BIRD – CHRIS JOINT EXPERIMENTS FOR FIRE MAPPING

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ABSTRACT

Vegetation and peat fires play a major role in the global carbon cycle. CO_2, CH_4, and NO_2 and aerosols – emitted during biomass combustion - perturb Earth's radiative budget. The amount of biomass combusted in a vegetation fire depends on fire intensity and fire severity. The determination of fire radiative energy release (FRE) per unit area allows to characterise the fire intensity, to assess the fire severity, and therefore, to distinguish also devastating fires from ecological useful "cleaning" fires.
The experimental Bi-spectral InfraRed Detection (BIRD) satellite – a first dedicated fire recognition mission - provided unique data which permit the retrieval of the FRE of selected vegetation fires.
PROBA - CHRIS measurements of selected fire scars, observed by BIRD during the active fire phase in Siberia, Australia, Portugal and Africa in 2002 and 2003, shall allow to determine how spectral reflectance characteristics change during vegetation recovery what can be used as an indicator of fire severity. CHRIS measurements over such selected test sites – to be conducted in 2004 - are considered as high resolution spectral signature examples of fire scars.

1. ISSUES OF CONCERN

The Carbon issue is one of the central themes of ESAs Living Earth Programme. Vegetation fires may release ~ 40% of the worldwide fossil fuel burning.
World-wide burn in one year:

- about (350-500) x 10^6 ha savannah area,
- about (5 - 10) x 10^6 ha tropical rain forest (including peat lands), and
- about (5 - 20) x 10^6 ha boreal forests (including peat lands).

The fire impacts on atmosphere (radiative balance affected by trace gases, e.g. ozone, CO/CO2, aerosols), global carbon cycle, and climate change are not yet fully understood.
Large quantities of radiatively active (greenhouse) gases are annually emitted into the troposphere by vegetation fires [1] and by peat and coal seam burning [2], with significant amounts also emitted by active volcanoes [3]. These High Temperature Events (HTEs) play a major role in the global carbon cycle, with the pyrogenic gases CH_4, CO, and NO specifically affecting the chemistry and functioning of Earth's atmosphere and CO_2, CH_4, and NO_2 perturbing Earth's radiative budget [4]. Furthermore, burning of vegetative matter (free-burning vegetation fires, burning of biofuels) is the second largest anthropogenic source of sub-micron aerosols, which themselves greatly influence Earth's radiation budget but in ways that are currently poorly quantified [5]. In recent years the 1997/98 forest and peat land fires in South-East Asia stand out as a particularly significant event resulting in large-scale regional atmospheric pollution. Burning of life and dead organic matter in desiccated peat-swamp ecosystems was a major contributor to this smoke-haze episode. The amount of carbon released during this event has been estimated to 0.81-2.57 Gt, corresponding to 13 to 40 percent of the global carbon emission annually released by burning of fossil fuels [2].

Despite numerous studies of individual vegetation fires, the global magnitude of pyrogenic emissions is still not yet known exactly, though it is known that it is subject to very large annual and regional variations. Therefore, a challenging and important task is to monitor, characterise and quantify HTE emissions in order to

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Fig. 1. Example of a destructive high intensive stand-replacement fire observed in Eastern Siberia (airborne and on ground photo)

better assess their effect on the whole Earth system [1]. Since HTE activities occur over widely distributed areas of the Earth's surface, space-borne remote sensing is the only feasible method to undertake such a task, supported by the appropriate ground-based observations.

The relationship between remotely sensed parameters and the actual mass of fuel burned is strongly dependent upon other variables such as the vegetation density and the fraction of available fuel burned, parameters that are very difficult to estimate accurately via remote sensing [6]. A recent study has demonstrated order of magnitude differences between biomass combustion estimates based (a) on current EO-driven approaches and (b) on historical fire frequencies, concluding that new methodologies are required to provide new and independent assessments of this parameter to reduce current levels of uncertainty [1].

One new analytical tool suggested for this purpose, termed the Fire Radiative Energy release (FRE), was first developed during preparations for the MODerate Imaging Spectro-radiometer (MODIS) instrument [7], [8]. FRE is a remotely sensed measure of the rate of radiative heat output during burning (or volcanic activity), which has been shown to be well related to rates of emission of smoke and of vegetation combustion [9]. Temporal integration of FRE over a fire's lifetime should therefore allow the total biomass combusted to be estimated and support the derivation of the quantity of emitted pollutants [9].

New methodologies such as FRE, along with recent developments in sensors and techniques for identifying and analysing active fires [10], [11], [16] mapping burned area [12], [13], and analysing the resultant atmospheric emissions [14], [15], represent significant advances in our ability to analyse HTE events and their effects from space.

The characterization of ongoing (active) fires at the detection phase and during the monitoring phase is currently restricted to the localization of the fire fronts.

The characterization of **fire intensity** by determining <u>fire energy release per area unit</u>, however, would also allow the estimation of fire severity [17].

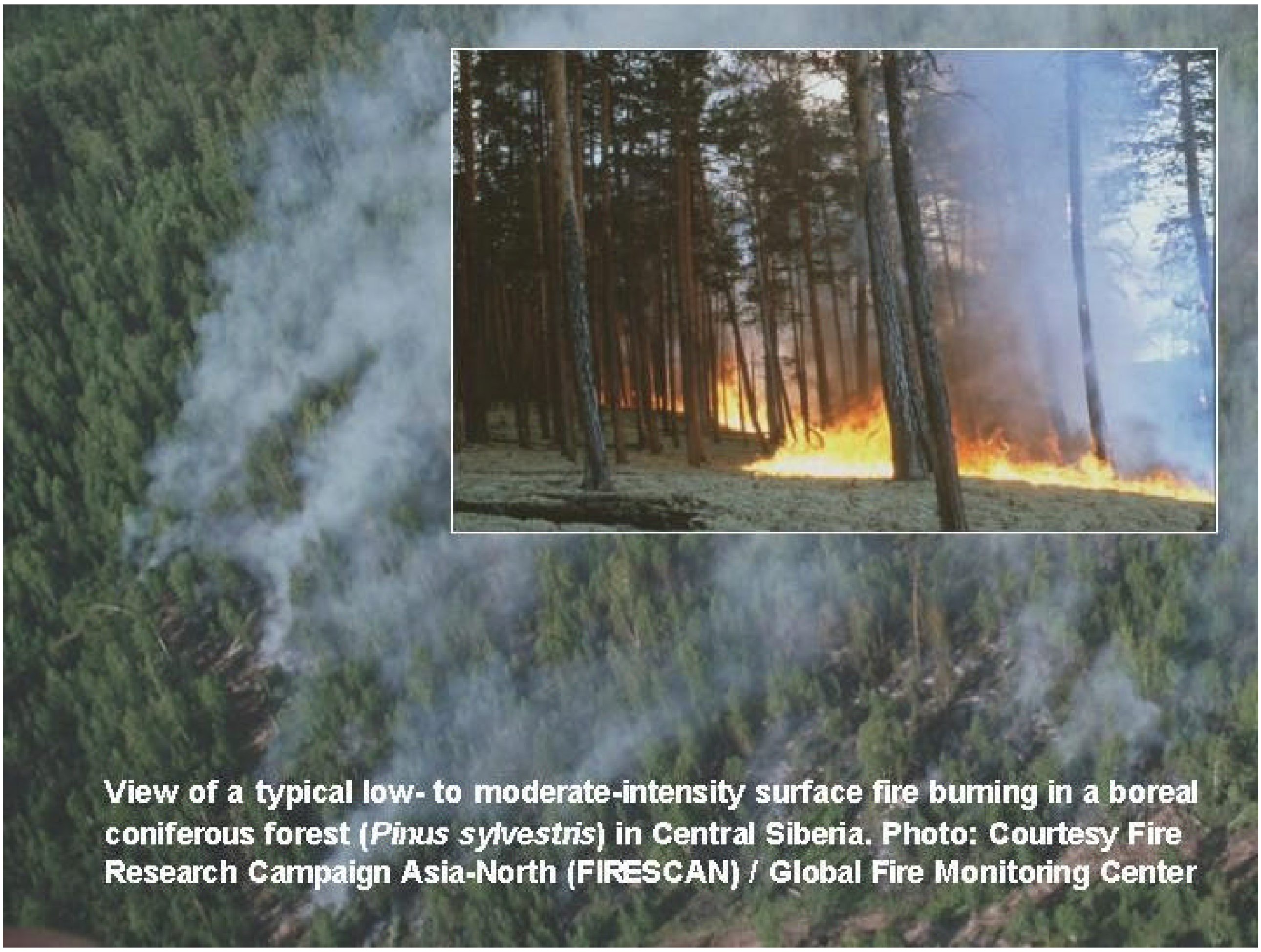

Fig. 2. Example of low to medium intensity fire observed in Siberia (airborne and on ground photo)

Fire severity is an important determining agent of post-fire development. There are a range of ecosystems where fires of low to medium intensity and severity are beneficial for ecosystem stability and productivity.
For instance, the vast amount of seasonal tropical vegetation (tree, grass and bush savannas, monsoon forests) are well adapted and require regular influence of low- to moderate-intensity fires. Similar interdependences between fire and forest ecosystems are found in North America and Australia.
With the ongoing change of the policy of the Russian Federation to abandon the "Fire Control Policy" which involves the intent to control all fires if possible, towards developing a "Fire Management Policy" that integrates natural and human-made fires burning under prescription, a space borne tool for assessing the radiative energy release would be extremely important.

Fig. 1 shows a stand-replacement fire observed in Eastern Siberia. This type of fire has destructive effects on:

- Elimination of dominant plant species,
- Perturbations in biogeochemical cycles (influencing the Carbon, Nitrogen, Sulphur, Phosphor cycle), and
- Land surface degradation (i.e. deforestation, water run-off, soil erosion, landslides, flooding).

Fig. 2 shows a low to medium intensity fire in Central Siberia. This type of fire has beneficial effects on:

- Regulation of vegetation structure and composition,
- Increasing ecosystem stability and productivity, and, last not least,
- Reduction of the fuel load.

2. GENERAL OBJECTIVE OF THE BIRD – CHRIS /PROBA FIRE MAPPING EXPERIMENTS

The boreal forest ecosystems of Eurasia represent the most important example in this regard. A number of types of Northern Asia's coniferous forests are very well adapted to fire, and surface fires of low to moderate intensities are very important to reduce fuel loads and thus stabilizing the forest by making less likely to be affected by high-intensity, stand-replacement fires.

The wildfires in Portugal during 2003 in a large number of cases burned extremely hot due to the high amounts of combustible materials in the wild lands and plantation forests. Ecosystem recovery after these high-severity fires is extremely slow, sometimes even impossible due to secondary effects. The secondary effects include surface water runoff due to reduced water-holding capacity of the topsoil, erosion, landslides and flooding.

As of now there is no air- or space borne decision-support system available which would deliver criteria for deciding whether an ongoing fire is “beneficial” or “destructive”. This can be recognized during the active fire phase by the estimation of the Fire Radiative Energy release (FRE) and by spatial high resolution observations of the vegetation re-grow development after the fire. BIRD and CHRIS/PROBA observations may deliver prototype data products for such a future decision support system.
The BIRD data obtained in 2003 over active fires in selected regions (test sites) of the world will be used to define the FRE, i.e. to assess the type of fire during the burning phase.
CHRIS on PROBA will be used to observe these test sites in 2004. The multi-angle hyperspectral data of CHRIS shall allow to study the re-growing process.
The combination of the higher level data products:

- FRE retrieved from BIRD data of active fires, and
- Hyperspectral and multi-view angle CHRIS data of fire scars

will allow to assess the fire severity for the selected test sites.

3. BIRD MISSION OVERVIEW

The DLR satellite BIRD is a technology demonstrator of new infrared push-broom sensors dedicated to recognition and quantitative characterisation of thermal processes on the Earth surface [18], [19]. BIRD was piggy back launched with the Indian Polar Satellite Launch Vehicle in a 570 km circular sun-synchronous orbit on 22 of October 2001 (together with the PROBA satellite) and is successfully operated by DLR since that time.

3.1 BIRD primary mission objectives

The BIRD primary mission objectives are:

- test of a new generation of infrared array sensors with an adaptive radiometric dynamic range,
- detection and scientific investigation of high temperature events such as forest fires, volcanic activities, and coal seam fires,
- test of small satellite technologies, such as an attitude control system using new star sensors and new actuators, an on-board navigation system based on a new orbit predictor and others.

3.2 The BIRD main sensors

The BIRD main sensor payload consists of:

- a two-channel infrared Hot Spot Recognition Sensor system (HSRS),
- a Wide-Angle Optoelectronic Stereo Scanner (WAOSS-B).

Their characteristics are given in Tab. 1.

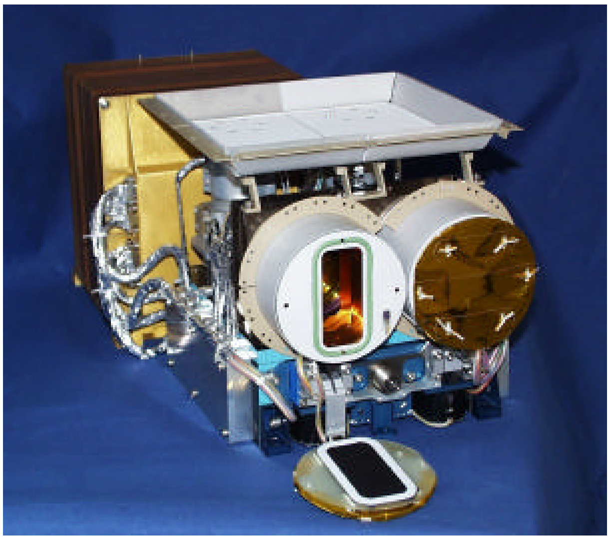

Fig. 3. The BIRD Hot Spot Recognition System (HSRS)

HSRS is a two-channel push-broom scanner with spectral bands in the mid-infrared (MIR) and thermal infrared (TIR) spectral ranges. The sensitive devices are two Cadmium Mercury Telluride (CdHgTe) photodiode lines. The lines - with identical layout in the MIR and TIR - comprise 2 x 512 elements each in a staggered structure. HSRS sensor head components of both spectral channels are based on identical technologies to provide good pixel co-alignment. Both spectral channels have the same optical layout but with different wavelength-adapted lens coatings [20]. The detector arrays are cooled to 100 K in the MIR and to 80 K in the TIR. The cooling is conducted by small Stirling cooling engines. The maximal TIR photodiode cut-off wavelength of about 10.5 µm, which can be achieved at 80 K, on one hand and the atmospheric ozone band at 9.6 µm on the other hand require to use the 8.5 – 9.3 µm band for TIR channel of the HSRS instead of the usual 10.5 – 11.7 µm band. The HSRS sensor data are read out continuously with a sampling interval that is exactly one half of the pixel dwell time. This time-controlled “double sampling” and the staggered line array structure provide the sampling step that is a factor of 2 smaller

Tab. 1. Characteristics of the BIRD main sensor payload

Characteristic	WAOSS-B	HSRS
Spectral bands	VIS: 600-670nm NIR: 840-900nm	MIR: 3.4-4.2µm TIR: 8.5-9.3µm
Focal length	21.65mm	46.39mm
Field of view	50°	19°
f-number	2.8	2.0
Detector	CCD lines	CdHgTe Arrays
Detector cooling	Passive, 20°C	Stirling, 80-100 K
Detector element size	7µmx7µm	30µmx30µm
Detector element number	2880	2x512 staggered
Quantisation	11bit	14bit (for each exposure)
Ground pixel size	185m	370m
Sampling step	185m	185m
Swath width	max. 533km	190km

than the HRSR pixel size, coinciding with the sampling step of the WAOSS NIR nadir channel. The observation of high temperature events in the sub-pixel range requires a precise designed real time signal adaptation control mechanism. A special real time procedure for this signal adaptation is applied to the signals of both HSRS channels. This procedure recognises the element signals which are close to saturation. A repeated sampling within the same clock time period is provided and the values from this additional sampling of the highly illuminated areas are transmitted in a special "Hot Area Set (HAS)". The saturated pixel signals are automatically replaced by values from this HAS during the on-ground data processing.

The overall detector control makes it possible to synchronise both IR-sensor channels externally by WAOSS sampling clock signal. This is a basic pre-requisite for the on-ground pixel co-registration procedure as, for instance, required for the application of the bi- spectral (Dozier) method [21].

Due to its higher spatial resolution, BIRD can detect fires with the area a factor of seven smaller than operational polar orbiting systems such as the Advanced Very High Resolution Radiometer (AVHRR) or the Moderate Resolution Imaging Spectro-radiometer (MODIS). However, one has also to keep in mind that AVHRR and MODIS can provide daily global coverage while BIRD is a demo mission providing in the best case semi-operational data sets.

3.3 Retrieval of active fire characteristics

In spite of the fact that fires are well recognizable in the MIR channel, a more sophisticated detection procedure is required to reject sun glints and warm surfaces that may also appear like bright spots in the MIR causing false alarms. For this purpose, the BIRD hotspot detection algorithm was developed [16] that includes the following thresholding tests:

- Adaptive MIR thresholding to detect potential hot pixels,
- NIR thresholding to reject strong sun glints and thick clouds,
- Adaptive MIR/NIR radiance ratio thresholding to reject weaker sun glints, thinner clouds and other high-reflective objects,
- Adaptive MIR/TIR radiance ratio thresholding to reject warm surfaces,
- Consolidation of the adjacent hot pixels in hot clusters (hotspots) and estimation of hotspot characteristics: the effective fire temperature and area, radiative fire energy release (FRE).

The effective fire temperature T_F and the effective fire area A_F are retrieved with the Bi-spectral technique [21] using the MIR and TIR cluster radiance fluxes and background radiance estimation from the neighboring pixels. In contrast to the usual application of the Bi-spectral technique, we apply it not to separate hot pixels but to entire hot clusters. The advantages of the cluster-level approach are:

- the effective fire area does not depend on the point spread function (PSF) of the MIR and TIR channels,
- the estimations of effective fire temperature and area are low sensitive to sub-pixel inter-channel MIR/TIR geometric co-registration errors and MIR/TIR PSF difference, and
- the effects of background clutter are reduced.

Nevertheless, an estimation of the effective fire temperature and area with a reasonable accuracy is possible only if the fire proportion in the hotspot in not less than ~1% since otherwise the retrievals are strongly sensitive to the TIR background clutter.

The Fire Radiative Energy release (FRE) is a more stable parameter for a quantitative characterisation of both large and small fires [22], and, therefore, it is principally used for coding hotspots in the standard BIRD data products. FRE is useful for parameterisation of the amount of burning fuel, as well as for practical fire fighting purposes where the energy release per a unit length of a fire front characterises the front strength.

FRE can be estimated using the effective fire temperature and area as retrieved by the Bi-spectral technique:

$$P_F = s\,(T_F^4 - T_{bg}^4)A_F\ , \qquad (1)$$

where s is the Stefan-Boltzmann constant, T_{bg} is the background temperature that is assumed
to be equal to the mean at-surface TIR temperature in the vicinity of the hot cluster.

A low sensitivity of the FRE/MIR radiance ratio to fire temperature above 700 K is exploited in the MIR radiance method [22] for a direct FRE estimation for hot pixels without a preliminary retrieval of T_F and A_F :

$$P_F = 17.3 \cdot 185^2 \cdot (I_{MIR} - \bar{I}_{MIR,bg})\ \text{[W]}, \qquad (2)$$

where I_{MIR} and $I_{MIR,bg}$ are the BIRD MIR radiances of a hot pixel and of the background. In order to obtain the FRE of a hot cluster, the FRE (7) has to be summed ver all pixels in the hot cluster. However, at lower temperatures, the method may lead to a drastic FRE underestimation. Generally, the MIR radiance method is equivalent to the MODIS method [23] but has a more transparent physical sense.

In the BIRD algorithm, we use the bi-spectral method for FRE estimation for hot clusters. In case the bi-spectral retrievals confirm that the fire temperature exceeds 700 K, we apply the MIR radiance method for hot pixels to analyze FRE distribution within a cluster (it can make sense only for large hot clusters significantly exceeding the BIRD PSF width).

FRE can be estimated with a reasonable accuracy also for small fires (down to the detection limit) in contrast to the estimation of the effective fire temperature and area.

The FRE characterizes the intensity of burning. However, it accounts only for the radiated part of the energy released by a fire, while a significant portion of fire energy is consumed by convection, evaporation and heat transfer in the ground. This has to be taken into account when interpreting the FRE magnitude in terms of fire severity.

3.4 BIRD active fire observation in Central Portugal in summer 2003

On 4 August 2003, BIRD imaged huge forest fires in the central region of Portugal where catastrophic fires took place in the area of Castello Branco. Fig. 4 shows a 100 x 100 km^2 fragment of the BIRD image. The

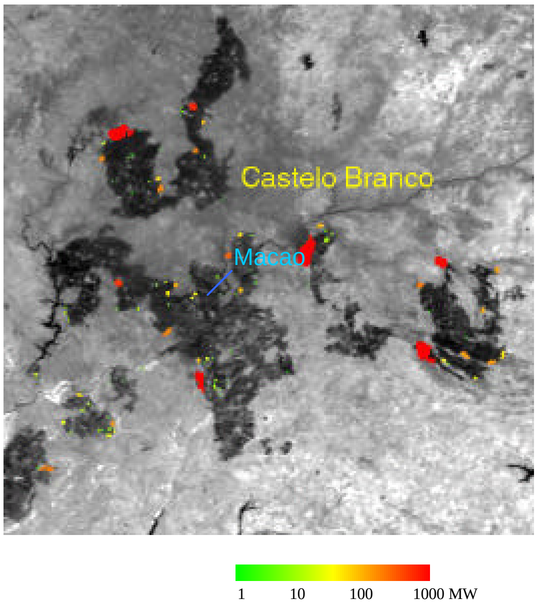

Fig. 4. Active fires in the Central Portugal region of Castelo Branco observed by BIRD on 4 of August 2003. The fire clusters are coded with their radiative energy release and projected on the NIR image. An arrow indicates the Macao test site (see Table 3)

detected hotspots with their energy release are projected on the NIR image, showing the burned areas (fires scars) as dark patches and active fires as color coded hotspots.

4. CHRIS ON PROBA

ESA's small, low-cost PROBA (Project for On-Board Autonomy) satellite is designed to validate new spacecraft autonomy and 3-axis control and data system technology as part of the Agency's In-orbit Technology Demonstration Programme [24].

The Compact High Resolution Imaging Spectrometer (CHRIS) - which shown on Fig. 5 - is the main payload of PROBA. PROBA's high-performance attitude control and pointing system supports the multi-view angle spectral reflectivity measurements of CHRIS as schematically shown on Fig. 6.
Tab. 2 explains the CHRIS/PROBA multi-viewing angle image sequence [25].

Tab. 2. CHRIS/PROBA multi-view angle imaging sequence

Chronological imaging order	Tag No. order	Scan direction	Fly-by zenith angle
First	3	N-S	+ 55°
Second	1	S-N	+ 36°
Third	0	N-S	0°
Fourth	2	S-N	- 36°
Last	4	N-S	- 55°

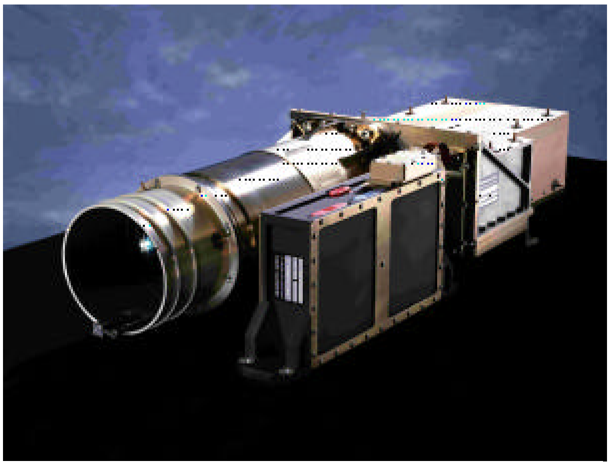

Fig. 5. The Compact High Resolution Imaging Spectrometer (CHRIS)

There are five formal CHRIS imaging modes, classified as Modes 1 to 5 [25]. Mode 3 with 18 “land channels” between 442 and 1019 nm, a ground sampling distance of 18 m and 13 km swath width will be used for the fire severity mapping.

5. JOINT FIRE SEVERITY OBSERVATION TARGETS

Principal Investigators from four continents (Asia, America, Australia and Europe) declared their interest in December 2003 and January 2004 to contribute to the BIRD–CHRIS/PROBA Fire Mapping Experiment.

5.1 Selection and grouping of the targets/test sites

Fire severity estimation shall be conducted for regions of Siberia, Portugal, Australia and Alaska by repeated observations of selected fire scars by CHRIS/PROBA, preferably for scars where BIRD provided active fire data in summer and fall 2003.

Fig 6. The multi-view angle observation scheme of CHRIS on PROBA

Taking into account the expression of interest of the Principal Investigators (PI’s) from different international organisations involved in fire ecology and remote sensing of fires, there may be considered two groups of fire severity experiments:

Group 1 with ground truth provision for fire scars during or close to CHRIS/PROBA observations in 2004 where active fires were observed by BIRD in 2003 and possibly other satellites in 2003 or before. This group consist of test sites in Siberia (Angara Priority 1), SE-Australia, Central Portugal and South Africa / Botswana.

Group 2 with ground truth provision for fire scars during or close to CHRIS/PROBA observations in 2004 where active fires were observed by other satellites in 2003 or before. This group consist of test sites in Siberia (Angara Priority 2), Yakutsk and Alaska.

5.2 Imaging requirements

The imaging of CHRIS/PROBA during fire severity mapping experiments in 2004 is made based on the following criteria:

- the sites should contain fire scars which were preferably observed by BIRD in 2003 during the active burning phase (if possible, in several passes within several consecutive days), i.e. pre-selection of sites is “BIRD record guided”,
- the sites shall possibly contain fire scars from vegetation fires burning before spring – summer 2003, which are analysed by other science groups, and
- in-situ information from international scientific Co-investigators is desired.

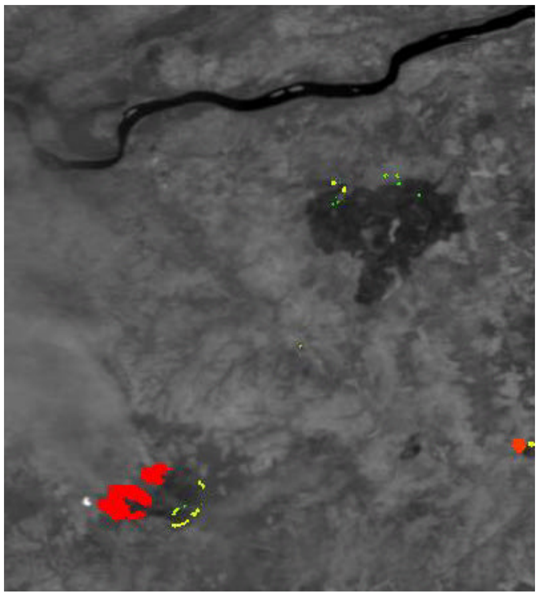

Fig. 7. A BIRD image of one of the Angara test sites, observed during the active fire phase on 10 of July 2003. The fire clusters are coded with their radiative energy release and projected on the NIR image

Tab. 3. Test sites for fire severity mapping experiments

Site	Longitude	Latitude	In-situ Data	Principal Investigator
Group 1				
Angara – Priority 1 Sites A, B, C Average height a.s.l: 150–300 m	A: 97.87° E B: 96.92° E C: 96.78° E	58.70° N 57.95° N 57.36° N	A. Sukhinin, IFOR Krasnoyarsk (RU)	C. George, Section for EO CEH Monks Wood (UK)
South-East Australia	148.40° E	35.80° S	CSIRO EO Centre	A. Held, A. Marks, CSIRO, Australia
Central Portugal, Macao site, Average height a.s.l: 300 m	7.84° W	39.57° N	Camara Municipal de Mação and Instituto Politecnico de Tomar	P. Barbosa, Institute for Environment and Sustainability- JRC, Ispra (I)
South Portugal, Herdade da Parra site Average height a.s.l: 109 m	8.42 W	37.31 N	Direcção-Geral dos Recursos Florestais	P. Barbosa, Institute for Environment and Sustainability- JRC, Ispra (I)
South Africa, Botswana Average height a.s.l: tbd	25° E (tbd)	17.8° S (tbd)	tbd.	M. Wooster, Kings College, University of London (UK)
Group 2				
Angara – Priority 2 Sites D and E Average height a.s.l: 150–300 m	D: 98.42° E E: 59.99° E	58,81° N 58.57° N	A. Sukhinin, IFOR Krasnoyarsk (RU)	C. George, Section for EO CEH Monks Wood (UK)
Yakutsk, Average height a.s.l: 100 m	129.50 E	62.30° N	N. Sedelnik, Forest Service of Sakha, Yakutia, (Ru)	Hiroshi Hayasaka Graphics & Fire Science Division, University of Hokkaido, (Jp)
Alaska, Fairbanks, Average height a.s.l: tbd	147.50° W	65.16° N	tbd.	Hiroshi Hayasaka Graphics & Fire Science Division, University of Hokkaido, (Jp)

Day time CHRIS/PROBA observations of the selected site are mandatory.
Timely close BIRD observations of the site are desirable, but not mandatory.
For the fire severity experiment, 3-monthly imaging of the site for ~ 24 months after the burn are required to track it's recovery.

Fig. 7 shows a BIRD image fragment of one of the Angara test sites which was observed during active fire phase on 10 July 2003. CHRIS will observe this test site (as well as the other test sites indicated in Tab. 3) in 2004 in Mode 3 to provide hyperspectral multi-view angle data in the visible and near IR wavelength region.

5.3 Description of the test sites

Tab. 3 indicates and describes the test sites which are currently considered for the study

6. NEXT STEPS IN 2004

CHRIS observations was performed of the South East Australian Trial test site at 148.40°E and 35.80°S (see Table 3, Group 1) for the 19, 20, 28 of January, the 4, 13, 20, 28 of February and the 24 of March 2004.
BIRD data with major active fires in the region – including the Trial test site area – was obtained 26, 28, and 31 January 2003. The possibility of vegetation re-grow analysis based on the CHRIS data of 2004 for scars from fires observed by BIRD in January 2003 will be evaluated by CSIRO and DLR.

CHRIS observed the Macao test site in Central Portugal first time on 13 of May 2004. Fig. 8 shows a true colour CHRIS image fragment with the Macao test site in the red box. The first observation of the South Portugal Herdade da Parra test site is planned for May 21, 2004.

BIRD observed major active fires in Central Portugal on 4 of August 2003 and in South Portugal on 14 of August 2003, including the Macao test site and Herdade da Parra test site, respectively.
The CHRIS observations of Macao and Herdade da Parra areas in May 2004 were accompanied by ground truth measurements conducted by Portuguese organisations as indicated in Table 3. Repeated CHRIS measurements of both test sites in Portugal are foreseen for summer 2004 with the aim to study the severity of the 2003 fires and the vegetation re-grow.

BIRD observed active fires in the Angara region at 96°-98°E and 56°-58°N in Siberia in mid of July 2003.
CHRIS observations of the Angara test sites A, B, and C are envisaged for June and /or July 2004, depending on the time slot of the ground truth collection in these test areas by a team from the Sukachov Institute of Forest (IFOR) of the Siberian Branch of Russian Academy of Sciences which shall be led by Dr. Anatoly Sukhinin. These threefold measurements (BIRD, CHRIS and ground truth) will be used for fire severity analysis in the test sites Angara A, B, and C.

Fig. 8 True colour image fragment of the Macao test site shown in the red box in Central Portugal obtained by CHRIS on 13 of May 2004

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