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MET*IMAGE* – AN INNOVATIVE MULTI-SPECTRAL IMAGING RADIOMETER FOR THE EUMETSAT POLAR SYSTEM FOLLOW-ON SATELLITE MISSION

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ABSTRACT

The evolving needs of the meteorological community concerning the EUMETSAT Polar System follow-on satellite mission (Post-EPS) require the development of a high-performance multi-spectral imaging radiometer. Recognizing these needs, Jena Optronik GmbH proposed an innovative instrument concept, which comprises a high flexibility to adapt to user requirements as a very important feature. Core parameters like ground sampling distance (GSD), number and width of spectral channels, signal-to-noise ratio, polarization control and calibration facilities can be chosen in a wide range without changing the basic instrument configuration.

Core item of the MET*image* instrument is a rotating telescope scanner to cover the large swath width of about 2800 km, which all polar platforms need for global coverage. The de-rotated image facilitates use of in-field spectral channel separation, which allows tailoring individual channel GSD (ground sampling distance) and features like TDI (time delay and integration). State-of-the-art detector arrays and read-out electronics can easily be employed.

Currently, the German DLR Space Agency, Jena-Optronik GmbH and AIM Infrarot Module GmbH work together implementing core assemblies of MET*image*: the rotating telescope scanner and the infrared detectors.

The MET*image* instrument phase B study was kicked-off in September 2008. Germany intents to provide MET*image* as an in-kind contribution of the first MET*image* flight model to the EUMETSAT Post-EPS Programme.

1. INTRODUCTION

The currently implemented imaging radiometer on the operational polar system satellites of EUMETSAT and NOAA is the AVHRR (Advanced Very High Resolution Radiometer). It provides an on-ground sampling distance of 1.1 km and records six spectral channels in the visible and infrared region. Current trends may take future requirements into the range of about ten times the density of sampling points, increase of signal-to-noise ratios by an order of magnitude or more and considerable reductions of spectral band width. The number of spectral channels recorded may well be several times of the current value, e.g. ten to thirty.

Though not all of these improvements may be required in all channels to the same extent, one aspect is quite obvious: the trend to increase the resolution in all domains (i.e. spectral, radiometric and spatial) comes at the cost that less and less photons are available for measurement at the detector level. The next generation of operational imaging radiometers will therefore have to leave the concept of one detector pixel per spectral channel, which is the current standard. Instead, detector lines are employed in each spectral channel, imaging a couple of ground pixels (e.g. 20) at the same time. In this way, the scanning motion can be slowed down, without losing the gapless ground coverage. Due to slower scanning motion, the integration time of each pixel can be increased, producing the required gain in signal strength.

A next generation instrument should have a spectral range from about the near UV/blue edge of the optical range to the thermal infrared. Combining them into a single optical instrument leads to the use of reflective optics, as the imaging properties of reflective optics have only low wavelength dependency (a lens system could hardly be corrected to a reasonable optical quality ranging from UV to thermal IR).

To provide the required large revisit rate, the instrument should image the ground scene nearly horizon to horizon. For polar low Earth orbit, this means a field-of-view of about 110°. With reflective optics, such a wide field-of-view is not feasible. Instead, a mechanical scan motion of the instrument is introduced. Different approaches for mechanical scanners exist. However, the simplest ones have the disadvantage that the images rotates around the optical axis, while scanning the scene. More advanced scanners allow using matrix fields of detectors, which image the scene subsequently on the different spectral channels.

In Europe, preparatory activities for a follow-on programme for the EUMETSAT Polar System (Post-EPS) have been started. The first satellite of Post-EPS needs to be ready for launch in 2018. The candidate mission VII (VIS/IR Imager) has requirements similar to those of the US-American VIIRS (Visible/Infrared Imager Radiometer Suite), but optimized for the European user needs. An innovative concept for VII called MET*image* was proposed by Jena-Optronik. The actual MET*image* concept was defined in a Phase A study co-financed by DLR Space Agency. The MET*image* instrument phase B study was kicked-off in September 2008. Additionally, the MET*image* project is supported by technology breadboard activities on the scanner assembly and the infrared detectors. The MET*image* concept, which has a high potential for Post-EPS, is described in detail in this paper.

2. MET*IMAGE* INSTRUMENT CONCEPT

MET*image* is a family of imaging radiometer instruments for operational applications. It is shaped for flexibility in adaptation to user needs. It is based on an instrument system design with subsystems, which only have a weak impact onto each others design. So "standardisation" is performed on basic technical approaches in these subsystems.

During the feasibility study (Phase A) of MET*image* two smaller instrument versions were analyzed (versions "A" & "B1"). These instrument versions do not match the user requirements for mission VII priority 1&2 spectral channels of the current Post-EPS MRD draft version (16 P1 and 9 P2 channels). These smaller MET*image* types will not be further studied. The remaining instrument versions are:

MET*image* B2: Scaled version of B1 allowing for higher resolution, higher signal-to-noise ratio, larger number of channels

MET*image* C: Modified concept for better polarisation sensitivity and slightly better performance than B2

Core element of the instrument is a rotating telescope scanner to provide the large swath width needed for global coverage in the METOP orbit. Performance parameters are summarized in Table 1.
MET*image* uses focal plane arrays facilitating the use of in-field spectral channel separation. For example, number and resolution of individual channels can be easily reshuffled on the focal plane, without impact on the optical/mechanical design. The same is true for choosing the number of calibration sources within the maximum limits.

Table 1: Performance parameters for the two MET*image* configurations. Common to both is an operating FOV of +/- 55° for 2800 km swath width from a 817 km orbit.

MET*image* Type		**B2**	**C**
Channels		up to 30	up to 30
GSD	[m]	250-1000	100-500
Pol. Sensitivity	[%]	<5 (λ > 0,5 μm)	<1
Polarization Scrambler		no	yes
Volume (Optical Head)	$[cm^3]$	66 x 80 x 68	90 x 80 x 68
Mass	[kg]	96	150
Power Consumption	[W]	72 (16 channels)	85 (16 channels)
		50 (for active cooling)	50 (for active cooling)

It is *not* attempted to design off-the-shelf standard modules. For the sophisticated instruments discussed here, such approaches often fail in practice, because the need for standard interfaces between modules leads to penalties with respect to budgets, which the end-users normally do not want to bear. Moreover, the instrument is not expected to be the only one on the platform, so there has to be flexibility in implementing the user's constraints.

So the development focuses on a system design, which has the desirable property of weakly interdependent subsystems and on mastering the core technologies within each subsystem. An important aspect is the distinct need for solutions with high reliability and long term stability: operational systems like the post-EPS must operate for many years without interruption, as a large user community relies on the availability of its data for vital services.

Mastering of core technologies is the subject of the ongoing technology developments: the rotating telescope development provides an optical/mechanical system with the required optical quality and mechanical stability, including the synchronisation of the two rotating elements. The detector development provides detector elements and read-out electronics for the demanding infrared range. Both these areas are discussed in more detail below.

3. TECHNICAL FEATURES OF MET*IMAGE*

3.1 Scanner Design

MET*image* employs a rotating telescope scanner, which produces no image rotation, as required. This scanner does not need a big rotating front mirror (like the so-called in-plane scanners). It rotates the telescope itself and uses at the telescope output a small half-angle mirror, which is synchronised to the telescope rotation and produces a standing image from the rotating telescope output. The principle of the MET*image* scanner geometry is shown in Fig.1.

MET*image* employs a permanent rotation of the scanner, rather than an oscillation. Due to its large useable field-of-view, several calibration sources can be viewed during one rotation, providing various calibration options without any additional mechanisms to get the calibration source into the field-of-view. Such calibration sources could be "black bodies" for infra-red calibration, or sun reflectors for visible light or spectral sources. This configuration is therefore very well suited to fulfil the upcoming needs of more precisely calibrated absolute measurements.

3.2 Optical System

The core of the MET*image* instruments is the rotating telescope. It is a three-mirror anastigmatic design. This advanced mirror telescope type has properties which can not be achieved by the more traditional two-mirror telescopes.

The higher technical effort in terms of number of optical elements and use of aspherical optical surfaces leads to strongly improved performances: The field-of-view can be much larger, which is necessary to record a couple of ground traces at the same time with detector lines, and implement the in-field spectral separation. So from an altitude of 800 km, e.g. a 20 km long swath can be recorded, rather than e.g. a 1 km swath.

The radiometric sensitivity can be higher than in a comparable size two-mirror telescope, as there is no central obscuration and the f-number, which characterizes the optical throughput, is also better. At the same time, a high image quality can be achieved throughout the field of view, nearly diffraction limited (which is a physical limit). This is due to the availability of three optical elements plus the use of an aspheric mirror, instead of two spherical mirrors in earlier designs.

On the one hand, this quality is high enough to accommodate most demanding ground resolution requirements in the future, e.g. 100 m. On the other hand, the high quality of the basic design opens space for trades with other parameters, should mission requirements not be that demanding.

3.3 Mechanical Design

While the necessity for a well adapted optical design is easy to perceive, the intricacies of the mechanical design may not be so obvious. However, the accuracy and stability of the mechanical structure supporting the assemblies like “rotating telescope” and “half angle

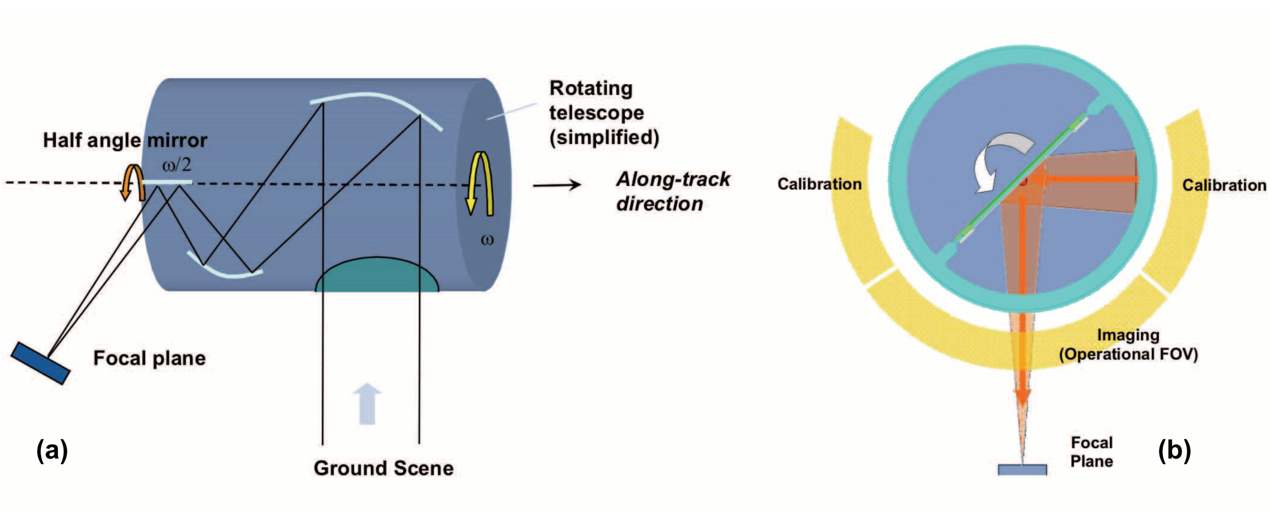

Fig. 1: (a) Simplified principle of a rotating telescope scanner. The off-axis telescope rotates around an axis perpendicular to the viewing direction. A stationary image in the focal plane is produced by the plane “half-angle mirror”, which rotates at half the rate. (b) Different portions of the field-of-view (FOV) are used for imaging and calibration, without need for additional mechanisms to move calibration sources into the optical path or interruption of normal operation.

mirror" is crucial for core performances related to line-of-sight stability: should rotation axes deviate from their ideal positions, the direction of the optical axis would change, and with it the line-of-sight as well. The knowledge, to what location on-ground a certain recorded radiometric value is referenced, would get lost. As a result, requirements for relative stability of subassemblies can be as low as a few arc seconds.

3.4 Focal Plane

MET*image* employs so-called "in-field separation" of spectral channels (Fig. 2). This implies that the detectors for the different spectral channels are located in a row on the focal plane. Due to the spacecraft motion, the image of the ground scene moves sequentially over all these detectors. So by appropriate synchronisation of the detector read-out, the same ground pixel is sequentially measured by the different detectors in different spectral ranges.

In this design, no separate optical paths for different spectral channels are needed. The approach is therefore very flexible regarding the number and kind of spectral channels; they are just located side-by-side on the focal plane.

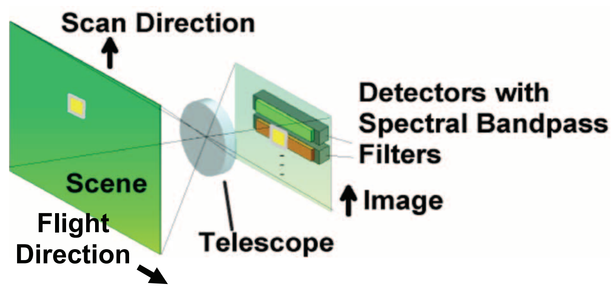

Figure 2: In-field separation of spectral channels. Due to the satellite motion, the image of a certain pixel moves straight over the focal plane with an arrangement of detectors. There it is sequentially imaged by detectors with different spectral filters.

This approach has another big advantage: the size of the detector pixels can be different for different spectral channels (Fig. 3). In effect, the ground resolution of different channels can easily be made different, dependent e.g. on the amount of optical signal available, and on the specific optimisation with respect to ground resolution and signal-to-noise ratio.

Finally, the focal plane approach allows doing multiple exposures of the same pixel very easily: the same spectral channel is simply duplicated as many times as multiple exposures are desired. The reason to do so is simply to increase the available signal by adding up these multiple exposure results, in order to increase the signal-to-noise ratio at low signals.

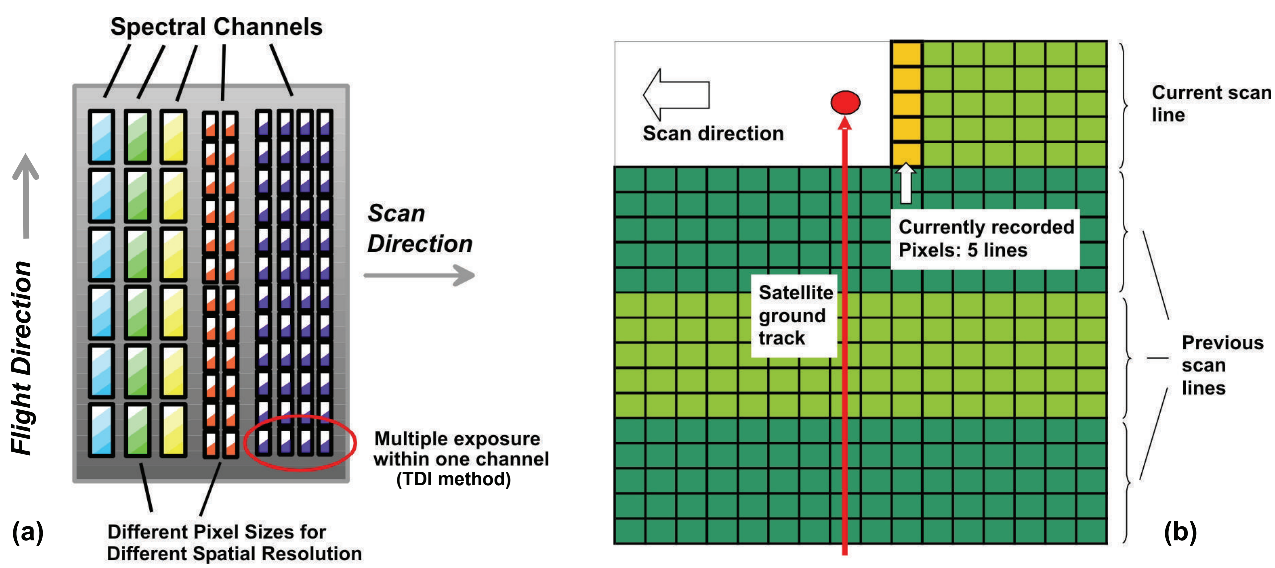

Figure 3: (a) Detector arrangements in the focal plane Depending on detector size, spacing and number for each spectral channel, the ground resolution can be individually tuned and multiple exposure capability included or not. The vertical extension gives the number of ground traces simultaneously recorded (here six for the low resolution and twelve for the high resolution channels).
(b) Recording pattern of a rotating scanner with multiple pixel lines per scan. In this example, five lines are recorded simultaneously in along-track direction, while the scan is across track. As the scan speed is high with respect to the satellite ground speed, the scan lines provide gapless ground coverage, in spite of the scanner rotating through some "dead angle" where no imaging is performed.

3.5 Infrared Sensor Arrays

Detectors are a second crucial element in the imaging radiometer. The quality of the detection chain, consisting of detector plus read-out electronics, is decisive for the radiometric accuracy. A couple of detectors made from different semiconductor materials will be necessary to be employed, as the spectral sensitivity is dependent on the material and the performance is generally the better, the better the material is matched to the target wavelength range. This is especially true in the infrared region. As there is a tendency to use more and more infrared channels, and the IR are normally the most demanding ones here, we focus on IR detectors.

The space-borne rotating telescope MET*image* is planned for observing the earth in the spectral range from below 1 µm up to 14 µm in a polar orbit in east-west direction. The second image dimension is provided by the satellite forward motion. The optically rectifiable field requires a compact design of an infrared focal plane covering the system specific infrared sensitive elements. Essentially, the sensor parameters determine the instrument overall performance. As the given spectral range can not be covered by a single infrared focal plane array complying with the expected performance characteristics, one is forced to subdivide the focal plane in sub-arrays, optimised in accordance to the defined spectral channels of MET*image*. The adjustment of the infrared sensitivity to the specific infrared channels can be accomplished using the pseudo-binary infrared sensitive semiconductor $Hg_{1-x}Cd_xTe$ (MCT) as available at AIM. The adaptation of the material composition x, (i.e. ratio Hg1-x / Cdx) enables to optimise the spectral sensitivity with respect to the MET*image* specific channels:

Short wavelength infrared (SWIR):	λ = 0.9-2.5 µm
Mid wavelength infrared (MWIR):	λ = 3-6 µm
Long wavelength infrared (LWIR):	λ = 7-9 µm
Very long wavelength infrared (VLWIR):	λ =10-13.5 µm

The infrared arrays are cooled down to approximately 90 K in order to optimise their signal-to-noise ratio. The minimum detector operation temperature also defines the infrared sensor technology: high-sensitive SWIR, MWIR, and LWIR arrays will be based on photo-voltaic MCT detectors, whereas for the VLWIR spectral range photo-conductive infrared detectors need to be considered. Both detector MCT detector technologies are available at AIM being the workhorse for infrared production programmes. MET*image* infrared focal plane arrays require a customised design regarding the peculiar rotating telescope constraints including application specific readout integrated circuits (ROIC) adapted to the radiometric requirements.

The conceptual design and the specific feature of MET*image* infrared focal plane arrays allows a signal-to-noise improvement by applying a Time Delay and Integration procedure (TDI) utilising the rotating scan of the MET*image* instrument, perpendicular to the flight direction (Fig. 3a). The TDI mode is achieved by arranging an array of infrared detector elements in the focal plane where the signal of the same foot print will be scanned via the rotating telescope to successive sensor pixels. The signals of the individual detector pixels are integrated resulting in a signal-to-noise improvement of the square root of the number of pixels.

The optically correctable area of the MET*image* focal plane limits the number of detector elements and hence the number of pixels on the focal plane. Another limitation for the array size is given by the maximum heat to be dissipated by the radiation cooler.

4. MET*IMAGE* INSTRUMENT CONFIGURATIONS

A basic block diagram of a possible configuration of a MET*image* instrument is shown in Figure 4. The basic "building blocks" are the scanner, which produces the optical image, and the focal plane, where the detectors are located to convert light into electrical signals. A more advanced instrument version may have three focal planes (for detectors with different cooling needs) with e.g. 25 spectral channels. Multiple calibration sources are implemented to guarantee high long-term absolute accuracy. A sophisticated thermal control makes the instrument independent of thermal effects from the outer environment. For applications where e.g. visible and infrared optics can no longer be handled in a single optical path, an instrument configuration exists where two different optical paths can be combined in a still very compact instrument (MET*image* version C). The design for such an instrument is shown in Figure 5.

5. SUMMARY

Recognizing the evolving needs for advanced imaging radiometers in the operational meteorology field, the MET*image* family of instruments has been designed. MET*image* instruments can be flexibly configured according to user needs, while relying on a limited number of high quality internal subassemblies.

The German DLR Space Agency, Jena-Optronik GmbH and AIM Infrarot Module GmbH currently implement together core technologies of the METimage

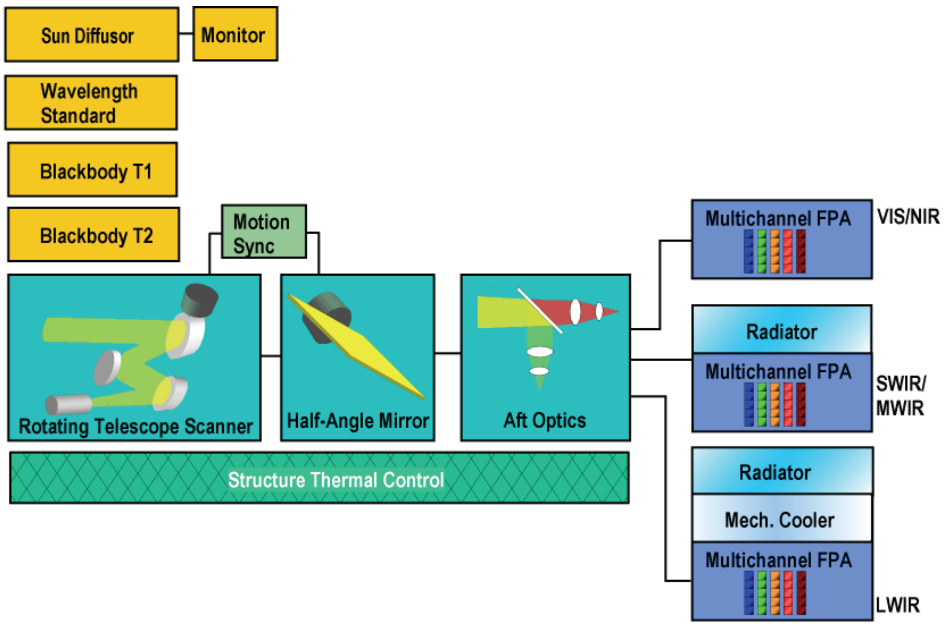

Figure 4: Advanced configuration of a MET*image* instrument schematic block diagram of MET*image*, containing the basic "building blocks", i.e. the scanner, which produces the optical image, and the focal plane, where the detectors are located to convert light into electrical signals. The instrument may have three focal planes (for detectors with different cooling needs) with e.g. 25 spectral channels. Multiple calibration sources are implemented to guarantee high long-term absolute accuracy. A sophisticated thermal control makes the instrument independent of thermal effects from the outer environment. For applications where e.g. visible and infrared optics can no longer be handled in a single optical path, a configuration exists where two different optical paths can be combined in a still very compact instrument (MET*image* C).

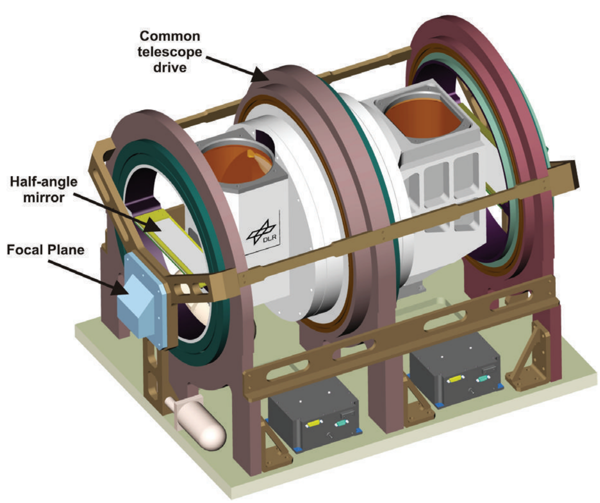

Figure 5: Design of a MET*image* instrument with visible and infrared light processed separately (MET*image* version C), therefore with two apertures. A common structure and common telescope drive provide good synchronisation and a compact design.

instrument. National technology breadboard activities are running concerning mechanical aspects of the rotating telescope and concerning SWIR and VLWIR focal plane detector array designs. Additional activities are in preparation.

The MET*image* instrument phase B study was kicked-off in September 2008. The study will be finished with a preliminary instrument design in 2010.

Germany intents to provide MET*image* as an in-kind contribution of the first MET*image* flight model to the EUMETSAT Post-EPS Programme. Preparatory activities towards establishing a co-operation agreement with EUMETSAT regarding a national contribution of the first MET*image* flight model to Post-EPS. MET*image* have been successfully started in association with EUMETSAT and ESA.

6. ACKNOWLEDGEMENTS

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