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Xavier Gnata

Matthias Weidinger

Frank Schmülling

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METIMAGE – CALIBRATION & PERFORMANCE VERIFICATION

Xavier Gnata[1], Matthias Weidinger[2], Frank Schmülling[3]
[1] *Airbus DS GmbH, 81663 Munich, Germany*
[2] *Airbus DS GmbH, 88039 Friedrichshafen, Germany*
[3] *DLR, Königswinterer Straße 522-524, 53227 Bonn, Germany*

I. INTRODUCTION TO METimage

The METimage instrument is designed to serve the VIS/IR Imaging Mission (VII) of the EUMETSAT Polar System – Second Generation. It is a cross-purpose medium resolution, multi-spectral optical imaging instrument dedicated for operational meteorology, and climate applications.
METimage is implemented as passive imaging spectro-radiometer, capable of measuring thermal radiance emitted by the Earth and solar backscattered radiation in 20 spectral bands from 443nm to 13.345 µm. The instrument will be embarked on MetOp-SG satellite A.
The METimage instrument is designed to provide the users with two kind of calibrated products: Calibrated top of atmosphere radiances for the solar channels up to 2.250µm and calibrated equivalent temperatures for the thermal channels up to 13.345µm. A comprehensive description of the METimage is given in [1]. Therefore in this paper we assume familiarity with the METimage overall concept and design. We present the challenges and the selected means to perform the calibration and performance verification of the METimage instrument.

II. CALIBRATION AND PERFORMANCE VERIFICATION LOGIC

The performance verification of the METimage starts with the breakdown of the customer requirements into system and then subsystem requirements. In parallel, performance models and budgets are set up for each major METimage performance parameter such as SNR. During the C/D phase, these budgets are kept up to date using the characterizations performed at component level, subsystem level and during the Assembly Instrument Integration and Test (AIT) process. This process ensures a correct balance of the system margins and eventually compliant performances at system level. However, the results of the models and of the performances computations still need to be validated by end-to-end measurements at system level. Following the "Test as you fly, fly as you test" principle, this validation is performed on METimage in its flight configuration and in a thermal vacuum environment mimicking in-orbit conditions. The end-to-end tests performed primarily for validation also serve the calibration process. They are often more accurate than a sum of several measurements on subsystems. One typical example is the absolute radiometric calibration. In theory, a radiometric calibration is a characterization of the throughput of the instrument. This throughput can be defined as the product of the throughput of each component of the optical train. The issue is that the sum of the errors bars on the throughput measurement of each optical surface results in a total inaccuracy which is not compatible with the required absolute radiometric calibration accuracy. Therefore, the absolute radiometric calibration shall be based on end-to-end measurements at instrument level. Nevertheless, the characterizations performed at subsystem level are key to secure the performance budgets and to accumulate knowledge on the instrument to support debugging in case of malfunction.

II. RADIOMETRIC CALIBRATION CONCEPT ON GROUND AND IN FLIGHT

The radiometric calibration process of the METimage starts on-ground with collection of all the data needed to convert raw detector data and telemetries (Level 0) into radiances or brightness temperatures (Level 1). These data called keydata are used as input parameters to the algorithms implemented in the Ground Prototype Processor (GPP) to compute Level l products.

To calibrate the radiometry of METimage thermal channels, an Optical Ground Support Equipment (OGSE) blackbody is placed in front of the Earth View. For the sake of clarity of this paragraph, we assume that the non-linearity of the detection chain has been calibrated out. Under this assumption, the radiometric calibration comes down to a gain and an offset calibration. The OGSE blackbody serves as the reference for the absolute radiometric calibration of the thermal channels. The offset is measured separately when the scanner is pointing to the Deep Space View (DV). See Fig. 1. On-ground the deep space is mimicked by a Beam Dump. The Beam Dump is a black cavity cooled by LN_2 down to less than 100K. The cavity is mounted as close as possible to the METimage DV in order to minimize the coupling of background flux coming from the surrounding into the cavity and eventually into METimage optics. This ensures that the radiance at the exit of the Beam Dump is not significantly higher on-ground than in-space. The temperature of the OGSE blackbody is varied to cover the specified dynamic range of METimage and to derive the radiometric gain calibration. METimage is also equipped with an on-board Thermal CAlibration Device (TCAD) which is essentially a temperature controlled black plate equipped with 1mK accurate temperature sensors throughout the lifetime of the instrument. The TCAD serves as a reference to monitor the radiometric gain of thermal channels in-orbit. This monitoring starts by the acquisition of reference points during the on-ground calibration of METimage.

The concept of the calibration of the solar channels is different. METimage does not rely on an absolute radiometric standard (e.g. an FEL lamp) as an anchor point for the absolute radiometry of the solar channels. The role of this anchor point is played by an absolute sun irradiance spectrum provided by the customer. It implies that METimage must have the capability to observe the sun in-orbit. This functionality is implemented by the Solar CAlibration Device (SCAD). The SCAD consists of a diffuse surface which is illuminated by the sun once per week. The Bidirectional Reflectance Distribution Function (BRDF) and the orientation of this surface are designed to convert the sun irradiance into typical Earth radiances. The ratio between the radiometric transfer function of the METimage in Earth View and in SCAD view is measured on ground. This measurement requires a sun beam simulator to mimic the sun illumination on the SCAD. The same sun beam simulator is then used to illuminate an OGSE diffuser which is observed by the METimage Earth View. The BRDF of this OGSE diffuser has been calibrated; hence one can derive the ratio between the METimage throughput in SCAD View and in Earth View. During the commissioning of METimage, a first Sun observation with the SCAD is performed. This observation and the absolute sun irradiance provided by the customer define the radiometric anchor point to derive absolute Earth radiance. As the SCAD measurements are repeated every week throughout the mission lifetime, drifts of the instrument throughput are monitored and accounted for in the Earth radiance computations. The SCAD diffuser is made of Spectralon. Aging of Spectralon plates facing the sun every week is a known issue. Hence, METimage is also equipped with a Reference SCAD diffuser. When a significant throughput degradation of the SCAD View is detected, the reference diffuser is used to determine if the degradation comes from the diffuser itself of from the optical train. Only the degradations of the throughput of the optics, i.e. changes of the radiometric gain, are accounted for the Earth radiance computations. The offset of the solar channels is monitored by observing the Deep Space View in the same way as for the thermal channels.

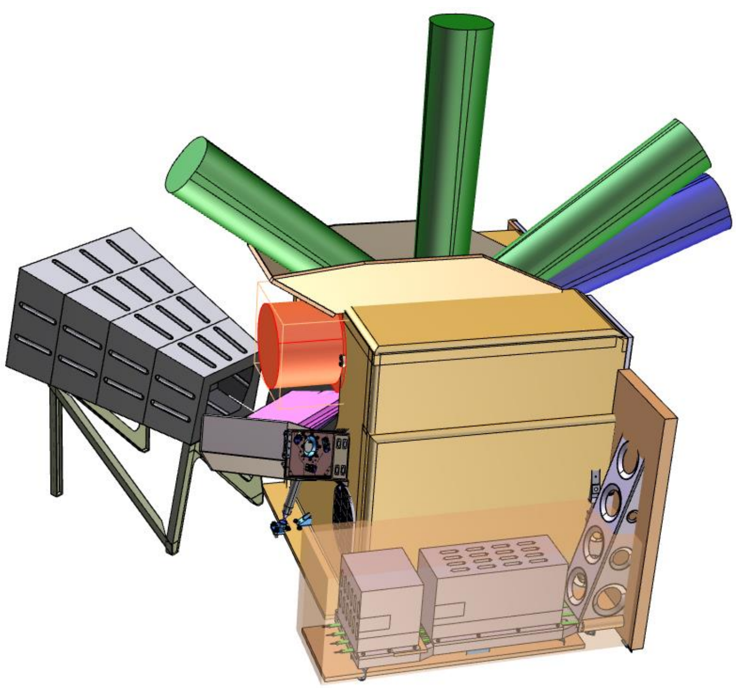

Fig. 1. View of the METimage featuring from left to right the SCAD diffuser in pink, the TCAD in red, the Earth View in green and the Deep Space View in blue.

II. ON GROUND CALIBRATION METHODS AND EQUIPEMENT

A. On ground radiometric calibration equipment

As per customer requirements, the radiometric bias error of the shortwave channels (< 3µm) and the longwave channels (> 3µm), shall be less than 5%, respectively 0.5K. Moreover, in order to ensure the spectral uniformity of the scientific products, this bias error is required to be the same error on each channel within 1.00 to 1.25% for the shortwave channels and within 0.100K to 0.120K for the longwave channels. The spatial uniformity of the products is controlled by a requirement asking for the same bias within 1% (<3µm) and 0.1 K (>3µm) for each pixel of one given channel. Based on these customer requirements and following the calibration concept described in the above section, driving requirements on the OGSE have been derived.

For the blackbody:

- Emissivity shall be greater than 0.999.
- Blackbody temperature shall be tunable over the 180K to 350K temperature range.
- Temperature stability shall be better than ±0.010K (3σ) and thermal uniformity better than ±0.02K.
- The black body diameter shall be larger than 200mm.
- Vacuum and cleanliness compatibly with the METimage contamination control plan.

For the Sun Beam simulator:

- ISO 8 compatible.
- Beam Diameter larger than 300mm
- Beam divergence of 0.5°.
- At least 10% of a solar constant from 400nm to 3µm
- The flux stability of the SBS shall be better than 0.1% over 2 hours.
- The flux repeatability of the SBS shall be better than 0.2%
- Homogeneity of the beam better than 10%

The OGSE diffuser BTFD from 400nm to 3µm shall be calibrated down to state of the art accuracy by a NMI.

Each of these requirements is challenging. Moreover, the sketch of the radiometric calibration concept in the above section does not mention the angular dependencies. The radiometric gain is a function of the scan angle across the Earth view. This angular dependency has to be calibrated. As the blackbody has a static position during the calibration campaign, it is necessary to compensate the scanner rotation with a contra-rotation of METimage. The same holds true for the SCAD calibration with a static Sun Beam Simulator. The sun incidence angles vary as a function of the season and of the exact time at which the SCAD measurement is performed. The range of these variations is covered on ground by a rotation of METimage around the SCAD. This requires a sophisticated Mechanical Ground Support Equipment (MGSE) which shall be compatible with the thermal-vacuum test environment. See Fig. 2 and Fig. 3.

Once the radiometric calibration has been performed, the noise of the detection chain and the throughput of the instrument are known. The METimage performance models are eventually updated with these as-built parameters to perform a straightforward verification of the SNR requirements at instrument level.

B. Spectral response and pointing characterization

On top of absolute radiometry, the spectral response of each channel shall be characterized over the spectral range where they exceed a value of 0.1% of the peak response with accuracy better than 2 % of the peak response and sampling interval of 1 nm. This requires an OGSE able to illuminate the entrance pupil of the METimage with monochromatic light source, tunable over a range from the 400nm to 14 µm range. This OGSE called the Collimation Assembly is implemented as a collimator in vacuum with the sources in the object plane of this collimator. The choice of a collimator and not e.g. of an integrating sphere is driven by the fact that the same OGSE is also used to verify the co-registration requirement. In a nutshell, the co-registration requirement limits the physical distance between detector pixels PSF barycenters when viewing the same target on Earth.

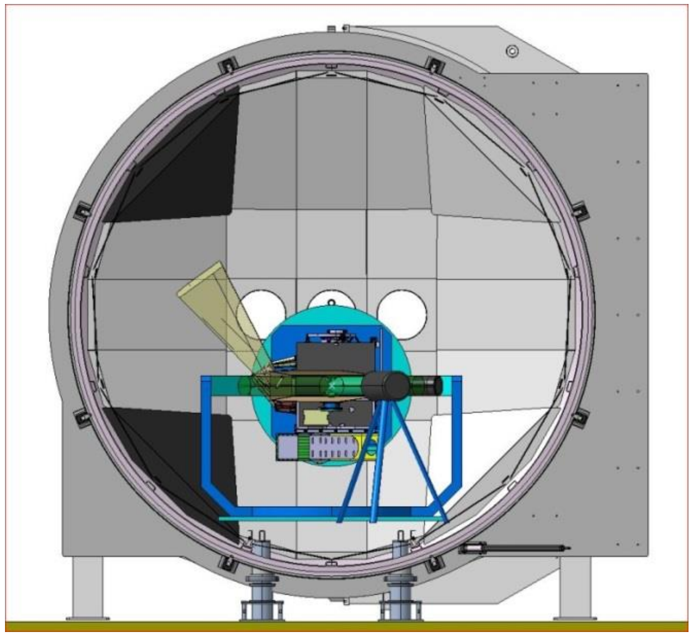

Fig. 2. METimage and its MGSE is the vacuum chamber.
Configuration for the Earth port measurements (beams in green).

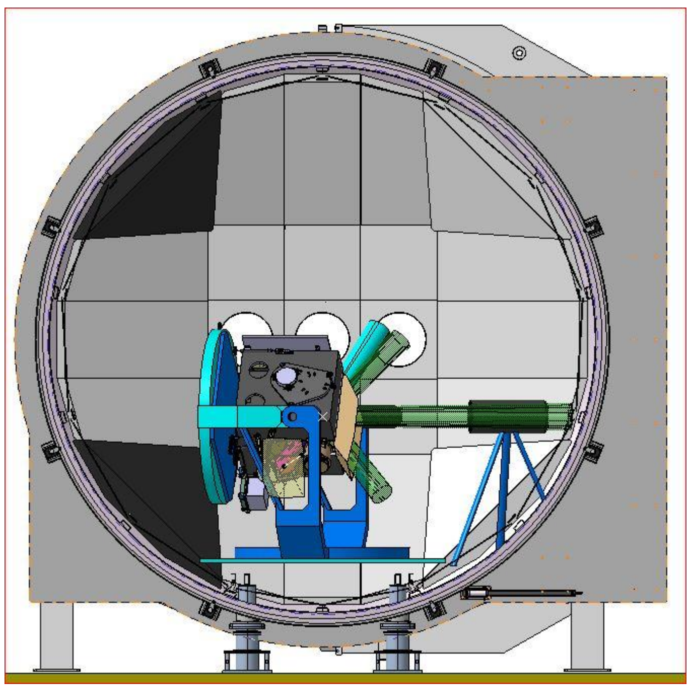

Fig. 3. METimage and its MGSE is the vacuum chamber.
Configuration during the SCAD measurements (beams in yellow) around water level with the sun beam simulator.

The verification of this requirement is based on a broadband point source in the object plane of the Collimation Assembly. When scanned across the field of view, the image of the broadband point source shall be centered at the same time on the corresponding pixels of the three METimage detectors. Being able to image point sources also allows the characterization of the pointing (versus an optical cube mounted on the METimage) and of the distortion. This characterization has to be accurate enough to serve as a starting point for the Image Navigation and Registration process, knowing that other error sources, such as the alignment of METimage on the platform or in-orbit thermo-elastic effects, have to be taken into account. These measurements needs drive the specifications of the Collimation Assembly. It is a challenge to design an OGSE providing both a tunable and a broadband illumination over the METimage wavelength range as well as imaging capabilities with a good contrast. See Fig. 4. for an example of a Collimation Assembly serving similar purposes in the frame of the Sentinel 4 project. One major difference is that Sentinel 4 infrared channel ranges only from 750 to 775nm whereas METimage covers the thermal infrared up to 13.345µm. As a result, for contrast and radiometric stability reasons, the METimage Collimation Assembly has to be in vacuum and not in air as for Sentinel 4. Nevertheless, the basic concepts underlying the design of these two Collimation Assemblies are similar.

C. Straylight verification and calibration

Several types of straylight have been identified in the early phases of the project. For each of these straylight contributors, a detailed model has been developed to assess the impact in terms of radiometric accuracy. These models are also used to predict the straylight levels dependencies e.g. to the scan mirror positions or to wavelengths. Based on these simulations, the measurements sequences at instrument level are defined as well as the OGSE needs and the GPP algorithms to correct Level 0 data from straylight.

The first type of straylight is the out-of-band straylight. “Out-of-band straylight” is defined as the light which reaches one detector channel at a wavelength which is outside of the corresponding channel bandwidth. The main sources of out-of-band straylight are the ghost images in the relay optics of the infrared channels. Part of the photons which went through the filter corresponding to their wavelength reach the wrong detector pixel due to spurious reflections in the relay optics. Ghost processes in the relay optics can couple light from any detector pixel to another one. If these two pixels are in the same channel, then the impact is on the spatial radiometric homogeneity requirement. If these two pixels belong to different channels, then the spectral homogeneity performance is impacted. The ghosts are characterized on-ground using the Collimation Assembly. As explained in the previous section, the Collimation Assembly offers the capability of illuminating only one channel or even one pixel at the time. The wavelength of the illumination can also be tuned. A comprehensive measurement sequence at instrument level using the Collimation Assembly is analyzed to populate a 4D table. Each entry of this 4D matrix is one detector pixel (2D) and, for each entry, the level of straylight coupled into each detector pixel (again 2D) is stored. On top of the ghosts in the relay optic, ghosts on the visible detector are also taken into account by this approach. These ghosts can be due to e.g. reflection on the beamsplitters or to the broadening of the Point Spread Function of the relay optics inducing optical pixel cross talk. This 4D table is an input to the out-of-band straylight correction algorithm in the GPP. Such a flexible approach to correct straylight is possible because the fairly limited number of METimage pixels. Note that this type of straylight is not a function of the angular position of the scanner.

The second type of straylight is the in-band straylight. We define “in-band straylight” as false light which reaches the detector channel corresponding to its wavelength. The main contributor is the straylight is coming from the METimage structure in the thermal channels. This type of straylight is a priori a function of the scanner/derotator angular position. A detailed modeling of the structure and of the way its thermal emission is coupled into the optical train has been implemented in Zemax. See Fig. 5. The challenge for the on-ground characterization of this type of straylight is to predict and to reproduce the in-orbit thermal gradients (both spatial and temporal) inside METimage in a representative way. Part of the in-band straylight also comes from light from the Earth in the neighborhood (up to 10°) of the instantaneous Field of View for on scanner position in the Earth View. This light is coupled into the nominal optical train via the BTDF of the scan mirror. The BTDF is driven by both the level of particulate contamination on the scan mirror and by its micro roughness. The micro roughness has been specified down to very stringent levels. Concerning contamination, the main issue is to perform the on-ground characterization with a number of particles on the scan mirror which is close to the one in-orbit. This is ensured by a recalibration after storage of the METimage models which are subject to long term storage.

E. Polarization verification

The polarization sensitivity of METimage has to be characterized to within 0.5 percentage points. The polarization sensitivity is defined as a maximum of the relative throughput variation when the linear polarization of the scene is gradually rotated over 180°. The polarization sensitivity of the instrument is also required to be lower than 5% for the shortwave channels and 11% for the longwave ones. During the phase C/D, a Zemax model including each type of coating is set up and then updated based on components/subsystems measurements to ensure compliance to the polarization sensitivity requirement. The characterization of the polarization sensitivity is challenging because one single type of polarizer cannot span the full METimage wavelength range. Furthermore, the flux emitted by the OGSE during the rotation of the polarization state has to be either spectrally stable or monitored with an accuracy much better than 0.5%. The

Collimation Assembly specification contains as section dedicated to polarization which enables an end-to-end polarization characterization of METimage. However, if the implementation of the specified polarizers turns out as being too complex and risky, a characterization on some channels only, plus a model correlation to extend the results to all the channels will be considered. As explained in the first section, a comprehensive characterization of the subsystems (here of the coatings) and detailed performance models are essential to ensure compliance at system level throughout the C/D phase and its set of unavoidable changes.

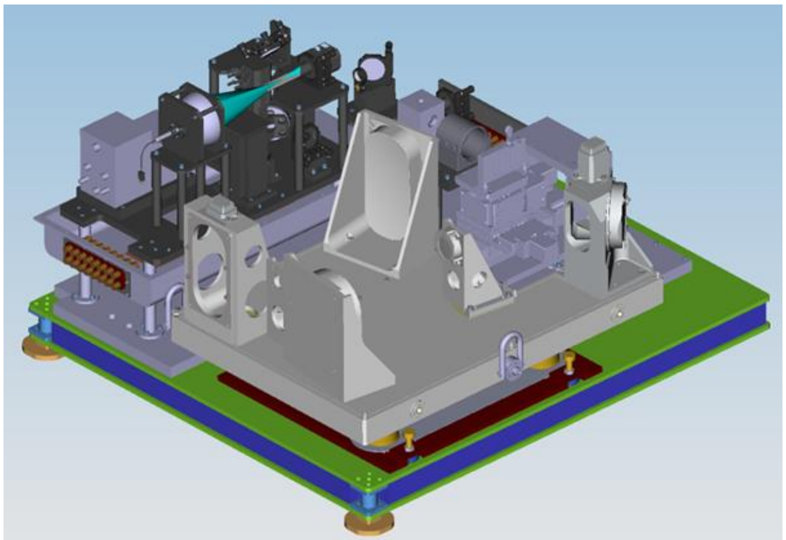

Fig. 4. One example of a collimation assembly (Sentinel-4 project)

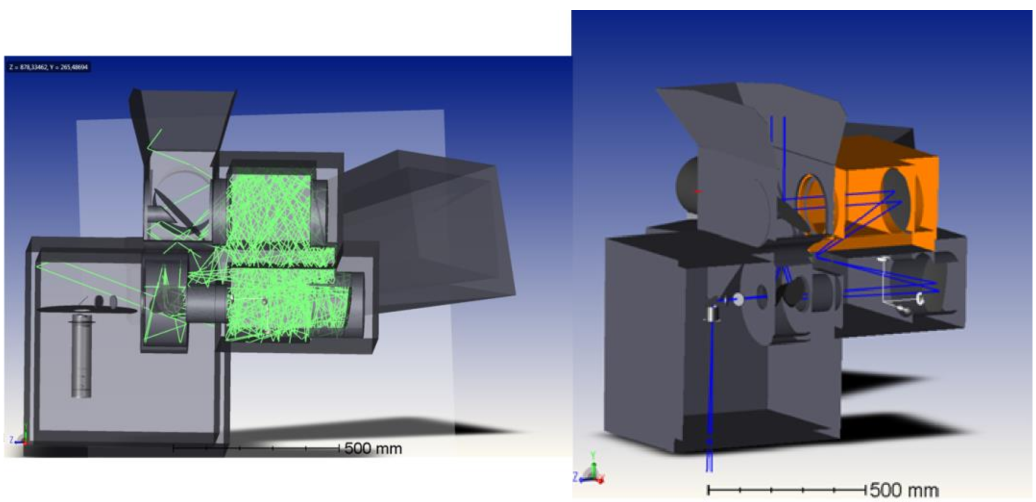

Fig. 5. Modelling of the mechanical straylight in Zemax.

E. Electronic Ground Support Equipment

The Electronic Ground Support Equipment (EGSE) is also an essential part of the GSE needed to perform the verification and calibration at system level. The EGSE shall allow METimage and M/OGSE in a flexible way which minimizes the overheads while keeping an excellent level a configuration control. Experience shows that the users should be included as early as possible in the design of the EGSE human interfaces. All the EGSE interfaces and scripts shall be thoroughly validated before the start of the test campaigns. For each requirement and each keydata computation, scripts (based on GPP modules) have to be developed to analyze the data and produce a compliance status in a human readable way. Most of these computations are based on fairly trivial image processing algorithms. However, the main challenge is to sort out the relevant data live while METimage is producing about 9000 images per second.

F. Detection chain characterization

In the above sections, we assume that METimage non-linearity has been calibrated out. As all radiometric calibration algorithms in the GPP assume a linear system, the non-linearity correction is the first correction to be applied on the raw data. A step by step approach is taken to ensure that the sources of non-linearity of the detection chain are well mastered. First, the non-linearity is measured by the detectors suppliers with a test electronic. In parallel, the non-linearity of the Front End Electronic is characterized. Eventually, a linearity characterization is performed on the detector coupled to its flight Front End Electronic. At this level, the detection chain is illuminated by a dedicated OGSE via the field marks, the filters and relay optics of the infrared channels. The challenge is to control the background levels during these linearity measurements and to ensure the optical and thermal stability of the both the M/OGSE and the detectors. The non-linearity characterizations are performed in dedicated dewars and vacuum chambers. Inaccuracies in the non-linearity characterization of the pixels impact the spectral and spatial uniformities quoted in Section II A. That is why the linearity of the METimage detection chains has to be characterized with unprecedented accuracy over the full dynamic range.

III CONCLUSION

The METimage calibration and performance verification requires a complex set of ground support equipment. This set of OGSE consists of a Tunable Blackbody, a Beam Dump, a Sun Beam Simulator and Collimation optics including unpolarized and polarized broadband sources as well as tunable monochromatic ones. All the OGSE and METimage are controlled on-ground by one EGSE system which also provides us with test data storage and processing capabilities. The performance of both the ground support equipment and of the METimage subsystems are closely monitored during phase C/D to ensure compliance at system level.

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