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THE INFRARED INSTRUMENTATION OF THE MINI-SATELLITE MISSION BIRD

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ABSTRACT - A small bispectral infrared push broom scanner for a mini satellite mission is described, which is dedicated to the detection and analysis of high temperature events (HTE). For this purpose two infrared line scanners (3.4-4.2μm and 8.5-9.3μm) will be combined with a VIS/NIR camera. With respect to the limited recourses of the mini satellite the design of all instruments is based on the usage of staring focal plane arrays. Achieving a reasonable swath width the analysis of HTE which covers only some m² on ground requires the application of subpixel target detection methods and analysis. The BIRD instrumentation is a precursor of the FOCUS proposal for the International Space Station.

1-INTRODUCTION

The phase C/D of the small satellite project BIRD [Brie 96] is currently going on in the Institute for Space Sensor Technology of the DLR. The payload of the BIRD satellite (80kg) is dedicated to the detection and the analysis of high temperature events (HTE) and to the remote sensing of vegetation by means of new advanced methods and technologies. To achieve the mission objectives a two channel imaging infrared sensor system (3.4-4.2μm and 8.5-9.3μm) is combined with a modified Wide Angle Optoelectronic Stereo Scanner (WAOSS) [WAOS 92]. Adding such a VIS/NIR CCD-line push broom scanner to the IR-sensors a significant improvement of the false alarm rejection capability can be achieved.

The new approach of this mission is characterised by a strictly design-to-cost philosophy. The WAOSS camera was designed and qualified for the MARS 96 mission and the adaptation to the BIRD mission requires only a change in the layout of its optical filters and lenses.

Corresponding to the basic design of the WAOSS camera the IR channels are also designed as push broom scanners to achieve a large swath width keeping at the same time a reasonable ground resolution. The imaging parameters of the IR channels were chosen using the respective parameters of the existing WAOSS camera as the guideline. A special design of the IR optics ensures identical parameters for both IR channels and an ground pixel size which is exactly the twice of the WAOSS camera. This simplifies the matching of the three spectral channels.

The radiometric requirements on the IR sensors are mainly determined by the large dynamic range of the signal, necessary as well for the observation of the HTE as for the acquisition of information about the vegetation conditions. An autonomous adaptation of the detector sensitivity to the actual scene will be provided mainly by the stare time control.

The main cost driver for the IR instruments is the development of a cryostat design with an integrated stirling cooler suitable for the application on board of such a small satellite. To ensure the space qualification of the cooling engine a RICOR cooler proven in the CLEMENTINE mission was chosen.

In Fig. 1 is shown the principle design of the BIRD satellite and the accommodation of the instruments in the upper half of the main body.

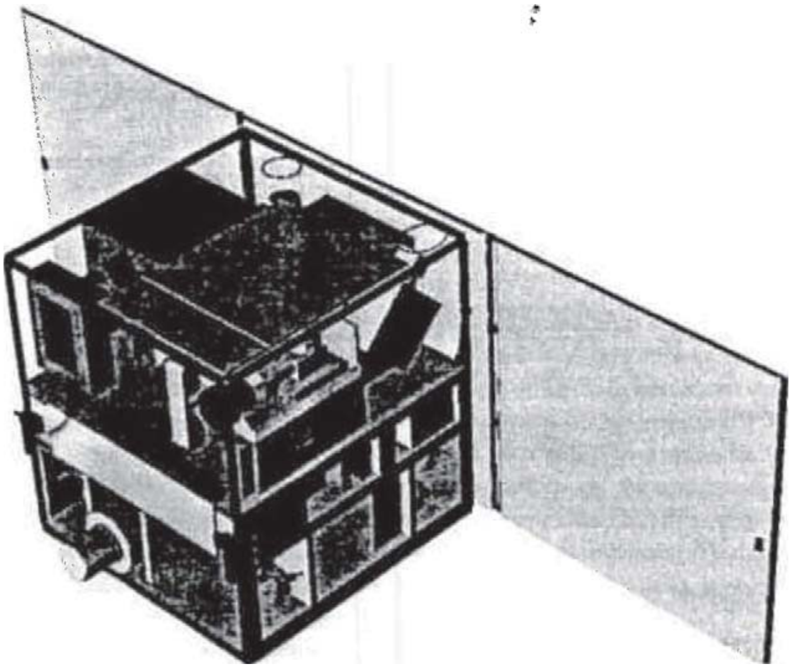

Fig. 1: Basic design of the BIRD satellite and the accommodation of the instruments

2- MISSION OBJECTIVES AND TECHNICAL REQUIREMENTS

Considering the restrictions caused by the limited budget of a 80kg satellite a strictly economical design of all instrument components is necessary. This can be obtained only by a careful analysis of the mission objectives and a resulting consequent adaptation of the instrumentation.

A typical scenario for the wild fires is the existence of a number of relatively small hot areas (hot spots) [Flyn 95]. To measure the temperature and the extension of the small hot areas directly a high spatial resolution is necessary. Because of the limited number of sensor elements in the IR-lines currently available this is in contradiction to the swath width required for a reasonable coverage. The conflict can be dissolved applying the method proposed by Dozier [Dozi 81]. The main feature of this technique is the usage of two spectral channels to analyse the deviation of the received radiation from Planck's law. In the case of hot spots this deviation is given by the existence of a remarkably higher temperature compared to the background temperature within a subpixel area.

Observing slightly increased detector signal U_i by the corresponding sensor elements in the different spectral channels i ($i=1,2$) it must be clarified whether it is a large scale temperature increase by some K or it is a small hot spot with a temperature T_F of some hundred K higher than the background. The detector signal levels U_i describe a well defined functional dependence $U^{(i)}(L(T))$ on the radiance $L(T)$ of a black body with the temperature T. This dependence will be determined by the calibration process and can be accomplished in the most simplified cases by a look-up table [Jahn 96], but an analytical expression would be preferred. This calibration curve is the base for the different modes of the temperature measurement.

Measuring, for instance, the signals U_i of a grey body with the temperature T_G and the emissivity $\varepsilon<1$ $(U_i=\varepsilon * U^{(i)}(L(T_G)))$ the temperature T_G can be estimated solving the well known equation (1) [Gaus 84].

$$\frac{U_2}{U_1}=\frac{L^{(2)}(T_G)}{L^{(1)}(T_G)}$$

In case of the observation of a hot spot with the temperature T_F which covers a portion q of the observed ground pixel the temperature T_F can be estimated solving a similar, highly non-linear equation (2) [Jahn 96. Dozi 81]. Thereby is assumed that the temperature T_{BG} of the remaining background portion (1-q) is equal to that of the surrounding pixels.

$$\frac{U_2-U_2(T_{BG})}{U_1-U_2(T_{BG})}=\frac{L^{(2)}(T_F)-L^{(2)}(T_{BG})}{L^{(1)}(T_F)-L^{(1)}(T_{BG})}$$

If the temperature T_F is known the calculation of the area factor q can be provided solving a linear equation.

Considering the properties of equation (2) for the precise determination the hot spot temperature T_F a high Signal to Noise Ratio (SNR) is necessary. Spectral broad band systems (3-6µm to 8-12µm) can deliver a reasonable high signal level but unfortunately a restriction is necessary to avoid annoying atmospheric effects. Therefore a good compromise is the usage of the spectral bands 3.4µm to 4.2µm and 8.5µm to 9.3µm.

The parameters which determine the imaging properties are chosen using the respective parameters of the existing WAOSS camera as the guideline to simplify the matching of the different channels.

Summarising all the discussed constrains a parameter set of the BIRD mission was identified which is shown in Tab. 1.

Sensor parameter	WAOSS	MWIR	LWIR
wavelength	(forward) 600-670nm (nadir, backw) 840-890nm	3.4-4.2µm	8.5-9.3µm
Focal length	21.65mm	46.39mm	46.39mm
Field of View (FOV)	50°	19°	19°
f# number	2.8	2.0	2.0
detector element number	2884	512x2 staggered	512x2 staggered
detector element size	7x7 µm	30x30µm	30x30µm
ground pixel size (altitude 450 km)	145m	290m	290m
swath width (altitude 450 km)	420km	148km	148km
Quantisation	11Bit	16Bit	16Bit
Data rate	597 kbps compressed	420kbps	420kbps

Tab. 1 Main Parameters of the BIRD sensor system

The expected resulting parameters of the detectable hot spots are shown in Fig. 2. The smaller the size of the hot spot compared to the ground resolution the higher must be the temperature to be become detectable. The sizes of the hot spots are significantly less than the ground resolution given in Tab.1

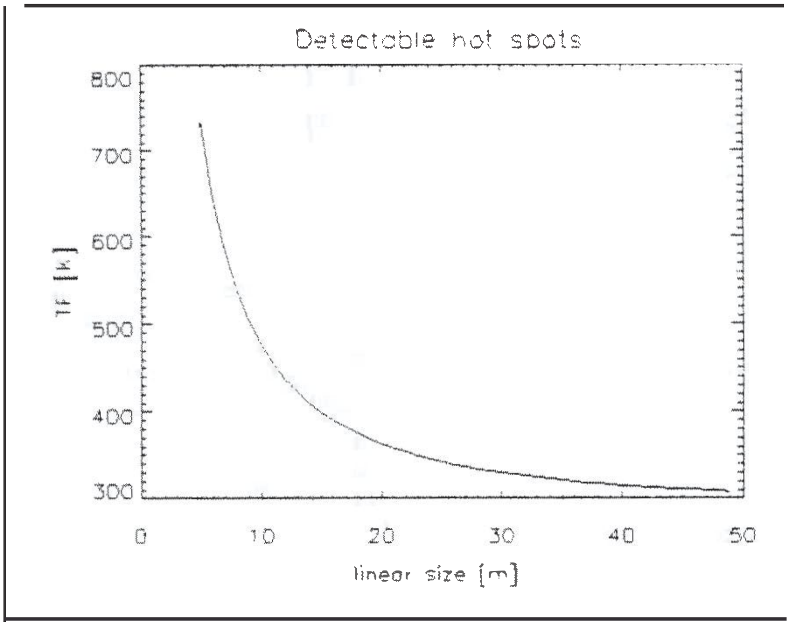

Fig. 2 Parameters of detectable hot spots

In contradiction to the demands of the hot spot analysis a large area HTE requires a reduced radiometric sensitivity to avoid the saturation of the detector and to ensure the estimation of the temperature also in these cases. Therefore it is necessary to obtain some special features of the detector readout circuit which enable a signal adaptation :

- control of integration time
  switching of charge collecting capacity
- control of detector's bias voltages

The main mechanism for the signal adaptation will be the control of integration time. If saturation will be expected due to a high temperature event the integration time has to be decreased drastically. In Fig. 3 is shown the expected limitation of the integration time in dependence on T_F and for q=1. On the other hand the integration time will be also limited by the push broom principle which produces a smearing effect because of the movement of the satellite. To minimise the decrease of the image quality caused by this movement the integration time must be much smaller than the dwell time (about 0.1 of the dwell time) For the planned 450km orbit a dwell time of about 40ms will be expected. The radiometric calculations show that for scenes without a high temperature event the integration time should be less than 140µs for the LWIR and less than 8ms for the MWIR to avoid a saturation. It is obvious that for the LWIR exist reserves which can be used for an improvement of the SNR. For this reason a digital accumulation circuit located behind the analogue to digital converters (ADC) converter will be implemented. Additional a range control will be realised to detect a saturation and to implement a signal adaptation.

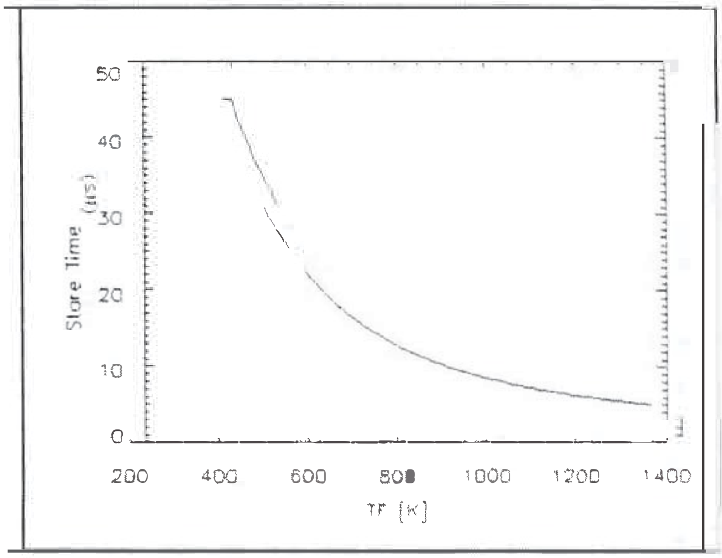

Fig. 3 Maximum integration time to avoid a saturation of the integration capacitors

3 - DESIGN OF THE INFRARED CHANNELS

3.1 Focal Plane Assembly and Electronics

The design of the infrared channels is based on the described requirements and on principles of a reliable and flexible system architecture. Therefore a modular concept of the IR-sensors was preferred. This means that the two infrared channels are independently from each other but their design parameters are chosen identically. Beginning with the definition of the detector array a $Hg_{1-x}Cd_xTe$ type is the best choice because it is easy to realise identical structures for different spectral regions changing the stochiometric mixture ratio x. Further more it is possible to construct nearly identical read out circuit components for both IR channels.

The arrangement of the sensor elements should be comparable with this of the WAOSS camera and should support techniques of a pre detection to realise a signal adaptation. For these reasons a commercial available focal plane array (FPA) was chosen which is shown in Fig. 4.

To ensure a reasonable thermal environment of the detectors and the optics each of the two IR-channels consists of the sensor head and the separated sensor electronics (Figure 5). In the sensor head are located the detector/dewar -ensemble with an integrated cooling engine, the optics and the head electronics (HEE) controlling the bias voltages and clock regime. The sensor electronics includes the front-end-electronics (FEE) with amplifier and ADC and the head controller (HCTR) with a micro controller system, a line controller and an accumulator. The power modul is also a part of the sensor electronics.

The interface electronics to the FPA including the clock drivers, amplifier and digital adjustable bias voltages require a carefully low noise design. Therefore these components are located very close to the FPA in the head electronics. The HEE generates the power supply voltage for the FPA and the bias voltages necessary for the operation point adjustment to the input signal. The read out electronics of the focal plane array is controlled by three clock pulse sequences and several input levels providing the selection of the two array lines and the configuration of the integration capacitors.

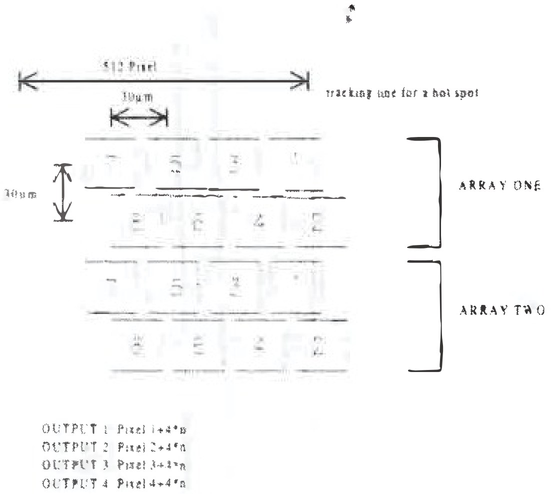

Fig. 4 The focal plane arrangement

Each of the four signal chains of the head electronics is connected via a driver circuit to the sampling ADCs located on the Front End Electronic (FEE) (Fig. 5). Besides these ADCs the FEE contains also slow rate ADCs for the digitisation of house keeping data (HKD) such as different local temperatures controlling the thermal regime of the sensor head.

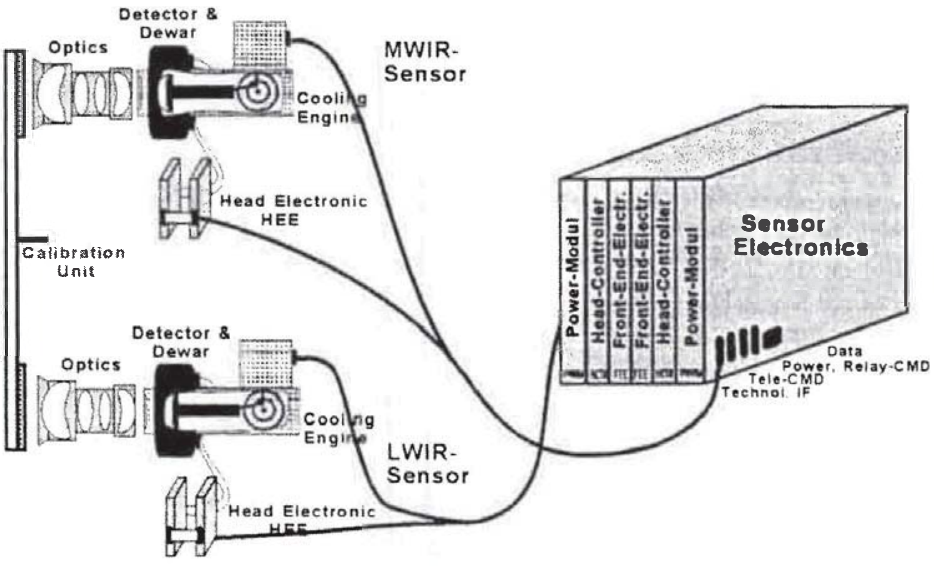

Fig. 5 Electro-optical design of the IR-Channel

3.2 FPA cooling

The HgCdTe diode array requires an operating temperature of 80K. In case of a small satellite mission such a temperature can be realised only by a space qualified closed cycle cooler. Therefore an important criterion for the selection of the detector was the availability and efficiency of its cooling system. Besides the power consumption of the cooling engine its mass and volume are also significant parameters. The probably best solution for a satellite mission is the integration of the engine and the detector dewar. This reduces the thermal losses remarkably and consequently also the power consumption. Therefore the design of an optimised cooling system is the main delivery subject keeping the commercial available FPA unchanged. The selected cooling engine is the RICOR cooler K508 used in the CLEMENTINE mission.

Redesigning the dewar system it was also possible to optimise the cold shield parameters with respect to the optics and, therefore, to reduce the disturbing straylight effects.

3.3 The Opto-mechanical design

The application of the Dozier method [Dozi 91] and therefore of equation (2) for the subpixel target detection and analysis requires a parallel measurement in at least two different infrared channels and a matching of the corresponding pixels which contain the same hot spot. These matching requirements were the main driver for the opto-mechanical design.

A technical realisation of the two channels on one focal plane array was analysed and rejected due to the co-registration requirements and other reasons (costs, reliability). It was also analysed the usage of a unique entrance optics for both channels with beam separation by a splitter. This version has also some disadvantages with regard of the required FOV (19°).

Consequently two independent, but nearly identical designed units are used. The doubling ensures a minimal observation mode if details of one channel fail, for instance the cooling engine. The radiometric calculation shows that a f-number f#=2 and a focal length f=46.39mm meet the mission requirements and, therefore, a small and lightweight optics can be used.

A peculiarity of this solution is the necessity to achieve and to guarantee an exact geometric co-alignment of the channels required for the processing of the extraction of subpixel information on the target.

The optics of the two infrared channels are built identical and have some features to realise an acceptable alignment. The spectral specification will be realised by a special coating. The effective focal length of the infrared optics is 46.39mm to obtain an exactly twice larger IFOV compared to the WAOSS camera. Considering various tolerances in the manufacturing process the focal length can be adjusted within ±0.5mm with an accuracy of 40µm.

The main features of the opto-mechanical structure of an infrared channel are shown in the exploded drawing Fig. 6.

3.4 Calibration Subsystem and thermal design

The laboratory calibration has to provide as well the radiometric as the geometric characterisation of the instruments. The laboratory radiometric calibration has mainly to deliver the dependence of the detector output voltages U(L(T)) on a reference source temperature T (black body). This is a fundamental prerequisite for the further usage of the equations (1) and (2).

An other radiometric calibration issue is the handling of the sensor offsets. The remote measurement of absolute temperatures by IR-sensors requires to know different kinds of the signal offsets. The thermal offsets caused by the uncooled entrance optics etc. can be checked and considered measuring the temperature of the instrument. The main heat source in the sensor head is the cooling engine. With respect to the very compact and lightweight design this heat entry tends to destabilise the thermal regime of the instrument. Therefore it must be decreased and removed from the sensor head to stabilise the thermal regime and the thermal offsets.

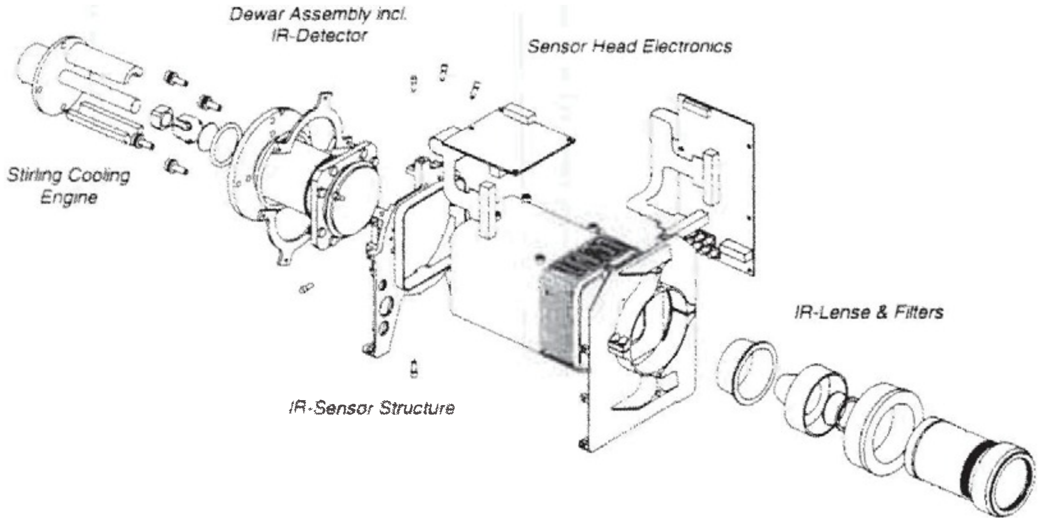

Fig. 6 Exploded view of the opto-mechanical structure

The handling of the electrical offsets generated by the readout circuit is much more complicated. The integration capacity of the readout circuit will be charged by the reset of the detector and discharged during the measurement. The accurate measurement and control of the reset voltage for each detector element is problematic and generates an additional offset noise. Besides the reset voltage one must consider also other offset components which depend on the electrical operating conditions of the detector. In the calibration process these components have to be analysed and considered in a suitable model.

Additional to the radiometric calibration the sensor element viewing direction has to be measured by a special geometric calibration. This laboratory calibration part is necessary for the alignment of the three sensors. The features of the opto-mechanical structure described above enable a reasonable handling of the adjustment. The geometrical calibration and the sensor head adjustment have to be organised in a high degree of dependence to ensure an optimisation of the mechanical structure.

The radiometric characterisation of the sensor in flight can be provided by a measurement towards the deep space to check the signal offsets and by a measurement of an known reference target (entrance flap/shutter) which internally should be covered by a black coating. The flap/shutter may realise also a protection function of the front lens.

For the geometric in-flight verification of the channel co-alignment a well known identifiable target like the moon is necessary.

4 - CONCLUSION

An infrared sensor system for subpixel hot spot recognition from a small satellite has been designed. The system consists of two IR-sensors in the MWIR (3.7µm) and LWIR (8.9µm), a wide angle push broom scanner and an onboard data processing system. Opposite to the current remote sensing satellite sensor systems the new generation of IR-sensors can adapt itself autonomously to different scene temperatures. Estimations of the expected IR-flux levels and performed simulations have shown that it is possible

-to adapt the signal levels of the sensor to different scenes

- to evaluate hot spots in the subpixel range of detector

Special calibration procedures are considered with respect to the peculiarities of the detector arrays to ensure the quantitative estimation of the hot spot temperatures.

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