ESA Contract 4000110267/14/NL/BJ/lf

"Technical Assistance to fieldwork in the Harth forest during SEN2Exp"

Final Report

Kristin Vreys

TAP/N7923/11-03
March 2014
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<td>CIP</td>
<td>Campaign Implementation Plan</td>
</tr>
<tr>
<td>CWC</td>
<td>Canopy Water Content</td>
</tr>
</tbody>
</table>

*Table 1 List of acronyms*
CHAPTER 1  INTRODUCTION

1.1. PURPOSE OF THIS DOCUMENT

This document aims at reporting about the activities performed in the frame of the SEN2Exp campaign in the Harth forest, Mulhouse, France during summer 2013. It provides a full description of the campaign, including the campaign planning, the instrumentation used, the measurements made, and the processing applied to the data collected. It is furnished with photographic material, documenting the locations, the work performed and the instruments.

1.2. SCOPE

This document applies to the activities performed by VITO, INRA and UNIMIB in the frame of the SEN2Exp campaign in the Harth forest, Mulhouse, France (summer 2013).
### 1.3. Applicable Documents

| AD1 | The VITO Proposal, reference TAP/NI7923/13-10, dated 04/10/2013 |
| AD2 | Sen2Exp_CIP_d0-6.pdf SEN2Exp Campaign Implementation Plan |
| AD3 | N7923_SEN2Exp_DataAcquisitionReport_v2.0 SEN2Exp Data Acquisition Report |
| AD4 | UNIMIB-calval_1st_campaign_report.pdf Spectroradiometric Measurements of Surface Calibration Targets 1st France Field Campaign |
| AD5 | UNIMIB-calval_2nd_campaign_report.pdf Spectroradiometric Measurements of Surface Calibration Targets 2nd France Field Campaign |
| AD6 | UNIMIB-calval_3rd_campaign_report.pdf Spectroradiometric Measurements of Surface Calibration Targets 3rd France Field Campaign |

**Table 2: List of Applicable documents**

### 1.4. Reference Documents

| RD5 | A. Hueni, RSL: “Overview of APEX radiometric uncertainty Estimation” |
| RD9 | Meroni, M.; Barducci, A.; Cogliati, S.; Castagnoli, F.; Rossini, M.; Busetto, L.; Migliavacca, M.; Cremonese, E.; Galvagno, M.; Colombo, R., et al., The hyperspectral irradiometer, a new instrument for long-term and |


*Table 3: List of reference documents*
In the framework of its Earth Observation Envelope and GMES Space Segment Programmes the European Space Agency (ESA) carries out a number of ground-based and airborne campaigns to support end to end mission design, geophysical algorithm development, calibration/validation and the simulation of future spaceborne Earth Observation missions.

The Agency normally does not conduct a campaign in isolation but seeks collaboration with national research organisations in the ESA Member States as well as with other international organisations. As the Agency does not generally operate instrumentation, it relies for the implementation of a campaign on contracts/agreements with sensor developers, owners and operators.

**SENTINEL-2 MISSION**

For its part in the Global Monitoring for Environment and Security (GMES) Copernicus programme, ESA is undertaking the development of the space segment with a series of satellite missions, known as Sentinels. Sentinel-2 addresses the following main themes:

- provision of systematic global acquisitions of high-resolution multispectral imagery with a high revisit frequency;
- provision of enhanced continuity of multi-spectral imagery provided by the SPOT series of satellites;
- provision of observations for the next generation of operational products such as land-cover maps, land-change detection maps, and geophysical variables.

The context for the current activity is derived from the support needs of the scientific and industrial activities taking place during the different phases of the mission and the previous related campaigns that took place in different locations in the past years. During the previous related campaigns experimental data mainly for agricultural areas and needle leaf forests were gathered.

In this campaign, the data gap for broad leaf forests is addressed as suitable reference datasets of sufficient quality do not exist. This campaign will therefore complement existing data sets in terms of the type of vegetation, range of Leaf Area Index (LAI), Fraction of Absorbed Photosynthetically Active Radiation (fAPAR), Canopy Chlorophyll Content (CCC), and Canopy Water Content (CWC) observed. In addition it will improve the reliability of the measurements both for:

- The radiometric data required to simulate Sentinel-2 data;
- The validation of ground measurements.

The Sen2Exp campaign addresses these topics for broad leaf forested areas in mid-latitude regions that represent a significant fraction of the land cover in Europe.
CHAPTER 3 CAMPAIGN LOCATION

The campaign work has been performed at the Harth forest (47.74°N 7.45°E). This site is a relatively compact managed forest close to Mulhouse, France (Figure 1). It is about 2-3km wide and 15km long. A 3×3km² site within the forest is used for validation as part of the GEOLAND2 project (Table 4).

The site is generally flat with vegetation patches of at least 500m minimum dimension. The forest is composed of many species, the dominant one being the Hornbeam (Carpinus betulus L.) which grows to 25m height at maximum. Several patches show a relatively large variability in terms of management stages (age of the forest).

Each patch can be accessed easily along forest tracks.

<table>
<thead>
<tr>
<th>Centre</th>
<th>ULC</th>
<th>LRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat/Lon WGS84</td>
<td>Lat</td>
<td>Lon</td>
</tr>
<tr>
<td>47.821102N</td>
<td>7.455386E</td>
<td>47.8073395</td>
</tr>
<tr>
<td>UTM, 32N WGS84</td>
<td>5297571.77</td>
<td>384382.31</td>
</tr>
</tbody>
</table>

*Table 4: Coordinates of the site used for validation within the GEOLAND2 project*
Figure 1. The Harth Forest site; the yellow mark corresponds to the centre of the 3×3km² validation site; the red rectangle represents the area of interest.
The objective of the Sen2Exp campaign is to provide a consistent set of BOA reflectance data with corresponding in-field measurements. These data will be used by ESA in another activity to simulate Sentinel-2 representative data up to prototype Level 2b products. The campaign combines airborne, satellite and coincident ground activities.

The complete detailed objectives of the activity are:

- pre-flight check of the radiometric calibration and cross-calibration uncertainties of all the airborne instruments that will be used;
- acquire airborne remote sensing data with spectral and spatial resolution at least three times better than Sentinel-2 with a local time of 12h30 ± 30 minutes; the images shall be taken in nadir view;
- Sample within a temporal window of at least of 90 days with a minimum of 3 observations;
- Collect, process and validate ground measurements to be used for radiometric vicarious calibration, geometric and atmospheric correction (e.g. reflectance signatures, GCPs, GPS measurements, aerosol measurements, regional meteorological data);
- Collect, process and validate in-field measurements for well-defined and precisely geolocated ESU for L2b product validation;
- Acquire VHR satellite images within a few days of the ground measurement collection (e.g. Ikonos, Quickbird);
- Process VHR satellite data to make these image usable in support of geolocation assessment, ground truth collection, image registration and ESU individuation (e.g. pan-sharpening, ortho-rectification using RPCs, refinement using GPS);
- Generate a consistent and validated set of bottom of atmosphere reflectance data and coincident and geolocated validation ground measurements;
- Generate adequate documentation reporting at least: chronological diary of the campaign, image quality assessments, format/data user manual and processing methods.

The Sen2Exp campaign includes a number of participating institutions, coordinated by the Agency.

These institutes and their project responsible for these activity are:

**VITO**
Koen Meuleman

**University of Milano - Bicocca**
Roberto Colombo

**INRA**
Frédéric Baret
CHAPTER 5 CAMPAIGN INSTRUMENTATION

5.1. AIRPLANE

The airplane used for the flights is a Dornier 228-101 (D-CODE) operated by the Flight Department of DLR-Braunschweig. It has two Garret Turboprop TPE 331-5 engines and was manufactured by Dornier GmbH in 1986.

Figure 4 shows the APEX-crew (pilots, technicians, operators), being (from left to right): Johan Mijnendonckx (VITO), Silvio Heyne (DLR), Regina Gebhard (DLR), Peter Baumann (DLR), Georg Mitscher (DLR), Bart Ooms (VITO), Bart Bomans (VITO)
5.2. AIRBORNE INSTRUMENTS

5.2.1. APEX

APEX is an airborne (dispersive push broom) imaging spectrometer developed by a Swiss-Belgian consortium on behalf of ESA. It is intended as a simulator and a calibration and validation device for future spaceborne hyperspectral imagers. Furthermore, APEX is an advanced scientific instrument for the European remote sensing community. It records hyperspectral data in approximately 300 bands in the wavelength range between 400nm and 2,500nm for 1,000 pixels across track, with a FOV of 28° giving a typical spatial ground resolution of 2-5 m depending on the actual flight altitude.

The instrument specifications are provided in Table 5.
The instrument is mounted on a stabilized mount in the aircraft for aircraft movement compensation (roll, pitch and yaw). Figure 5 shows some pictures of APEX, Figure 6 shows the computer rack installed in the D-CODE.

<table>
<thead>
<tr>
<th>Spectral Range</th>
<th>VNIR 380 – 970 nm</th>
<th>SWIR 940 – 2500 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Bands</td>
<td>VNIR default 114 bands, reprogrammable through customized binning pattern</td>
<td>SWIR 199 bands</td>
</tr>
<tr>
<td></td>
<td>Max. unbinned bands: 334</td>
<td></td>
</tr>
<tr>
<td>Spectral Sampling Interval</td>
<td>VNIR 0.55 – 8 nm over spectral range (unbinned)</td>
<td>SWIR 5 – 10 nm over spectral range</td>
</tr>
<tr>
<td>Spectral Resolution (FWHM)</td>
<td>VNIR 0.6 – 6.3 nm over spectral range (unbinned)</td>
<td>SWIR 6.2 – 11 nm over spectral range</td>
</tr>
<tr>
<td>Spatial Pixels</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>FOV (across track)</td>
<td>28°</td>
<td>0.48 mrad</td>
</tr>
<tr>
<td>Spatial Sampling Interval (across track)</td>
<td>1.75 m @ 3500 m AGL (2 - 5 m at flight altitudes of 4 - 10 km)</td>
<td></td>
</tr>
<tr>
<td>Sensor dynamic range</td>
<td>VNIR CCD, 14 bit encoding</td>
<td>SWIR CMOS, 13 bit encoding</td>
</tr>
<tr>
<td>Pixel size</td>
<td>VNIR 22.5 μm x 22.5 μm</td>
<td>SWIR 30 μm x 30 μm</td>
</tr>
<tr>
<td>Smile (average over FOV)</td>
<td>0.35 pixels</td>
<td></td>
</tr>
<tr>
<td>Keystone (frown, average over FOV)</td>
<td>0.35 pixels</td>
<td></td>
</tr>
<tr>
<td>Co-Registration (average over FOV)</td>
<td>0.6 pixels</td>
<td></td>
</tr>
<tr>
<td>Signal-to-Noise</td>
<td>SNR for various applications are available upon request</td>
<td>Highest signal to noise ratio through advanced detector technology and pressure/temperature stabilization</td>
</tr>
<tr>
<td>Output medium</td>
<td>LTO-2 tape</td>
<td></td>
</tr>
</tbody>
</table>
Table 5: APEX instrument specifications

Figure 5: APEX in clean room, and installed in the D-CODE

Figure 6: APEX computer rack in the D-CODE and operator position
5.2.2. POSITION AND ORIENTATION SYSTEM AND FLIGHT PLANNING SYSTEM

The APEX system is equipped with an Applanix POS/AV system (see Figure 7) with integrated Flight Management System (FMS) software from Track’Air, designed for direct georeferencing of airborne sensor data.

It is comprised of four main components: an IMU (Inertial Measurement Unit), a GPS receiver, a POS Computer System (PCS) and a post-processing software suite called POSPac MMS. Further the APEX sensor system is installed on a stabilized mount in the aircraft which corrects for aircraft movements in roll, pitch and yaw.

The data from the exterior GPS antenna (1), mounted on top of the DORNIER fuselage, from the IMU (2), integrated in the APEX sensor, and from the gimbal (stabilized mount) (3) are processed on board for monitoring and flight management. They are also recorded on PCMCIA cards (and internal memory for backup) for post-processing.

During the post processing, the POSPac Mobile Mapping Suite (POSPac MMS) software uses as input the onboard recorded data (see higher), together with GPS Base Station data to generate SBET files, i.e. Smoothed Best Estimated Trajectory files. These are used for georeferencing the APEX imagery.

![Figure 7: POS AV hardware with pilot screen for Flight Management](image-url)
CHAPTER 5 Campaign Instrumentation

5.3. GROUND-BASED INSTRUMENTS

5.3.1. MEASUREMENTS OF SUN-INDUCED FLUORESCENCE AND REFLECTANCE

During the campaigns the following ground spectral measurements are collected:

- top-of-canopy radiance to derive reflectance and fluorescence over the forest;
- top-of-canopy radiance to derive reflectance and fluorescence over a grassland site;
- radiance and reflectance of different reference targets.

Top-of-canopy spectral measurements over the forest

Three spectrometric systems will be operated manually from a mobile platform placed at about 5m over the top of the canopy. Measurements will be collected during the overpass (1 hour before and 1 hour after).

- A portable spectrometric system will be used to measure high resolution top-of-canopy radiances. The system is composed of two portable spectrometers (HR4000, OceanOptics, USA) operating in the visible 400-1,000nm spectral range with a full width at half maximum (FWHM) of 1nm and in the 700-800nm spectral range with a finer resolution (FWHM = 0.15nm). This spectrometer is specifically intended for sun-induced fluorescence measurements in the oxygen absorption band O2-A positioned at 760nm (F760). Bare fibre optics with a field of view (FOV) of 25° will be used to alternately measure a white reference calibrated panel (Labsphere Inc., U.S.A.) and the forest target. Ocean Optics spectrometers will be housed in a Peltier thermally regulated box (model NT-16, Magapor, Zaragoza, Spain) keeping the internal temperature at 25°C in order to reduce dark current drift.
- A third OceanOptics spectrometer (model QE 65000) operating in the 657-740nm spectral range with a FWHM of 0.25nm will be used to measure sun-induced fluorescence at the oxygen absorption band O2-B.
- Top-of-canopy measurements will be simultaneously collected with an ASD (Analytical Spectral Device, USA) FieldSpec FR Pro covering the visible, near infrared and shortwave infrared region (350-2,500nm).

The three spectrometers will be spectrally calibrated with known standards (CAL-2000 mercury argon lamp, OceanOptics, USA) while the radiometric calibration will be inferred from cross-calibration measurements performed with a reference calibrated FieldSpec spectrometer (Analytical Spectral Device, USA). Different plantations will be measured according to standard protocol for fluorescence measurements.

Top-of-canopy spectral measurements over grassland

Sun-induced fluorescence at top of canopy will be recorded by a custom-made fluorescence box comprising high performance spectrometers. The box is designed for high temporal frequency acquisition of continuous radiometric measurements. This system is based on a commercial optical multiplexer (MPM-2000, OceanOptics, USA), able to switch between a channel measuring the incident irradiance (cosine response optic), a down-looking bare fiber (FOV of 25°) for the measurement of the upwelling radiance and a “blind” channel for the dark current measurement, and hosts two portable spectrometers (HR4000, OceanOptics, USA) operating in the visible and near-infrared region but with different spectral resolutions. The first covers the 400-1,000nm spectral range with a FWHM of 1nm and allows the computation of vegetation indices. The second
one covers with a finer resolution (FWHM = 0.15nm) a restricted spectral range (700-800nm) and it is specifically intended for sun-induced fluorescence measurements in the O2-A oxygen absorption band. Spectrometers will be spectrally calibrated with known standards (CAL-2000 mercury argon lamp, OceanOptics, USA) while the radiometric calibration will be inferred from cross-calibration measurements performed with a reference calibrated FieldSpec spectrometer (ASD, USA). Measurements will be collected during the overpass (1 hour before and 1 hour after).

5.3.2. SPECTRAL MEASUREMENTS OF REFERENCE TARGET

During all three campaigns, a mobile team equipped with a calibrated FieldSpec FR Pro field spectrometer (Analytical Spectral Device, USA) covering the visible, near infrared and shortwave infrared region (350-2,500nm) will measure various surface calibration/validation targets. Natural “pseudo-invariant” features at the site and artificial targets specifically placed into the flight lines will be used as calibration/validation targets. Pseudo–invariant surfaces will be for example asphalt, concrete, gravel or soil.

Three artificial targets (black, white and grey) will also be placed into the flight lines. Target reflectance will be measured by recording (i) incoming radiation using a white reference calibrated panel (Labsphere Inc., U.S.A.) and (ii) upwelling radiation from the surface.

5.3.3. SUNPHOTOMETER MEASUREMENTS

During APEX acquisition flights, sunphotometer measurements will be performed using a Microtops II sunphotometer. Those measurements are used to derive visibility, and water vapour and aerosol concentration which are important parameters for further atmospheric correction of the hyperspectral imagery.

5.3.4. LEAF AREA INDEX (LAI) AND FAPAR: DHP MEASUREMENTS

It is proposed to use digital hemispherical photography (DHP) to estimate LAI and FAPAR. This technique has been proven to be very efficient. However, great care should be taken to:

- optimise illumination conditions: it is better to use diffuse conditions;
- use colour cameras with high resolution (minimum 10 Mega pixels);
- sample both overstory (looking upward) and understory (looking downward)

Processing could be conveniently achieved using the CAN-EYE Software (https://www4.paca.inra.fr/can-eye/CAN-EYE-Home/Welcome) that will provide estimates of effective LAI (actually more related to PAI since trunks and branches will contribute to light interception), true LAI (using several methodologies to estimate leaf clumping) and FAPAR (actually FIPAR) for a range of sun positions. The aggregation at the ESU level of the 13 replicas of overstory and understory should follow the recommendations proposed in the validation concept document.

5.3.5. CANOPY CHLOROPHYLL (CCC) AND WATER (CWC) CONTENTS

Because of the time required to collect and process these data, a sub-sample of the ESUs sampled for LAI and FIPAR measurements will be considered. This sub sample of ESUs will be selected in order to represent the largest range of conditions in terms of species composition and canopy state. The visual notations achieved over each ESU regarding the species composition will allow estimation of the corresponding CCC and CWC.
CC and CWC are derived from individual measurements of leaf chlorophyll (LCC) or water (LWC) contents: $\text{CCC} = \text{LAI} \times \text{LCC}$; $\text{CWC} = \text{LAI} \times \text{LWC}$. Since LAI measurements will be completed as described in §5.3.4, it is mandatory to measure LCC and LWC. The sampling for LCC and LWC will consist in collecting over each of the 10 sampling points a sample representative of the top leaves (according to the expected fraction seen from the airborne or satellite sensors. The sample could be gathered by shooting into the top branches, expecting that small branches with leaves will fall down. A sample of 10 leaves is recommended for each dominant species of a considered ESU.

- **Leaf chlorophyll content.** The Dx4 device (Dualex4, http://www.force-a.eu/) or SPAD instrument (http://www.konicaminolta.com/instruments/products/color-measurement/chlorophyll-meter/spad502/index.html) could be conveniently used for indirect estimation of leaf chlorophyll content. For the sake of accuracy, reflectance and transmittance measurements using a spectrometer could be used to verify on a well contrasted sample that the field instruments provide consistent estimates of LCC. The aggregation of individual measurements should follow the principles proposed in the validation concept document.

- **Leaf water content.** The gravimetric method will be used on the same sample size as for LCC. Once collected, the leaves will be put immediately in a plastic bag and kept in a cooler. Then, at the lab the whole sample will be weighed (Wf: fresh weight) and the corresponding area measured (Af). The leaves will be put in the oven at 80°C, to finally weigh the dry leaves (Wd) after 24 hours drying. LWC is then computed as: $\text{LWC} = (\text{Wf} - \text{Wd})/\text{Af}$

### 5.3.6. Visual Indices of Crown Condition

Visual assessment of forest condition will be conducted by means of a terrestrial survey following a visual assessment of the proportion of yellowing and loss of leaves from individual crowns which may eventually serve for a preliminary damage assessment.
CHAPTER 6  AIRBORNE DATA ACQUISITION

6.1. SCENARIOS

The time is expressed here in local solar time (LST). Local Official Time (LOT) is shifted by 1:31 hours (sun is at zenith (solar noon) at 13:31 LOT or 11:31 UMT (Universal Meridian Time)). The date of the flight is here fixed at day of year 170, i.e. the 20 June 2013 (very close to the summer solstice). Variations around this date will affect only marginally the computations.

The orbit inclination of Sentinel-2 is 98°, i.e. the azimuth of track of the satellite on the earth surface is approximately 8° shifted from the north towards east.

In this proposed scenario, only the morning is considered. Flights could be also planned in the afternoon at the same zenith angles; in this case, time and sun azimuth will be symmetric with regards to solar noon.

The time corresponding to a range of sun zenith angles is indicated in Table 6. Three different sun zenith angles are proposed: 60°, 31.8° (the actual sun position at 10:30 solar time when Sentinel-2 is supposed to pass over the site) and minimum sun zenith angle corresponding to solar noon. The azimuth of the flights (relative to geographic North) should be consistent with the azimuth of Sentinel-2, i.e. maintaining an azimuth difference of 131°-8° between the sun azimuth and the flight azimuth. As a result, the proposed azimuths of the flight lines are presented in the following table (last column).

<table>
<thead>
<tr>
<th>Local Solar Time</th>
<th>Sun zenith (°) on day 170 (20 June)</th>
<th>Sun azimuth (°) on day 170 (20 June)</th>
<th>Proposed azimuth of the flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>07:18</td>
<td>60.0°</td>
<td>87.3°</td>
<td>87.3-(131-8)=-35.7°</td>
</tr>
<tr>
<td>10:30</td>
<td>31.8°</td>
<td>131.0°</td>
<td>8°</td>
</tr>
<tr>
<td>12:00</td>
<td>24.4°</td>
<td>180.0°</td>
<td>180-(131-8)=57°</td>
</tr>
</tbody>
</table>

Table 6: Time corresponding to a range of sun zenith angles

6.2. APEX FLIGHTLINES

The APEX flight lines are presented in Figure 8. Seven flight lines with 30% lateral overlap are planned with a heading of 195.3° to cover the area of interest. The total length of the flight strips is around 153km (82 nautical miles) and the overall flight time is +/- 1 hour. As a consequence, the proposed time window is set from 12:00-13:00 local time in order to be as close as possible to the overpass time of Sentinel-2 (12.38 LST). The flying height (AGL) for this mission is 6000m resulting in a swath width on the ground of 2997m and a GSD of approximately 3m. The APEX flight line coordinates are given in Table 7.
Figure 8: SEN2Exp flight lines above Harth forest

<table>
<thead>
<tr>
<th>Coordinate system: World WGS 84 coordinate system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projection: Transverse Mercator</td>
</tr>
<tr>
<td>Ellipsoid: WGS84</td>
</tr>
</tbody>
</table>

Total strips: 7  
Total length: 153km (82 nautical miles)

**Strip number: 1**  
Terrain height = 230m / 755ft  
Course: 015°/195°  
Length: 13.7km  
Swath width: 2,997m

WGS84 Start: 47°48'26.5" / 007°22'33.6"  
WGS84 End: 47°55'37.9" / 007°25'14.5"

**Strip number: 2**  
Terrain height = 230m / 755ft  
Course: 015°/195°  
Length: 19.7km  
Swath width: 2,997m

WGS84 Start: 47°45'02.0" / 007°23'01.2"  
WGS84 End: 47°55'21.3" / 007°26'52.6"

**Strip number: 3**
Terrain height = 230m / 755ft
Course: 015°/195°
Length: 28.7km
Swath width: 2,997m

WGS84 Start: 47 40 03.2 / 007 22 53.9
WGS84 End: 47 55 04.8 / 007 28 30.7

**Strip number: 4**
Terrain height = 230m / 755ft
Course: 015°/195°
Length: 28.7km
Swath width: 2,997m

WGS84 Start: 47 39 46.6 / 007 24 31.3
WGS84 End: 47 54 48.3 / 007 30 08.7

**Strip number: 5**
Terrain height = 230m / 755ft
Course: 015°/195°
Length: 28.7km
Swath width: 2,997m

WGS84 Start: 47 39 30.2 / 007 26 08.8
WGS84 End: 47 54 31.7 / 007 31 46.5

**Strip number: 6**
Terrain height = 230m / 755ft
Course: 015°/195°
Length: 20.5km
Swath width: 2,997m

WGS84 Start: 47 39 13.7 / 007 27 46.4
WGS84 End: 47 49 56.4 / 007 31 47.0

**Strip number: 7**
Terrain height = 230m / 755ft
Course: 015°/195°
Length: 12.7km
Swath width: 2,997m

WGS84 Start: 47 38 57.1 / 007 29 24.0
WGS84 End: 47 45 36.8 / 007 31 53.0

*Table 7: APEX flight line coordinates*
6.3. APEX DATA ACQUISITION

APEX data has been acquired above the Harth forest 6 times between 17/06/2013 and 04/09/2013. The acquisition dates are:

- 16/06/2013
- 17/06/2013
- 01/07/2013
- 05/07/2013
- 30/08/2013
- 04/09/2013

The acquisition dates, as well as the number of acquisitions, have been decided upon in close cooperation between VITO and ESA’s technical officer, based upon the weather forecast.

The flight of 16/06 was delayed due to technical issues and imaging started only from 13h40. Data for this day are processed and will be delivered at ESA’s request, despite the fact that they do not comply the ESA requirement that images should be taken with a local time of 12h30 ± 30 minutes.

The flight of 05/07 was performed under cloudy conditions, despite this fact and at ESA’s request data for this day have been processed and will be delivered.

For the 4 other flights, the imagery has been taken in nadir view with a local time of 12h30 ± 30 minutes under good weather conditions. Data of these days have been processed and will be delivered.

On each day, seven flight lines have been captured, as shown in Figure 8. Flight line 4 is the ‘priority’ flight line, special care has been taken in the flight planning to ensure that this line was captured around 12h38 local time. An image mosaic of the data acquired each day is given in Figure 10.

The imaging times for the flightlines on the different flight days are given in the tables on the next pages.
Figure 9: SEN2Exp ‘priority’ flight line above Harth forest
Figure 10: SEN2Exp mosaic of the 7 flight lines
### 6.3.1. APEX FLIGHT 16/06/2013

<table>
<thead>
<tr>
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<tbody>
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<td>13:41</td>
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<tr>
<td>3</td>
<td>APEX_SEN2Exp_130616_a03</td>
<td>13:52</td>
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<tr>
<td>2</td>
<td>APEX_SEN2Exp_130616_a02</td>
<td>14:04</td>
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<tr>
<td>1</td>
<td>APEX_SEN2Exp_130616_a01</td>
<td>14:14</td>
</tr>
<tr>
<td>5</td>
<td>APEX_SEN2Exp_130616_a05</td>
<td>14:23</td>
</tr>
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<td>6</td>
<td>APEX_SEN2Exp_130616_a06</td>
<td>14:34</td>
</tr>
<tr>
<td>7</td>
<td>APEX_SEN2Exp_130616_a07</td>
<td>14:43</td>
</tr>
</tbody>
</table>

*Table 8: Image acquisition times for the flight of 16/06/2013*

### 6.3.2. APEX FLIGHT 17/06/2013

<table>
<thead>
<tr>
<th>Flight line ID</th>
<th>Name</th>
<th>Acquisition time (local time)</th>
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<tr>
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<td>APEX_SEN2Exp_130617_a05</td>
<td>12:46</td>
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<td>6</td>
<td>APEX_SEN2Exp_130617_a06</td>
<td>12:58</td>
</tr>
<tr>
<td>3</td>
<td>APEX_SEN2Exp_130617_a03</td>
<td>13:09</td>
</tr>
<tr>
<td>2</td>
<td>APEX_SEN2Exp_130617_a02</td>
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<td>1</td>
<td>APEX_SEN2Exp_130617_a01</td>
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</table>

*Table 9: Image acquisition times for the flight of 17/06/2013*

### 6.3.3. APEX FLIGHT 01/07/2013

<table>
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<td>1</td>
<td>APEX_SEN2Exp_130701_a01</td>
<td>11:51</td>
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<td>2</td>
<td>APEX_SEN2Exp_130701_a02</td>
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</tr>
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<td>3</td>
<td>APEX_SEN2Exp_130701_a03</td>
<td>12:09</td>
</tr>
<tr>
<td>4</td>
<td>APEX_SEN2Exp_130701_a04</td>
<td>12:20</td>
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<td>APEX_SEN2Exp_130701_a05</td>
<td>12:31</td>
</tr>
<tr>
<td>6</td>
<td>APEX_SEN2Exp_130701_a06</td>
<td>12:42</td>
</tr>
<tr>
<td>7</td>
<td>APEX_SEN2Exp_130701_a07</td>
<td>12:52</td>
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<tr>
<td>8</td>
<td>APEX_SEN2Exp_130701_a08_grass (*)</td>
<td>14:19</td>
</tr>
</tbody>
</table>

*Table 10: Image acquisition times for the flight of 01/07/2013*

(*) This is an additional flight line for imaging a grass-field that was sprayed with chemicals for the purpose of testing fluorescence retrieval.
### 6.3.4. APEX FLIGHT 05/07/2013

<table>
<thead>
<tr>
<th>Flight line ID</th>
<th>Name</th>
<th>Acquisition time</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>APEX_SEN2Exp_130830_a04</td>
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<td>13:01</td>
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<td>6</td>
<td>APEX_SEN2Exp_130830_a06</td>
<td>13:12</td>
</tr>
<tr>
<td>7</td>
<td>APEX_SEN2Exp_130830_a07</td>
<td>13:20</td>
</tr>
<tr>
<td>2</td>
<td>APEX_SEN2Exp_130830_a02</td>
<td>13:28</td>
</tr>
<tr>
<td>1</td>
<td>APEX_SEN2Exp_130830_a01</td>
<td>13:38</td>
</tr>
</tbody>
</table>

Table 11: Image acquisition times for the flight of 05/07/2013

### 6.3.5. APEX FLIGHT 30/08/2013

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<th>Name</th>
<th>Acquisition time</th>
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<tbody>
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<tr>
<td>6</td>
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<td>2</td>
<td>APEX_SEN2Exp_130830_a02</td>
<td>12:15</td>
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<tr>
<td>3</td>
<td>APEX_SEN2Exp_130830_a03</td>
<td>12:24</td>
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<tr>
<td>5</td>
<td>APEX_SEN2Exp_130830_a05</td>
<td>12:46</td>
</tr>
</tbody>
</table>

Table 12: Image acquisition times for the flight of 30/08/2013

### 6.3.6. APEX FLIGHT 04/09/2013

<table>
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<th>Name</th>
<th>Acquisition time</th>
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</thead>
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</tr>
<tr>
<td>6</td>
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<td>APEX_SEN2Exp_130904_a04</td>
<td>12:52</td>
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<tr>
<td>3</td>
<td>APEX_SEN2Exp_130904_a03</td>
<td>13:04</td>
</tr>
<tr>
<td>2</td>
<td>APEX_SEN2Exp_130904_a02</td>
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<td>APEX_SEN2Exp_130904_a01</td>
<td>13:28</td>
</tr>
</tbody>
</table>

Table 13: Image acquisition times for the flight of 04/09/2013
Spectral measurements have been performed by UNIMIB, and include:

- Top-of-canopy spectral measurements over the forest
- Top-of-canopy spectral measurements over the grassland
- Spectral Measurements of reference target

Protocols and instruments characteristics are presented in section 5.3. More details on the methods applied are provided in reference documents [RD6] till [RD12].

7.1. **Top-of-canopy spectral measurements over the forest**

The portable spectrometer system was employed on the top of a mobile hydraulic platform (Figure 11) to measure top of canopy fluorescence and reflectance of different species and location at the Hearth Forest. The manual system was used from a mobile hydraulic platform positioned 4.4 m above the canopy plane. The optical fibers were held at the end of a 2.5 m long arm positioned at a distance between 3.7 - 5 m above the canopy plane allowing to observe an area of 1.7 to 2.3 m diameter from nadir.

*Figure 11: Mobile platform with portable spectrometric system for top of canopy fluorescence and reflectance measurements.*
When possible, two species have been measured keeping the base of the mobile platform in a fix position and moving the basket alternatively in the two positions (Figure 12).

![Sampling scheme used to collect top-of-canopy spectral measurements over the forest.](image)

Table 14 gives an overview of the measurements collected and the species sampled on each date.

<table>
<thead>
<tr>
<th>Species</th>
<th>Date</th>
<th>DOY</th>
<th>Vis-NIR</th>
<th>SWIR</th>
<th>O$_2$-A</th>
<th>O$_2$-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oak</td>
<td>16 June</td>
<td>167</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Hornbeam</td>
<td>16 June</td>
<td>167</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Pine</td>
<td>17 June</td>
<td>168</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Maple</td>
<td>17 June</td>
<td>168</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Larch</td>
<td>02 July</td>
<td>183</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Hornbeam</td>
<td>02 July</td>
<td>183</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 14 List of the species measured during the field campaign, the date of sampling and the spectral range covered during measurements: Vis-NIR is the visible nearinfrared region, SWIR is the shortwave infrared.
7.2. **TOP-OF-CANOPY SPECTRAL MEASUREMENTS OVER THE GRASSLAND**

The s-Fluor box has been installed at the top of a small tower (4 m) (Figure 13). The optical fibers were held at the end of a 3 m long arm pointing South. The canopy plane was observed from nadir at a distance from the canopy plane of about 3 m corresponding to a circular field of view of 1.4 m diameter. The s-Fluor box has been operated from June 15 to 23 and on July 2.

![Figure 13: S-fluorbox installed over the grassland field.](image)

A meteorological station measuring air temperature and relative humidity and a Apogee SI-111 sensor measuring canopy radiometric temperature were also installed on the same tower and they have been operated from June 15 to 23 and on July 2 (Figure 14).

![Figure 14: APOGEE SI-111 sensor installed over the grassland field.](image)
Procedure used for data collection

The field spectroscopy technique referred to as ‘single beam’ ([RD6] Milton and Rollin 2006) was employed to evaluate the incident and upwelling fluxes. Target measurements were sandwiched between two incident irradiance measurements made by a single device a few seconds apart. The incident irradiance at the time of the target measurement was estimated by linear interpolation. With the manual system, the incident irradiance was estimated measuring the radiance upwelling from a white reference calibrated spectalon panel (Labsphere Inc., USA) using bare fiber optics with an angular field of view (FOV) of 25°. On the contrary, S-fluor used a cosine-response optic (cc3, OceanOptics, USA) to measure the incident irradiance and a bare fiber optic with an angular FOV of 25° to observe the target surface. For every acquisition, different scans were averaged and stored as a single file. Additionally, the instrument dark current was collected for every set of measurements. Spectral data were acquired with a dedicated software ([RD8] Cogliati 2011; [RD7] Meroni and Colombo 2009).

7.3. Spectral Measurements of Reference Target

Calibration targets were selected 1) large enough to cover an area of 3x3 APEX pixels, 2) homogeneous, 3) fairly Lambertian and 4) encompassing a range of brightness levels (bright to dark). More in details, four artificial targets were used (2 black, 1 grey and one white). These consisted of PVC coated canvas material ('Odyssey' trademark material, from Kayospruce Ltd. –UK) suggested for their good optical properties by the NERC Field Spectroscopy Facility (Edinburgh). Some ‘pseudo-invariant’ features were also selected: concrete, asphalt with different brightness and pit material. Additionally two homogeneous vegetation targets were selected showing quite different spectral characteristics, a soccer field and a dry cut meadow grass.

The measurement protocol was:

- 9x9 m² areas were defined according to flight lines orientation. The four vertex coordinates were recorded with a GPS receiver (GMS-2 Pro, Topcon - accuracy < 1m) and were saved as *kmz files.
- Target radiometric measurements were acquired along several parallel lines (Figure 15, b). The optical fiber was oriented to the sun in order to minimize shadows.
- The fiber was mounted on a leveled tripod with an extended arm (height = 120 cm, length= 80 cm).
- The white reference was mounted on a leveled tripod (height = 95 cm) (Figure 15, a).
- The Fieldspec acquisition was set to an average of 25 spectra for dark current, white reference and sample. The white reference spectra were acquired every 5 target measurements. Fifteen to twenty-five measurements were taken in order to characterized the target area (details are reported in the target descriptions).
- Spectra were acquired in DN saving Spectralon white reference in a separate file. Radiance and reflectance (hemispherical conical reflectance factors - HCRF) were calculated in post processing. Reflectance was calculated normalizing each target spectrum for the average of two white reference spectra acquired before and after five target measurements through
Equation 1. Reflectance was then multiplied by the Spectralon calibration file. Target description and related Filedspec file information are reported below.

\[ HCRF_{\text{target}} = \frac{(L_{\text{target}} \times R_{\text{wr}})}{L_{\text{wr}}} \]  

[Eq. 1]

Where \( L_{\text{target}} \) is the upwelling radiation from the target, \( R_{\text{wr}} \) is the white reference panel calibration factor and \( L_{\text{wr}} \) is the incoming radiation measured on the white reference calibrated panel (Labsphere Inc., U.S.A.).

Figure 15 – a) Measurement set up; b) measurement scheme conducted in the 9x9 m\(^2\) square oriented according to the flight line direction.

Spectroradiometric measurements were conducted in three sites (i.e. stop), located in Apex RUN 1, 3 and 5 respectively (Figure 16). In each site different targets were measured.
Figure 16 – Location of the three cal/val sites and of the 13 targets selected and measured.
Sunphotometer measurements have been performed by UNIMIB people using a Microtops II sunphotometer provided by VITO. The sunphotometer was located at coordinates (47°47’47.42” N, 7°27’34.71”E) during the first and second campaigns and at coordinates (47°51’46.98”N, 7°27’8.54”E) during the third campaign. Direct solar radiation measurements were acquired with a, between 11.00 a.m. and 2.00 p.m. local time. Ten consecutive close scans were taken every 4 minutes.
Vegetation measurements have been performed by INRA, and include:
- Leaf Area Index (LAI)
- Fraction of Absorbed Photosynthetically Active Radiation (fAPAR)
- Canopy Chlorophyll Content (CCC)
- Canopy Water Content (CWC)

The methodology used was consistent with the validation concept proposed within the VALSE2 project, that incorporates the recommendations by CEOS/LPV for validating remote sensing products as described in Figure 17.

*Figure 17. The validation concept*

It is based on a bottom up approach. Individual measurements on the ground are grouped over an elementary sampling unit (ESU) to get a representative value of the sampled area, i.e. around 20 m. Then several ESUs are selected on the site to get a good description of the several vegetation types and status. The validation may then be applied over the site, by comparing at the ESU level the ground measured values with the corresponding products. The validation may be also extended to additional sites.
9.1.1. Selection of the ESUs

The ESUs were selected to sample the range of vegetation types and conditions encountered in the Harth forest. ESUs were selected along paths to facilitate the sampling. Generally ESUs were set on each side of the path. The ESU centre was at about 50 m from the path. The following Table 15 provides a description of the ESUs with the dates of sampling and the corresponding measurements. Three main campaigns have been completed:

- 11-12 June. DHPs were taken over 42 ESUs. At this time the leaves were fully developed. However, a significant fraction of leaves were eaten by worms, particularly for oaks and carpinus. This first campaign was also used to best select the ESUs on which leaf measurements will be completed.
- 27-28 June. The campaign was focusing on the leaf properties. Only 20 ESUs were sampled because of the time required for shooting the leaves, collecting the samples and making the destructive and ground measurements. At this time, some new leaves were appearing, to replace those that were eaten by the worms.
- 3-4 September. This was corresponding to a very early senescence period. Some leaves fall on the ground, due to the stresses experienced by the forest and as a result of the start of the senescence period. Leaf measurements was achieved over 11 ESUs, while DHPs was made over 45 ESUs.
Table 15. The several ESUs sampled during the 3 campaigns (6 days). The geographic coordinates are indicated in °. The green color corresponds to DHP measurements only, while the orange color corresponds to DHP and leaf optical properties measurements.

Figure 18 shows the location of the ESUs. For each campaign, a minimum of 30 ESUs have been sampled. The area covered by the ESUs represents about 15 km². The location of the ESUs was recorded using a GPS that provides an accuracy of few meters. The details of the location of the ESUs are stored in file ‘Consolidated data base.xlsx’, sheet ‘ESU measurements’.
Figure 18. Location of the ESUs over the Harth forest. The yellow line indicates the track used.

9.1.2. **Digital Hemispherical Photos**

Over each ESU, 13 upward and 13 downward DHPs have been taken (Figure 20). The sampling was made according to the scheme described in Figure 19. The ESU size at the ground level corresponded roughly to a 20 m x 20 m area. However, because of the height of the trees, the footprint of the images was much larger. Assuming a 20 m height of the forest, this makes an effective footprint of the measurements of 100 m.

Figure 19. Sampling scheme used at the ESU level.
Hemispherical photos were taken with Sigma cameras equipped with a fish-eye lens. It was set to automatic mode with priority to speed. ISO was set to 200. The photos were then downloaded and organized into folders: one folder per campaign, one sub-folder per ESU containing one Sub-sub-folder for the upward looking, and an other for the downward looking.

Figure 20. The typical images taken with the Sigma cameras. On the left, downward looking photo to sample the understory. On the right, upward looking photo so sample the overstory.

9.1.3. LEAF CHARACTERISTICS

For each ESU where leaf properties were measured, the three dominant species were considered. For each species, sample leaves were shot from the ground using guns. These samples correspond to a random selection of leaves from the top of the trees. The leaves were then immediately collected and put into plastic bags, labeled, sealed and put into a cooler. They were then transported for destructive and non-destructive measurements.

9.1.3.1 Destructive measurements for water and dry matter contents

For the destructive measurements, eleven leaves were considered. For needles, this was corresponding to about 5 g of fresh matter. The same eleven leaves were used for the reflectance measurements. The fresh weight was measured at maximum 12 hours after leaf collection. Then the leaves were set back into plastic bags that were sealed and put in a cooler. Finally, leaf area was measured with a licor3000 planimeter, then they were put in an oven for 48 hours at 70°. The dry weight was measured.

9.1.3.2 Leaf Reflectance measurements for chlorophyll

Leaf reflectance measurements were achieved over the sample of leaves gathered over the ESU for the dominant species and that were also used for destructive measurements. At maximum 12 hours after leaf collection (but most of the time the measurements were completed within 3 hours after leaf collection in the field), reflectance measurements were achieved over a Spectral Evolution spectrometer equipped with an integrative sphere. The sample was illuminated using a xenon lamp connected on a power regulation system. The spectrometer covers the 400-2500 nm spectral range with a spectral resolution going from 1nm (shorter wavelengths) to 5 nm (longer wavebands). Absolute directional hemispherical reflectance was computed using a spectralon reference panel. The system was frequently recalibrated to avoid any drift in the signal: before and
after a series of 11 measurements (one measurement over 11 leaves for each ESU and species), the signal of a secondary reference panel was measured. The signal of a primary reference (spectralon of known properties) was measured every 30 minutes to one hour.

The reflectance spectra measurements are stored for each campaign under a subdirectory corresponding to the date of the measurements (Figure 21). The name of the spectra have always the same prefix (in the example ‘3500_SN1268029_’) and then a suffix that is incremented (in the example ‘00022’) and is terminated by ‘.sed’: ‘SM-3500_SN1268029_00022.sed’.

![Figure 21. The structure of the database containing the leaf reflectance measurements.](image)

The structure of the ‘.sed’ files is easy to read (see Figure 22). The correspondence of each ‘.sed’ file with ESU and species is given in the excel files ‘Leaf_Spectral_Evolution_27_28_June_2013.xlsx’ and ‘Leaf_Spectral_Evolution_03_04_Spetember_2013.xlsx’. These files are selfexplanatory and use a code (in addition to the usual name) for the species and ancillary observations (background, primary and secondary references).
Figure 22. Typical structure of the `.sed` files containing the reflectance measurements.

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<th>species</th>
<th>species</th>
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</thead>
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<td></td>
</tr>
<tr>
<td>74</td>
<td></td>
<td>REF</td>
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</tr>
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<td></td>
</tr>
<tr>
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<td>A1</td>
<td>13 Acer</td>
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</tr>
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<td>90</td>
<td>B2</td>
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</table>

Figure 23. Structure of the excel files describing the reflectance measurements. The code for the species is given in Table 16.
<table>
<thead>
<tr>
<th>Code</th>
<th>Species names</th>
</tr>
</thead>
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<td>Quercus petraea (Chêne sessile)</td>
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<tr>
<td>5</td>
<td>Quercus robur (Chêne pédonculé)</td>
</tr>
<tr>
<td>6</td>
<td>Quercus rubra (Chêne Rouge)</td>
</tr>
<tr>
<td>1</td>
<td>Carpinus betulus (Charme)</td>
</tr>
<tr>
<td>7</td>
<td>Acer campestra (érable champêtre)</td>
</tr>
<tr>
<td>13</td>
<td>Acer platanoide (érable plane)</td>
</tr>
<tr>
<td>12</td>
<td>Prunus Avium (merisier)</td>
</tr>
<tr>
<td>8</td>
<td>Pinus Sylvestrus (pin sylvestre)</td>
</tr>
<tr>
<td>2</td>
<td>Tilia (tilleul)</td>
</tr>
<tr>
<td>9</td>
<td>Larix (mélèze)</td>
</tr>
<tr>
<td>11</td>
<td>Crateagus (Aubepine)</td>
</tr>
</tbody>
</table>

Table 16. The species and codes used to describe the leaf reflectance measurements
10.1. OVERVIEW

After a flight, the APEX operators return to VITO with LTO-2 tapes containing the raw image data, and PCMCIA cards containing the raw Position and Orientation System (POS) data. This data is dumped onto the archive and working storage, ensuring its long term backup.

The raw POS data is processed up till Smoothed Best Estimated Trajectory (SBET) data, to be used in the geometric correction process afterwards. Processing is done using the Applanix POSPac MMS software suite.

The raw image data and corresponding metadata is extracted from tape, and quicklooks are generated to verify data quality (i.e. L0 processing). The Quicklooks are generated from the raw, uncalibrated, uncorrected sensor data, and contain 2 black stripes, caused by the wires that are placed on the entry slit of the APEX instrument. At the wire positions, no sensor data is available, however data interpolation is performed afterwards to remove these black stripes.

The L0 data is radiometrically calibrated (i.e. L1b processing), thereby using the calibration cubes, generated from data measured and collected during the yearly calibration campaign on the APEX Calibration Home Base (CHB) at DLR. This campaign has been performed in May 2013, before the flight season.

L0 and L1 processing is done using dedicated IDL software, developed and maintained within the APEX consortium.

The radiance cubes and corresponding metadata, are archived in HDF5 file format, and registered in the database of the Central Data Processing Center (CDPC), accompanied by a georeferenced quicklook.

Once registered in the CDPC database, the radiance cubes are selected for higher-level processing through an automated processing workflow. Both the geometric correction and the atmospheric correction are configured and run through this workflow.

The geometric correction is performed using a DTM of the Mulhouse region delivered by the INRA, and the data is projected to UTM, WGS84, with a final resolution of 3m by 3m.

The sunphotometer data is analysed to derive initial estimates for the atmospheric correction parameters: visibility, columnar water vapor and aerosol type.

After applying the atmospheric correction, the radiometric accuracy is checked by comparing the target reflectances in the imagery with the spectral measurements on-ground. If deemed necessary by the image processing team, vicarious calibration is performed.

Wavelength dependent spectral smoothing of the data is performed to remove noise and spikes remaining after atmospheric correction. Smoothing is done using dedicated IDL software, developed and maintained at VITO.

The reflectance data is resampled to the wavelengths of the central pixel, as measured during the sensor spectral calibration on the Calibration Home Base (CHB).

A graphical representation of these processing steps is provided on the next page.
Figure 24: APEX processing steps
10.2. DATA FORMATS

10.2.1. IMAGE DATA AND METADATA

The hyperspectral image cubes are delivered in ENVI format, i.e. pairs of .img and .hdr files:
- Level-0 (L0) data, i.e. raw, uncalibrated image data
- Level-1b (L1b) data, i.e. radiometrically calibrated (radiance) data
- Level-1c (L1c) data, i.e. radiometrically calibrated and geometrically corrected data
- Level-2a (L2a) data, i.e. radiometrically calibrated and geometrically and atmospherically corrected (reflectance) data

The Quicklooks are delivered in jpg and png format.
The metadata is delivered in ASCII format.
File naming is as shown in Table 17 below:

<table>
<thead>
<tr>
<th>Level</th>
<th>Data description</th>
<th>File naming</th>
</tr>
</thead>
</table>
| L0    | ImageData                 | APEX_SEN2Exp_130617_a01_raw.img  
APEX_SEN2Exp_130617_a01_raw.hdr |
|       | Quicklooks                | APEX_SEN2Exp_130617_a01_raw.jpg                                             |
|       | PositionAndOrientationData| APEX_SEN2Exp_130617_a01_pos.txt                                            |
| L1    | L1b_RadianceData          | APEX_SEN2Exp_130617_a01_Part_0_rad.img  
APEX_SEN2Exp_130617_a01_Part_0_rad.hdr |
|       | L1c_RadianceData_Geo      | APEX_SEN2Exp_130617_a01_Part_0_radGeo.img  
APEX_SEN2Exp_130617_a01_Part_0_radGeo.hdr |
|       | Quicklooks                | APEX_SEN2Exp_130617_a01_Part_0_rad.png  
APEX_SEN2Exp_130617_a01_Part_0_rad.pngw  
APEX_SEN2Exp_130617_a01_Part_0_radGeo.png  
APEX_SEN2Exp_130617_a01_Part_0_radGeo.pngw |
|       | SpectralProperties        | APEX_SEN2Exp_130617_a01_Part_0_SpectralProperties_1.xml                     |
| L2    | ReflectanceData           | APEX_SEN2Exp_130617_a01_Part_0_refl.img  
APEX_SEN2Exp_130617_a01_Part_0_refl.hdr |
|       | Quicklooks                | APEX_SEN2Exp_130617_a01_Part_0_refl.png  
APEX_SEN2Exp_130617_a01_Part_0_refl.pngw |

Table 17: Image data file naming

10.2.1.1 L0 image data/quicklooks

The level-0 (L0) data, i.e. raw, uncalibrated image data contains 316 bands.
In the raw image cubes and the corresponding quicklooks, one will notice 2 black lines, caused by the wires that are placed on the APEX entry slit. In the L1 and L2 data, the data at this wire positions has been interpolated, thereby removing the black lines.
10.2.1.2 Position And Orientation Data

The position and orientation data file provides for each scanline in the image the information listed in Table 18. The boresight misalignment angles are not yet included, and have to be added to the roll, pitch and yaw parameters before usage.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS-time</td>
<td>seconds</td>
</tr>
<tr>
<td>Longitude</td>
<td>Radians, WGS84</td>
</tr>
<tr>
<td>Latitude</td>
<td>Radians, WGS84</td>
</tr>
<tr>
<td>Height</td>
<td>Meters, WGS84</td>
</tr>
<tr>
<td>Roll</td>
<td>Radians</td>
</tr>
<tr>
<td>Pitch</td>
<td>Radians</td>
</tr>
<tr>
<td>Yaw</td>
<td>Radians</td>
</tr>
</tbody>
</table>

Table 18: Position and orientation parameters

10.2.1.3 L1 image data/quicklooks

The Level-1 (L1b and L1c) data, i.e. radiometrically calibrated (radiance) data contains 288 bands. Overlapping bands between VNIR and SWIR detectors, and some bands with suspect radiometric quality are removed. More details on the band cutting and the uncertainty in the radiometric calibration are provided in section 10.3.12 and section 10.3.11 respectively. Data at the wire positions has been interpolated, thereby removing the black lines. Because the large amount of scan lines, the flight line has been split in parts, to ease the file handling.

There is an overlap of 200 lines between two consecutive flight line parts.

The L1 image data has not yet been corrected for the spectral shifts. The parameters to correct for the shifts are provided in the Spectral properties file, and the formula to apply these parameters is given in Table 24.

10.2.1.4 Spectral Properties

In the spectral properties file, the central wavelength and FWHM is given for each band, together with 5 parameters to allow for spectral smile correction. For more information on how to apply these parameter, refer to section 10.3.7 “APEX spectral shift detection”

10.2.1.5 L2 image data/quicklooks

The Level-2a (L2a) data, i.e. radiometrically calibrated and geometrically and atmospherically corrected (reflectance) data contains 288 bands. Wavelength dependent spectral smoothing of the data is performed to remove noise and spikes remaining after atmospheric correction.
Furthermore, the reflectance data is resampled to the wavelengths, as measured during the sensor spectral calibration on the Calibration Home Base (CHB).
10.2.2. CALIBRATION DATA

The calibration cubes are delivered in ENVI format, there is one cube for the VNIR detector and one cube for the SWIR detector.

The e-loss compensation parameters and boresight angles are provided as ASCII files.

File naming of the calibration data is as shown in Table 19.

<table>
<thead>
<tr>
<th>Data description</th>
<th>File naming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration cube - VNIR</td>
<td>VNIR_CHB_calibration_cube_26-Jun-2013_v1</td>
</tr>
<tr>
<td></td>
<td>VNIR_CHB_calibration_cube_26-Jun-2013_v1_hdr</td>
</tr>
<tr>
<td>Calibration cube - SWIR</td>
<td>SWIR_CHB_calibration_cube_26-Jun-2013_v1</td>
</tr>
<tr>
<td></td>
<td>SWIR_CHB_calibration_cube_26-Jun-2013_v1_hdr</td>
</tr>
<tr>
<td>e-loss compensation parameters</td>
<td>e_loss_comp_coeffs_2013_iteration_1.csv</td>
</tr>
<tr>
<td>Boresight angles</td>
<td>APEX_2013_BoresightAngles_July.txt</td>
</tr>
</tbody>
</table>

Table 19: Calibration data file naming

10.2.2.1 Calibration cubes

The calibration cubes contain all the data related to the radiometric, spectral and geometric calibration of the raw data.

10.2.2.2 e-loss compensation parameters

The e-loss compensation parameters file holds gain coefficients for the energy loss compensation in the blue region of the VNIR detector.

10.2.2.3 Boresight angles

The boresight angles are given in degrees, and must be added to the roll, pitch and yaw parameters (radians) in the PositionAndOrientationData file.
10.3. DATA PROCESSING

<table>
<thead>
<tr>
<th><strong>POS data processing</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>SBET generation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>APEX data processing</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>L0/L1 processing</strong></td>
</tr>
<tr>
<td>Raw data extraction</td>
</tr>
<tr>
<td>Radiometric/spectral and geometric calibration</td>
</tr>
<tr>
<td>Destriping</td>
</tr>
<tr>
<td>Boresight calibration</td>
</tr>
<tr>
<td>Spectral shift detection</td>
</tr>
<tr>
<td>Data “archiving”</td>
</tr>
<tr>
<td><strong>L2 processing</strong></td>
</tr>
<tr>
<td>Geometric correction</td>
</tr>
<tr>
<td>Atmospheric correction</td>
</tr>
<tr>
<td>Vicarious calibration</td>
</tr>
<tr>
<td>Band cutting</td>
</tr>
<tr>
<td>Spectral resampling</td>
</tr>
<tr>
<td>Spectral smoothing</td>
</tr>
</tbody>
</table>

Table 20: APEX data processing steps

10.3.1. POS DATA PROCESSING

The Position and Orientation data logged during the flight is post-processed using the APPLANIX POSPac MMS software (v6.1).

Inputs are:
- The raw GPS position data (longitude, latitude, height)
- The raw IMU orientation data (roll, pitch, yaw)
- The gimbal (stabilized mount) data
- GPS base station data (for the differential GPS correction)
- Lever arms and mounting angles (GPS/IMU installation parameters)

Output is:
- SBET-file, i.e. smoothed Best Estimated Trajectory, providing enhanced position and orientation data for the full flight trajectory at a frequency of 200Hz.

After the SBET has been generated for a particular flight, several plots are checked to evaluate the quality of the obtained solution:
- The trajectory plot for the flight:
  Figure 26 provides the trajectory plot for the Mulhouse flight of 01/07/2013
- The plot indicating the attitude accuracy:
  Figure 26 provides the roll/pitch/yaw accuracy for the Mulhouse flight of 17/06/2013
- The plot indicating the attitude accuracy:
  Figure 27 provides the latitude/longitude/height accuracy for the Mulhouse flight of 17/06/2013
Typical values for the accuracy indicators are:

- **Attitude:** RMS [arc-min] 0.5 – 3
- **Position:** RMS [cm] 3 - 10

**Figure 25:** POSPac MMS trajectory plot for a Mulhouse flight

**Figure 26:** POSPac MMS accuracy indicator plot for the attitude parameters
10.3.2. **APEX RAW DATA EXTRACTION**

The raw image data (in DNs, as shown in Figure 29), dark current data, and corresponding metadata is extracted from tape and quicklooks are generated to verify data quality (i.e. L0 processing). Contained in the metadata is the UTC of each scanline, which is required for linking the sensor data to the corresponding position and orientation data (from the SBET-file). The Quicklooks are generated from the raw, uncalibrated, uncorrected sensor data, and contain 2 black stripes, caused by the wires that are placed on the entry slit of the APEX instrument (as can be seen from Figure 28). At the wire positions, no sensor data is available, however data interpolation is performed afterwards to remove these black stripes. The across track wire positions are: columns 336-337 and 676-677, the interpolated region currently encompasses a buffer of 1 pixel around the wire positions.
Figure 28: Black wires in a raw APEX cube

Figure 29: Sample spectrum (Digital Numbers) of a raw APEX cube
10.3.3. **Radiometric/Spectral and Geometric Calibration**

The APEX radiometric, spectral, and geometric calibration is performed using dedicated IDL-software, developed and maintained within the APEX consortium. It is using:

- the calibration cubes generated from data measured and collected before the flight season on the APEX Calibration Home Base (CHB) hosted at DLR Oberpfaffenhofen, Germany [RD3].
- the dark current data recorded in flight
- the e-loss compensation parameters file, holding the gain coefficients for the energy loss compensation in the blue region of the VNIR detector

In this calibration step also the data interpolation at the wire positions is performed to remove the black stripes.

![Figure 30: Black wires removed from a calibrated APEX cube](image)

![Figure 31: Sample spectrum (mW/m²/nm/sr) of an APEX radiance cube](image)
10.3.4. **Destriping**

APEX is a line scanner, inherently prone to along track striping effects. Furthermore, wire pixel interpolation artefacts need to be removed. For these purposes, a destriping step is being applied after radiometric calibration of the data.

*Figure 32: Detail of an APEX radiance cube before and after destriping*
10.3.5. **Boresight Calibration**

The aim of the boresight calibration is to determine the boresight angles, i.e. misalignment angles between the IMU and the sensor frame.

### 10.3.5.1 Image data

The APEX data selected for the geometric calibration consists of 6 flight lines flown above the city of Ostend (Belgium) on 07/07/2013, at a height of 3350m ASL. The cross-like pattern was specifically designed in support of the geometric calibration. A screenshot of the Ostend flight lines is given in Figure 33.

4 flight lines were selected for the actual boresight computation:
- M0029130707_a010b.img
- M0029130707_a030b.img
- M0029130707_a090b.img
- M0029130707_a110b.img

and 2 were reserved for visual validation:
- M0029130707_a050b.img
- M0029130707_a070b.img

![Figure 33. Position of the APEX flight lines above Oostende (Belgium), used for boresight calibration/validation](image)
To check the consistency of the geometric calibration parameters, additional flight lines have been used for visual validation. These flight lines have been selected from 3 other datasets flown over respectively Zeebrugge and Nieuwpoort (Belgium), and Mulhouse (France).

These flight lines were selected because they cover a large variability in flight altitude:
- Zeebrugge: 6190m ASL
- Nieuwpoort (IJzer): 3940m ASL
- Mulhouse: 5720m ASL

The selected flight lines are shown in Figure 34, Figure 35 and Figure 36.

*Figure 34. Position of the APEX flight line above Zeebrugge (Belgium), used for boresight validation*
Figure 35. Position of the APEX flight line above Nieuwpoort (Belgium), used for boresight validation

Figure 36. Position of the APEX flight line above Mulhouse (France), used for boresight validation
10.3.5.2 POS data

Besides the APEX imagery, also the position and the orientation of the detector at the time of the imaging are needed to perform the boresight calibration. These position and orientation parameters are extracted from the POSPAC SBET file (cfr section 10.3.1). For every image, the corresponding POS data is provided in an ASCII file, containing for every image line the corresponding time stamp, position (latitude/longitude/height) and orientation (roll,pitch,yaw).

10.3.5.3 APEX sensor model

Besides the exterior orientation parameters (POS data), one also needs the interior orientation parameters in the boresight calibration. The number of interior orientation parameters depends on the sensor model. For scanner systems (like APEX), there are two major types: the pushbroom model and whiskbroom model.

Figure 37: Interior orientation parameters (indicated in red) of the pushbroom (left) and whiskbroom sensor model.

However, from the APEX Acceptance Review, it is clear that APEX behaves as a whiskbroom sensor, implying that only the FOV must be used in this definition of the sensor.

The FOV is measured at the CHB in 2009 and was found to equal: 27.9842712347 degrees.

10.3.5.4 GCP selection

For the Belgian sites (Oostende, Nieuwpoort, Zeebrugge), orthophotos at a resolution of 0.25 m were chosen as reference and were accessed via the following WMS: http://wms.agiv.be/ogc/wms/omkl

A screenshot of such an orthophoto is given in Figure 38.
For the retrieval of the Z-coordinate, a Digital Elevation Model (DEM) was used. This DEM was generated from a LIDAR campaign and has a resolution of 5 m with a vertical accuracy of 7 cm for areas covered with short grass or under pavement and 20 cm for areas under complex vegetation. This DEM was created and is distributed by AGIV\(^1\) (Agency for Geographical Information in Flanders). In total 106 GCPs were selected, spread over the overlapping region of the 4 flight lines.

![Figure 38. Orthophotos of the Ostend area used for GCP selection.](image)

Ground Control Points were simultaneous selected from the orthophotos (X/Y coordinates and image number) and the raw APEX imagery (row and column number). The GCP points layer was converted to shape format, projected in latitude/longitude WGS84 and overlaid with the DEM to automatically assign the corresponding Z-coordinate to each point. As a final step the sensor XYZ coordinates (in WGS84) and roll, pitch, true heading (radians), taken from the housekeeping data, were linked to the GCP based on the row number. The resulting table links the reference coordinates, image coordinates with the sensor location and orientation.

### 10.3.5.5 Geometric calibration

The actual calibration is performed through a Monte Carlo optimization running 20 loops/20,000 simulations to optimize for three parameters: (1) boresight roll, (2) boresight pitch and (3) boresight yaw.

The resulting boresight angles for roll, pitch and yaw are given in Table 21.

\(^1\) [http://www.agiv.be/gis/projecten/?artid=102](http://www.agiv.be/gis/projecten/?artid=102)
Boresight angles

<table>
<thead>
<tr>
<th>Boresight angles</th>
<th>July 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll (degrees)</td>
<td>-0.1969148996</td>
</tr>
<tr>
<td>Pitch (degrees)</td>
<td>0.3231659230</td>
</tr>
<tr>
<td>Yaw (degrees)</td>
<td>-0.5463498106</td>
</tr>
</tbody>
</table>

*Table 21: Boresight angles for roll, pitch and yaw for the APEX July 2013 boresight mission*

The positional accuracy of the direct georeferencing with and without the inclusion of the estimated boresight angles is given in Table 22.

<table>
<thead>
<tr>
<th></th>
<th>July 2013 - mathcad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without boresight</td>
</tr>
<tr>
<td></td>
<td>angles</td>
</tr>
<tr>
<td>Mean Deviation</td>
<td>20.6908m</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.914m</td>
</tr>
<tr>
<td></td>
<td>With boresight</td>
</tr>
<tr>
<td></td>
<td>angles</td>
</tr>
<tr>
<td>Mean Deviation</td>
<td>1.793m</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.983m</td>
</tr>
</tbody>
</table>

*Table 22: Positional accuracy of the direct georeferencing with and without the inclusion of the estimated boresight angles for the APEX flights 2013*

Figure 39 and Figure 40 illustrate for every GCP the deviation from the actual GCP position before and after applying the boresight angles in the direct georeferencing.

*Figure 39: Deviation from GCP position (in meter) before applying any boresight angles*
Figure 40: Deviation from GCP position (in meter) after applying the boresight angles

In the 3 images below, the deviation values are plotted against the column number in the image, after the boresight calibration. These images show that after boresight calibration the positional accuracy is equal across the FOV of the sensor, and less than 1.5 pixel.

Figure 41: Deviation from GCP position (in meter) after applying the boresight angles
10.3.5.6 Geometric calibration validation

To validate the result of the boresight calibration, a visual inspection has been performed. Independent flightlines of the Oostende, Zeebrugge, IJzer and Mulhouse mission were georeferenced and resampled in the VITO Central Data Processing Centre, thereby using the obtained boresight angles. The resolution of the digital elevation models used for georeferencing is: 5m for the flanders DEM, and 25m for the Mulhouse DEM. The reference imagery used for the visual inspection is: AGIV orthophotos @0.25m resolution for the flanders sites, Google Earth for the Mulhouse site.

- The GCP’s used for visual inspection are marked as red crosses (+) and small bullets (○) in the figures on the next pages. Figure 44 till Figure 47 show the distribution of the GCP’s over the flight lines, whereas the Figure 48 till Figure 51 provide an impression of the absolute geolocation accuracy.
Figure 44: Oostende GCP’s selected for visual validation

Figure 45: Zeebrugge GCP’s selected for visual validation

Figure 46: IJzer GCP’s selected for visual validation
Figure 47: Mulhouse GCP’s selected for visual validation
The images below give an idea of the absolute geolocation accuracy:

Figure 48: Oostende absolute geolocation check: AGIV ortho (left) vs APEX image (right)

Figure 49: Zeebrugge absolute geolocation check: AGIV ortho (left) vs APEX image (right)

Figure 50: Lijzer absolute geolocation check: AGIV ortho (left) vs APEX image (right)
Figure 51: Mulhouse absolute geolocation check: Google Earth (left) vs APEX image (right)
**Conclusion:**

Visual inspection of the absolute geolocation on the selected flight lines confirms the result of the average deviation, i.e. 1 pixel, found in the boresight calibration procedure.

### 10.3.6. APEX DATA ARCHIVING

All APEX data is automatically ‘archived’, i.e. HDF5 archive files are created, containing:
- at-sensor radiance (all 313 bands)
- sensor metadata, comprising:
  - sensor spectral characteristics (incl shift parameters)
  - sensor geometry
  - sensor exterior orientation (POSdata for each scanline)
  - additional quality information

These HDF5 files are registered in the Central Database, and made available for further processing in VITO’s Central Data Processing Center (CDPC).

It is noted that flight lines are cut in parts of 3000 scan lines to ease the file handling afterwards, and that there is an overlap of 200 scan lines for adjacent image parts.

Figure 52 shows the content of a L1 HDF5 file.

![Figure 52: content of L1 HDF5 file](image-url)
10.3.7. APEX SPECTRAL SHIFT DETECTION

APEX is suffering from spectral shifts during flight, caused by pressure and temperature variations, this is the so-called ‘smile-effect’.

The observed spectral shift varies:
- Across-track, i.e. depends on the column pixel location
- During the course of a particular flight line
- Between different flight days

The figures below illustrate this shift in the (continuum removed) radiance spectrum around 1100 nm and 762 nm for flight lines of 2 different flight days.

![Figure 53: radiance spectral shift for flight lines of 2 different flight days](image)

During the archiving process, an automatic spectral shift detection is performed, which is:
- radiance-based (Gao et al., 2004), i.e. a spectrum-matching technique applied on the at-sensor radiance
- using a set of atmospheric absorption features
- run on each image part separately (pressure variations during long flightlines)

The atmospheric features used in the spectral shift detection algorithm are listed in Table 23.

<table>
<thead>
<tr>
<th>VNIR atmospheric features</th>
<th>SWIR atmospheric features</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO2 at 430 nm</td>
<td>H2O at 935 nm</td>
</tr>
<tr>
<td>O2 at 687 nm</td>
<td>H2O at 1137 nm</td>
</tr>
<tr>
<td>O2 at 762 nm</td>
<td>CO2 at 2007 nm</td>
</tr>
<tr>
<td>H2O at 815 nm</td>
<td>CO2 at 2060 nm</td>
</tr>
<tr>
<td>H2O at 935 nm</td>
<td>CH4 at 2210 nm</td>
</tr>
<tr>
<td></td>
<td>CH4 at 2415 nm</td>
</tr>
</tbody>
</table>

*Table 23: atmospheric features used for APEX spectral shift detection*
Figure 54 shows the absorption regions in the radiance spectrum for an APEX pixel in columns 1 (c1), 500 (c500) and 1000 (c1000) of the image.

![Absorption regions in an APEX radiance spectrum](image)

*Figure 54: absorption regions in an APEX radiance spectrum*

The output of the algorithm provides for each spectral band 5 correction parameters (contained in the *SpectralProperties.xml* files, cfr section 10.2.1) to reassign new central wavelengths to each pixel, according to the formula:

For pixel $i$ with $i$ between 1 and 1000
\[
\text{wvl}(i) = (\text{ns1:CentralWavelengths-Micrometer}) + \\
(\text{ns1:CentralWaveLength-Parameter1}) + \\
(\text{ns1:CentralWaveLength-Parameter2})i + \\
(\text{ns1:CentralWaveLength-Parameter3})i^2 + \\
(\text{ns1:CentralWaveLength-Parameter4})i^3 + \\
(\text{ns1:CentralWaveLength-Parameter5})i^4
\]

*Table 24: Formula to correct for the spectral smile*

It has to be noted that the smile correction has NOT been applied to the L1 data, but it was applied to the L2 data, i.e. the atmospheric correction was ‘smile-aware’, was taken into account the spectral shifts.

To illustrate the spectral shift variations, 3 Mulhouse flight lines of 17/06/2013 have been used, each flight line cut in parts of 3000 scan lines:

First line captured = APEX_SEN2Exp_130617_a07 part0,1,2
3rd line captured = APEX_SEN2Exp_130617_a07 part0,1,2
Last line captured = APEX_SEN2Exp_130617_a01 part 0,1,2
Spectral shift observed
- different for each image part \((plot \ i = image \ part \ i)\)
- \(f(\text{across-track pixel})\)

Figure 55: spectral shift detection for the 1\(^{st}\), 3\(^{rd}\) and last flight line of 17/06 using absorption feature O2 at 762 nm (VNIR)
Spectral shift observed

- different for each image part (plot $i = image part i$)
- $f(\text{across-track pixel})$

Figure 56: spectral shift detection for the 1$^{\text{st}}$, 3$^{\text{rd}}$ and last flight line of 17/06 using absorption feature H2O at 1137 nm (SWIR)
Spectral shift observed
• different for each flight line (Plot i = part0 of flight line i of 17/06/2013)

Figure 57: spectral shift detection for the seven flight lines of 17/06 using absorption feature O2 at 762 nm (VNIR)

Figure 58: spectral shift detection for the seven flight lines of 17/06 using absorption feature H2O at 1137 nm (SWIR)
Spectral shift observed

- different for each flight day (Plot i = part0 of flight line i of 17/06/2013)

Figure 59: spectral shift detection on single flight lines of different flight days using absorption feature O2 at 762 nm (VNIR)

Figure 60: spectral shift detection on single flight lines of different flight days using absorption feature H2O at 1137 nm (SWIR)
10.3.8. **GEOMETRIC CORRECTION**

The geometric correction was performed in the CDPC by VITO’s own developed C++ module and is based on Direct Georeferencing (DG). Input data from the sensor’s GPS/IMU, boresight correction data (cfr section 10.3.5) and a DTM of the Mulhouse region (@25m resolution) delivered by INRA were further used during the geometric correction process. Finally the data were projected to UTM (zone32N), WGS84, with a resolution of 3m by 3m.

Figure 61 presents a graphical overview of the output of the Direct Georeferencing orthorectification module integrated in the CDPC. The output grid features 10 information layers, containing all pixel dependent position and viewing geometry parameters of importance for the atmospheric correction of the observed radiance.

![Image of the 10 output layers of the CDPC direct georeferencing module]

**Figure 61: The 10 output layers of the CDPC direct georeferencing module**

To assess the accuracy of the geometric correction:
1. The position of the artificial tarps in the imagery was checked
2. The position of some GCPs selected from high resolution orthophotos on the geo-portal of the IGN (http://www.geoportail.gouv.fr/accueil) was checked
10.3.8.1 Artificial tarps in the APEX imagery

In the *.kmz–files that were delivered by UNIMIB for the ground measurements, the vertex coordinates of the artificial tarps were provided for some of the flight days. These were overlayed with the APEX imagery, the tarp corners are displayed as red crosses (+) in the images on the next page.

Table 25 lists the vertex coordinates (UTM), Table 26 shows in which APEX images these tarps can be found.

<table>
<thead>
<tr>
<th>Tarp</th>
<th>Date</th>
<th>Upper Left</th>
<th>Upper Right</th>
<th>Lower Left</th>
<th>Lower Right</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Panel 9x9</td>
<td>17/06/2013</td>
<td>380785.53</td>
<td>380794.19</td>
<td>380782.64</td>
<td>380790.5</td>
<td>m E</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5302221.4</td>
<td>5302218.44</td>
<td>5302212.5</td>
<td>5302210.49</td>
<td>m N</td>
</tr>
<tr>
<td>Black Panel 9x9</td>
<td>4/09/2013</td>
<td>384274.15</td>
<td>384283.28</td>
<td>384273.55</td>
<td>384281.86</td>
<td>m E</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5302235.4</td>
<td>5302234.6</td>
<td>5302226.15</td>
<td>5302225.98</td>
<td>m N</td>
</tr>
<tr>
<td>Grey Panel 9x9</td>
<td>17/06/2013</td>
<td>380779.45</td>
<td>380787.49</td>
<td>380777.4</td>
<td>380785.45</td>
<td>m E</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5302208.86</td>
<td>5302205.92</td>
<td>5302200.26</td>
<td>5302197.62</td>
<td>m N</td>
</tr>
<tr>
<td>Black Panel 6x6</td>
<td>4/09/2013</td>
<td>384303.22</td>
<td>384308.61</td>
<td>384302.06</td>
<td>384308.28</td>
<td>m E</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5302233.89</td>
<td>5302233.47</td>
<td>5302227.74</td>
<td>5302226.99</td>
<td>m N</td>
</tr>
<tr>
<td>Black Panel 6x6</td>
<td>1/07/2013</td>
<td>384248.3</td>
<td>384253.46</td>
<td>384246.09</td>
<td>384252.09</td>
<td>m E</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5302241.79</td>
<td>5302240.14</td>
<td>5302235.04</td>
<td>5302233.99</td>
<td>m N</td>
</tr>
</tbody>
</table>

Table 25: vertex coordinates of the artificial tarps

<table>
<thead>
<tr>
<th>Tarp</th>
<th>Date</th>
<th>APEX img</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black Panel 9x9</td>
<td>17/06/2013</td>
<td>APEX_SEN2Exp_130617_a01_Part_1</td>
</tr>
<tr>
<td>Black Panel 9x9</td>
<td>4/09/2013</td>
<td>APEX_SEN2Exp_130904_a03_Part_3</td>
</tr>
<tr>
<td>Grey Panel 9x9</td>
<td>17/06/2013</td>
<td>APEX_SEN2Exp_130617_a01_Part_1</td>
</tr>
<tr>
<td>Black Panel 6x6</td>
<td>4/09/2013</td>
<td>APEX_SEN2Exp_130904_a03_Part_3</td>
</tr>
<tr>
<td>Black Panel 6x6</td>
<td>1/07/2013</td>
<td>APEX_SEN2Exp_130701_a03_Part_1</td>
</tr>
</tbody>
</table>

Table 26: tarps in the APEX imagery
Figure 62: Black 9x9 panel 17/06/2013

Figure 63: Grey 9x9 panel 17/06/2013

Figure 64: Black 9x9 panel 04/09/2013

Figure 65: Black 6x6 panel 04/09/2013

Figure 66: Black 6x6 panel 01/07/2013
10.3.8.2 Ground Control Points in the APEX imagery

3 GCPs (lat/lon) have been selected from high resolution orthophotos on the geo-portal of the IGN (http://www.geoportail.gouv.fr/accueil) Their location was cross-checked in Google Earth (Figure 67 till Figure 69), and in the APEX images of 17/06, 01/07, 30/08 and 04/09 (Figure 70 till Figure 72).

Table 27 lists the GCP coordinates and shows in which APEX images these GCPs can be found:

<table>
<thead>
<tr>
<th>GCP</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Easting</th>
<th>Northing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tennis Court</td>
<td>47.75475185</td>
<td>7.38729768</td>
<td>379132.11</td>
<td>5290301.9</td>
</tr>
<tr>
<td>Water</td>
<td>47.76729216</td>
<td>7.38640261</td>
<td>379094.1</td>
<td>5291696.96</td>
</tr>
<tr>
<td>Road</td>
<td>47.79238226</td>
<td>7.39859253</td>
<td>380065.19</td>
<td>5294466.42</td>
</tr>
</tbody>
</table>

Table 27: GCP coordinates

<table>
<thead>
<tr>
<th>GCP</th>
<th>APEX img</th>
</tr>
</thead>
<tbody>
<tr>
<td>All 3 GCPs</td>
<td>APEX_SEN2Exp_130617_a02_Part_0</td>
</tr>
<tr>
<td></td>
<td>APEX_SEN2Exp_130701_a02_Part_0</td>
</tr>
<tr>
<td></td>
<td>APEX_SEN2Exp_130830_a02_Part_0</td>
</tr>
<tr>
<td></td>
<td>APEX_SEN2Exp_130904_a02_Part_2</td>
</tr>
</tbody>
</table>

Table 28: GCPs in the APEX imagery

Figure 67: Tennis Court in IGN ortho (left) and Google Earth (right)
Figure 68: Water in IGN ortho (left) and Google Earth (right)

Figure 69: Road in IGN ortho (left) and Google Earth (right)
Figure 70: Tennis Court in APEX image 17/06, 01/07, 30/08 and 04/09
Figure 71: Water in APEX image 17/06, 01/07, 30/08 and 04/09
Figure 72: Road in APEX image 17/06, 01/07, 30/08 and 04/09
10.3.9. Atmospheric correction

The atmospheric correction of the acquired APEX data is performed in the VITO Central Data Processing Center [RD4] with the MODTRAN4 radiative transfer code following the algorithms given in de Haan et al. (1991, [RD1]) and de Haan and Kokke (1996, [RD2]) and taking into account the in-flight determined central wavelengths for each pixel (column) (i.e. smile aware atmospheric correction).

After the geometric correction, the orientation of every pixel relative to the sun and the sensor position is known. Based on these orientation parameters and the in-situ measured atmospheric parameters (sun photo measurements), MODTRAN4 is configured and executed, resulting in the necessary information to apply the correction. The geometry is pixel-dependent. In principle the atmospheric correction should be performed for each pixel independently, but this is practically not possible with respect to the necessary amount of computing time. As a workaround one often uses pre-calculated look up tables (LUT): these are produced by running the RTC for a discrete set of samples in the geometry space and saved to disk. Later in the atmospheric correction the LUT is combined with an interpolation technique. LUT values depend on the atmospheric state and are sensor-dependent due to the specific spectral bands. Hence, the pre-calculated LUT approach is non-generic. Therefore, the atmospheric correction in the CDPC is equipped with a direct interpolation method: for each image and each spectral band a band specific and image geometry specific LUT is created in memory during the atmospheric correction. A number of samples is taken from the relevant geometry space, for these samples a number of RTCs are executed just before the atmospheric correction, which is performed by interpolating the RTC results in the geometry space. Hence, the CDPC does not use the traditional approach of a disk-stored LUT, but performs the MODTRAN4 configuration “on the fly”: during the image processing MODTRAN4 configuration files are created, the needed parameters are determined by the given image geometry and in-situ measurements, the MODTRAN4 runs are performed and finally the MODTRAN4 output is used to calculate the atmospheric correction. The major advantage of running MODTRAN4 ‘on-the-fly’ is that all 176 configuration parameters can be customized. Consequently, all MODTRAN4 functionality becomes available for atmospheric processing in the CDPC by submitting custom processing parameters.

Initial settings for visibility, aerosol type and water vapor content are derived from the sunphoto meter measurements (see CHAPTER 12), validation/fine tuning is done using target reflectances measured by UNIMIB teams on the different flight days.

The figures below compare some APEX reflectance spectra to measured ground spectra. After analyzing the spectra of all measured targets, it was decided to apply a vicarious calibration for the 1030nm region and the end-SWIR region.

![Figure 73: Dark Asphalt target reflectance measured on ground (01/07) vs APEX reflectance (01/07)](image_url)
**Figure 74:** Black (9mx9m) target reflectance measured on ground (01/07) vs APEX reflectance (01/07)

**Figure 75:** Asphalt target reflectance measured on ground (17/06 and 01/07) vs APEX reflectance (17/06, 01/07, 30/08 and 04/09)
10.3.10. Vicarious Calibration

The following approach was taken for the vicarious calibration of the APEX data:

“Best-fit” target selection
- Compare APEX reflectances with target reflectances for ALL measured targets
- Select subset of targets to be used for vicarious calibration (homogeneous/invariant)

APEX “best-fit” pixel selection
- Select target “best-fit” pixel in the reflectance image
- Save radiance for this pixel from the radiance image

Perform MODTRAN-5 runs for upscaling the target reflectance to at-sensor radiance, thereby taking into account water vapor content, aerosol type, visibility, terrain and flying height, day-of-year, measurement time and target location.

Resample the MODTRAN output to (spectrally shifted) APEX frequencies.

Perform linear regression to fit APEX radiance with MODTRAN output in the 1030 region and the end-SWIR region.

Derive gain parameters and apply them to the radiance data through the use of the APEX-PAF.

Archive the re-calibrated cubes (v2) in the CDPC for further atmospheric and geometric processing.

As an example, Figure 76 compares the APEX target radiance (APEX_T3_p769) with the MODTRAN modelled radiance (MODYTRAN) for a particular target in the 1030nm region. It should be noted that ‘MODTRAN_T3_weighted’ is a combination of ‘MODTRAN_T3’ simulation without adjacency and ‘MODTRAN_T3_Adj’ simulation with adjacency effect.

![Figure 76: APEX measured radiance (APEX_T3_p769) vs MODTRAN modelled radiance (MODTRAN_T3_weighted) in the 1030nm region.](image)

Figure 77 and Figure 78 show an APEX gravel spectrum before and after the vicarious calibration. The spectrum after the vicarious calibration has also got the VNIR/SWIR overlap cut.
Figure 77: Gravel target reflectance measured on ground (01/07) vs APEX reflectance (01/07) before vicarious calibration

Figure 78: Gravel target reflectance measured on ground (01/07) vs APEX reflectance (01/07) after vicarious calibration (VNIR/SWIR overlap cut)
10.3.11. **Radiometric Uncertainty Estimation**

The figures in this chapter quantify the uncertainty of the radiometric calibration for the pixel spectra that have been used for vicarious calibration. Uncertainties are provided both as envelope around the calibrated spectrum (left) and as relative uncertainty (right). Detailed information about the APEX radiometric uncertainty model can be found in [RD5].

![Figure 79: estimated radiometric uncertainty for Target T3 Asphalt measured on 17/06/2013](image)

![Figure 80: estimated radiometric uncertainty for Target T13 Light Asphalt measured on 17/06/2013](image)
Figure 81: estimated radiometric uncertainty for Target T10 Gravel measured on 01/07/2013

Figure 82: estimated radiometric uncertainty for Target T13 Asphalt measured on 01/07/2013

Figure 83: estimated radiometric uncertainty for Target T6 Gravel measured on 30/08/2013
Figure 84: estimated radiometric uncertainty for Target T6 Gravel measured on 04/09/2013

Figure 85: estimated radiometric uncertainty for Target T14 Sparse Grass measured on 04/09/2013
10.3.12. **Band cutting**

After vicarious calibration, the reflectance spectra are analyzed to decide which bands are to be removed in the VNIR/SWIR overlap region to get the best fit in the spectrum. Bands to be removed are deselected for processing in the CDPC.

<table>
<thead>
<tr>
<th>The Mulhouse APEX L0 (raw) data contains 316 bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Mulhouse APEX L1 and L2 data contains 288 bands</td>
</tr>
<tr>
<td>The bands that have been removed are:</td>
</tr>
<tr>
<td>- 1 till 5</td>
</tr>
<tr>
<td>- 115 till 127 (VNIR/SWIR overlap)</td>
</tr>
<tr>
<td>- 307 till 316</td>
</tr>
<tr>
<td>The Mulhouse APEX data thus contains 288 bands.</td>
</tr>
</tbody>
</table>

*Table 29: APEX bands that have been removed during the processing*
10.3.13. SPECTRAL RESAMPLING

The atmospheric correction is smile-aware, taking into account the spectral shifts. This implies that the resulting reflectance cubes all have slightly different wavelengths for corresponding bands. Therefore, after atmospheric correction, the reflectance data is resampled to the wavelength of the center pixel, as measured during the sensor spectral calibration on the Calibration Home Base (CHB). This spectral resampling is automatically performed in the CDPC.
10.3.14. **Spectral Smoothing**

As a last step in the processing, wavelength dependent spectral smoothing of the data is performed to remove noise and spikes remaining after atmospheric correction.

Smoothing of the reflectance spectra is done using the semi-interactive Colibri application (VITO development), which allows to:

- Subdivide the spectrum in discrete groups of wavelengths
- Define individual smoothing factors for these groups
- Preserve some parts of the spectrum, while other parts can be treated more thoroughly
- Do test runs on representative parts of an image before final (batch) processing is done
CHAPTER 11  GROUND SPECTRAL DATA PROCESSING AND ANALYSIS

11.1. **Top-of-canopy reflectance and fluorescence measurements**

Collected data were processed with an IDL (ITTvis IDL 7.1.1®) application specifically developed. This application allowed the basic processing steps of raw data necessary for the computation of the reflectance factors:
- correction for CCD detector non linearity;
- correction for dark current and dark current drift;
- wavelength calibration and linear resampling;
- radiance calibration;
- incident radiance computation by linear interpolation of two white reference measurements and correction for the known white reflectance.

A set of quality criteria described in Meroni et al. 2011 ([RD9]) has been applied for automatic data selection, in order to reject poor-quality data due to unfavourable meteorological conditions (e.g. clouds, rain or fog).

Different spectral indexes were computed from the top of canopy reflectance spectra. In this report results using the normalized difference vegetation index (NDVI, Rouse et al. 1974, [RD12]) are described.

$F_{760}$ and $F_{687}$ were estimated using the spectral fitting method described in Meroni and Colombo (2006, [RD10]) and Meroni et al. (2010, [RD9]), assuming that a polynomial model can describe the shape of fluorescence and reflectance in a restricted range around the absorption bands. The spectral interval used for $F_{760}$ estimation was set to 759.00 - 767.76 nm for a total of 439 spectral channels used.

**Top-of-canopy spectral measurements over the forest**

Sun-induced chlorophyll fluorescence estimates at the $O_2$-A band ($F_{760}$) made under different illumination intensities vary from near 0 to 2 mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$ (Figure 86), while fluorescence estimates at the $O_2$-B band ($F_{687}$) show lower values (Figure 87). Preliminary results highlight that different forest species are characterized by different fluorescence values, with generally higher emissions in broadleaf compared to needleleaf species.
The relationship between $F_{760}$ and NDVI (Figure 88) shows that $F_{760}$ can provide additional information in species characterized by high green biomass and chlorophyll content, while NDVI tends to saturate.
Figure 88: Relationship between $F_{760}$ (mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$) and NDVI for the forest species sampled using the mobile platform.

**Top-of-canopy spectral measurements over the grassland**

Figure 89 shows the NDVI time series acquired with the S-fluor box installed on the tower over the grassland from June 15$^{th}$ to 23$^{rd}$ and July 1$^{st}$.

Figure 89: NDVI time series acquired with the S-fluor installed on the tower over the grassland. Lin747.5 is the incident radiance (mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$) at 747.5 nm. DOY is day of the year.
The sky was clear during the days of APEX and Hyplant overpasses (DOY 167-168 and 182) as evidenced by the diurnal shape of the incident radiance (Lin) at 747.5 nm, even if the sky conditions were not optimal during the afternoon on DOY 182.

NDVI values were quite stable during the first period of measurements, with value at midday higher than 0.8, and they show slightly lower values on the last day of measurements. At diurnal level, NDVI showed a characteristic shape due to the anisotropy of target reflectance in the red and near-infrared wavelengths generated by the movement of the Sun from sunrise to sunset. Near-infrared reflectance decreases in the morning with decreasing sun zenith angle and increases in the afternoon when sun zenith angle increases again, red reflectance increases in the morning with decreasing sun zenith angle and decreases in the afternoon when sun zenith angle increases again, probably because the optical path in the canopy is minimum when the sun is at nadir.

Figure 90 shows the $F_{760}$ time series acquired during the same period of measurements. During sunny days $F_{760}$ clearly mirrored the course of the incident radiance, with the highest values around midday ($F_{760}$ around 1.8 mW m$^{-2}$ sr$^{-1}$ s$^{-1}$). At the diurnal time scale, in fact, the variation in $F_{760}$ is modulated by photosynthetic activity which is in turn mainly driven by the incident radiance. As for NDVI, also $F_{760}$ shows slightly lower values on the last day of measurements. Compared to NDVI, $F_{760}$ is more affected by the unstable sky conditions.

![Figure 90: $F_{760}$ (mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$) time series acquired with the S-fluor installed on the tower over the grassland. Lin$_{747.5}$ is the incident radiance (mW m$^{-2}$ sr$^{-1}$ nm$^{-1}$) at 747.5 nm. DOY is day of the year.](image)
11.2. Spectral Measurements of reference target

The spectral measurements acquired on the reference targets were organized in a database, that include the raw measurements (i.e. radiance and reflectance) of each target, their average and standard deviation values. The white panel radiance used to calculate the target reflectances were also recorded in the database. In Table 30 all the targets selected and measured for the calibration and validation activities during the three Sen2Exp campaigns are summarised. The location of the artificial tarps may slightly vary during their reposition in different measurement dates. Therefore GPS locations of the target center are reported for each date. Google *kmz files with each target vertex position are uploaded on the VITO server.

<table>
<thead>
<tr>
<th>ID</th>
<th>Target</th>
<th>Date of measurement</th>
<th>Time of meas. (UTC+2)</th>
<th>N</th>
<th>E</th>
<th>RUN APEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Black panel 9x9</td>
<td>16.06.2013</td>
<td>On the ground, but not measured</td>
<td>47°51'43.54&quot;N</td>
<td>7°24'21.96&quot;E</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.06.2013</td>
<td>h12.28 - 12-37</td>
<td>47°51'43.96&quot;N</td>
<td>7°24'21.99&quot;E</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01.07.2013</td>
<td>h11.08 - 11.21</td>
<td>47°51'43.89&quot;N</td>
<td>7°24'22.13&quot;E</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.08.2013</td>
<td>h12.14 - 12.20</td>
<td>47°51'46.72&quot;N</td>
<td>7°27'9.76&quot;E</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>04.09.2013</td>
<td>h12.01 - 12.06</td>
<td>47°51'46.76&quot;N</td>
<td>7°27'9.90&quot;E</td>
<td>3</td>
</tr>
<tr>
<td>02</td>
<td>Grey panel 9x9</td>
<td>16.06.2013</td>
<td>h12.29 - 12.43</td>
<td>47°51'43.54&quot;N</td>
<td>7°24'21.96&quot;E</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.06.2013</td>
<td>h12.41 - 12.48</td>
<td>47°51'43.55&quot;N</td>
<td>7°24'21.73&quot;E</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01.07.2013</td>
<td>h11.22 - 11.36</td>
<td>47°51'43.54&quot;N</td>
<td>7°24'21.96&quot;E</td>
<td>1</td>
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<tr>
<td></td>
<td></td>
<td>30.08.2013</td>
<td>h12.25 - 12.31</td>
<td>47°51'46.85&quot;N</td>
<td>7°27'10.27&quot;E</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>04.09.2013</td>
<td>h12.09 - 12.14</td>
<td>47°51'46.76&quot;N</td>
<td>7°27'10.43&quot;E</td>
<td>3</td>
</tr>
<tr>
<td>03</td>
<td>Asphalt</td>
<td>16.06.2013</td>
<td>h12.51 - 13.04</td>
<td>47°51'43.21&quot;N</td>
<td>7°24'22.23&quot;E</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.06.2013</td>
<td>h12.50 - 12.57</td>
<td>47°51'43.21&quot;N</td>
<td>7°24'22.23&quot;E</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01.07.2013</td>
<td>h11.37 - 11.49</td>
<td>47°51'43.22&quot;N</td>
<td>7°24'22.33&quot;E</td>
<td>1</td>
</tr>
<tr>
<td>04</td>
<td>Black panel 6x6</td>
<td>16.06.2013</td>
<td>h10.49 - 11.10</td>
<td>47°51'46.56&quot;N</td>
<td>7°27'10.30&quot;E</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>01.07.2013</td>
<td>h14.28 - 14.39</td>
<td>47°51'46.97&quot;N</td>
<td>7°27'8.54&quot;E</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.08.2013</td>
<td>On the ground, but not measured</td>
<td>47°51'46.76&quot;N</td>
<td>7°27'10.99&quot;E</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>04.09.2013</td>
<td>On the ground, but not measured</td>
<td>47°51'46.76&quot;N</td>
<td>7°27'11.22&quot;E</td>
<td>3</td>
</tr>
<tr>
<td>05</td>
<td>White panel 6x6</td>
<td>16.06.2013</td>
<td>h10.34 - 10.46</td>
<td>47°51'46.61&quot;N</td>
<td>7°27'9.83&quot;E</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.08.2013</td>
<td>h12.35 - 12.41</td>
<td>47°51'46.70&quot;N</td>
<td>7°27'10.67&quot;E</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>04.09.2013</td>
<td>h12.17 - 12.21</td>
<td>47°51'46.77&quot;N</td>
<td>7°27'10.83&quot;E</td>
<td>3</td>
</tr>
<tr>
<td>06</td>
<td>Gravel 1</td>
<td>16.06.2013</td>
<td>h11.11 - 11.31</td>
<td>47°51'46.68&quot;N</td>
<td>7°27'9.28&quot;E</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30.08.2013</td>
<td>h12.49 - 12.55</td>
<td>47°51'47.08&quot;N</td>
<td>7°27'8.68&quot;E</td>
<td>3</td>
</tr>
</tbody>
</table>
### Table 30: Summary of the targets selected for the cal/val activities during the three Sen2Exp campaigns held in France (summer 2013).

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>04.09.2013</td>
<td>12.33-12.38</td>
<td>47°51'47.04&quot;N</td>
<td>7°27'8.75&quot;E</td>
<td>3</td>
</tr>
<tr>
<td>16.06.2013</td>
<td>15.02-15.18</td>
<td>47°51'45.64&quot;N</td>
<td>7°27'10.50&quot;E</td>
<td>3</td>
</tr>
<tr>
<td>04.09.2013</td>
<td>12.58-13.03</td>
<td>47°51'45.23&quot;N</td>
<td>7°27'10.74&quot;E</td>
<td>3</td>
</tr>
<tr>
<td>01.07.2013</td>
<td>12.30-12.38</td>
<td>47°51'11.42&quot;N</td>
<td>7°30'51.44&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>01.07.2013</td>
<td>14.05-14.18</td>
<td>47°51'8.68&quot;N</td>
<td>7°30'57.34&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>10.06.2013</td>
<td>14.14-14.21</td>
<td>47°50'49.75&quot;N</td>
<td>7°31'6.18&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>01.07.2013</td>
<td>13.42-13.52</td>
<td>47°50'49.75&quot;N</td>
<td>7°31'6.18&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>16.06.2013</td>
<td>13.45-13.54</td>
<td>47°50'48.93&quot;N</td>
<td>7°31'2.86&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>17.06.2013</td>
<td>14.00-14.06</td>
<td>47°50'48.93&quot;N</td>
<td>7°31'2.86&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>01.07.2013</td>
<td>13.24-13.35</td>
<td>47°50'48.93&quot;N</td>
<td>7°31'2.86&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>16.06.2013</td>
<td>13.57-14.07</td>
<td>47°50'48.50&quot;N</td>
<td>7°31'0.78&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>17.06.2013</td>
<td>14.07-14.12</td>
<td>47°50'48.50&quot;N</td>
<td>7°31'0.78&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>01.07.2013</td>
<td>13.56-14.04</td>
<td>47°50'48.47&quot;N</td>
<td>7°31'0.82&quot;E</td>
<td>5</td>
</tr>
<tr>
<td>30.08.2013</td>
<td>13.20-13.28</td>
<td>47°51'48.16&quot;N</td>
<td>7°27'8.83&quot;E</td>
<td>3</td>
</tr>
<tr>
<td>04.09.2013</td>
<td>12.42-12.48</td>
<td>47°51'48.20&quot;N</td>
<td>7°27'8.77&quot;E</td>
<td>3</td>
</tr>
</tbody>
</table>

The targets spectrally encompass a good range of brightness levels (i.e. bright to dark). Reflectances of the invariant targets were compared between the first and the second campaign. Reflectances of the same targets measured in the three campaigns were compared. Differences in all the spectral domain were < 1 %, confirming their good optical properties, close to Lambertian. We can conclude that radiances can provide good data for APEX radiance calibration, since they were acquired contemporary to the airplane overpass and reflectances for atmospheric correction validation. Target mean radiances and reflectances are shown in Figure 91 and Figure 92, respectively.
CHAPTER 11 Ground Spectral Data processing and Analysis

Figure 91 - Mean radiance of the different targets measured approximately between 12.00 and 1.00 PM local time (UTC+2).

Figure 92 - Mean reflectance of the different targets measured approximately between 12.00 and 1.00 PM local time (UTC+2).
Chapter 12 Sun Radiance Data Processing and Analysis

The measured data is downloaded from the instrument using the ‘Microtops organizer’ software. This results in an excel file with the following columns:

- DATE
- TIME
- DATA_DESCR
- LOCATION
- LNV01
- LNV02
- LNV03
- LNV04
- LATITUDE
- LONGITUDE
- ALTITUDE
- WATER
- AM
- SIG440
- SIG675
- SIG870
- SIG936
- AOT440
- AOT675
- AOT870
- AOT936
- AOT1020

In the preprocessing, the measurements that have been made more than 30 minutes before airborne data acquisition and more than 30 minutes after data acquisition are removed. Also, the rows with high AOT values (AOT675 > Min + StDev (AOT675)) are removed, as they may indicate pointing errors of the sunphotometer.

From the remaining data, initial estimates for the visibility, water vapor content and aerosol type are retrieved.

12.1. Water Vapor

Water vapor content is a direct measurement output (WATER) of the microtops.

12.2. Visibility

The visibility is not a direct output parameter of the sunphotometer data and should be estimated by comparing the aerosol/total optical thickness outputs with modtran simulations of aerosol/total optical transmittance at 550 nm.
From the measurements, the average 550nm vertical optical depth (AOT550) is calculated, by interpolating the AOT values at the other available wavelengths (AOT440 and AOT675). This AOT550 value together with the ground altitude for the flight region (250m mean) are then used to lookup visibility in a precompiled table:

- 17/06: 550nm vertical optical depth (0.168064) corresponds to a visibility of 42 km
- 05/07: 550nm vertical optical depth (0.142370) corresponds to visibility of 51 km
- 30/08: 550nm vertical optical depth (0.287548) corresponds to visibility of 23 km
- 04/09: 550nm vertical optical depth (0.111155) corresponds to visibility of 69 km

12.3. Aerosol Type

The aerosol type is based on the angström coefficient calculated from the measurements. Since the angström coefficient varies between -1 and -1.8 for all flight days, and Mulhouse is a rural area, it was decided to use ‘rural’ aerosol type for the atmospheric corrections.
13.1. EVALUATION OF THE ABUNDANCE OF THE DOMINANT SPECIES.

For each ESU, the species composition was evaluated visually using forest experts. The abundance refers to the leaf area index of each dominant species (between 1 to 5 dominant species). Species representing less than 5% of the leaf area were not accounted for. The sum of the abundance for the dominant species equals 1. The excel file ‘Species_Composition.xls’ contains the species composition. Figure 93 shows that carpinus represent on the average about 46% of the leaf area, while Oaks (several Quercus) represents 24%, Tillia 11% and Pinus 8%. The other species are more anecdotic.

Figure 93. The average species composition over the Harth forest.

13.2. CANOPY STRUCTURE MEASUREMENTS: LAI AND FAPAR

The processing was completed with the CAN-EYE software (http://www6.paca.inra.fr/can-eye). It produces a processing report as an html document ‘CE_P180_Report_CE_P180_xxxx.html’, where xxxx is either ‘Down’ or ‘Up’ depending on the type of images processed. The results are stored in the excel file ‘CE_P180_xxxx.xls’ with self explanatory sheets. The documentation of the methods is accessible at: http://www6.paca.inra.fr/can-eye/Documentation-Publications/Documentation.
CHAPTER 13 Vegetation Data processing and Analysis

Figure 94. Organization of the folders containing the DHPs.

CAN-EYE provides a range of alternative outputs for LAI and FAPAR. For FAPAR, among the values coming directly from the measurements was preferred to limit the impact of possible assumptions in the models used. For LAI, a model with assumptions on leaf orientation and spatial distribution is required. A detailed analysis (see Figure 95 and Figure 96) was showing that the more reliable estimates of LAI is that coming from CAN-EYE V6.2.

Figure 95. Comparison between estimates of the effective LAI (LAIeff) from different methods.
A weak relationship is observed between the understory and overstory LAI as demonstrated by Figure 97.

Figure 96. Comparison between estimates of the effective LAI (LAIeff) from different methods.

Figure 97. Comparison between estimates of the effective LAI (LAIeff) of understory (LAIdown) and overstory (LAIup).
CHAPTER 13 Vegetation Data processing and Analysis

The distribution of LAI values are strongly skewed for the understory, with generally low LAI values while the overstory values are more Gaussian.

Figure 98. Distribution of LAI values for the several ESUs sampled for the 3 measurement periods.

Figure 99. Distribution of LAI values for the several ESUs sampled for the 3 measurement periods.
13.3. LEAF PROPERTIES: CHLOROPHYLL AND WATER CONTENT.

Leaf properties (mainly chlorophyll and water content) were estimated over each ESU using the dominant species composition. The estimation of the canopy level contents in chlorophyll and water will be computed as:

\[ CCC = LAI \times \sum \alpha_i LCC_i \quad \text{and} \quad CWC = LAI \times \sum \alpha_i LWC_i \]

where LCC and LWC refer respectively to the leaf level chlorophyll and water contents, and \( \alpha_i \) is the abundance of species \( i \) within the dominant species, with \( \sum \alpha_i = 1 \) and \( i < 5 \). Note that this is equivalent to estimating the ‘average’ leaf chlorophyll or water contents:

\[ \bar{LCC} = \sum \alpha_i LCC_i \quad \text{and} \quad \bar{LWC} = LAI \times \sum \alpha_i LWC_i \]

Although it was possible to compute the average leaf chlorophyll, \( \bar{LCC} \) or water, \( \bar{LWC} \) contents from the measurements at the ESU level, it was preferred to use the average value for each species across all the available ESUs. As a matter of facts, most of the variability is observed across species and also between dates. However, since only 2 weeks separate the first measurement period (11 of June) from the second one (27 of June), the leaf measurements from the 27th of June were considered representative of the 11th of June.

13.3.1. LEAF DESTRUCTIVE MEASUREMENTS: WATER (AND DRY MATTER) CONTENTS

The data are compiled into the excel file ‘Leaf_Spectral_Evolution.xlsx’ under sheet ‘Leaf_Area_Weight’. Figure 100 shows typical results by species for the June and September campaigns.

Figure 100. The relative water content, Specific Leaf Area (SLA) and Leaf Area measured for several species for the June (27-28 June) and September 3-4 campaigns. Boxplot representation.
The detailed results of the measurements are stored in the excel file ‘Consolidated data base.xlsx’ under sheets ‘Area’, ‘Leaf Cw’ and ‘Leaf Cdm’ respectively for the average leaf area, leaf water and dry matter contents per species for each ESU.

13.3.2. **Leaf Reflectance Measurements: Chlorophyll Content**

The leaf was setup over a white background to enhance absorption features and get better estimation of the leaf biochemical composition. The PROSPECT model is used to estimate chlorophyll content from these reflectance measurements. PROSPECT simulates the directional hemispherical reflectance and transmittance of the leaf from the knowledge of the contents in chlorophyll, carotenoid, water and dry matter, as well as brown pigments if added. The mesophyll structure parameter, $N$, and a parameter describing the surface reflectivity are also required. The surface reflectivity was here assumed to be independent on wavelength as suggested by (Comar et al., 2012a). This allows representing the possible variation in leaf surface reflectivity in a more simple and flexible way. The leaf over its white background is described in Figure 101.

![Figure 101. The system of the leaf over the white Teflon background. On the right, the bi-hemispherical reflectance and transmittance values of each layer is indicated.](image)

The system is solved in two steps. First the reflectance of the leaf volume over the white Teflon background, $R^{wb}_{vol}$, is computed as:

$$R^{wb}_{vol} = R_{leaf} + \frac{R_{wb} T_{leaf}}{1 - R_{leaf} R_{wb}}$$

Where $R_{leaf}$ is the leaf reflectance computed from the PROSPECT model where the reflectivity of the surface was set to 0; $T_{leaf}$ is the corresponding leaf transmittance and $R_{wb}$ is the hemispherical reflectance of the white background. Then, the reflectance of the leaf over the white background was computed using the surface reflectivity, assuming that the transmittivity of the first interface was $1 - R_{surf}$, i.e. there is no absorption:

$$R^{wb}_{leaf} = R_{surf} + \frac{R^{wb}_{vol} (1-R_{surf})^2}{(1-R_{surf} R^{wb}_{vol})}$$

Finally, since the incident light on the leaf may sometimes illuminate partly but directly the white background in case of small leaves or needles, an additional parameter was introduced to describe this situation: $f_{wb}$, the fraction of white background illuminated directly by the light source. The corresponding reflectance of the system writes:

$$R = R_{wb} f_{wb} + (1 - f_{wb}) R^{wb}_{leaf}$$

The parameters of the implementation of the PROSPECT model [$C_{ab}, C_{dm}, C_w, C_s, N, R_{surf}, f_{wb}$] are adjusted over over each of the leaves for each species and ESU. To prevent possible accounting for outliers due to measurement problems, the 2 most disparate spectra over the 11 available ones were discarded. The estimation of chlorophyll content was achieved using the 500-900 nm spectral domain. Further, to prevent possible radiometric calibration problems, the reflectance measurements values were normalized: $r(\lambda) = \frac{R(\lambda)}{\bar{R}}$, where $r(\lambda)$ is the normalized reflectance for wavelength $\lambda$ and $\bar{R}$ the mean reflectance over the 500-900 spectral domain. The cost function, $J$,
used to find the solution in the LUT corresponds to the Euclidian distance between the measured and the simulated relative reflectance spectra:

\[
J = \sqrt{\frac{1}{400} \sum_{\lambda=500}^{900} \left( \frac{r_{\text{wb}}}{r_{\text{leaf}}}(\lambda) - r_{\text{wb}}(\lambda) \right)^2}
\]

The LUT is made of 500000 random uniform drawing of the input model variables within the range specified by Table 31. Figure 102 shows the good theoretical performances of the inversion system when using the relative reflectance for the chlorophyll content.

Table 31. The range of variation of the PROSPECT model input variables used to build the LUT.

<table>
<thead>
<tr>
<th>Variables</th>
<th>(C_{ab})</th>
<th>(Cw/(C_w + C_{dm}))</th>
<th>(C_{dm})</th>
<th>(Cs)</th>
<th>(N)</th>
<th>(R_{\text{surf}})</th>
<th>(f_{\text{wb}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>(\mu g/cm^2)</td>
<td>-</td>
<td>(g/cm^2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Minimum</td>
<td>15</td>
<td>0.5</td>
<td>0.003</td>
<td>0</td>
<td>1.2</td>
<td>0.005</td>
<td>0</td>
</tr>
<tr>
<td>Maximum</td>
<td>100</td>
<td>0.85</td>
<td>0.012</td>
<td>2.5</td>
<td>4.5</td>
<td>0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 102. Results illustrating the performances of PROSPECT model performances when using relative reflectances in the cost function. Note that the contents are well retrieved (except the water content because the 500-900 nm spectral domain was used).

Figure 104 shows the typical good agreement reached between the measured relative reflectance values and the simulated one. However, because in most situations the sample was covering the whole sample port of the integrative sphere, the introduction of the \(f_{\text{wb}}\) term was sometimes inducing possible ambiguities. For each spectra, the chlorophyll content was estimated both with the \(f_{\text{wb}}\) as free as well as fixing it to \(f_{\text{wb}} = 0\) (all the sample covers the sample port). Results show generally very consistent Cab estimates (Figure 103 on the left). However in some cases, particularly for the needle measurements where the assumption \(f_{\text{wb}} = 0\) is obviously not valid, The RMSE increases drastically (Figure 103 on the right). The case providing the best RMSE values was used as the solution.
Figure 103. On the left, comparison of the leaf chlorophyll content retrieval with $f_{wb}$ being a free variable (Cab(Bw)) or assuming $f_{wb} = 0$ (Cab(no Bw)). On the right the corresponding RMSE values (in relative reflectance unit).

Figure 104. Comparison between the simulated and measured reflectance spectra.

Figure 105 shows that the inversion was quite well efficient with no major compensations between estimates variables. The RMSE shows as well no clear trends with the estimates variables.
13.4. SYNTHESIS OF MEASUREMENTS

The processed measurements are mainly stored into two different excel files:

- **Consolidated data base.xlsx.** It contains several sheets:
  - *ESU measurements.* It lists the ESU along with the latitude and longitude and details the measurements made for each of the 3 periods.
  - *Species composition:* it presents the visual estimates of the species composition.
  - *Area:* the average area (cm²) of leaves measured over the 11 samples per species and ESU.
  - *Leaf Cw:* the leaf water content (g/cm²) measured from destructive methods based on the 11 samples per species and ESU.
  - *Leaf Cab:* the leaf chlorophyll content estimated from the reflectance measurements over 9 samples within the 11 available per species and ESU.
  - *LAI up:* the LAI and FAPAR values of the overstory for each ESU as derived from the DHP measurements. All the results from the alternative methods are presented.
  - *LAI down:* the LAI and FAPAR values of the understory for each ESU as derived from the DHP measurements. All the results from the alternative methods are presented.
  - *LAI:* the summary of the LAI values for each ESU and measurement period.
  - *FAPAR:* the summary of the FAPAR values for each ESU and measurement period.
- CCC: the summary of CCC measurements at the ESU level from the average species LCC estimates for each period.
- CWC: the summary of CWC measurements at the ESU level from the average species LWC estimates for each period.

ESU description Final: The standard format for presenting the main LAI, FAPAR, CCC and CWC measurements for each ESU for the 3 periods, each one being in a specific sheet:
- SEN2EXP_11_June
- SEN2EXP_27_June
- SEN2EXP_03_Sept