and will hopefully be operational end of May.

Other changes compared to the MUFSPEM measurement system is concerning the sequence of measurements and the positions to be measured. The change of view zenith angle being faster than of azimuth angle, the measurement sequence will now start with positioning the azimuth angle than performing the zenith angle measurements for half a hemisphere and than changing to the next azimuth position. The discussion on the establishment of the positions to be measured is still not finished. The points are whether it make sense to measure with a higher density around the hot spot position and to reduce or not at other positions as the results of [27][28] indicate and which is the best mesh for optimizing the BRDF approximation.

Due to the uncertainty with the shutter solution and until the final measurement sequence is not fixed the time period for one measurement series can not be given exactly at the present. A period of less than 20 minutes is envisaged and should be possible.

6.2 Field survey

The necessity to improve the accompanying measurements for the quantitative and qualitative description and parameter determination is a point which is recognized as a severe bottleneck for modelling but for interpreting results as well. We do not know any report addressing this special topic. During our work on divers projects [1][3][21][25][28][29] we learned that the parameter estimation by field surveying methods, the so called “ground truth”, is gaining errors of around 20%. In vegetation related disciplines like agriculture, forestry, biology, such errors are accepted as common for ground sampling methods. For remote sensing based assessments of parameter, which should be further used for decision making, e.g. in precision agriculture, forestry, environmental sciences, etc., or even in a case for developing and improving models, such an error is not acceptable. It is practically not possible to control the whole chain of a ground sampling process, which covers the steps from sample design, sample collection, sample transport, sample measurement in the laboratory (analysis) or in the field (number, position, etc.).

We tried at least to improve the assessment of parameter, which are required from backscatter physical models and are illumination and view geometry dependent. Of special interest was the assessment of the Leaf Angle Distribution (LAD), a parameter which is of high significance in crop status determination in precision farming and is influencing directly the angular signature of vegetation. State of the art determination is the rough estimate in three categories, from plano- to erectophile.

Fig. 12: Stereo pair imaged with two Canon G2 digital cameras from about 5 m above the canopy. The frame includes an area of 1m², is fixed in horizontal position and marks approx. the same area as measured by the goniometer system.

The solution under development is based on stereo photo pairs taken with two digital cameras (Canon G2) from a unit integrated in the goniometer device. Additionally to the well known nadir view photographs used to derive parameter like shaded, sunlit, mirrorlike fractions, ground coverage, soil fraction, etc. ([3][29] for stereoscopic analysis, the stereo pairs should deliver the LAD. An automatic extraction process was initially envisaged. Being a “multiple stories” problem standard photogrammetric packages, developed for digital surface model derivation, failed. Dr. Dr. Ing. W. Linder, from the IPI in Hannover, is developing a semi-automatised solution integrated in the software environment of the LISA and BLUH. The prototype proved to be able to deliver the parameter LAD, LAI (or better leaf total projected area) as well as fraction of sunlit, shaded, mirror like backscatter fraction, stand height, etc. Fig. 12 shows a stereo pair as imaged with the two Canon G2 digital cameras from about 5 m above the canopy. Fig. 13 is showing an “anaglyph” image of a stereo pair of a wheat canopy. With a
red/green eyeglass the 3D effect is visible. The parameter estimation is restricted on the 1m² area inside the horizontal adjusted frame which marks approximately the same area as measured by the goniometer system.

7. OUTLOOK
The described system will be operated to take systematic measurements for adapting backscatter models for specific vegetation surfaces, to relate growth with the corresponding physical backscatter models and so to contribute improving the reliability of remote sensing data evaluations. Our present interests are in nature close vegetation surfaces, - especially wetlands,- in agriculture and forestry.

Introducing and establishing remote sensing methods in operational application chains is the overall goal of our research activities.

8. ACKNOWLEDGMENTS
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DIRECTIONAL MEASUREMENTS FOR REED DIFFERENTIATION

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ABSTRACT

Chris/Proba water mode data were acquired from two test sites in the Danube Delta on the 27\textsuperscript{th} of September and on the 14\textsuperscript{th} of October 2003. The multispectral imaging capability of the system should be used for water content analysis and macrophyte abundance mapping. In the test images aquatic macrophytes already disappeared due to the late registration date. The existing data set is used to test the synergy between the so called “multispectral approach” evaluating the spectral information, and the “anisotropy approach”, which is exploring the backscatter differences between correspondent off-nadir view angles in the different spectral bands. An improvement in reed geno- and/or phenotype identification is expected, which in the field are mainly differentiated by morphological features. Preliminary results show a couple of features supporting the work hypothesis.

5 INTRODUCTION

Wetlands, being predominantly natural or semi-natural land cover types are in several cases subject of conservation or at least restrictions controlled by national or international treaties, conventions or directives like Ramsar, Natura 2000, UNESCO biosphere reserve, the water framework directive, etc. and should not change her character and/or function. Reed is a dominant species of wetlands and a sensitive indicator for disturbances of the natural balance. The problem addressed with our research may be fixed by some few words: invasion or uncontrolled expansion on the one hand side, but decline and dieback on the other hand. Both developments are associated with severe, partially irreversible disturbances of the affected ecosystems. In Northern America the haplotype M of common reed (Phragmites australis) is counted to the top ten of most invasive species. Haplotype M is on the way to substitute the native genotypes gaining substantial disturbances of wetland ecosystems in the US. In Europe reed populations of the prealpine lakes are diminishing whereas in the Masurian Lake District an ecologic balance disturbing expansion is to be observed. Additionally, predictions of climate change simulations let expect an expansion of Mediterranean reed types into Northern latitudes.

National programs in Europe try to stop the decrease of reed in the prealpine environment and to stop or at least to control the expansion in the Masurian Lake District. National programs in the US focus on identification of haplotype M populations, on concepts for the monitoring of the expansion of these populations and on the development of mitigation strategies. As most prospective strategy, the control by specialised bio-agents was identified.

All these tasks require a stable and reliable method for detection, inventory and monitoring of reed population dynamics. The areas affected but the dynamics of the observed phenomena exceed the possibilities of terrestrial surveys and direct the expectations toward RS based methods. The strategic objectives addressed by our research are:

- To develop and demonstrate a reed phenotype identification and status assessment prototype based of advanced remote sensing systems and data analysis software solutions.
- To develop an RS based monitoring prototype for invasion detection and mitigation measure success evaluation.

Recent projects on wetland monitoring by remote sensing in Upper Bavaria exploring Ikonos data sets ([1] finished end 2003) as well as HyMap/Rosis/HRSC data sets ([2] ongoing up to the end of 2005 [2]) gained promising results applying a strategy based on rule based classification routines incorporating existing information with object-oriented software [3][4]. The requirements on a reed geno- and/or phenotype identification prototype based on state of the art remote sensing data are higher then for wetland types in general and need further development. Solely by considering all the specific features of the new generation of remote sensing instruments as they are high to very high spatial, spectral but radiometric resolution, it seems to be possible to solve the problems and to realise the envisaged semi- to automatic data evaluation chain for reed identification and status assessment.
2 BACKGROUND

2.1 Remote sensing technical background

Satellite remote sensing systems with ground resolutions in the 1m range are already operational. Systems equipped with multi- to hyperspectral sensors and multiangular look capabilities are scheduled to become operational in near future. The integration of more efficient scanners with better spectral resolution and almost simultaneous acquisition of on track panchromatic stereo-, multi- to hyperspectral data with different looking angles should provide the means for extrapolating essential parameters for vegetation analysis, expanding the present data evaluation options. CHRIS/Proba, developed as technology demonstrator, proved to be of high interest for the scientific community dealing with data analysis aspects as well. Basically three approaches can be tested with CHRIS/Proba data sets:

(i) The increase in information reliability by hyperspectral in front of multi-spectral data sets, subdivided in land and water applications
(ii) Investigation of the so called “anisotropy approach” [5] evaluating the angular signatures as derivable from the five view angles
(iii) The calculation and thematic implementation of pixel sharp and simultaneously registered surface models into thematic evaluations

The majority of the ongoing investigations are concerned with the hyperspectral aspect of CHRIS/Proba data evaluations. At least during the 2nd CHRIS/Proba workshop the “anisotropy approach” has been addressed solely by one forest application [6] and the research proposal presented in this paper. An attempt to calculate digital elevation models from multiangular CHRIS/Proba data was missed at all.

The focus of the planned research as described in this paper is on the synergistic use of spectral and angular signatures derived from the hyperspectral and multiangular CHRIS/Proba data sets. Data acquired simultaneously from different view angles provide information about the angular signature. In case of CHRIS/Proba data there are two sets of corresponding registration angles with opposite view directions, one with +/- 36° and the second with +/- 55°. First estimates on the potential of angular signature evaluations are reported from agriculture [5] and forestry [7]. The present investigations should give an estimate on the potential of the approach for reed identification and status assessment.

2.2 Thematic background

The trend in remote sensing data evaluation is oriented toward the retrieval of bio- chemo- and geo-physical parameters. Such parameters are used in modelling from the local scale, where identification and status assessment are in the focus, to matter and flux transport modelling at regional and global scales. In vegetation mapping the focus is on the derivation of parameter describing the canopy. Profiling methods for the identification and the assessment of the status of the canopy incorporated in expert systems are based on such parameter. In traditional spectral based remote sensing, canopy status is estimated by parameter like LAI, biomass, equivalent water thickness (EWT), etc., which are correlated to the spectral reflectance in different wavelength and are exploring the spectral signature. Using ratios of specific wavelength some of the radiometric effects can be eliminated. Unfortunately few of the common used indices, namely the normalised differentiated vegetation index (NDVI) and the simple ratio (SR) (both evaluating the differences between chlorophyll a, b absorption in the red and the high reflecting and the cell structure related signal in the near infrared region of the reflective spectra) are running into the saturation once canopy is closed and more than three to four leaf layers occur (LAI 3-4). Additionally, in vegetation oriented field spectroscopy it is a well known fact that a slight drought stress can lead to an accentuation of vitality indicators. This is related to leaf shrinking and connected effects like concentration of pigments and an increase of the shadow fraction, which can result in an increase in NIR reflectance and a decrease in VIS reflectance, both indicating a higher vitality and are leading to errors in status assessment, especially at the starting point of drought stress phases [8].

The deduction of bio- chemo- and geo-physical parameter from multi- to hyperspectral data is considered to be in general solved. In our overall research concept emphasis is there fore given to the description of data flow from the anisotropy information derived from angular signals to the step of structure parameter extraction on behalf of “inverted” physical models of surface backscattering (see[9]).

For vegetated surfaces the property of anisotropic backscattering is considered to be a function of plant architecture and stand structure. Both are changing with the phenologic phase and the physiologic condition. From ground observations in the agricultural domain it is well known, that already slight differences in crop development inside one plot can be detected on behalf of leaf position. For example cereals show a significant change in leaf alignment from erectophile towards planophile during the transition phase from the vegetative to the reproductive phase of plant development. Other crop types show specific reactions on water deficit. A typical reaction on drought stress for maize for example, is the rolling of leafs. Other crops react to drought with the reduction of turgor pressure and leaf shrivelling. This is a very significant reaction of sugar beet but also of rape and bean.

The backscatter characteristic as formalised in the Bidirectional Reflection Distribution Function (BRDF) proved to be very sensitive to structural changes of the canopy [10][11].
The reaction on reed reflectance on differing environmental conditions is still not investigated. The expectancies on evaluating angular data following the anisotropy approach are in the derivation of structure parameters, especially of the leaf angle distribution (LAD). LAD is a very sensitive parameter describing phenologic/physiologic differences inside the plot and one of the most important parameter in physical models. LAD can not be derived from nadir looking spectral data sets.

3 TEST SITE
The Danube Delta in Romania is one of the largest reed covered areas in the world with differing reed type populations from land-, aquatic and floating reed. In the Danube Delta our partner from National Danube Delta Institute (INDD) in Tulcea, Romania is involved in different national and international long term studies. Ground reference data on water quality, macrophytes, fisheries, reed stands as well as on restored polder areas are regularly collected with funds from the World Bank and the WWF. The centre co-ordinates of the "red" lake test site are 45,0833 N, 29,5833 E. The location is near the seaside, in the "brackish" zone of the delta (Fig. 1). The evaluated data is from 27th of September 2003, registered with the so called “water-mode” with 18 bands. The special goal for CHRIS/Preoba data analysis is oriented toward the evaluation synergies between the so called “multispectral-” and the “anisotropy- approach” as described by [5].

4 INVESTIGATION CONCEPT
The work hypothesis of our ongoing research is that angular signatures as retrieved by the multangular imaging capability of the CHIS/Preoba system, deliver information which may be related to morphological differences of reed stands. The differentiation of reed from other wetland types should be possible by spectral and textural analysis [12][13]. The differentiation of reed geno- and/or phenotypes solely by these signature types often fails due to the effect of spectral confusion and similar texture. For this case angular signatures may be a solution. In the field the differentiation of reed geno- and/or phenotypes is mainly based on morphological features. Angular signatures are controlled by plant architecture and canopy structure. Combining spectral and angular signatures we expect a better differentiation of reed geno- or at least phenotypes.

In the long term the identification of reed stands should be possible within automatic procedures evaluating multi- to hyperspectral multangular data by combining ancillary data, growth- and backscatter models in a joint model environment as described in [14] for precision agriculture applications. The presented work is part of that general investigation concept for bio-geo-chemophysical parameter extraction and status assessment, dealing with the satellite data, while the work presented in [9] is addressing the ground segment "laboratory loop".

Fig. 1: MOMS-2P mode D image showing the location of the CHRIS/Preba test site Danube Delta “Red Lake” (red frame) imaged on 27th of September 2003

"Multispectral approach": The multispectral imaging capability of the system should be used for water content analysis and macrophyte abundance mapping. From the approach we expect information on pigments, cell structure, water contents (chlorophyll, yellow matter, suspended matter, etc.)

"Anisotropy approach": multidirectional imaging capability should be used for deriving structural parameter from land vegetation. The general evaluation concept is shown in Fig. 2.

![Fig. 2: Principle of information extraction from nadir symmetric angular image pairs shown for the MOMS-02 stereo data registration geometry and the assumed backscatter function of a forward (green) and a backward (brown) scattering surface.](image-url)
5 PRELIMINARY RESULTS

The present level of data evaluation is a first “quick and dirty” estimate of the potential. No state of the art georectification and radiometric correction for sensor and atmospheric attenuations have been performed. The results show solely relative differences.

Fig. 3: Three different RGB composites giving an impression on the potential of spectral data evaluations in the domain of water content and vegetation analysis. No radiometric correction was applied.

Fig. 3 displays three different RGB composites giving an impression on the potential of spectral data evaluations in the domain of water content and vegetation analysis. As the striping proves no radiometric correction was applied, the only image enhancement step was a standard data stretch. At the present stage no water content analysis has been performed. It is envisaged to apply methods of water content analysis developed at the DLR [15][16] on the data sets of the 2004 vegetation period.

For a first “quantitative” comparison of surface types we processed the data with the object oriented image analysis system eCognition. The first step in an eCognition analysis is the segmentation of the data, which is resulting in homogeneous regions. A detailed description of the process is given in [17]. For each segment a data base is created with a couple of features describing spectral, textural, form parameter and neighbourhood relations. Evaluating the mean value of each segment we take the assumption that the segmentation is working like a filter process which is eliminating the striping effects in the data (Fig. 4). Based on this assumption we restricted the comparison on the mean values of the segments.

Fig. 4: Filter effect of the eCognition segmentation assumed to balance the disturbance of the mean object value by striping due to detector sensitivity differences. The left image shows the “original”, the right image the mean value per segment, both overlaid by segment polygons

Fig. 5: Composite of CHRIS bands 6/4/2 (RGB) of the “water” mode overlaid with the objects chosen for comparison

Fig. 5 is displaying a RGB composite of a subset with the location of the visually selected and labelled objects chosen for comparison: “deep” and “shallow” water and
three reed stand objects called land cover 1 to 3, all of them in the central part of the nadir scene. The objects used are the result of a second processing step which is merging segments according predefined criteria and that fore different in shape from the segments in Fig 4.

![Fig 6: Spectral signatures of the three reed stand land cover types displayed for the five view directions of the analysed CHRIS/Proba water mode data set.](image)

The diagrams in Fig. 6 show the mean value of the three land cover objects, Fig. 7 of the two water objects for the five view directions and eighteen spectral bands of the CHRIS/Proba water mode data set analysed.

Already on the first glimpse the different behaviour of land cover type 2 is to be observed. Especially the NIR response of the 55° fore and backward looking positions is different from the backscatter intensity as well as from the shape of the signature curves. Remarkably as well is the relatively high backscatter intensity of land cover type 3 in the NIR range of the forward looking 55° position.

In case of the two water objects “lake deep” as well as “lake shallow” for the nadir and 36° view directions shows the expected backscatter behaviour with higher values in the visible and continuously decreasing values toward longer wavelength in the NIR. Unexpected high are the NIR values for the 55° view angles of the shallow water object.

A more profound analysis of the spectral signatures in relation two view angels has not been performed.

The next step was to compare the anisotropy ratio [5] also called anisotropy quotient [11] for the five objects. The “anisotropy ratio” is calculated by dividing the signals of the corresponding view angles (-36°/+36°; -55°/+ 55°) and is considered to be a measure of the anisotropic behaviour. The “anisotropy ratio” was chosen instead of the difference index shown in Fig. 2 for the MOMS-02 geometries, as while no radiometric corrections have been done and the difference index is influenced by absolute signal heights.
Fig. 8: Spectral behaviour of the “anisotropy ratio” of the corresponding view angles (-36°/+36°; -55°/+ 55°) for the five objects under investigation displayed for the eighteen bands of the evaluated CHRIS/Proba data set.

Fig. 8 is displaying the values of these ratios for the eighteen bands of the data set and the 36° and 55° ratio.

The graph of the 36° ratio in the upper part of Fig.7 shows a clear differentiation of land and water objects. The 36° ratio of land objects is for all spectral bands higher than for water objects. Land cover 1 and 2 objects show a trend to increase from the VIS to the NIR and to decrease in the NIR with longer wavelength. The land cover 3 36° ratio is decreasing continuously similar to both water object 36° ratios, but at significantly higher ratio values.

The graph of the 55° ratio in the lower part of Fig.7 show a similar trend for land cover 1 and 3 as well as for “lake deep”. “Land cover 2” and “lake shallow” practically changed their behaviour: “lake shallow” signs similar to the “land cover” objects and “land cover 2” like “lake deep”.

6 CONCLUDING REMARKS

Due to the preliminary character of the research a discussion of the results seems not to be appropriate at this stage. Nevertheless we got some insight in data handling of CHRIS/Proba data and found some very interesting aspects worth to be investigated more in detail:

- The work hypothesis, that an improvement of reed geno- or at least phenotypes which differ from morphology is possible by combining spectral and angular signatures, was supported by the preliminary results.
- The use of angular signature for quantitative information is much more difficult than for spectral signatures and needs a further development of physical backscatter models for reed.
- The radiometric calibration for sensor but atmospheric and topographic effects needs to be adapted for off nadir view angles.
- The very sophisticated imaging geometry of CHRIS/Proba needs special georectification approaches. The simple image to image rectification does not work accurate enough.

All over it should be stated that the experimental CHRIS/Proba system offers a couple of very interesting research aspects which can not be investigated by operational space sensors. For a follow on experimental system we suggest an orbit which allows registering data at differing daytimes. This will broaden the experimental aspects on changes over the day and will definitively bring advantages in mountainous terrain where shading effects of a sun synchronous orbit may be reduced.

As recommendations for an operational follow on system we would suggest the following changes in system design, which we assume to increase the value of the data and facilitate the evaluation:

- The same pixel sizes for all view directions should be envisaged to allow a direct matching of nadir looking and off nadir looking bands and derived information at the highest possible spatial resolution.
- The different view angle due to the, admittedly, very sophisticated method to increase integration time, is introducing an error source very hardly to be considered during processing.

7 ACKNOWLEDGEMENTS

We wish to thanks ESA and the CHRIS/Proba technical and scientific team for providing us with data of the system and offering a forum for discussing the results.

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The CHRIS sensor, mounted on the PROBA satellite, is one of the first space-borne hyperspectral sensors offering high spatial resolution (18 m × 18 m). This, combined with the possibility of multi-temporal coverage, makes CHRIS-PROBA exceptionally well suited for lake water monitoring. MEMAMON is a project to monitor the water quality of lakes in the Mecklenburg (Germany) and Mazurian (Poland) lake districts. Both test sites contain a large number of lakes with high variability and different trophic states. This paper presents a study, which aims to determine the trophic parameter chlorophyll-a using hyperspectral CHRIS-PROBA data.

To investigate the seasonal dynamics of lakes, CHRIS-PROBA data were acquired in spring, summer and autumn 2002 and 2003. A first analysis of the data showed that CHRIS radiance data have strong artefacts in column direction. Standard destriping techniques were not sufficient to correct the data. Therefore, a novel iterative destriping technique was developed and successfully applied to CHRIS-PROBA data.

At the same time to the CHRIS-PROBA data recording, spectral field measurements and acquisition of in-situ data took place in several test-sites. Using these data, chlorophyll algorithms were developed and optimised to the spectral characteristics of the CHRIS sensor. Finally, seasonal maps of chlorophyll concentration are presented, derived from the corrected CHRIS-PROBA data.

Key words: water quality, monitoring, destriping, feature extraction, hyperspectral.

1. INTRODUCTION

The most common ecological problem of inland water bodies is the anthropogenic eutrophication. For this reason, the monitoring of lake water quality is specified and regulated by European (European Parliament 2000) and German water directives (LAWA-Arbeitskreis 1998). Especially CHRIS-PROBA, with its unique possibility of multi-temporal coverage, combined with high spectral and spatial resolution, has the potential for fulfilling the requirements of these environmental directives.

The trophic state is an important parameter to evaluate the water quality. One of the main parameters to determine the trophic state is chlorophyll-a in accordance to the German water directive (LAWA-Arbeitskreis 1998). Chlorophyll-a is a phytotpigment, which is present in all algae groups in marine and freshwater systems. The chlorophyll-a concentration is a good indicator for bioproduction in inland water bodies (DIN 38 412 - Part 16; Iizh et al. 2003).

Characterised on well-defined specific optical properties in the visible range, chlorophyll-a is suitable for the direct observation with optical instruments (Kirk 1994). In oligotrophic aquatic systems, chlorophyll-a is usually determined by the blue-green reflectance ratio such as the ratio at 440 and 550 nm (Gordon & Morel 1983). Otherwise, studies of productive marine and freshwater systems demonstrated that the back-reflected signal between wavelengths of about 670 and 740 nm allows an estimation of chlorophyll-a concentration (Ruddick et al. 2001; Thiemann 1999; Schalles et al. 1998; Yacobi et al. 1995; Gitelson 1993; Vos et al. 1986). Within this spectra range, chlorophyll information is not effected by dissolved organic matter and by other pigments.

The primary aim of this study is the development of chlorophyll-a algorithms, optimised to the spectral characteristics of the CHRIS sensor. Additionally, the characteristics of reflectance spectra during different seasons in the year will be investigated.
have various sizes and depths and are characterised by a wide range of trophic states. For example, the oligotrophic lake Wummsee has a very low chlorophyll content. It varies from 1 to 3 µg/l in summer. The Braminsee is a hypertrophic lake and shows very high chlorophyll-a concentrations, varying from 50 to over 100 µg/l. The other lakes in the test area show intermediate concentrations.

3. DATA BASE

During the last two years eight CHRIS-PROBA scenes were acquired. Table 1 shows the acquisition dates of different test sites and the corresponding cloud coverage. The satellite data of the Rheinsberg lake district reflect very well the seasonal lake dynamics of the water bodies. Additionally, the acquisition dates are similar to the seasonal dates of limnological field work in accordance to the German water directive (LAWA-Arbeitskreis 1998).

Table 1. Acquired CHRIS-PROBA data sets.

<table>
<thead>
<tr>
<th>Date</th>
<th>Test site</th>
<th>Cloud cover [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002/10/10</td>
<td>Mueritz</td>
<td>10</td>
</tr>
<tr>
<td>2003/08/09</td>
<td>Mueritz</td>
<td>2</td>
</tr>
<tr>
<td>2003/08/11</td>
<td>Mueritz</td>
<td>0</td>
</tr>
<tr>
<td>2003/04/23</td>
<td>Rheinsberg</td>
<td>0</td>
</tr>
<tr>
<td>2003/08/10</td>
<td>Rheinsberg</td>
<td>0</td>
</tr>
<tr>
<td>2003/09/26</td>
<td>Rheinsberg</td>
<td>0</td>
</tr>
<tr>
<td>2003/09/10</td>
<td>Mazurian</td>
<td>60</td>
</tr>
<tr>
<td>2003/09/11</td>
<td>Mazurian</td>
<td>65</td>
</tr>
</tbody>
</table>

Therefore, field expeditions for the acquisition of ground truth data took place at lake Mueritz as well as at the Rheinsberg and Mazurian lake district at the same time. The data include spectral measurements and sea truth data of chlorophyll-a (chl-a), suspended matter (SPM) and dissolved organic carbon (DOC). They show a wide variety of trophic states, from oligotrophic to hypertrophic, and different seasonal conditions (Tab. 2).

Table 2. Changes of chlorophyll-a concentration in selected lakes of the Rheinsberg lake district; Schwarzer See(1) and (2) are different lakes with the same name.

<table>
<thead>
<tr>
<th>Period</th>
<th>Water bodies</th>
<th>Chl-a [µg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>spring to summer</td>
<td>Rheinsberger See</td>
<td>25 → 16</td>
</tr>
<tr>
<td>spring to summer</td>
<td>Schwarzer See(1)</td>
<td>15 → 7</td>
</tr>
<tr>
<td>spring to summer</td>
<td>Zechliner See</td>
<td>3 → 5</td>
</tr>
<tr>
<td>summer to autumn</td>
<td>Schwarzer See(2)</td>
<td>14 → 17</td>
</tr>
<tr>
<td>summer to autumn</td>
<td>Zethner See</td>
<td>21 → 34</td>
</tr>
<tr>
<td>summer to autumn</td>
<td>Vilzsee</td>
<td>17 → 21</td>
</tr>
</tbody>
</table>

The above water measurements of the surface reflectance $R_+^+(\lambda)$ as well as the up-welling $L^+_\text{up}(\lambda)$ and the sky radiance $L^+_\text{sky}(\lambda)$ were performed with an ASD field spectrometer (FieldSpec Pro). The ASD radiometer has a spectral range between 350 and 2500 nm and a radiometric resolution of about 3 nm. During the spectral measurements the sensor was adjusted with observation angles of 45° in zenith and 135° in azimuth direction. This setting minimises the effect of reflected skylight (NASA 2000).

Parallel to the spectral field measurements, water samples were collected in the upper water layer for the analytical determination of chl-a, SPM and DOC. The chlorophyll concentration and the dissolved organic carbon concentration were analysed at the Institute of Applied Freshwater Ecology Brandenburg (IaGB), in accordance to the German norm standard (DIN 38 412 - Part 16). The suspended matter content was determined at the GeoForschungsZentrum (GFZ) using a gravimetric method. These sets of ground truth data are used in the following to extract the empirical relationships among the spectral measurements and water quality parameters.

4. PRE-PROCESSING

For the investigation of spatial and seasonal variations of lake properties, CHRIS-PROBA data has to be geocoded and transformed to reflectance values, allowing the comparison of different scenes. However, a first analysis of the radiance data showed strong stripes in along track direction. This noise...
has a magnitude of about 6 to 7 percent of the signal in some of the image bands. This means that the noise variance affects the accuracy of the classification results and therefore has to be corrected. Standard destriping techniques such as the FFT-filtering were not able to produce a reasonable result. Thus, a novel iterative destriping technique was developed which is able to deal with the specific sensor characteristics of CHRIS.

The analysis of noisy image columns showed that they can be corrected by a column and band specific gain $x_1$ and offset $x_0$:

$$g^* = x_0 + x_1 \cdot g$$  \hfill (1)

To calculate those values it is necessary to estimate the real grey value $g^*$ for each pixel in the column. This $g^*$ is calculated as the mean grey value of the adjacent pixels in row direction (Eq. 2). The filter has a size of 11 pixels.

$$\bar{g}_r = \frac{1}{11} \sum_{i=-5}^{5} g_{r+i}$$  \hfill (2)

However, two problems arise from this mean calculation which require adaptations in the software. First, grey value extrema (Fig. 3(b)) which have no or less similar pixels in their neighbourhood have to be treated separately. This extrema have a very strong effect on the calculation of the gain and offset. Therefore, an algorithm was included which selects only spectrally similar pixels from the window for the mean calculation. This linear function was defined by a empirical investigation analysing neighbouring pixels.

Second, columns without similar pixels in the window (Fig. 3(c)) have to be smoothed. Based on the total number of similar pixels within the column, an automatic differentiation takes place between sensor error and small linear objects, which may also be oriented in stripe direction. If the column is detected as a sensor artefact, 75% of the most similar pixels are used for the mean calculation. If not, the previous adaption is processed.

Based on the estimated $\bar{g}$ values, a least square estimation (Eq. 3) is used to calculate the gain and offset for each column and band.

$$\bar{g} = \begin{bmatrix} 1 & g_{r1} \\ 1 & g_{r2} \\ \vdots & \vdots \\ 1 & g_{rj} \end{bmatrix} \begin{bmatrix} x_0 \\ x_1 \end{bmatrix}$$

$$\bar{g} = A \bar{x}$$

$$\bar{x} = (A^T A)^{-1} A^T \bar{g}$$  \hfill (3)

Since the new grey values depend on their neighbourhood, this technique is applied iteratively (3-5 iteration) to allow for an overall good equalisation of the data.

Figure 2 presents some results of the gain and offset calculation. It can be observed, that both gain and offset values approach one respectively zero with increasing wavelengths. In the first bands, the modifications by the calculated gain and offset values are stronger than in last bands.

The successful radiometric enhancement is exemplarily shown in Figure 3 presenting subsets of the CHRIS-PROBA scene (April 2003, band 1). The striping effect is well eliminated. The magnitude of change is about 1 to 3% for most image columns, but can also reach values up to 35% in case of the strong artefacts. Furthermore, little point objects are well preserved (Fig. 3(e)). The described radiometric correction method was applied to all CHRIS data including all bands using identical thresholds in the algorithm.

After the radiometric correction, the CHRIS dataset with the best ground truth data was atmospherically corrected with the empirical line method. This correction was optimised for water. Input spectra were water reflectance spectra, which were resampled using the CHRIS specific spectral response functions. This master scene (CHRIS-PROBA scene 2003-08-10) was then used for the correction of all other scenes using corresponding image spectra.

The diagram (Fig. 4) shows some of the resulting CHRIS surface reflectance spectra. The water spectra show a high variability, which allows the extraction of different water parameters.
Figure 3. Radiometric enhancement of the CHRIS-PROBA scene, from April 23th 2003, spectral band 1; (a),(b),(c) before and (d),(e),(f) after the correction.

Figure 4. Selected reflectance spectra of the atmospherically corrected master scene; 1: Zethner See, 2: Vilzsee, 3: Schwarze See, 4: Zechliner See, 5: Zootzener See, 6: Wummsee.

With a set of ground control points (GCPs), taken from the topographic map 1:10000, the master scene was rectified to a Gauss Krueger map projection. To preserve the boundary shape of objects a cubic convolution resampling method was used. For a perfect overlap of the multi-temporal datasets, the remaining satellite images were registered to the master scene using a first degree polynomial transformation. The resulting root mean square errors are less than ±15 m.

5. AUTOMATED FEATURE EXTRACTION METHOD

Water reflectance spectra contain information about the concentration, as well as the composition of dissolved and suspended constituents in the water. This study is focused on spectral features of the reflectance spectra influenced by chlorophyll-a.

For the extraction of spectral features, which are linked to specific parameters, an automatic processing method was developed. This method correlates spectral information with selected ground truth parameters. For the water application, CHRIS reflectance spectra are correlated with chlorophyll concentration. For this purpose, reflectance spectra were extracted from the CHRIS-PROBA images at the location of the water samples. During the automatic feature extraction, the spectra are gradually scanned and selected features are calculated such as ratios, absorption depths, the position of minima and maxima as well as the area above or below a baseline. This feature values are then correlated with the specific parameter of interest. Finally, the program delivers the best correlation results for each type of feature.

6. RESULTS AND DISCUSSION

In the productive water bodies of the Rheinsberg lake district, with chlorophyll concentrations from 1 to over 100 µg/l, the reflectance peak in near infrared range (672-742 nm) was found to contain the best...
information for the estimation of chlorophyll concentration in CHRIS data. As an result of the automated feature extraction process, the area delimited by the reflectance curve and the baseline from 672-742 nm (CHRIS spectral bands 8-12) shows the best correlations results and the maximal sensitivity to changes in chlorophyll concentration (Fig. 5).

The described peak in the near infrared is an outcome of an interaction between strong absorption by chlorophyll and water, as well as scattering by algae cells and other sestonic matter (Thiemann 1999; Schalles et al. 1998; Yacobi et al. 1995; Gitelson 1993; Vos et al. 1986). The magnitude of the peak, as well as its position, depends strongly on chlorophyll concentration and scattering by all suspended matter. With increasing biomass, the height of the peak will simultaneously increase (Yacobi et al. 1995; Gitelson et al. 1994). Otherwise, the position of the peak shifts towards longer wavelengths, with increasing chlorophyll concentration (Schalles et al. 1998; Yacobi et al. 1995; Gitelson 1993; Vos et al. 1986). The lakes in the test area are characterised by phytoplankton and its detritus as main suspended matter components. Therefore, the peak in near infrared is correlated with the chlorophyll concentration via the relationship between chlorophyll and the suspended matter of the phytoplankton biomass.

Additionaly, there is a seasonal trend. The quantitative accuracy of the developed algorithm is limited by varying phytoplankton populations and changes of absorption and scattering processes by water constituents (Gitelson 1993). Figure 5 shows the strong differences between reflectance spectra, which were acquired in August and September. They represent spectra of the same lakes, but show a very different spectral behaviour related to the chlorophyll content. In summer, the magnitude of the entire reflectance spectra is higher than in autumn. This also applies to the peak in the near infrared. The reason is the seasonal lake dynamic, i.e. different phytoplankton compositions and amounts of degradation products (Schwoerbel 1994). Therefore, two specific algorithms for summer as well as for spring and autumn were developed to improve the quality of chlorophyll quantification.

Figure 6 shows the seasonal differences in the linear relationship between chlorophyll-a and the evaluated spectral features. The seasonal correlation of corresponding spectral features, against chlorophyll-a concentrations yielded high correlation coefficients (see Fig. 6 and Tab. 3). In Table 3, the regression coefficients are listed. Note, that the correlation coefficients of both regressions have similarly values.

On the basis of these two algorithms, seasonal maps of chlorophyll concentration were produced, derived from the CHRIS-PROBA data of April, August and September. Figure 7 shows subsets of the extracted chlorophyll maps. The calculated chlorophyll-a values are classified in accordance to the limnological classification of the German water directive (LAWA-Arbeitskreis 1998).
7. CONCLUSIONS

The primary aim of this study is the development of chlorophyll-a algorithms, optimised to the spectral characteristics of the CHRIS sensor. Especially for water applications, CHRIS-PROBA data have to be pre-processed to eliminate the strong stripes along track direction. To remove these noise variances, a novel iterative destriping technique was developed. The radiometrically corrected CHRIS-PROBA data have been atmospherically corrected with an empirical line method.

An automated feature extraction method was used for the development of chlorophyll-a algorithms from CHRIS-PROBA data. This method correlates spectral information with selected ground truth parameters. Reflectance spectra, which have been extracted from CHRIS-PROBA data and corresponding chlorophyll-a concentrations are the input parameters.

As a result of the automated feature extraction process, the area delimited by the reflectance curve and the baseline from 672 to 742 nm (CHRIS spectral bands 8-12) shows the best correlation results and the maximal sensitivity to changes in chlorophyll concentration. However, the quantitative accuracy is limited by varying phytoplankton compositions and varying amounts of degradation products. Therefore, two specific algorithms for summer as well as for spring and autumn have been developed to improve the quality of chlorophyll quantification. The correlation coefficients of both regressions show similar high values.

On the basis of these two algorithms, seasonal maps of chlorophyll concentration have been produced. This data show the spatial and the seasonal variations of chlorophyll.

Finally, it can be concluded, that CHRIS-PROBA has the potential for monitoring of the trophic parameter chlorophyll-a with high accuracy. Particularly, the high spatial resolution of the sensor allows the water monitoring of small lakes, such as in the Rheinsberg lake district.

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HIGH SPATIAL RESOLUTION REMOTE SENSING OF THE PLYMOUTH COASTAL WATERS.

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ABSTRACT

CHRIS-PROBA has the potential to provide high spatial resolution satellite ocean colour imagery that is applicable to the mapping of estuarine and coastal waters. This paper outlines an appropriate atmospheric correction technique and preliminary results from its application to an example 06 March 2003 image acquired using mode 2 (water bandset). The results are encouraging and demonstrate that CHRIS-PROBA has the required radiometric sensitivity.

Further research will be carried out in 2004, including the continuing goal of acquiring contemporaneous airborne data and in-situ measurements.

1. INTRODUCTION

Remote sensing is a tool that can provide an increasing number of environmental properties over a range of spatial and temporal ranges. It can be used both in its own right (e.g. mapping of foam lines formed by fronts) and as a means of extrapolating in-situ surface measurements in space and time (e.g. mapping of sediment concentrations). Most spaceborne ocean colour sensors are of use for studying the coastal environment, but are of a limited value for estuaries. However, Compact High Resolution Imaging Spectrometer (CHRIS)-PROBA offers observing capabilities appropriate to estuarine monitoring. It has a spatial resolution of 25 metres and provides multi-look angle imagery, which can be used to improve the atmospheric correction (AC).

In the United Kingdom (UK), the Rame Head water test site is in the South West (see Fig. 1). The site includes the turbid Case II (dominated by suspended particulate matter, SPM, and coloured dissolved organic material, CDOM) waters of the Tamar estuary, less turbid waters of Plymouth Sound and summer Case I waters (dominated by phytoplankton) of the English Channel. These waters have therefore been the focus of many studies using remote sensing, including sensors such as the Natural Environment Research Council (NERC) Compact Airborne Spectrographic Imager (CASI), which has 15 configurable wavebands in its spatial mode.

Table 1 shows the CHRIS-PROBA 2003 imagery acquisitions and attempts at contemporaneous airborne (CASI) and in-situ campaigns. Truly contemporaneous data collection was not achieved due to the juggling of logistics and cloud conditions, but the datasets provide valuable information with the future prospect of qualitative comparisons.

The uncorrected colour composite CASI imagery shown in Fig 2 is from April 2003 where four flightlines were flown over the same area, at height of 1 500 metres, to map changes in the turbidity throughout a tidal cycle. Sampling was carried out from a moored pontoon in the river at Calstock (Fig. 1) and included parameters such as reflectance, SPM and CDOM.
2. METHODOLOGY

A CASI atmospheric correction was developed [2] using the knowledge gained from the development and implementation of the SeaWIFS [3] and MERIS [4] processing code. This has been modified to take the CHRIS-PROBA imagery so that a preliminary validation of its ocean colour capabilities can be performed.

The AC takes the total sensor detected reflectance, $\rho_T(\lambda)$, and splits it into the total atmospheric path reflectance, $\rho_{atm}(\lambda)$, and desired water-leaving reflectance, $\rho_W(\lambda)$. Where $t(\lambda)$ is the diffuse transmittance.

$$\rho_T(\lambda) = \rho_{atm}(\lambda) + t(\lambda) \cdot \rho_W(\lambda)$$  \hspace{1cm} (1)

The atmospheric path reflectance is then split into the aerosol, $\rho_A(\lambda)$, and Rayleigh path reflectance, $\rho_R(\lambda)$, according to Eq. 2.

$$\rho_{atm}(\lambda) = \rho_A(\lambda) + \rho_R(\lambda)$$  \hspace{1cm} (2)

A non-water mask is then used to discard the land and cloud pixels. The mask is based on the threshold values at two near infrared (NIR) wavelengths [2]: wavebands 16 and 17 in Table 2. Any further computations are then only applied to the water pixels.

Table 2. CHRIS mode 2 water bands with the CASI bands indicated using an asterisk.

<table>
<thead>
<tr>
<th>Waveband</th>
<th>Application</th>
<th>Waveband</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>MERIS</td>
<td>(10)</td>
<td>MOS</td>
</tr>
<tr>
<td>405.6 - 415.2*</td>
<td></td>
<td>645.7 - 655.8*</td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td>CIMEL/MERIS</td>
<td>(11)</td>
<td>CIMEL/MERIS</td>
</tr>
<tr>
<td>438.0 - 446.8*</td>
<td></td>
<td>666.3 - 677.2*</td>
<td></td>
</tr>
<tr>
<td>(3)</td>
<td>MERIS</td>
<td>(12)</td>
<td>MERIS/FLH</td>
</tr>
<tr>
<td>485.6 - 494.8*</td>
<td></td>
<td>677.2 - 682.8</td>
<td></td>
</tr>
<tr>
<td>(4)</td>
<td>MERIS</td>
<td>(13)</td>
<td>MERIS/FLH</td>
</tr>
<tr>
<td>504.5 - 514.8*</td>
<td></td>
<td>682.8 - 688.5</td>
<td></td>
</tr>
<tr>
<td>(5)</td>
<td>MODIS</td>
<td>(14)</td>
<td>MERIS</td>
</tr>
<tr>
<td>525.6 - 534.2*</td>
<td></td>
<td>700.2 - 712.4*</td>
<td></td>
</tr>
<tr>
<td>(6)</td>
<td>MERIS</td>
<td>(15)</td>
<td>Red Tide Index (RTI)</td>
</tr>
<tr>
<td>556.1 - 566.3*</td>
<td></td>
<td>751.9 - 758.9</td>
<td></td>
</tr>
<tr>
<td>(7)</td>
<td>SPM/Bathymetry</td>
<td>(16)</td>
<td>MERIS</td>
</tr>
<tr>
<td>566.3 - 577.1*</td>
<td></td>
<td>773.4 - 788.4*</td>
<td></td>
</tr>
<tr>
<td>(8)</td>
<td>SPM/Bathymetry</td>
<td>(17)</td>
<td>CIMEL/MERIS</td>
</tr>
<tr>
<td>584.6 - 596.4*</td>
<td></td>
<td>863.1 - 881.3*</td>
<td></td>
</tr>
<tr>
<td>(9)</td>
<td>MERIS</td>
<td>(18)</td>
<td>CIMEL</td>
</tr>
<tr>
<td>617.5 - 626.6*</td>
<td></td>
<td>1002.7 - 1035.5</td>
<td></td>
</tr>
</tbody>
</table>
The Rayleigh scattering reflectance was computed using the well established theory [5]. At present the Rayleigh correction does not attempt to use actual meteorological values, but climatological values: atmospheric pressure of 1013.25 mbar; water vapour concentration of 2 g cm$^{-2}$; ozone concentration of 0.33 atm cm.

For the Case I assumption, the NIR water-leaving reflectance was assumed to be near zero [6], which is termed a Dark Pixel (DP) atmospheric correction. Eq. 1 can then be rewritten to give Eq. 3 when the Rayleigh reflectance is subtracted. The aerosol path reflectance can then be calculated for NIR wavelengths (greater than 700 nm) using an exponential relationship for the spectral behaviour of aerosol optical depth [7].

$$\rho_{tc}(\lambda > 700nm) = \rho_{a}(\lambda)$$

(3)

The Case II (or bright pixel, BP) atmospheric correction uses several sensor look-up-tables, which hold standard values such as the NIR inherent optical properties. The NIR water reflectance at a given wavelength is a function of the optical properties of seawater, the optically active water constituents and the solar and viewing geometry. The optical effects of CDOM and phytoplankton are assumed to be negligible in the NIR, which gives Eq. 4 [3].

$$\rho_{tc}(\lambda) = \rho_{t}(\lambda) - \rho_{w}(\lambda) = \rho_{a}(\lambda) \cdot f(\lambda, SPM, \theta, \beta, \phi)$$

(4)

Eq. 4 is then solved for the two NIR wavebands using a non-linear, least squares, Newton-Raphson minimisation. The SPM NIR reflectance is subtracted from the Rayleigh corrected reflectance values to give aerosol reflectance in the NIR. The DP atmospheric correction method is re-applied to extrapolate this NIR aerosol radiance to the visible bands.

3. RESULTS

The AC was carried out on an example CHRIS-PROBA image from the 06 March 2003 with a combination of wavebands 11, 6 and 3 used to produce colour composites. Fig. 3 shows the various stages of the AC as the imagery was processed, the final BP AC is not shown as it was very similar to Fig 3d. The uncorrected image shows cloud contamination and cloud shadows (Fig. 3a). Most of the cloud and land was successfully removed by the non-water mask (Fig. 3b), where black represents the masked pixels. However, the Rayleigh corrected image (Fig. 3c) still shows the influence of cloud shadow in the bottom left corner and just outside of the Plymouth Sound.

Fig. 3. CHRIS-PROBA imagery for the 06 March 2003. The coloured images represent composites of wavebands 11, 6 and 3 as red, green and blue.  
a) Uncorrected image  
b) Non-water mask  
c) Rayleigh corrected image  
d) Aerosol corrected image.
The aerosol (DP) corrected image (Fig 3c) shows over-correction of Case II pixels in the top left corner, due to the removal of too much reflectance since the water reflectance in the NIR was treated as atmospheric scattering. This can be corrected when a full atmospheric correction, with the BP method, is applied. The BP AC was switched on, but the AC process needs further tuning as several aspects (including the geometry) were roughly approximated for this preliminary analysis.

Further work will continue on the processing of the satellite (CHRIS-PROBA) and aircraft (CASI) imagery, and there will also be enhanced biological sampling as previous research has indicated a summer bloom in the upper reaches of the Tamar.

5. REFERENCES

1. Landmap Project. WWW site: http://www.landmap.ac.uk/


6. ACKNOWLEDGEMENTS

This work was supported by a European Marie Curie fellowship (Framework 5, EVK3-CT-2002-50012), NERC small grant (NER/B/S/2002/00555, PI Lavender) and the NERC Airborne Remote Sensing Facility. Research on the processing of Earth Observation imagery is more generally supported within the NERC Centre of Observation of Air-Sea Interactions and Fluxes (CASIX).
MAPPING OF CHLOROPHYLL AND SUSPENDED PARTICULATE MATTER MAPS FROM CHRIS IMAGERY OF THE OOSTENDE CORE SITE

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1. ABSTRACT

The image set created on 5 August 2003 by CHRIS/PROBA is analyzed to assess the feasibility of producing suspended particulate matter (SPM) and chlorophyll (CHL) maps. To produce these maps images are first destriped, atmospherically corrected and georeferenced. Once the data processing is finished, the results are compared with seaborne measurements and data products retrieved from other ocean colour sensors. The data processing with its associated problems, the comparison with seaborne and other data and the creation of SPM and CHL maps are described in this paper. Conclusions and recommendations are made in the context of considering CHRIS/PROBA as a model for the future generation of small ocean colour missions.

2. INTRODUCTION

Mapping of chlorophyll-a (CHL) concentration is required to assess the eutrophication of the Belgian waters [1, 2]. Further interest comes from marine scientists, for whom CHL maps would provide information on the marine ecosystem, and especially for ecosystem modelers who require data for model validation [2]. The interest in maps for Suspended Particulate Matter (SPM) concentrations in Belgian coastal waters is associated with the need to provide boundary, initial and validation data for sediment transport models [3].

While seaborne measurements of CHL and SPM provide high quality (low uncertainty) data for a limited number of locations, mapping of a large area is confounded by very sparse spatial coverage and, for highly dynamic tidal waters, by the asynchronicity of measurements. Satellite mapping offers the potential for covering large areas (+/- 13*13 km² in the case of CHRIS) at a “snapshot” moment with resolution of spatial variability down to tens of meters, thus revealing features associated with fine-scale bathymetry and river discharges.

The potential for mapping of SPM and CHL has already been demonstrated for SeaWiFS and MERIS and is under development for MODIS. CHRIS/PROBA must be considered as a relatively low budget technology-proving mission in comparison to these well-supported operational or pre-operational ocean colour sensors, which provide daily global coverage for a large user base. However, the interest in CHRIS/PROBA lies in a number of original technological features which may form the basis of a future generation of ocean colour sensors:

• Economic constraints are likely to lead over the next twenty years to preference for small satellites with a very limited number of sensors (e.g. one) facilitating system design and launch. In this sense PROBA is seen as a model for a new generation of small low-cost satellites with consequent challenges for system engineers and for product developers.

• The optical complexity of coastal and inland waters and their overlying atmosphere drives a need for much greater spectral resolution than is available on current ocean colour sensors, e.g. to separate phytoplankton absorption from coloured dissolved organic matter (CDOM) absorption or to perform accurate atmospheric correction for turbid waters. It is becoming clear that the future for coastal and inland waters is hyperspectral and CHRIS thus offers a first chance to test future algorithms.

• Pointability of the platform allows imaging of the same sea area from different angles, thus offering more information for use in correction of atmospheric and air-sea interface effects, as used by AATSR for sea surface temperature measurements. In a more general context pointable platforms offer

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Fig. 1: Oostende Core site

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28-30 April (ESA SP-578, July 2004)
the possibility of on-demand imaging for example in the case of special events, as used already for terrestrial applications in SPOT series.

- Finally, the high spatial resolution of CHRIS is more comparable to that of terrestrial sensors such as Landsat and SPOT than to that of ocean colour sensors (e.g. 1.1 km for SeaWiFS, 250m for MERIS) and offers the possibility of mapping much smaller features for example in nearshore, estuarine or inland waters.

These potential advantages of the CHRIS/PROBA system are discussed here in the framework of production of CHL and SPM maps for coastal waters as tested specifically for the Oostende core site (Fig. 1). CHRIS mode one produces imagery with a spatial resolution of 30*30m² and 62 spectral bands which cover wavelengths from 411 nm up to 997 nm.

The final objective is to assess the potential of multi-look angle hyperspectral imagery for SPM and CHL mapping. To reach this objective the raw CHRIS/PROBA images are processed and the detectability of SPM and CHL is investigated.

This paper describes the image processing steps, describes problems encountered and gives preliminary SPM and CHL maps.

Since the launch of CHRIS/PROBA, 10 datasets of the core site Oostende have been acquired (Table 1). In this paper only the dataset acquired on 5 August 2003 is considered in detail because this day was cloud free and simultaneous seaborne measurements are available.

Table 1: data acquisition at the Oostende core site

<table>
<thead>
<tr>
<th>Date</th>
<th>n° images</th>
<th>CHRIS data</th>
<th>Sea data</th>
</tr>
</thead>
<tbody>
<tr>
<td>21/06/2002</td>
<td>5</td>
<td>clouded</td>
<td>4 stations</td>
</tr>
<tr>
<td>26/07/2002</td>
<td>5</td>
<td>clouded</td>
<td>2 stations</td>
</tr>
<tr>
<td>05/03/2003</td>
<td>5</td>
<td>clouded</td>
<td>No</td>
</tr>
<tr>
<td>19/06/2003</td>
<td>5</td>
<td>clouded</td>
<td>3 stations</td>
</tr>
<tr>
<td>27/06/2003</td>
<td>4</td>
<td>clouded</td>
<td>3 stations</td>
</tr>
<tr>
<td>21/07/2003</td>
<td>3</td>
<td>partially clouded</td>
<td>No</td>
</tr>
<tr>
<td>05/08/2003</td>
<td>5</td>
<td>clear</td>
<td>2 stations</td>
</tr>
<tr>
<td>06/08/2003</td>
<td>5</td>
<td>partially clouded</td>
<td>3 stations</td>
</tr>
<tr>
<td>20/09/2003</td>
<td>5</td>
<td>clear</td>
<td>No</td>
</tr>
<tr>
<td>21/09/2003</td>
<td>3</td>
<td>clear</td>
<td>No</td>
</tr>
</tbody>
</table>

3. METHOD

The image processing can be subdivided into four steps: destriping, atmospheric correction, georeferencing and SPM/CHL retrieval. All the image processing is done with ENVI/IDL software version 4.0. CHRIS/PROBA data for water-leaving reflectance, SPM and CHL is then compared with seaborne data and with other sensors.

3.1 Destriping

All the retrieved data show “vertical lines” on the image (Fig.2). Each image has these vertical lines at the same pixels, suggesting a sensor problem. To minimize this problem a correction factor for each column is calculated, individually for each band and image.

The correction factors are based on a 5 column moving average. For each column (denoted i) and each band (denoted k) the column-average radiance (denoted L\(_{i,k}\)) is calculated for a block of water pixels (Fig.3). A correction factor (denoted C\(_{i,k}\)) is then calculated for each column by smoothing over 5 columns (Eq. 1):

\[
C_{i,k} = \frac{L_{i-2,k} + L_{i-1,k} + L_{i,k} + L_{i+1,k} + L_{i+2,k}}{5 \times L_{i,k}}
\] (1)

The variation of this correction factor over adjacent columns is about 1%.

3.2 Atmospheric correction

The top-of-the atmosphere radiance measured by CHRIS is composed of the atmospheric path-, sea-surface- and water-leaving radiances. The quantity of
interest for marine applications is the water-leaving reflectance.
Two approaches were tried for subtracting the atmospheric path and sea-surface reflectance from the top-of-atmosphere reflectance: a simple method based on the darkest pixel and an alternative method based on a radiative transfer model.

3.2.1 Darkest pixel correction
This is a very simple correction, based on 2 assumptions:
- The first assumption is that in the darkest water pixel of the image there is total light absorption i.e. this pixel represents black water and the light recorded for this pixel is equal to the atmospheric path radiance.
- Secondly it is assumed that the atmospheric path radiance is uniform all over the image.
The spectrum of the darkest water pixel (assumed to represent the atmosphere) is subtracted from the whole image. The darkest pixel is found by searching for the lowest values over water for all wavelengths. The pixel with the lowest value in most of the bands was selected as the darkest pixel.

3.2.2 Radiative transfer model
The darkest pixel method described above is useful for achieving preliminary results and assessing sensor performance. However, a more accurate atmospheric correction requires use of a radiative transfer model to assess contributions to top-of-atmosphere reflectance from water-leaving reflectance (attenuated by transmission from sea to sensor) and from scattering of light by atmospheric particles ("aerosol" reflectance) and air molecules ("Rayleigh" reflectance). The algorithm of Gordon and Wang [4] with non-zero NIR water-leaving reflectance is used. Sunlight is neglected here because only the viewing angle away from sun is considered (image with Fly By Zenith angle, FBZ = -36°) and whitecaps are neglected because the sea was flat on 5 August 2003. Rayleigh reflectance was removed using the pre-computed look-up table for the zenith and azimuth angles of the sun and the sensor. However, aerosol reflectance cannot be present be calculated using the near infrared spectrum because of excessive noise there.

3.3 Georeferencing
Georeferencing the CHRIS/PROBA satellite images is a major problem for marine sites because no georeferencing information is supplied with imagery and ground control points (GCP) cannot be identified at sea. The test site was chosen to contain some land for GCP identification. The image of 5 August with the best recognizable land is chosen as base image. On this image 5 GCPs are identified. The image is georeferenced by applying an image to map registration with 5 GCPs. After the registration, coordinates are inter- and extrapolated a rotation scaling translation transformation and nearest neighbour remapping.
This newly georeferenced image is used as the base map to georeference the other images from the 5 August set by an image to image registration.

3.4 Comparison with other data
3.4.1 Seaborne data
On 5 August 2003 seaborne measurements were made for two stations within the Oostende test site. The parameters measured are water-leaving reflectance, SPM and CHL. The water-leaving reflectance is measured by the TriOS instruments (fig. 4). This system comprises 3 sensors which are mounted on the bow of the ship at zenith angles of 0°, 140° and 40°, and measure respectively downwelling irradiance, water leaving reflectance and sky reflectance following the protocol used by MUMM for MERIS validation [5] based on the NASA protocols [6]. Water samples are collected simultaneously with TriOS measurements and analyzed for SPM and CHL (using the HPLC method) in the MUMM laboratory at Oostende. The positions and times of the measurements are given in table 2.

3.4.2 Satellite reflectance data
On 5 August 2003 there were overpasses from MERIS and SeaWiFS. These satellites sensors produce images all over the world. The analyzed MERIS and SeaWiFS images have respectively a resolution of 1.1 km and 1.2 km and a spectral resolution of 15 bands from 412 to 900 nm and 8 bands from 412 to 865 nm.

Table 2: Radiometric data acquired on 5 August 2003

<table>
<thead>
<tr>
<th>Sensor</th>
<th>UTC time</th>
<th>latitude</th>
<th>longitude</th>
<th>FBZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>TriOS/station 130</td>
<td>10:30</td>
<td>51.27</td>
<td>2.90</td>
<td></td>
</tr>
<tr>
<td>TriOS/station 230</td>
<td>11:16</td>
<td>51.31</td>
<td>2.84</td>
<td></td>
</tr>
<tr>
<td>CHRIS/image A</td>
<td>11:11:42</td>
<td>51.28</td>
<td>2.88</td>
<td>36°</td>
</tr>
<tr>
<td>CHRIS/image 9</td>
<td>11:12:31</td>
<td>51.28</td>
<td>2.88</td>
<td>0°</td>
</tr>
<tr>
<td>CHRIS/image B</td>
<td>11:13:20</td>
<td>51.28</td>
<td>2.88</td>
<td>-36°</td>
</tr>
<tr>
<td>MERIS</td>
<td>10:25:31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEAWIFS</td>
<td>13:02:39</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The spectra from the different sensors are compared at station 130 and station 230. Only the images with FBZ 36°, 0° and -36° are taken into consideration as the georeferencing from the other images is not accurate enough and station 130 falls out of the image.

### 3.5 Creation of suspended particulate matter maps (SPM) and chlorophyll-a (CHL) maps

After the image processing Eq.2 is used to transform CHRIS images from reflectance into reflectance [7].

$$\rho_w = \frac{L_w \pi}{E_d}$$ (2)

where $$\rho_w$$ = water leaving reflectance, $$L_w$$ = above water leaving reflectance and $$E_d$$ = above water downwelling reflectance. The $$E_d$$ used in the calculations comes from the TriOS measurements and is corrected for time difference. As the creation of SPM and CHL maps based on CHRIS/PROBA imagery is still in a test phase, the algorithms are only applied on image CHRIS_OT_030805_367B_31.hdf with FBZ= -36°. This image was taken on 5 August 2003 and is selected for processing because it has no sunglint, no drop-out lines and the two stations with seaborne measurements fall inside the image.

#### 3.5.1 Suspended Particulate Matter

The retrieval of SPM maps is based on the Eq. 3

$$SPM (g/m^3) = A_Q \frac{\rho_w}{0.187 - \rho_w} + B_Q$$ (3)

where $$A_Q$$ and $$B_Q$$ are wavelength dependent and calibrated using the method of [7]. For the production of SPM maps the wavelength 555 nm was chosen with $$A_Q = 25.99 \text{ mg/l}$$ and $$B_Q = 4.98 \text{ mg/l}$$.

#### 3.5.1 Chlorophyll

For transforming the reflectance maps into chlorophyll maps the wavelengths 664nm, 708nm, and 778nm are used as in Eq. 4-6 [2] based on the work on [8].

$$b_{b_0} = 1.2 \times 2.69 m^{-1} \times \frac{\rho_{w,778nm}}{0.187 - \rho_{w,778nm}}$$ (4)

$$\gamma = \frac{\rho_{w,708nm}}{\rho_{w,664nm}}$$ (5)

### 4. RESULTS AND DISCUSSION

#### 4.1 Destriping

Applying the correction factors described in 3.1 results in a much smoother image than the original (Fig. 5). Outliers are greatly reduced but not eliminated completely.

#### 4.2 Atmospheric correction

##### 4.2.1 Darkest pixel correction

Subtracting the spectrum of the darkest pixel from the whole image results in spectra with a typical shape for water masses. The weakness of this correction lies in the two assumptions. Because the water even in the darkest pixel is not perfectly black, there is an overestimation of the atmospheric path reflectance. This results in an underestimation of the water leaving reflectance. The assumption of an equal atmosphere all over the image site has less consequence on a clear day.

$$CHL(mg/m^3) = \frac{1}{0.0146 m^2 mg^{-1}} \left[ (\gamma \times 0.699 m^{-1} + b_{b_0}) - 0.402 m^{-1} - b_{b_0} \right]$$ (6)

Fig. 5: destriped CHRIS/PROBA image. 5 August 2003, FBZ = 36°, 411nm

Fig.6: darkest pixel atmospheric correction
then on a clouded day. Despite such drawbacks the darkest pixel approach provides an acceptable data.

4.2.2 Radiative transfer model

The radiative transfer model is a more accurate method to calculate the atmospheric correction than the darkest pixel approach if all factors can be calculated properly. Unfortunately this is not yet the case for the CHRIS/PROBA sensor which provides images with considerable spectral noise. Because of these variations it is impossible to estimate the spectral slope which is needed to calculate the aerosol reflectance, one of the input parameters for the model.

It could be possible to smooth the spectra and in this way estimate the spectral slope, but it is preferred not to do this at this stage because this would hide a sensor problem which could be solved more comprehensively for example by increasing electronic gain [9]. Another problem is the unrealistic values in the lowest band for wavelength 410 nm.

Therefore the darkest pixel atmospheric correction is preferred above the radiative transfer model until smoother spectral data becomes available.

4.3 Georeferencing

Georeferencing images by the use of 5 ground control point (GCPs) on land gives a good result for the interpolated points on land but the error increases for extrapolated points far from the GCPs. This approach is not very accurate because all GCPs are located in the same corner of the image. The GCP location error for any image is typically half a pixel, if ground control points like for example a cross road, the corner of a bridge, a pool in a park are identified correctly. Here this uncertainty is amplified considerably going from the land corner of the image to the opposite sea corner. Georeferencing image to image assumes that the base image is perfectly georeferenced. Otherwise the georeference errors of the base image are extrapolated to the other images.

The results of georeferencing the images from 5 August 2003 are acceptable for the land and points close to land but information about georeferencing or even the nominal size, location and orientation of the image would lead to better results. Figure 7 shows the difference between the original image and the same image after destriping and georeferencing.

4.4 Comparison with other data

Figure 8 shows the water leaving reflectance spectra at station 130 and 230 for the CHRIS/PROBA images with FBZ -36°, 0° and 36° and for the TriOS measurements. Figure 9 presents the water reflectance spectra at station 130 and 230 for the CHRIS/PROBA images with FBZ -36°, 0° and 36°, TriOS, MERIS and SeaWIFS.

All sensors show a higher reflectance and reflectance at station 130. This is explained by the concentration of particles in suspension at station 130 which leads to a higher reflection. Analysis of the water samples for SPM shows the same tendency (table 3).
The values are lower for CHRIS/PROBA in comparison with other sensor data. This can be explained by the darkest water pixel assumption. Time differences may also affect the comparison. The CHRIS/PROBA spectra are similar at station 130 for wavelengths until 600nm for the 3 look angles. Higher wavelengths show a discrepancy for the data from the CHRIS/PROBA image with FBZ equal to -36°, possibly due to sunglint. The CHRIS/PROBA spectra at station 230 show more variation between the different view angles. These variations could be due to the increased georeferencing error further from land.

The CHRIS/PROBA radiance and reflectance spectra show spectral noise. This noise could be reduced by applying a spectral smoothing but because less is known about which values are correct and which are not, it is preferred at present not to smooth the spectra until good correction factors are available because important data could be lost.

Table 3: Data from water samples

<table>
<thead>
<tr>
<th>Station</th>
<th>Sample date</th>
<th>SPM (mg/l)</th>
<th>CHL a (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>5/08/2003</td>
<td>8.20</td>
<td>11.37</td>
</tr>
<tr>
<td>230</td>
<td>5/08/2003</td>
<td>7.27</td>
<td>11.49</td>
</tr>
</tbody>
</table>

4.5 SPM and CHL maps

4.5.1 SPM maps

Figure 10 and 11 show SPM maps deduced from the reflectance at wavelength 551 nm for CHRIS/PROBA images with fly by zenith angle -36° and 0° respectively. The image with FBZ 36° is not processed because of sunglint. The black lines at the bottom of figure 10 are drop-out lines, generated during the data acquisition. Both maps give similar results. SPM varies from +/- 4 to 25 mg/l. The calculated values for SPM are in the same range as the measured values (Table 4).

The higher concentrations of SPM in the East are explained by a high turbidity zone in the Belgian/Dutch coastal area. The processes responsible for the high turbidity zone formation are the currents and the import of SPM through the Strait of Dover. Also the erosion of clay and Holocene mud layers is partly responsible for the increase of SPM concentration here. However, the Strait of Dover remains the major source of SPM [3].

Table 4: Satellite vs. seaborne measured SPM concentrations

<table>
<thead>
<tr>
<th>Station</th>
<th>SPM (mg/l) FBZ = -36°</th>
<th>SPM (mg/l) FBZ = 0°</th>
<th>Measured SPM (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>11.41</td>
<td>11.35</td>
<td>8.20</td>
</tr>
<tr>
<td>230</td>
<td>7.98</td>
<td>7.16</td>
<td>7.27</td>
</tr>
</tbody>
</table>

Figure 10: SPM map based on CHRIS/PROBA, 5 August 2003, FBZ = -36°, wavelength 551 nm
Comparison with the SPM maps deduced from MERIS (Fig. 12) and SeaWiFS (Fig. 13) shows agreement and indicate that the strong SPM gradient across the CHRIS image corresponds to a frontal region between high SPM waters near the coast between Oostende and the Scheldt and low SPM waters offshore and further West. The stability of this feature over the 2.5 hour period considered and its appearance in many other SeaWiFS and MERIS images confirm that CHRIS detects successfully SPM.

4.5.2 Chlorophyll maps

The chlorophyll map in figure 14 is deduced from the CHRIS/PROBA image with FBZ -36° and is based on 3 bands: 664 nm, 708 nm and 778 nm. At first sight it seems it might be possible to create chlorophyll maps from CHRIS/PROBA images since the CHL distribution in Fig.15 is not correlated with SPM nor with any obvious atmospheric feature. However, comparison with seaward measurements and inspection of the highest values shows that the values are not realistic...yet (table 5).

<table>
<thead>
<tr>
<th>Station</th>
<th>Satellite value (mg/m³)</th>
<th>Measured value (mg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>39.27</td>
<td>11.37</td>
</tr>
<tr>
<td>230</td>
<td>52.25</td>
<td>11.49</td>
</tr>
</tbody>
</table>
5. CONCLUSION

The processing of CHRIS images involves some problems due to the data quality: vertical stripes, spectral noise, drop-out lines and strange values at band 1 (410 nm). Most of these problems are mitigated in the processing adopted here but a missionwide solution would be better. The major problem in the image processing of marine images is the georeferencing. As long as this problem is not solved properly, it is difficult to validate accurately the end products (SPM and chlorophyll maps) with seaborne measurements.

The simple dark pixel atmospheric correction gives reasonable results for the creation of SPM maps. An atmospheric correction by radiative transfer modeling would be better but requires better spectral data.

CHRIS/PROBA image data are good enough to create useful SPM maps. The possibility to create CHL maps needs further research.

The advantages of the different viewing angles are at this stage used only to eliminate sun glint. In the future the image set with different viewing angles may help to improve atmospheric correction or may be used as test data to validate sun glint algorithms e.g. for MERIS. The potential of multi-look angle hyperspectral imagery for suspended particulate matter and chlorophyll mapping remains promising but requires further assessment after improvement of image data and atmospheric correction.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


QUANTITATIVE ESTIMATION OF SUSPENDED PARTICULATE MATTER FROM CHRIS IMAGES

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ABSTRACT

This paper highlights the utility of standard hyper-spectral techniques and algorithms to retrieve useful information from CHRIS imagery. The end-objective being the demonstration of CHRIS capability in retrieving marine bio-geophysical quantities. The major conclusion of this present study is that CHRIS-imagery, in its present status, can be used for operational retrieval of marine bio-geophysical quantities within reasonable accuracy. Though improvements are still needed to enhance the quality of the retrieved products.

Key words: SPM.

1. INTRODUCTION

Suspended particulate matter (SPM) is an important environmental indicator for geomorphological change, pollution, primary production and climate change. The knowledge on SPM loads, spatial distributions and physical properties is essential to maintain navigational routes and to monitor coastal morphology. Sediments in suspension are capable of transporting loads of adsorbed nutrients, pesticides, heavy metals, and other toxins and decreasing the light penetration into the water. This affects fish feeding, photosynthesis and water temperature. The last two phenomena have a direct link to the climate change. Data acquired by the Compact High Resolution Imaging Spectrometer (CHRIS) mounted on PROBA satellite provide wealth of information on the spatial, temporal and angular distribution of SPM in the Belgian coastal waters.

The processing of CHRIS images was subdivided into three phases namely, pre-processing, retrieval and validation. The objective of the preprocessing was to retrieve accurate values of the water leaving reflectance. This was realized through noise removal, georeferencing, atmospheric correction and vicarious calibration. Marine bio-geophysical quantities were then retrieved in the second processing-phase of CHRIS images. The results were validated with in-situ measurements. The post-processing phase will encompass improving the quality of retrieved parameters using hyperspectral and multi-viewing capabilities of CHRIS sensor.

1.1. Site description

The study area is the Belgian coastal water. This water-region is extremely shallow with a depth ranging from 2 to less than 30 meters. The area is under strong meteorological forcing and tidal current. The combined effects of strong motion and shallow water result in a vertically homogeneous water column. The Belgian coastal water, therefore, exhibits a permanent high load of suspended matter reaching 40 g.m$^{-3}$ off the coast and may increase (especially in the winter off Oostende) to more than 100 g.m$^{-3}$ [Eisma & Kalf (1979)]. This high load of suspended sediment arises from transport and re-suspension of sediment materials through hydrodynamic processes, from river discharge and from the nearly continuous dredging activities in the area.

1.2. Characteristics of the Sensors

The operational mode of CHRIS was set to 1 (table ??, i.e. 62 spectral bands distributed on the
range between 0.4 $\mu$m and 1.05 $\mu$m with 30meter spatial resolution.

Table 1. The operational mode of CHRIS sensor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CHRS</th>
</tr>
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<tbody>
<tr>
<td>Dynamic range [bit]</td>
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</tr>
<tr>
<td>FOV [$^\circ$]</td>
<td>$\pm 1.3$</td>
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<tr>
<td>spectral range [$\mu$m]</td>
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<tr>
<td>Number of bands</td>
<td>62</td>
</tr>
<tr>
<td>Spatial resolution [m]</td>
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</tr>
<tr>
<td>flight altitude [km]</td>
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</tr>
<tr>
<td>SNR</td>
<td>200: 0.2</td>
</tr>
</tbody>
</table>

2. PRE-PROCESSING

2.1. De-striping and noise removal

Prominent vertical striping was evident in all CHRIS images. This might be due to the difference in noise level (and thus calibration) between adjacent detectors. This difference in calibration arises because each vertical column represents the sequential output of a single detector. The minimum noise fraction (MNF) transforms was employed to remove noise including vertical stripes from data Green et al. (1988). This was by performing a forward transform, determining which bands contain the coherent images, and running an inverse MNF transform using a spectral subset to include the noise free bands only. An example is shown for a CHRIS image acquired on the 05th of August with FZA=$+36$. This image was de striped using the first three eigen-modes of the forward MNF (figure [1]).

From figure [1] we can observe that the MNF transform has retained the spatial distribution of the blue band while removing the stripe and other noise including some spikes (e.g. ship induced waves). One can argue that using the first three eigne modes, only, to perform inverse MNF transform will lead to losses in the data which have high frequency in a similar manner to a low-pass filter. In other words, some of the information will be lost in the inverse procedure of the MNF transform. However a high frequency signal, surrounded by low water-signals, arises from either an object floating on the water surface (e.g. boat, buoy etc..), sun glint or whitecaps. It is of importance for water studies to remove these signals to get reliable results. Still to what degree (i.e. number of the eigen-modes used in the inverse) the MNF will contributes in whitening the data, this will be left to future investigations.

2.2. Geo-referencing CHRIS image using ground control points

Number of ground control points (GCP) were extracted from cartographical map which were visible on CHRIS images. These GCP were then used to perform the geometric correction. The results are shown for a CHRIS image acquired on the 20th of September 2003 (figure [2]). This approach has three major disadvantages:

1. finding GCP on land is not always feasible (e.g. when clouds are present).

2. over a sea scene these GCP has to be on land, and since it is a rubber-sheeting technique the sheet will be fixed, in the best case, from two corners while the other two are flapping with considerable errors on the X and Y directions. The magnitude of this two dimensional error depends on number and distribution of GCP, the extrapolation procedure being employed in the geo-referencing and on the offshore distance (i.e. it increases in the offshore direction).
3. subject to operator error due to the scale difference between a real point on a cartographical map and a grid point of CHRIS image with a minimum size of 900 m².

A better approach would be by using the telemetry data of the PROBA satellite and the geographical coordinates of the observed location to perform geometric correction of the acquired scene by CHRIS on board on PROBA.

2.3. Atmospheric correction of CHRIS images

The fly-by-zenith and the minimum-zenith angles of each acquisition were used with satellite altitude and time of overpass to compute the viewing zenith and azimuth angles for a geographical location on the ground.

The data from the sunphotometer fixed at Ostend station were used to estimate the contribution of aerosol scattering to the total recorded radiance at the sensor level.

The water vapor transmittance at 0.94 μm was estimated from the band ratio technique Gao et al. (2000) assuming small variations in the surface reflectance as follows:

\[ T(940)_w = \frac{5 \times \rho_t(0.94)}{3 \times \rho_t(0.87)} \]  

where \( \rho_t(\lambda) \) is the apparent optical quantity at the wavelength \( \lambda \) measured by the sensor. The resulting transmittance is then compared to a look up table of transmittance as a function of water vapor content. The resulting image of water vapor content is shown in figure 3.

Atmospheric radiative transfer was then simulated using the second simulation of the satellite signal in the solar spectrum Vermote et al. (1997).

2.4. Vicarious calibration

The objective in this step is to realize the radiometric closure between CHRIS corrected spectra and in-situ measurements. At each band a linear relationship is assumed between CHRIS water leaving reflectance and in-situ measured spectra. The calibration coefficients are then defined to achieve the best fit between the two spectra. The ground-reference sites were divide into calibration and validation sites. Figure 4 shows inter-comparison between the measured spectrum at the validation site st130 and the CHRIS spectrum at the same location. As we can see form figure 4 the relative error between both spectra did not exceed 10%. This is extremely good providing that we have used one site only for the calibration. The results can be improved by having

Figure 2. The ground truth cartographical map overlayed on top of the georeferenced CHRIS image.

Figure 3. Example of CHRIS byproduct: water vapor content estimated from CHRIS imagery CHRIS0508A.

Figure 4. Comparison of image and measured reflectances at st130 (lat: 51.26922 long: 2.89902)
two sites that represent two different water bodies, eventually case 1 and case 2 water. Let us note, however, that the two spectra have the same values of reflectance at the NIR. Therefore SPM can be retrieved from the NIR band (0.8 µm) of CHRIS image with high accuracy. Moreover the blue/red ratios have close values in both spectra. In consequence using the band ratio approach to estimate the concentrations of chlorophyll-a form CHRIS image will give close estimates to measured concentration. Upon that the goodness of fit between the measured and CHRIS spectra in the visible range is at its maximum at the blue bands. This feature will increase the accuracy of the retrieved DOM absorption coefficient form the blue bands of CHRIS.

3. HYDRO OPTICAL MODELLING

The water leaving reflectance $\rho_{\text{w}}^{(\lambda)}$ of a uniform radiance field can be related to the inherent optical properties (IOP) as Gordon et al. (1988):

$$\frac{\rho_{\text{w}}^{(\lambda)}}{T_{0}^{(\lambda)}} = 0.54\pi l_1 \frac{b_{b}(\lambda)}{b_{b}(\lambda) + a(\lambda)} \quad (2)$$

Where $l_1 = 0.0949$ is the subsurface expansion coefficients due to internal refraction, reflection and sun zenith. $T_{0}^{(\lambda)}$ is the solar transmittance from sun-to-target. The absorption $a(\lambda)$ and backscattering $b_{b}(\lambda)$ coefficients are expressed as:

$$a(\lambda) = a_{w}(\lambda) + a_{\text{dom}}(\lambda) + a_{\text{chl}}a$$

$$b_{b}(\lambda) = b_{b}(w)(\lambda) + b_{b}(\text{spm})(\lambda) \quad (4)$$

The subscripts $\text{w}$, $\text{dom}$, $\text{chl}$a and $\text{spm}$ represent water, dissolved organic matter, chlorophyll-a and suspended particulate matter respectively. Measured values of specific inherent optical properties in the North Sea [IVM (1999-2000)] will be used to compute the concentration of chlorophyll-a and SPM from retrieved absorption and backscattering coefficients.

For the SPM retrieval we used the NIR band centered at 0.8 µm and direct inversion of equation (2), (see figures 5,8 and 11). In this inversion process, other constituents than SPM and water molecules were ignored. The concentrations of chlorophyll-a were retrieved form the single band ratio model of Lee et al. (1996) (see figures 6,9 and 12). Equation (3) was then inverted for DOM having the values of the Chl-a and SPM (see figures 7,10 and 13).

3.1. maps of marine bio-geophysical quantities in the Belgian coastal waters

![Figure 5. The concentrations of SPM retrieved from CHRIS image acquired on 05/08/2003, FZA=0.](image)

![Figure 6. The concentrations of chlorophyll-a retrieved from CHRIS image acquired on 05/08/2003, FZA=0.](image)

![Figure 7. DOM absorption coefficient at 0.44 µm retrieved from CHRIS image acquired on 05/08/2003, FZA=0.](image)

The retrieved concentration of SPM (figures 5, 8 and 11) have realistic spatial distribution and ranges of values. The first SPM map (figure 5)
was computed one hour after the ebb-condition. Therefore the concentration of SPM rises from local stirring in shallow areas due to the rises of the water level and the interaction of different hy-
drodynamical forces. This is clearly visible along the Wenduinebank sandbank. The other two SPM maps (figures 8 and 11) were computed one and two hours before the ebb-condition, respectively. In this case the tide residual current is still an effective factor in determining the concentration and spatial distribution of SPM. This especially for the SPM map computed two hours before the ebb (figure 11). Here we can see how the interaction of the different hydrodynamical forces is contributing to the magnitude and spatial distribution of SPM along the Belgian coast. In a similar manner the spatial distribution of chlorophyll-a and DOM maps can be explained in the view of the hydrodynamical conditions at the time of image acquisition.

4. CONCLUSION

This paper demonstrated the potential use of CHRIS imagery over water target. It was shown that CHRIS operational processing chain follows those of standard algorithms designed for hyperspectral imagery. In other word CHRIS-imagery in its present status can be used for operational retrieval of marine bio-geophysical quantities. The retrieved marine quantities from CHRIS images showed realistic ranges of values. Moreover their spatial distribution were in accordance to what is expected from hydrodynamics simulation at the time of image acquisition. Though improvements are still needed to enhance the quality of the retrieved products. Especially the multi-angularity feature of CHRIS sensor, employing this capability will improve our understanding on the bidirectional effects of the water signal, besides it might provide a better way to correct for the interference of non desirable signals.

5. ACKNOWLEDGEMENT

The authors would like to thank: the European Space Agency (ESA) for providing the opportunity to exploit CHRIS imageries, SIRA for their scientific and technical assistance, Management Unit of Mathematical Models of the North Sea for providing in-situ measurements, Institute for Environmental Studies-Free University of Amsterdam for providing the specific inherent optical properties. The financial support of ESA-PRODEX Experiment Arrangement No. 90018 is gratefully acknowledged.

PUBLISHED WORK IN THE CONTEXT OF CHRIS/PROBA MISSION


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INVESTIGATIONS ON THE CAPABILITY OF CHRIS-PROBA FOR MONITORING OF WATER CONSTITUENTS IN LAKE CONSTANCE COMPARED TO MERIS

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ABSTRACT

CHRIS-PROBA data were acquired on 3 days in 2003 at the Eastern part of Lake Constance. Field campaigns were organised on these days in order to measure optical parameters of the water and the atmosphere and concentrations of water constituents from ship for validation. For two dates also MERIS full-resolution data are available. Based on the in-situ measurements, forward calculations were made to simulate for different conditions the expected CHRIS and MERIS top-of-atmosphere radiance spectra. The result is a comparison of CHRIS with MERIS and with simulated radiances. CHRIS spectra were reproduced in a satisfying way, whereas MERIS spectra are misaligned. Further, the calculated spectra were adjusted to the measured ones by fitting the concentrations of 3 aerosol types (rural, maritime, urban) and 3 water constituents (suspended matter, chlorophyll, Gelbstoff). The values for concentrations of suspended matter and Gelbstoff have a mean relative difference to the in-situ values of 16 % and 26 %, respectively, which is within the error margin of in-situ data. The accuracy of chlorophyll retrieval is not yet satisfying: the mean relative difference is 47 %, and outliers occur. All calculations were done using the modular inversion program MIP, which is under development for processing multispectral and hyperspectral images from surface waters.

1. INTRODUCTION

The development of remote sensing algorithms for inland waters has a long tradition at Lake Constance. Due to the good research infrastructure and the well-studied biological, physical and optical properties, the lake is a nearly perfect site for algorithm improvements and validation activities.

Actually, the main problem of remote sensing of inland lakes is the atmosphere. There exists no operational software for sensors on satellite and aircraft which corrects automatically and reliably the atmospheric influence. Such a program is actually being developed at DLR and TUM in cooperation with the Russian Academy of Sciences. Basis is a software which has been developed for analysis of data from the airborne sensor DAEDALUS [1]. It was re-designed as a generic, sensor-independent program, which is now in the testing and optimisation stage. The paper presents first results for CHRIS and MERIS, obtained with the actual version of this Modular Inversion Program (MIP). Particularly, the potential of CHRIS is investigated and compared to MERIS for determining the concentrations of the water constituents chlorophyll, suspended matter, and Gelbstoff.

2. MATERIALS AND METHODS

2.1 Optical in-situ data

In water. Three TriOS RAMSES submersible radiometers (www.trios.de) were used for optical measurements in the water: one for measuring upwelling radiance spectra (L_u), one for upwelling irradiance (E_u), and one for downwelling irradiance (E_d). Each sensor has 190 useable channels from 320–950 nm, i.e. the spectral sampling interval is 3.3 nm. The three instruments are mounted on a frame such that their optical axes are aligned parallel to each other and the three entrance optics are on the same level. Also a pressure and a tilt sensor are attached to the frame in order to measure depth and inclination. All devices are connected to a control unit which ensures that all measurements are made simultaneously. The measurements were performed in 0.5 m depth at a distance of 3–4 m from the ship’s bow which was oriented into the direction of the sun.

Atmosphere. The optical density (OD) of the atmosphere was measured using two Microtops II instruments (www.solar.com). A Sunphotometer was used to measure OD at 380, 440, 500, 675, and 870 nm, and a Ozonometer to determine OD at 305, 312, 320, 936, and 1020 nm. The aerosol optical thickness (AOT) at 380, 440, 500, 675 and 870 nm was calculated by correcting for ozone and water vapour, whose concentrations were derived from the Ozonometer data, and for Rayleigh scattering.
2.2 Biochemical in-situ data

The water samples were collected from ship using a Ruttner bottle of 1 m length in 0.5 m and 2.5 m depth, i.e. the average concentrations of the depth ranges 0-1 m and 2-3 m were obtained. The analysis was done by two independent laboratories at the University of Konstanz (KN) and the Biologiebüro Weyhmüller (BBW).

CHL. Pigment concentration CHL was measured photometrically as the sum of chlorophyll-a and pheophytin-a after the method of Nusch [2]. Depending on the concentration of particulate matter, a defined volume of water (0.5 to 3.0 l) was filtered directly after sampling through a glass fibre filter, which retains particles larger than ca. 1 µm. The KN laboratory uses as filter Schleicher & Schuell No. 6 VG, BBW uses Whatman GF/F. The pigment-loaded filters were stored in cooling boxes for few hours until the end of the campaign. Then, in the laboratory, they were either immediately analysed, or further stored in a refrigerator at −18 °C. The samples were always kept in darkness from the beginning of the filtration process on. The analysis started with pigment extraction in hot ethanol (90 %). The BBW laboratory treated the samples with ultrasonic in order to enhance the yield and performed a centrifugation of the solution in order to separate particulate matter; these steps were not performed a centrifugation of the solution in order to separate particulate matter; these steps were not made at the KN laboratory. The transmission of the solution was measured in a 10 cm cuvette at 665 and 750 nm using a photometer. After treating the solution with hydrochloric acid (2 mol/l HCl), which converts chlorophyll-a into pheophytin-a, the transmission was measured again at the same wavelengths. From the transmission measurements and the filtration volume the concentrations of chlorophyll-a and pheophytin-a were calculated using the equations in [2].

TSM. For measuring total suspended matter, a defined volume of water (0.5 to 3.0 l) was filtered directly after sampling through a pre-weighed glass fibre filter, which retains particles larger than ca. 1 µm. The KN laboratory used as filter Schleicher & Schuell No. 6 VG (preheated), BBW uses Whatman GF/F (not preheated). The filters were transported in a cooling box to the laboratory and stored at about -18 °C for some hours. Then, spectral measurements were made using a Perkin-Elmer Lambda-2 dual-beam spectrophotometer and two quartz cuvettes of 5 and 10 cm pathlength. At both pathlengths the transmission of each sample was measured from 190 to 1100 nm at a sampling interval of 1 nm. The ratio of the two transmission spectra was converted into absorption of water plus Gelbstoff using the Lambert-Beer law. The Gelbstoff absorption spectrum a_T(λ) was calculated by subtracting the absorption spectrum of pure water. Two parameters were derived from this spectrum: absorption at 440 nm (Y) as a measure of concentration, and spectral slope S as an indicator of the wavelength-dependency. Both parameters were calculated by linear regression of ln a_T(λ) from 420 to 460 nm; the logarithm accounts for the nearly exponential wavelength dependency of a_T(λ).

2.3 CHRIS-PROBA data

PROBA is a small ESA satellite launched on 22 October 2001. The instrument payload includes the Compact High Resolution Imaging Spectrometer CHRIS, which is both a hyperspectral and multi-angle sensor. It has a ground sampling distance of 17 m at nadir and covers the spectral range from 400 to 1050 nm with a spectral sampling interval between 1.25 and 11 nm. CHRIS is operated in different modes. Our data were acquired in mode 2 (“water mode”), which provides images of 766 x 748 pixels at full geometric resolution and 18 spectral channels, whose gains are adjusted individually such that the dynamic range is suited for water targets. The center wavelengths (nominally at 410.5, 442.4, 490.2, 509.6, 529.6, 561.2, 569.8, 590.4, 622.0, 650.7, 671.7, 679.9, 685.6, 706.3, 755.3, 780.8, 872.1, 1019.0, 11307). The filtered water was stored in glass bottles in darkness for some hours. Then, spectral measurements were stored at about -18 °C for some hours. Then, spectral measurements were made using a Perkin-Elmer Lambda-2 dual-beam spectrophotometer and two quartz cuvettes of 5 and 10 cm pathlength. At both pathlengths the transmission of each sample was measured from 190 to 1100 nm at a sampling interval of 1 nm. The ratio of the two transmission spectra was converted into absorption of water plus Gelbstoff using the Lambert-Beer law. The Gelbstoff absorption spectrum a_T(λ) was calculated by subtracting the absorption spectrum of pure water. Two parameters were derived from this spectrum: absorption at 440 nm (Y) as a measure of concentration, and spectral slope S as an indicator of the wavelength-dependency. Both parameters were calculated by linear regression of ln a_T(λ) from 420 to 460 nm; the logarithm accounts for the nearly exponential wavelength dependency of a_T(λ).
Fig. 1: CHRIS images from Lake Constance and sampling positions (red circles).
2.4 MERIS data

The MERIS data are available from ESA as Level-1b and as Level-2 products in full (FR) and reduced resolution (RR). Level-1b data are calibrated radiances of the 15 spectral bands at top of atmosphere (TOA). Level-2 comprises the bottom of atmosphere (BOA) reflectances and geophysical parameters like the concentrations of water constituents (TSM, CHL, YS), atmospheric parameters (AOT at 865 nm, Ångström exponent), and others. The geometric resolution is 300 m for the FR and 1200 m for the RR data. Radiance spectra were extracted from Level-1b data using the Basic Envisat AATSR and MERIS Toolbox (BEAM), which is distributed as an open source software by ESA (http://envisat.esa.int/services/beam/).

3. DATA SET

3.1 Test site

Lake Constance (Bodensee) is a pre-Alpine lake, which is shared between Germany, Switzerland, and Austria. It serves as drinking water reservoir for about 4 million people and as important recreation area. After water quality had decreased towards the eutrophic state at the end of the 1970ies, the lake is now on its way to re-oligotrophication after sewage diversion and waste water treatment in the catchment area. With an area of 571 km² it is the third largest lake in Central Europe. The length is 63 km, the maximum width 14 km, the maximum depth 254 m. The river Rhine, which passes the lake, is the main inflow and outflow. It imports significant amount of mineral particles.

3.2 Available data

Three CHRIS data sets à 5 look angles are available for 2003. Each image was destriped by J. Settle (ESSC) and geometrically corrected using ground control points. True colour images of the nadir scenes are shown in Fig. 1. Validation campaigns were performed on each of these days. Optical and biochemical in-situ data were measured from ship, and for 2 days additionally MERIS data are available. Table 1 gives an overview on the collected data. Only a part of the data is used and described in this paper (marked as "X" in Table 1); the other data are mentioned for completeness, but no description is given here.

The research vessel "Robert Lauterborn" of the University of Constance and the RV "Thienemann" of the Institute for Lake Research in Langenargen were used for the campaigns. Ship measurements were performed at 6 to 8 stations. Water samples were taken in 2 depths at each station (at 0.5 and 2.5 m). A duplicate determination of the concentrations of pigment (CHL = sum of chlorophyll-a and phaeophytin), total suspended matter (TSM), and Gelbstoff (YS) was performed on 10, 11 and 19 July 2003 by two independent laboratories.

3.3 Situation at the CHRIS overflight days

The atmospheric and geometric conditions and the variability of the water constituents on the three days with CHRIS overpass are summarised in Table 2. The atmospheric conditions were quite different for the three days, while the concentrations of water constituents were similar. The variability of each constituent was low at each day, i.e. less than a factor of 2.

Although there was no large variability in water constituents, all three CHRIS images of Fig. 1 show distinct patterns in the lake which can be attributed clearly to the water body, e.g. on 10 July the two gyres near the mouth of the river Rhine, or on 11 July the greenish coloured regions. This indicates that CHRIS is suited to monitor concentration values typical for Lake Constance and small concentration differences.

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>X</td>
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<td>( L(\lambda)_{\text{TOA}}, \text{Level-2} )</td>
<td>MERIS</td>
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</tr>
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<tr>
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4. MODULAR INVERSION PROGRAM

The Modular Inversion Program (MIP) is a processing and development tool designed for the recovery of hydro-biological parameters from multi- and hyperspectral remote sensing data. A flow chart is shown in Fig. 2. The architecture of the program consists of general and transferable algorithms based on physical inversion schemes that derive biophysical parameters from the measured radiance signal at the sensor. Inverted parameters include e.g. the variable constituents of the atmosphere, the concentration of water constituents and the reflectance characteristics of substrates in shallow waters.

Program modules exist for the retrieval of aerosols, atmosphere and water surface corrections, and the retrieval of water constituents in optically deep waters. MIP developments focus on easy generation and access to needed radiative transfer databases in order to manage hyperspectral image data from different sensors as well.

In present applications, two radiative transfer databases are used for the aerosol retrieval: the atmospheric correction and the bi-directionality correction of the underwater light field. The databases are generated by a radiative transfer model. Radiative transfer is simulated in a coupled, plane-parallel atmosphere-ocean system, currently by use of the FEM-method [3]. The model calculates radiances in a vertically inhomogeneous (multilayer) atmosphere-ocean system with respect to all angle dependencies of the sun and observer geometry.

Both databases were calculated with optical parameters for a mid-latitude summer standard atmosphere. The first database was generated for an atmosphere-ocean system with a Lambert reflector of defined reflection $R_L$ at 1 cm depth. Therefore, for the first database the underwater radiance was assumed to be isotropic. The water surface was modeled as flat, so that no sun glitter contributed to the upwelling radiances. The free parameters of the database are three types of aerosols $\tau_1, \tau_2, \tau_3$ (continental, maritime, urban), each with 4 optical depths between 0.01 and 0.5 (at 550 nm), 7 reflection values for $R_L(\lambda)$ between 0 and 0.6, 17 observer altitudes $h$, 17 azimuth differences $\Delta \phi$ between sun and observer, 8 sun zenith $\theta_{sun}$ and 8 observer zenith angles $\theta$. The main data base contains 3 wavelength regions with different resolutions. The second database is needed to correct the artificial Lambert reflectance values $R_L$ for the bi-directionality of the underwater light field to $R = E_{uf}/E_{down}$ by $R = R_L \pi Q$. Values of $Q = E_{uf}/L_{up} \pi Q$ were calculated with a standard atmosphere as described above, but with a fixed medium aerosol concentration and an expanded water body. $Q$ is calculated as function of $\lambda, h, \Delta \phi, \theta, \theta_{sun}$ and the water constituent concentrations.

Table 2. Conditions at CHRIS overpasses.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Overflight time of CHRIS (local time)</td>
<td>12:40</td>
<td>12:52</td>
<td>12:48</td>
</tr>
<tr>
<td>Overflight time of MERIS (local time)</td>
<td>–</td>
<td>12:25</td>
<td>12:25</td>
</tr>
<tr>
<td>Sun zenith / azimuth angle (°)</td>
<td>28 / 149</td>
<td>28 / 149</td>
<td>47 / 163</td>
</tr>
<tr>
<td>CHRIS zenith / azimuth angle (°)</td>
<td>5 angles</td>
<td>5 angles</td>
<td>5 angles</td>
</tr>
<tr>
<td>MERIS zenith / azimuth angle (°)</td>
<td>–</td>
<td>35 / 290</td>
<td>35 / 290</td>
</tr>
<tr>
<td>Aerosol optical thickness at 870 nm</td>
<td>0.155</td>
<td>0.064</td>
<td>0.082</td>
</tr>
<tr>
<td>Aerosol Angström exponent</td>
<td>0.82</td>
<td>1.63</td>
<td>1.52</td>
</tr>
<tr>
<td>Number of stations in CHRIS / MERIS image</td>
<td>6 / –</td>
<td>6 / 8</td>
<td>5 / 6</td>
</tr>
<tr>
<td>Secchi depth (m)</td>
<td>2.9 – 3.5</td>
<td>2.9 – 4.5</td>
<td>3.1 – 3.9</td>
</tr>
<tr>
<td>CHL (µg/l)</td>
<td>1.8 – 3.3</td>
<td>1.4 – 2.6</td>
<td>2.6 – 4.4</td>
</tr>
<tr>
<td>TSM (mg/l)</td>
<td>1.5 – 2.6</td>
<td>1.1 – 2.0</td>
<td>1.4 – 1.8</td>
</tr>
<tr>
<td>Y (m$^2$ at 440 nm)</td>
<td>0.13 – 0.20</td>
<td>0.15 – 0.23</td>
<td>0.23 – 0.30</td>
</tr>
<tr>
<td>S (nm$^2$ at 440 nm)</td>
<td>0.013 – 0.019</td>
<td>0.011 – 0.014</td>
<td>0.009 – 0.012</td>
</tr>
</tbody>
</table>

Fig. 2: Flow chart of the Modular Inversion Program MIP.

Various program modules are implemented for the inversion and processing of remote sensing data [1]. These modules are partly iteratively coupled. The internal structure of MIP is also modular, so that a separate treatment of different functions is possible. The most important internal modules are libraries of algorithms and optimisation methods, functions for the interaction of different databases, and program-user-dialog functions.
5. RESULTS AND DISCUSSION

5.1 Accuracy of in-situ data

In order to estimate the accuracy of the concentrations of water constituents, a duplicate determination of CHL and TSM was performed for 44 samples from 10, 11 and 19 July 2003 by two independent laboratories (KN, BBW). Water samples were taken in two depths (0.5 m, 2.5 m) at 6-8 stations each day. The comparison of the obtained concentration values is shown in Fig. 3.

CHL. The CHL values obtained at KN are on average 19% higher than those measured at BBW. If this systematic effect is corrected by dividing all KN values by 1.19, the relative differences |KN−BBW| / 0.5 |KN+BBW| range from 0 to 36% at an average of 11%. If, alternately, the mean of the KN and BBW values is taken as correct value, the relative differences range from 0 to 52% at an average of 19%. Thus, the in-situ CHL values of an individual laboratory may have a systematic error in the order of 20%; the statistical error is also ~20%.

TSM. No significant systematic difference exists between the two laboratories. The relative differences range from 0 to 48% at an average of 15%. Thus, the statistical error of TSM is in the same order as that of CHL.

5.2 Forward calculation

The initial step of using MIP, irrespective of making forward calculations or inverse modelling, is to reduce the two data bases to smaller mission data bases. This is accomplished by using the geometric and flight information given of the recorded scene.

The main parameters which have to be taken into account are flight heading, pitch angle and the position of the sun. Regarding the pitch angles, some difficulties have arisen as the calculation of the angles under which CHRIS had recorded the images proved to be difficult. Therefore, an error for the length of path through the atmosphere cannot be excluded.

Forward calculations in MIP require six input parameters. The water body is parameterised by the concentrations of pigment (CHL), total suspended matter (TSM), and Gelbstoff (Y). The atmosphere is parameterised by aerosol optical depths $\tau_a$ of maritime, rural and urban aerosol.

- First step is the calculation of the subsurface irradiance reflectance, $R'$, which utilises the Gordon et al. [4] equation $R' = f \cdot b / (a+b)$. It is based on the inherent optical properties absorption, $a$, and backscattering, $b$. Both are additive, i.e. the contributions from pure water and all optical active water constituents have to be added. MIP includes a data set of consistent inherent optical properties from Lake Constance [1]. The factor $f$ is parameterised as a function of the mean cosine of the incident light field, $\mu$, which is calculated as a function of absorption $a$ and scattering $b$ after Bannister [5].

- The second step is conversion of $R'$ to remote sensing reflectance $R_L = R' \cdot Q(\lambda, \Delta \phi, \theta, \theta_{sun}, CHL, TSM, Y) / \pi$ by accounting for sun and viewing geometries using the Q database.

- The third step is conversion to radiance at sensor altitude, $L$, using the L-R database.

Forward calculations were performed for 19 Sept. 2003 for the five stations within the CHRIS image and the five viewing angles of CHRIS. For calculating $R'$ and $R_L$, the in-situ data of CHL, TSM, Y from the five stations were taken. For calculating the atmospheric influence, the aerosol type was determined by analysing the OD measurement of the Microtops sun photometer at the time of the
CHRIS-PROBA overflight. Fig. 4 shows the comparison between this measurement and the normalised OD spectra of the three aerosol types included in MIP. It can be seen that the measurement reveals a slightly steeper increase from long to short wavelengths than any of the three aerosol types. The closest agreement yields urban aerosol, hence this aerosol type was used for forward calculation. Its optical thickness was set to the value of the measurement, $\tau(a)(870) = 0.082$.

The results of forward calculation were compared to CHRIS spectra from the five stations, for which the averages of 3 x 3 pixels were taken. A typical example is shown in Fig. 5. The overall agreement is very good, except for the first two channels. This may be caused by a systematic calibration error of CHRIS. Furthermore, the CHRIS spectra are undulating in the wavelength range up to 600 nm, whereas the theoretical spectra are smooth. This may be caused by interference effects induced by the coating of the optical components of CHRIS. Another possible explanation is that incorrect spectral response functions of the channels in question were taken for modelling, and hence the theoretical spectra are faulty. Apart from these problems, the theoretical spectra match the measured ones, although, the slopes of the fitted spectra seem to be too low. If the spectral characterisation of the aerosol types is considered (see Fig. 4), it seems clear that no one of the used aerosol types has a steep enough spectral characteristic to cover this. Therefore, a new or additional aerosol type has to be included in MIP in order to model the atmosphere correctly.

A comparison between CHRIS and MERIS radiance spectra at top of atmosphere (TOA) is shown in Fig. 6 for station A. The zenith angle of MERIS was 35°, thus the CHRIS image with 36° was taken for the comparison. Also the azimuth angles of both sensors were comparable (CHRIS: 280°, MERIS: 290°). The CHRIS overflight was 23 minutes later than the MERIS overflight. As the two dotted lines illustrate, for CHRIS slightly higher radiances are expected than for MERIS due to the time difference and the slightly different viewing geometry. Indeed, the CHRIS radiances are higher than those of MERIS, but the differences are larger than expected. There are several possible explanations for the discrepancies. Forward calculation can be erroneous, either due to the above-mentioned lack of a fitting aerosol type, or due to incorrect aerosol optical depth, for example caused by changing atmospheric conditions between the two satellite overpasses. Calibration of CHRIS and/or MERIS can be in error. Which effect is the most relevant, cannot be stated at the moment.

5.3 Inversion

Inverse modelling is accomplished by calculating a theoretical spectrum using a set of initial values for the required six parameters. Assumed water constituent concentrations are converted into subsurface irradiance reflectance $R$. A bi-directional correction for the underwater light field is applied to calculate $R_L$ using the Q database. Using assumed aerosol optical thicknesses of the three aerosol types urban, rural and maritime, radiances at sensor altitude, $L$, are calculated and compared to the measured spectra. The set of 6 parameters is changed until the difference between measured and
modelled spectra is minimal. Since there exists an infinite number of possible parameter combinations, an effective algorithm of the iteration process has to be used to select a new set of parameter values from the previous set. MIP uses the downhill Simplex method [6, 7].

As the success of the minimisation method depends on the initial values, it is important to achieve reasonable first approximations of water constituent concentrations and aerosol optical thickness. If water constituent concentrations and aerosol optical thickness from previous optimisations of surrounding image pixels exist, their mean value is taken as initial value. Otherwise, a routine for the search of start values is initialised. In the 6-dimensional parameter space of the database some combinations are statistically chosen and the inversion is started from all these grid points. The region with the majority of points is taken as the region where the absolute minimum is searched. The borders of this region are determined and a set of parameters inside this region is chosen as start values.

For testing inversion, the CHRIS image of 19 Sept. 2003 was selected as no cirrus clouds were visible on this day. CHRIS spectra were extracted at all five stations by averaging 3 x 3 surrounding pixels. These served as input spectra for the inversion algorithm. The first two channels were ignored due to the results of forward calculation which indicated large differences between simulated and measured radiances (see section 5.2). Fig. 7 shows the comparison of top of atmosphere radiances between fitted and CHRIS spectra.

There is an overall reasonable agreement of magnitude and curve form. However, it is striking that the fitted spectra of the five stations differ much more than the CHRIS spectra. This points to a numerical problem of inversion, which is underpinned by Fig. 8. In this Figure all inversion results are plotted against the in-situ measurements of chlorophyll, suspended matter, Gelbstoff and aerosol optical thickness. All nadir scenes available for Lake Constance were used and all stations are accounted for. While TSM and Y values scatter around the 1:1 line, almost half of the fitted CHL values are outliers which drop to a concentration of 0.5 µg/l.

![Fig. 7: Fits of 5 CHRIS spectra.](image)

![Fig. 8: Comparison of fitted parameters with in-situ values.](image)
Fig. 8 shows that total suspended matter is retrieved in an acceptable way with a mean relative difference of 16%, which is within the error margin of in-situ data. Gelbstoff is retrieved with a mean relative difference of 26%, which is within the error margin as well. Improvements are necessary for chlorophyll; the mean relative difference is 47%. No conclusion can be drawn for aerosol optical thickness since the 3 data points are not enough for doing statistics.

A further test of inversion results is shown in Fig. 9. Calculated remote sensing reflectance spectra $R_{\text{L}}$ (blue) are compared with measured spectra (red). The comparison is done for all five stations of 19 Sept. 2003 and the nadir image of CHRIS. A very good agreement is observed for wavelengths above 500 nm. However, a systematic difference of the spectral shape is observed in the blue: the decrease towards shorter wavelengths is steeper for the spectra derived from CHRIS than for the spectra measured using RAMSES. A possible explanation is the spectral shape of Gelbstoff absorption, for which a value of $S = 0.014 \text{nm}^{-1}$ was taken during inversion, while the measurements yielded values in the range from 0.009 to 0.012 nm$^{-1}$ for 19 Sept. 2003 (see Table 2). Hence, the measured Gelbstoff absorption spectra are flatter than those used in the model, which fits to the observation that the measured reflectance spectra are flatter than the modelled ones. The spectral shape of Gelbstoff absorption is a very critical factor concerning chlorophyll retrieval [8], hence the reason for the CHL outliers of Fig. 8 may be small errors in the spectral shape of Gelbstoff absorption.

6. SUMMARY AND OUTLOOK

Although CHRIS was not designed for ocean colour applications, its spectral coverage, radiometric resolution, and calibration accuracy are well-suited to derive quantitatively the concentrations of the water constituents total suspended matter and Gelbstoff from mode 2 data. The results for chlorophyll were not satisfactory, i.e. almost half of the retrieved concentration values were significant outliers at an unrealistically low concentration of 0.5 µg/l. However, we expect that also chlorophyll can be retrieved accurately if some improvements in calibration and modelling are made. Three problems were identified which may lead to errors in chlorophyll determination:

- The first two channels of CHRIS at 410 and 442 nm could not be used since they were affected by a systematic calibration error (too high radiance values). Since this is the most important spectral region for chlorophyll determination, the inclusion of these channels provides additional information about chlorophyll.
- Atmospheric correction seems to require an alternate or additional aerosol type which causes a steeper increase of optical depth from long to short wavelengths. Errors induced by using a spectrally too flat aerosol optical depth affect mainly the shortwave region, i.e. chlorophyll retrieval.
- Some variability of the specific optical properties of Gelbstoff absorption was observed, which is so far not accounted for in the model. It affects mainly the shortwave region, which is important for chlorophyll determination.

SIRA promised to improve calibration and to re-calibrate CHRIS images on demand. We will work on improving atmosphere correction and characterisation of Gelbstoff absorption. When this is done, we will repeat the presented analysis with focusing on chlorophyll retrieval. If the results are satisfactory, the CHRIS images will be processed in order to obtain distribution maps of chlorophyll, total suspended matter, Gelbstoff, and aerosol optical depth. By comparing the results from different viewing angles, the accuracies can be determined and error sources can be identified.
ACKNOWLEDGEMENT

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CEDEX PROPOSAL FOR CHRIS/PROBA ACTIVITIES IN 2004 ON VALIDATION OF MERIS MODELS

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ABSTRACT

This paper present the CEDEX proposed activities for 2004, in the frame of a Project funded by the Spanish Environment Ministry for Monitoring of Water Quality, specifically Cyanobacteria dynamics and toxicity in reservoirs, related to ESA AO-594 MERIS project.

Objectives using CHRIS/Proba mode 2:
- Mapping of Cyanobacteria temporal and spatial distribution.
- Validation of Algorithms developed for MERIS bands.
- Testing and improvement of MERIS atmospheric correction models.
- Using the multiangular capabilities of PROBA to improve the model accuracy and study the Fresnel reflectance effects.

Methods:
- Ground campaigns measuring: Phytoplankton taxonomic composition and biomass; Phytoplankton pigment composition (HPLC, etc.); Nutrients concentration; Physicochemical parameters analysis; Cyanotoxins toxicity tests; Water optics: Above water and in water radiometry, Inherent optical properties measurement, reflectance measurements; Atmospheric optical measurements.

Area of work:
- Rosarito reservoir, Tiétar river, Tajo river basin, central Spain.

Several Partners of the project:
- CEDEX (Heading the Project), three Universities, Netherlands Institute of Ecology, Tajo Basin Authority, one consultant; INTA and ICC.

1. SCOPE AND OBJECTIVES

Last year the CEDEX proposed the inclusion in the CHRIS/Proba activities for 2004, the acquisition of some images sets over an Spanish site, in the frame of a Project funded by the Spanish Environment Ministry for Monitoring of Water Quality, specifically Cyanobacteria dynamics and toxicity in reservoirs, related to ESA AO-594 MERIS project.

1.1 CHRIS-PROBA objectives

- Mapping of Cyanobacteria temporal and spatial distribution, testing several algorithms for Phycocyanin and other Phytoplankton pigments.
- Validation of Algorithms developed for MERIS bands.
- Testing and improvement of MERIS atmospheric correction models, considering the adjacency and aerosols effects.
- Using the multiangular capabilities of PROBA to improve the model accuracy and study the Fresnel reflectance effects.

1.4 Area of work

Fig. 1. Map of Spain showing the biggest reservoirs

In Spain there are almost 1500 reservoirs very important for the adequate balancing between mean precipitation and water demand.
In that frame is essential to preserve the water quality in condition as good as possible, and also provide the most accurate assessment of ecological status of water bodies.

The CEDEX proposed as area of work the Rosarito reservoir, located in the Tietar river, Tajo river basin, central Spain, at foot of the Gredos mountains.

Center Lat/Lon: 40º 06’ 06” N / 05º 16’ 47”W
Top level area: 12.824 km².
Top level elevation: 311.23 aslm.
Maximum capacity: 92 hm³.

Fig. 2. Location of Rosarito reservoir

1.5 Partners of the project

The Centre for Studies and Experimentation on Public Works (CEDEX), through his Centre for Hydrographic Studies, will be the Coordinator of the Project. In the beginning of the proposal, stimulating the initiative and supporting the activities, mainly the atmospheric correction and processing, the University of Valencia is involved now in the project and will be an essential contribution to these topics. In addition the Centre for Limnology of the Netherlands Institute of Ecology will be very important support in the photosynthetic pigments analysis and modelling. Otherwise is fundamental the collaboration of the Confederación Hidrográfica del Tajo, Tajo Basin Authority, opening the facilities and helping to the lake and field operations. A consultant is charged of field campaigns on the water quality in swimming areas and cyanobacterial toxicity assessment.


ICC. Institut Cartogràfic de Catalunya, acquisition and processing of Airborne Hyperspectral sensor CASI imagery.
INTA. Instituto Nacional de Técnica Aeroespacial. acquisition and processing of Airborne Hyperspectral sensor AHS imagery.
SAR. Air Forces. Rescue Helicopter Unit. Ministry of Defence of Spain

2. METHODOLOGY
2.1 Ground campaigns tasks

Each 15 days from May 2004 until October 2006 (adapted to CHRIS-Proba calendar and, if possible, to MERIS calendar), measuring:

The campaigns comprise many different observations, measurements and water sampling for analytical and taxonomic determinations.

Phytoplankton taxonomic composition and biomass, pigment composition (HPLC, etc.); Nutrients concentration; Physicochemical parameters analysis; Cyanotoxins toxicity tests;

Will take Pigment concentration measurements vertical profiles: Temperature, conductivity and induced fluorescence of chlorophyll a, CDOM (Coloured Dissolved Organic Matter) and phycobiliproteins (phycocyanin and phycoerytrin) using a typical Multiparametric probe with CTD sensor and several associated fluorimeters.

In addition will take in vivo absorption coefficients of phytoplankton, detritus and CDOM.

Water Sampling for HPLC determinations of chlorophyll and carotenoids and for Phytoplankton composition and biomass assessment.

The water samples for analytical laboratory measurements and taxonomic assessment are taken in the first optical depth for the PAR radiation. According to Gordon and McCluney (1975), this depth (also called penetration depth) is where 90% of the remotely sensed light originates.

Using an ASD FR field spectroradiometer as detector, an commuter to alternate sensors and an integrating sphere to scattering determination, will be taken several Water optics measurements:
In order to guarantee the same conditions in every radiometric data (following the most accepted protocols), the optical fiber of spectroradiometer is mounted over an Above Water Measurement Device, incorporating both Azimuthal and Zenithal angle Controller, following the sun position.

Above water radiometry (multiangular reflectance measurement).

In water radiometry (upwelling and downwelling irradiance profiles).

Inherent optical properties measurement (absorption coefficients).

Surrounding land targets reflectance measurement; Atmospheric optical measurements (transmittance, aerosol optical thickness).

2.2 Multimission campaigns

In some dates we will try to coordinate several sensors and platforms over Rosarito reservoir, in order to rise the objective of complement, compare and improve the understanding of accuracy level and confidence interval in the fit, depending the applied sensor in each case.

Platforms/sensors:

CHRIS/Proba hyperspectral sensor image
MERIS sensor image
Airborne CASI hyperspectral sensor campaign (ICC)
Airborne AHS hyperspectral sensor campaign (INTA)
Helicopter (SAR) validation campaign with radiometry and sampling data collection.

2.3 Imagery acquisition proposal

Quantity: desirable 1 image per month, preferably may-november (to be defined)

Type: Water bands (Mode 2)
Full Swath
High Resolution
Multiangular (5 angles)

Sent the proposal by December 5th 2003, the sensor CHRIS/Proba was taken successfully the first image set over Rosarito reservoir the past April 10th 2004.

3. SOME RESULTS FROM THE FIELD DATA

Progressing in the MERIS Project, many radiometric data has been integrated in a database in order to relate that measurements with the other “in situ” water information.

As an initial approach to algorithm development, we have examined the relationships between ratios of MERIS bands and pigment concentrations through simple linear regression analysis.

The band selection process was based on the spectral properties of each pigment and a peak analysis of the Radiation spectra.
We found a very good linear relationship for chlorophyll a, \( (R^2=0.919) \) using the ratio between MERIS bands 9 and 7. Similar results are found using band 8 instead of 7.

The ratio between MERIS bands 9 and 6 (CHRIS/Proba 11 & 7) for cyanobacteria detection (the latter being centred at 620 nm) shows a good correlation \( (R^2=0.723) \) with phycocyanin concentration measured fluorometrically, and an even better correlation \( (R^2=0.945) \) with zeaxanthin measured using HPLC.

The correlation of other indicator pigments with MERIS band ratios is not as good, but it is still possible to develop some different algorithms more accurate for algal bloom monitoring.

In same direction, our Project has proposed, following the invitation of ESA, a dedicated MERIS experiment campaign to use the spectral programmability of the MERIS instrument to evaluate information (about photosynthetic pigment composition in Spanish Inland Water) from a modified MERIS band set.

4. REFERENCES


BIRD – CHRIS JOINT EXPERIMENTS FOR FIRE MAPPING


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ABSTRACT

Vegetation and peat fires play a major role in the global carbon cycle. CO₂, CH₄, and NO₂ and aerosols – emitted during biomass combustion - perturb Earth’s radiative budget. The amount of biomass combusted in a vegetation fire depends on fire intensity and fire severity. The determination of fire radiative energy release (FRE) per unit area allows to characterise the fire intensity, to assess the fire severity, and therefore, to distinguish also devastating fires from ecological useful “cleaning” fires. The experimental Bi-spectral InfraRed Detection (BIRD) satellite – a first dedicated fire recognition mission - provided unique data which permit the retrieval of the FRE of selected vegetation fires. PROBA - CHRIS measurements of selected fire scars, observed by BIRD during the active fire phase in Siberia, Australia, Portugal and Africa in 2002 and 2003, shall allow to determine how spectral reflectance characteristics change during vegetation recovery what can be used as an indicator of fire severity. CHRIS measurements over such selected test sites – to be conducted in 2004 - are considered as high resolution spectral signature examples of fire scars.

1. ISSUES OF CONCERN

The Carbon issue is one of the central themes of ESAs Living Earth Programme. Vegetation fires may release ~40% of the worldwide fossil fuel burning. World-wide burn in one year:

- about (500 - 500) x 10⁶ ha savannah area,
- about (5 - 10) x 10⁶ ha tropical rain forest (including peat lands), and
- about (5 - 20) x 10⁶ ha boreal forests (including peat lands).

The fire impacts on atmosphere (radiative balance affected by trace gases, e.g. ozone, CO/CO₂, aerosols), global carbon cycle, and climate change are not yet fully understood.

Large quantities of radiatively active (greenhouse) gases are annually emitted into the troposphere by vegetation fires [1] and by peat and coal seam burning [2], with significant amounts also emitted by active volcanoes [3]. These High Temperature Events (HTEs) play a major role in the global carbon cycle, with the pyrogenic gases CH₄, CO, and NO specifically affecting the chemistry and functioning of Earth’s atmosphere and CO₂, CH₄, and NO₂ perturbing Earth’s radiative budget [4]. Furthermore, burning of vegetative matter (free-burning vegetation fires, burning of biofuels) is the second largest anthropogenic source of sub-micron aerosols, which themselves greatly influence Earth’s radiation budget but in ways that are currently poorly quantified [5]. In recent years the 1997/98 forest and peat land fires in South-East Asia stand out as a particularly significant event resulting in large-scale regional atmospheric pollution. Burning of life and dead organic matter in desiccated peat-swamp ecosystems was a major contributor to this smoke-haze episode. The amount of carbon released during this event has been estimated to 0.81-2.57 Gt, corresponding to 13 to 40 percent of the global carbon emission annually released by burning of fossil fuels [2].

Despite numerous studies of individual vegetation fires, the global magnitude of pyrogenic emissions is still not yet known exactly, though it is known that it is subject to very large annual and regional variations. Therefore, a challenging and important task is to monitor, characterise and quantify HTE emissions in order to...
better assess their effect on the whole Earth system [1]. Since HTE activities occur over widely distributed areas of the Earth’s surface, space-borne remote sensing is the only feasible method to undertake such a task, supported by the appropriate ground-based observations.

The relationship between remotely sensed parameters and the actual mass of fuel burned is strongly dependent upon other variables such as the vegetation density and the fraction of available fuel burned, parameters that are very difficult to estimate accurately via remote sensing [6]. A recent study has demonstrated order of magnitude differences between biomass combustion estimates based (a) on current EO-driven approaches and (b) on historical fire frequencies, concluding that new methodologies are required to provide new and independent assessments of this parameter to reduce current levels of uncertainty [1].

One new analytical tool suggested for this purpose, termed the Fire Radiative Energy release (FRE), was first developed during preparations for the MODerate Imaging Spectro-radiometer (MODIS) instrument [7], [8]. FRE is a remotely sensed measure of the rate of radiative heat output during burning (or volcanic activity), which has been shown to be well related to rates of emission of smoke and of vegetation combustion [9]. Temporal integration of FRE over a fire's lifetime should therefore allow the total biomass combusted to be estimated and support the derivation of the quantity of emitted pollutants [9].

New methodologies such as FRE, along with recent developments in sensors and techniques for identifying and analysing active fires [10], [11], [16] mapping burned area [12], [13], and analysing the resultant atmospheric emissions [14], [15], represent significant advances in our ability to analyse HTE events and their effects from space.

The characterization of ongoing (active) fires at the detection phase and during the monitoring phase is currently restricted to the localization of the fire fronts.

The characterization of fire intensity by determining fire energy release per area unit, however, would also allow the estimation of fire severity [17].
Fire severity is an important determining agent of post-fire development. There are a range of ecosystems where fires of low to medium intensity and severity are beneficial for ecosystem stability and productivity. For instance, the vast amount of seasonal tropical vegetation (tree, grass and bush savannas, monsoon forests) are well adapted and require regular influence of low- to moderate-intensity fires. Similar interdependences between fire and forest ecosystems are found in North America and Australia.

With the ongoing change of the policy of the Russian Federation to abandon the “Fire Control Policy” which involves the intent to control all fires if possible, towards developing a “Fire Management Policy” that integrates natural and human-made fires burning under prescription, a space borne tool for assessing the radiative energy release would be extremely important.

Fig. 1 shows a stand-replacement fire observed in Eastern Siberia. This type of fire has destructive effects on:

- Elimination of dominant plant species,
- Perturbations in biogeochemical cycles (influencing the Carbon, Nitrogen, Sulphur, Phosphor cycle), and
- Land surface degradation (i.e. deforestation, water run-off, soil erosion, landslides, flooding).

Fig. 2 shows a low to medium intensity fire in Central Siberia. This type of fire has beneficial effects on:

- Regulation of vegetation structure and composition,
- Increasing ecosystem stability and productivity, and, last not least,
- Reduction of the fuel load.

2. GENERAL OBJECTIVE OF THE BIRD – CHRIS/PROBA FIRE MAPPING EXPERIMENTS

The boreal forest ecosystems of Eurasia represent the most important example in this regard. A number of types of Northern Asia’s coniferous forests are very well adapted to fire, and surface fires of low to moderate intensities are very important to reduce fuel loads and thus stabilizing the forest by making less likely to be affected by high-intensity, stand-replacement fires.
The wildfires in Portugal during 2003 in a large number of cases burned extremely hot due to the high amounts of combustible materials in the wild lands and plantation forests. Ecosystem recovery after these high-severity fires is extremely slow, sometimes even impossible due to secondary effects. The secondary effects include surface water runoff due to reduced water-holding capacity of the topsoil, erosion, landslides and flooding.

As of now there is no air- or space borne decision-support system available which would deliver criteria for deciding whether an ongoing fire is “beneficial” or “destructive”. This can be recognized during the active fire phase by the estimation of the Fire Radiative Energy release (FRE) and by spatial high resolution observations of the vegetation re-grow development after the fire. BIRD and CHRIS/PROBA observations may deliver prototype data products for such a future decision support system.

The BIRD data obtained in 2003 over active fires in selected regions (test sites) of the world will be used to define the FRE, i.e. to assess the type of fire during the burning phase.

CHRIS on PROBA will be used to observe these test sites in 2004. The multi-angle hyperspectral data of CHRIS shall allow to study the re-growing process.

The combination of the higher level data products:
- FRE retrieved from BIRD data of active fires, and
- Hyperspectral and multi-view angle CHRIS data of fire scars
will allow to assess the fire severity for the selected test sites.

3. BIRD MISSION OVERVIEW

The DLR satellite BIRD is a technology demonstrator of new infrared push-broom sensors dedicated to recognition and quantitative characterisation of thermal processes on the Earth surface [18], [19]. BIRD was piggy back launched with the Indian Polar Satellite Launch Vehicle in a 570 km circular sun-synchronous orbit on 22 of October 2001 (together with the PROBA satellite) and is successfully operated by DLR since that time.

3.1 BIRD primary mission objectives

The BIRD primary mission objectives are:
- test of a new generation of infrared array sensors with an adaptive radiometric dynamic range,
- detection and scientific investigation of high temperature events such as forest fires, volcanic activities, and coal seam fires,
- test of small satellite technologies, such as an attitude control system using new star sensors and new actuators, an on-board navigation system based on a new orbit predictor and others.

3.2 The BIRD main sensors

HSRS is a two-channel push-broom scanner with spectral bands in the mid-infrared (MIR) and thermal infrared (TIR) spectral ranges. The sensitive devices are two Cadmium Mercury Telluride (CdHgTe) photodiode lines. The lines - with identical layout in the MIR and TIR - comprise 2 x 512 elements each in a staggered structure. HSRS sensor head components of both spectral channels are based on identical technologies to provide good pixel co-alignment. Both spectral channels have the same optical layout but with different wavelength-adapted lens coatings [20]. The detector arrays are cooled to 100 K in the MIR and to 80 K in the TIR. The cooling is conducted by small Stirling cooling engines. The maximal TIR photodiode cut-off wavelength of about 10.5 µm, which can be achieved at 80 K, on one hand and the atmospheric ozone band at 9.6 µm on the other hand require to use the 8.5 – 9.3 µm band for TIR channel of the HSRS instead of the usual 10.5 – 11.7 µm band. The HSRS sensor data are read out continuously with a sampling interval that is exactly one half of the pixel dwell time. This time-controlled “double sampling” and the staggered line array structure provide the sampling step that is a factor of 2 smaller

Fig. 3. The BIRD Hot Spot Recognition System (HSRS)
than the HRSR pixel size, coinciding with the sampling step of the WAOSS NIR nadir channel. The observation of high temperature events in the sub-pixel range requires a precise designed real time signal adaptation control mechanism. A special real time procedure for this signal adaptation is applied to the signals of both HSRS channels. This procedure recognises the element signals which are close to saturation. A repeated sampling within the same clock time period is provided and the values from this additional sampling of the highly illuminated areas are transmitted in a special “Hot Area Set (HAS)”. The saturated pixel signals are automatically replaced by values from this HAS during the on-ground data processing.

The overall detector control makes it possible to synchronise both IR-sensor channels externally by WAOSS sampling clock signal. This is a basic prerequisite for the on-ground pixel co-registration procedure as, for instance, required for the application of the bi-spectral (Dozier) method [21].

Due to its higher spatial resolution, BIRD can detect fires with the area a factor of seven smaller than operational polar orbiting systems such as the Advanced Very High Resolution Radiometer (AVHRR) or the Moderate Resolution Imaging Spectro-radiometer (MODIS). However, one has also to keep in mind that AVHRR and MODIS can provide daily global coverage while BIRD is a demo mission providing in the best case semi-operational data sets.

3.3 Retrieval of active fire characteristics

In spite of the fact that fires are well recognizable in the MIR channel, a more sophisticated detection procedure is required to reject sun glints and warm surfaces that may also appear like bright spots in the MIR causing false alarms. For this purpose, the BIRD hotspot detection algorithm was developed [16] that includes the following thresholding tests:

- Adaptive MIR thresholding to detect potential hot pixels,
- NIR thresholding to reject strong sun glints and thick clouds,
- Adaptive MIR/NIR radiance ratio thresholding to reject weaker sun glints, thinner clouds and other high-reflective objects,
- Adaptive MIR/TIR radiance ratio thresholding to reject warm surfaces,
- Consolidation of the adjacent hot pixels in hot clusters (hotspots) and estimation of hotspot characteristics: the effective fire temperature and area, radiative fire energy release (FRE).

The effective fire temperature $T_f$ and the effective fire area $A_f$ are retrieved with the Bi-spectral technique [21] using the MIR and TIR cluster radiance fluxes and background radiance estimation from the neighboring pixels. In contrast to the usual application of the Bi-spectral technique, we apply it not to separate hot pixels but to entire hot clusters. The advantages of the cluster-level approach are:

- the effective fire area does not depend on the point spread function (PSF) of the MIR and TIR channels,
- the estimations of effective fire temperature and area are low sensitive to sub-pixel inter-channel MIR/TIR geometric co-registration errors and MIR/TIR PSF difference, and
- the effects of background clutter are reduced.

Nevertheless, an estimation of the effective fire temperature and area with a reasonable accuracy is possible only if the fire proportion in the hotspot is not less than ~1% since otherwise the retrievals are strongly sensitive to the TIR background clutter.

The Fire Radiative Energy release (FRE) is a more stable parameter for a quantitative characterisation of both large and small fires [22], and, therefore, it is principally used for coding hotspots in the standard BIRD data products. FRE is useful for parameterisation of the amount of burning fuel, as well as for practical fire fighting purposes where the energy release per a unit length of a fire front characterises the front strength.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>WAOSS-B</th>
<th>HSRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral bands</td>
<td>VIS: 600-670nm</td>
<td>MIR: 3.4-4.2µm</td>
</tr>
<tr>
<td></td>
<td>NIR: 840-900nm</td>
<td>TIR: 8.5-9.3µm</td>
</tr>
<tr>
<td>Focal length</td>
<td>21.65mm</td>
<td>46.39mm</td>
</tr>
<tr>
<td>Field of view</td>
<td>50°</td>
<td>19°</td>
</tr>
<tr>
<td>f-number</td>
<td>2.8</td>
<td>2.0</td>
</tr>
<tr>
<td>Detector</td>
<td>CCD lines</td>
<td>CdHgTe Arrays</td>
</tr>
<tr>
<td>Detector cooling</td>
<td>Passive, 20°C</td>
<td>Stirling,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80-100 K</td>
</tr>
<tr>
<td>Detector element size</td>
<td>7µmx7µm</td>
<td>30µmx30µm</td>
</tr>
<tr>
<td>Detector element number</td>
<td>2880</td>
<td>2x512 staggered</td>
</tr>
<tr>
<td>Quantisation</td>
<td>11bit</td>
<td>14bit (for each</td>
</tr>
<tr>
<td></td>
<td></td>
<td>exposure)</td>
</tr>
<tr>
<td>Ground pixel size</td>
<td>185m</td>
<td>370m</td>
</tr>
<tr>
<td>Sampling step</td>
<td>185m</td>
<td>185m</td>
</tr>
<tr>
<td>Swath width</td>
<td>max. 533km</td>
<td>190km</td>
</tr>
</tbody>
</table>
FRE can be estimated using the effective fire temperature and area as retrieved by the Bi-spectral technique:

\[ P_F = \sigma (T_F^4 - T_{bg}^4)A_F, \]  

(1)

where \( \sigma \) is the Stefan-Boltzmann constant, \( T_{bg} \) is the background temperature that is assumed to be equal to the mean at-surface TIR temperature in the vicinity of the hot cluster.

A low sensitivity of the FRE/MIR radiance ratio to fire temperature above 700 K is exploited in the MIR radiance method [22] for a direct FRE estimation for hot pixels without a preliminary retrieval of \( T_F \) and \( A_F \) :

\[ P_F = 17.3 \cdot 185^2 \cdot (I_{MIR} - \bar{I}_{MIR,bg}) [W], \]  

(2)

where \( I_{MIR} \) and \( I_{MIR,bg} \) are the BIRD MIR radiances of a hot pixel and of the background. In order to obtain the FRE of a hot cluster, the FRE (7) has to be summed over all pixels in the hot cluster. However, at lower temperatures, the method may lead to a drastic FRE underestimation. Generally, the MIR radiance method is equivalent to the MODIS method [23] but has a more transparent physical sense.

In the BIRD algorithm, we use the bi-spectral method for FRE estimation for hot clusters. In case the bi-spectral retrievals confirm that the fire temperature exceeds 700 K, we apply the MIR radiance method for hot pixels to analyze FRE distribution within a cluster (it can make sense only for large hot clusters significantly exceeding the BIRD PSF width).

FRE can be estimated with a reasonable accuracy also for small fires (down to the detection limit) in contrast to the estimation of the effective fire temperature and area.

The FRE characterizes the intensity of burning. However, it accounts only for the radiated part of the energy released by a fire, while a significant portion of fire energy is consumed by convection, evaporation and heat transfer in the ground. This has to be taken into account when interpreting the FRE magnitude in terms of fire severity.

3.4 BIRD active fire observation in Central Portugal in summer 2003

On 4 August 2003, BIRD imaged huge forest fires in the central region of Portugal where catastrophic fires took place in the area of Castello Branco. Fig. 4 shows a 100 x 100 km² fragment of the BIRD image. The detected hotspots with their energy release are projected on the NIR image, showing the burned areas (fires scars) as dark patches and active fires as color coded hotspots.

4. CHRIS ON PROBA

ESA’s small, low-cost PROBA (Project for On-Board Autonomy) satellite is designed to validate new spacecraft autonomy and 3-axis control and data system technology as part of the Agency’s In-orbit Technology Demonstration Programme [24].

The Compact High Resolution Imaging Spectrometer (CHRIS) - which shown on Fig. 5 - is the main payload of PROBA. PROBA’s high-performance attitude control and pointing system supports the multi-view angle spectral reflectivity measurements of CHRIS as schematically shown on Fig. 6.

Tab. 2 explains the CHRIS/PROBA multi-viewing angle image sequence [25].

Tab. 2. CHRIS/PROBA multi-view angle imaging sequence

<table>
<thead>
<tr>
<th>Chronological imaging order</th>
<th>Tag No. order</th>
<th>Scan direction</th>
<th>Fly-by zenith angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>1</td>
<td>N-S</td>
<td>+ 55°</td>
</tr>
<tr>
<td>Second</td>
<td>2</td>
<td>S-N</td>
<td>+ 36°</td>
</tr>
<tr>
<td>Third</td>
<td>3</td>
<td>N-S</td>
<td>0°</td>
</tr>
<tr>
<td>Fourth</td>
<td>4</td>
<td>S-N</td>
<td>- 36°</td>
</tr>
<tr>
<td>Last</td>
<td>5</td>
<td>N-S</td>
<td>- 55°</td>
</tr>
</tbody>
</table>
There are five formal CHRIS imaging modes, classified as Modes 1 to 5 [25]. Mode 3 with 18 “land channels” between 442 and 1019 nm, a ground sampling distance of 18 m and 13 km swath width will be used for the fire severity mapping.

5. JOINT FIRE SEVERITY OBSERVATION TARGETS

Principal Investigators from four continents (Asia, America, Australia and Europe) declared their interest in December 2003 and January 2004 to contribute to the BIRD–CHRIS/PROBA Fire Mapping Experiment.

5.1 Selection and grouping of the targets/test sites

Fire severity estimation shall be conducted for regions of Siberia, Portugal, Australia and Alaska by repeated observations of selected fire scars by CHRIS/PROBA, preferably for scars where BIRD provided active fire data in summer and fall 2003.

Taking into account the expression of interest of the Principal Investigators (PI’s) from different international organisations involved in fire ecology and remote sensing of fires, there may be considered two groups of fire severity experiments:

Group 1 with ground truth provision for fire scars during or close to CHRIS/PROBA observations in 2004 where active fires were observed by BIRD in 2003 and possibly other satellites in 2003 or before. This group consist of test sites in Siberia (Angara Priority 1), SE-Australia, Central Portugal and South Africa / Botswana.

Group 2 with ground truth provision for fire scars during or close to CHRIS/PROBA observations in 2004 where active fires were observed by other satellites in 2003 or before. This group consist of test sites in Siberia (Angara Priority 2), Yakutsk and Alaska.

5.2 Imaging requirements

The imaging of CHRIS/PROBA during fire severity mapping experiments in 2004 is made based on the following criteria:
- the sites should contain fire scars which were preferably observed by BIRD in 2003 during the active burning phase (if possible, in several passes within several consecutive days), i.e. pre-selection of sites is “BIRD record guided”; 
- the sites shall possibly contain fire scars from vegetation fires burning before spring – summer 2003, which are analysed by other science groups, and
- in-situ information from international scientific Co-investigators is desired.
### Tab. 3. Test sites for fire severity mapping experiments

<table>
<thead>
<tr>
<th>Site</th>
<th>Longitude</th>
<th>Latitude</th>
<th>In-situ Data</th>
<th>Principal Investigator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angara – Priority 1 Sites A, B, C Average height a.s.l: 150–300 m</td>
<td>A: 97.87° E</td>
<td>58.70° N</td>
<td>A. Sukhinin, IFOR Krasnoyarsk (RU)</td>
<td>C. George, Section for EO CEH Monks Wood (UK)</td>
</tr>
<tr>
<td></td>
<td>B: 96.92° E</td>
<td>57.95° N</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: 96.78° E</td>
<td>57.36° N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South-East Australia</td>
<td>148.40° E</td>
<td>35.80° S</td>
<td>CSIRO EO Centre</td>
<td>A. Held, A. Marks, CSIRO, Australia</td>
</tr>
<tr>
<td>Central Portugal, Macao site, Average height a.s.l: 300 m</td>
<td>7.84° W</td>
<td>39.57° N</td>
<td>Camara Municipal de Mação and Instituto Politecnico de Tomar</td>
<td>P. Barbosa, Institute for Environment and Sustainability- JRC, Ispra (I)</td>
</tr>
<tr>
<td>South Portugal, Herdade da Parra site Average height a.s.l: 109 m</td>
<td>8.42 W</td>
<td>37.31 N</td>
<td>Direcção-Geral dos Recursos Florestais</td>
<td>P. Barbosa, Institute for Environment and Sustainability- JRC, Ispra (I)</td>
</tr>
<tr>
<td>South Africa, Botswana Average height a.s.l: tbd</td>
<td>25° E (tbd)</td>
<td>17.8° S (tbd)</td>
<td>tbd.</td>
<td>M. Wooster, Kings College, University of London (UK)</td>
</tr>
<tr>
<td><strong>Group 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angara – Priority 2 Sites D and E Average height a.s.l: 150–300 m</td>
<td>D: 98.42° E</td>
<td>58.81° N</td>
<td>A. Sukhinin, IFOR Krasnoyarsk (RU)</td>
<td>C. George, Section for EO CEH Monks Wood (UK)</td>
</tr>
<tr>
<td></td>
<td>E: 59.99° E</td>
<td>58.57° N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yakutsk, Average height a.s.l: 100 m</td>
<td>129.50 E</td>
<td>62.30° N</td>
<td>N. Sedelnik, Forest Service of Sakha, Yakutia, (Ru)</td>
<td>Hiroshi Hayasaka Graphics &amp; Fire Science Division, University of Hokkaido, (Jp)</td>
</tr>
<tr>
<td>Alaska, Fairbanks, Average height a.s.l: tbd</td>
<td>147.50° W</td>
<td>65.16° N</td>
<td>tbd.</td>
<td>Hiroshi Hayasaka Graphics &amp; Fire Science Division, University of Hokkaido, (Jp)</td>
</tr>
</tbody>
</table>

Day time CHRIS/PROBA observations of the selected site are mandatory. Timely close BIRD observations of the site are desirable, but not mandatory. For the fire severity experiment, 3-monthly imaging of the site for ~ 24 months after the burn are required to track its recovery.

Fig. 7 shows a BIRD image fragment of one of the Angara test sites which was observed during active fire phase on 10 July 2003. CHRIS will observe this test site (as well as the other test sites indicated in Tab. 3) in 2004 in Mode 3 to provide hyperspectral multi-view angle data in the visible and near IR wavelength region.

#### 5.3 Description of the test sites

Tab. 3 indicates and describes the test sites which are currently considered for the study.

#### 6. NEXT STEPS IN 2004

CHRIS observations was performed of the South East Australian Trial test site at 148.40°E and 35.80°S (see Table 3, Group 1) for the 19, 20, 28 of January, the 4, 13, 20, 28 of February and the 24 of March 2004. BIRD data with major active fires in the region – including the Trial test site area – was obtained 26, 28, and 31 January 2003. The possibility of vegetation re-grow analysis based on the CHRIS data of 2004 for scars from fires observed by BIRD in January 2003 will be evaluated by CSIRO and DLR.

CHRIS observed the Macao test site in Central Portugal first time on 13 of May 2004. Fig. 8 shows a true colour CHRIS image fragment with the Macao test site in the red box. The first observation of the South Portugal Herdade da Parra test site is planned for May 21, 2004.
BIRD observed major active fires in Central Portugal on 4 of August 2003 and in South Portugal on 14 of August 2003, including the Macao test site and Herdade da Parra test site, respectively.

The CHRIS observations of Macao and Herdade da Parra areas in May 2004 were accompanied by ground truth measurements conducted by Portuguese organisations as indicated in Table 3. Repeated CHRIS measurements of both test sites in Portugal are foreseen for summer 2004 with the aim to study the severity of the 2003 fires and the vegetation re-grow.

BIRD observed active fires in the Angara region at 96°-98°E and 56°-58°N in Siberia in mid of July 2003. CHRIS observations of the Angara test sites A, B, and C are envisaged for June and/or July 2004, depending on the time slot of the ground truth collection in these test areas by a team from the Sukachov Institute of Forest (IFOR) of the Siberian Branch of Russian Academy of Sciences which shall be led by Dr. Anatoly Sukhinin. These threefold measurements (BIRD, CHRIS and ground truth) will be used for fire severity analysis in the test sites Angara A, B, and C.

Fig. 8 True colour image fragment of the Macao test site shown in the red box in Central Portugal obtained by CHRIS on 13 of May 2004

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Assessment of CHRIS PROBA data for land cover derivation and flood mapping. Application over the Dongting - Poyang lake sectors and to the Songhuajiang River (China)

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Abstract
The goals of the Chris Proba Flood Dragon project are to assess the potential of HR multispectral Chris Proba imagery for wetland and flood mapping in conjunction with MERIS and ASAR data from ENVISAT. Chris Proba data would be used as reference data in order to derive information on land use/land cover. In addition a number of Chris Proba images would be acquired during a flood event and used to validate the information derived from ASAR and medium resolution optical data. Test sites are located within the major wetland areas of China and correspond to flood prone sensitive ecosystems.

1 - General context

Within the framework of the flood Dragon project nr 2551, "Assessment of the synergistic exploitation of ENVISAT ASAR and MERIS data for Plain Flood Rapid Mapping and for Flood Support Risk Management", accepted as part of the ESA Dragon Programme [1], a specific Chris Proba data request have been made.

The goals of the Flood Dragon project are to enhance the ENVISAT objectives of monitoring natural disasters such as floods. ENVISAT ASAR and MERIS’s spatial and temporal resolution potential in flood mapping will be explored: ASAR spatial resolutions ranging from Precision to Global modes will be assessed in order to maximize the revisit and coverage, as well as evaluating polarization modes for thematic accuracy. One of the major ultimate goals is to give the guidelines/recommendations for a Near Real Time exploitation of SAR data in flood monitoring. Another aspect of the proposal deals with the exploitation of ENVISAT data as an input to monitoring tools at this at a catchment’s scale. This is necessary to improve flood prediction and water resources management.

2 - Test sites

In the framework of the Flood DRAGON project, two major test sites, known as high-risk areas, have been selected in China. The first, the Dongting-Poyang lakes sector, covering 300*600 km$^2$ and located in Central China, is an important part of the Yangtze watershed. The Dragon Project’s second test site, part of the Songhua Jiang flood zone, a 200*450 Km$^2$ area located in the Heilongjiang province (NE China, eg. Manchuria) consists of a very flat zone where huge marshlands, internationally renowned for their biodiversity interest, coexist with a wide agricultural plain. Furthermore, this is a very sensitive area from an economic point of view, such as the Daqing oilfield or the city of Harbin.

Fig. 1. Flood Dragon test sites: Songhua Jiang and Poyang-Dongting Lakes

Over these test sites, reference data such as ERS, Landsat SPOT data are already collected and integrated
into database. Three areas, within these large Flood Dragon Chinese test sites, and sensitive in terms of both economic-human impact and their ecosystems, have been selected. Each Chris Proba test site size is equivalent to a mosaic of 4 Chris Proba scenes, 26°26km².

Firstly, the ZHALONG national nature reserve, near Qiqihar in the Heilongjiang Province. The ZHALONG at 210,000ha is the biggest wetland nature reserve in China. This internationally renowned RAMSAR nature reserve is a very sensitive ecosystem, prone to flooding, drought and fire.

The second Chris Proba test site is in the KANGSHAN area, Jiangxi Province, a flooded area near Poyang Lake the biggest freshwater lake in China, covering 391,400ha. Kangshan area is an important wetland reserve zone and also a key area for flood control, acting as storage area. The last Flood Dragon test site is in the XIHU area, Hunan Province, near the Dongting Lake; one of the biggest freshwater lakes in China covering 274,000 ha. The Xihu area is an important wetland reserve zone, a rare transient birds habitat, and plays an important role in floodwater storage and control, ecosystem balance and socio-economically.

CHRIS Proba data would be used as reference data and to derive information on land cover. Over each test site the acquisition of a 4-image mosaic will be required. One site will be covered each year, the Zhalong in 2004, the Kangshan in 2005 and Xihu in 2006. The format of the required data is full spatial resolution, the 18 wavelengths with Land configuration and a near nadir acquisition angle.

Moreover, whenever a major event will occur over the next three years affecting the test sites, a fast programming would be carried out in order to get the Chris Proba data as crisis data.

The High resolution Land configuration is requested, as the goals are to derive land cover information as well as to extract water bodies. During this project it will not be possible to explore BRDF capabilities in land use recognition and extraction nor the suspended component in floodwaters.
4 - Chris Proba data exploitation plan

Within the framework of the Flood Dragon project Chris Proba data will have been used in order to:

- Generate a land cover map
- Generate reference background imagery for crisis products (i.e. it is difficult to access topographic maps or aerial photographs in China, so HR data are a good substitute)
- Use as reference to be compared with crisis data in order to differentiate between flooded areas and permanent water bodies. In these wet landscapes, using only a crisis image it can be very difficult to distinguish these types of water. So a reference is needed and it is easier to use the same type of data as both reference and crisis data.

The second point concerns the access to crisis data; i.e. the flooding period usually lasts from May to September. For us the Chris Proba data exploitation goals are the following:

- Use Chris Proba data to calibrate/validate the MERIS results
- Use Chris Proba as a "HR crisis reference data" in order to calibrate the results obtained from the multi-resolution SAR data
- Carry out an assessment of the Chris Proba data for flood mapping in a R&D context. Presently, only a few Chris Proba data exploitation tests have been performed, and this always in a rush during International Charter “Space and Major Disasters” actions [2, 3].

5 - Conclusion

This Chris Proba project will provide information on the use of multi-spectral high-resolution data for flood mapping as well as calibrating results obtained from similar sensors of lower resolution and ASAR data.

Acknowledgements: The authors would like to thank R. Bianchi and F. Sarti from ESA for their help, encouragement and advice during the elaboration of the Chris Proba flood Dragon proposal.

References:

[1] Dragon web site: http://earth.esa.int/dragon/


ABSTRACT
In recent years, hyperspectral remote sensing has stepped into a new stage in China. There are several advanced hyperspectral imaging systems developed in Chinese. Especially the Chinese Academy of Sciences (CAS) has been playing a very important role in such High-technology developing activities. Pushbroom Hyperspectral Imager (PHI) and Operative Modular Imaging Spectrometer (OMIS) are two types of representative hyperspectral imagers developed by CAS. A hyperspectral digital camera system (HDCS), with limit-number bands but high spectral resolution, was also developed and tested in 2000. Aiming to different observation objects and applications, the spectral wavelength and resolution of HDCS can be easily changed by selecting different interference filters. According to these airborne hyperspectral sensors, some data processing and info-extraction models are also developed in China. These models have been widely used in many remote sensing projects, such as precise agriculture, mineral exploration, urban investigation, and so on. In addition, a Hyperspectral Image Processing and Analysis System (HIPAS) software were also developed.

Keywords: Hyperspectral Remote Sensing, Imaging spectrometer, Image processing.

1. INTRODUCTION
The trend in the development of remote sensing has been, with the increase of the spectral resolution, to move from the panchromatic multispectral to the hyperspectral, and then to the ultraspectral. During the last 15 years, studies on the hyperspectral remote sensing have been carried out intensively in China. In the Chinese airborne remote sensing system, the hyperspectral sensor is already in place as one of the basic systems. Under the great supports of Chinese High Technology Developing Project, two new kinds of hyperspectral sensors, PHI and OMIS, were designed specifically for hyperspectral applications. In addition, a small hyperspectral digital camera system (HDCS) with limited number but narrow band was also implemented for environmental and agricultural monitoring. With the development and perfection of the hyperspectral remote sensing technologies, hyperspectral remote sensing has been the major technique applied in many studies. For hyperspectral sensors have become available to provide both high spatial and high spectral resolution with high signal/noise ratio. Due to the sufficient spectral features such as spectral reflectance with wavelength it provides, hyperspectral data plays an important role in the different fields. So it is a rush now to develop some special algorithms and models for hyperspectral data processing, information extraction, classification and identification. The technical characteristics of some hyperspectral imagers in the world are presented in table 1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Spectral Coverage (µm)</th>
<th>Number of Bands</th>
<th>Spectral Interval (nm)</th>
<th>IFOV (mrad)</th>
<th>FOV (degree)</th>
<th>Developer</th>
<th>Available Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIS</td>
<td>0.44-11.8</td>
<td>71</td>
<td>20/600</td>
<td>3</td>
<td>90</td>
<td>China</td>
<td>1991</td>
</tr>
<tr>
<td>AVIRIS</td>
<td>0.38-2.5</td>
<td>224</td>
<td>10</td>
<td>1</td>
<td>30</td>
<td>JPL, U.S.A</td>
<td>1987</td>
</tr>
<tr>
<td>GERIS</td>
<td>0.4-2.5</td>
<td>63</td>
<td>25/120/1</td>
<td>2.5</td>
<td>90</td>
<td>GER Corp. U.S.A</td>
<td>1986</td>
</tr>
<tr>
<td>CASI</td>
<td>0.4-1.0</td>
<td>288</td>
<td>2.9</td>
<td>1</td>
<td>35</td>
<td>ITRES Research, Canada</td>
<td>1989</td>
</tr>
<tr>
<td>MIVIS</td>
<td>0.43-12.7</td>
<td>102</td>
<td>20/50/8/4</td>
<td>2.0</td>
<td>70</td>
<td>Daedalus Enterprise Inc., U.S.A</td>
<td>——</td>
</tr>
</tbody>
</table>

Table 1. some technical characteristics of the hyperspectral imagers.

In the field of vegetation study especially for precise agriculture, some successful progresses are already achieved. They are the works of Tanvir[1], Chadbum[2].

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Proc. of the 2nd CHRIS/Proba Workshop, ESA/ESRIN, Frascati, Italy 28-30 April (ESA SP-578, July 2004)
et al. [3, 4, 5, 6] by using derivative spectral analysis model for background noise elimination, “red edge” determination or biochemical parameter detection. Another attempt is to search all kinds of spectral parameters or parameter combinations to build reliable relationship with biochemical parameters such as LAI [7–8]. Furthermore, special angle mapper (SAM) model is also proved to be effective [9, 10]. However, there still are many difficulties due to the unique spectral features of vegetation as: 1). The spectral shapes of all vegetation are somewhat similar while the spectra of a same species vary remarkably and therefore it is very difficult to classify using the usual method for multi-band image; 2). Vegetation is active with a high dynamic and therefor it has a strong spatial and temporal variation; 3). Usually it is a mixed spectrum and is strongly effected by many kinds of background even the weather; 4). The influencing factors and their effects are very complicated; 5). The spectral effects of different pixel size is variable. Therefore, new model to consider the complex, mixed, dynamic and temporal properties of vegetation spectrum must be studied and developed to promote the better application of hyperspectral remote sensing in vegetation detection. Due to the particularity of hyperspectral data processing, some special hyperspectral data processing and analysis models and software were developed for remote sensing applications.

2. HYPER SPECTRAL IMAGER DEVELOPMENT

2.1 Airborne Hyperspectral Imager

Following the world foreland of remote sensing, several kinds of applied hyperspectral imagers were built in China. Shanghai Institute of Technical Physics is working on the development of airborne multispectral scanner, imaging spectrometer and scanning laser ranging-imager sensor for 20 years. In 1991, the modular airborne imaging spectrometer (MAIS) had been tested in Darwin, Australia. Since 1994, the project group led by Pro. XUE Yong-Qi began to develop a new concept imaging spectrometer. Based on the fundament of optics imager technology and diffract technology, a series of multispectral scanner, imaging spectrometer and two generation of pushbroom hyperspectral imager had been developed and applied in the field of environment monitoring, geology study, oil and gas prospecting, vegetation, ocean observation, city layout, fine agriculture, forest fireproofing and so on.

Operational Modular Imaging Spectrometer (OMIS) has two models-OMIS-I and OMIS-II. The scanning mirror cross track, the flight of plane along track. OMIS collects reflective and radiation light from ground by RC telescope. The dispersal of light is by Grating.

Table 2 The specification of OMIS

<table>
<thead>
<tr>
<th></th>
<th>OMIS-I</th>
<th>OMIS-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Waveband Number</td>
<td>128</td>
<td>68</td>
</tr>
<tr>
<td>Spectral Range</td>
<td>0.40—1.1 10 64</td>
<td>0.4—1.1 10 64</td>
</tr>
<tr>
<td>Interval of Spectral Sampling (nm)</td>
<td>1.05—1.70 16</td>
<td>1.50—1.75 16</td>
</tr>
<tr>
<td>Bands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Range</td>
<td>2.0—2.5 32</td>
<td>2.05—2.35 16</td>
</tr>
<tr>
<td>Interval of Spectral Sampling (nm)</td>
<td>1.8—3.0 8</td>
<td>3.0—3.5 8</td>
</tr>
<tr>
<td>Bands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Range</td>
<td>3.0—5.0 8</td>
<td>3.0—5.0 16</td>
</tr>
<tr>
<td>Interval of Spectral Sampling (nm)</td>
<td>0.0—12.5 3</td>
<td>0.0—12.5 3</td>
</tr>
<tr>
<td>Bands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Range</td>
<td>5.0—8.0 32</td>
<td></td>
</tr>
<tr>
<td>Interval of Spectral Sampling (nm)</td>
<td>3.0—5.0 8</td>
<td></td>
</tr>
<tr>
<td>Bands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Range</td>
<td>8.0—12.5 500</td>
<td></td>
</tr>
<tr>
<td>Interval of Spectral Sampling (nm)</td>
<td>5.0—8.0 8</td>
<td></td>
</tr>
<tr>
<td>Bands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Instantaneous field of View (mrad)</td>
<td>5.0 optional</td>
<td></td>
</tr>
<tr>
<td>Field of View (°)</td>
<td>&gt;=70 Across-Track</td>
<td></td>
</tr>
<tr>
<td>Scan Rates(s)</td>
<td>5, 10, 15, 20 optional</td>
<td></td>
</tr>
<tr>
<td>Spatial Sampling</td>
<td>512 pixels/line</td>
<td>1024/512 pixels/line</td>
</tr>
<tr>
<td>Quantization (bit)</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Maximum Data Rate(Mbps)</td>
<td>21.05</td>
<td></td>
</tr>
<tr>
<td>Detector</td>
<td>Si, InGaAs, InSb</td>
<td>Si, InGaAs, InSb/MCT</td>
</tr>
</tbody>
</table>

Pushbroom Hyperspectral Imaging is a new method to acquire the imaging spectrum data with the developing of focal plane technology. As showed in Figure 1, the fore optics collects lights reflected from ground. The length and width of entrance slit effect the spectral resolution and swath. The incoming electromagnetic radiation will be separated into distinct angles. The spectrum of a single ground pixel will be dispersed and focused at different locations of one dimension of the detector array. The number of pixels is equal to the number of ground cells for a given swath. The motion of the aircraft provides the scan in along track direction, thus, the inverse of the line frequency is equal to the pixel dwell time.

PHI collects spectral images by using a grating. There are two kinds of diffraction grating used in the design of PHI. One is reflective grating and the other is transmission grating. The specifications of three kinds
of PHI are listed in the Table 3.

Table 3 The specification of PHI

<table>
<thead>
<tr>
<th></th>
<th>PHI-1</th>
<th>PHI-2</th>
<th>PHI-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Range</td>
<td>400-800nm</td>
<td>400-870nm</td>
<td>410-980nm</td>
</tr>
<tr>
<td>Spectral Bands</td>
<td>244</td>
<td>247</td>
<td>124</td>
</tr>
<tr>
<td>Spectral Samples Interval</td>
<td>1.8nm</td>
<td>1.9nm</td>
<td></td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>&lt; 5nm</td>
<td>&lt; 5nm</td>
<td>&lt; 5nm</td>
</tr>
<tr>
<td>Field of View</td>
<td>210</td>
<td>230</td>
<td>420</td>
</tr>
<tr>
<td>Spatial Samples</td>
<td>376</td>
<td>652</td>
<td>1304</td>
</tr>
<tr>
<td>Instant FOV</td>
<td>1.5o</td>
<td>1.2o (0.6o)</td>
<td>0.6o</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>12bits</td>
<td>14bits</td>
<td>14bits</td>
</tr>
<tr>
<td>Maximum Scan Rate</td>
<td>60fps</td>
<td>50fps</td>
<td>50fps</td>
</tr>
<tr>
<td>Cooling</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Grating Class</td>
<td>Reflective</td>
<td>Transmission</td>
<td>Transmissi on</td>
</tr>
</tbody>
</table>

Figure 1 Principle of PHI

The PHI system is composed by sensor head and electronics system. The sensor head outputs image signal and line interrupt signal to electronics system. The electronics system outputs control signal to sensor head and record data into hard disk or tape. There is GPS and IMU interface in the system. The hyperspectral image preprocessing software is provided with PHI. PHI-2 uses fiber optics data transmission and thermal electronic cooler technology.

Figure 2a PHI-1 sensor

Figure 2b PHI-2 sensor

PHI-III is newly developed based on the PHI-II. Compared with the former, it can provide higher spectral resolution and also higher spatial resolution because of the using of advanced optical components. And what is of most importance is that it has wider FOV up to 420. Till now it has been used in many fields of remote sensing, including the digital city programming of Shanghai in last October.

Since 1994, PHI series sensors had been applied in the field of environment monitoring, vegetation, ocean observation, city layout, fine agriculture and so on. The experiment area covers over the mainland of China and Southeast Asia. Every year PHI is used in the different project supported by National 863 plan, district technology plan, ministries and commissions plan etc. The distributing of experiment places are showed in Figure3.

Figure 3 Distributing Map of PHI Application

Since May 2001, PHI-2 had been installed in the China Sea Scout Plane every summer. It is used for studying hyperspectral application on red tide monitor.
On November 2002, PHI was used for inspecting water resource of Huang Pu River in Shanghai. In the experiment, PHI was combined with a 2K×3K area CCD camera. The relationship between PHI and CCD camera was carried out by GPS time.

In October 2001, PHI was invited by National Remote Sensing Center of Malaysia. The experiment site is at the west of Malaysia.

The Table4 lists the flights of PHI and OMIS during 2001 to 2003.

Table5 Flights with PHI and OMIS during 2001 to 2003

<table>
<thead>
<tr>
<th>Date</th>
<th>Where</th>
<th>Sensor</th>
<th>Aim</th>
<th>User</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001.4</td>
<td>Bei Jing</td>
<td>OMIS-I</td>
<td>agriculture</td>
<td>Institute of Remote Sensing Application,CAS</td>
</tr>
<tr>
<td>2001.4</td>
<td>Bei Jing</td>
<td>PHI-I</td>
<td>Fine agriculture</td>
<td>Beijing Academy of Agricultural Sciences</td>
</tr>
<tr>
<td>2001.5</td>
<td>Yan An</td>
<td>OMIS-I</td>
<td>Zoology programming of Yan River</td>
<td>Fei Tian Remote Sensing</td>
</tr>
<tr>
<td>2001.7</td>
<td>PHI-II</td>
<td>Red Tide Detection</td>
<td>The First Institute of Oceanography,S OA</td>
<td></td>
</tr>
<tr>
<td>2001.8</td>
<td>Japan</td>
<td>OMIS-I</td>
<td>Fine agriculture</td>
<td>NTT DATA</td>
</tr>
<tr>
<td>2001.10</td>
<td>Malaysia</td>
<td>PHI-II</td>
<td>Rain Forest Detection</td>
<td>Remote Sensing Center Of Malaysia</td>
</tr>
<tr>
<td>2002.4-6</td>
<td>Bei Jing</td>
<td>PHI-I</td>
<td>Fine agriculture</td>
<td>Beijing Academy of Agricultural Sciences</td>
</tr>
<tr>
<td>2002.5</td>
<td>Yi Xing,</td>
<td>OMIS-I</td>
<td>The Research of Resource Secondary Planet Application System</td>
<td>National Resource Ministry</td>
</tr>
<tr>
<td></td>
<td>Jiang Su</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002.9</td>
<td>Zhao Yuan,</td>
<td>OMIS-I</td>
<td>Country Resource Investigation</td>
<td>National Resource Ministry</td>
</tr>
<tr>
<td></td>
<td>Shan Dong</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002.10-11</td>
<td>Shanghai</td>
<td>PHI-2</td>
<td>Digital City Programming</td>
<td>Shanghai Council of Science</td>
</tr>
<tr>
<td></td>
<td>6000</td>
<td>OMIS-I</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003.4</td>
<td>Xi an</td>
<td>OMIS-II</td>
<td>Remote Sensing Archaeologize</td>
<td>Shan Xi Remote Sensing Center</td>
</tr>
<tr>
<td>2003.10</td>
<td>Shanghai</td>
<td>PHI-2</td>
<td>Digital City Programming</td>
<td>Shanghai Council of Science</td>
</tr>
<tr>
<td></td>
<td>6000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3K×2K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>Da lian, Tian jin,</td>
<td>PHI-2</td>
<td>Ocean Monitor</td>
<td>State Ocean Bureau</td>
</tr>
</tbody>
</table>

Multi-Sensor Integrated Remote Sensing System composed of one laser range finder and one PHI-III, then can provide many different kind of remote sensing data at one time. All those devices have been integrated by using optic, mechanical and electronics methods. To get a synchronized operation, all the sensors are driven by synchronized pulses which are generated by dividing a 1PPS signal from GPS information. The whole system is based on master-slaver network architecture. Every sensor has its own data capture system and is integrated in a star style LAN. A high performance computer is used as the center controller of the whole system, which is also the only machine that provides user interface to operators. Friendly interface make it very easy to control all the sensors, and network structure increases the modularity of the system. Users can select different sensors to work with as to their own requirement. Till now this system has also been used successfully in the digital city program of Shanghai in last October. The following is its specifications.

<table>
<thead>
<tr>
<th>PHI-III</th>
<th>The same as those specifications of PHI-III above.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LASER</td>
<td>5 points distance information per hyperspectral line, resolution 7.5cm</td>
</tr>
<tr>
<td>SENSOR</td>
<td></td>
</tr>
<tr>
<td>POS</td>
<td>Applanix POS AV 510</td>
</tr>
<tr>
<td>Platform</td>
<td>Leica PAV30</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.2 Narrow Band Hyperspectral Camera

For rapid and steady collection of high spectral resolution airborne data, a narrow band hyperspectral digital camera system (HDSCS) was developed and tested in 2000 by Institute of Remote Sensing Applications Chinese Academy of Sciences. The HDSCS was built based on three 1024×1024 pixels, 12bits digitalized area CCD cameras, FOV and IFOV of which are about 20 degree and 0.34 mrad respectively. Precise exposure control and synchronic trigger control are provided in this system, and the problem of collection and recording of large digital image data has been well solved. The center
wavelength and bandwidth of the bandpass optical filters in this system can be customized to fit different application. The filter bandwidth can be changed from 10 to 25nm, and the filter center wavelength can be changed from 400nm to 900nm. The 10nm bandpass filters centered at 555, 650, 725nm and 650, 725, 825nm were used for agriculture research in the test phase. High spatial-resolution hyperspectral images were acquired on December 5, 2000 with the HDCS. At an altitude of approximately 3500 meters, the spatial resolution was 1.2 meter. Image processing was made for improvement of the image quality.

The most useful feature of this system is its low overall cost and its flexibility to meet user needs. Because it is mounted in a small airplane, the HDCS can be flown over specific regions at varying altitudes to produce whatever spatial and temporal resolution. Researchers can now obtain hyperspectral data when and where they want it instead of being limited by relatively rigid imaging schedule of satellite. Users can do their hyperspectral band selection according to their application. And then, the only modification of the HDCS is to change the filters to fit the customized bandwidth and center wavelength.

3. HYPERSONTICAL DATA PROCESSING AND APPLICATIONS

3.1 Hyperspectral Remote Sensing Data Classification Model

Many materials can be identified by unique absorption feature in their reflectance spectra. Consequently, hyperspectral image have been so widely used in the mineral mapping, vegetation classification and environment analysis, etc. Due to the complicated urban scene and relative disorder earth object in city, it is not easy to get a satisfactory classification result only depending on pixel-to-pixel spectral analysis, especially when the materials lacked strong absorption features and the remote sensing data have a low signal-to-noise ratio. However, there are always very large requirement for urban mapping, particularly in China, whose city scene have been changing with almost each passing day. The airborne hyperspectral remote sensing technology can pay an important role in the urban landcover survey, particularly for the classification based on material composition difference.

This new method for classifying hyperspectral remote sensing data in urban area is described in this section, that combines the edge detection and spectral analysis together. Due to the varied surface scene in city and limitation of imaging spectrometer’s signal-to-noise ratio, normal classification based on pixels were not satisfied for thematic classification and mapping in urban area. Comparing with the classification on individual and isolated pixels, this classification on spectral polygons provides a great improvement of landcover mapping results in Beihai city. Because the appearance of the objects has been extracted from digital photographic data, the continuous spectral classification will not decompose the integration of object-classes. This is very important for the hyperspectral data usually with low signal-to-noise ratio and low spatial resolution. In addition, the spectral mean square deviation between different polygon-classes is larger than the deviation between different pixel-classes. Apparently, this approach has the advantage of increasing the diversity of different classes of spectra, which improve the accuracy of spectral classification. This technology could meet with the need of urban mapping in large scale.

3.2 POS Based Correction Model

Technology of airborne remote sensing is widely used in agriculture, geology, urban management and many other spheres. However, the problems of images’ quality stunt its development all along. Because the latitude of flying plane is low enough to be affected by air currencies, it is a challenge to keep flight flying stably, even if stable platform is put into use. As a result, airborne remote sensing images have more distortions and worse quality than images of satellite images. We have no high precise parameters and coefficients in airborne remote sensing system till now. Usually, airborne images’ correction is done by registration of ground control points. This method needs too much ground work and cost a lot. It is not feasible well. Position and Orientation System / Direct Georeferencing (POS/DG) data is important to hyperspectral images, for it has much information of flight attitude, such as absolute position (x,y,z) and platform attitude parameters, which make it possible for geometric correction of airborne images with receiving POS/DG data. It can save much work and the cost of stable platform. It is an attempt in China that remote sensing images are corrected with airborne POS/DG data.

3.3. Mineral Diagnostic Spectra and Recognition

Mineral recognition is the initiatory application area of hyperspectral remote sensing. The field spectral measurement shows that the distinguishable spectral features for different minerals can be seen clearly in
short-wave infrared region (Figure 1). They are caused by the bending-stretching features of OH-, CO32-, Al2+-OH, Mg+-OH and SO42- borne minerals. The airborne hyperspectral data acquired in Tarim area Xinjiang China have been processed and analyzed for geological application. Very exiting results have been obtained in stratigraphic mapping of the studying area by hyperspectral technique. The different strata from Cambian-Ordovician, Silurian, Devonian, Carboniferous and Permain Periods in the Keping area West Tarim have been clearly separated and classified for its dominant minerals of each stratum. The limestone in Cambian-Ordovician and Permian strata almost has same display in the wide-band remotely sensed data such as Landsat and SPOT and it cannot be distinguished each other. Due to the different dominant minerals in these two strata i.e the calcite for Cambian-Ordovician and dolomite for Permian strata. Based on the mini. difference of mineral absorption location (2.331, 2.347 and 2.364 µm), two strata of Cambian-Ordovician and Permian have been clearly separated. The depth of the absorption band is closely related to the amount of the minerals in the rocks. By analysis of the wavelength location and intensity of the absorption, the distribution of clay and carbonate minerals in the area has been identified and then mapped.

3.4. Vegetation Red-Edge Spectral Feature and Recognition

Unlike minerals, all vegetation is composed of a limited set of spectrally active compounds. The relative abundances of these compounds, including water, are indicators of the condition of the vegetation and of the environment in which the vegetation is growing. Vegetation architecture has a very strong influence on overall characteristics of the reflectance spectrum. The spatial scale of the reflectance measurement is important in determining the observed reflectance. Its reflectance in visible and near infrared region (350 to 800 nm) is dominated by absorption from chlorophyll and other accessory pigments. Its reflectance in the SWIR (800 to 2500 nm) is dominated by absorption from liquid water in the plant’s tissue and is additionally modified by minor absorption features associated with C-H, N-H, and CH2 bearing compounds such as starches, proteins, oils, sugars, lignin and cellulose. In addition, Scale dependence of vegetation spectra should be given more attentions in vegetation recognition. Generally the scales of vegetation include leaf/needle scale, branch scale, crown scale and canopy scale. Under current hyperspectral remote sensing technique, the canopy scale is the main sensing object. So, the mixed pixels mainly include three kinds of information: crown scale reflectance, crown density and background reflectance (soil, understory, litter, etc.)

In China, Pushbroom Hyperspectral Imager (PHI) was specially used for the vegetation precise classification and recognition. A solid state area array silicon CCD device of 780×244 elements is used as the detector of PHI. PHI has three parts: optic-mechanical system, signal process box and industrial control computer. This imager can acquire high spatial resolution because of its long focus length. High spectral resolution, light weight and relatively high spatial resolution, and low cost enabled PHI to be widely used in vegetation survey and recognition. In August of 2000, PHI was taken to Japan by Chinese scientists and completed a successful hyperspectral image data acquisition. Some main kinds of vegetables, such as Japanese cabbage, Chinese cabbage, radish, lettuce, pasture, yam, etc., were automatically recognized and mapped. Figure 2 shows the spectra extracted from hyperspectral reflectance image and Figure 3 shows the related continuum removed spectra.

The spectra of camouflage materials are most similar to vegetation and soils in the visible to near-infrared wavelengths (400 to 1000 nm). In the SWIR, the positions and relative intensities of the major absorption feature associated with water are difficult to duplicate due to the complex architecture of vegetation. Absorption features associated with minor vegetation biochemical constituents are often not present or are not of the appropriate relative intensity. The plastic resins found in many camouflage materials have absorption features that are distinct from those of natural materials. The effects of wavelength dependence of optical path length on the liquid water absorption features in a natural vegetation canopy make it very difficult to create a good vegetation camouflage. Two examples are shown in figure 4, figure 5 and figure 6. In OMIS VIS image, natural and artificial plastic grass can not be distinguished. They are all in green color in RGB composition. From figure 4, the difference in NIR region is obvious. Additionally in N-dimension spectral space, the pixels of natural and artificial plastic grass distribute in different locations (figure 5).

3.5. Hybrid Decision Tree Model (HDT) for classification

According to the rice spectral features of hyperspectral image data acquired during the rice is growing, a hybrid
decision tree classification algorithm dealing with the variety of rice is developed. The decision tree is defined as a classification procedure that recursively partitions a data set into smaller subdivisions according to a set of tests defined at each branch node in the tree. The tree is composed of many nodes, a set of inter-nodes (splits), and a set of terminal nodes (leaves). Each node in a decision tree has only one parent node and two or more descendant nodes. A data set is classified according to the decision framework defined by the tree; a new class label is assigned to each object according to the leaf node into which the object falls. There are three sorts of decision tree. That is, univariate decision tree, multivariate decision tree and hybrid decision tree. Among them, hybrid decision tree is the most complex and flexible, where different classification algorithms can be used in different subtrees of a larger tree. So in principle, the hybrid decision tree should be more precise and more effective than the other two, which was verified in the study. The feature bands are selected according to the separability among bands, but the classification algorithm is selected according to its classification result. The separability among bands is calculated by the normalized mean value of each band. In the end, a classification experiment is done. In the experiment the hyperspectral image data acquired in Jintan rice breeding farm is used. A good classification result is achieved. The classification accuracy of test samples is reached 94.9 percent. Another classification test is based on OMIS data (128 spectral bands, acquired in Yayunchun, Beijing) under this model. Several spectral bands which are more sensitive to the building materials (metal, plastic, sand, cement etc.) were extracted for such objects identification.

3.6. Vegetation pigments extraction and dynamic analysis

Since new hyperspectral sensors now have become available to provide both high spatial resolution and high spectral resolution data. These characteristics combined with high signal to noise ratio allow that more possible to differentiate vegetation types and extract biophysical or biochemical information which are of great importance for precision crop management. For the detection of vegetation pigment content per unit area, two main approaches are widely used, one focus on the narrow bands ratios, including ratios within visible and near-infrared region, ratios only in the visible region and ratios in the red edge region. The other approach utilizes the characteristics of the first and second derivatives of reflectance spectra. The majority of researchers use the wavelength position of the red edge as the best predictor of chlorophyll, while others prefer to the amplitude of the first and second derivatives of reflectance at particular wavelengths. Some studies identify, when predicting chlorophyll content, first derivative spectra value can get same results with ratio vegetation index (RVI). Apart from pigment, LAI and percent cover were related to ratios of reflectance in narrow bands on the near-infrared plateau and red edge features of canopy reflectance spectra, as well as with the amplitude of the first derivative in the red edge and visible regions respectively. Some water absorption peaks (e.g. 970nm) were found useful to estimate the leaf water content. Fouché, found that the single narrow band wavelengths 707nm and 589nm provide the better nitrogen (N) applications detection at different N-levels, based on the balloon hyperspectral image data with 8 filters digital camera. The airborne hyperspectral data was acquired in Changzhou by Pushbroom Area-array Hyperspectral Imager in high spectral resolution (less then 5nm). Especially, all the maps were achieved only by several channels. By this token, hyperspectral CCD camera with limited channels can play an important and independent role in the crop growth investigations.

In August, 2000, a set of reflectance spectra were gathered for two kinds of vegetables, eight distinctive growth stages for lettuce and seven for Japanese cabbage in Minamimaki area, Japan. The spectra were measured by an ASD FieldSpec FR spectroradiometer, which records a continuous spectrum between 350nm and 2500nm with a nominal sampling interval of 3nm (350-1000nm) and 10nm (1000-2500nm). In order to display the dynamic trend of all the indices in the same coordination, all the indices are normalized by the average of the corresponding eight or seven stages. These temporal index curves diagnostically embody pigment and biophysical parameters in crop periods of duration.

3.7 Spectral Recognition Based on Edge Search and Polygon Generation

Due to the varied surface scene in city and limitation of imaging spectrometer’s signal-to-noise ratio, normal target spectral recognition based on pixels were not satisfied in urban area. A method for object recognition in urban area is described in this section. At present, the hyperspectral RS satellite always take a panchromatic sensor but with high-spatial resolution. We can do the edge detection and polygon extraction with the high-spatial panchromatic data according to the
difference of DN value. And then all spectral analysis are based on these polygons\(^4\). Because the appearance of the objects has been extracted from high-spatial resolution data, the continuous spectral classification will not decompose the integration of object-classes. Comparing with the classification on individual and isolated pixels, this classification on spectral polygons provides a great improvement of spectral identification results. This is very important for the hyperspectral data usually with low signal-to-noise ratio and low spatial resolution. In addition, the spectral mean square deviation between different polygon-classes is larger than the deviation between different pixel-classes. Apparently, this approach has the advantage of increasing the diversity of different classes of spectra, which improve the accuracy of spectral recognition. This technology could meet with the need of urban mapping in large scale.

4. HYPERSPECTRAL IMAGE PROCESSING AND ANALYSIS SYSTEM (HIPAS)

In order to understand and design a system completely and efficiently, the primary goal of the system must be defined and detailed firstly. The design of HIPAS is a challenge because it is such a software system which incorporates a number of special algorithms and features designed to allow remote sensing scientist to take advantage of the wealth of information contained in large scale imaging spectrometer data easily and efficiently.

4.1 HIPAS Design Criteria

Based on researching into HIPAS V1.0 (written in IDL), we defined the following requirement for the new generation of imaging spectrometer software.

1. The system should be not relate to any software and hardware platform. This means the software is dependent on IDL (the Interactive Data Language) no more and compatible for other platforms (Unix, Linux) with little modification.

2. It should be independent of specific image display hardware.

3. The system should allow routine analysis of imaging spectrometer data sets to include AVIRIS, GERIS, Eos HIRIS, Landsat MSS, Landsat TM and SPOT minimally. It should support the following data format straight: BSQ (band sequential), BIL (band interleaved by line) and BIP (band interleaved by pixel).

4. The flexible and powerful utilities should be provided for data input, data formatting, data calibration and other common image processing tasks. Data visualization for rapid, exploratory spectra and image analysis should be established especially.

5. The fundamental function of GIS (Geographic Information System) should be included in HIPAS. The analysis result can be exported via standard vector format to exchange with other common GIS software.

6. The system should be easy-to-use and easy-to-understand.

4.2 System Structure

4.2.1 File Input and Output

The key classes for File I/O are HipasFileManager and ImageFileManager. HipasFileManager is the only way to access Hipas format Image data. For other external format Image files are accessed by ImageFileManager after decoder. The file I/O flow is shown in Figure 1.
4.2.2 Image Tiling and Processing

Tiling is an efficient buffer method to improve the display and processing for the huge image. In general, it means the huge image will be divided into many small blocks. There are two kinds of block in HIPAS: spatial block and spectral block.

Theoretically, the size of image in HIPAS should not be limited. The size of block is equal approximately under defined regulation. The finite Call-Back mechanism is adopted. A specific architecture of ROI (Region Of Interest) is designed and implemented. ROI is significant for HIPAS operation.

4.2.3 Execution Architecture

The errors of overflow and underflow is very common in such kind of software. In HIPAS, every function has mechanism to handle those errors. ALL the processing of image can be concluded two kind operation: in-place and out-of-place. In-place operation is that this operation can change the source image. Out-of-place operation creates a new image on disk or in system memory vis-à-vis in-place operation.

4.3 Function description

According to the system detailed design, the programming language chosen for implementation was the standard C++ language. The system interface was designed to isolate with image processing function because this part has to use MFC (Microsoft Foundation Class) Partially. In order to be compatible for other UNIX platforms with little modification, the whole programming process was based on the modularized and object oriented software engineering construction. UML (Universal Modeling Language) was adopted to improve the implementation of system class in the process of object-oriented programming. The main function of HIPAS was described in the following figure2.

Compared with other RS image processing software, HIPAS is mainly for hyperspectral data processing mission. Its data pre-processing functions have some special tools for Airborne Hyperspectral Sensors made in Shanghai institute of technical physics, such as PHI-1, PHI-2, OMIS-1, OMIS-2. These special tools include data format transformation, radiance calibration, geometric correction based on POS data, etc.

5. CONCLUSION

It is obviously that Hyperspectral Remote Sensing in China has made big strides with the advance of technique. The progress has also enhanced the demand of its applications in resources inventory and environmental monitoring. The more programs and projects conducted in the late years, the more models developed or improved for hyperspectral image processing to promote its applications. As a result, the model development can strengthen the potential of the hyperspectral imagers and expand the market of hyperspectral imager application. And also, the hyperspectral imagers will have been perfected in the courses of these applications. This has led to a positive circulation, which is the main reason why hyperspectral remote sensing is booming in recent years in China.

REFERENCE

1. Opening Session
During the opening session an overview of Proba mission and operations was presented as well as the new initiative of a CHRIS data archive integrated within the ESRIN Multi-Mission ground segment.

2. Assessment of satellite performance and data quality
During the calibration session Mike Cutter presented CHRIS calibration issues addressing comments relating to the possibility of bias and response errors in the released data sets. Luis Guanter, within the SPARC campaign activities, implemented an atmospheric correction method for CHRIS/Proba data taken over land. The method does not need any ancillary data, retrieving the atmospheric state from the hyperspectral information. Luis Alonso presented a parametric approach for CHRIS data geometric correction that can operate with minimum supervision, so it can handle large number of images in a short time. The method can work without GCPs allowing the geo-rectification of sea images provides accurate observation angles on a per-pixel basis and solves the problem of resampling pixels of different size. Finally, José Carlos Garcia presented new methods for drop-outs and vertical striping noises correction.

The following specific points for discussion were raised and the following actions were proposed:

- The low signals acquired in the water bands (Mode 2) can generate bias errors of the order of 1%. This is not very large but it does raise the question whether the gains should be increased in Mode 2, accepting some saturation, which will have the benefit of reducing bias errors but probably also increasing S/N. It might also be worth acquiring “specific” dark images for each mode which could be used at a later stage to improve bias errors in critical cases.

  **Action:** selectively increase gains in Mode 2 and consider acquiring some “specific” dark image data files.

- A calibration correction curve has been generated by Sira, which takes into consideration the temperature dependent wavelength shift. This curve looks very close to the results presented by Luis Guanter following the SPARC campaign. The correction curve is dependent on the CHRIS temperature and band configuration. Therefore it cannot be released without re-running the image processing routine.

  **Action:** Sira should implement the new correction within the processing code, compare the output with the results from the SPARC campaign and then apply the correction to new acquisitions. For old acquisitions PIs should notify Sira about high priority acquisitions to be corrected first as updating all image sets is a big task and will take time.

- It is clear that many people are implementing their own de-striping and pixel drop-out correction routines. Sira has routines that can be implemented. The de-striping routine uses the method developed by Jeff Settle. The drop-out routine uses a technique based on an average of local pixels. In principle these techniques could routinely be applied but it was felt that image sets should be released without these corrections since there is always the possibility of artefacts and errors. However, if PIs wish to have versions with these modifications implemented this could be supplied.

  **Action:** If PIs are having problems implementing these routines and want this option implemented they should contact Sira.

- Luis Alonso gave a presentation on the calculation of azimuth and zenith observation angles using both spherical geometry and Kelso’s orbit propagator algorithms. It was indicated that this latter routine is time consuming. For the case of the SPARC campaign it was shown that the spherical orbit model only introduces errors of about 1%. This is considered small enough.
**Action:** Target centre azimuth and zenith angles, derived from a spherical model should be included in the HDF files.

- It was requested that the TOA irradiance figures are included for each band with the image data.

  **Action:** Add TOA irradiance to HDF files.

### 3. Scientific exchange on results achieved with CHRIS data in various application areas

The three workshop sessions dedicated to scientific exchange gave an overview of the results obtained using CHRIS data. The principal investigators made a concerted effort to undertake field validation at the time of CHRIS/Proba image acquisition. The majority of presenters implemented their own routines for removal of noise, addressed data calibration issues and applied geometric and atmospheric correction.

José Moreno gave an overview of the SPARC campaign and showed that CHRIS/Proba presented a unique opportunity for improving crop growth models. Guido D’Urso spoke about retrieval of canopy parameters by using multi-angular and super spectral information and Soledad Gandia showed that significant improvements in modelling hyperspectral and multi-angular data is still needed before effective inversion methods can be used.

Heike Bach listed the following lessons learned:

- The highest spectral resolution (mode 5) is required for sensor calibration;
- CHRIS/Proba helps to identify BRDF parameters in surface reflectance models;
- Spatial homogenous pixels must be selected for BRDF parameterisations;
- CHRIS/Proba data are suitable for validation of SPECTRA scene simulations.

Christian Nadeau presented a Canadian project (ISIES) where various remote sensing data sources, such as CHRIS, MERIS and ASAR will be integrated with in-situ data as input to plant growth models. Optical data used for generation of Leaf Area Index (LAI) maps and SAR data will be used for soil moisture mapping.

Paolo Marcoionni addressed calibration issues and introduced the development of a physical model to compute BRDF from remotely sensed data.

Massimo Menenti outlined the importance of using hyper-spectral data to improve the estimation of forest parameters such as Leaf Area Index (LAI). LAI observations are a major determinant of C-fluxes, but understanding of C-balance requires understanding of the evolution of forests. He reported on the significant interest for CHRIS data in Italy and asked for new opportunities to extend the investigations to other sites.

François Kayitakire has shown how most of the forest types could be discriminated on the basis of the near-nadir spectral signature alone, but both spectral and multiple view angle information is relevant in differentiating some forest types, notably those having different stand densities.

Ray Merton used CHRIS images for a more user-oriented project. He presented an analysis of spectral signatures of multi-temporal and multi-angular data over large mono-culture commercial Australian cotton crops to investigate the variations in BRDF properties of cotton related to crop health, maturity, and yield. He stated that CHRIS data, despite a persistent drought affecting their test area, is able to differentiate between cotton species and also between high and low fertility of the underlying soil.

Philip Lewis presented the UCL/Swansea CHRIS/Proba activities over Carbon-oriented sites. He addressed image co-registration, cloud masking and atmospheric correction as well as model inversion using Empirical Orthogonal Functions.

Natascha Oppelt presented the activities over the core site Gilching. Cloud cover was an important limitation of multi-temporal observations. She stressed the importance of scaling with multi-resolution data.

Mark Chopping presented an experiment for the exploitation of CHRIS/Proba data over a typical desertification site. He presented radiometric and geometrical models and discussed inversions and scaling aspects.

Thomas Schneider gave two presentations. The first presentation on optimization the use of field goniometers for field measurements of vegetation properties (structure + BRDF) during the planned 2004 CHRIS/Proba campaign at the Gilching test site for crops and for reed related investigations at
the Upper Bavarian Lakes. The second presentation was on an investigation of the angular signatures of reed for the development of classification methods as a complement to the well known methods based on spectral signatures.

Sandra Mannheim spoke about water quality monitoring of inland water bodies according to European and German (EU Water Framework 2000, LAWA) water directives. She concluded that CHRIS/Proba data have high potential for monitoring lake water quality and are suitable for high accuracy determination of seasonal chlorophyll variation.

Samantha Lavender presentation showed how CHRIS/Proba has been used in a study on coastal waters for the determination of suspended particulate matter. CHRIS/Proba provides high spatial resolution ocean colour imagery that bridges the gap between the spatial resolution of global mapping ocean colour sensors and airborne imagery.

Barbara Van Mol presented an assessment of the potential of multi-look angular hyperspectral imagery for the determination of suspended particulate matter (SPM) and for chlorophyll mapping in coastal areas. The conclusion is that with CHRIS data SPM determination is possible while further investigations are needed for chlorophyll mapping.

Suhyb Salama presented a paper on the estimation of marine related optical quantities from CHRIS images in the Belgian coastal waters. He stressed that vicarious calibration is essential to obtain the correct water-leaving spectrum and has showed how three marine bio-geophysical quantities (suspended particulate matter, chlorophyll-a and dissolved organic matter) were retrieved using three different viewing angles of CHRIS.

Peter Gege presented a study to assess the capability of CHRIS/Proba for monitoring lake water constituents. In a comparison of CHRIS with MERIS data with simulated radiances it was shown that retrieval errors of total suspended matter and gelbstoff were within the error margin of the in-situ data.

Although CHRIS imagery acquired for different sites vary in quality and quantity but the principal investigators have successfully processed the data and preliminary products have been generated for geophysical parameter retrieval. It was requested to add actual measurements of observation angles to the data products in order to ease handling multi-angular information. Assistance in geometric calculations and geometric correction would be welcomed. Better calibration in the blue channels, below 450 nm, by improving vicarious calibration with sufficient and coincident in-situ measurements is required for investigations of inland and coastal waters. For this field of research the requirement was expressed to improve the SNR by setting the gain to the maximum in all bands (saturation and smearing may not be a problem) and a requirement for the acquisition of dark images for each mode/subset.

The scientific exchange sessions showed promising results and requirements were identified for further CHRIS imagery acquisitions during 2004 over existing sites as well as over some additional sites to explore additional features.

A general conclusion was that CHRIS data are suitable to support the development of data products for land and water application.

4. Presentation of future CHRIS/Proba data exploitation projects

The CHRIS/Proba programme, after a successful year of exploitation in 2003, has been extended and for 2004 new acquisition requests came from new users for sensor inter-calibration (CHRIS-MERIS), satellite joint experiments (CHRIS-BIRD), ESA PR activities, and in support of application projects (GLOBWETLAND, International Major Disaster Charter, DRAGON).

Ramon Pena-Martinez explained how CEDEX was preparing to use CHRIS data in support of a project employing the MERIS instrument to detect traces of potentially harmful phytoplankton in Spanish reservoirs. The use of CHRIS imagery will be for mapping the temporal and spatial distribution of Cyanobacteria, and for testing several algorithms for Phycocyanin and other Phytoplankton pigments.

Dieter Oertel presented a scenario for joint CHRIS-BIRD experiments for fire mapping. CHRIS will re-acquire the forest sites mapped last year by BIRD in order to determine the extent of the burnt area and to identify any vegetation re-growth.

Diego Fernandez explained how CHRIS/Proba observations plays an important role in providing hyperspectral/multi-angular high spatial resolution optical data for the sites selected for the GLOBWETLAND project for increasing classification accuracy.

Stefano Pignatti presented a proposal for CHRIS acquisitions over a high relief area to exploit multi-angular images for forest characterization in mountainous areas.
Fulvio Drigani explained the importance of CHRIS acquisitions for ESA public relation and outreach purposes. The images are to be acquired as near nadir as possible and are required as three-band image sets.

Francesco Sarti presented a proposal to insert CHRIS/Proba into the International Charter on “Space and Major Disaster” activations. CHRIS/Proba should be used as an additional (non-operational) data source provided by ESA, on a best-effort basis.

Hervé Yesou proposed CHRIS acquisitions of flood-prone areas as part of the flood research element of the joint ESA-China DRAGON Programme. CHRIS data will be used to generate reference maps to be compared with crisis data in order to extract flooded areas and permanent water bodies.

Qingxi Tong presented China’s broad interest in hyperspectral imaging for a variety of applications ranging from mineral prospecting to disaster relief. He proposed CHRIS acquisitions over a test site near Beijing for data analysis and application development.

5. Review of individual projects for final definition of 2004 CHRIS acquisition plan

During the final general discussion the review panel agreed to include the new requests presented at the workshop in the 2004 acquisition plan.
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