International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas

The 3MI instrument on the Metop second generation

I. Manolis

J.-L. Bézy

R. Meynart

M. Porciani

et al.

International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 1056324 · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304182

THE 3MI INSTRUMENT ON THE METOP SECOND GENERATION

I. Manolis[1], J-L. Bézy[1], R. Meynart[1], M. Porciani[1], M. Loiselet[1], G. Mason[1], D. Labate[2], U. Bruno[2], R. De Vidi[2]
[1]*ESA/ESTEC, Keplerlaan 1, PO Box 299, NL-2200 AG Noordwijk, The Netherlands,*
[2]*Selex ES, via A. Einstein 35, 50013, Campi Bisenzio, Italy*

INTRODUCTION

In order to ensure continuity and further enhancement of the European operational meteorological observations in the timeframe of 2020 to 2040, the MetOp-SG programme has been initiated by ESA in collaboration with EUMETSAT. ESA develops the prototype MetOp-SG satellites (including associated instruments) and procures, on behalf of EUMETSAT, the recurrent satellites (and associated instruments). EUMETSAT is responsible for the overall mission, funds the recurrent satellites, develops the ground segment, procures the launch and LEOP services and performs the satellites operations. The corresponding EUMETSAT Programme is termed the EUMETSAT Polar System – Second Generation or EPS-SG.

The payload of the MetOp-SG satellites consists of the following instruments: the visible and infrared imager (METimage), to provide information on clouds, cloud cover, land surface properties, sea, ice and land surface temperatures; the Infrared Atmospheric Sounding Interferometer–New Generation (IASI-NG), to provide atmospheric temperature and humidity profiles, as well as monitor ozone and various trace gases; the MicroWave Sounder (MWS), to provide atmospheric temperature and humidity profiles; the SCAtterometer (SCA), to provide ocean surface wind vectors and land surface soil moisture; the Radio Occultation sounder (RO), to provide atmospheric temperature and humidity profiles, as well as information about the ionosphere; the Sentinel-5 (S-5) instrument, to monitor various trace gases, air quality and support climate monitoring; the MicroWave Imager (MWI), to provide precipitation monitoring as well as sea ice extent information; the Ice and Cloud Imager (ICI), to measure cloud ice water path, properties and altitude; the Multi-viewing, Multi-channel, Multi-polarization Imager (3MI), to provide information on atmospheric aerosols; and the Data Collection System Argos-4, for the collection and transmission of observations and data from surface, buoy, ship, balloon or airborne data collection platforms.

From the above, the MWS, SCA, RO, MWI, ICI and 3MI instruments are developed under the ESA MetOp-SG Programme, while the Sentinel-5 instrument is developed by ESA under the Space Component of the EU Copernicus Programme. The other instruments will be provided as Customer Furnished Items to the MetOp-SG contractor through EUMETSAT under its cooperation agreements with its partners, DLR (Germany) for METimage and CNES (France) for IASI-NG and Argos-4, and will be provided as Customer Furnished Items to the MetOp-SG contractor. Targeting an operational system of at least 21 years of operations, the current approach foresees the implementation of the above payload complement in a two parallel series of satellites (designated as ‘Satellite A’ and ‘Satellite B’) in a three units per series (so-called “3+3” configuration).

So far, two parallel Phase A/B1 studies have been completed confirming the feasibility of all planned missions including the 3MI mission. Following a competitive bid, the implementation phases (B2/C/D/E) were successfully kicked-off in May 2014. Airbus Defence & Space (France) is the selected satellite prime (both for “Sat-A” and “Sat-B”), while the 3MI instrument is under the direct development responsibility of Selex ES (Italy). Satellite-A is scheduled for launch in 2021.

THE 3MI MISSION OBJECTIVES

Polarimetry is considered today to be a crucial technique in atmospheric remote sensing, in particular for characterization of airborne aerosol particles. Aerosol measurements are not only required to assess the health hazards of aerosols and to probe volcanic ash clouds that impact air traffic; they are also crucial to measure aerosol scattering/absorption properties being currently one of the largest source of uncertainty within climate modelling. The 3MI mission, being a key future polarimetric mission, focuses primarily to provide aerosol characterization for climate monitoring, Numerical Weather Prediction (NWP), atmospheric chemistry and air quality [1][2]. The 3MI measurements will facilitate the derivation of essential aerosol parameters, such as aerosol optical depths, particle types and sizes, refractive index, sphericity and height index and allow us to study in depth the radiative and microphysical properties of the clouds and aerosols. When used as constrains to the models, these products will be used to provide improved Air Quality Index and Aerosol Load Masses for different particles sizes.

EARTH POLARIMETRY FROM SPACE

Aerosol properties can only be fully and unambiguously derived by measurements of the Top Of Atmosphere (TOA) polarised radiances at several wavelengths and several viewing angles for any given target on Earth. While, up to now, products of various (optical passive) missions have been used to derive aerosol properties, in the majority of cases, this was done in a non-optimised manner. Limitations of those measurements are due to either the limited numbers of angular samples, number of spectral channels, or indeed polarisation sampling ("modulation") capability. Some examples include the MODerate resolution Imaging Spectro-radiometer (MODIS) on Aqua and Terra satellites (NASA), the MEdium Resolution Imaging Spectrometer (MERIS) on board Envisat satellite (ESA) as well as the Advanced Very High Resolution Radiometer (AVHRR) on board Metop satellite (EUMETSAT), all of them offering a single viewing angle capability/geometry (per target). Some instruments do offer multi-view capability, such as the Multiangle Imaging SpectroRadiometer (MISR) on boar Terra satellite (NASA) or the Advance Along Track Scattering Radiometer (AATSR) on board Envisat satellite (ESA), nevertheless, they lack multi-polarisation capability.

The POLDER instrument [3], on the other hand, was the first instrument of its kind, to offer multi-angular, multi-spectral and multi-polarisation measurements in one go, offering unique opportunities for targeted aerosol data and cloud retrieval [4]. In its three different incarnations (on-board ADEOS-1, -2, and PARASOL satellites), the POLDER instrument has pioneered space-based polarimetric remote sensing. 3MI will be an evolution of the POLDER-3 / PARASOL instrument. It will therefore provide similar suite of measurements (multi-angle, multi-wavelength and multi-polarisation), nevertheless, with an improved spatial resolution (4 km at nadir) and coverage, and over an extended spectral range (400 to 2100 nm).

The Aerosol Polarimetric Sensor (APS) [5], a descendant of NASA's Earth Observing Scanning Polarimeter (EOSP) design, specifically designed to provide even higher polarimetric accuracy and a larger number of viewing angles, unfortunately failed during launch of the Glory satellite in March 2011. The Multi-angle SpectroPolarimeter Imager (MSPI) [6] as well as the SPEX instrument concept [7], offer equally powerful measurement techniques for the retrieval of polarimetric products, albeit both using a different modulation technique than that of POLDRER and 3MI (the first implementing a temporal modulation approach, while the later an innovative spectral modulation approach).

THE 3MI INSTRUMENT AND ITS KEY PERFORMANCES

I. OVERVIEW:

An view of the 3MI instrument is shown in Fig.1 (only the optomechanical unit (OMU) is shown; the instrument control unit (ICU) is hosted within the satellite platform) . As shown, the key design elements of 3MI are the two optical camera modules (each being in effect a 2D imager) supported on the dedicated optical bench and the filter wheel assembly (mechanism + filter disk), which is used to facilitate the insertion of the various spectral filters and polarizers in the optical path of the two cameras during the measurement sequence.

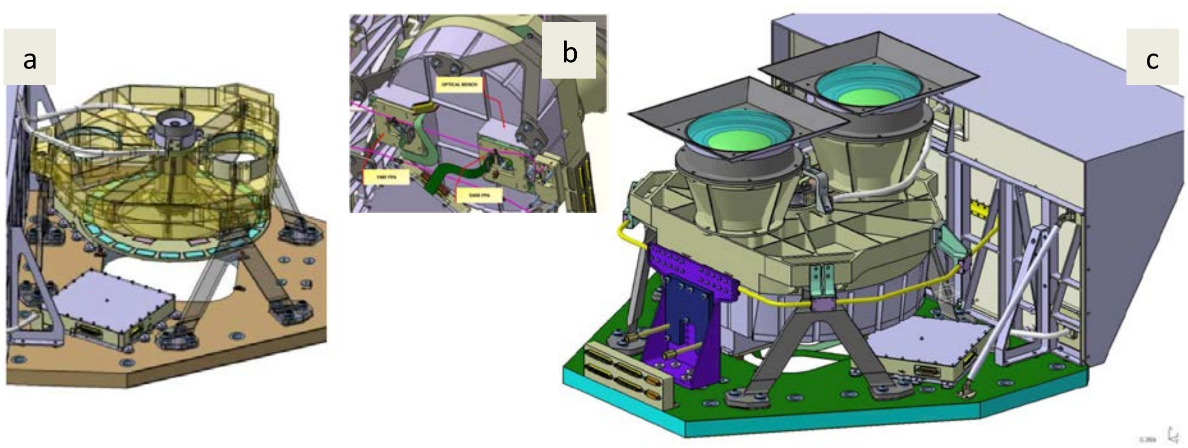

Fig. 1. Key elements of the 3MI Instrument OMU: (a) filter wheel mechanism and disk, (b) focal plane assemblies, and (c) the two optical heads and the thermal hardware.

The two modules are similar in form and function, each featuring a wide FOV dioptric telescope (minimum Ø 114°) with telecentric optics, and they are meant to cover respectively the two different specified spectral domains of the instrument (VNIR & SWIR – see also Table 3). Channel 3MI-9a (910 nm) is duplicated in both modules to assist with geometrical registration of the two groups of channels. Measurement of the different spectral channels and polarizations is performed sequentially in time and it is facilitated by means of a continuously rotating filter wheel performing one revolution every 5.5 seconds. The wheel features two concentric rings each accommodating the filter slots for the VNIR and SWIR modules respectively. The key budgets of the 3MI instrument are given in Table 1 below.

Table 1. 3MI Budgets

Envelope (mm x mm x mm)	*OMU : 800 x 750.5 x 501.5* *Radiator : 1000 x 10 x 501.5* *OMU incl. radiator and earth shields: 1000 x 1007 x 501.5*
Mass (Kg) – no margins	*OMU: 60* *Instrument control unit: 4.5*
Power (W) – Avg. / Max.	*Operational: 67 / 75* *Safe: 50 /54*
Date Rate(Mbit/s)	*Daytime: 6.5* *Night: 0.1*

II. MEASUREMENT CONCEPT:

As mentioned above, aerosol properties can only be fully and unambiguously derived by measurements of the Top Of Atmosphere (TOA) polarized radiances at several wavelengths and several viewing angles for any given target on Earth. Like POLDER, 3MI acquires multiple views of the same target on Earth (hence, multi-angular measurements) by consecutively recording 2D images at regular point along its orbits (called along-track (ALT) acquisition points). The images overlap on ground offering several angular samples for any given target within the swath of the instrument. This is demonstrated schematically in Fig. 2. At every ALT acquisition point, a full set of spectral and polarization images are recorded, by means of the rotating filter wheel. In reality, the overlap is much more dense than the one shown in the figure, thus leading to a minimum of 14 angular samples for the VNIR channels and 6 angular samples for the SWIR channels in each pass.

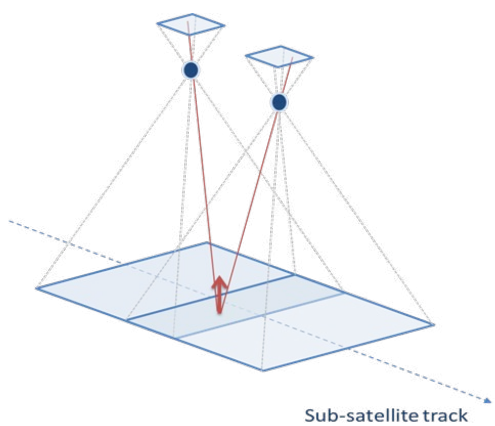

Fig. 2. The 3MI measurement concept

It is worth noting that the field of view (FOV) of the two modules are not identical (see Table 2), they are both, however, aligned symmetrically with respect to the sub-satellite track (SST), while the SWIR FOV is slightly displaced towards north in the ALT direction to favor more the acquisition geometry for targets in the north hemisphere. At nadir, the 3MI SSD is better than 4km square (ALT x ACT) over the full MetOp-SG orbit. This compares with approximately 6km of POLDER3 on the PARASOL orbit. 3MI, furthermore, features a minimum swath of 2200 km over the MetOp-SG orbit. This compares with the 1366 km of the POLDER3/PARASOL instrument, thus proving improved coverage.

The reduced FOV of the SWIR in the ALT direction, would normally mean a reduced number of angular samples in a single pass (nominally 6), however, in principle, more samples can be acquired, given the fact that the time between two consecutive ALT acquisition points is 22s while a single filter wheel rotation lasts 5.5s.

Table 2. The 3MI VNIR and SWIR FOVs

	ACT	*ALT*
VNIR FOV	[-50.2° … +50.2°]	[-50.2° … +50.2°]
SWIR FOV	[-50.2° … +50.2°]	[-38.6° … +21.9°]

This oversampling 'trick' unfortunately cannot be used to increase also the total angular sampling range of the SWIR channels, which is only determined by the actual size of the FOV in the ALT direction. For targets on the SST, this is estimated to be approximately 110° for VNIR channels and 50° for the SWIR ones.

III. SPECTRAL CHANNELS:

3MI will measure TOA radiances in 12 spectral channels, out of which, 9 will be polarized (see Table 3). The covered range has been significantly extended compared to the one of POLDER, as well as the actual number of polarized channels has been increased compared to that of POLDER. For each of the polarized channels, three consecutive slots are reserved in the filter wheel, each fitted with the same spectral filter combined with a polarizer oriented at 0°, 60° and 120° respectively, to achieved the required polarization modulation.

The larger extension over the SWIR region of the spectrum has necessitated the introduction of a second camera module to allow for feasibility at detector level as well as coating design. a duplicate of the 910 nm channel is also foreseen in the SWIR module in order to allow spatial registration of the images acquired by the two modules. While all channels are acquired within less than 5.5 second per along-track (ALT) acquisition point, hence, generating an angular misregistration error for any given target on Earth of less than 3 degrees, a further optimization in the temporal sequence of acquisition can be implemented by shuffling around the filters on the filter wheel, to further improve the temporal co-registration of group of channels of particular interest. This is the case for example of the two "oxygen" channels (754nm & 763nm), or for the double of the 910nm channels (one in each module).

Table 3. The 3MI spectral channels. (*) The definition of this channels is currently under review

	PARASOL POLDER				3MI		
	Central Wavelength (nm)	*Bandwidth (nm)*	*Polarisation*		*Central Wavelength (nm)*	*Bandwidth (nm)*	*Polarisation*
VNIR				VNIR	410	20	Y
	443	20	N		443	20	Y
	490	20	Y		490	20	Y
	565	20	N		555	20	Y
	670	20	Y		670	20	Y
	763	10	N		763	10	N
	765	40	N		754 (*)	20 (*)	N
	865	40	Y		865	40	Y
	910	20	N		910	20	N
	1020	20	N				
SWIR				SWIR	1370	40	Y
					1650	40	Y
					2130	40	Y

IV. RADIOMETRIC PERFORMANCES:

3MI is not designed to handle very low signal levels; indeed in most cases a neutral density filter is deployed to limit the amount of incoming radiation. It is nevertheless required to deal with a very large dynamic range, which, in some cases, is in the order of 200 (Lmax / Lmin), while maintaining a good signal to noise ratio for most part of it (over 200). This, together with limitations imposed by the fact that consecutive measurements need to be closely co-registered (temporal co-registration), leads to rather stringent requirements for the dynamic sizing of the focal plane assembly, in particular in terms of required full well capacity. An extra limitation comes from the fact that strong sun glint will be present in many of the images acquired along the orbit of 3MI. To limit the contamination of neighboring pixels from such erroneous signal, an anti-blooming capability is requested from the detector, which further limits the available well capacity. Currently, for the VNIR module focal plane assembly (FPA) a customization of an existing CCD detector (e2V CCD47-20) is planned to increase its full well capacity, while for the SWIR module a SATURN-like (SOFRADIR) detector performance will suffice. The operational temperature for the two FPAs is currently baselined to -20 °C (target value) for the VNIR and -88 °C for the SWIR.

Similarly to the POLDER instrument, 3MI does not feature an on-board calibration system. As a consequence, while an absolute bias performance of 3% to 5% is made applicable for the in-orbit product, such absolute radiometric calibration cannot be guaranteed at instrument level, but will be subject to the accuracy of the vicarious calibration campaigns to be performed during the lifetime of the instrument. As a result, the output product of 3MI at instrument level (conventionally noted as Level 1b1), will be subject to absolute radiometric scaling and correction during the actual operations. Multiple image re-sampling and registration will be required in addition before radiometric inversion to the Level 1b product, which will be the polarized TOA radiance (Stokes components). A detailed characterization campaign (detection chain, radiometric polarimetric and geometric) is under definition to ensure that all critical parameters are fully characterized to allow for subsequent successful vicarious calibration operations. A heavy requirement in radiometric and polarimetric stability is currently imposed at instrument level (i.e. L1b1 product), to ensure that vicarious updates can deliver the required radiometric and polarimetric performances over the life-time of the instrument. Furthermore, the radiometric stability of the instrument shall be compatible with the frequency of the updates foreseen using the vicarious calibration updates during operations. Currently, a gain stability of better than 1% (orbital average) over 6-months is specified for the instrument.

IV. GEOMETRICAL PERFORMANCES:

Each module features a wide FOV dioptric telescope (minimum Ø 114º) with telecentric optics. Good telecentricity is necessary in order to obtain uniform spectral response from the filters positioned in front of the detectors following the camera optics. To ensure minimum increase of spatial sampling distance (SSD) of the instrument on the surface of the Earth for the off-nadir fields, an *f.tan(theta)* design is further implemented. The current optical design of the VNIR module is shown in Fig. 3

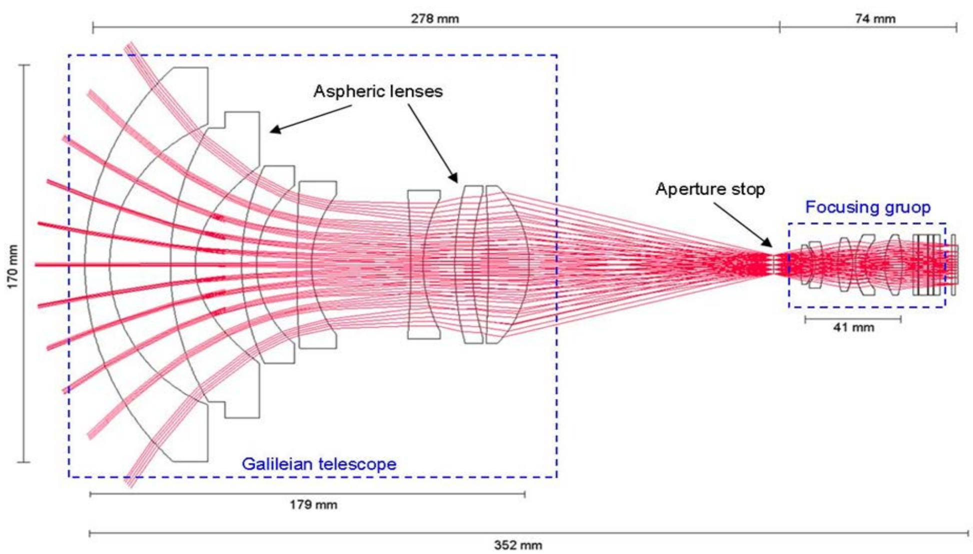

Fig. 3. The 3MI VNIR module optical design

The design is using non-rad hard glasses apart from the first lens, which is made of fused silica (Suprasil) and also acts as a protective element against radiation. Specific manufacturing challenges are imposed by the surface finishing quality required in the two aspheric lenses contained in the first group of lenses as well as by two elements in the "focusing group" made of CaF2, which is a material well known for its brittleness. One key challenge of the design has been to incorporate a fast increase of the effective pupil for off-axis angles to counteract typical $\cos^4\theta$ apodisation performances at the focal plane, thus facilitating a feasible radiometric sizing of the instrument. Typical performances in terms of effective pupil variation and irradiance uniformity at the 3MI focal plane are given in Fig. 4. Key geometrical performances are summed in Table 4.

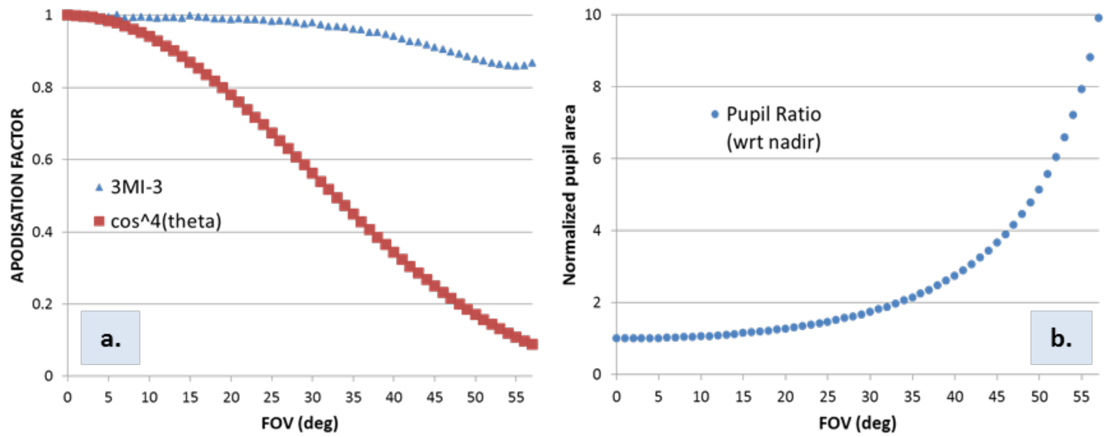

Fig. 4. (a) Typical 3MI (blue curve) irradiance variation over the focal plan assuming a uniform scene, (b) typical variation of the effective pupil over the FOV of 3MI

Table 4. 3MI VNIR Camera module key geometrical performances

Effective Focal Length	*5.512 mm*
F-number	*4.2*
FOV	*57° circular*
Optical MTF (ACT & ALT) @ F_nyquist (FOV: 0° -50°)	*> 76%*
Telecentricity	*< 0.1°*
Distortion from paraxial f.tan(θ)	*< 2%*
Spectral variation of distortion	*< 0.5%*

V. POLARISATION PERFORMANCES:

Polarisation sensitivity (PS) is a key performance of a polarimeter like 3MI. Assuming measurement of a stable, spatially uniform and linearly polarised scene, the polarisation sensitivity of the instrument is defined as PS = (Smax-Smin)/(Smax+Smin), where Smax and Smin are the maximum and minimum sample values, respectively obtained when the polarization is gradually rotated over 180 deg. While in conventional radiometers this is kept to a minimum (typically using a polarisation scrambler), for a polarimeter, and more specifically for the polarised channels of the instrument, it is desirable to maximize this parameter. The table 5 gives the target performances for 3MI.

Table 5. 3MI polarisation sensitivity performances

	Polarisation Sensitivity	
3MI channel	***OZA ≤60°***	***OZA > 60°***
All 3MI polarised channels (except 410 nm)	> 0.96	> 0.94
410 nm channel	> 0.93	> 0.91
All 3MI non-polarised channels	< 0.05	< 0.07

Crucial to achieving such stringent polarisation performances at system level, is the optimized design of anti-reflection (AR) coatings on the lenses of the two modules. Typically, an AR coating would be optimized to deliver high average transmission and small polarisation sensitivity (difference between -s and -p components), however, in the case of 3MI, the phase shift between -s and -p components ("de-phasing") needs also to be kept to a minimum (ideally less than 2°) even for quite large angles of incidence (up to 40° for some elements). The diagrams below (Fig. 5) show typical individual AR coating performances in terms of both PS and de-phasing for the maximum angle of incidence foreseen by the optical design. Fig. 6 shows typical end-2-end PS simulated performances for a polarised and a non-polarised 3MI channel respectively, using such coatings. Further coating optimization is on-going and expected to further improve the system performances reported here.

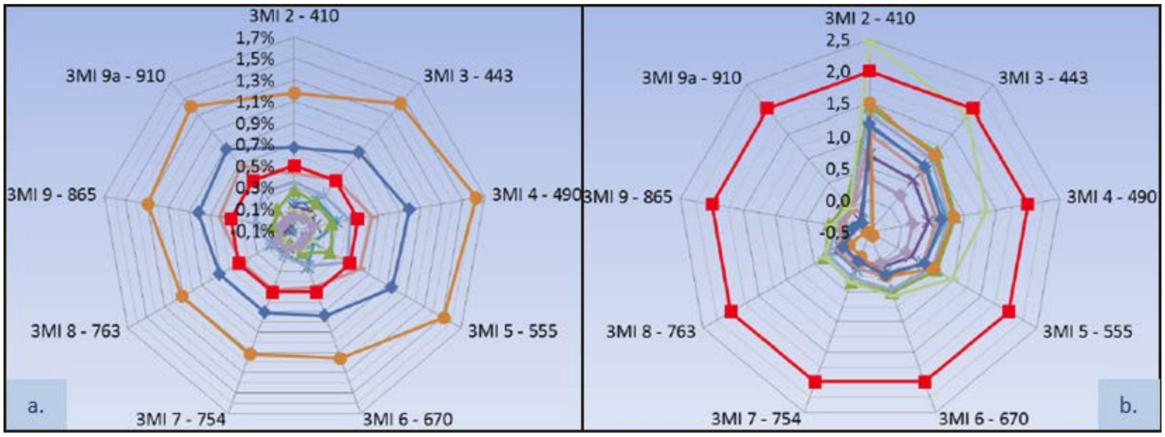

Fig. 5. Typical 3MI AR coating performances optimised to deliver minimum polarisation sensitivity (a) as well as minimum de-phasing (b) at component level. The red line shows the target performance for this run. The coloured lines indicate the coating performance for the various lens elements at a typically large AOI.

VI. STRAYLIGHT PERFORMANCES:

3MI will suffer from straylight in a similar way that POLDER did. While all steps are taken to minimize straylight at Level 0, it is certain that a straylight correction step will be required to reach tolerable straylight level. This implies not only the definition of a good straylight correction algorithm but also a rigorous and accurate straylight characterization and calibration on ground. Straylight sources for 3MI are various, however they are linked predominately to ghost reflections occurring between the detector surface and its window or between the detector and the filter stack. The sequence of the filter stack components (optical compensator, BP filter, polarizer and neutral density (ND) filter) is found to be particularly important in that respect. The straylight analysis has clearly shown that placing the ND filter closer to the detector leads to better straylight performances.

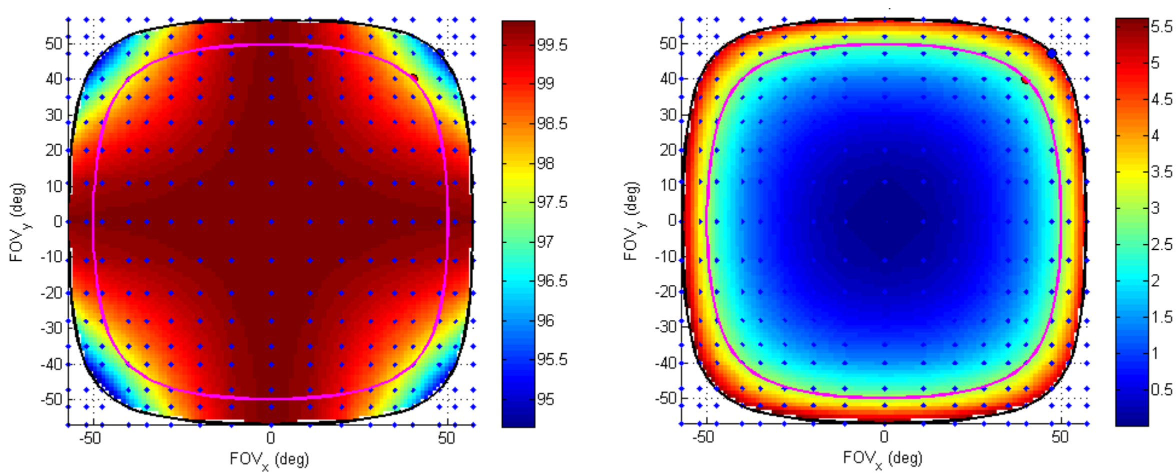

Fig. 6. Typical e2e polarisation sensitivity simulation for a 3MI polarised channel (left) and a 3MI un-polarised channel (right). Performances degrade for increasing field angles given the increased AOIs on the AR coatings.

PRE-DEVELOPMENT ACTIVITIES

Despite the heritage of POLDER, in order to retire any technological risks associated with the 3MI instrument development, ESA has initiated several pre-development activities. The most relevant ones are listed below:

I. 3MI OPTICS BREADBOARD:

This activity covers, the detailed design, manufacturing, assembly, integration and testing of an elegant breadboard of fully representative form, function and performance to the 3MI VNIR optics module. The scope of the breadboard includes the full camera optics as well as the filter stacks for several 3MI channels but excludes any mechanisms or indeed a detector representative to one used in the flight version. Two parallel activities have been initiated in mid-2013, the first with Selex ES (Italy) and the second with SODERN (France). The activities will demonstrate end performances and will highlight any areas of criticalities where more effort shall be placed during actual instrument development

II. NON-POLARISING BROADBAND OPTICAL COATINGS:

This is an activity funded by the ESA TRP programme. Its objective is to design, manufacture and test broadband AR coatings with high average transmission, low polarisation sensitivity and low de-phasing over a large angular range of incidence (AOIs) suitable for wide FOV optics as in the case of 3MI. The activity was initiated in Q2/2013. The selected contractor is CILAS (France) with SODERN (France) and the Institut Fresnel (France) as a sub-contractors). The detailed design phase was completed in Q2/2014 and currently AR coatings are under manufacturing.

III. POLISHING TECHNIQUES FOR LOW SCATTER SURFACES:

The objective of this activity is to develop and optimise super-polishing technologies able to achieve surface qualities exhibiting a very low optical scattering. While for 3MI ghosts are expected to dominate straylight sources, still the number of lens elements requires that scatter on those surfaces is kept to the minimum. Control of the polishing quality to such high levels is therefore very important also for 3MI. In the activity, scattering is specified in terms of BSDF (BRDF for reflective and BTDF for transmissive substrates). Values as low as 2e-2 for the BTDF on scatter angles of 0.1 degrees are targeted. Monitoring and modelling tools of the scatter are also under the scope of the activity. The activity is funded also by the ESA TRP programme and was initiated in Q4/2012. The selected contractor is REOSC-SAGEM. ESTEC facilities are used to perform the scattering measurements.

CONCLUSIONS

The 3MI mission, being an evolution of the POLDER/PARASOL mission will enhance and guarantee high accuracy aerosol monitoring for the next two decades. We have discussed some key aspects of the instrument and related technology pre-developments.

REFERENCES

[1] I. Manolis, S. Grabarnik, J. Caron; J-L. Bézy; M. Loiselet; M. Betto; H. Barré; G. Mason; R. Meynart, “The MetOp second generation 3MI instrument,” in Proc. SPIE 8889, Sensors, Systems, and Next-Generation Satellites XVII, October 2013.

[2] T. Marbach; P. Phillips; A. Lacan; P. Schlüssel, “The Multi-Viewing, -Channel, -Polarisation Imager (3MI) of the EUMETSAT Polar System - Second Generation (EPS-SG) dedicated to aerosol characterisation,” Proc. SPIE 8889, Sensors, Systems, and Next-Generation Satellites XVII, October 2013.

[3] P.-Y. Deschamps, F.-M. Bréon, M. Leroy, A. Podaire, A, Bricaud, J.-C. Buriez, and G. Sèze, “The POLDER mission: Instrument Characteristics and Scientific Objectives,” IEEE Transactions On Geoscience and Remote Sensing 32(3), pp. 598-615, May 1994.

[4] F. Parol, J.C. Buriez, C. Vanbauce, J. Riedi, L. C.-Labonnote, M. Doutriaux-Boucher, M. Vesperini, G. Sèze, P. Couvert, M. Viollier, F.M. Bréon, “Review of capabilities of multi-angle and polarization cloud measurements from POLDER,” Advances in Space Research, 33 (7), pp. 1080-1088, 2004.

[5] R. J. Peralta, C. Nardell, B. Cairns, E. E. Russell, L. D. Travis, M. I. Mishchenko, B. A. Fafaul, and R. J. Hooker, "Aerosol polarimetry sensor for the Glory Mission," in Proc. SPIE 6786, MIPPR 2007: Automatic Target Recognition and Image Analysis; and Multispectral Image Acquisition, November 2007.

[6] D. J. Diner, F. Xu, M. J. Garay, J. V. Martonchik, B. E. Rheingans, S. Geier, A. Davis, B. R. Hancock, V. M. Jovanovic, M. A. Bull, K. Capraro, R. A. Chipman, and S. C. McClain, “The Airborne Multiangle SpectroPolarimetric Imager (AirMSPI): a new tool for aerosol and cloud remote sensing,” Atmos. Meas. Tech., 6, 2007–2025, 2013.

[7] G. van Harten, F. Snik, J.H.H. Rietjens, J.M. Smit, J. de Boer, R. Diamantopoulou, O.P. Hasekamp, D.M. Stam, C.U. Keller, E.C. Laan, A.L. Verlaan, W.A. Vliegenthart, R. ter Horst, R. Navarro, K. Wielinga, S. Hannemann, S.G. Moon, R. Voors, “Prototyping for the Spectropolarimeter for Planetary EXploration (SPEX): calibration and sky measurements,” in Proc. SPIE 8160, Polarization Science and Remote Sensing V, September 2011.