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MICROBOLOMETER SPECTROMETER OPENS HOIST OF NEW APPLICATIONS

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Abstract

Current Thermal infra red (7..14µm) multispectral imager instruments use cryogenically cooled Mercury Cadmium Telluride (MCT or HgCdTe) detectors. This causes the instruments to be bulky, power hungry and expensive.
For systems that have medium NETD (Noise Equivalent Temperature Difference) requirements and can operate with high speed optics (<1.5), room temperature microbolometer performance has increased enough to enable people to design multispectral instruments based on this new detector technology.
Because microbolometer technology has been driven by the military need for inexpensive, reliable and small thermal imagers, microbolometer based detectors are almost exclusively available in 2D format, and performance is still increasing.
Building a spectrometer for the 7 to 12 µm wavelength region using microbolometers has been discarded until now, based on the expected NETD performance.
By optimising the throughput of the optical system, and using the latest improvements in detector performance, TNO TPD has been able to design a spectrometer that is able to provide co-registered measurements in the 7 to 12 µm wavelength region yielding acceptable NETD performance.
Apart from the usual multispectral imaging, the concept can be used for several other applications, among which
imaging in both the 3 to 5 and 7 to 12 µm atmospheric windows at the same time (forest fire detection and military recognisance) or wideband flame analysis (Nox detection in industrial ovens).

1. Introduction

When looking at TIR multispectral imagers that are currently in operation, the spectral ranges and required NETD's are quite similar.

Table 1 gives a short overview of some operational instruments and instruments for which currently designs are being produced.

Instrument	λ_0 µm	BW µm	NETD @ 300K
Current			
ATSR	10.8/12	1	0.13
AATSR	10.8/12	1	0.10
AVHRR	10.8/12	1	0.12
MODIS	7…14	0.5	0.05..0.35
Future			
MSI	8.8/10.8/12	0.9	0.25
LCI	12	0.9	0.25

N.B. MODIS is a hyper spectral imager.

Table 1. TIR imager requirements

Results of the THEMA study [1] also show required NETD values that can be obtained with microbolometer-based instruments.
Using currently available microbolometers, it is possible to obtain the EarthCARE-MSI requirements as quoted in table 1. With the improvements expected within a number of years, much smaller and cheaper instruments based on microbolometers could provide the same quality data as the current instruments.

2. MCT versus microbolometers

Cryogenically cooled MCT detectors have been the only detectors available that could provide acceptable NETD performance for systems that operated in the 7 to 12 µm wavelength region for years.
The technology is recently challenged by microbolometer-based detectors which are currently capable of delivering acceptable performance when used in high-speed optical systems.
Main advantage of microbolometer detectors is the absence of a cryogenic cooler system.
For doing absolute measurements, the microbolometers require a tight temperature control of the environment instead.
Contrary to MCT detectors (which are photon detectors), microbolometer detectors are energy-balancing devices.

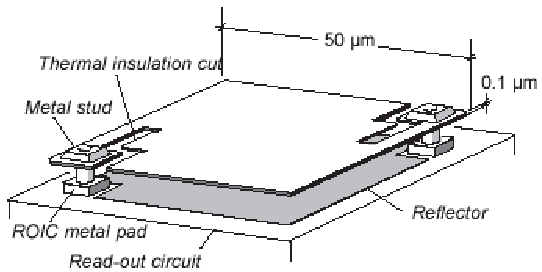

Figure 1: Schematic of microbolometer pixel

Figure 1 Shows a typical pixel format as given in [2]. Thermal radiation from the environment heats or cools a slab of material, that is suspended above the substrate (containing the readout electronics) by means of two supporting thermally isolating legs. The equilibrium temperature depends on the temperature of the surroundings and the viewfactor to the scene. This is the reason why microbolometer based systems need to have a high-speed optical system, and a thermally stable background (absolute temperature is less important). The slab is coated with a material that has a high temperature coefficient of resistance. The temperature is measured by measuring the resistance between the two supporting legs. By minimising the thermal capacitance, the response time of the detector is kept fast enough to allow imaging (5..25ms). The spectral response of a microbolometer depends on the absorption characteristics of the absorber, which is deposited on the slab, and can therefore be very broadband. This is another difference with photonic bandgap MCT detectors.

When comparing microbolometers and MCT detectors, a distinctly different spectral response can be noticed.

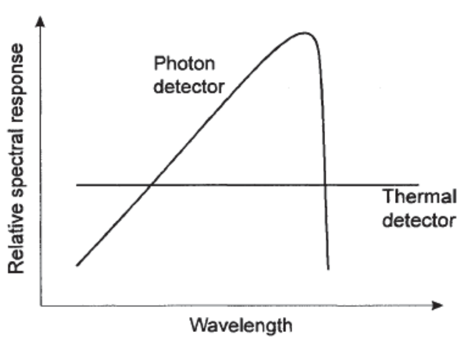

Fig.2. MCT versus microbolometer spectral response

Although this response will be markedly different in case resonating structures are used, in general the response will be more broadband, and limited by the transmission of the optical system used.

As an example the below graph gives the difference in measured spectral response for a Sofradir MCT and a Ulis microbolometer

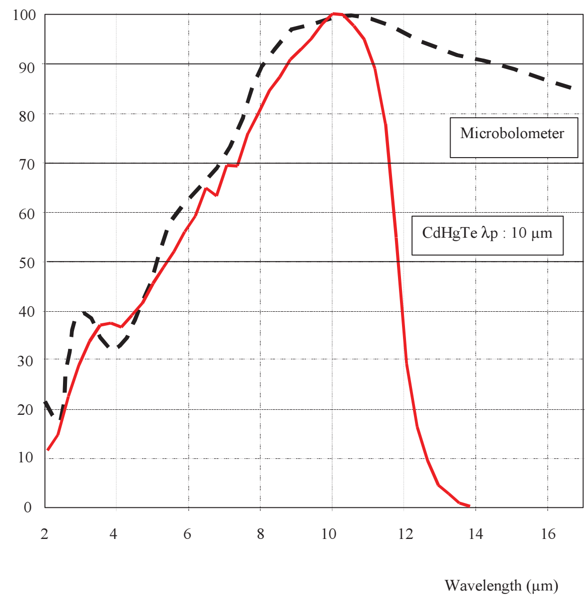

Fig.3. MCT versus microbolometer spectral response. (Courtesy of Ulis)

NOTE: These detectors are specifically optimised for detection of radiation in the 8 to 12 µm region.

For standard imaging systems the broader spectral response can be a burden, because the microbolometers are sensitive to radiation outside the atmospheric window.

In some cases however (like detection of gasses in the atmosphere), the broader response can be used to detect features that cannot be detected using standard MCT detectors.

3. Bandfilter properties

Typical multispectral imagers use interference filters to create the required spectral response.
For instruments operating in the TIR spectral region (7 to 14 µm) this calls for thick layers that need to be deposited on the optical components and associated manufacturing problems.

When building a microbolometer-based instrument a number of additional problems need to be solved in addition to the general manufacturing problem.

First of all the spectral response of a microbolometer is very broad, and so is the transmission of the commonly used germanium. This creates a problem in case thermal images need to be acquired during daytime. This is because the used bandpass filters 'open up' for radiation sufficiently far outside of the required passband, and signal intensity is much higher in for instance the 2 to 3 µm region than in the 7 to 14 µm region.

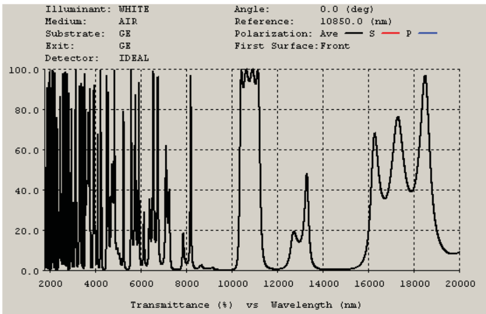

Fig. 4.Typical multi layer filter response

In addition to this, stopband rejection is not 100% causing spectral leakage (out of band radiation causing detector signal).

Therefore several bandfilters and highpass filters will have to be combined to give the required spectral response.

The last general problem related to bandpass filters is related to the so-called central wavelength shift. Central wavelength shift is caused in case the optical rays have a non-perpendicular incident angle on the optical surface containing the filter. An approximation of the shift can be calculated using the formula below

$$\lambda\alpha = \lambda_0 \left[1- \left(\frac{\mathrm{Ne}}{\mathrm{N}^*} \right)^2 \mathrm{Sin}^2\, \alpha \right]^{1/2}$$

Where: $\lambda\alpha$ = Center wavelength at angle of incidence
λ_0 = Center wavelength at normal incidence
Ne = Refractive index of external medium (Ne = 1.0 for air)
N* = Effective refractive index of the filter
α = Angle of incident light

Formula 1. centre wavelength shift as a function of incidence angle.

When using a value of 3 for the effective refractive index of the coating, the shift can be calculated to be 17nm for an angle of incidence of 10 degrees (this is the maximum angle for which this approximation is considered to be valid), and a centre wavelength of 10 µm. The half-width opening angle of an f/1 system however is 26.5 degrees and this increases to 32 degrees for an f/0.8 system (causing 157nm shift if the formula where valid).Due to this wavelength shift, reaching a good spectral definition will be difficult in high speed optical systems.

4. In-field separation.

In first instance, an in-field separated system looks attractive from an optical system point of view.
The optical system consists in essence of an imaging telescope (which will typically be multi-element) and filters near the detector plane of a standard 2D array detector.

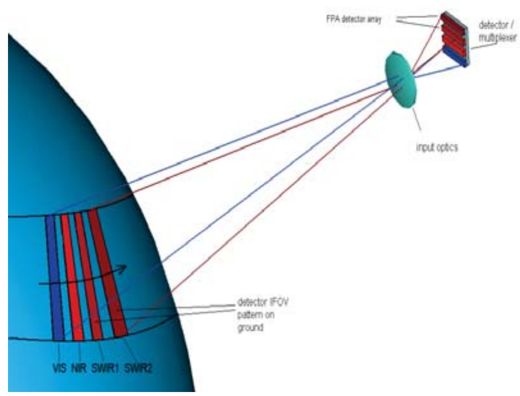

Fig. 5 In-field separation

Apart from the before mentioned drawback of a bad filter response definition (when used in a high-speed optical system), the main drawbacks of this approach are bad straylight performance and ground swath separation.

The first one is caused by the fact that baffling possibilities are extremely limited in combination with filter positioning directly in front of the focal plane, and the latter one is inherent in the in-field separation concept but has impact on the co-registration of the science data collected.

When using an in field separated system, the instrument looks at different position on the earth for different bands.

It is presumed that when the satellite flies over, the other bands cross the same area and the data can be time delayed to co-register.

The truth is that especially when the target is varying in height, co-registration can be seriously affected as demonstrated in figure 6.

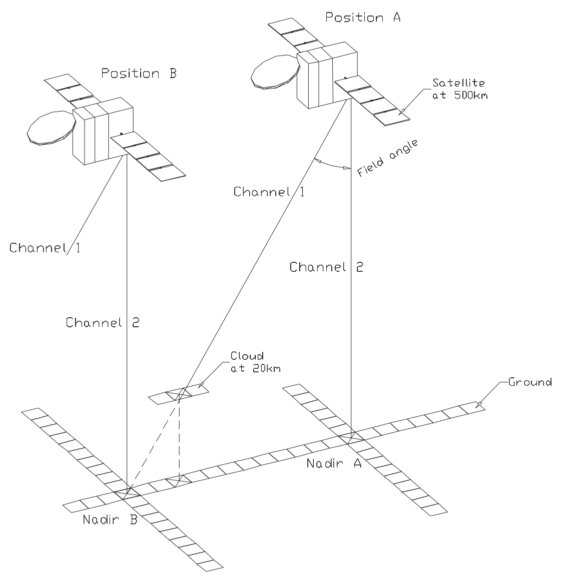

Fig. 6. Co-registration

This causes the need for co-registration software and the need to know the target altitude.
The co-registration software will have to correct the data for the movement of the platform with respect to the optimal trajectory (yaw pitch and roll errors), the target height, and possibly even the target movement.
Some errors, like those caused by the different angle of incidence can never be corrected.

Large field angles require large calibration systems and apertures and should be avoided as much as possible.
Small field angles however create the need to position the filters very close to the detector and make mounting impractical

5. Co-registered systems

Given the above drawbacks of in field separated systems it is logical to look at co-registered systems.

For co-registered systems a number of general options exist.

In case a limited number of channels are defined, separate cameras with filters in front of the exit apertures can be used.

The main drawbacks of this approach are that the final system is heavy, alignment between channels is difficult and on-board calibration is also creating problems.

As a first alternative, systems with a larger focal length and intermediate focus can be designed, which will allow placing the filters in a slower optical beam, thus largely reducing straylight problems, filter manufacturing problems and calibration problems (one aperture allows to use a common calibration system).

Drawback of this approach is the fact that to obtain the required performance, several filters will need to be designed. In addition to this, different optical paths for different wavelengths make modelling the radiometric performance difficult.

Another possibility is to use a dispersive element for the wavelength separation, and built a spectrometer.

In order to be able to use a microbolometer without reaching unacceptable NETD levels, the optical system will have to be throughput optimised.
This can be done, by using gold-coated reflective optics and a minimum amount of germanium transmission optics.

The advantages of the spectrometer are excellent straylight rejection, well-defined spectral response, relative easy performance modelling and an optical system that can be largely aligned using visible light.
The disadvantage is a lower NETD and restrictions in selecting bandwidths of interest and absolute positioning of the centre wavelengths.

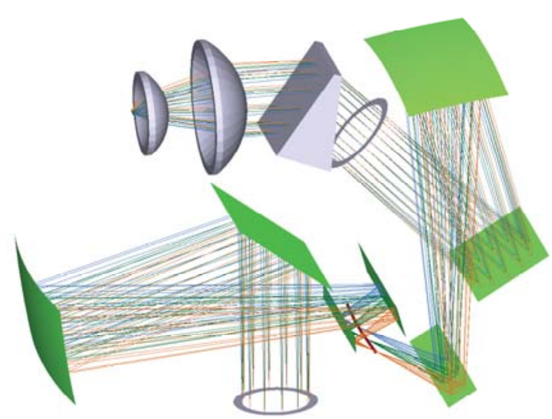

Fig. 7. Optical diagram MIBS

6. Microbolometer spectrometer (MIBS)

The microbolometer spectrometer as depicted in figure 6, consists of a telescope which focuses the scene of interest on a slit, This is done by means of a mirror which can be rotated and which will point to either the scene or one of the two calibration blackbody's, the actual telescope mirror and a folding mirror which is used to compact the system.
A collimator transforms the slit image into a parallel beam going to the prism. This collimator is build using two folding mirrors, the actual collimator mirror and a third folding mirror. The ZnSe prism disperses the light and a high-speed thermal camera (f/0.8) images the dispersed signal on the detector. The camera is build using only two optical elements in order to keep the absorption low. Given the high reflectance for TIR radiation, the use of folding mirrors only marginally influences the throughput of the system. The folding mirrors however allow the design of a mechanically compact system.

The excellent straylight rejection is caused by the fact that off axis radiation is rejected by the slit. The spectral purity stems from the fact that the prism disperses out of band radiation away from the pixel of interest, thus providing good out of band radiometric performance. The relative easy performance modelling of the spectrometer is mainly caused by the fact that performance is largely determined by the temperature control of the direct surroundings of the microbolometer and the slit. The temperature of the germanium lenses is the second most important items to control.(Since there is practically no absorption in the ZnSe prism, nor in the gold coated mirrors, the temperature control of these items is less important.)
For the purpose of mimicking a filter-based spectrometer, the signals of a number of channels (pixel rows spanning the required wavelength range) can be co-added to give the required spectral response. The higher the dispersion of the prism, the higher the number of wavelength channels that can be co-added to create the required response, and the better the spectral definition. The disadvantage however is that the NETD reduces with N/√N (N being the number of spectral channels co-added).
The entire system can be mounted on a fairly compact optical bench.

The depicted optical bench (figure8) is for an instrument which has a ground swath of 150km with a resolution of 500m at an altitude of 485km (EarthCARE MSI)

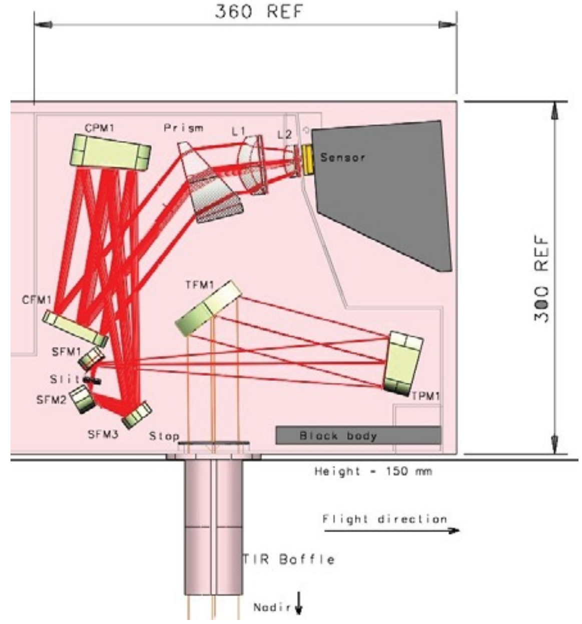

Fig. 8. Mechanical setup.

7. Radiometry

In order to be able to predict the performance of the spectrometer, a radiometric model has been build, the setup of which is given below.

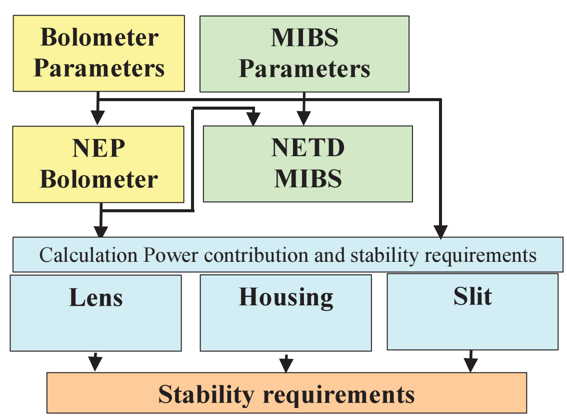

Fig. 9. Flow radiometric calculations

First of all, based on the data provided by the detector manufacturer, the noise equivalent power for the microbolometer is calculated. Secondly, the required spectral response as derived from the optical calculations is input and the amount of energy incident on the detector is calculated using the throughput data of the optical system. This data allows calculation of the obtained NETD.

In order to calculate the level of thermal stability required, the sensitivity of the signal to variations in the lenses of the camera, the housing surrounding the microbolometer, and the slit are calculated.

Interestingly thermal engineers performed these calculations, since the energy balancing is driven by radiative heat transfer, and not by photon counts as for MCT based systems.

When looking at an optimised system, already today acceptable performance levels can be obtained. The required NETD of 0.25K at a spectral bandwidth of 900nm can be obtained when using the new 35 µm Ulis microbolometer technology [2] (although 1/f noise signal processing may be necessary to obtain this performance). In the future, microbolometer performance will increase to near background limited performance (BLIP) and far less 1/f noise will be present when better absorbers are developed (for instance on basis of YbaCuO).[3],[4],[5]. Therefore it seems valid to pursuit the MIBS concept even if proven that for a given application at this moment in time the obtainable NETD is below requirements.

One of the main input parameters is the spectral response of the system, which is calculated using the slit function and the detector function. This way the spectral response can be tailored to the requirements.
In the graph below (figure 9) the individual pixel responses are given for a system using the MSI optical bench with a 50 µm pixel size camera and 80% fillfactor pixels.
Each of these response curves is about 450nm wide.

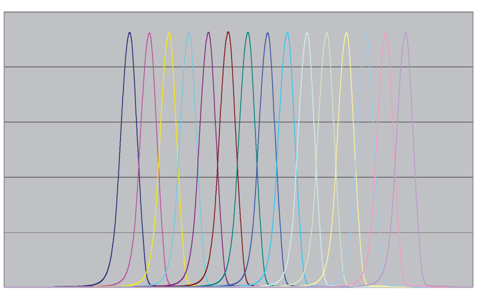

Fig. 10 MIBS channel spectral response

By combining a number of pixels, a required spectral response can be generated.

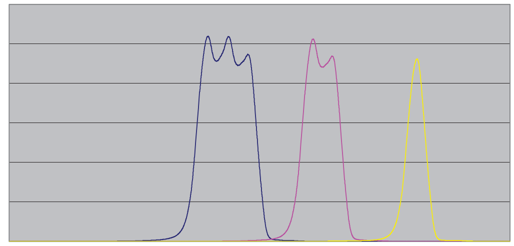

Fig. 11. Co-added spectral channels

The spectrometer allows to more accurately separate radiation from different channels, and over a wider spectral range. Current available microbolometer detectors are all fitted with a high pass spectral filter, cutting off as much as possible all radiation below 7 µm (because this radiation would largely influence imaging quality during daytime imaging), therefore the spectrometer can only be used above 7 µm when using standard detectors. The microbolometer response extends beyond the commonly available 12 µm for MCT detectors, opening possibilities to image 13 and 14 µm radiation despite of the increasing absorption in the germanium. The wavelength region already disclosed, opens up the possibility to determine the amount of NOx in industrial burners, but more trace gasses could be successfully determined if the full potential of microbolometers where to be exploited. (NOTE germanium in transparent between 2 and >14 µm but absorption is increasing above 10 µm)

8. Applications

The increased wavelength sensitivity would allow imaging in the 3..5 µm and 7..13 µm atmospheric windows simultaneously.

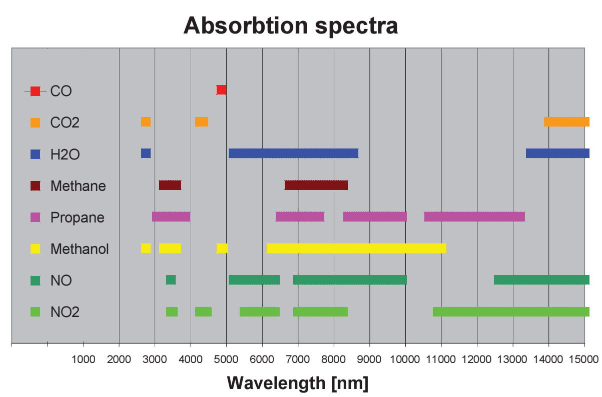

Fig. 12. Absorption spectra of trace gasses.

This feature can be used for instance to decrease falls alarm rates in forest fire detection systems, or for military imaging purposes (reconnaissance and rocket plume analysis).

9. The future according to MIBS (conclusions)

It is to be expected that microbolometer detector performance increases in the future, and detectors with lower NETD and smaller pixel sizes will become available. In order for MIBS to fully benefit from these improvements, the detectors should have a fillfactor as high as possible in the spectral direction, an as low as possible NETD and an as broad and flat as possible spectral response. In addition to this, a low 1/f corner would be helpful to avoid noise reduction processing and associated hardware.
These new microbolometer detectors enable building even more compact and better performing systems, that could replace current much larger and more expensive systems. The small size of the spectrometers would allow flying on micro satellites or as a strap on instrument on larger platforms, thus enabling the build of constellations that provide a high temporal coverage over a wide area at acceptable costs.

In case a spectrometer would be used for military imaging and or industrial applications, space optical systems could benefit from the economy of scale that would be involved, and the other applications could benefit from the modelling and environmental rigidising that will need to be performed for the space segment.

10. References

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