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## *MUST: an infrared instrument based on mlcrobolometer array*

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# MUST: AN INFRARED INSTRUMENT BASED ON MICROBOLOMETER ARRAY

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**RÉSUMÉ** - Un senseur infrarouge de résolution moyenne dédié à des applications en agriculture, hydrologie, prévention des feux de forêts nommé MUST (MediUm scale Surface Temperature) a été étudié dans le cadre d'un contrat de la Commission Européenne. Un concept type "push broom" utilisant une barrette de microbolomètres non refroidis a été préféré à un concept plus traditionnel à balayage utilisant des détecteurs photoconducteurs refroidis à des températures cryogéniques, tant par ses performances que par l'absence de refroidissement et de vibrations. L'instrument offre une résolution de 250 m pour une fauchée de 1400 km. Il présente une résolution radiométrique (NEDT) inférieure à 0.5 K dans 2 bandes spectrales autour de 11 et 12 µm permettant une correction atmosphérique optimale et une restitution de la temperature des sols avec une précision de 1,5 K parfaitement compatible des applications envisagées.

***ABSTRACT** - A medium scale infrared sensor dedicated to applications in agriculture, irrigation, hydrology, forest fires and environment called MUST (MediUm scale Surface Temperature) has been studied within the frame of a European Commission (DG XII) contract. An innovative push broom concept using linear arrays of uncooled microbolometers has been preferred to a traditional scanner concept using cryogenically cooled photoconductor detectors, for its performances and because it does not require any cooling, and is free of micro-vibrations. The instrument offers a resolution of 250 m for a swath width of about 1400 km. It provides a radiometric resolution (NEDT) better than 0.5 K in two spectral channels around 11 and 12 µm wavelength optimised to correct the atmospheric effects by the split window method. This allows a final accuracy on land surface temperature of about 1.5 K after emissivity and atmosphere corrections which is fully adequate for the foreseen applications.*

## 1. INTRODUCTION

The MUST instrument definition is performed within the MUST study carried out from November 96 to November 97 in the frame of the European Commission (DG XII) Environment and Climate fourth 'Research and Development Framework Programme'. The objective of the study is the definition and demonstration of interest of a large swath, medium resolution, thermal infrared mission called MediUm scale Surface Temperature (MUST) The MUST study is coordinated by MMS (Matra Marconi Space) and the partners are CEMAGREF (F), the University of Valencia (Spain), the CNRS/CETP (F), INFOCARTO (Spain) and NRSC (UK) as partners. This paper is devoted to the definition of the instrument which has been studied by MMS with the support of National Optics Institute (NOI) in Canada for the microbolometer focal plane. In the study, the MUST instrument is considered as passenger on board the CNES French Agency SPOT 5 satellite because of its complementarity with the VEGETATION Monitoring Instrument (VMI) although the MUST sensor could also be proposed in the frame of the Earth Watch Programme of the European Space Agency.

## 2. THE MUST MISSION [1]

The applications of MUST are basically derived from the correlation between the soil or vegetation hydric state and the surface temperature. The applications can be sorted out in tree main classes related to the parameter which is assessed:

- the vegetation hydric state for agriculture, irrigation management and forest fire risk assessment,
- the surface evapotranspiration for irrigation management and hydrology,
- the surface temperature for frost mappings and heat islands on urban surfaces.

In addition, the thermal infrared data of MUST could be a complement of the visible and near infrared data of VMI for the global monitoring of the biosphere and for the improvement of the Global Circulation Models with the knowledge of the water fluxes.

## 3. INSTRUMENT PERFORMANCE REQUIREMENT

The main characteristics of the instrument have been derived from the mission analyses and from the instrument constraints in an iterative process and are presented in table 3/1. The minimum 1200 km swath width ensures a 1 to 3 day revisit at latitude around 40°. The spectral channels are selected to allow an efficient atmospheric correction, simulations have shown a certain flexibility in the spectral band definition.

| | |
|---|---|
| ground sampling | 250 m at nadir |
| swath width | > 1200 km |
| spectral channels | 10.3-11.3 µm ; 11.3-12.3 µm |
| spatial resolution | MTF at Nyquist frequency ≥ 20% |
| scene temperature range | 250 K - 350 K |
| temperature resolution | NEDT < 0.5 K scene at 300 K |
| temperature accuracy | ≈ 1 K |
| inter band registration knowledge | 0.3 pixel |

Table 3/1: MUST instrument requirements

## 4. SCANNER OR PUSH BROOM ?

The first question which arises for a low earth orbit instrument is which kind of instrument: a scanner or a push broom ? Both concepts use the satellite velocity to generate one dimension of the image (say the columns), but differ by the formation of the second dimension of the image. The scanner uses a unique photodetector and the image lines are generated by a mechanical scanning. The scanning can be performed either inside or outside the instrument (scanning mirror). The push broom uses a linear array of photodetectors and the image lines are generated by an electrical scanning. From an optical standpoint, the scanner with an external scanning does not require any field, on the contrary of the puhbroom. In broad terms, the scanner is preferable for optics and focal plane with a penalty for the scanning mechanism. Instruments with large sampling, in the range of 1 km, are usually scanners, as AVHRR while instruments with small sampling, say less than 100 m are pushbrooms. The MUST resolution of 250 m, considered as medium resolution, is at the limit and both concepts can be contemplated and were investigated.

### The scanner concept

The focal plane of the scanner consists, basically, of a monoelement detector. The line period (period corresponding to an along track motion of the sub satellite point of one sampling period) is 38 ms for a 250 m resolution and a 820 km orbit. The pixel period (period corresponding to an across track scan motion of one sampling period) is 1.8 µs. This very short acquisition period prevents the use of thermal detector and requires photon detectors which have a very quick response. The use of a HgCdTe photoconductor cooled at 100 K has been preferred to that of a photovoltaic detector which would require a lower operating temperature because of its important dark current. In order to limit the scan speed to 360 rpm, 4 lines are scanned in parallel. An improvement of radiometric performances can be further obtained by setting 4 photoconductive elements in series and using a post integration. The 2 options of focal plane are depicted in figure 4/1.

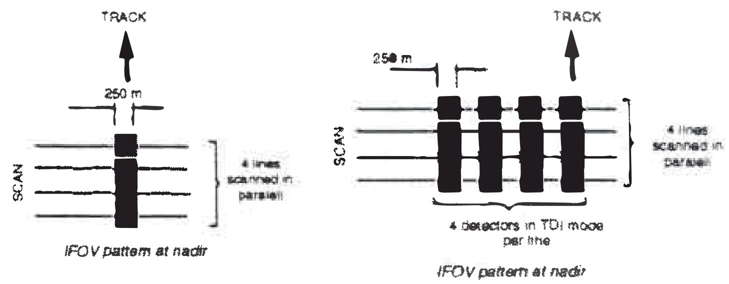



Figure 4/1 : The scanner focal plane in both options

The figures 4/2 provides a general view of the scanner. The radiometric performance of the scanner is characterised by a NEDT of ≈ 0,3 K in both bands without post integration. A gain of a factor 2 is expected with 4 monoelements in series applying post integration (addition of the 4 stage digital data). The scanner provides the suitable performance but requires a cooling down to 100 K. Depending on the platform, this cooling can be performed passively or by use of mechanical coolers. With the assumption of SPOT 5 passenger, the position of MUST in front of the HRV cameras prevents a passive cooling. The use of mechanical coolers can be a penalty for the high resolution visible cameras because of the microvibrations.

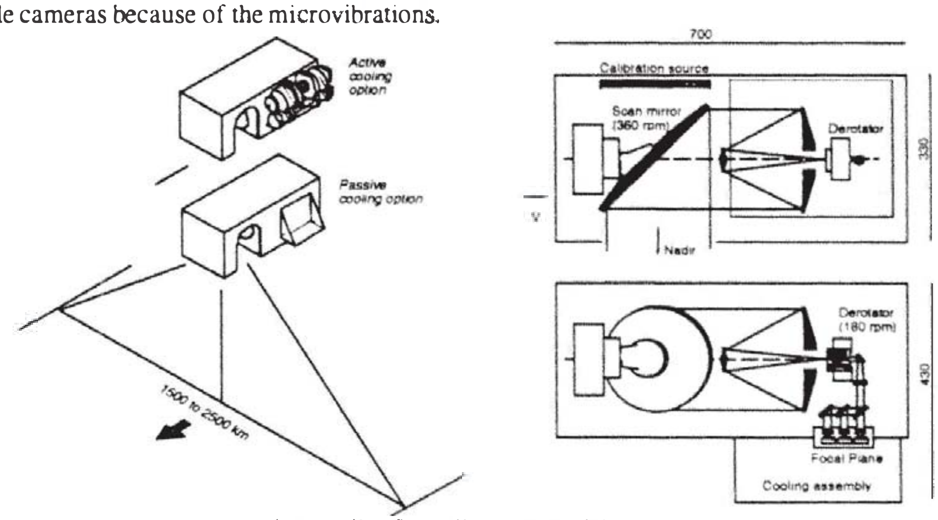



Figure 4/2 : Overall concept of the scanner

**The pushbroom concept**

The pushbroom concept is based on the use of a linear array of detectors which provides an electrical scan of the lines. The columns (along track) are still generated by the satellite motion. The required long linear arrays of detectors (several thousands pixels) are not compatible with photoconductor detectors and marginally compatible with photovoltaic techniques. But, because the integration period is very low (38 ms), thermal detectors, whose time responses are relatively slow, can be used. Microbolometers are selected because they are available in long arrays and they do not require neither chopping nor cooling. The microbolometers and the thermal detectors in general are less sensitive than photon detectors but the large measurement period offered by the pushbroom compensates the lack of sensitivity. A push broom with microbolometers provides good radiometric performances. Preliminary investigations on push broom instruments allows a first order design to be compared with the scanner. Use of microbolometers requires high speed optical system (at least f/1). This is hardly compatible with a very large field (a minimum swath width of 1200 km requires an optics field of more than 70°). Dioptric systems can provide f/1 optics on relatively large field (about 25°) but not on 70°. The overall field is then covered by 3 modules each with 1500 pixels of 250 m providing a 400 km field (at nadir). The channel separation is performed in field because the large angle of the beam prevents the use of dichroics.

### Trade off scanner/push broom

The figure 4/3 provides a synthesis of the main features and performances of both options. The radiometric performances of the scanner are slightly better than those of the push broom but both are suitable to the MUST mission. The push broom option has been preferred to the scanner and selected, despite its slight penalty on performance, because it does not generate any microvibration with no cooling and no permanent rotating mechanism. The instrument is fully compatible with SPOT 5 passenger constraints and its cost is expected to be significantly lower than a scanner. In addition, the microbolometer technology is in progress with several manufacturers and an improvement of microbolometer NEDT performance can be expected on a short time basis.

| | scanner | push broom |
|---|---|---|
| modules | 1 | 3 |
| optics | Cassegrain telescope + relay dioptric | wide field dioptric system |
| focal plane | 1 or 4 PC detectors per channel | 1 line of 1536 µbolometers per channel |
| cooling | yes : 100 K | no |
| channel separation | by dichroics | in field |
| calibration | 2 blackbodies or 1+ cold sky at each scan | 2 blackbodies : 1 or few per orbits |
| mechanism | scanning mirror at 6 Hz | rotating mechanism for calibration |
| SPOT 5 compatibility | questionable because microvibrations | yes |
| on ground resolution | 250 m at nadir | 250 m at nadir |
| swath width | 2500 km ; ± 53° | 1400 km ; ± 39° |
| NEDT | ≈ 0,3/0,15 K (post integration) | ≈ 0,25 to 0.45 K |
| absolute temperature | ≈ 1K | ≈ 1 to 1.5 K |
| mass | 100 kg | 60 kg |
| power | 130 W | 100 W |

Figure 4/3: Comparaison of scanner and push broom mean features and performances

## 5. PUSH BROOM OVERALL CONCEPT

The pushbroom concept is made of 3 optical modules of 26° field (400 km swath). The lines of sight of the modules are biased by ±26° in order to provide a total field of 78° and a swath width of about 1400 km. The 3 modules are fixed on an angle bracket which provides the interface with the SPOT5 platform. A calibration system made of 2 blackbodies at about 250 K and 350 K is fixed on the same bracket in front of the modules. A calibration mechanism allows the 3 modules to be fed successively by the blackbody. In rest position, the cold blackbody faces the cold sky. Heaters on both blackbodies are used to adjust the temperature. Electronics boxes are fixed on the opposite side of the bracket.

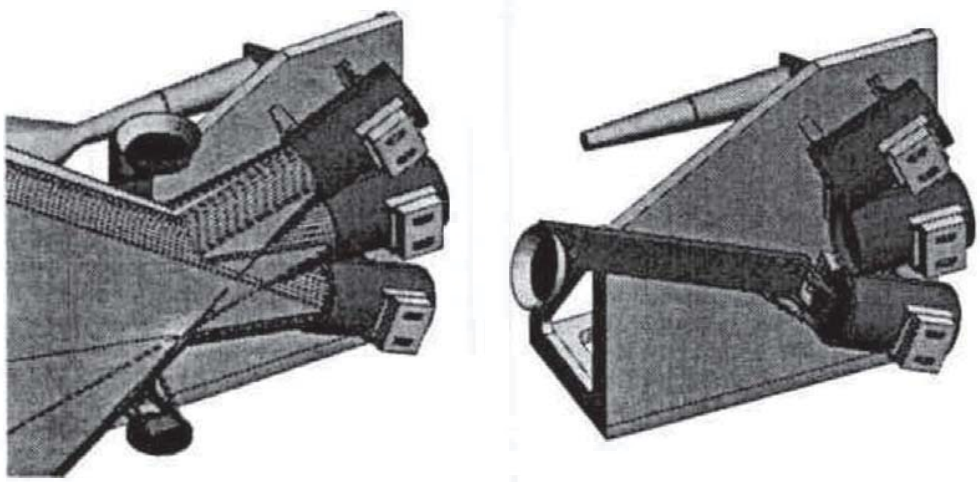


Figure 5/1: Overall concept of MUST instrument in observation and calibration modes

Each module consists of a 4 lens dioptric system with a bolometer package at its focus. A ZnSe entrance window limits the flux entering the telescope and ensures a quiet environment to the optics. The detector package consists of 2 linear arrays of microbolometers each made of 3 sub arrays of 512 elements in a staggered configuration. The detector package includes an entrance window and 2 filters and is connected to an external radiator by Peltier elements used for temperature regulation. A cylindrical housing covered of multilayer insulation performs a radiative decoupling. The front end electronics of the microbolometers is fixed on the housing. The near isostatic mountings provide a conductive decoupling from the bracket.

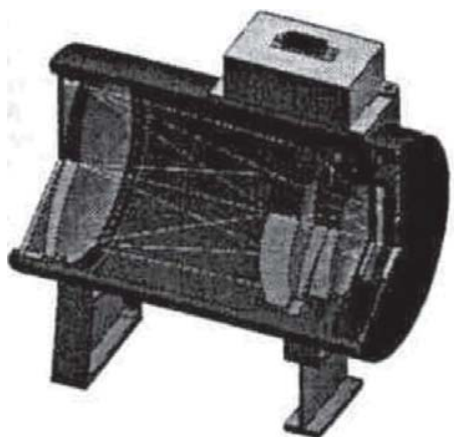


Figure 5/2: Optical module concept

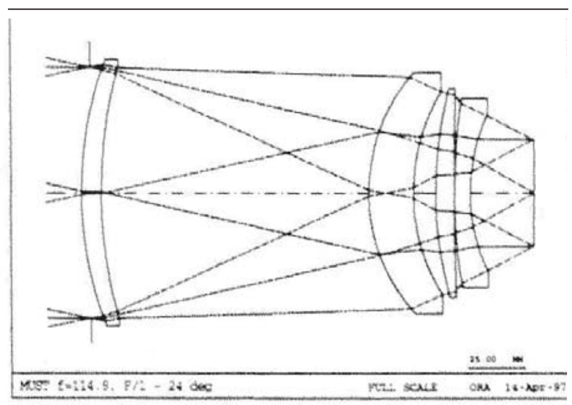


Figure 6/1: MUST module optical concept

## 6. THE OPTICAL CONCEPT

The optical concept is a 11.5 cm pupil diameter pure dioptric system. It consists of 4 lenses in Ge (Germanium) and ZnSe (Zinc Selenide). Zinc Selenide has been selected for its excellent transmission above 12 µm. Germanium presents a maximum of absorption at about 11.8 µm and its thickness has been limited to 17.5 mm not to penalise the optics transmission. The total transmission of the optics including the entrance window, the detector window and the detector filter is 60% in the lower band and 51% in the higher band. The optics provide a high speed (f/1) and a large field (about 26°) with good image quality. The optical concept is provided in figure 6/1. The MTF at Nyquist frequency (period of 500 m) is given in table 6/2.

| Spectral channel | 10.3-11.3 µm | 11.3-12.3 µm |
|---|---|---|
| MTF diffraction limit | 0.8 | 0.8 |
| MTF at Nyquist along track | 0.64 | 0.67 |
| MTF at Nyquist across track | 0.70 | 0.65 |

Table 6/2: MTF of MUST optics

The Germanium index is very sensitive to temperature changes. Lenses in Ge must be kept within a couple of tenths of K to avoid defocus. The first lens which is in Ge is submitted to environment change and can fluctuate in temperature. To minimise its temperature fluctuations, a ZnSe window is added at the entrance of the telescope which transmits only in the 8 to 14 µm band. The off band radiations are rejected by reflection by a dedicated coating.

## 7. THE MICROBOLOMETER FOCAL PLANE ARRAY

### The choice of microbolometer technology for the MUST instrument

Infrared thermal detectors are basically different from the photon detectors. By contrast with photon detectors in which photons are converted in electron-hole pairs, the thermal detectors respond to incoming infrared radiation by changing their temperature. Thermal detectors, although less sensitive than photon detectors at low temperature, overcome the latter at room temperature. The uncooled thermal focal planes are well suitable to high flux applications with moderate requirements on radiometric performance , with fast optics and large spectral bands.

Thermal detection is a technology which has been around for several decades. but which has remained until recently limited to monodetectors (or to few discrete detectors) with a sensitivity at room temperature approximately 100 times lower than cooled quantum detectors, and a severe limitation in response time. The amazing evolution of microelectronics, micromachining and thin films technologies has allowed recently 2-D arrays of thermal detectors to be built, at low cost, with better sensitivity and response speed for use in staring cameras[2] dedicated to commercial and military applications, as the 320x240 pixels thermal vision cameras. The performance of uncooled thermal detector is driven by the efficiency of the thermal isolation of the pixels with respect to their surroundings. Most recently developped thermal detector arrays are based on the micromachined microbridges which allows a drastic improvement of the detector thermal insulation. NEDT lower than 100mK in the 8-12 µm range have been reported by several detectors suppliers [3,4,5].

Three main types of thermal detector are available. according to the physical parameter which senses the temperature change: the thermopile (electromotive voltage generated by Seebeck effect at junction as in thermocouples), the pyroelectric (polarisation change by variation of the dielectric constant) and the bolometer (carrier density and mobility change which results in a resistance change). A trade-off analysis of these different technologies has been carried out, in the frame of the MUST program, on the basis of criteria such as the electro-optics performances, the need for a chopper. the need for a thermal regulation. the expected behaviour in space environment, the perennially, the expected evolution of the technology, the number of potential suppliers of such focal planes and the commonality with other space applications. Definitely, the microbolometer is today considered as the best candidate for the MUST instrument.

These detectors, either resistors or capacitors, are read out sequentially. The readout of the signal of each pixel of the detector array is performed by an electronically addressable array of readout cells connected to each individual detector. The detector signals are then multiplexed out of the focal plane for signal processing and data handling.

### The MUST focal plane architecture

The pixel size of 35 µm results from a compromise between the need to have a small pixel for the optics and the noise performances and technological constraint. Microbolometers structures are micromachined at the top of the dedicated CMOS Si read-out circuit. To be compatible with standard CMOS foundry (distance of 20 mm for photorepeaters), 3 elementary butted modules of 512 pixels (18 mm) are considered for the MUST focal plane. The two spectral channels separation needed for the temperature retrieval is performed by an in-field separation with the 2 linear arrays on a common substrate, each with a dedicated bandpass filters in front of it (figure 7/1).

The performances of microbolometers are closely related to the quality of the thermal insulation of their detectors and heat exchanges by convection have to be minimised. The internal volume of the detector package, sealed by a ZnSe window, needs to be evacuated for on-ground operation then opened just before the launch. As thermal detectors behave as temperature sensors, their absolute response is therefore sensitive to thermal variation of their environment. As usually done, the MUST focal plane will use thermo-electrical heat pumps to regulate its temperature[6]. In addition, masked structures (blind pixels) will be used to compensate the residual temperature variations.

A large electrical capacitance is associated to each pixel in order to perform a filtering of the noise. Further filtering is performed by taking advantage of the large available acquisition time (38 ms) to perform an oversampling of 90. One video output per 512 pixel submodule (six per optical head) allows the output frequency not to exceed 1.2 MHz. The alternative way of digital TDI (Time Delay Integration) operation with several lines of pixels for improving the noise performance has been investigated and ruled out because not compatible with the large capacitance.

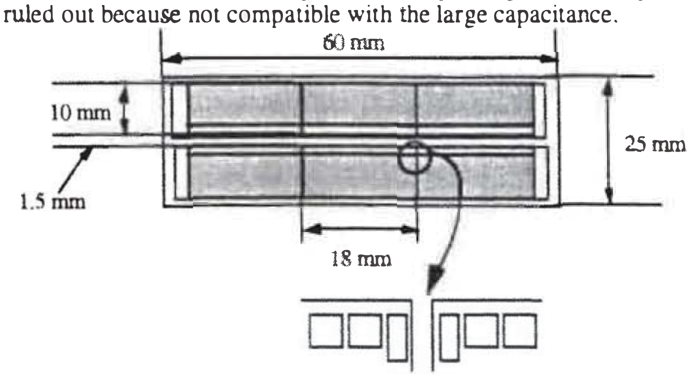



Figure 7/1: Focal plane architecture

**Expected performances for the focal plane**

Apart from the spatial noises assumed to be greatly reduced by to the in-flight calibration strategy, the two main parameters of MUST focal plane which need to be optimised are the NEDT and the MTF. The microbolometer MTF is, in addition to the window effect, only related to the time constant. A maximum time constant of 12 ms is allowed not to penalise the instrument MTF. In the present design, the time constant is about 6 ms. Note that, thanks to the excellent thermal insulation, microbolometer do not suffer from cross-talk.

The NEDT for a thermal imaging system is given by the formula[7]: $NEDT = \frac{4F^2.V_n}{A_d.\tau_o.R(T,f).(dP/dT)}$

where F is the optics f-number, $V_n$ the integrated temporal noise affecting the measurement (V rms), $A_d$ the useful detector area ($m^2$), $\tau_o$ the optical transmission, R(T,f) the responsivity at temperature T and operating frequency f ($V.W^{-1}$), dP/dT the temperature contrast (in $W.m^{-2}.K^{-1}$). At focal plane level, the parameters which can be optimised are the useful detector area through the pixel fill factor (more than 90 % can be reached in linear arrays), the responsivity and the temporal noise.

**Optimisation of the responsivity**

The responsivity R(T,f) at frequency f and temperature T is given, assuming a constant absorption in the spectral range, by[8]: $R(T,f) = \frac{R_b.I_b.\alpha.\eta}{G\sqrt{1+(2\pi f\tau)^2}}$ where $I_b$ is the bias current injected in the bolometer (A), α the temperature coefficient of resistance (TCR, in $\%.K^{-1}$), $R_b$ the electrical resistance of the bolometer (Ω), η the absorptivity of the bolometer, G the thermal conductance between the bolometer and its environment ($W.K^{-1}$) and τ the thermal time constant of the bolometer (s).

The responsivity depends from many parameters, which are not independent, and some of them impact on the noise too. In addition, the parameters are related to the technologies, mainly the material used for the temperature probe, which are different in the world (vanadium oxide in North America[9,10], amorphous silicon[11] in France and titanium film[12] and polysilicon[13] in Japan). Only vanadium oxide is considered here, as the most addressed in the literature and used by the National Optics Institute (Quebec, Canada), which were consulted on the MUST focal plane optimisation.

The choice of injected bias current Ib and of the bolometer resistance Rb results from compromises. High bias current or resistance improve the responsivity but increase the bolometer temperature. Note that, with constant current source, an equilibrium is reached if the TCR is negative. In addition, an increase of the resistance increases the Johnson noise and an increase of $I_b$ increases other sources of noise. For vanadium oxide, resistances of 15 to 50 kΩ are typical at operating temperature, with a continuous current bias of 10 to 20 μA[6]. Pulsed bias with very short high current improves the responsibility without temperature increase but has been ruled out because not compatible with the oversampling selected approach.

The temperature coefficient of resistance (TCR) $\alpha$ is the relative variation of the resistance of the bolometer with temperature. Typical values of TCR are few tenths of $\%.K^{-1}$ for metals and few $\%.K^{-1}$ for semiconductors. For vanadium oxide, a standard figure[6] is -3/-4 $\%.K^{-1}$. The absorptivity $\eta$ of microbolometers is optimised by a suitable matching of the resistivity of its upper layer with the vacuum impedance and by designing the microbridge structure as an optical cavity[10]. With such techniques and for MUST spectral range, an absorption in the 60 to 80 % range can be expected.

The improvement of the responsivity requests also the minimisation of the thermal conductivity. An ideal thermal detector would be only limited by its radiative exchanges with its surrounding. Thanks to the use of microbridge structures, the conductive exchanges have been strongly reduced when compared to performances of previous discrete bolometers. Typical figures achieved today for the thermal conductivity are in the 1 to $5.10^{-7}$ $W.K^{-1}$ range. The thermal time constant depends both of the thermal conductivity and of the thermal capacity of the microbolometer. A reduction of capacity in proportion of conductivity is needed not to penalise the thermal time constant and thus the MTF.

For continuous bias mode as selected, the responsivity for a bolometer in the 10 000 to 30 000 $V.W^{-1}$ range but responsivity close to 50 000 $V.W^{-1}$ could be reached in the near future without any degradation of the noise source. For pulsed bias current, 500 000 $V.W^{-1}$ has been reported.

**Noise budget for the microbolometer focal plane**

Data about the noise sources and their corresponding electrical bandwidths is unfrequently provided or poorly presented in the literature. Usually, only detectivity figures are provided without sufficient information to allow retrieval of the system performances in operating conditions different from the standard applications, i.e. thermal vision at video frame rate. As for photons detectors, the temporal noise appears at three different stages in the detection chains.

The first stage is related to the conversion between the radiative power and the heating of the bolometer. A perfect thermal detector is only limited by the fluctuation of its radiative exchanges. This limit called background fluctuation noise provides the ultimate limit of detection for a thermal detector, as the photon noise is the limit for the photon detectors. For detectors and environment at ambient temperature, this limit corresponds to a detectivity D* of $1.8.10^{10}$ Jones and thus a NEP of $1.9.10^{-13}$ $W.Hz^{-1/2}$ for 35 $\mu$m square pixel. This ultimate limit is not achieved today because the conductive thermal exchanges dominate the radiative exchanges. The so called temperature fluctuation noise corresponds to the fluctuation of the power conducted by the microbridges. Typical NEP for vanadium oxide microbolometers is about $10^{-12}$ $W.Hz^{-1/2}$. The temperature fluctuation noise is filtered by the time constant of the bolometer and is estimated to 0.29 $\mu$V in MUST application.

The second stage to be considered is the electrical part of the bolometer. Two main electrical sources of noise affect the detector. The first is the Johnson noise, typically in the 10 to 30 $nV.Hz^{-1/2}$ range for vanadium oxide bolometer. The second is the Low Frequency Noise, whose main contributor is the 1/f noise. Its depends largely of the choice of the material used for the thermometer and of the maturity of the technology for this material.

One of the major challenge for reducing the electrical noise of the detectors is to include filtering stages. The state-of-the-art read-out circuits for 2-D arrays use a semi-parallel architecture, in which read out is performed line by line, with read-out circuit located at the end of each column. During this line period, the bias current is injected in all the bolometers from this line and the corresponding useful signals are integrated in capacitances (one per column), acting as a low-pass filter. The situation is different for the MUST instrument with a linear array to be read-out each 38 ms. In principle, low-pass filtering at 15 Hz is possible. The main problem for filtering is its on-chip implementation. The available surface beside the array allows the implementation of a large capacitance providing a on-chip low-pass filtering down to about 10 kHz. With current technology, 15 mm is needed for the capacitance but improvements are expected to get it down below 10 mm. Further equivalent bandwidth reduction down to 200 Hz will be achieved by a temporal oversampling of 90. With the filtering the Johnson noise is reduced to 0.36 $\mu$V. Estimation of 1/f noise is 0.14 $\mu$V from NOI experimental data.

The last stage is related to the read-out of the electrical information, and is mainly driven by the pre-amplifier noise density, about few $nV.Hz^{-1/2}$. Estimated integrated noise is 0.36 µV for MUST.

| | |
|---|---|
| temperature noise | 0.29 µV |
| Johnson noise | 0.36 µV |
| 1/f noise | 0.14 µV |
| pre-amplifier noise | 0.33 µV |
| total | 0.58 µV |

Table 7/2: MUST sensor noise budget

### Expected NEDT performances

With a f/1 optics with 51% transmissions in the 11.3-12.3 µm band and 60% in 10.3-11.3 µm band, temperature contrasts of 0.394 $W.m^{-2}.K^{-1}$ (11.3-12.3 µm band) and 0.455 $W.m^{-2}.K^{-1}$ (10.3-11.3 µm band), the MUST NEDT on a 300 K scene can be estimated to **0.43 K** for the 11.3-12.3 µm channel and to **0.24 K** for the 10.3-11.3 µm channel using the above NEDT relation with a 35 µm pitch pixel with a 90 % fill factor , a responsivity of 32 600 $V.W^{-1}$ and a total detection noise of 0.58 µV.

Thanks to on going improvements of microbolometers, better NEDT is expected for the near-future.

## 8. THE ELECTRONICS

The MUST electronics, sketched in figure 8/1, includes basically the detection electronics and the data handling and communications. Each of the three optical heads are connected to a dedicated detection electronic chain that converts the analogue signal of the microbolometers into a digital bit stream. This conversion itself includes a set of steps that are described after. These electronic chains are not redundant. This has the main advantage to highly simplify the hardware and therefore to reduce its cost. The drawback is that, in case of a failure of one of the three chains, a third of the instrument swath is lost. Regarding the high reliability achievable for space electronic hardware, this risk is considered acceptable. Next to the conversion in a digital bit stream, the data handling and communication electronics multiplex the data from the three channels in a single data flow, format and encrypt this single stream before space to ground transmission. The electronics boxes are fixed on the backside of the MUST supporting bracket (figure 8/2).

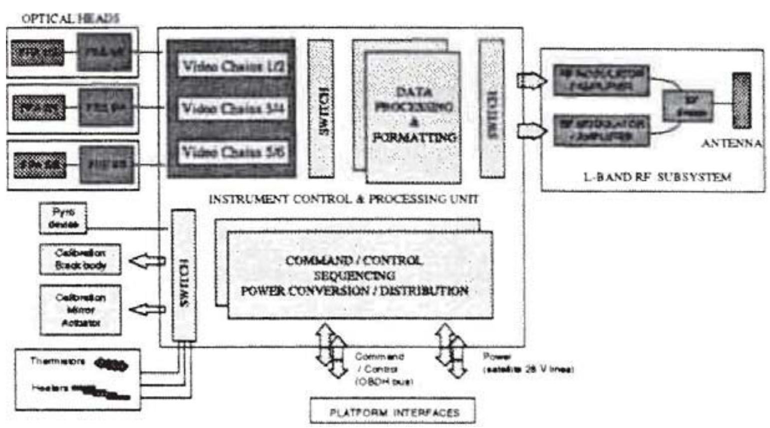



Figure 8/1: The MUST electronics box diagram

### The detection electronics

Analogue electronics associated to the focal planes features the standard functions incorporated in a detection electronics. A sequencer board will supply the read-out circuits with the timing diagram necessary for focal plane operations. Only few clocks are necessary thanks to the use of a dedicated CMOS read-out circuit. Power supplies will be provided to the focal plane by a DC/DC board. As the baseline uses one video output per submodule, 18 front end electronics plus video chains will be necessary for the read-out of the pixel data. Each video chain is a 12 bits and 200 kHz for bandpass, which is not critical. The main feature of the video chain is its pixel to pixel analogue pre-compensation of the offset, mainly due to the array pixel to pixel resistance non uniformity, combined with the large difference of amplitudes between the pedestal and the useful signal. This compensation is therefore necessary in view of matching for each pixel the useful analogue signal range with the input range of the analogue to digital converter. As the dispersion between resistors requests a calibration, the design of the video chain will also feature an iterative process for precise determination of the calibration parameters, by varying the gain of the video chain.

**The data handling and communications electronics**

Formatting includes the addition of the ancillary data needed for the payload data on ground processing (orbit ephemeris, satellite attitude, sensor calibration coefficients). Encryption is required by the commercial character of the mission. Accordingly a simple commercial encryption scheme, similar to the one planned for the future METOP meteorological satellites is envisaged. This part of the chain, common to the three optical heads, includes a redundant channel. This redundance implies switching capacities at input and output in order to drive the data towards the operating channel. The encrypted data are finally fed at 3 Mbps into the L band communications subassembly (modulation onto a L band carrier, amplification, transmission by an L band antenna). The overall chain is operating continuously, as the MUST sensor is, so that any local user present in the satellite circle of visibility can receive the MUST information in real time.

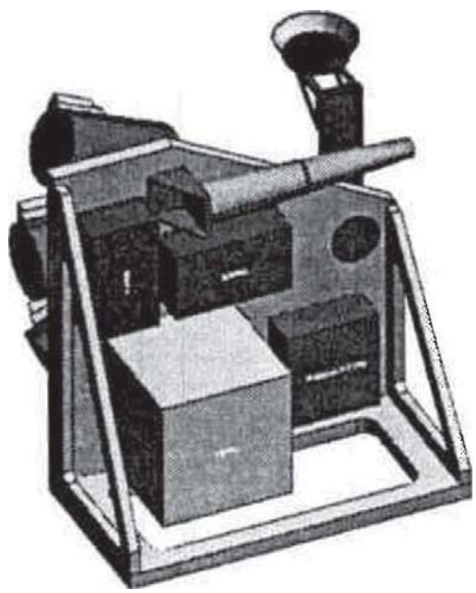


Figure 8/2: Implementation of electronics boxes

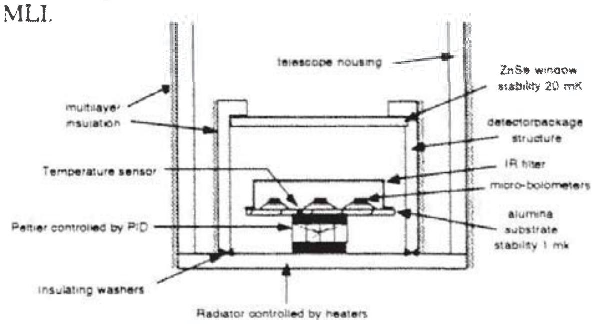
## 9. THE THERMAL CONTROL

The main objectives of the thermal control are to ensure a detector package temperature less than 20°C, to guaranty a good temperature stability of the telescope (0.1 K on lenses) and in particular of its focal plane (1 mK for the microbolometer substrate, 20 mK for the detector window), to provide the required temperatures on the 2 blackbodies (250 K and 350 K) and to keep the electronics in their qualification temperature range while minimising the heating power demand.

The main principles which have driven the thermal control design were to insulate the telescope housing from the external environment to limit its temperature variations, to control the detector temperature and its stability by a Peltier based thermoelectric heat pump, to evacuate the Peltier element and the detector dissipations with a radiator, to stabilise the Peltier radiator temperature by an active thermal control, to control the black bodies temperature with heaters, to evacuate the electronics dissipation with a radiator, and to provide heating during cold orbit phase.

To reduce temperature excursions, the telescope structure is insulated from albedo fluxes by a classical MLI (multilayer insulation) and decoupled from the structural panel with titanium feet and insulating washers. Sun and albedo fluxes are filtered by a ZnSe window with a special coating at the entrance of the telescope. Infra red flux is transmitted only in the 8-14 µm band.

The micro-bolometer focal plane, more precisely the Si substrate on which the microbolometers are micromachined, requires a severe temperature stability of 1 mK. Detector Si modules are fixed on a high conductivity alumina substrate used as support and heat diffuser. The alumina substrate is mounted on Peltier elements to control its temperature level under 20°C and to regulate its temperature. The other side of the Peltier is fixed on a radiator to evacuate dissipated power (by detector and by Peltier). The conductive couplings between the Peltier and the detector substrate and between the Peltier and the radiator are optimised. Temperature fluctuations are monitored by temperature sensors which can be either blind micro-bolometers coupled with the substrate or thermistors. Precision of the temperature sensor is fundamental for control loop performance and the self-heating of the sensor itself must not disturb the measure. The sensor is located near the controlled point to provide unbiased temperatures. Peltier regulation is obtained by a servo-controlled alimentation (PID) which will use thermal sensor informations to provide the electric flow. The radiator at the back of the telescope structure is white painted and its temperature is controlled by heaters commanded by a servo-control system to provide the maximum of stability to the Peltier. The detector package structure is conductively decoupled from the radiator and the telescope housing by insulated washer and MLI.




The required 1 mK stability of the detector substrate is expected to be reached because, there is no internal heat sources excepted the bolometers themselves, the optical modules are insulated from the external environment to the maximum extent, the only element sensitive to external disturbances is the Peltier radiator which is actively thermally controlled, the environment is kept very stable and the Peltier element is driven in a control loop based on temperature monitored by blind microbolometers.

The electronics are mounted on the structural bracket with thermal interface fillers to improve conductive coupling. Both equipments and bracket are white painted or covered with SSM (Second Surface Mirror) if necessary to reject dissipated power to space. The bracket is made in a high conduction material. The electronics temperature excursions are kept low in order to minimise thermal disturbances on optical modules. Black bodies are discoupled from their structure and heated. The cold body is protected from albedo and earth fluxes by a baffle covered with MLI and is oriented to the cold space. It is heated on its back side to control its temperature. The hot body temperature is also controlled by heaters.

## 10. INSTRUMENT CALIBRATION

As MUST is dedicated to radiometric measurements, its design must limit variations of any parameter which impact its radiometric response. Optics transmission, bolometer electrical resistance, bolometer TCR, bias current, gain and offset of the electronics vary only at low frequency and thus can be calibrated using the two on board blackbodies. During operations, a systematic calibration is made at each orbit, above the pole to detect any drift. Short term (during one orbit) variations are due to temperatures changes of the optics, of the detector window and filter or of the detector substrate itself. Thermal design is made to minimise the temperature change and an in flight calibration strategy is foreseen to check the instrument behaviour along the orbit at the beginning of life, for a potential correction for an orbital evolution. The active thermal control of the microbolometer substrate with a

Peltier can generate high frequency temperature fluctuations below the 1 mK level. A temperature drift compensation with blind reference pixels is implemented on the microbolometer chip to remove these residual substrate temperature fluctuations.

## 11. PERFORMANCE OVERVIEW

The major performances of the MUST instrument are given in table 11/1.

| | |
|---|---|
| Ground sampling | 250 m at nadir, 460 m at swath edge |
| swath width | 1420 km |
| spectral channels | 10.3 µm - 11.3 µm, 11.3 µm - 12.3 µm |
| MTF | 24% along track, 40% across track |
| temperature resolution | 0.24 K (lower band), 0.43 K (upper band) |
| absolute temperature accuracy | 1 K |
| mass | 60 kg |
| power consumption | 100 W |
| data transmission rate | 3.5 Mbps |

Table 11/1: MUST instrument performances

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