5th ESA Round Table on Micro/Nano Technologies for Space

MIcroBolometer Spectrometer MIBS: Smaller and smarter

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INTRODUCTION

ESA is planning to fly the EarthCARE mission around 2012. The mission is designed to gather information about clouds, aerosols and radiation properties of earth. Part of these measurements will be made by the multi spectral imager (MSI). The MSI will measure 7 bands in the visible and infrared radiation spectrum. There is an intrinsic differences between the origin of reflected solar visible/near infrared (band 1-4) and self emitted thermal infrared (band 5-7) radiation. So during the phase A study at TNO it was decided to split MSI into two parts. For the thermal infrared system a dispersive spectrometer called MIcroBolometer Spectrometer (MIBS) was designed (See Figure 1). A breadboard model is currently being built and will be ready for validation testing at the end of 2006.

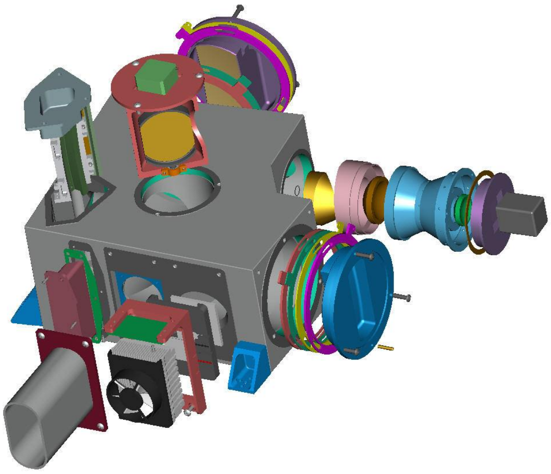


Figure 1: Exploded view of the Breadboard of MIBS

MIBS is a thermal infrared spectrometer based on a microbolometer detector. Compared to a MCT detector based system MIBS is approximately 3 times lighter, uses less energy and will be about 50 times smaller. These savings are accomplished while working at the same resolution with a performance that is only slightly decreased (NETD = 0.25 @ 0.9 µm compared to NETD = 0.1 @ 1µm). These savings are due to the fact that a 2D array of microbolometers can be used without need for bulky cryogenic coolers

To give a good overview of the most important differences, this paper will first explain the working principle of both MCT and bolometer detectors. Then the impact of these differences on the system design is explained. Finally some challenges faced during the design of microbolometer based spectrometers are discussed.

THE DETECTORS

Bolometer

The microbolometer family of detectors absorbs the (thermal infrared) radiation in a suspended slab of material (see figure 2) so that the detector surface temperature is changed, making them effectively energy balancing devices. The result of this temperature change is to change the material properties which can then be determined via a measurement process.

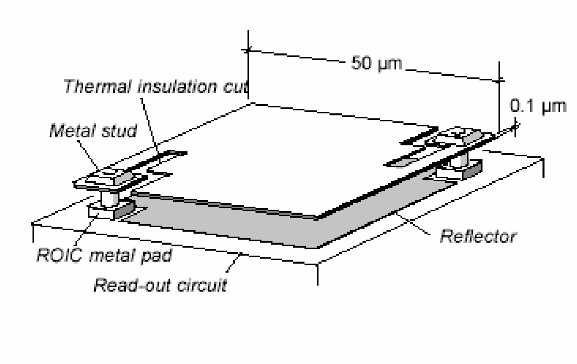


Figure 2: Micro bolometer detector pixel

The variable material property which most bolometers are based on is the electrical resistance. The resistance in a material is temperature dependant, thus making it possible to detect a temperature change by measuring a change in the resistance. The knowledge of the temperature can be used to determine the intensity of the incident radiation.

Other properties of the bolometer are a low thermal capacity and a high absorption coefficient. These two properties make sure that the temperature of the bolometer respond quickly and accurately to a change in intensity of the radiation (less energy needed to change the temperature a certain amount). The current microbolometers have a response time of $\tau_0 \approx 10$ms. To decrease the influence of heat leakage to the read-out circuit the legs of the bolometer pixel are used to thermally isolate the sensing surface as well as possible

MCT Detector

MCT is a ternary semiconductor that exhibits a composition dependant bandgap. Due to the band gap only highly energetic electrons are capable of entering the conduction band to be part of the current. Normally the electrons have insufficient energy to pass the band gap. But when a photon hits an electron the energy level of the electron is increased. Thus by measuring the current an estimation of the number of electrons in the conduction band can be made, which is a measure for the number of incident photons. The number of photons can finally be coupled to the intensity of the radiation.

Main Difference

As explained above, the detector types differ in operating principle. The bolometer is dependant on energy absorption and its capability to change its temperature due to the absorbed energy, while the MCT is dependent on the absorption of individual photons by electrons, promoting them to a higher energy level.

IMPACT ON SYSTEM DESIGN

Responsivity

The responsivity of a bolometer (thermal) detector is different from the responsivity of a MCT (Photon detector). As indicated in Figure 3.

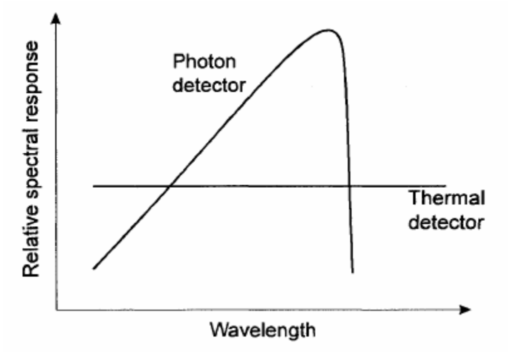


Figure 3: Spectral response of a photon detector and a Thermal detector

Here two things become apparent:

- The peak responsivity of the MCT detector is a few factors larger than the responsivity of the micro bolometer
- The bolometer has a response that is less dependant on the wavelength

First look at the difference in peak responsivity. The photon detector has a higher response, meaning that less radiation power is needed to get the same performance. Because this radiation power is proportional to the aperture area of the optical system, the aperture of a bolometer based system must be larger than that of a MCT based system.

For the ratio between the focal length and the aperture diameter (f/D) this has the following effect. Due to the requirements on the resolution and the range the focal length is given, and equal for both systems. The f/D of a bolometer based system will be lower compared to that of a MCT based system, leading to a larger aperture for a microbolometer system.

Apart from this, a system with a smaller f/D (fast system) will tend to have larger aberrations in the optical path.

Now look at the difference in spectral response of some real detectors.

As said before bolometers respond to a much wider spectral range than MCT detectors. See Figure 4 for a detailed picture of the response

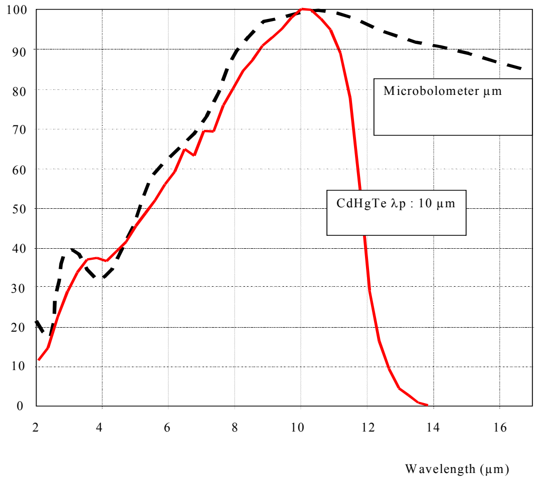


Figure 4: Response at different wavelengths, normalized to detectors own maximum(Courtesy of Ulis,(FR))

As explained above the difference in spectral response is due to the two detection mechanisms used in each type of detector.

In a bolometer the is determined by the spectral absorption coefficient of the material that is deposited at the surface. Another part is determined by the cavity height between the bolometer detector surface and the reflector. The decreased response for shorter wavelengths is due to the fact that the detectors are optimized for the thermal infrared atmospheric window (8..12 µm) and a fast temporal response. In MCT detectors the response characteristic is determined by other principles. Photons with longer wavelength have less energy. This means that from a certain wavelength the photons are no longer capable of elevating electrons to the conduction band. For longer wavebands this means that the response is zero. In Figure 4 this (cut off) happens at 12 ηm.

The conversion of photons from wavelengths smaller than 10 µm is approximately constant (quantum efficiency). But photons with a shorter wavelength carry more energy and so the number of photons per unit of energy is smaller. This leads to the fact that the response (defined per unit energy) declines with shorter wavelength. The small bump around 4 µm is due to the fact that the photons here have such a high energy that they can free 2 electrons.

For a system that must be able to measure small wavebands (0,9 µm) this means that MCT detector can be brought into specification by using waveband filters which filter away only a small band at the high frequency part of the detector. The other wavelengths fall outside the detection range of the MCT and thus are not harmful for the measurement. If the system is built on a bolometer detector a much larger spectrum must be filtered out, which in combination with the required low f/D makes the filters more difficult to produce. [1].

Noise

Both detector types have different noise sources. For MCT detectors literature states[2],[3]:

- Thermal noise
- Dark current noise
- Shot noise
- Flicker Noise (1/f)
- Noise from the surrounding

For microbolometers [1],[4]:

- Conductive thermal exchange noise
- Radiative thermal exchange noise
- Bolometer resistance noise
- Total electrical noise
- Preamplifier noise

For MCT detectors dark current noise is very important. This noise is a function of the temperature. In order to keep this noise within acceptable limits the detector must be cooled down to about 70K. The only way to achieve this is by using a cryogenic cooling system.

Because an MCT detector has an f/D that is comparative large, the total signal power received from the scene is small. The effect from this is that the MCT detector has a Background Limited Instrument Performance (BLIP). For an instrument that has a BLIP the thermal radiation coming from its surrounding is the limiting factor for the performance. If the surroundings thermal radiation and with that its random variation (Shot- , radiation noise) is to large, it becomes difficult to recognize the signal from the random noise. In order to keep the thermal radiation level of the surrounding small enough, they must be kept at a cryogenic temperature (Cold shielding).

For the microbolometer the two largest noise sources are the conductive and radiative thermal exchange noise.

The conductive thermal exchange noise is noise due to conductive heat flow between the absorber and the substrate. The size of this noise is dependant on the temperature difference between the absorber and the substrate and thus correction is not easy. The effect of this noise can be decreased by increasing the thermal resistance of the legs.

The radiative thermal exchange noise is due to the exchange of energy between the absorber and its surrounding. During calibration the influence of the radiation that is coming from the surrounding can be measure and during measurement corrected. Nevertheless if the temperature changes during the measurement period this will be a new noise source. In order to be able to measure correctly the temperature stability of the surrounding must be in the order of 10mk between calibrations.

CHALLENGES FOR THE DESIGN

During the design of MSI we had to take care of the effects described above.

Using a 2D detector

As said before filters that filter away the wide spectral range needed for the bolometer detector are difficult to manufacture. So during the design it was decided to use a prism. The prism will split the radiation beam in different wavelengths.

Each wavelength will be sent into another direction, removing the need for spectral filtering, in the mean time providing the (for MSI) required scene co-registration.

By using a prism the different wavebands of the swath in the entire spectral range will be imaged as parallel strips. This makes it highly advantageous to use a 2D detector array. In this way al the needed information of the entire swath can be detected at ones. This effectively eliminated the need for a scanning mechanism, increasing system reliability and increased the number of samples that can be taken from each target (same detector speed).

Thermal stability vs calibration

As described above the performance of a Microbolometer based instrument is highly dependant on the temperature stability of its surroundings. Calculations showed that the stability between calibrations must be in the order of 10mK.

There are two extreme approaches to achieve this stability:

- stay continuously in calibration mode to assure the fact that the energy coming from the surrounding is precisely known. As one can imagine this approach is not very practical because it would not allow any time for real measurements.
- The other approach is to use a very larger thermal system that can hold the temperature perfectly stable so that no calibration are needed during operation. Such a thermal system would be extremely large and heavy. So this second approach is also not very practical.

As usual in engineering the best solution is in between. By using a thermal system with passive coolers and some heating it is possible to keep the temperature stable enough to allow for a 15 minute calibration period. This is in practice a reasonable balance between thermal system size and the time between calibrations. As one can imagine this equilibrium point between thermal system size and the time between calibration is different for every design.

Achieving Low NETD

The NETD of an infrared system is dependant on the speed with which the energy output of a blackbody in a certain waveband changes when its temperature changes. Also the absorption in the system is important. So lets say the detector has a Noise equivalent power of 1 W (NEP, just for sake of discussion) and the system has a throughput of 80%. The blackbody has an energy output change of 1 W/K. This then means that a temperature change of 1.25K is needed to change the energy level that is detected by 1W, so the NETD=1.25K. The size of the waveband is also influential because a smaller band means that the energy level in that band is also smaller (this also changes with temperature). The size of the waveband is usually determined by the requirements coming from the customer.

For a the MSI instrument the required spectral band is in the order of 1μm. Due to the small spectral band the energy output change will be limited, making the low NETD values more difficult to achieve. In order to still keep the NETD reasonably low, the following things can be done:

- Making the detector more sensitive. By reducing the Noise equivalent power and increasing the fill factor and absorption coefficient of the detector it is possible to detect a weaker signal. This solution is not part of the instrument design, but of detector research.
- A second option is to increase the aperture diameter, in this way the instrument will pick-up a larger part of the radiation. A major drawback of this option is the fact that along with the aperture the instrument also will become bigger.
- The third remedy is to design the optical system in a way to reduce the transmission losses. The lower the losses the stronger the signal will be.

- Look at a larger part of the blackbody. This would mean to decrease the resolution of the scene. Because the resolution is usually given by the customer and thus can not easily be made smaller.
- Due to the fact that MIBS uses a 2D staring array that is fast, it is possible to make more samples of a single ground pixel. This means that due to averaging the influence of the temporal noise can be reduced, improving the NETD.

So a spectrometer instrument design must be such that the system transmission is as high as possible in order to keep the aperture and the system size as small as possible. On the other hand one should start with a bare detector that has an as good as possible NEP.

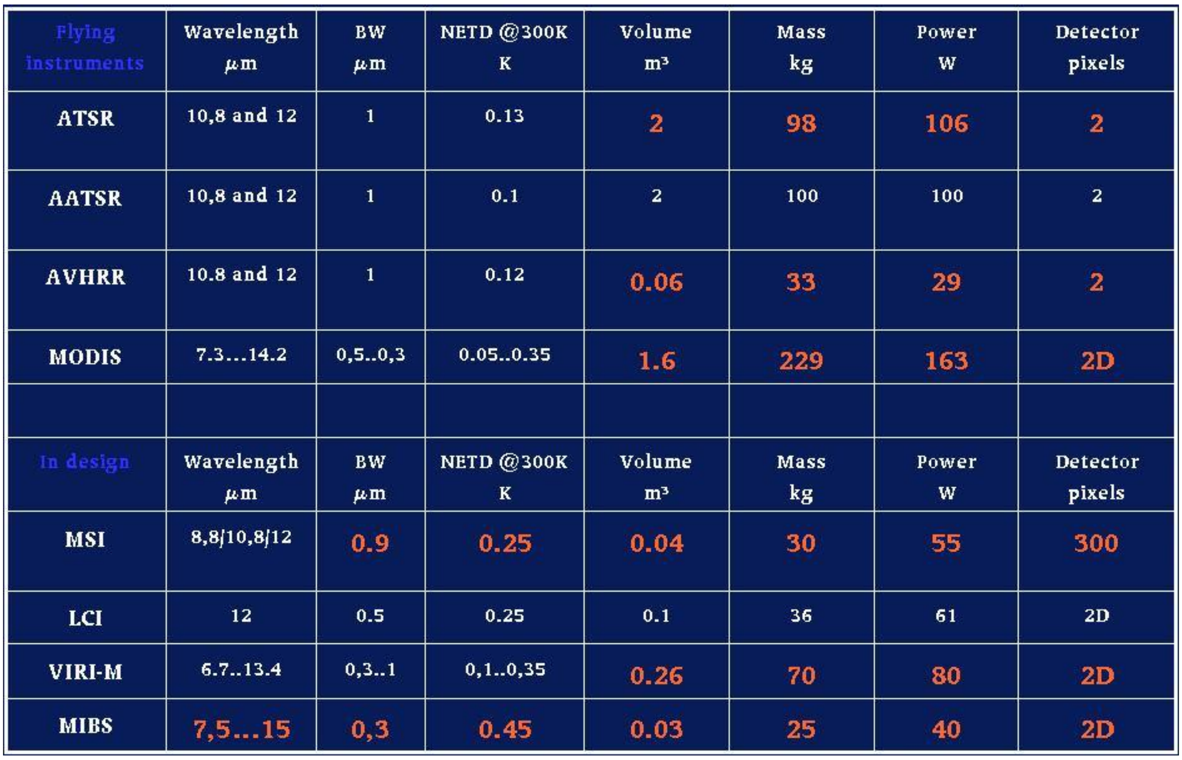
CONCLUSION

Although a somewhat changed design approach was needed, it was possible to design MIBS to have an almost similar performance as MCT based instruments.

In order to achieve the required NETD for the EARTHCare mission, a smaller f/D was needed as compared to a MCT instrument.

MIBS has no need for a cryogenic cooling system. This saves precious satellite mass and power budget.
This also makes it possible to use a 2D detector array. Leading to a high co registration and the absence of a scanning mechanism. This last point increases the reliability of the instrument.

If these effects are all summed up, we can compare MIBS with MCT based instruments that have approximately the same performance (see Fig 5).



Flying instruments	Wavelength µm	BW µm	NETD @300K K	Volume m³	Mass kg	Power W	Detector pixels
ATSR	10,8 and 12	1	0.13	2	98	106	2
AATSR	10,8 and 12	1	0.1	2	100	100	2
AVHRR	10.8 and 12	1	0.12	0.06	33	29	2
MODIS	7.3…14.2	0,5..0,3	0.05..0.35	1.6	229	163	2D
In design	Wavelength µm	BW µm	NETD @300K K	Volume m³	Mass kg	Power W	Detector pixels
MSI	8,8/10,8/12	0.9	0.25	0.04	30	55	300
LCI	12	0.5	0.25	0.1	36	61	2D
VIRI-M	6.7..13.4	0,3..1	0,1..0,35	0.26	70	80	2D
MIBS	7,5…15	0,3	0.45	0.03	25	40	2D

Fig 5: Overview of infrared instruments

From the figure it must be concluded that MIBS saves a lot of volume, mass and power compared to MCT instruments.

References

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