

Broadband relative spectral calibration of an HgCdTe photodetector

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ABSTRACT

The METimage instrument is an Airbus-primed passive superspectral imaging radiometer measuring thermal radiance emitted by the Earth and solar backscattered radiation in visible, near and thermal infrared wavelengths. One of the crucial parts of its development is its relative spectral calibration, especially in its difficult-to-access thermal bands, ranging from 3.55 μm to 13.80 μm and distributed over 9 channels. To characterize its instrument spectral response function (ISRF) in this region, Airbus has developed a measurement setup with tuneable lasers capable of providing tuneable monochromatic stimuli over the required bands. The radiometric monitoring of the laser's radiant power over its tuneability range is performed by a commercial HgCdTe (MCT) single-pixel photodetector attached to a laser-illuminated integrating sphere. While convenient, this sensor is too small for having its spectral responsivity calibrated by classical methods from standard institutes to the required precision over the METimage channels. To solve this, Airbus partnered with the German Physikalisch-Technische Bundesanstalt (PTB) and the US National Institute of Standards and Technology (NIST) to propose a novel relative spectral calibration method that is not limited by the small size of the device to be characterized. For this, a NIST pyroelectric detector whose absorptive coating consists of carbon nanotubes is used, providing a remarkably flat spectral response with $< 0.1\%$ flatness over the entire calibration spectral range. By detuning the lasers, simultaneously illuminating both tested and reference photodetectors via a roughed-gold coated integrating sphere, the comparative spectral response of both sensors is characterized. Thanks to a synchronous detection scheme, the measurement signal-to-noise (SNR) ratio is boosted, enabling a $< 1\%$ overall relative measurement uncertainty over the desired spectral domains. With this result, the MCT photodetector can be integrated into the complete optical setup that is evaluated to provide the final $\leq 2\%$ required ISRF measurement uncertainty.

Keywords: spectral, calibration, MCT, HgCdTe, pyroelectric.

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1. INTRODUCTION

To achieve precise modelling of the Earth's atmosphere, hydrosphere, cryosphere and surface lands, scientists rely heavily on accurate spaceborne observation instruments. Among those, spectrally-resolved optical measurements are of paramount importance as they capture crucial observations of clouds, aerosols, vegetation, sea temperatures and many surface phenomena, by spectrally distinguishing the backscattered light. It is therefore essential that space instruments deliver spectrally accurate optical measurements. To this end, ISRFs must be precisely spectrally characterized with methods minimizing their knowledge error [1].

To successfully perform this task on the superspectral imaging radiometer METimage [2], Airbus has developed a characterization setup named COLA. It includes tuneable lasers capable of providing tuneable monochromatic stimuli over the required bands of the instrument, namely 3.55 μm to 13.80 μm . This radiation is spatially homogenized using a dedicated gold-roughed integrating sphere and its output is collimated towards METimage's entrance pupil with an off-axis parabola mirror. Proper single-mirror-based collimation and sphere sizing ensure full-pupil and full-field illumination of the space instrument to be characterized. While the laser wavelength is measured using a spectrum analyser, its relative radiance is monitored by a commercial HgCdTe single-pixel photodetector attached to the laser-illuminated integrating

sphere. Note that bands of shorter wavelengths of METimage ($< 3.55 \mu\text{m}$) are addressed with another dedicated setup based on a different technology.

Since the response of the instrument to the spectral stimulus delivered by the COLA is to be characterized, it is crucial to minimize the knowledge error of this stimulus to reach a characterization inaccuracy of $\leq 2 \%$, as per METimage specification. Importantly, this figure of merit is relative within each band of the instrument, i.e. no absolute characterization is necessary.

After methodically evaluating all sources of errors in the instrument's characterization process, a remaining $\leq 1 \%$ relative inaccuracy is allocated to the MCT photodetector, for the critical task of providing the relative magnitude of the monochromatic radiation when lasers are detuned over many bands. Since this sensor is too small for having its spectral responsivity calibrated by standard calibration institutes to the required precision, Airbus partnered with the PTB and NIST to propose a novel relative spectral calibration method that is not limited by the small size of the device to be characterized. This method is described in this work.

2. MEASUREMENT SETUP

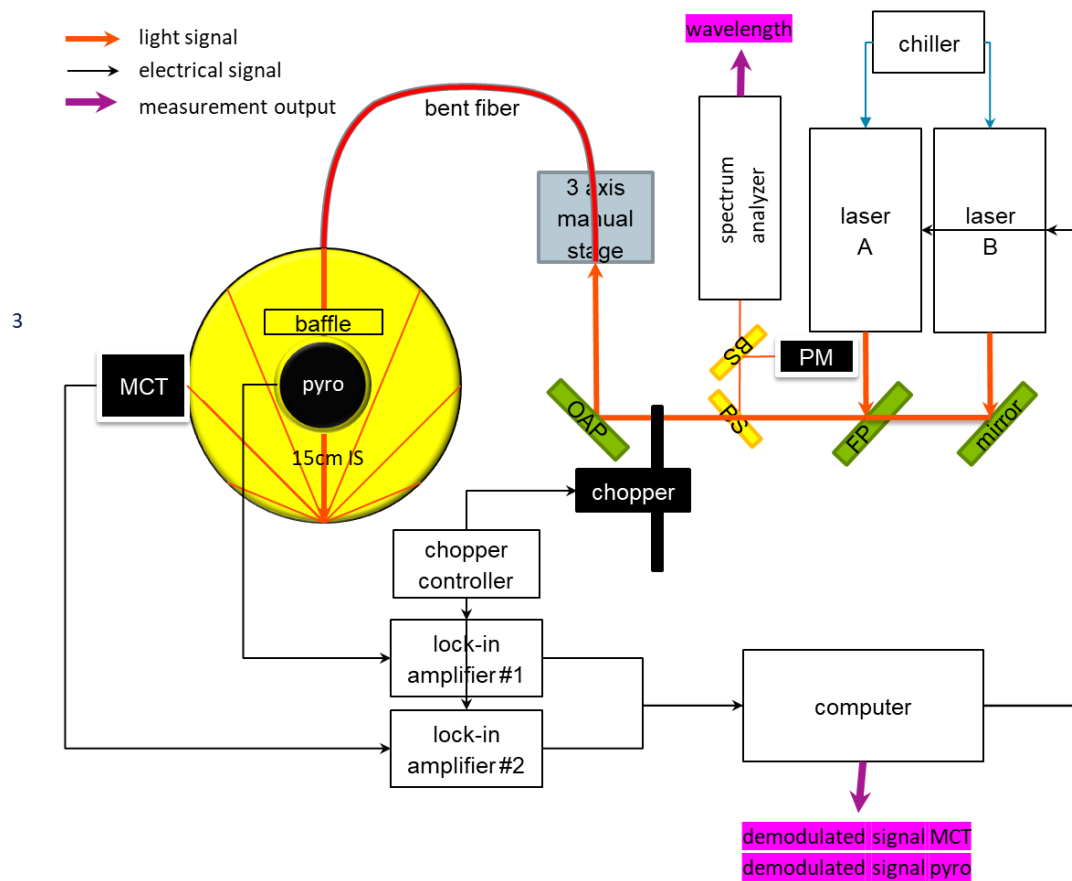


Figure 1. Sketch of the MCT/pyro cross-calibration measurement setup. IS: integrating sphere, OAP: off-axis parabola, BS: beam splitter, PM: powermeter, FP: flip mirror.

Since only the relative responses of the MCT photodetector over each band of METimage are needed, it does not require absolute radiometric calibration and only needs to be compared to a measurement device exhibiting a flat spectral response within that band. This last condition is fulfilled by a pyroelectric detector coated with carbon nanotubes, which is provided by NIST. This device is the core of the presented measurement setup and ensures a wavelength-independent absorption of

the radiation followed by a wavelength-independent transduction of the absorbed heat into a detectable electrical. The latter is guaranteed by the physics of the vertically-grown carbon nanotubes that act as myriads of individual radiation traps, providing outstanding absorptivity over a very large band [3]. It has in addition been measured to deviate from perfect spectral flatness by maximum of 0.04 % over the entire range of METimage [4].

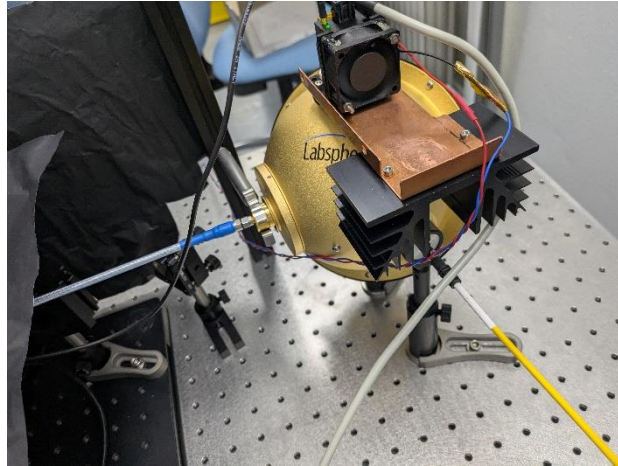


Figure 2. Test setup pictures with the integrating sphere including MCT and pyro photodetectors.

The setup developed by Airbus for the comparison of the METimage MCT detector and the pyroelectric detector is schematized in Figure 1 and photographed in Figure 2. Both lasers A and B are controlled and individually addressed with a combination of flip and fixed mirrors and focused by an off-axis reflective parabola into the entrance of a multimode fibre. With proper bending, this fibre depolarizes the strongly linearly polarized output of each laser to minimize any polarization-induced effects. A fraction of the beam is fed into a spectrum analyser by a beam splitter, providing a spectrally-resolved measurement of the input radiation. The fibre is directed towards the 150-mm diameter gold-roughed integrating sphere to spatially homogenize the radiation source, consequently delivering the same radiance to both the MCT and the pyroelectric (pyro) detector. The large diameter of the sphere minimizes radiance spatial inhomogeneities that could locally affect both intra- and inter-detector illuminations. The manual 3-axis stage optimizes the fibre coupling for the different laser modules. The radiation is modulated using a chopper at a frequency of 70 Hz. The demodulation of the detector's signal with 2 independent lock-in amplifiers allows for the subtraction of detrimental thermal background. The measurement setup is largely automated and remotely operable to ensure stable conditions of the measurement environment.

3. MEASUREMENT RESULTS

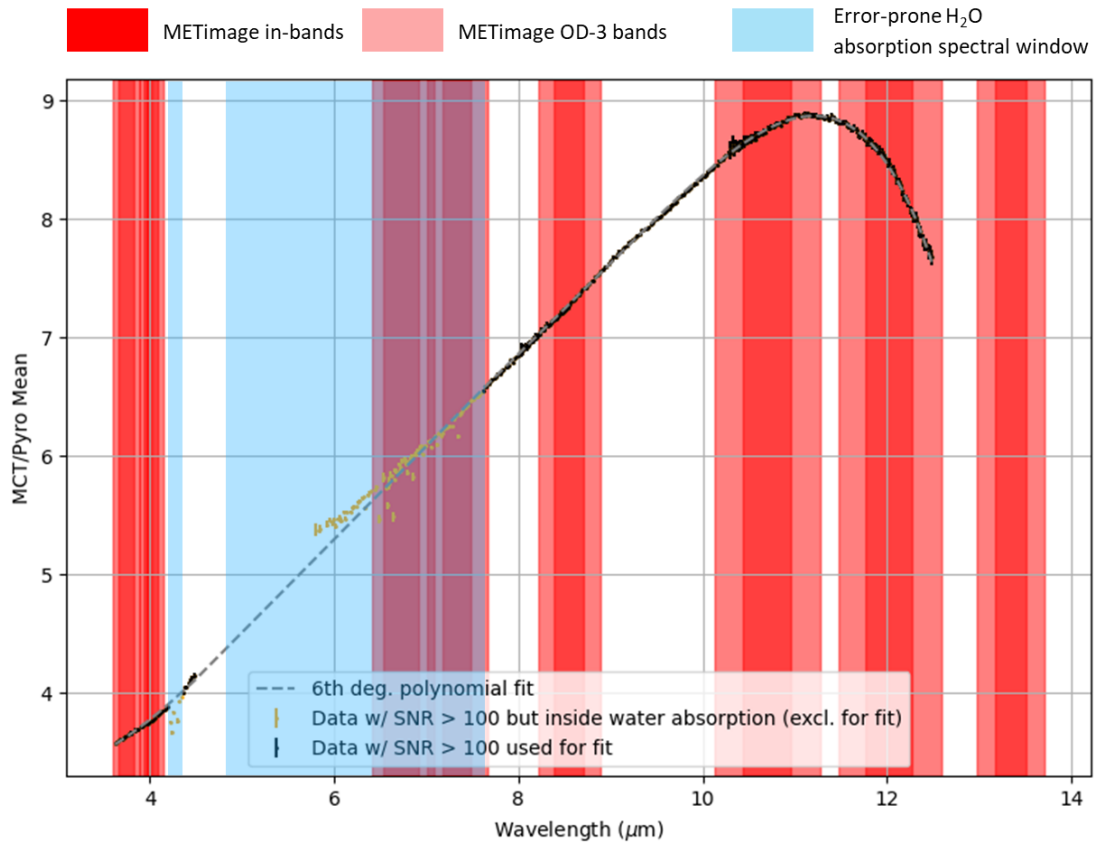


Figure 3. MCT/pyro cross-calibration measurement results. In red the METImage bands are given, where a saturated red indicates the full width at half-maximum regions of METImage and the light-shaded red gives the full band up to the estimated points where the signal of the ISRF goes below 10^{-3} (OD-3). As the measurement is performed in ambient conditions, spectral regions with stronger H_2O absorption are additionally highlighted.

The overall results are shown in in Figure 2. The datapoints there give the demodulated signal from the MCT divided by the demodulated signal from the pyro detector plotted over the laser wavelength measured by the spectrum analyser. Each plotted datapoint consist of a 1Hz-bandwidth acquired measurement from both detectors simultaneously, over 280 s, at a fixed wavelength. Detrimental laser fluctuations are minimized by waiting for the laser to stabilize after each detuning steps, and are moreover divided out by performing the point-by-point ratio of all MCT and pyro signals over the 280 s, and plotting the mean of it, in Figure 2. The native uncertainty of each point is symbolized by the vertical error bars ($\pm$ standard deviation) on the figure (barely visible). Note that native SNR < 100 are voluntarily ignored for clarity's sake. Horizontal error bars from the spectrum analyser are negligible.

As a reference, both METImage in- and OD-3 bands are shown, corresponding to the transmitting part of each instruments band (full width at half-maximum) and its region of relative transmission above 10^{-3} , respectively. As shown in the plot, the last instrument band above $12.48 \mu\text{m}$ cannot be properly addressed since both laser power and MCT response are too low in this band, leading to noisy measurements. This is not a principal limitation of the approach and can be overcome by using more powerful lasers in this region of the spectrum. In addition, the instrument's bands between 6.50 and $7.60 \mu\text{m}$ cannot be properly measured since they reside in the H_2O absorption bands that unavoidably deteriorate the measurements in the room-pressure and room-temperature conditions of the ISO5 laboratory in which the measurement setup is placed.

Table 1. MCT/pyro cross-calibration uncertainty budget.

Uncertainty	Value [%]	Summation
Pyro measurement imprecision	0.06	RSS
Pyro linearity uncertainty	0.10	RSS
MCT measurement imprecision	0.06	RSS
MCT linearity uncertainty	0.10	RSS
Pyro spectral response characterization inaccuracy	0.04	Linear
Wavemeter inaccuracy	0.01	RSS
Laser spectral sampling	0.01	Linear
Laser spectral linewidth inaccuracy	0.01	Linear
Total	0.23	
Allocation	1.00	

The uncertainty budget of each datapoint is shown in Table 1, highlighting a total uncertainty of 0.23 % (TBC), well within the allocation.

Measurement imprecision

For both MCT and pyro, native SNR > 100 mean points are computed over 280 points, providing a relative uncertainty well below 1 %.

Linearity uncertainty

Both MCT and pyro are used in a regime where they respond linearly, due to the low flux being injected to both of them. Hence, negligible residual linearity uncertainty is considered here. A value of 0.1% is provided in the budget, based on extrapolation of data from both detector's manufacturers.

Other uncertainties

The pyroelectric spectral response characterization is derived from a dedicated external verification measurement, in line with previously performed tests [4]. For the spectral uncertainty leading to a relative radiometric uncertainty, the inaccuracy provided by the manufacturer in nominal conditions are propagated to the MCT response, resulting in a negligible magnitude. Both laser's spectral sampling and linewidth contributions are considered negligible.

Interestingly, the overall shape of the curve Figure 2 exhibits a linear asymptote towards short wavelengths and drops off smoothly when approaching the energy cutoff of the MCT material. Since this behaviour is expected from an MCT detector, extra undetected fluctuations are smoothened out by fitting a polynomial to the overall data, as a convenient characteristic.

4. LONG-TERM BEHAVIOR RESULTS

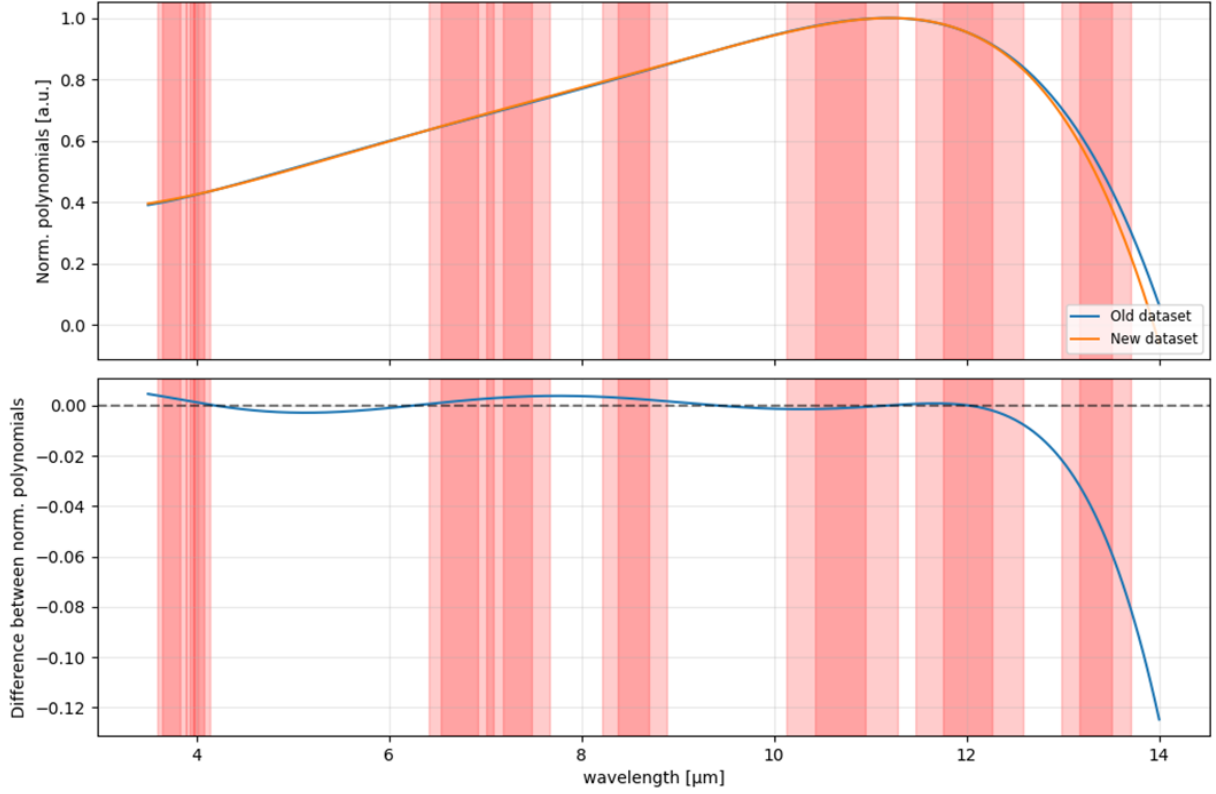


Figure 4. Polynomial fit extraction comparison between old (2022) and new (2026) dataset.

To test the relative stability of the presented calibration method, the exact same MCT detector has been calibrated after roughly 4 years (the original measurements were performed in late 2022 and the re-calibration then mid-2026, detailed in Figure 1). The comparison of both polynomial fits is shown in Figure 3. The top figure shows well matched fits while the bottom one quantifies the difference to be $< 0.50\%$ for the available datapoints. Since the fit is only extrapolated above $12.46\ \mu\text{m}$, it is evidently diverging in this region. However, the affected METImage band is analysed based on subsystem measurements and not an end-to-end calibration due to limited laser power.

Together with the measurement uncertainty of 0.23% detailed in Table 1, an overall 0.55% long-term measurement accuracy is achieved, well within the allocated 1.00% from the breakdown of all contributions participating to the METImage ISRF relative magnitude uncertainty.

5. CONCLUSION

With the presented setup, Airbus proposes a method for the relative spectral calibration of MCT detectors, even for detrimentally small sized detectors that are not accessible to the standard methods of precise spectral measurements. By carefully minimizing all sources of uncertainty, a 0.23% measurement accuracy is achieved over the bands from 3.55 to $12.46\ \mu\text{m}$ in ISO5 laboratory conditions, with an overall 0.55% accuracy when considering long-term behaviour over several years. This excellent performance has been made possible by exploiting the capabilities of a carbon-nanotube-covered pyroelectric detector judiciously provided by NIST. Combining it with the use of tuneable lasers to address a broad band and of a large integrating sphere to minimize geometrical effects, the presented calibration method has been proven to fit within the accuracy requirements requested by the METImage instrument, as reported by the instrument end-

user [5]. It is expected that this calibration method will play an essential role for the final spectral characterizations of major spaceborne optical instruments in the future.

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