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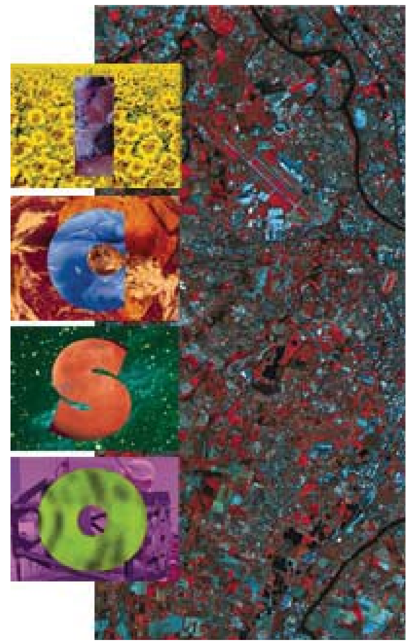

Prototype of microbolometer thermal infrared camera for forest fire detection from space

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PROTOTYPE OF MICROBOLOMETER THERMAL INFRARED CAMERA FOR FOREST FIRE DETECTION FROM SPACE

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RESUME :
La contribution de la caméra thermique (TIR) à la mission d'observation de la Terre FUEGO est d'aider

- à la discrimination des nuages et des fumées
- à la détection des fausses alarmes des feux de forêts
- au suivi des feux de forêts

Pour cela, la caméra doit couvrir une grande dynamique de luminances.
Faibles volume, masse et puissance sont demandées pour tenir les objectifs de la petite charge utile FUEGO.
Ces caractéristiques peuvent être intéressantes pour d'autres missions équivalentes.

ABSTRACT :
The contribution of the thermal infrared (TIR) camera to the Earth observation FUEGO mission is to participate

- *to discriminate the clouds and smoke*
- *to detect the false alarms of forest fires*
- *to monitor the forest fires*

Consequently, the camera needs a large dynamic range of detectable radiances.
A small volume, low mass and power are required by the small FUEGO payload.
These specifications can be attractive for other similar missions.

1. INTRODUCTION

This paper presents the design of the 2D-microbolometer camera performing in the thermal infrared range 8-12 µm. This work is part of a research and development contract- named FUEGO2 - awarded in September 1998 by the European Commission (DG XII) to a team of space industries, agencies and universities of Spain, Italy, Germany, France, Portugal and Greece to design, manufacture and test a prototype of the FUEGO payload.
This payload is composed of cameras observing in the medium infrared (MIR), thermal infrared (TIR), and visible/near infrared (VIS/NIR).

ALCATEL SPACE is in charge of the thermal infrared (TIR) camera : the camera is equipped with a SOFRADIR 2D microbolometer detector (IDML 07301) and an hybrid lens developed by THOMSON-CSF OPTRONIQUE.
Functional tests will be performed on the camera development model in January-February 2001.

2. THE FUEGO MISSION AND SYSTEM

The FUEGO project responds to the interest of the European Commission to address efforts towards the reduction of damages caused by forest fires in the Mediterranean region.
The long term objective of the FUEGO programme is to contribute in a cost effective manner to reduce the effects of forest fires in the Mediterranean forest land, and in similar biotopes around the world, i.e. temperate dry high value forests being defended by heavily staffed forest firefighting corps.
Actually, forests are an essential asset for the future of this European region because of the quality of the land and its economic and environmental value.

The first objective of FUEGO is to detect fire outbreaks with a good reliability and soon enough- less than 25 minutes - to facilitate their quick extinction.
The second objective is to monitor continuously fires once they have been detected.

The results of the mission analysis have defined the main characteristics of the space segment:

- Altitude 700 km
- Constellation of 12 satellites in 3 orbital planes, 47.5° inclination with equator, ensuring a maximum revisit time of 25 minutes.
- The satellites will be in the 275 kg mass range including propellant.
- The swath width is 2500 km, accessible by depointing the front mirror of satellite payload, see figure 1
- The payload will be composed of cameras observing in the medium infrared (MIR), thermal infrared (TIR), visible/near infrared (VIS/NIR)
- The field of view of each camera is 177 km, see figure 1
- The nadir resolution of the cameras is : 80m for MIR, 369m for TIR, 20m for VIS/NIR

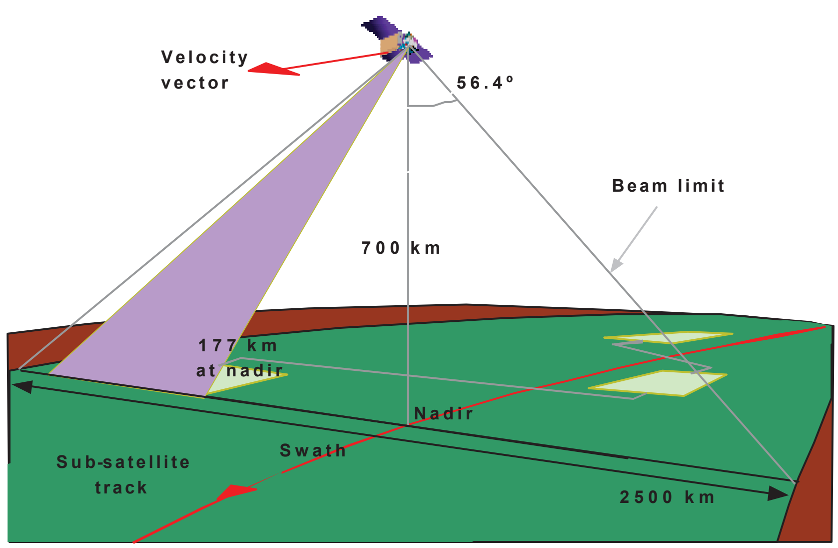

Figure 1 : Sketch of the swath and field of view of the FUEGO satellite

The payload is composed of:

- The MIR, TIR, VIS/NIR cameras
- The optical bench providing alignment and registration of the cameras
- The depointing mirror subassembly
- The processor to manage all the functions and modes of the payload
- Blackbody sources to provide in-flight radiometric calibration of the cameras

3. THE TIR CAMERA MAIN REQUIREMENTS

The main characteristics of the instrument, derived from the system requirements, are the following:

Spectral domain : 8 – 12 µm

Mode : pushbroom

Across track field of view : ± 7.2 °(which corresponds to a swath width of 177 km on ground, nadir looking, from 700 km altitude)

Detector : on-the-shelf uncooled microbolometer 2D array, 320 x 240 pixels

Focal plane configuration : the swath is oriented 45° with respect to its lines and columns, see figure 2

Number of across track pixels : 240 x 2 (2 successive 45°- pixel lines so-called diagonals are used to increase the number of pixels), see figure 2

Dynamic range of detectable radiance : Rmin/Rmax = 2.4 / 30.6 W/m2.sr.µm

MTF ≥ 0.22 (at camera Nyquist frequency)

Camera NEDT ≤ 1.5 K @ 300 K (extended, uniform and high emissivity infrared source)

Resolution of analog to digital converter : 12 bit

Mass ≤ 4 kg

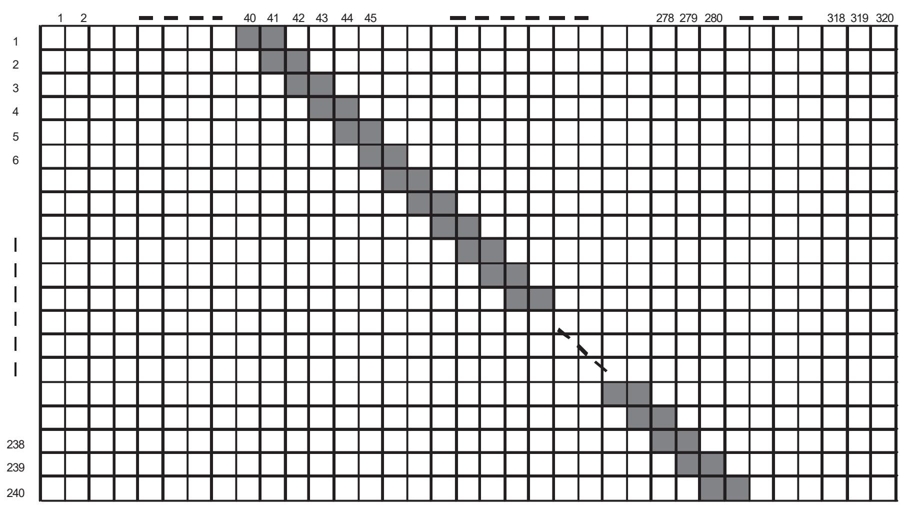

Figure 2 : 480 pixels define the across track field of view

The concern of minimising both the development and the recurrent costs of the camera is demonstrated

- by choosing an uncooled detector : this enables to simplify the thermal control of the camera and FUEGO payload, in comparison with a cooled detector.
- by choosing an on-the-shelf detector, which will be used in large quantities for many other applications

- by limiting the lens F-number to F/1.2 (instead of F/1) to reduce volume and mass of the camera head

4. GENERAL DESCRIPTION

To optimise the payload accommodation , the instrument is composed of 2 subassemblies, see figure 3 :

The camera head : composed of the lens, bandpass filter and detector, is mounted on the payload optical bench

The electronic box : composed of the detection and video electronic box (DAVEB) and the thermal control interface box (TCIB), is mounted on the payload structure.

A harness links the detector pins of the camera head to the corresponding connector of DAVEB. Consequently, the payload accommodation accounts that the DAVEB connector must be close to the detector pins.

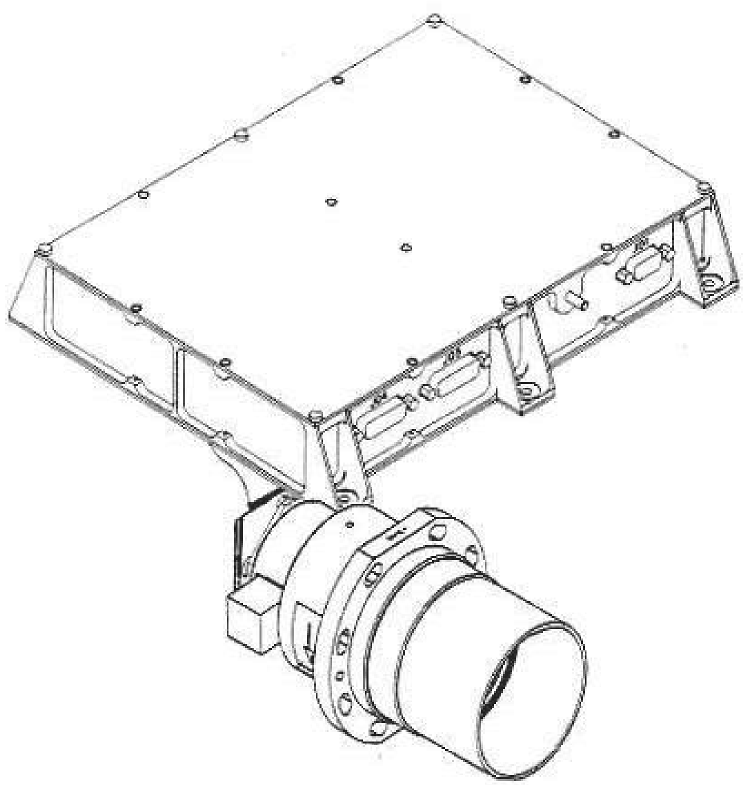

Figure 3 : TIR microbolometer camera

5. OPTICAL CONCEPT

The lens design has to cope with the following requirements :

- good optical quality : MTF $\geq$ Diffraction MTF - 0.22 for a spatial frequency of 15.7 pl/mm (0.19 x optical cut-off frequency)
- good transmission $\geq$ 0.70 (including the bandpass filter)
- minimisation of defocus sensitivity against temperature (global temperature change $\leq$ 5°C,

potential axial gradients)

- minimisation of the number of components to reduce cost and mass
- no mechanism dedicated to athermalism.

It can be shown that a Petzval design complies with the optical requirements (entrance pupil in the vicinity of the front lens to not oversize the optics, and chief exit ray perpendicular to the sensitive array to warrant a constant illumination over the full field of view) : in such a design, at least two air-spaced groups , both of positive power, are coming into play.

The refractive index drifts , the coefficients of expansion of the glass and mounting materials can be used to predict the shift of focal plane with temperature.

As for chromatism, one can define an equivalent Abbe number that depicts the lens power changes against temperature : materials with high Abbe number exhibit lower defocus.
Considering the thermal constringencies of some infrared materials (given in table 4 for λ = 9 µm), it is clear that germanium has a poor thermal behaviour.
It undergoes the most significant changes of refractive index.

Material	**Ge**	**ZnSe**	**ZnS**	**AMTIR1**	**AsGa**	**BaF2**	**KRS5**
	8200	28000	37000	28000	14000	- 18000	- 4400

Table 4 : Thermal constringencies of infrared optical materials (for λ = 9 µm)

In order to make the design less sensitive to thermal changes, an all-Ge solution should not be bested: unfortunately, other materials show higher wavelength dependencies, so that classical solutions would have needed more lenses.
In such designs, where negative and positive lenses of different materials are used to counterbalance chromatic changes, each optical power is increased : as a consequence, the aberration correction may become a troublesome issue.

Diffractive technology provides a means of cancelling the chromatism in infrared designs, without need for pairing different glasses : thanks to the anomalous dispersion of the diffractive profile, the refractive power is decreased when it is achromatised by being made into a hybrid lens.
The hybrid achromat will therefore require shallower surface curvatures than an equivalent conventional doublets.
Furthermore, the diffractive surfaces are quite temperature insensitive.

Finally, the optical concept is a 3-component lens, see figure 5 :
The front group is an hybrid ZnSe lens : such a material shows moderate changes with temperature whilst the diffractive profile is dedicated to achromatism. To decrease the amount of spherical aberration, the diffractive side is aspheric.
The second group is made of two germanium lenses.

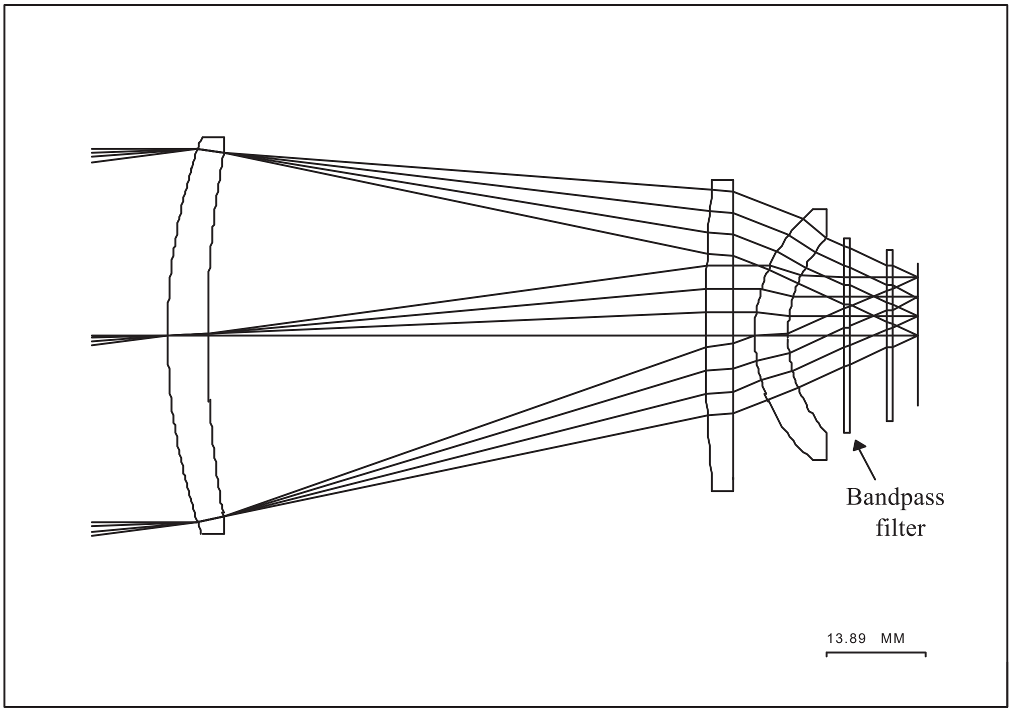

Figure 5 : Optical layout

The bandpass filter is placed close to the detector window to minimise the straylight caused by thermal emission.

6. THE MICROBOLOMETER 2D ARRAY

Because of the expected cost savings that can be reached in space applications with uncooled detectors in terms of compactness, low mass and cost as well as a simplified thermal control at instrument level, the product developed by SOFRADIR is implemented in the TIR camera.

6.1 Detector description

The strategy followed by CEA-LETI (LIR) and SOFRADIR avoids long and costly specific integrated circuit developments for bolometer integration with CMOS flow, and lends itself to high fill factors, because the entire pixels area is available for detector implementation.
The bolometer comprises a very thin microbridge thermometer (0.1 µm) of doped amorphous silicon with no extra supporting layer or membrane provided with an IR partially absorbing arrangement, supported by two legs anchored over the silicon substrate by metal studs (figures 6 & 7). The microbridge is built on a sacrificial polyimide layer, and is freed in a final step when the polyimide is ashed away to achieve a vacuum quarter wave cavity of 2.5 µm between the microbridge and the readout circuit in order to enhance 10 µm wavelength IR radiation absorption.

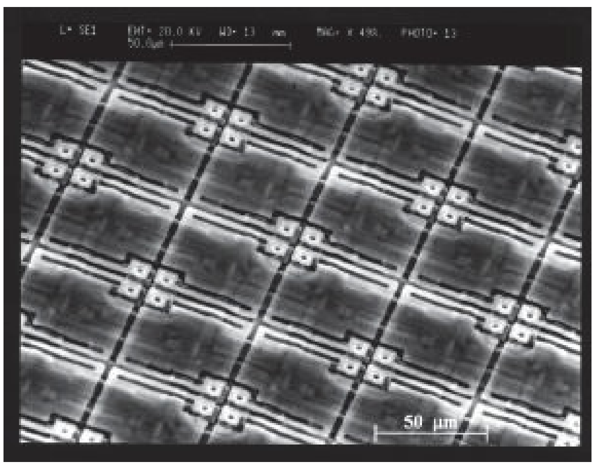

Figure 6 : SEM view of a microbolometer array

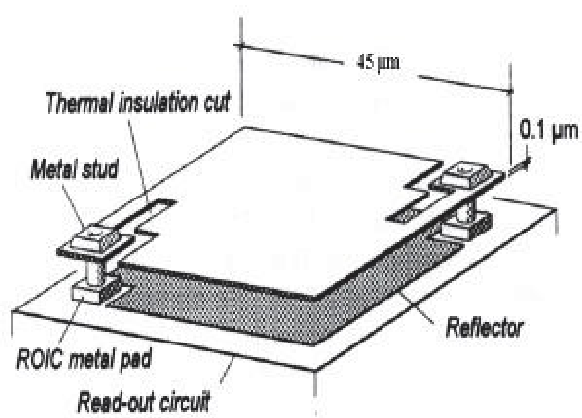

Figure 7 : Schematic structure of pixel

The thermal resistance (R_{th}) between the amorphous silicon (a-Si) thermometer and the isothermal readout circuit participates to a great extent in the final performance of the detector. So the design of the legs is of prime importance. Standard IRFPAs are designed with two 3 µm wide, 10 µm long legs leading to about $1.2x10^7$ K/W thermal resistance which is twice the conventional structure developed with VO_x technologies. Due to the very thin layer used for the microbridge, the thermal capacity (C_{th}) of the suspended parts amounts to 0.35 nJ/K, the thermal time constant $T_{th} = R_{th} \times C_{th}$ is then about 4.2 ms which is compatible with frame rates up to 100 Hz and therefore is compatible with 17.4 Hz frame rate required in FUEGO mission.
The IRFPA of the IDML07301 detector is a 320×240 focal plane array with a pitch of 45 µm with a fill factor higher than 80%. It is sensitive in the long wave spectral region (8 to 14 micrometer). The CMOS readout circuit associated to amorphous silicon thermometer is a standard 0.5 µm CMOS foundry. It enables a pulsed bias mode of operation of the detector which enhances the thermal response of the pixel and the IRFPA immunity to the focal plane temperature variations.

As well as every thermal detector, the use of vacuum and thermal stabilizer remains necessary in order to achieve a high performance by reducing thermal losses and the parasitic effects of the focal plane temperature variations.
The packaging is based on the miniaturization of the assembly linked to the small size of the thermoelectric stabilizer.

A good vacuum is ensured in the packaging thanks to the use of proven technologies adapted for uncooled detectors. This parameter is of high interest because it enables to reach productibility, cost effective products and low life cycle cost. One can highlight the advantages of the amorphous silicon material which can be processed at high temperature during manufacturing packaging steps for a better vacuum conditioning without performance degradation and a low cost process.

6.2 Test results

Electro-optical characterization of the IDML07301 detector were performed on the 320×240 IRFPA integrated in the packaging described above with F/1 optics, 60 Hz frame rate and 295 K background temperature. The results are presented in figures 8 and 9.

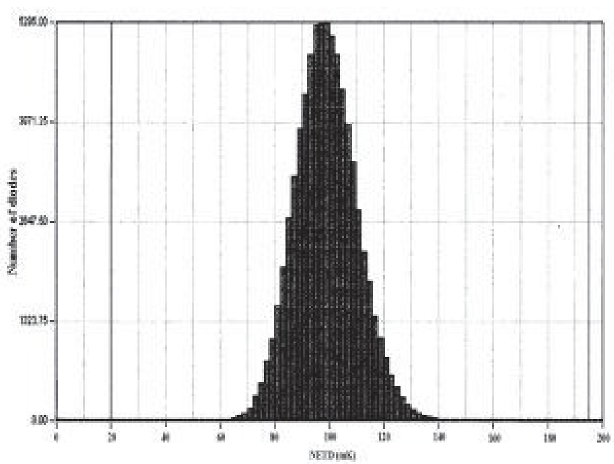

Figure 8 : 320×240 uncooled IRFPA NETD distribution (mK)

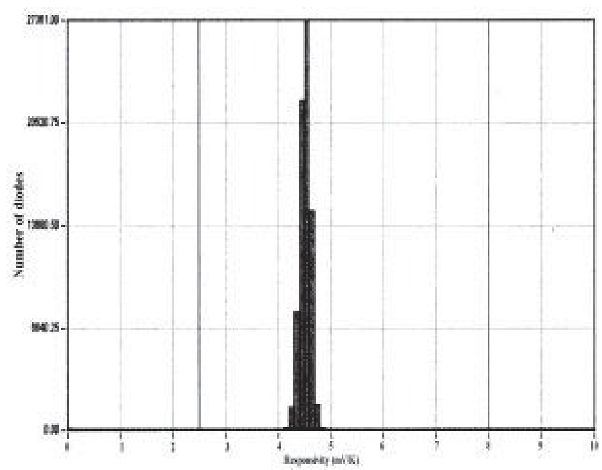

Figure 9 : 320×240 uncooled IRFPA responsivity distribution (mV / K)

The 320×240 uncooled IRFPA demonstrates a responsivity of about 4.5 mV/K with a non uniformity (standard deviation/mean) of 3%. The resulting NETD is about 100 mK. The operability of these IRFPAs is very good (over 99%) showing the high quality of the technology. It is also interesting to note the high performance obtained with a pitch of 45 µm which corresponds to 75 mK with a pitch of 50 µm.

Several technological improvements aiming at improving the NETD figures toward 70 mK with a pitch of 45 µm are actually implemented. In addition many tradeoffs can be done in order to adapt the thermal time constant of the detector to the mission requirements and therefore to improve the NETD figure.

7. THE DETECTION AND VIDEO ELECTRONICS

The detection and video electronics are conditioned in a dedicated box so called DAVEB. The main functions are the detector clocks and biases generation, the video signal processing and the video data transmission towards the payload processor, see figure 10.

The A/D chain has been designed around a standard architecture. It includes a high bandwidth input stage and an analog-to-digital converter (ADC). The main design constraint is to warrant a suitable signal-to-noise ratio covering the detector dynamic in FUEGO radiometric range. This is achieved by choosing a 12-bits ADC whereas the theoretical coding dynamic is required to be 7.8 bits, and a line-to-line offset compensation. The dynamic loss caused by the fixed pattern noise (offset and gain dispersion along the image zone) is then compensated.

The DAVEB is clocked by an internal oscillator that governs the detector and the real time signal processing, including the image data format . An external command signal synchronizes the image capture w.r.t. to the satellite attitude and location. The image period can be modified by means of fictive pixels insertion when the spacecraft is tilted out of nadir.

The DAVEB performs also auxiliary functions like telemetry / telecommand management and auxiliary data insertion.

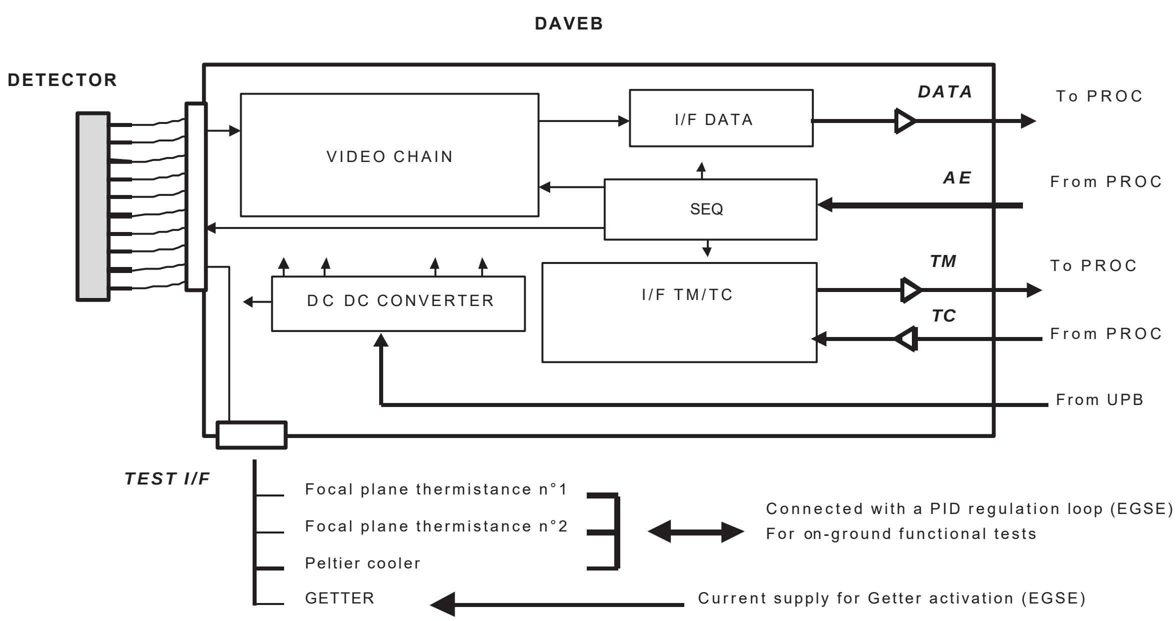

Figure 10 : Detection and video functional breakdown

8. THERMAL CONTROL CONCEPT

The main objectives of the instrument thermal control are :

- to ensure a temperature level of 30°C on the focal plane of the detector and 20°C on the lens during image acquisition mode
- to guaranty a good temperature stability of the focal plane (20 mK on 17s, 0.5K on 15min and 1K on 5-year orbit life) and of the lens (50 mK on 17s, 1K on 15min and 2K on 5-year orbit life) during image acquisition mode

- to keep the camera and the electronics in their qualification temperature ranges during all the phases of the mission

while minimising the heating power demand.

The main principles which have driven the design of the camera thermal control are :

- to insulate the camera head from the external environment and to reduce the conductive coupling between the entrance baffle and the lens structure so as to limit temperature variations
- to optimise the conductive coupling between the lens structure and the optical bench which temperature is lower than 15°C so as to ensure the temperature level of the lens.
- to control the lens temperature stability with an active PI regulation line
- to control the detector temperature and stability thanks to a Peltier thermoelement which thermal sink is the lens structure stabilized at 20°C.
- to evacuate the electronics dissipation by means of a radiator and provide heating during cold phases.

The lens structure is insulated from the external environment thanks to a classical MLI (Multi Layer Insulation). The entrance baffle is conductively uncoupled from the objective by thermal insulating washers.
The lens structure is fastened to the optical bench by 8 screws. The contact area is adjusted to obtain the required conductive coupling.
The PI regulation line of the lens consists of heaters located on the lens structure and 3 temperature sensors.
The detector assembly is tightly fastened to the lens structure by 4 screws so as to ensure a good conductive coupling.
The Peltier thermoelement of the detector works as a heater (since the focal plane temperature is higher than the lens temperature) and is driven by a PI regulation that will use a high precision temperature sensor located near the focal plane to provide the adjusted power.
For both regulation lines (detector and objective), the temperature reading, algorithm processing and power distribution are insured by the payload processor.
The focal plane short term stability requirements on 17s is met thanks to the camera head thermal inertia.
The focal plane temperature stability of 0.5K is obtained because :

- the only internal heat source is the detector itself with a constant and small dissipation.
- the camera head is insulated from external environment
- potential residual perturbations coming from the optical bench are filtered with a PI regulation located on the lens structure.

9. PERFORMANCE OVERVIEW

The major performances of the TIR camera are given in table 11:

Spatial sampling interval	369 m at nadir
Swath width / field of view	177 km @ 700 km altitude:/ ± 7.2 °
Spectral bandwidth	8.0 – 12.0 µm
MTF	≥ 0.22 @ camera Nyquist frequency
Radiance dynamic range	2.4 - 30.6 W/m².sr.µm (ratio 13)

NEDT	< 1.5 K
Mass	< 4 kg
Power consumption	6 W max (without thermal control regulation lines)
Data transmission rate	100 Kbits / s

Table 11 : Performances of the TIR camera

10. ACKNOWLEDGMENTS

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