Fire Remote Sensing by the Small Satellite on Bi-spectral Infrared Detection (BIRD)

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Abstract: Fire has a growing influence on the ecosystem of the Earth. This influence is still not investigated sufficiently, because there is a lack of measurement data obtained globally. So far there is no dedicated satellite sensor for fire remote sensing in an earth orbit.

One objective of the DLR small satellite mission on Bi-spectral Infrared Detection (BIRD) is to test a new generation of IR sensors – together with a modified Wide-Angle Optoelectronic Stereo Scanner (WAOSS) which was originally developed for the Mars-96 Mission – with regard to the remote sensing of High Temperature Events, such as vegetation fires, coal seam fires and volcanic activities.

The DLR satellite on Bi-spectral InfraRed Detection (BIRD) was piggy back launched with the Indian Polar Satellite Launch Vehicle in a 570 km circular sun-synchronous orbit on 22 October 2001 – together with the Indian main satellite TES and the small satellite PROBA from the European Space Agency.

The paper presents results of BIRD data based remote sensing of bush fires in Australia and coal seam fires in China.

Zusammenfassung: *Feuerfernerkundung mit dem DLR-Kleinsatelliten zur bispektralen IR-Detektion (BIRD)*. Feuer übt einen immer größeren Einfluss auf das Ökosystem der Erde aus. Der Einfluss ist jedoch noch ungenügend erforscht, da nur unzureichende Messdaten im globalen Maßstab zur Verfügung stehen. Bisher gab es keine Sensorik im Orbit, die auf Feuerfernerkundung zugeschnitten ist. Mit der DLR-Kleinsatellitenmission BIRD (Bi-spectral Infrared Detection) wird erstmals eine neue Generation von Infrarotsensoren in Kombination mit einer modifizierten WAOSS-Kamera (Weitwinkel-Stereo-Kamera für die Mars-96-Mission) im Weltraum erprobt, die für die wissenschaftliche Fernerkundung von Vegetationsbränden, Vulkanausbrüchen, Kohlefeuern und anderen Hot-Spot-Ereignissen geeignet ist. Am 22. Oktober 2001, 04:53:00 Uhr UTC, wurde der DLR-Kleinsatellit BIRD mit einer indischen Trägerrakete vom Typ PSLV-C3 zusammen mit dem indischen Hauptsatelliten TES und dem ESA-Kleinsatelliten PROBA erfolgreich vom indischen Raketenstartplatz Shar aus gestartet. Der Beitrag zeigt Ergebnisse der BIRD-datenbasierten Fernerkundung von Buschbränden in Australien und Kohleflözfeuern in China.

Introduction

Both the global change scientific community and the fire fighting authorities demand new and dedicated space-borne fire observation sensors with a resolution of 50–100 m for local/regional monitoring and of a few hundred metres for global observations that would be able to detect fires from a few to a few tens of square metres and to estimate quantitatively variables such as location, temperature, area, energy release, associated aerosol and gaseous emissions (AHERN et al. 2001).

The existing satellite sensors with 3–4 µm mid-infrared channels, such as:

– the Advanced Very High Resolution Radiometer (AVHRR) on the polar orbiting satellites of National Oceanic and Atmosphere Administration (NOAA),
– the MODerate-resolution Imaging Spectro-radiometer (MODIS) on the Earth Observing System (EOS) satellite Terra, and
– the Geostationary Operational Environmental Satellites (GOES)

used so far to provide data on active fires on Earth have limited spatial resolution of

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1 km or coarser and a low-temperature saturation of the MIR channels (with the exception of MODIS) leading in some case to false alarms and preventing a quantitative characterisation of larger fires.

High-resolution multi-spectral sensors like Thematic Mapper (TM), Enhanced Thematic Mapper (ETM) on Landsat 5 and 7, respectively, or the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on the EOS satellite Terra do not have a 3–4 µm channel, the principal channel for daytime fire recognition. Their 2.3 µm channels are less sensitive to smouldering fires and more affected by solar reflections.

The BIRD objectives and its main sensors

The BIRD small satellite mission is a technology demonstrator of new infrared push-broom sensors dedicated to recognition and quantitative characterisation of thermal processes on the Earth surface (Briess et al. 2002).

Fig. 1 shows the BIRD satellite during the test cycle at the DLR Institute of Space Sensor Technology and Planetary Exploration in Berlin. The BIRD sensors – covered mainly by multi-layer isolation, except the optical sensor entrances – are visible in the upper compartment of the satellite (the two IR sensor entrances – on top right hand site – are closed by the multi-layer-isolation covered back sides of the calibration units.)

The BIRD main sensor payload consists of:

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

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 2×512 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 (Skrbek & Lorenz 1998).

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 a on-ground sampling step of 185 m that is a factor of 2 smaller than the HRSR pixel size, coinciding with the sampling step of the WAOSS nadir channel.

Radiometric investigations of thermal anomalies require (a) a large dynamic range not to be saturated by HTE occupying the entire pixel and (b) a high signal to noise ratio to be able to observe small thermal anomalies at normal temperatures and de-

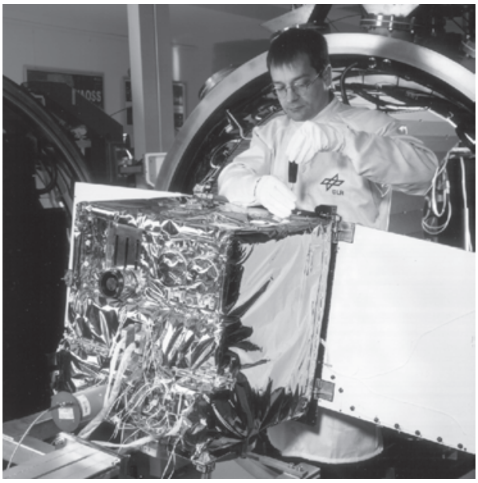

Fig. 1: The BIRD satellite during the test cycle at DLR Institute of Space Sensor Technology and Planetary Exploration in Berlin.

tect small sub-pixel HTE. To fulfil these requirements, a second scene exposure is performed with a reduced integration time (within the same sampling interval) if the real-time processing of the first exposure indicates that detector elements are saturated or close to saturation. As a result, the efficient HSRS radiometric dynamic range is significantly expanded keeping a very good temperature resolution at normal temperatures (Lorenz & Skrbek 2001).

WAOSS-B is a modified version of a scanner that was originally developed for the Mars-96 mission. It is a three-line stereo scanner operating in the push-broom mode. All three detector lines are located in the focal plane of a single wide angle lens. The forward- and backward-looking lines have a visible (VIS) and near-infrared (NIR) filters, respectively, while the nadir-looking line has a NIR filter.

Due to a higher resolution of the BIRD MIR and TIR channels in comparison to AVHRR and MODIS, it allows to achieve an order of magnitude smaller minimal detectable fire area. A possibility to observe fires and other HTE without sensor saturation provides: (a) an improved false alarm rejection capability and (b) a possibility of a quantitative estimation of HTE parameters (temperature, area, energy release) unrestricted by sensor saturation.

Hot spot detection and quantitative characterisation

The BIRD hot spot detection algorithm (Zhukov & Oertel 2001) includes the following tests:

- adaptive MIR thresholding to detect potential hot pixels,
- NIR thresholding to reject strong sun glints,
- adaptive MIR/NIR radiance ratio thresholding to reject weaker sun glints, clouds and other high-reflective objects,
- adaptive MIR/TIR radiance ratio thresholding to reject warm surfaces,
- consolidation of the adjacent hot pixels in hot spots and estimation of hot spots characteristics (the equivalent fire temperature and area, energy release, and – for resolved fire fronts – front length and strength).

The equivalent fire temperature T_F and area A_F are the temperature and area of a homogeneous fire at a uniform background that would produce the same MIR and TIR radiances as the actual non-homogeneous fire. They are estimated using the Bi-spectral technique (Dozier 1981). In contrast to the usual application of the Bi-spectral technique, we apply it not to separate hot pixels but to clusters of adjacent hot pixels (hot spots). The advantages of the cluster-level retrievals are:

- the equivalent fire area A_F does not depend on the point spread function (PSF) of the MIR and TIR channels,
- the estimations of T_F and A_F are low-sensitive to small inter-channel MIR/TIR geometric co-registration errors and MIR/TIR PSF difference.

In order to account for sub-pixel co-registration errors of the MIR and TIR channels and PSF 'wings', the pixels located within a distance of 1 sampling step from the detected hot pixels are also included in the corresponding hot cluster.

T_F and A_F are found by solving the system of two equations:

$$\bar{I}_{MIR} = \bar{q}_F B_{MIR}(T_F) + (1 - \bar{q}_F) I_{MIR,bg} ,$$
$$\bar{I}_{TIR} = \bar{q}_F B_{TIR}(T_F) + (1 - \bar{q}_F) I_{TIR,bg} , \qquad (1)$$

where $\bar{I}_{MIR}$ and $\bar{I}_{TIR}$ are the atmospherically-corrected mean MIR and TIR pixel radiances in a hot cluster, $B_{MIR}(T_F)$ and $B_{TIR}(T_F)$ are the band-integrated Planck function for the BIRD MIR and TIR channels, $\bar{q}_F$ is the mean fire proportion in the signal of cluster pixels that is related to the equivalent fire area as $\bar{q}_F = A_F/(A_{sampl} n_{pix})$, where n_{pix} is the number of pixels in a hot cluster, $A_{sampl} = 3.42 \cdot 10^4\,m^2$ is the BIRD sampling area that is defined as the square of the BIRD sampling step of 185 m. The BIRD sampling area is a factor of 4 smaller than the pixel area of its MIR and TIR channels due to the double sampling in the along-track and cross-track directions.

The MIR and TIR radiances of the background within a hot cluster $I_{MIR,bg}$ and $I_{TIR,bg}$ are estimated as the mean radiances $\bar{I}_{MIR,bg}$ and $\bar{I}_{TIR,bg}$ of background pixels in the vicinity of the hot cluster. However, since the TIR channel is relatively low sensitive to small sub-pixel fires, errors in the estimated TIR background radiance may lead to large errors in T_F and A_F. The effect of the MIR background errors is much smaller and can be neglected. In order to characterise the stability of the Bi-spectral retrievals to the TIR background radiance error, $\bar{I}_{TIR,bg}$ was varied in the range of $\pm\sigma_{TIR,bf}$ around its nominal value of $\bar{I}_{TIR,bg}$, where $\sigma_{TIR,bg}$ is the standard deviation of the TIR background radiance in the vicinity of the hot cluster. As a result, error intervals for T_F and A_F are obtained along with their nominal values that correspond to $I_{TIR,bg} = \bar{I}_{TIR,bg}$. The width of these error intervals depends on the fire temperature, on the fire proportion in the cluster and on background variability.

When the TIR background radiance is overestimated, it may lead to unrealistically large values of T_F for small fires that have the TIR pixel radiance close to the background. In order to account for this effect, the upper limit of 1200 K was accepted for the equivalent fire temperature. If this limit is exceeded during the nominal estimation of T_F, the retrievals are considered as failed. If it is exceeded during the estimation of the upper bound for T_F, the upper bound is set to 1200 K and the corresponding lower bound for A_F is adjusted to this temperature. However, a possibility is also left to analyse objects with a temperature higher than 1200 K in the case when the Bi-spectral retrievals are relatively stable. For this purpose, the temperature limitation is not used if the mean TIR radiance of a hot cluster $\bar{I}_{TIR}$ exceeds $\bar{I}_{TIR,bg} + 3\sigma_{TIR,bg}$.

A more stable parameter for a quantitative characterisation of fires is their radiative energy release. It is useful for a parameterisation of the amount of burning vegetation, as well as for practical fire fighting purposes where the energy release per a unit length of a fire front characterises the front strength.

We compared two methods of radiative energy release estimation: the Bi-spectral technique and the MODIS method (Kaufman et al. 1998).

The Bi-spectral technique, which provides the equivalent fire temperature T_F and area A_F, allows an estimation of the energy release of a hot cluster relative to the background level as:

$$P_{BS} = \sigma(T_F^4 - T_{bg}^4)A_F\,, \tag{2}$$

where σ 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. The error intervals for T_F and A_F define also the error interval for the fire energy release. The errors in T_F and A_F, which originate from the TIR background uncertainty, partly compensate each other. As a result, an acceptable error interval for the energy release can often be obtained if the error intervals for T_F and A_F are too large for a quantitative analysis.

The original MODIS method relates the radiative energy release of a fire pixel to its brightness temperature in the MODIS MIR channel at 3.9 µm. The method was adapted to energy release estimation of hot clusters in BIRD images as:

$$P_{MODIS} = k \cdot 4.34 \cdot 10^{-19} \; A_{sampl}\sum(T_{MIR}^8 - T_{MIR,bg}^8)\ [\mathrm{W}], \tag{3}$$

where T_{MIR} and $T_{MIR,bg}$ are the atmospherically corrected BIRD MIR temperatures of a hot pixel and of the background in Kelvin, A_{sampl} is the BIRD sampling area and the sum is taken over all pixels in a hot cluster. The constant factor of $4.34 \cdot 10^{-19}$ was obtained in (Kaufman et al 1998) from simulations of typical fire scenes. In order to be able to apply the MODIS method to the BIRD MIR band, a correction factor $k = 0.605$ was introduced in relation (3). It was defined from the regression of the cluster energy release as obtained by the Bi-spectral and MODIS methods

An advantage of the Bi-spectral method of energy release estimation is that it accounts for the fire temperature. The advantage of the MODIS method is its better stability for small fires.

Sydney Bush fire detection

Bush fires in the area of Sydney, Australia were imaged by BIRD and MODIS on 5 January 2002 with the time interval of only 12 min. Fig. 2 shows the MODIS and BIRD imaging stripes in their MIR bands. In order to represent a high dynamic range of the images, MIR pixel temperatures below 330 K are coded as grey levels while a colour coding is used for higher MIR pixel temperatures (as discussed below, these are only fire pixels). The image reveals catastrophic bush fires with extended fire fronts, especially in the northern part of the scene.

Enlarged fragments of the MODIS and BIRD MIR images are shown in Fig. 3 together with the corresponding fire maps. The MODIS fire map was obtained from the standard MODIS fire product. The BIRD fire map was obtained with the BIRD hot spot detection algorithm and colour-coded using the equivalent fire temperature (in cases when the Bi-spectral retrievals failed, the fire clusters are shown as white). As a result of the BIRD hot spot detection, all 'colour-coded' pixels with the MIR temperature above 330 K are recognised as fires in this fragment (as well as in the entire scenes in Fig. 2). Some of the pixels with a lower MIR temperature down to 322 K are also recognised as fires, what is confirmed by their location at the fire fronts. On the other hand, several white spots with the MIR pixel temperature of up to 328 K, which are seen in lower right part of the MIR image in Fig. 3, are rejected as false alarms due to their relatively low MIR/TIR radiance ratio. These areas have a relatively high TIR temperature and a low NIR radiance and thus evidently correspond to fire scars heated by the sun (but probably not to cooling fire scars since they look colder on the previous day). This type of objects could produce false alarms if data from sensors with a MIR channel saturation at ~ 320 K (like AVHRR) is used for fire detection.

Due to a higher resolution of BIRD, it allows recognition of fire fronts (fire lines) whereas only separate hot pixels are detected in the MODIS fire product. By comparing the BIRD and MODIS images, one can visually identify fire fronts also in the MODIS MIR image since they look brighter than the immediate background. Characteristics of some fire fronts in the BIRD data are given in Tab. 1.

The equivalent fire temperature for the indicated fire fronts was in the range of 800–970 K. In two cases (fire fronts 4 and 6), when the Bi-spectral retrievals failed, the lower bound for the equivalent fire temperature exceeded 760 K.

The equivalent front depth can be estimated as the ratio of the equivalent fire area

Tab. 1: Characteristics of fire fronts in the fragment of the BIRD image of 5 January 2002 (please see Fig. 3).

No.	Equivalent fire temperature [K]	Equivalent fire area [ha]	Front length [km]	Radiative energy release [MW]	Front strength [kW/m]
1	966	0.20	$\sim$ 4	100	$\sim$ 30
2	803	0.91	$\sim$ 7.5	210	$\sim$ 30
3	846	0.70	$\sim$ 3	199	$\sim$ 70
4	> 760	< 0.73	$\sim$ 5	127	$\sim$ 30
5	908	0.65	$\sim$ 10	246	$\sim$ 30
6	> 730	< 0.24	$\sim$ 4	34	$\sim$ 90
7	814	0.33	$\sim$ 3	81	$\sim$ 30

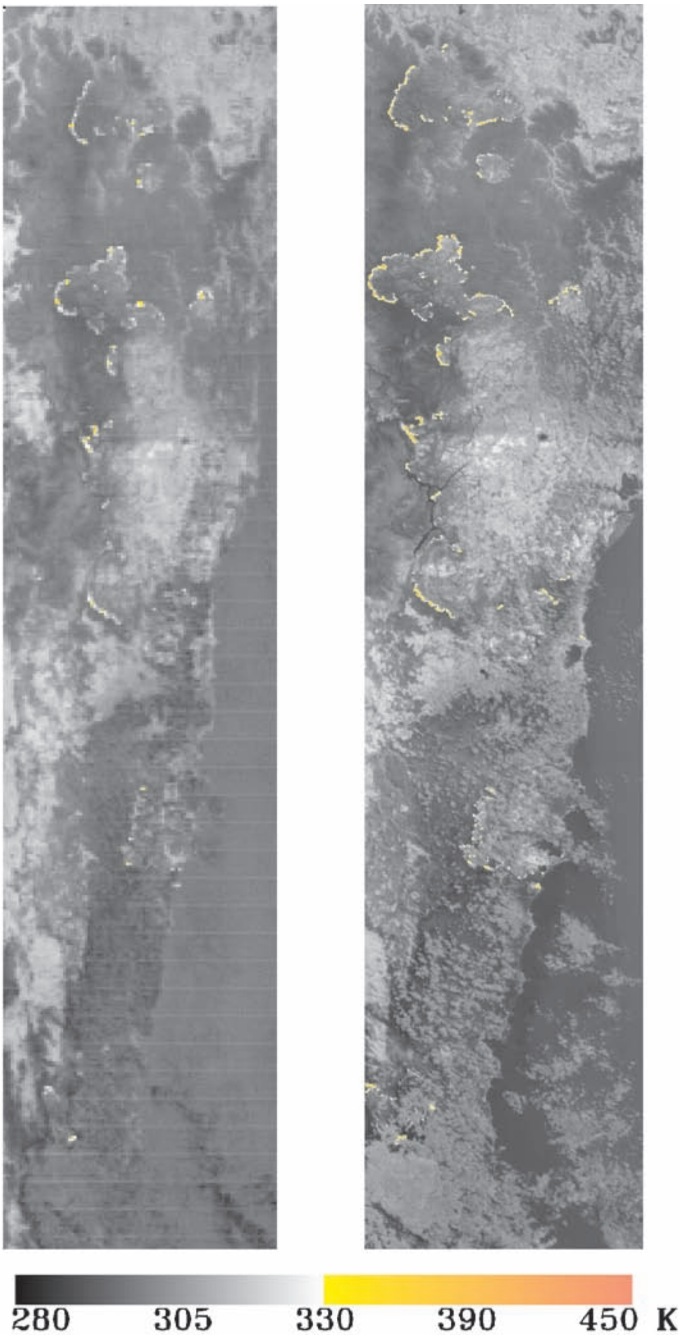

Fig. 2: Images of bush fires in the area of Sydney obtained by MODIS in channel 21 (left) and by BIRD in the MIR spectral band (right) on 5 January 2002.

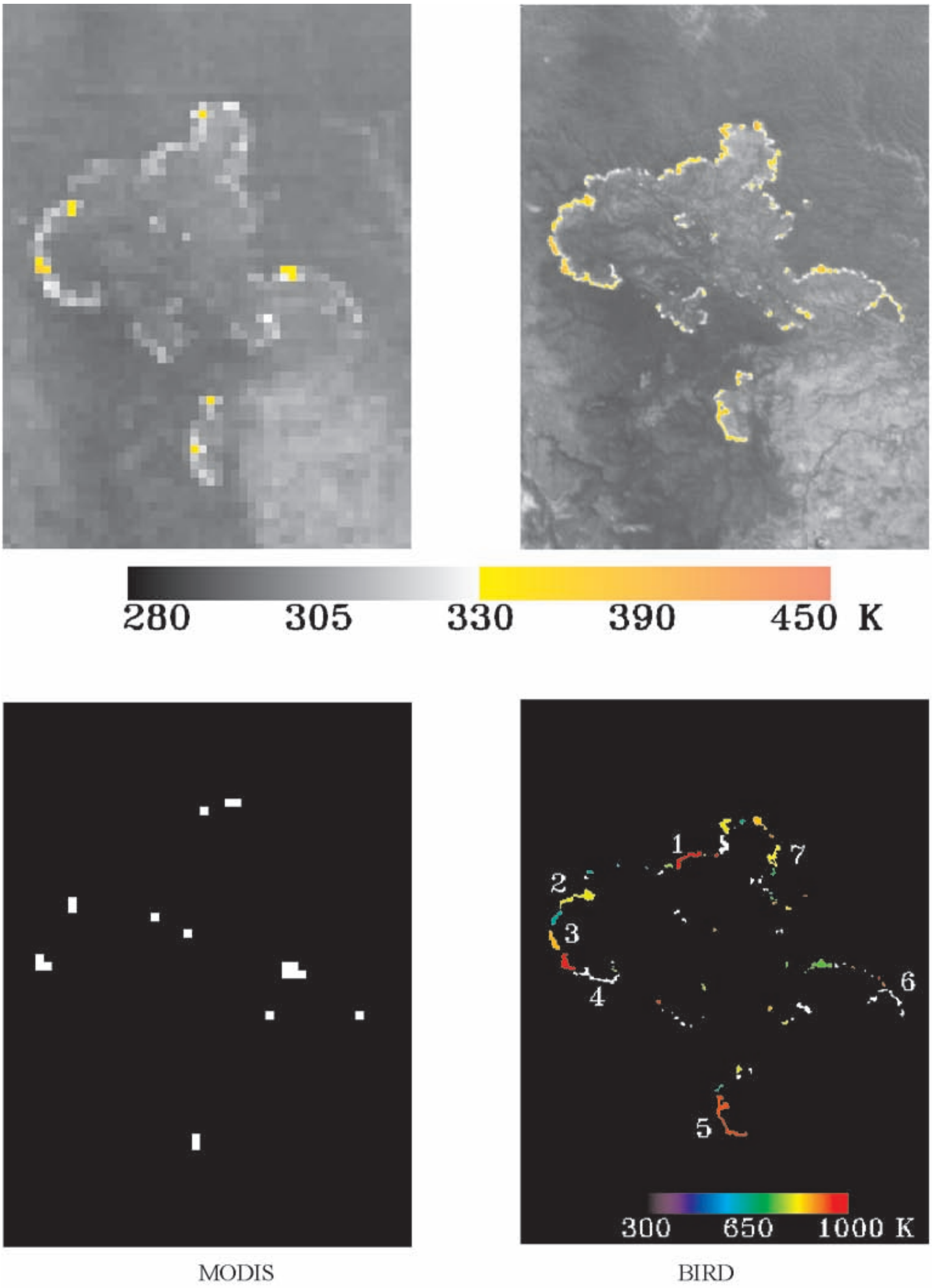

Fig. 3: Fragments of MODIS and BIRD images (upper row) and fire detection results (lower row).

to the front length. Its nominal values range from 1 to 3 m that is an order of magnitude smaller than a typical visible front depth of bush fires. Probably, it can be explained by non-homogeneity of the fire fronts where the actual high-temperature burning occupies only ~10% of the visible fire front area.

In spite of the uncertainty in the equivalent fire temperature and area, the Bi-spectral technique provides a fire energy release estimation that agrees well with the MODIS method. After an additional rough estimation of the front lengths, the average energy release per 1 m of the front length (front strength) was obtained. It varied in the range of 30–90 kW/m for the selected fronts.

The radiative fire energy release in the entire MODIS and BIRD image fragments in Fig. 3 was estimated as 1.3 and 2.5 GW respectively. The radiative energy release in the entire MODIS and BIRD scenes in Fig. 2 was 4.0 GW and 6.5 GW respectively. Thus, MODIS underestimates significantly the radiative energy release in comparison to BIRD due to missing of small fires. Though the energy release of small fires is also small, it is compensated by their large number.

Coal fire recognition in the North China Province Ningxia

Starting from January 2002, BIRD performs coal fire imaging on a number of test sites in China. Fig. 4 shows BIRD images of the Gulaben/Rujugou test site in the NIR, MIR and TIR spectral bands that were obtained on 31 January and 6 February 2002. Despite the observation time interval of 7 days and the varying viewing angles, these hot spots can be seen on both dates in the MIR channel. Some of these hot spots can also be recognised in the TIR images but there they appear much weaker.

Using the MIR and TIR images, the equivalent fire temperature and area of the detected hot spots were estimated. The equivalent fire temperatures was in the range of 350–450 K. The equivalent fire area varied from 0.1 to 1.1 ha. The values of the equivalent fire temperature obtained on different dates differed for most of the hot spots not more than ~20 K.

Using the equivalent temperature and area of the detected hot spots, values of their energy release was estimated ranging from 1 to 11 MW.

Conclusion

Multispectral infrared data of BIRD are used as input for a new hot spot recognition algorithm which has been successfully tested.

A unique feature of the mid infrared and thermal channels of the BIRD Hot Spot Recognition System (HSRS) is the real-time control of their dynamic range. That allows the observation of hot events without sensor saturation, preserving at the same time a good radiometric resolution of ~0.2 K at ambient temperatures of about 300 K.

Due to that and its higher spatial resolution, BIRD can detect fires with the area an order of magnitude smaller than operational polar orbiting systems such as the Advanced Very High Resolution Radiometer (AVHRR) or the Moderate Resolution Imaging Spectro-radiometer (MODIS).

The remote measurement of fire radiative energy release has been proposed by the MODIS fire team (KAUFMAN et al. 1998) as a novel method for providing information on variations in the amount of biomass consumed per unit time in vegetation fires, theoretically allowing the total amount of biomass combusted to be derived. Until recently only the MODIS sensor of the EOS Terra satellite possessed the necessary spectral and radiometric characteristics suitable for providing fire energy release observations from low-Earth orbit. The HSRS sensor of the new experimental BIRD satellite now allows fire energy release derivation at high spatial resolution and for fires of a smaller size and intensity than does MODIS, albeit at a much lower revisit time. This is also a unique feature for space borne remote sensing of coal seam fires.

BIRD successful demonstrates new small satellite fire recognition technologies, allow-

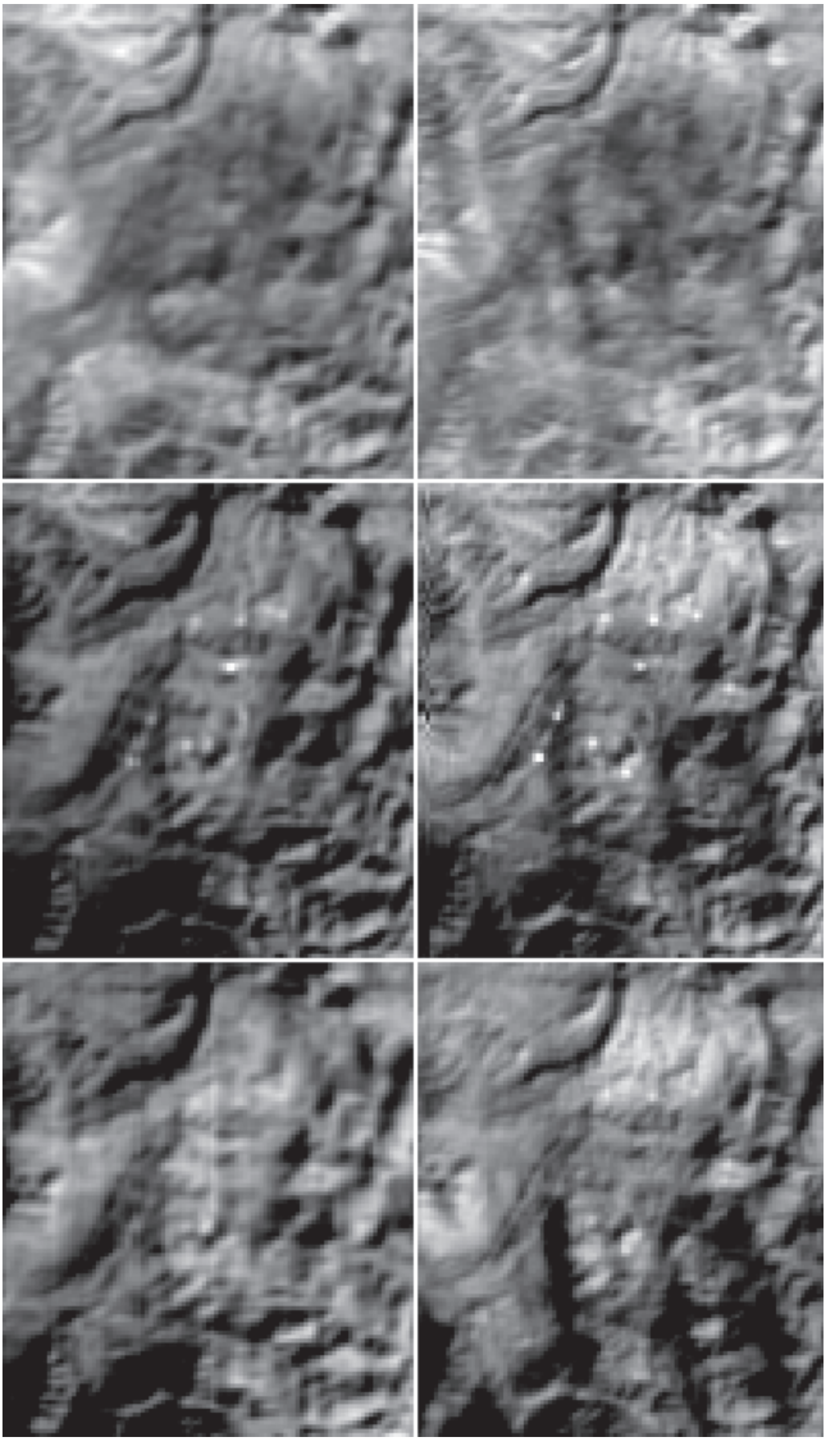

Fig. 4: BIRD images of Gulaben/Rujugou test site on 31 January 2002 (left) and 6 February 2002 (right): row 1 – NIR band; row 2 – MIR band; row 3 – TIR band.

ing the estimation of five quantitative characteristics of vegetation fires, such as temperature, area, radiative energy release, front length and front strength.

References

AHERN, F.J., GOLDAMMER, J.G. & JUSTICE, C.O. (eds.), 2001: Global and regional vegetation fire monitoring from space: Planning a co-ordinated international effort. – SPB Academic Publishing bv., The Hague, The Netherlands.

BRIESS, K., JAHN, H. & ROESER, H.-P, 1996: A DLR Small Satellite Mission for the Investigation of Hot Spots, Vegetation and Clouds. – Acta Astronautica, **39**: 899–908.

BRIESS, K., BÄRWALD, W., LURA, F., MONTENEGRO, S., OERTEL, D., STUDEMUND, H. & SCHLOTZHAUER, G., 2002: The BIRD MISSION is completed for Launch with the PSLV-C in 2001. – Photogrammetrie, Fernerkundung, Geoinformation (PFG), **2002** (1): 55–58.

DOZIER, J. 1981: A method for satellite identification of surface temperature fields of Subpixel Resolution. – Remote Sensing of Environment, **11**: 221–229.

FIRES, 1994: Fire Recognition System for Small Satellites, Phase A Study. – DLR Institute of Space Sensor Technology, Berlin and OHB-System, Bremen, Germany.

KAUFMAN, Y.J., JUSTICE, C.O., FLYNN, L.P. et al., 1998: Potential global fire monitoring from EOS-MODIS. – J. Geophys. Res., **103:** 32215–32238.

LORENZ, E. & SKRBEK, W., 2001: Calibration of a Bi-spectral Infrared Push-Broom Imager. – Proceedings of SPIE, Infrared Spaceborne Remote Sensing IX, San Diego, 29 July – 3 August 2001, in press.

PRINS, E.M. & MENZEL, W.P., 1994: Trends in South American biomass burning detected with the GOES VAS from 1983–1991. – J. Geophy. Res., **99**: 16719–16735.

SKRBEK, W. & LORENZ, E., 1998: HSRS – An infrared sensor for hot spot detection. – Proceedings of SPIE, Infrared spaceborne remote sensing VI, Vol. **3437:** 167–176.

ZHUKOV, B. & OERTEL, D., 2001: Hot Spot Detection and Analysis Algorithm for the BIRD Mission. – Algorithm Theoretical Basic Document (ATBD), DLR-Berlin.

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