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Space-borne high resolution fire remote sensing in Benin, West Africa

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Abstract. An experiment on high resolution remote sensing of fires was conducted in the Ouémé catchment area of Benin, West Africa using the Bi-spectral InfraRed Detection (BIRD) satellite. The high spatial resolution capability of the BIRD system allows the detection of fires with active burning areas less than a few hundred square metres in the sub-pixel domain, as well as the estimation of quantitative characteristics of these fires, such as the radiative fire energy release and (less accurately) the effective fire temperature and area.

1. Challenge of spatial high resolution fire recognition

Vegetation has various spatial and temporal dynamics, like inner-annual vegetation dynamics within the phenological cycle and long-term vegetation dynamics caused by human or environmental factors such as long-term climatic change (Braithwaithe 1996, Barbosa *et al*. 1999, Kusserow and Haenisch 1999). For the assessment of inner-annual vegetation dynamics, bush fires are an important field of investigation (Aubréville 1953). Bush fires can change the vegetation of large areas in a short time (Baker 1992). The knowledge of the area and the timing of the fires are important for meteorological modelling and the nutrient cycle (Cahoon *et al*. 1992, Baker 1993).

More than 40% of the area in the Upper Ouémé catchment area of Benin in West Africa is subject to burning (Thamm *et al*. 2002). The timing of bush fires is also significant in the land use management concept for the area in order to prevent nutrients being washed out with the onset of the rainy season. A large number of the human induced bush fires in tropical regions have active burning areas less than

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a few hundred square metres. The recognition of these fires is a major challenge and an important task for local environment protection and regional ecology.

Satellite sensors have been used for mapping and monitoring of active fires for more than two decades. However, they are confined to the determination of the location of a fire hotspot, without further information on the size, temperature, or intensity of the fire. This limitation has been primarily the consequence of the meteorological observation dominated specifications of available instruments such as the Advanced Very High Resolution Radiometer and the Along-Track Scanning Radiometer (Arino *et al.* 1999). Specifically, the low saturation temperatures of the thermal channels of these sensors cause ambiguities in the fire signal (Csiszar *et al.* 2003) and greatly limit the use of physically explicit temperature/area estimations by the bi-spectral method (Dozier 1981). The aim of the conducted controlled fire experiment in Benin, and the objective of this Letter, is to demonstrate the high (fine) spatial resolution fire recognition capability of the bi-spectral infrared push broom sensor system on board the micro-satellite BIRD, i.e. to detect and quantify active burning areas less than a few hundred square metres from a polar orbit.

2. Bi-spectral Infrared Detection (BIRD) mission

The small satellite BIRD was designed and built in the German Aerospace Centre (DLR) in cooperation with other scientific and industrial partners. Its major objectives are the testing of a new generation of infrared array sensors for satellite-based detection and quantitative analysis of high-temperature events (HTE) like vegetation and coal-seam fires and volcanic activities.

The BIRD main imaging payload consists of a Hot Spot Recognition System (HSRS) and a Wide-Angle Optoelectronic Stereo Scanner (WAOSS-B). HSRS possesses a mid-infrared (MIR, at 3.8 μm) and a thermal infrared (TIR, at 8.8 μm) channel. An innovative and unique feature of the BIRD HSRS is its real time adaptation of the dynamic range, avoiding saturation effects (Skrbek and Lorenz 1998). WAOSS-B possesses a nadir-looking near-infrared (NIR, at 0.9 μm) channel and two off-nadir stereo channels (VIS and NIR). All the BIRD nadir channels (NIR, MIR, TIR) have the same sampling step of 185 m, though the spatial resolution of the MIR and TIR channels is coarser by a factor of 2. The fire recognition potential of the Bi-spectral InfraRed Detection (BIRD) satellite has been described by Briess *et al.* (2003).

The temporal resolution of BIRD depends on its orbit characteristics and across-track tilt capability for the sensors' line of sight. BIRD provides this across-track capability, allowing observation of a target during daytime or night-time overpasses on up to four consecutive days. After these observation days, the BIRD is not able to observe the same target during the following week. The scenario is then repeated. A constellation of several low orbiting polar satellites on altitudes of about 550–800 km over ground is needed to permit a global daily coverage with space-borne push broom sensors of the BIRD type.

3. Controlled fire campaign in Benin, West Africa

Benin reaches from the Gulf of Benin (6° N) to the southern edge of the Sahel region (12° N) over a wide range of climatic and vegetation zones. A controlled fire campaign was performed on 1 December 2002 in the Ouémé region of Benin during a BIRD overpass at 11:55 a.m. local time. Sixteen test plots of different sizes (100 m $\times$ 100 m, 60 m $\times$ 60 m and 30 m $\times$ 30 m) in two different vegetation types, tree

(a) (b)

Figure 1. Controlled fire campaign within prepared areas of tree savannah (*a*) and a test plot just after the fire (*b*).

savannah and grass savannah, had been prepared for a controlled burning and set on fire 5–10 minutes before the BIRD overpass (figure 1(*a*)). Figure 1(*b*) shows one test plot after the fire. The amount of scorched vegetation depended very much on the wetness of the plants.

On-ground estimation of the fire temperature was performed using fire chalks that change their colour in response to specific ranges of temperatures. For this purpose, five metal plates with chalks were established on each plot 50 cm above ground: four plates in each corner and one in the centre of the test plot (figure 2). Recording fire temperature with fire chalks, in spite of some uncertainty, is an effective, cheap, and practicable method to compare on-ground fire temperature with estimations from satellites.

Figure 3 shows the BIRD MIR channel data and the two boxes where the controlled fires took place.

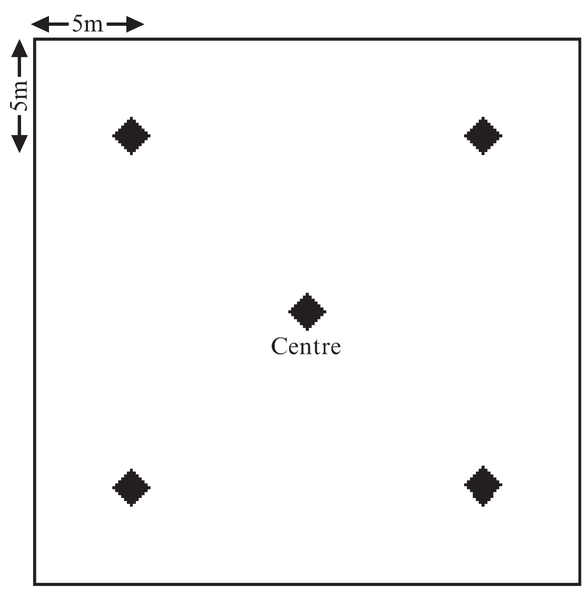

Figure 2. Location of fire chalks (♦) on a test plot.

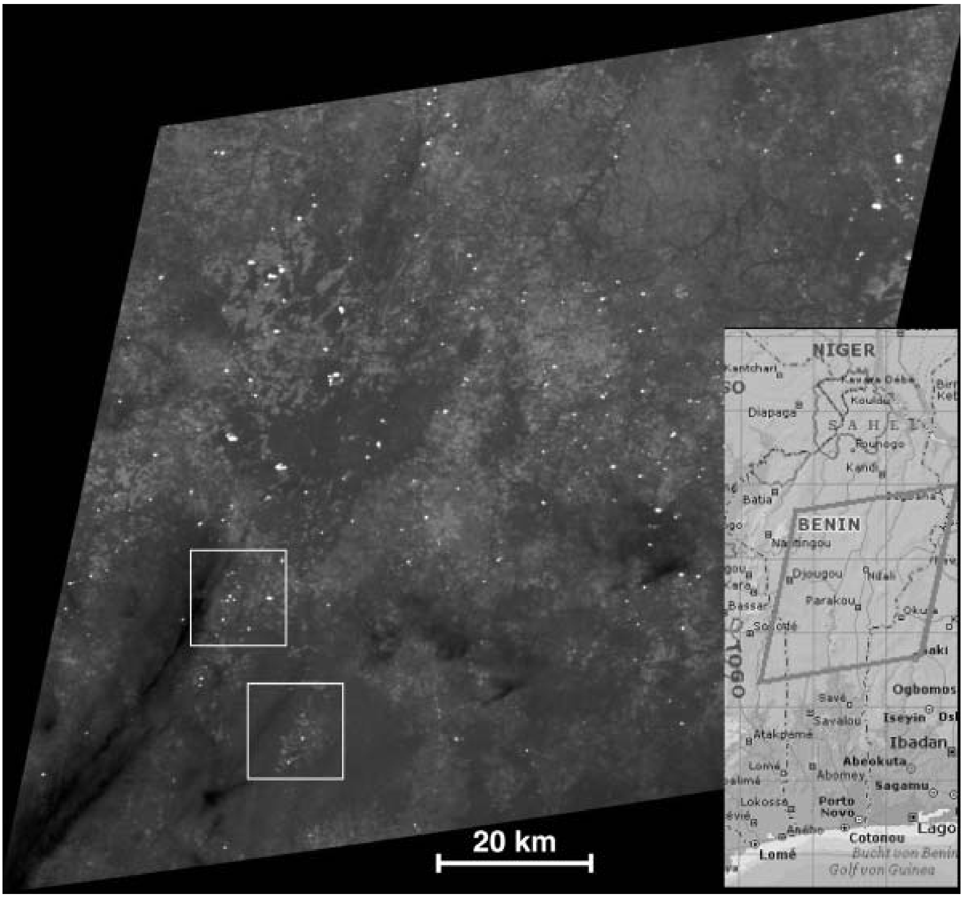

Figure 3. Image of numerous fires in Benin obtained on 1 December 2002, 11:55 a.m. in the MIR channel of the HSRS sensor on the BIRD satellite; the boxes indicate areas with controlled fires that are zoomed in figure 5.

The following processing was applied to the BIRD data:

- absolute radiometric correction and inter-channel geometric co-registration using on-ground calibration files that are periodically updated by in-flight calibration;
- geo-referencing using ground control points from detailed maps of the region, providing an accuracy of a few hundred metres; and
- detection and estimation of hot spot characteristics (effective fire temperature, effective fire area, fire radiative energy release) as described by Zhukov *et al.* (2003).

The detection and estimation of hot spot characteristics is conducted on a sub-pixel level, providing spatially and radiometrically high-resolution remote sensing of high temperature events with a push broom IR sensor which has (1) a moderate spatial resolution of about 200 m for 'normal' temperature targets and (2) an adaptive radiometric dynamic which avoids saturation.

Figure 4 demonstrates the fire radiative energy (FRE) release of the recognized hotspots. FRE is the portion of the power liberated by the combustion process that

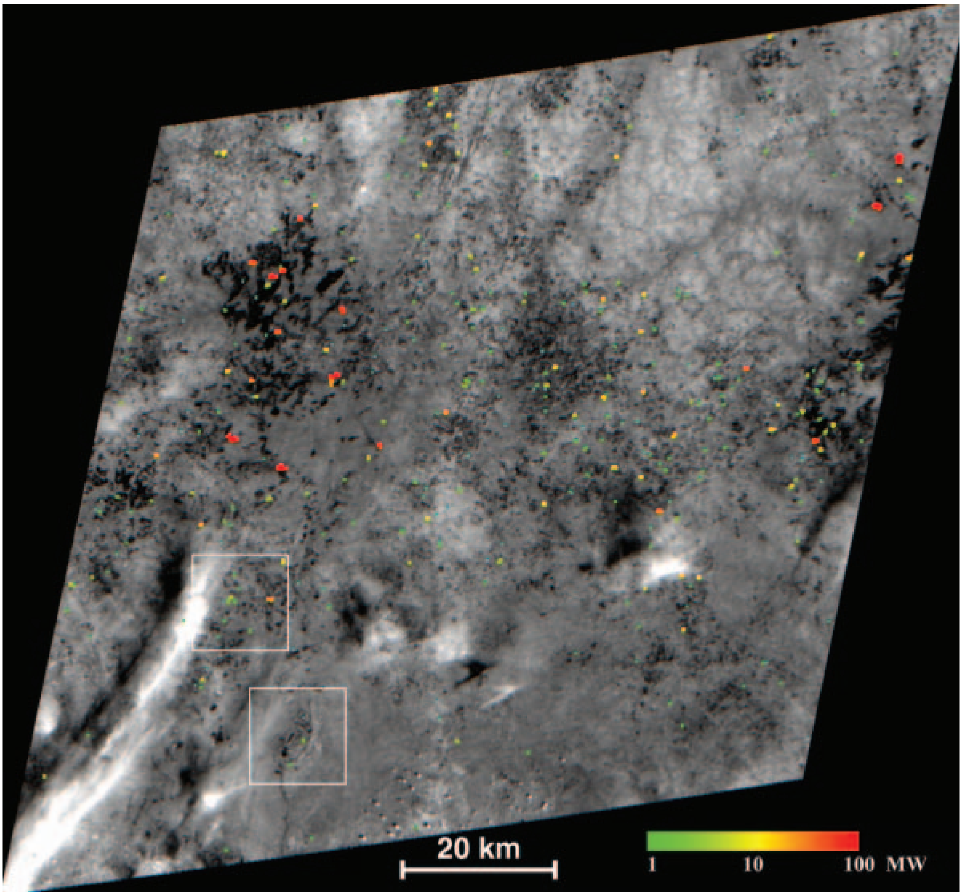

Figure 4. Hotspots with their radiative energy release projected on the image obtained in the nadir NIR channel of the WAOSS-B sensor on the BIRD satellite.

is emitted as radiation (Wooster *et al.* 2003). Most of the hotspots are associated with fire scars that look dark-toned in NIR imagery. For comparison, the data of the MODIS sensor on the Terra satellite from this region (obtained 24 minutes before the BIRD record took place) allowed only the identification of major—red coloured—hot spots in figure 4 with FRE values of more than $\sim$10 MW.

Figure 5 shows the correspondence of hot spots in the boxes of the MIR images (figure 3) to the controlled fires that were verified on-ground. BIRD was able to detect all the controlled fires except for plot F5 that is located between BIRD hotspots 3 and 4 in figure 5. The controlled fire plot F5 (100×100 m) was ignited at 11:33 a.m. and was totally on fire at 11:48 a.m. At the time of BIRD data acquisition the fire had already died down in the whole plot and the temperature had rapidly decreased. Hence, the satellite sensor had not detected this target as being on fire.

4. Estimation of fire characteristics

The detected hot spots 1–5 (shown in the upper left box of figure 3 and in the left row of the enlarged box images of figure 5) as well as hot spot 6 (shown in the lower right box of figure 3 and in the right row of figure 5) were analysed in detail

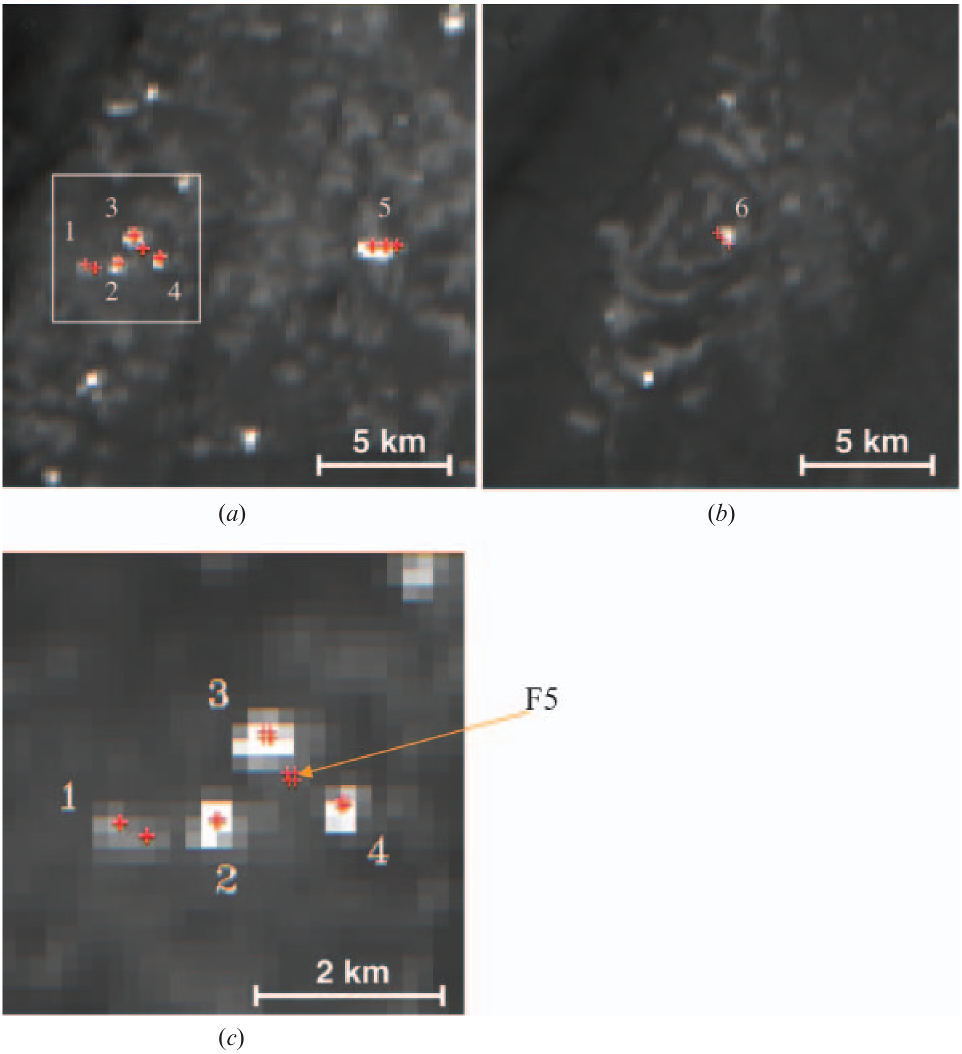

Figure 5. On-ground verification of the detected hotspots: (*a*), (*b*) location of on-ground temperature measurements (red crosses) in the enlarged fragments of figure 3 (the hotspot numbers correspond to table 2); (*c*) zoomed fragment of image (*a*); the controlled fire plot F5 cannot be recognized as a hot spot in the BIRD image.

with regard to effective fire temperature, effective fire area and FRE using the bi-spectral method (BS) and the MIR radiance (MIR rad.) method (Wooster 2002, Wooster *et al*. 2003). The mean values and confidence intervals (in brackets) of the estimates are given in table 1 which are derived as in Zhukov *et al*. (2003).

Table 2 provides the link of the hot spot to the controlled fire plots F5–F16 ignited for burning during the BIRD data record. This table contains further on-ground estimates of the mean fire temperature obtained by the use of 'fire chalk' and the area of the fire plots measured 50 cm above ground.

The effective fire temperature and area could be estimated from the BIRD data only with a significant uncertainty, due to a low fire proportion in the BIRD pixels. This was significantly less than 1% of the BIRD IR pixel area (of $\sim$14 ha) in the

Table 1. Hotspot characteristics from the BIRD data (the values in brackets indicate the confidence intervals for the corresponding characteristics).

Hot spot number	Effective fire temperature (K)	Effective fire area (ha)	FRE, MW	
			BS	MIR rad.
1	628 (544–912)	0.03 (0.004–0.07)	2.2 (1.5–3.0)	1.7
2	991 (826–1200)	0.02 (0.009–0.04)	10.0 (10.0–10.6)	10.5
3	809 (702–1082)	0.07 (0.02–0.15)	17.0 (15.8–19.8)	16.4
4	– (1028–1200)	– (0.006–0.010)	6.6 (6.4–6.8)	6.9
5	886 (687–1200)	0.16 (0.05–0.57)	53.7 (52.7–68.2)	53.0
6	779 (652–1200)	0.04 (0.007–0.12)	8.8 (7.9–11.2)	8.9

majority of the hot spots. As shown in Zhukov *et al.* (2003), the temperature estimation error in this case may be as high as a few hundred Kelvin due to low fire signal in the TIR that is masked by TIR background radiance variations. Nevertheless, there is a reasonable agreement between the confidence levels for the BIRD temperature estimations (given in table 1) and the on-ground temperature estimates (given in table 2). Here, one should also take into account that the BIRD temperature estimates are averaged over the entire fire plots at the time of the BIRD overpass while on-ground measurements with 'fire chalks' show the maximal temperature reached during the entire burning process at the fire chalk location.

The effective fire area, which characterizes the 'net area' of the flames, is in some cases one to two orders of magnitude smaller than the plot area measured on-ground. Obviously, the 'plot area' includes unburned as well as already burned areas that were not on fire during the BIRD overpass (it would be unrealistic to expect a homogeneous burning at the scale of the entire plots).

The bi-spectral method and the MIR radiance method give very close FRE estimates for each hot spot, the maximal difference being 0.8 MW (see table 1). An inter-comparison of the satellite- and ground-based FRE estimation was not feasible due to a clear under-sampling of the plots by on-ground measurements (see the related discussion about the effective fire area).

5. Conclusion

The controlled fire experiment in Benin has confirmed that BIRD is able to detect even small vegetation fires and to estimate their radiative energy release and (less accurately) the effective fire temperature and area. Therefore, IR sensors of the

Table 2. Correspondence between the detected hot spots and the controlled fire plots with on-ground estimates of the fire temperature and plot area (one hot spot in the BIRD image may cover a few fire plots).

Hot spot number in figure 5	Controlled fire plots	Temperature (K)	Plot area (Ha)
1	F7, F8	>870	0.18
2	F6	780–870	0.36
3	F5, F9	610–870	2.0
4	F10	780–870	0.36
5	F11, F12, F13	780–870	1.45
6	F14, F15, F16	520–780	1.45

type used on BIRD can provide a useful tool for sustainable fire management, if a suitable orbit and repetition rate are provided.

References

Arino, O., Rosaz, J.-M., and Goloub, P., 1999, The ATSR World Fire Atlas. A synergy with 'Polder' aerosol products. *Earth Observation Quarterly*, **64**, 1–6.

Aubréville, A., 1953, Les expériences de reconstitution de la savane boisée en Côte d'Ivoire. *Bois et Forêts des Tropiques*, **32**, 4–10.

Baker, W. L., 1992, Effects of settlement and fire suppression on landscape structure. *Ecology*, **73**, 1879–1887.

Baker, W. L., 1993, Spatially heterogeneous multi-scale response of landscapes to fire suppression. *Oikos*, **66**, 66–71.

Barbosa, P. M., Stroppiana, D., Gregoire, J. M., and Pereira, J. M. C., 1999, An assessment of vegetation fire in Africa (1981–1991): burned areas, burned biomass, and atmospheric emissions. *Global Biogeochemical Cycles*, **13**, 933–950.

Braithwaithe, R., 1996, Biodiversity and fire in the savanna landscape. In *Biodiversitiy and Savanna Ecosystem Processes – A Global Perspective*, edited by O. T. Solbrig, E. Medina, and J. F. Silva (Berlin: Springer), pp. 121–142.

Briess, K., Jahn, H., Lorenz, E., Oertel, D., Skrbek, W., and Zhukov, B., 2003, Fire recognition potential of the Bi-spectral InfraRed Detection (BIRD) satellite. *International Journal of Remote Sensing*, **24**, 865–872.

Cahoon, D. R., Stocks, B. J., Levine, J. S., Cofer, W. R., and O'Neill, K. P., 1992, Seasonal distribution of African savanna fires. *Nature*, **359**, 812–815.

Csiszar, I., Abdelgadir, A., Li, Z., Jin, J., Fraser, R., and Hao, W.-M., 2003, Interannual changes of active fire detectability in North America from long-term records of the Advanced Very High Resolution Radiometer. *Journal of Geophysical Research*, **108**, 4075.

Dozier, J., 1981, A method for satellite identification of surface temperature fields of subpixel resolution. *Remote Sensing of Environment*, **11**, 221–229.

Kusserow, H., and Haenisch, H., 1999, Monitoring the dynamics of 'tiger bush' (brousse tigrée) in the West African Sahel (Niger) by a combination of Landsat MSS and TM, SPOT, aerial and kite photographs. *Photogrammetrie - Fernerkundung - Geoinformation*, **2**, 77–94.

Skrbek, W., and Lorenz, E., 1998, HSRS – An infrared sensor for hot spot detection. *Proceedings of SPIE: Infrared Space-borne Remote Sensing VI*, **3437**, 167–176.

Thamm, H.-P., Doevenspeck, M., Orekan, V., and Menz, G., 2002, Remote sensing as a tool in an integrated approach to monitor and interpret land use/land cover changes. *Actes de la IXéme Journée de l'Association Béninoise de Pastoralisme (A.Be.Pa), Cotonou, le 16 Novembre 2002*.

Wooster, M. J., 2002, Small-scale experimental testing of fire radiative energy for quantifying mass combusted in natural vegetation fires. *Geophysical Research Letters*, **29**, 2027–2034.

Wooster, M. J., Zhukov, B., and Oertel, D., 2003, Fire radiative energy for quantitative study of biomass burning: derivation from the BIRD experimental satellite and comparison to MODIS fire products. *Remote Sensing of Environment*, **86**, 83–107.

Zhukov, B., Briess, K., Lorenz, E., Oertel, D., and Skrbek, W., 2003, BIRD detection and analysis of high-temperature-events: first results. *Proceedings of SPIE: Remote Sensing for Environmental Monitoring, GIS Applications, and Geology II*, **4886**, 160–171.