IMAGING RADIOMETER MET*image* FOR FUTURE OPERATIONAL EARTH OBSERVATION PLATFORMS IN POLAR ORBITS

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ABSTRACT

Recognizing the evolving needs of the meteorological community, Jena-Optronik developed a medium resolution imaging radiometer. An important objective is the flexibility to adapt to user requirements. Core parameters like ground sampling distance, number and width of spectral channels, SNR, polarisation control and calibration facilities can be chosen in a wide range without changing the basic instrument configuration.
Core item of the instrument is a rotating telescope scanner to cover the large swath width which all polar platforms need for global coverage. The derotated 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. The reflecting telescope design can be expected to support even demanding upcoming requirements on image quality and ground resolution.
Currently, DLR, Jena-Optronik and AIM work together implementing core assemblies of MET*image*: the rotating telescope scanner and the infrared detectors.

INTRODUCTION

The world's first meteorological satellite named TIROS was launched in the USA already in 1960 to demonstrate the advantage of observing the earth's cloud cover from space. In addition, the US Department of Defence (DoD) started the Defence Meteorological Satellite Program (DMSP) in parallel. In the mid-sixties the first polar orbiting satellite of the TIROS series was launched. In the early seventies, an operational satellite programme in the polar orbit called Polar Operational Environmental Satellites (POES) followed. The operational geostationary satellite systems, which were started in the seventies both in the USA (Geostationary Operational Environmental Satellites, GOES) and Europe (METEOSAT), provide a high temporal sampling needed for nowcasting and numerical weather prediction - except for regions at high latitudes. In contrast, the polar orbiting satellites provide global coverage and a good sampling of the polar region, while the temporal sampling of most regions is rather poor.

The NOAA satellites of the POES series improved with time with respect to live time and observational capabilities. The imaging instrument was improved in 1978 by the launch of the imaging radiometer AVHRR (Advanced Very High Resolution Radiometer), which had four spectral channels. The instrument was further improved to five channels (AVHRR/2) in 1981 and to six channels (AVHRR/3) in 1998. The AVHRR/3 with a spatial resolution of 1.1km at nadir is still used today on NOAA satellites and is also foreseen for the European METOP Satellites. The first satellite, METOP-A, was launched in October 2006. METOP-B and -C will be launched in 2011 and 2015, respectively. The EUMETSAT Polar System (EPS) and POES build the Initial Joint Polar System (IJPS), where EUMETSAT assumes responsibility for the mid-morning orbit.

Combining the POES and DMSP programmes, NOAA, NASA and DoD plan for the National Polar-orbiting Operational Environmental Satellite System (NPOESS), which will carry an improve imaging radiometer called Visible Infrared Imager / Radiometer Suite (VIIRS). VIIRS has 22 spectral channels and a higher spatial resolution than AVHRR. The first VIIRS will be accommodated on NPP (NPOESS Preparatory Project) to be launched in 2009. The first NPOESS satellite is planned for 2013.

In Europe, preparatory activities for a follow-on programme for the EUMETSAT Polar System (Post-EPS) have 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 VIIRS, 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. The MET*image* project is currently continued with the development of two key assemblies: the scanner and the infrared detectors. The MET*image* concept, which has a high potential for Post-EPS, and the current activities are described in detail in this paper.

THE USE OF IMAGING RADIOMETERS IN OPERATIONAL METEOROLOGY

Use of the optical spectrum, from the near UV to the thermal infrared, for meteorological applications started very early in the development of space flight. Images of large scale cloud patterns can be interpreted by meteorologists; use of thermal infrared imaging extends such observation from daytime to around-the-clock operations.

Two lines of development drove the use of optical methods much beyond this broad-band imaging: Firstly, there was a development of more optical narrowband applications, which allowed extracting information not immediately discernible in broad-band images. A good example is the "water vapour channel" which shows the density of water vapour in the atmosphere, even when it has not yet formed visible clouds. Secondly, the ability to measure the amount of optical radiation more and more precisely opened the way for quantitative methods, beyond simple imaging. A good example for this is the use of thermal IR to measure temperatures of clouds or the sea surface. Combining the quantitative data from several spectral channels allows extracting more and more specific information and suppress "cross talk" of other effects that may otherwise contaminate the desired information.

Instruments which measure the incoming optical radiation, in limited spectral bands, are called spectro-radiometers. If such an instrument also has a spatial resolution, it is called "imaging spectro-radiometer", often shortly imaging radiometer.

In modern weather satellites, such imaging radiometers play a twofold role: they provide a wealth of directly useful information stand-alone and they are the instruments with the highest spatial resolution, providing the spatial reference for other instruments on-board. In addition, many other applications rely on supporting information from the imaging radiometer, like atmospheric corrections, for the performance of their specific tasks.

TRENDS IN IMAGING RADIOMETER REQUIREMENTS

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 energy is 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.

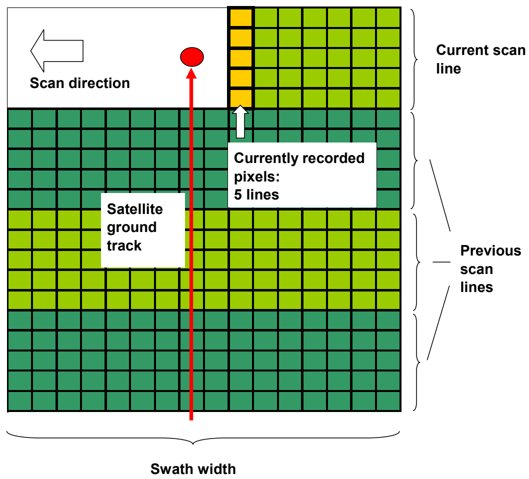


FIG. 1*: Recording pattern of a rotating scanner with multiple pixel lines per scan*
In this example, five lines are recorded simultaneously in along-track direction, while the scan is across track. As the scan speed is high with respect to the satellite ground speed, the scan lines provide gapless ground coverage, in spite of the scanner rotating through some "dead angle" where no imaging is performed.

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 most simple ones have the disadvantage that the images rotates around the optical axis, while scanning the scene. While this is of no importance when only a single point detector is located in focal plane, it precludes using matrix fields of detectors, which image the scene subsequently on the different spectral channels.

CONCEPT OF THE MET*image* FAMILY OF INSTRUMENTS

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. 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.

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 does 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 users 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.

TECHNICAL FEATURES OF MET*image*

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.

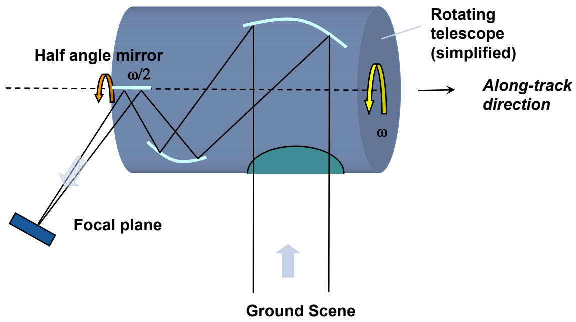


FIG. 2: *Simplified principle of a rotating telescope scanner The off-axis telescope rotates around an axis perpendicular to the viewing direction. A stationary image in the focal plane is produced by the plane “half-angle mirror”, which rotates at half the rate.*

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.

Optical system

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

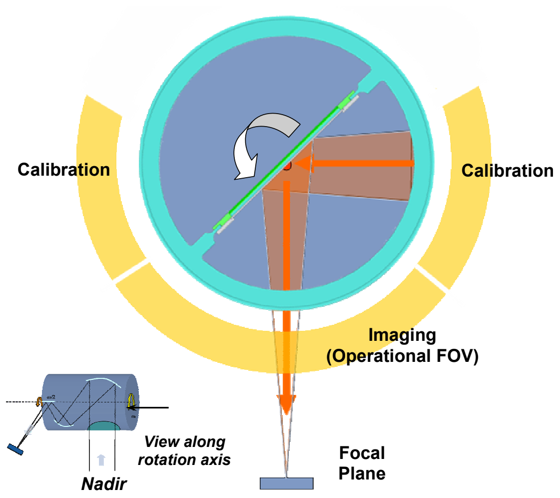
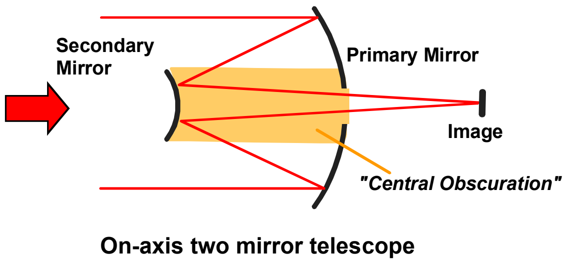


FIG. 3: *Different portions of the field-of-view (FOV) are used for imaging and calibration, without the need for additional mechanisms to move calibration sources into the optical path or interruption of normal operation.*



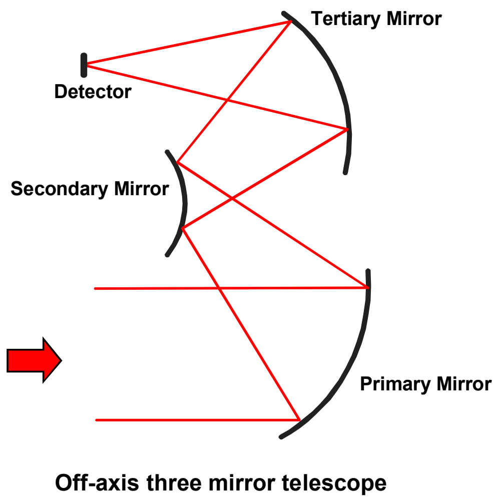


FIG. 4*: Two different basic designs of mirror telescopes The off-axis triple mirror design needs more elements, but this introduces additional degrees of freedom for image enhancement. The "central obscuration", leaving the central portion of the primary mirror in the two-mirror design without function and deteriorating the image quality, can be avoided.*

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.

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 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.

Focal plane

MET*image* employs so-called "in-field separation" of spectral channels. 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.

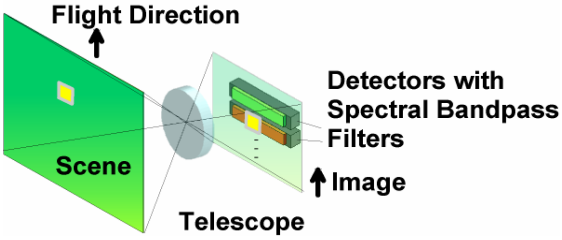


FIG. 5*: In-field separation of spectral channels*
Due to the satellite motion, the image of a certain pixel moves straight over the focal plane with an arrangement of detectors. There it is sequentially imaged by detectors with different spectral filters.

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.

This approach has another big advantage: the size of the detector pixels can be different for different spectral channels. 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.

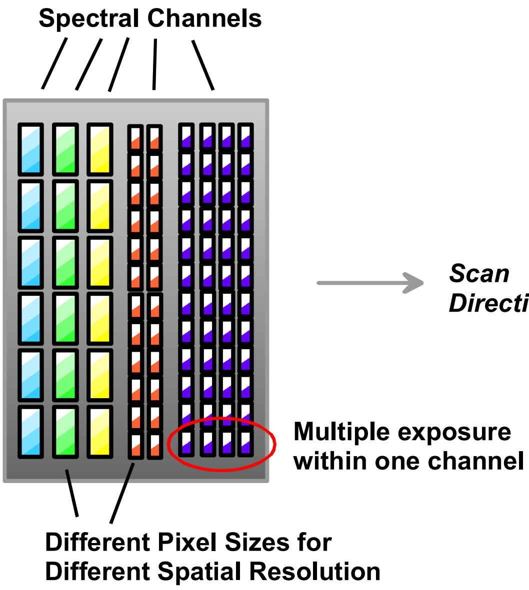


FIG. 6*: Detector arrangements in the focal plane*
Depending on detector size, spacing and number for each spectral channel, the ground resolution can be individually tuned and multiple exposure capability included or not. The vertical extension gives the number of ground traces simultaneously recorded (here six for the low resolution and twelve for the high resolution channels).

Finally, the focal plane approach allows to do 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.

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.

Detector Types

The spaceborne rotating telescope MET*image* is planned for observing the earth in the spectral range between 1 µm and 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 subarrays, 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:

(i) Short wavelength infrared
SWIR-channel $0.9\ \mu m < \lambda < 2.5\ \mu m$
(ii) Mid wavelength infrared
MWIR-channel $3\ \mu m < \lambda < 6\ \mu m$
(iii) Long wavelength infrared
LWIR channel $7\ \mu m < \lambda < 9\ \mu m$
(iv) Very long wavelength infrared
VLWIR-channel $10\ \mu m < \lambda < 13.5\ \mu m$

The infrared arrays are cooled down to approximately 90 K in order to optimise their signal/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.

Focal Plane Arrays Design and Technology

The conceptual design and the specific feature of MET*image* infrared focal plane arrays stipulates a signal/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. 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 individual detector signals are summed up by the synchronous integrated TDI-function resulting in a signal/noise improvement of SQRT(number of pixels). This procedure (TDI-1) is outlined in the following FIG. 7 showing also the additional TDI-mode (TDI-2) performed via the forward motion of the satellite, which remains an option.

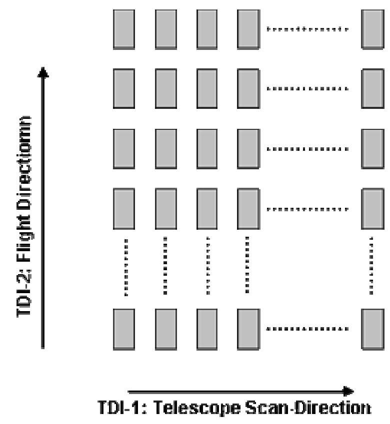


FIG. 7 *Options for improvement of S/N-ratio: TDI-1 procedure performed over detector elements in scan-direction of rotating telescope TDI-2 procedure in satellite forward motion*

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.

To achieve a compact focal plane design as required by the MET*image* concept, the individual infrared arrays will be assembled by AIM in a Multi-Chip-Module technology on specific ROICs,as shown in the following figure FIG. 8:

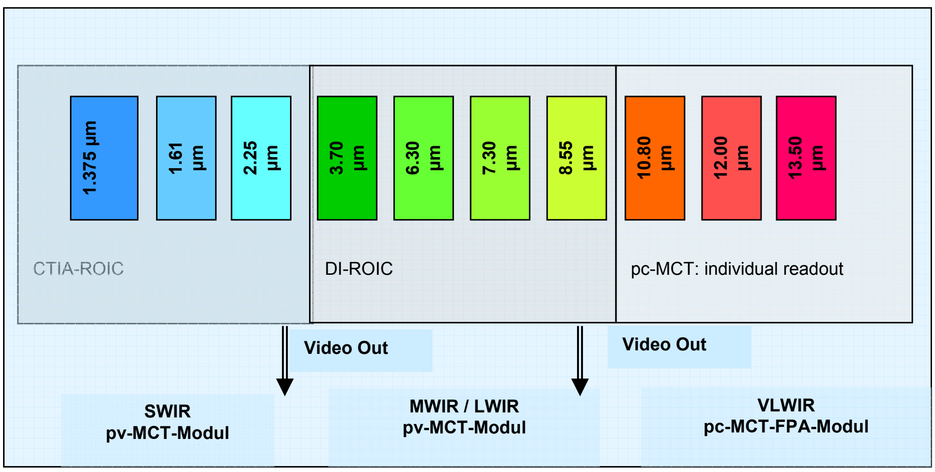


FIG. 8 *METImage Infrared Focal Plane assembled as MCM consisting of 3 basic infrared submodules. Typical size of such focal plane is around 30 mm long, requiring a very compact design.*

As indicated in FIG. 8, three MCM-submodules covering the SWIR, MWIR/LWIR-, and VLWIR-channels constitute the MET*image* focal plane array.

Obviously, this approach easily allows to split the infrared range into several focal planes, should the required number of channels dictate this. Backside

illuminated SWIR and MWIR/LWIR photo-voltaic MCT arrays will be hybridised onto corresponding ROICS via flip chip technology enabling high adjustment accuracy, the frontside illuminated photo-conductive MCT-detectors need to be readout individually thus limiting the number of pixels in thus submodule.
In accordance to the radiometric requirements in the various spectral bands, the individual ROICs for the SWIR- and MWIR/LWIR sensor arrays are provided with adjusted interface stages to inject the photon generated current with highest efficiency into the ROIC. A compact assembly will be achieved by mounting three SWIR and 4 MWIR/LWIR subarrays on individual ROICs, respectively.

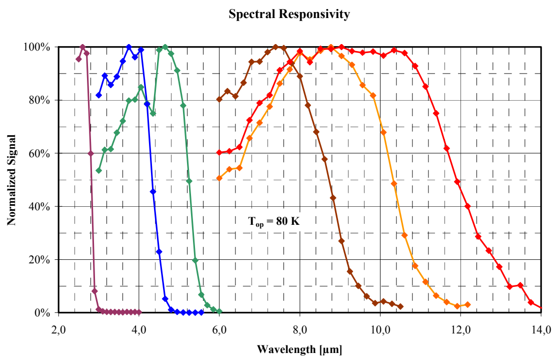


FIG. 9 *Adjustment of MCT-infrared sensors in accordance to system requirements*
Responsivity behaviour for various MCT-detectors, operation temperature = 80K

FIG. 9 showing the spectral responsivity of specific MCT-detectors demonstrates the capability of manufacturing optimised MCT-sensors according to the required spectral band. The respective responsivities are normalised to their maximum signal.

As an example for focal plane array technology, FIG. 10 shows a section of a MCT array with pixel size of 24 µm x 24 µm, together with the corresponding ROIC, prepared with Indium bumps for flip chip technology in FIG. 11. The resulting focal plane array is shown in FIG. 12.

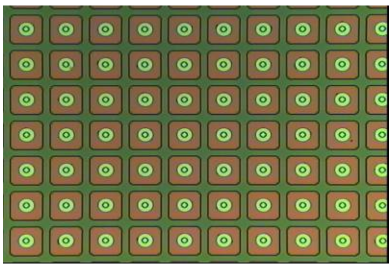


FIG. 10 *Section of a MCT-sensorarray*

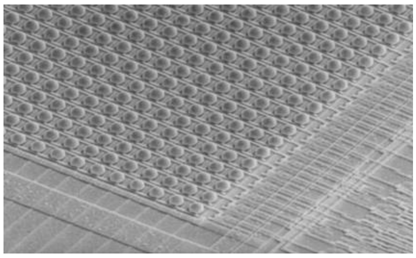


FIG. 11 *ROIC, provided with Indium bumps for flip chip mounting*

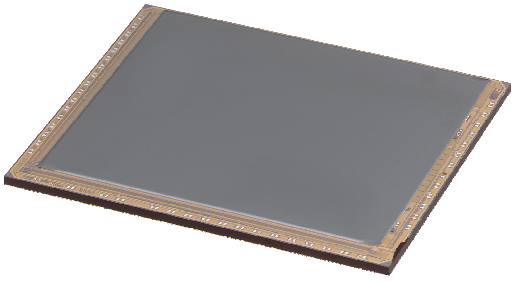


FIG. 12 *Infrared Focal Plane Array (here: 640 x512 pixels)*

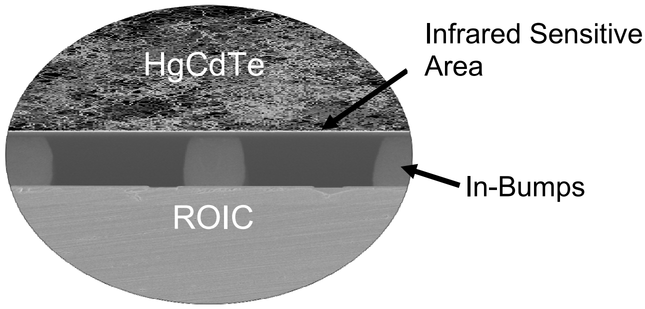


FIG. 13 *Cross section of MCT-Focal Plane Array: Indium bumps providing electrical, thermal, and mechanical interface between MCT and ROIC (diameter of In-bump □ 10 µm), the infrared light is impinging MCT from the back side.*

Whereas normal applications require the hybridisation of one MCT-chip with one ROIC, the specific feature of the MET*image* focal plane array is the hybridisation of several dedicated MCT-chips on one specific ROIC. Thus, 3 infrared submodules will be mounted, tested for electro-optical performances, and finally assembled to the MET*image* focal plane.

Specific Features of the MET*image* Infrared Focal Plane Array are:

- plurality of specific infrared channels covering the SWIR to VLWIR spectral range

- very compact infrared focal plane assembly, in compliance to the rotating telescope MET*image*
- Multi-Chip-Infrared Module assembly, consisting of 3 focal plane array submodules
- each FPA-submodule consists of 3 to 4 MCT sensor arrays, hybridised in flip chip technology onto a specific an adjusted injection stage, adapted to the radiometric requirements and to the electrical MCT detector characteristics (SWIR, MWIR, LWIR)
- easy to handle video signal output due to the multiplexing of the infrared detector signals
- on-ROIC integrated TDI-function for signal/noise improvement
- on-ROIC implemented digital core for commanding and controlling the ROIC readout
- easy to handle mechanical, thermal, optical, and electrical system interfaces

MET*image* INSTRUMENT CONFIGURATIONS

Basic block diagrammes of two possible configurations of MET*image* instruments are shown in FIG. 14 and FIG. 15. They contain as basic "building blocks" the scanner, which produces the optical image, and the focal plane, where the detectors are located to convert light into electrical signals. A simple version may use just one focal plane with e.g. 10 channels and one calibration source. A more advanced member of the instrument line 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. The design for such an instrument is shown in FIG. 16.

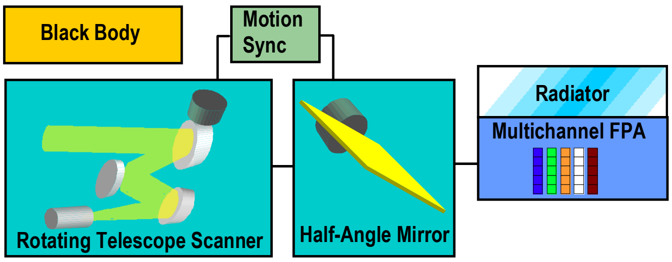


FIG. 14*: Basic configuration of a METimage instrument*

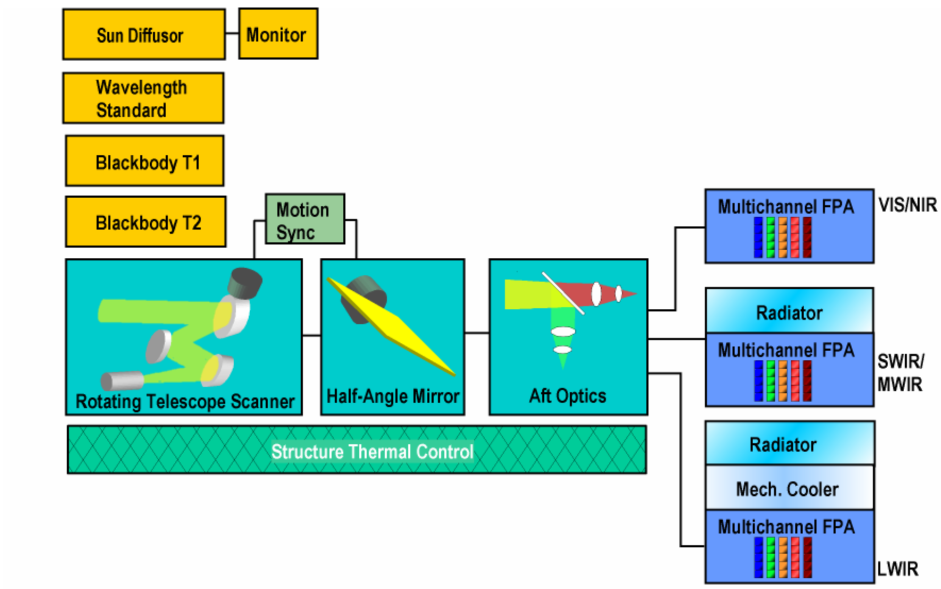


FIG. 15*: Advanced configuration of a METimage instrument*

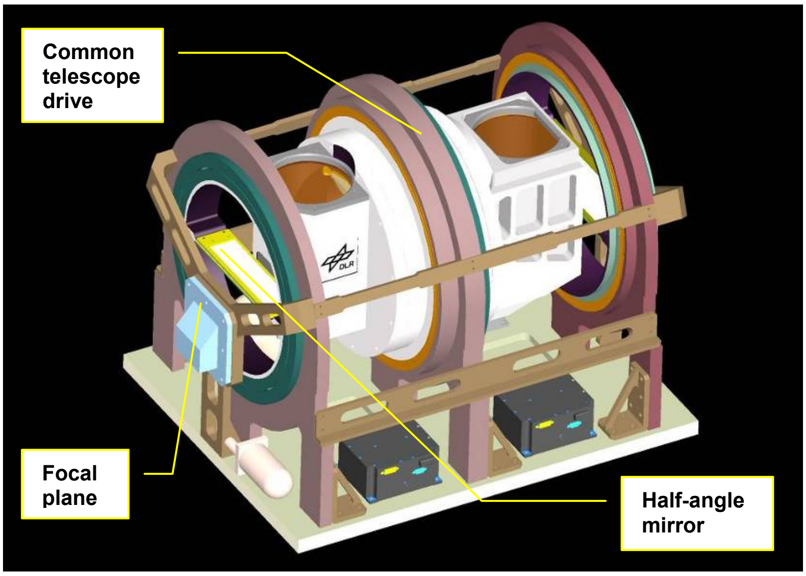


FIG. 16*: Design of a METimage instrument with visible and infrared light processed separately, therefore with two apertures. A common structure and common telescope drive provide good synchronisation and a compact design.*

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. DLR, Jena-Optronik and AIM currently implement together the core rotating telescope scanner and infrared detector assemblies.

ACKNOWLEDGEMENTS

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