

The 3MI Polarimeter on board of MetOP-SG: a comparative assessment of analytical prediction, on-ground calibration and in-flight performance

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ABSTRACT

The Multi-viewing, Multi-spectral, Multi-polarisation Imager (3MI), developed by Leonardo as prime contractor within the EUMETSAT Polar System Second Generation (EPS-SG) Programme, is a spaceborne polarimeter dedicated to global observations of polarised solar radiation for climate monitoring, atmospheric composition, and numerical weather prediction. Compared with previous-generation instruments, 3MI provides enhanced capabilities through an extended spectral coverage up to 2130 nm, increased spectral and polarisation channels, and improved spatial resolution and swath coverage. Among the key design challenges, polarisation sensitivity represented a major driver for the optical architecture. Achieving the stringent polarimetric performance required across both VNIR and SWIR spectral ranges and over a wide field of view demanded the optimization of optical materials and anti-reflection coatings with low polarisation effects and retardance. Instrument performance was supported by analytical modelling during the Optics Pre-Development (OPD) phase and validated through dedicated ground characterization campaigns. Following the successful development and testing of the Proto-Flight Model (PFM) and the Second Flight Model (FM2), the first 3MI instrument was launched aboard MetOp-SG A1 in August 2025. This paper presents a comparison of pre-launch predictions, ground-test results, and initial in-flight measurements collected during the commissioning and calibration-validation phase. The results provide a first assessment of the instrument performance in orbit and demonstrate its capability to meet the demanding scientific objectives of the EPS-SG mission from an industrial and hardware perspective.

Keywords: 3MI, Wide-Field Polarimeter, Polarisation Sensitivity, Optical Design, Polarimetric Calibration, Earth Observation

1. INTRODUCTION

The 3MI mission [1] is primarily aimed at providing aerosol characterization for climate monitoring, Numerical Weather Prediction (NWP), atmospheric chemistry and air quality. The high quality aerosol imagery delivered by the 3MI mission will facilitate the measurement of all the essential aerosol parameters for climate records, such as aerosol optical depths, particle types and sizes, refractive index, sphericity and aerosol height. Secondary objectives of the 3MI mission include measurement of the surface albedo as well as improved cloud characterization.

The multi-viewing and multi-polarisation measurements delivered by the 3MI mission allows for accurate characterization of the microphysical and optical properties of aerosol and cloud particles (ice crystal and water) such as optical depth, particle size, refractive index, sphericity factor. Utilization of the aforementioned aerosol and cloud parameters is becoming increasingly important in operational NWP, as the representation of radiative processes in the atmosphere is a recognized area of deficiency. Hence, the 3MI mission is expected to provide great benefit to both real-time and non-real-time user communities.

The 3MI concept is based on the heritage of the POLDER/PARASOL instrument by the French Space Agency (CNES) [2] and extends the observations to the SWIR spectral range with improved spatial resolution and swath (4 km and 2200 km respectively).

The 3MI instrument combines sequential views of the same ground target with multi-channel spectral acquisitions in both polarised and un-polarised channels. The multi-viewing measurement concept is based on a multi-angle acquisition performed by forward, nadir and backward observations of the same on-ground target at different instants, taking advantage of the very wide Field of View (FOV) optical design, a 2D Focal Plane Array (FPA) and the push-broom scanning concept in which the satellite orbital motion is used as Along-Track (ALT) scanning, see Figure 1. In total a set of 14 views in Visible and Near Infrared (VNIR) spectrum and 12 views in Short Wave Infrared (SWIR) spectrum are acquired for the same ground target. This concept provides the means to sense the Top of Atmosphere (TOA) radiance at different Observation Zenith Angles (OZAs) for each target. The multi-channel and multi-polarisation measurement concepts are based on successive acquisitions of polarised and un-polarised spectral bands performed by means of a rotating Filter Wheel System (FWS), located between two optical assemblies (one for VNIR, one for SWIR) and their related focal planes. Such design enables to change the polarising filters in a wavelength coverage in VNIR and SWIR bands (see Figure 1). Each polarised spectral channel is equipped with a linear polariser (substituted by optical path compensator for non-polarised channels) that allows the selection of the polarisation direction to be analysed (-60° , 0° and $+60^\circ$).

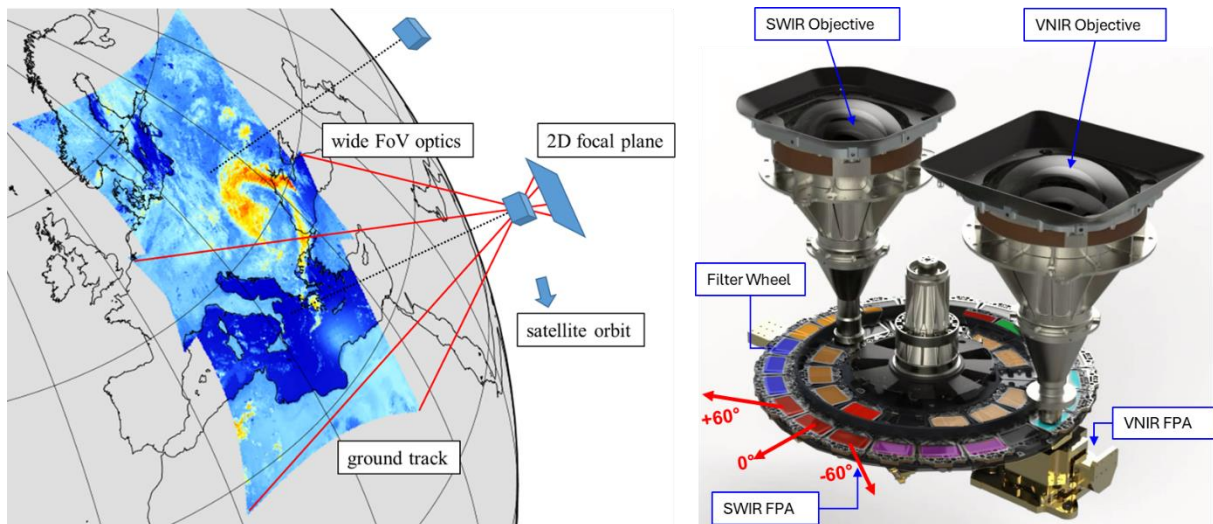


Figure 1 Left, 3MI multi-viewing concept exploiting push-broom scanning and very large FOV. Right, 3MI multi-channel and multi-polarisation concept exploiting two optical systems and a single rotating Filter Wheel

The achievement of the required scientific performance posed several technological challenges throughout the instrument development. Among them, the control of instrumental polarisation effects was one of the main design drivers, requiring dedicated optical design solutions, low-polarisation optical coatings, careful material selection and the development of dedicated polarimetric modelling tools. During the early development phases, analytical models were established to predict the end-to-end polarimetric performance of the instrument and to support the definition of the optical design and calibration approach.

Across the payload development phases, these predictions were progressively verified through a series of experimental campaigns. Initial validation activities were performed on dedicated development hardware representative of the flight optical system, the OPD model. Subsequently, extensive on-ground calibration campaigns were conducted on the flight PFM and FM2 instruments, providing the opportunity to compare measured performance against the initial design predictions and to identify effects not fully captured by the early models. Following the launch of the first 3MI instrument aboard MetOp-SG A1 in August 2025, the first in-flight observations became available, enabling a preliminary assessment of the instrument performance in an operational environment.

This paper provides an overview of the evolution of the 3MI polarimetric performance assessment from design to flight. First, the design rationale and the analytical models used to predict the instrument performance are reviewed. Experimental results obtained on OPD model are then presented, followed by a comparison with the on-ground calibration results measured on PFM and FM2 models. Finally, the first in-flight observations are discussed, providing an initial comparison between analytical predictions, ground measurements and operational performance.

2. POLARIMETRIC DESIGN RATIONALE AND PREDICTED PERFORMANCE

The 3MI instrument combines multi-angle, multi-spectral and multi-polarisation observations over a very wide field of view and an extended spectral range spanning from the visible to the short-wave infrared domain. The simultaneous requirement for high polarisation sensitivity, large angular coverage and operation across both VNIR and SWIR spectral ranges represented one of the primary design challenges of the optical system.

The polarisation sensitivity requirements allocated to the instrument imposed stringent constraints on the optical design, requiring careful control of instrumental polarisation, retardance and depolarisation over the full operational field of view and spectral range. To address these requirements, a dedicated end-to-end polarisation model was developed during the design phase of the payload. The complete optical chain was represented through a Mueller-matrix framework including the contributions of the optical assembly, anti-reflection coatings, filter stack elements, detector units and stress-induced birefringence effects. This approach enabled system-level performance predictions and provided the basis for the allocation of polarisation-related requirements to the various instrument subsystems.

The optical architecture adopted for the instrument is based on wide field telecentric optics specifically optimized for polarimetric measurements. Particular attention was devoted to the selection of optical materials exhibiting low stress birefringence and to the development of anti-reflection coatings characterized by low diattenuation and low retardance. Dedicated requirement flow-down activities were performed in order to control the contributions of optical surfaces, filter stack components, detector assemblies and birefringence effects to the overall polarisation performance budget.

Figure 2 shows the optical layout developed during the OPD phase for the VNIR module [3][2]. The design is based on a reverse Galilean telescope followed by a focusing group, with the aperture stop positioned to ensure image-space telecentricity and to support the spectral and polarimetric requirements of the filter stack.

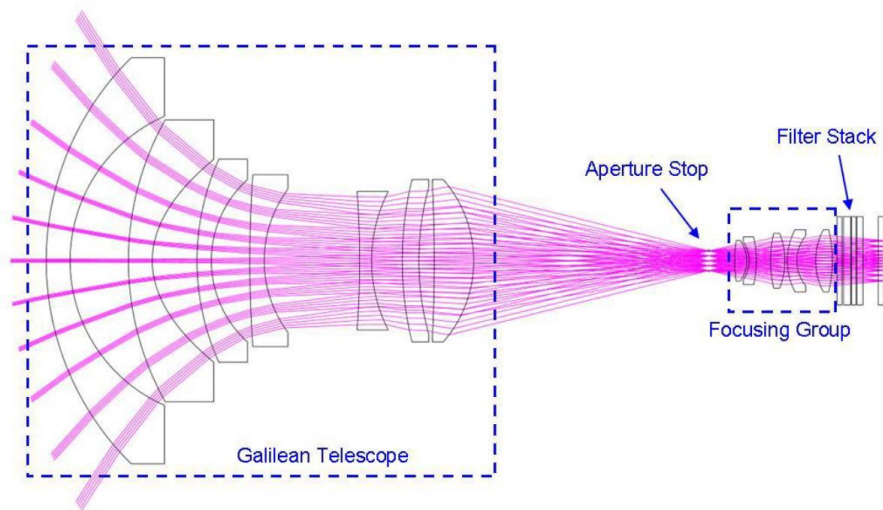


Figure 2 OPD VNIR module optical layout [3]

In parallel with the polarisation requirements, image irradiance uniformity represented another major design driver. Owing to the $\pm 57^\circ$ field of view, a conventional optical system would naturally exhibit a strong irradiance reduction towards the edge of the detector. During the OPD phase, dedicated analytical modelling was developed to assess the combined impact of entrance pupil variation, distortion and polarisation-dependent transmission on the spatial throughput distribution over the instrument field of view. To mitigate the natural irradiance fall-off, the optical design incorporated a controlled variation of the entrance pupil area as a function of field angle while maintaining distortion within the allocated limits. Combined with the telecentric optical architecture and the optimization of polarisation-related properties, this solution allowed a significant compensation of the intrinsic wide-field irradiance loss and established the baseline throughput uniformity expected before on-ground verification test [4].

The end-to-end model was subsequently used to predict instrument performance including the effects of optical coatings, filter stack properties, detector response, stress birefringence and acquisition dynamics. The analysis demonstrated compliance with the polarisation sensitivity requirements for both polarised and non-polarised channels and provided

quantitative margins against manufacturing and assembly tolerances. Model predictions indicated that the shortest-wavelength polarised channels exhibited the smallest compliance margins and therefore represented the most critical cases for 3MI performance, see Table 1.

Channel	POL	Predicted PS	Requirement
3MI-2	Y	0.945	>0.93
3MI-3	Y	0.965	>0.96
3MI-4	Y	0.975	>0.96
3MI-5	Y	0.982	>0.96
3MI-6	Y	0.988	>0.96
3MI-7	N	0.033	<0.05
3MI-8	N	0.033	<0.05
3MI-9	Y	0.991	>0.96
3MI-9a	N	0.035	<0.05
3MI-10	Y	0.973	>0.96
3MI-11	Y	0.986	>0.96
3MI-12	Y	0.991	>0.96

Table 1 - 3MI polarisation sensitivity predicted performances (worst value in 50° FOV)

Throughput uniformity distribution

Beyond polarisation sensitivity, the modelling framework also provided detailed predictions of throughput distribution across the focal plane. Figure 3 reports representative throughput uniformity maps obtained for polarised channel 3MI-2 and for unpolarised channel 3MI-7. As highlighted in [4][4], the throughput uniformity distribution for polarised channels results not radially symmetric, see top maps for 3MI-2 channel calculated for linearly polarised input light parallel to each polarizer transmission axis. In fact, in addition to the combined effects of entrance pupil area and distortion variation over the FOV, characterized by radial symmetry, a not negligible contribution is given by the effect of small polarisation introduced by optics, passing then through the linear polarizer in the FW: this effect is responsible of the non-radial symmetric distribution of the throughput uniformity across the focal plane. For unpolarised channel 3MI-7, where the high efficiency linear polarizer is not part of the optical path, effect of optics polarisation is not present and therefore the throughput uniformity distribution shows radial symmetry as expected, see bottom map of Figure 3.

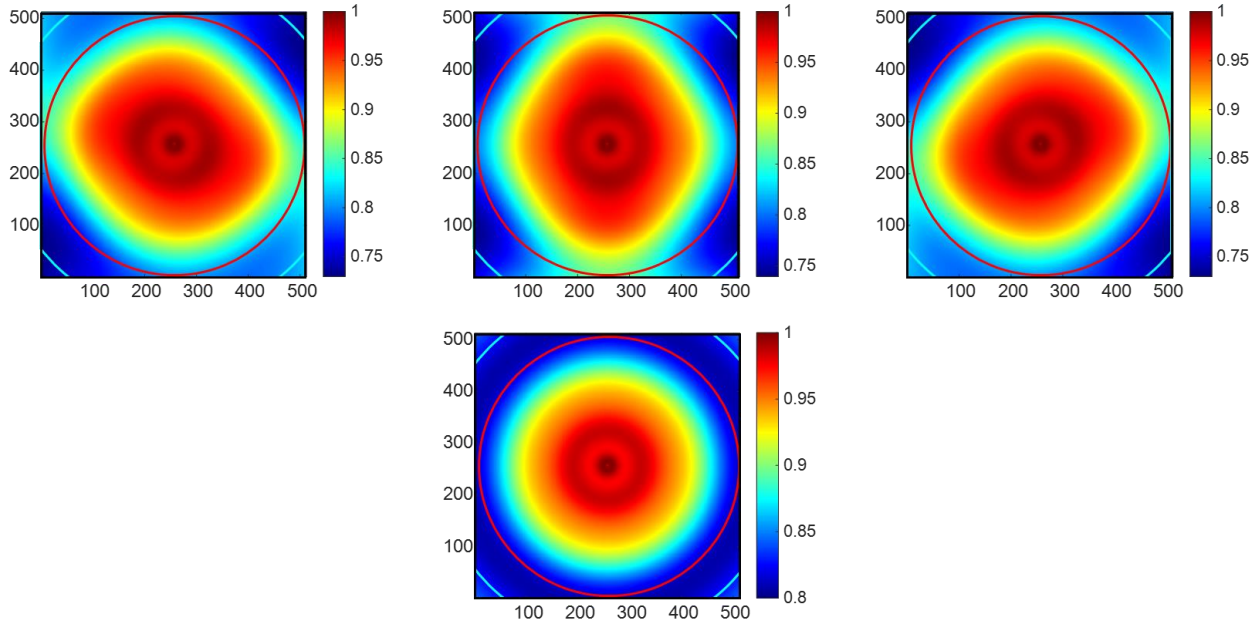


Figure 3 Predicted throughput-uniformity distribution for a representative 3MI polarised channel (3MI-2, top maps: left, slot with pol axis oriented at -60° ; center, slot with pol axis oriented at 0° ; right, slot with pol axis oriented at $+60^\circ$) and unpolarised channel (3MI-7, bottom map). Red circle corresponds to 50° FOV, while cyan circle corresponds to 57° FOV.

Polarisation sensitivity distribution

Similarly, 3MI polarisation model was used to predict the spatial distribution of polarisation sensitivity (PS) over the instrument FOV. Figure 4 presents a representative example of the resulting distribution for polarised channel 3MI-2 and for unpolarised channel 3MI-7. The predicted distribution reflects the combined contribution of optical surfaces, coating properties, filter stack components, detector effects and birefringence terms included in the polarisation end-to-end model.

In top maps of Figure 4, related to channel 3MI-2, a cross-shape pattern oriented accordingly to the channel polarisation axis can be clearly distinguished. The origin of this pattern (ideally the PS map should be flat across the whole FOV) is due to the small polarisation introduced by the lenses objective, introducing an overall degradation of the PS to lower values for angular directions not aligned (nor perpendicular) with the channel linear polarizer axis. The effect is larger at shorter wavelengths, for which the requirement of low retardance for the coatings becomes challenging; channel 3MI-2 represents the worst case, as already highlighted in Table 1.

In bottom map of Figure 4, related to channel 3MI-7, PS map shows axial symmetry due to the absence of the linear polarizer inside the optical channel, anyhow such symmetry is partially lost due to the effects introduced by residual polarisation sensitivity of all other optical components (lenses and other optical elements inside the filters stack).

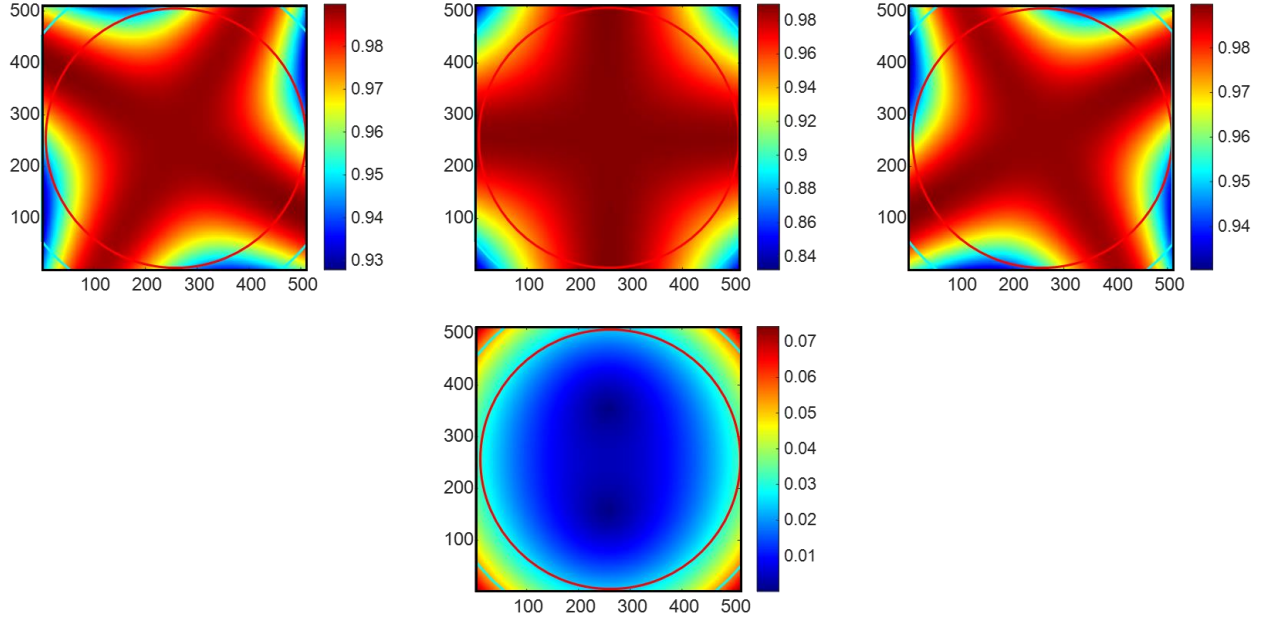


Figure 4 Predicted polarisation sensitivity maps for a representative 3MI polarised channel (3MI-2, top maps: left, slot with pol axis oriented at -60° ; center, slot with pol axis oriented at 0° ; right, slot with pol axis oriented at $+60^\circ$) and unpolarised channel (3MI-7, bottom map). Red circle corresponds to 50° FOV, while cyan circle corresponds to 57° FOV.

Instrument polarisation angle

As part of 3MI performance evaluation before on-ground test campaign, the end-to-end polarisation model was used to predict the variation of the instrument resulting polarisation angle across FOV. Ideally, for each 3MI channel the resulting polarisation angle should be the same for each pixel of the detector plane and aligned with the axis of the linear polarizer within the filter stack, i.e. oriented at -60° , 0° or $+60^\circ$ depending on the slot. Anyhow, also in this case the effect of optics polarisation plays a role for angular directions not aligned (nor perpendicular) with the channel linear polarizer axis. In Figure 5 is reported a representative example of the resulting polarisation angle for polarised channel 3MI-2, slot corresponding to linear polarizer oriented at 0° . Polarisation angle results at 0° , aligned with the linear polarizer axis, in the cross-shape pattern for which corresponding PS map (see Figure 4) resulted at the maximum values. 3MI channel resulting polarisation angle starts to deviate from 0° while changing the angular direction with respect to the cross-shape pattern and reaching the maximum deviation at $\pm 45^\circ$ of orientation. The deviation results of about $\pm 10^\circ$ in the 50° FOV range (red circle in left map of Figure 5).

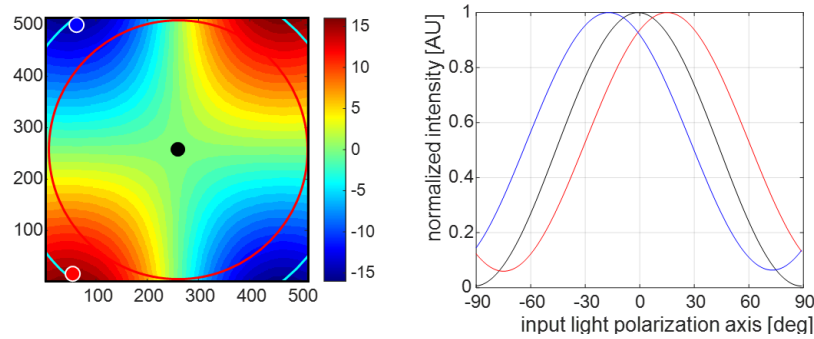


Figure 5 Left map, predicted variation across FOV of the absolute polarisation axis for 3MI polarised channel 3MI-2, slot with linear polarizer axis oriented at 0° . Right graph, normalized Malus law curves corresponding to the three circles in black/red/blue color, highlighted in left map, calculated with 3MI polarisation model and assuming in input linearly polarised input light with polarisation axis rotating in a range of about 180°

For a straightforward visualization of the expected effect in view of on-ground testing campaign, theoretical Malus law curves for different FOV positions were calculated using 3MI polarisation model and assuming in input linearly polarised input light with polarisation axis rotating in a range of about 180° around the channel designed polarisation axis 0° , see right graph of Figure 5. During the on-ground characterization of 3MI PFM and FM2 absolute polarisation angles across FOV a similar rigid shift was observed, even if with lower amplitude.

Mueller matrix elements variation with exposure time

Finally, 3MI polarimetric end-to-end model was used to assess potential variation of Mueller matrix elements (and therefore overall PS) as a function of instrument integration time. Indeed, since each 3MI polarised channel includes a linear polarizer optical element inside the Filter Wheel, the polarizer rotates during the frame exposition. For any exposure time selected up to the maximum limit of 100ms, acquisition cycle is synchronized with FW rotation speed such that the exposure window is centered always at the same angular position of the FW. In Figure 6 is reported an example of PS variation for different FOV points related to black circles in PS map of polarised channel 3MI-4, slot at -60° . It is worth noticing that for each 3MI channel the exposure time is adjusted across the daytime orbit by means of a scheduled time vector commanded by ground segment, to maximize SNR performance vs TOA radiance whose intensity depends on the Sun Zenith Angle (SZA) and therefore on latitude. On the other hand, 3MI polarisation sensitivity knowledge is requested below 0.001. Being the predicted variation in right graph of Figure 6 larger than 0.001, calibration of PS dependance from exposure time and retrieval of time modelling was included in the baseline for PFM and FM2 on-ground calibration test campaign.

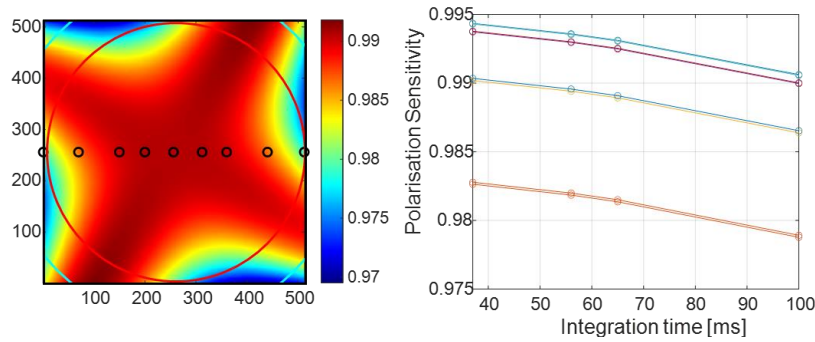


Figure 6 Left map, PS map for a representative 3MI polarised channel (3MI-4, slot corresponding to -60° polarizer axis). Black circles are FOV positions to which variation of PS value vs integration time was evaluated. Right graph, PS values corresponding to positions highlighted in left map by black circles as a function of 3MI channel exposure time

In summary, the analytical predictions discussed in this section established the reference baseline for the on-ground verification activities of 3MI phase D. The following sections therefore present the progressive validation of these predictions through measurements performed on OPD, during the on-ground calibration campaigns of PFM and FM2 models, and finally through the first observations acquired in orbit.

3. DEVELOPMENT MODEL PERFORMANCE VERIFICATION

The optical design and performances were fully demonstrated for the VNIR objective (and by similarity for the SWIR) in the frame of the OPD activity in Leonardo: an Elegant Breadboard of the 3MI VNIR lenses (representative in terms of form, function and performance) was manufactured as de-risking activity for the instrument development. OPD objective (see left picture of Figure 7) was coupled with a set of filters stacks representative for polarised channels 3MI-3, 3MI-9 and for unpolarised channels 3MI-7, 3MI-9a to verify by test radiometric, spectral, geometric, straylight and polarimetric performances of the end-to-end optical chain (objective and optical elements of FWS subsystem).

In right picture of Figure 7 test setup for polarimetric performance verification is shown: it consisted in an input source (NKT super-continuum laser) injected in a Beam Expander Unit to adjust testing beam diameter; a Polarisation Unit composed by a Glan-Taylor linear polarizer with a superachromatic Bi-Halle $\lambda/2$ plate working in VNIR spectral range. Polarisation angle was scanned between 0° and 180° with a 10° step to collect Malus law intensity curves as a function of

input light polarisation angle. Measured signal was normalized by means of a monitoring signal collected by a photodiode to mitigate impact of laser source stability during test.

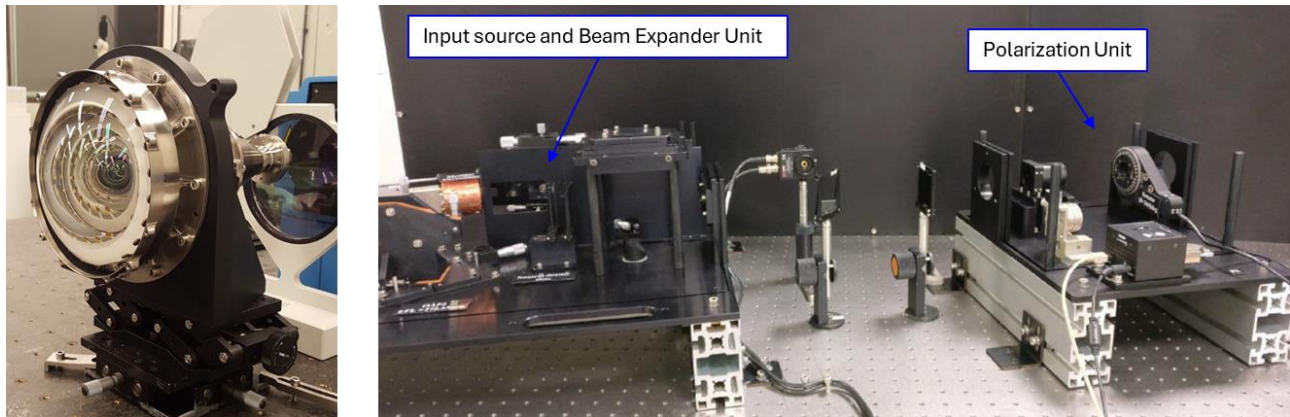


Figure 7 Left picture, VNIR OPD model under testing; right picture, OPD polarimetric measurements test setup

For the purpose of OPD polarimetric performance verification, a limited amount of Malus law curves were collected across the objective FOV, see results reported in Figure 8 for polarised channel 3MI-3 and for unpolarised channel 3MI-7 in comparison with prediction from 3MI polarimetric model. Globally, OPD PS values resulted compliant and well within the performances predicted in Table 1. Additionally, PS values distribution across FOV resulted nicely matching the predicted patterns of Figure 4, with a cross-shape pattern for 3MI-3 and 3MI-9 polarised channels due to the objective retardance and its combination with other polarisation contributors, while showing nearly axial symmetry for 3MI-7 and 3MI-9a unpolarised channels.

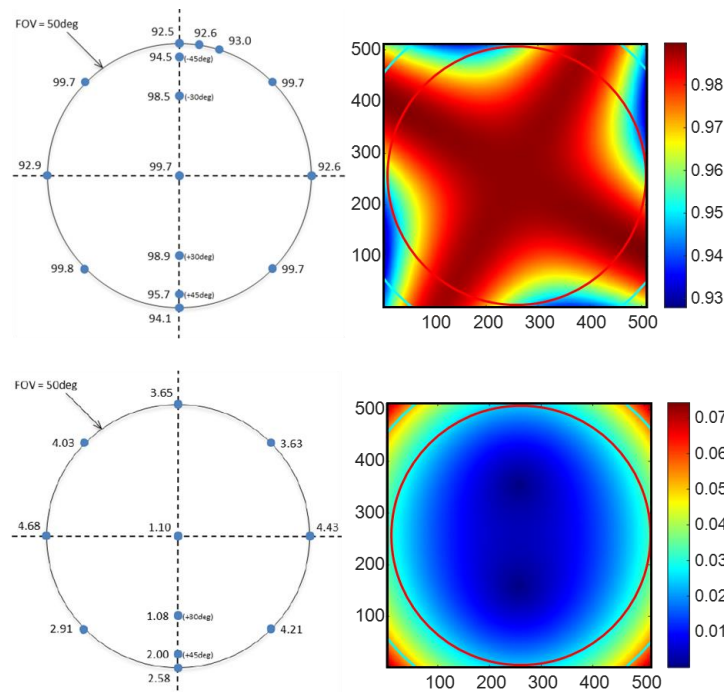


Figure 8 Comparison between OPD PS measured values and prediction from 3MI polarimetric model. Top left image, measured PS values for polarised channel 3MI-3. Top right image, PS predicted map for polarised channel 3MI-2, -60° slot. Bottom left image, measured PS values for unpolarised channel 3MI-7. Bottom right image, PS predicted map for unpolarised channel 3MI-7

4. FLIGHT MODELS ON-GROUND CALIBRATION RESULTS

As an important precursor to the PFM and FM2 on-ground calibration campaigns, a fully flight-representative Engineering Model (EM) was manufactured, integrated and aligned by Leonardo during the last quarter of 2020, and subsequently tested in the thermal-vacuum facility at the Centre Spatial de Liège (CSL) during the first quarter of 2021 [5]. The EM campaign provided a valuable opportunity to validate and refine the overall calibration approach, with particular emphasis on the optimization of Ground Support Equipments (GSEs) configurations and instrument operational settings to be used during the flight models campaigns. The nominal 3MI on-ground calibration campaign requires approximately 85 days of continuous electro-optical testing under thermal-vacuum conditions: such a demanding campaign requires extensive preparation activities, including detailed calibration planning, optimization of GSEs configurations, and definition of instrument operational settings prior to test execution.

Building upon the experience gained during the EM campaign, the PFM calibration campaign started in December 2021 and was completed in March 2022 [6]. Besides confirming a large fraction of the expected instrument performance, the campaign also revealed some instrument features that had not been fully predicted. The investigation of these non-compliances and of their impact on instrument performance required extensive post-test analyses and led to a deeper understanding of several aspects of the instrument polarimetric response.

The subsequent FM2 calibration campaign, performed in the first quarter of 2024, directly benefited from the lessons learned during PFM testing. In addition to refinements of procedures and operational settings, improvements were implemented on the calibration facility itself, resulting in a more mature test environment and enabling a more efficient execution of the campaign [7]. Finally, the combined calibration results obtained on PFM and FM2 models [8] provide a unique dataset for assessing the consistency between analytical predictions, experimental measurements and flight-instrument performance.

PFM and FM2 polarisation sensitivity performances

To correctly map 3MI PS variation across FOV and retrieve full pixel knowledge, a grid of 58 calibration points (see left image of Figure 9, for VNIR case) was established based on the predicted PS pattern given by 3MI polarimetric model and the accuracy of the 2D interpolation method. Indeed, the requested PS knowledge accuracy of 0.001 demanded to minimize errors contributors coming from PS values reconstruction from raw measurements, namely: accuracy of the fitting of the instrument sinusoidal response to input polarised light rotated in $[0^\circ, 360^\circ]$ range (Malus law reported in Figure 9, central graph) for each calibrated FOV point; 2D interpolation to retrieve pixel to pixel PS knowledge. A good improvement was introduced by Fourier analysis (Figure 9, right graph) showing better accuracy than Malus law fitting and requesting way less samples in the sinusoidal trend measured for each calibrated point. The method was tested during PFM data analysis and baselined for FM2 calibration where additional FOV points were introduced to the calibration grid (green X's in Figure 9, left image), taking advantage of the reduced testing time, for a total amount of 69 calibrated points.

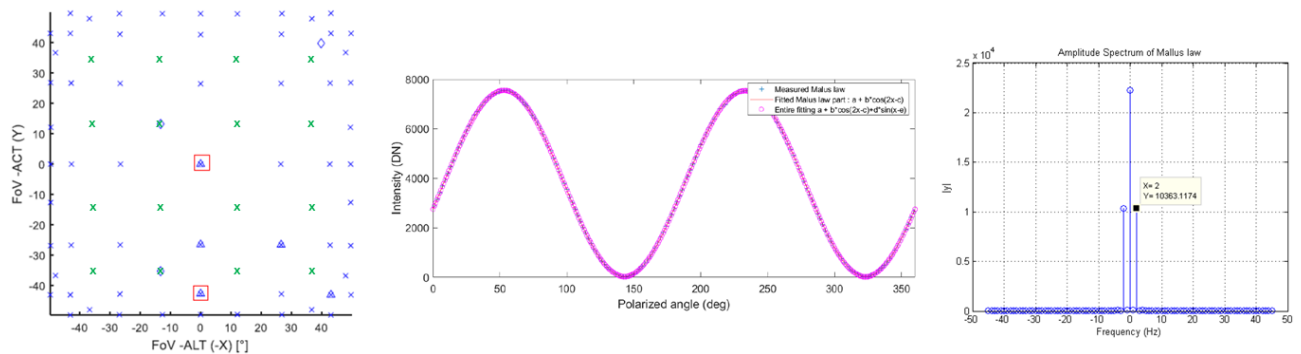


Figure 9 Left image, VNIR calibration grid for polarimetric measurements: blue X's account for nominal FOV grid, blue diamonds and triangles account for verification points; green X's are additional nominal FOV grid points added in FM2 calibration taking advantage of Fourier analysis method. Central graph, typical sinusoidal fitting of Malus law curve for a polarised 3MI channel (baseline method for PFM calibration). Right graph, amplitude spectrum of Malus law 3MI polarised channel response from Fourier analysis (baseline method for FM2 calibration)

In Table 2 are reported the worst case results obtained across the instrument FOV for each 3MI channel of both PFM and FM2 models, compared with prediction from 3MI polarimetric model and related requirement. As already mentioned in previous sections, low-retardance anti-reflection coatings become increasingly challenging at short wavelengths, especially at very large FOV. Indeed, lower PS values were found for 3MI VNIR channels 3MI-2, 3MI-3, 3MI-4 and for SWIR channel 3MI-10 resulting out of spec.

Channel	PFM	FM2	Prediction	Requirement
3MI-2	0.82	0.80	0.945	>0.93
3MI-3	0.90	0.88	0.965	>0.96
3MI-4	0.94	0.92	0.975	>0.96
3MI-5	0.95	0.96	0.982	>0.96
3MI-6	0.98	0.97	0.988	>0.96
3MI-7	0.04	0.02	0.033	<0.05
3MI-8	0.04	0.02	0.033	<0.05
3MI-9	0.99	0.99	0.991	>0.96
3MI-9a VNIR	0.04	0.02	0.035	<0.05
3MI-9a SWIR	0.03	0.02	0.035	<0.05
3MI-10	0.93	0.94	0.973	>0.96
3MI-11	0.96	0.97	0.986	>0.96
3MI-12	0.97	0.99	0.991	>0.96

Table 2 3MI PFM and FM2 polarisation sensitivity performances (worst value in 50° FOV) compared with prediction and requirement

PFM and FM2 PS retrieved maps well matched the prediction from 3MI polarisation model. See FM2 results example in Figure 10 for VNIR polarised channel 3MI-4 and in Figure 11 for SWIR polarised channel 3MI-10. Cross-shaped patterns show some level of distortion with respect to prediction. This is the direct consequence of the instrument as-built retardance and the way it combines with other polarimetric terms that cannot be fully predicted a priori; there is therefore the need to model, through on-ground measurement data, all polarisation signatures mapped inside 3MI polarimetric Key Data Parameters (KDPs) with the aim to build a robust as built model for interpretation of the in-flight vicarious calibration results [9].

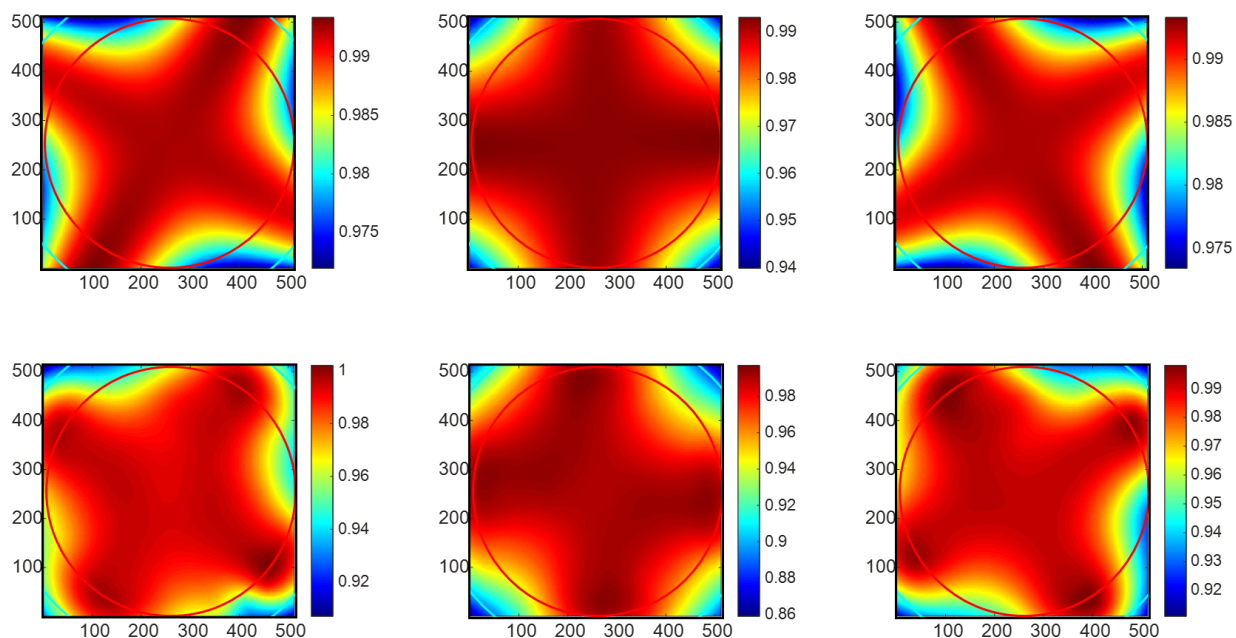


Figure 10 Comparison between predicted PS maps (top) and measured ones (bottom) for FM2 VNIR polarised channel 3MI-4. Left images account for slots with -60° of polarisation axis, central images for slots with 0° of polarisation axis, right images for slots with $+60^\circ$ of polarisation axis

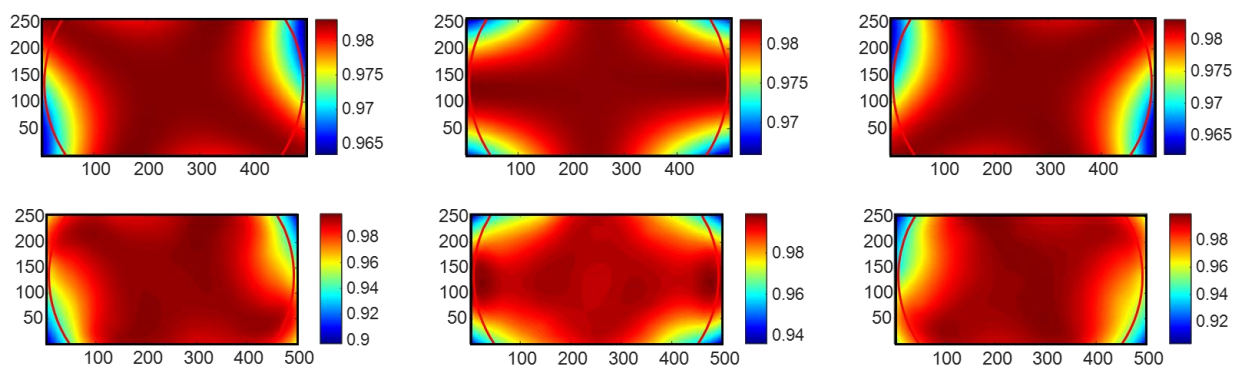


Figure 11 Comparison between predicted PS maps (top) and measured ones (bottom) for FM2 SWIR polarised channel 3MI-10. Left images account for slots with -60° of polarisation axis, central images for slots with 0° of polarisation axis, right images for slots with $+60^\circ$ of polarisation axis

A good match between measured PS values and prediction was obtained also for unpolarised channels, see FM2 results example in Figure 12 for VNIR unpolarised channel 3MI-7 and for SWIR unpolarised channel 3MI-9a.

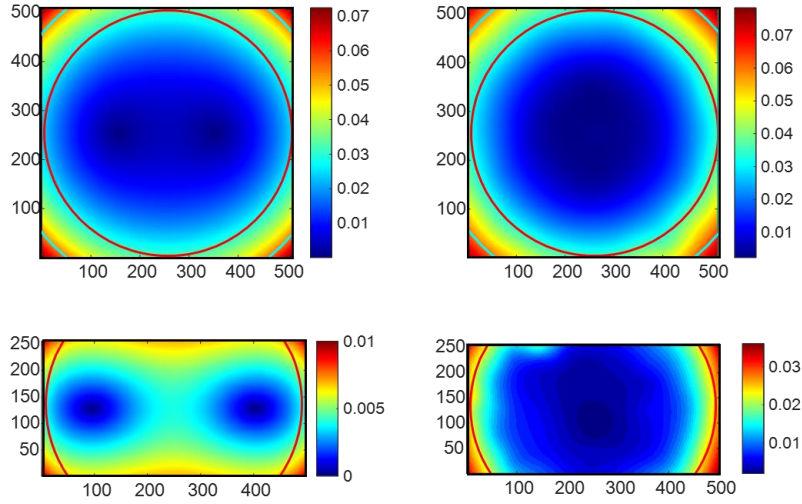


Figure 12 Comparison between predicted PS maps (left) and FM2 measured ones (right) for VNIR unpolarised channel 3MI-7 (top) and SWIR unpolarised channel 3MI-9a (bottom)

PFM and FM2 throughput uniformity linked to m_{11} term

As highlighted in [4], 3MI polarimetric model demonstrated that the expected throughput uniformity (or Flat Field) distribution for polarised channels is not radially symmetric across the focal plane due to the optics polarisation on the channel transmittance. Predicted distribution shown for polarised channels in Figure 3 and [4] was calculated assuming input polarised input light. During on-ground calibration campaign, flat field measurements have been performed with unpolarised input light.

Notably, as shown in Figure 13 (top maps), a residual effect of the optics polarisation is still present even when calibrating the flat field with unpolarised light. The reason is that, as already mentioned in previous sections, there are at least two polarising optical contributors within the instrument: the lenses, and the linear polariser inside the FWS. Even if input unpolarised light enters the optics, the output light exiting the optics, and reaching the linear polariser, can be partially polarised. The effect was already hidden within 3MI polarisation model, see calculated distribution in Figure 13 (middle maps) assuming this time unpolarised input light. Indeed, variation of instrument throughput as a function of the input polarisation status is mainly linked to the m_{11} term of the Mueller matrix (bottom maps of Figure 13). As described in POLDER analytical model of [9], evaluating the difference between flat field maps of slots at -60° , 0° and $+60^\circ$ (top maps of Figure 13), the polarisation introduced by optics can be quantified as separated contributor.

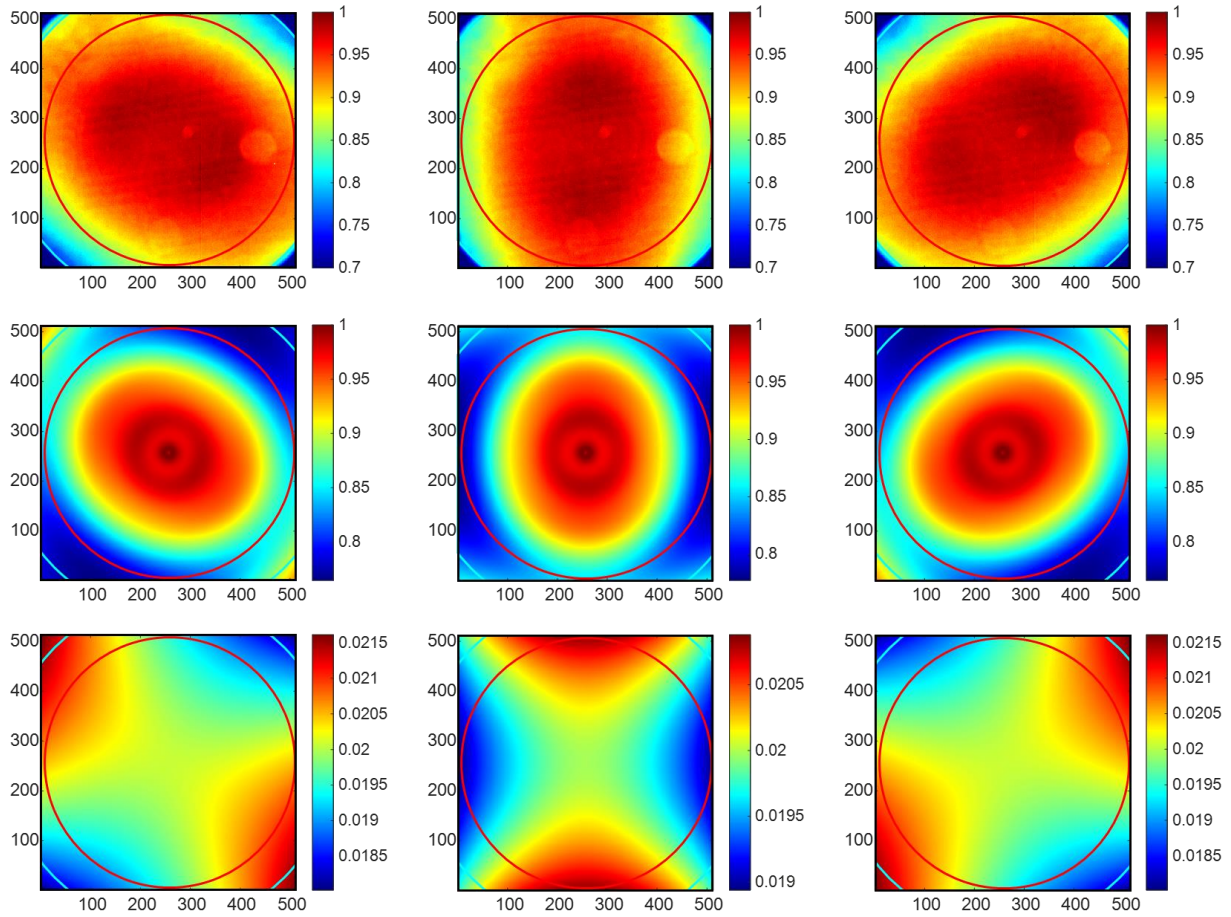


Figure 13 Comparison between FM2 measured flat field maps (top), predicted throughput uniformity maps assuming unpolarised input light (middle) and predicted m11 term of the Mueller matrix (bottom) for polarised VNIR channel 3MI-4 in the three slot configuration at -60° (left), 0° (center) and $+60^\circ$ (right)

PFM and FM2 polarisation angles

As shown in previous section, due to the effect of optics polarisation the instrument resulting polarisation angle is expected to deviate from 0° while changing the angular direction with respect to the cross-shape pattern (corresponding to parallel and orthogonal directions of the linear polarizer axis), reaching the maximum deviation at $\pm 45^\circ$ of orientation.

The effect was noticeable also in PFM and FM2 on-ground measurements, see in Figure 14 comparison between prediction (left map) and FM2 result (right map) for VNIR polarised channel 3MI-2, slot 0° . If the predicted deviation was about $\pm 10^\circ$ in the 50° FOV range (red circle), the actual as built deviation with respect to the on-axis value results about $\pm 3^\circ$. Moreover, the measured pattern shows some level of distortion with respect to prediction, result which is quite similar to the discrepancies observed for PS. These findings could be related again to the instrument as-built retardance and its coupling with other polarimetric terms that could not be predicted by 3MI polarisation model.

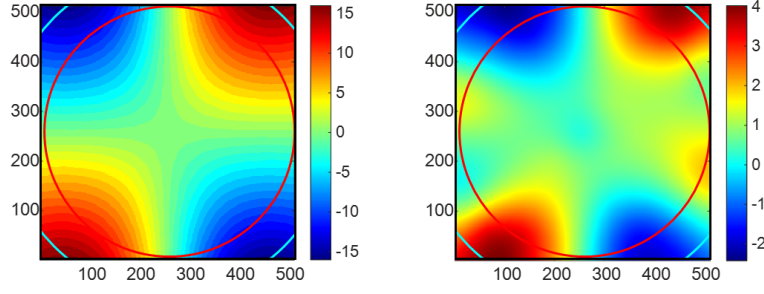


Figure 14 Comparison between predicted variation across FOV of the absolute polarisation axis (left map), and FM2 measured polarisation axis (right map) for 3MI polarised channel 3MI-2, slot 0°

PFM and FM2 PS variation with exposure time

As explained in previous section, since the predicted temporal dependence of 3MI PS (and related Mueller matrix elements) was expected to be larger than the requested knowledge accuracy of 0.001, calibration of 3MI channels PS as a function of integration time was included as baseline for PFM and FM2 on-ground calibration test campaign, to retrieve a time modelling to be used in the on ground radiometric processor pipeline.

Some dedicated FOV points among ones identified in the on-ground calibration grid (Figure 9 left map, for VNIR example) were chosen for time modelling characterization and verification. In Figure 15, right graph, is reported an example of the 2nd order polynomial fitting of PS values for polarised channel 3MI-4, compared with the expected variation for the same channel by 3MI polarimetric model, left graph.

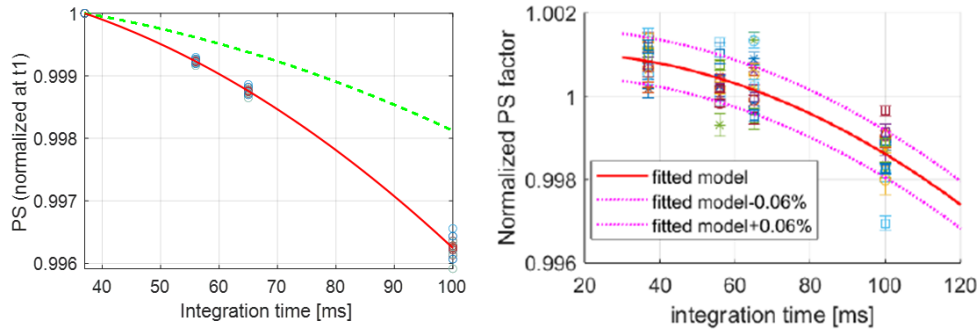


Figure 15 Left graph, 3MI-4 PS variation with integration time predicted by 3MI polarisation model. Circles corresponds to PS values evaluated at different FOV points and normalized with respect PS value at $t_1=37\text{ms}$; red solid line is the average fit across all FOV points under evaluation; green dotted line is the theoretical sinc law that would be applicable to a pure linear polarizer. Right graph, FM2 result for channel 3MI-4. Normalized PS values variation with integration time, symbols, are compared with average fit, red solid line

It is interesting to notice that, in average across all FOV points (see red solid lines), the PS predicted variation for this specific channel was about 0.004 in the range from 37ms (nominal integration time t_1) and 100ms (maximum integration time allowed by 3MI acquisition timeline); this is in line with the experimental observation from PFM and FM2. Whereas a smaller variation, of about 0.002 (see green dotted line), would be expected considering an ideal rotating polarizer and integrating the corresponding Malus-law modulation over the detector integration time: under this assumption, the expected reduction of the modulation amplitude would follow a sinc function of the angular displacement swept by the polarizer during the exposure, calculated as:

$$PS(t) = PS_{t_1} \cdot \text{sinc}\left(\frac{\Delta_{phi}(t)}{\pi}\right)$$

where $\Delta_{phi}(t) = 2\pi t/T_{rev}$ represents the angular displacement of the polarizer during the detector integration time, t is the integration time vector from 37ms up to 100ms, $T_{rev} = 5500ms$ is the revolution period of the FWS and PS_{t1} is the PS value measured at reference time $t1$.

The good agreement between measurements and end-to-end predictions, together with the discrepancy with respect to the ideal rotating-polarizer approximation, suggests that the effect is dominated by the combination of filter-wheel motion and instrument polarisation properties rather than by the temporal averaging process alone.

PS variation with OOB contribution

During the PFM calibration campaign, a time-dependent degradation of the measured PS was observed for the shortest wavelength polarised channels, particularly 3MI-2 and 3MI-3. The effect, reaching up to approximately 2% for channel 3MI-2, was unpredicted and represented a significant deviation with respect to the PS knowledge requirement of 0.1%. Therefore, a dedicated investigation was initiated to determine whether the observed behaviour originated from the instrument itself or from the calibration setup.

The phenomenon was monitored throughout the FM2 campaign, see left upper graph of Figure 16, and was eventually found to correlate with the ageing of the lamp used in the polarisation source, see bottom graph of Figure 16 [7]. Spectral measurements performed before and after lamp replacement revealed significant changes in the source spectral power distribution, particularly at shorter wavelengths. The immediate recovery of the measured PS after lamp replacement (Figure 16, right upper graph) excluded a degradation of the instrument polarisation optics and redirected the analysis towards the interaction between the source spectrum and the instrument spectral response.

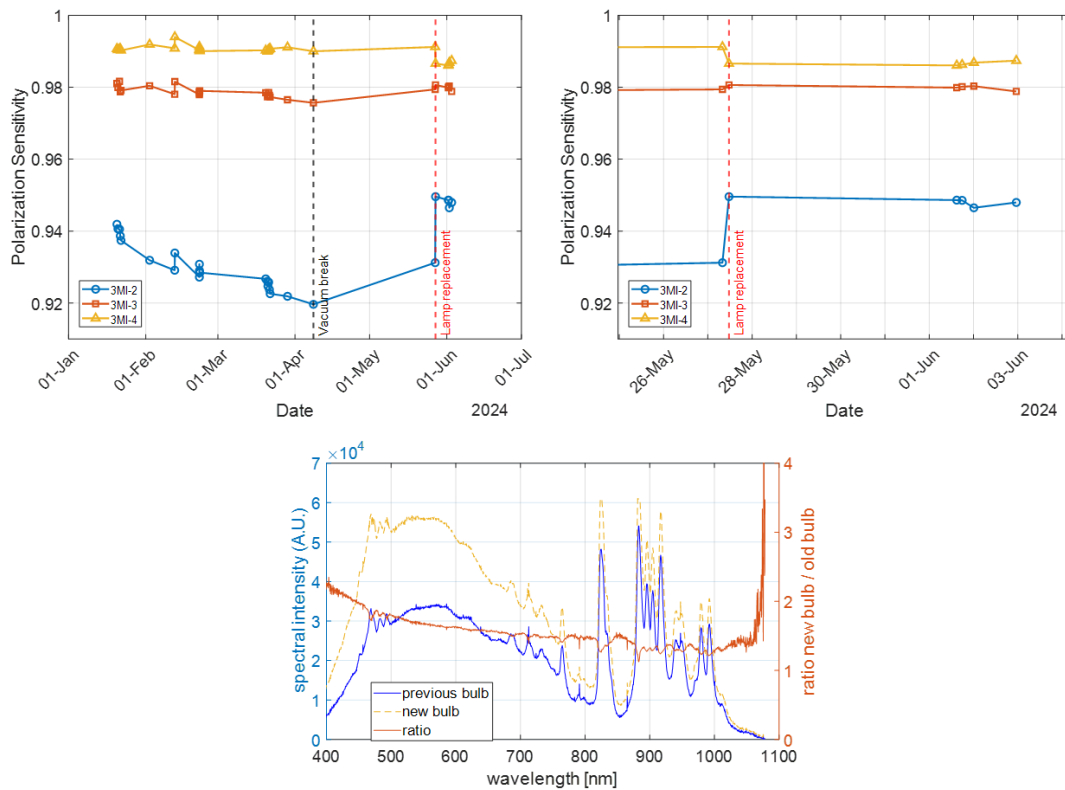


Figure 16 Left upper graph, polarisation sensitivity values at the reference FOV measured every 10 days during the FM2 campaign; Right upper graph, extract to highlight 3MI-2 PS value jump after light bulb replacement. Bottom graph, spectra of the previous bulb and the replaced bulb [7]

Figure 17 compares the spectral properties relevant to the out-of-band (OOB) polarisation behaviour of VNIR channels 3MI-2 (left graphs) and 3MI-6 (right graphs). Upper graphs report the measured FM2 ISRF profiles extended over the full

spectral range: the integrated OOB signal for both channels resulted well within the instrument requested value, which is 0.1% of the signal integrated in the full spectrum.

Middle graphs show the polarizer Contrast Ratio (CR) provided by manufacturer Codixx over the full VNIR spectral range. It is noticeable that, while the CR is maximized inside the nominal spectral range provided by the bandpass filter, a strong decrease is observed immediately outside the in-band (IB) regime. At even larger spectral offset the CR rises again, revealing a spectral inversion of the polarizer behaviour, where the polarisation state that is nominally rejected becomes preferentially transmitted. This effect has limited impact on 3MI channels radiometric performance because of the very low out-of-band transmission, but it becomes relevant when investigating polarisation sensitivity variations driven by changes in the source spectral distribution.

Inversion of the polarizer behaviour across the spectrum is also visible in the blocking measurements provided by manufacturer Materion (formerly, Optics Balzer Jena) reported in bottom graphs of Figure 17. The measured transmittances for input light polarised parallel (blue curve) and orthogonal (red curve) to the nominal transmission axis cross each other outside the nominal operating band, causing the following polarisation modulation (green curve)

$$PSM(\lambda) = \frac{T_{para}(\lambda) - T_{ortho}(\lambda)}{T_{para}(\lambda) + T_{ortho}(\lambda)}$$

to decrease and eventually change sign. The sign reversal indicates that the linear polariser can therefore alter the effective polarisation sensitivity when weighted by an out-of-band spectral contribution. In fact, while the nominal in-band region is characterized by values close to unity, the modulation rapidly decreases outside the design spectral range. The effect is particularly relevant for channel 3MI-2: even the OOB integrated signal is compliant and below <0.1% of the entire transmitted integrated signal, for most of the OOB spectral range the polarisation modulation of 3MI-2 undergoes a sign inversion and approaches -1. Conversely, channel 3MI-6 combines a lower out-of-band contribution with a much more favourable PSM behaviour over the corresponding OOB spectral range.

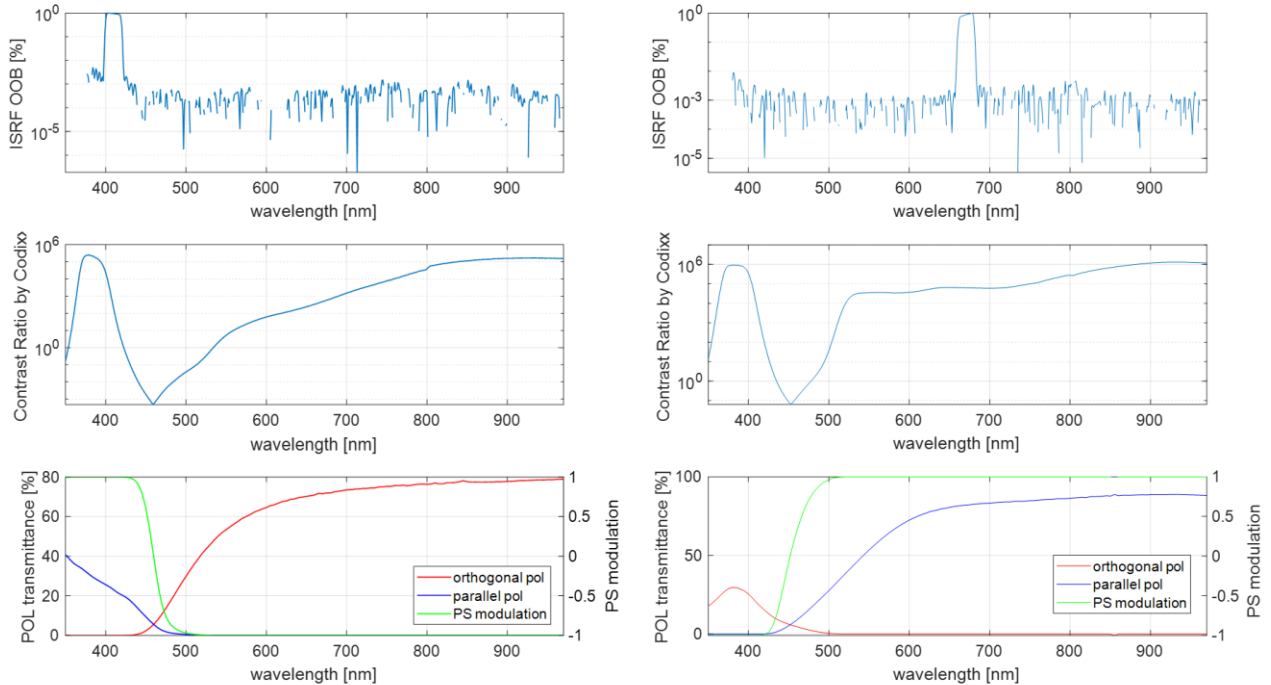


Figure 17 Top graphs, FM2 ISRF profiles extended to the out of band (OOB) spectral region. Middle graphs, Contrast Ratio values in the full VNIR range provided by Codixx manufacturer. Bottom graphs, transmittance curves of polarizer element provided by Materion (formerly Optics Balzer Jena) related to blocking measurements: red line, transmittance for input orthogonal polarised light;

blue line, transmittance for input parallel polarised light; green line, related PSM expected across VNIR range. Left graphs are related to VNIR channel 3MI-2, right graphs to VNIR channel 3MI-6

These observations suggest that spectral variations of the calibration source can affect the effective polarisation sensitivity measured on channel 3MI-2, whereas only a negligible impact is expected for other 3MI channels. This hypothesis was investigated through the simplified spectral weighting model using the lamp spectra measured immediately before and after bulb replacement (Figure 16, bottom graph).

The model combines the measured out-of-band spectral response of the channel (Figure 17, top graphs), the spectral channel-dependent calibrated 3MI gain and the wavelength-dependent polarisation modulation PSM curves derived from the blocking measurements (Figure 17, green curves in bottom graphs).

An effective polarisation sensitivity PS_{eff} was then calculated as the weighted average of the spectral polarisation modulation:

$$PS_{eff} = \frac{\int S(\lambda) ISRF_{OOB}(\lambda) G(\lambda) PSM(\lambda) d\lambda}{\int S(\lambda) ISRF_{OOB}(\lambda) G(\lambda) d\lambda}$$

where $S(\lambda)$ is the measured source spectrum, $ISRF_{OOB}(\lambda)$ is the measured out-of-band spectral response function and $G(\lambda)$ is the channel calibrated gain. The calculation was performed using both the spectrum measured before bulb replacement and the spectrum measured after replacement (Figure 16, bottom graph). The model predicts a variation of the effective PS of about 1.3% for channel 3MI-2, while the corresponding variation for channel 3MI-6 remains negligible. Although the calculated magnitude does not fully reproduce the maximum variation observed during the calibration campaign, it correctly predicts both the order of magnitude of the effect and its strong channel dependence.

The result supports the hypothesis that the PS drift observed during the campaign was primarily driven by changes in the spectral distribution of the calibration source. In particular, the combination of residual out-of-band response and degraded or inverted polarisation behaviour outside the nominal spectral band makes channel 3MI-2 significantly more sensitive to source spectral variations than other VNIR channels.

For the final FM2 calibrated PS values of channel 3MI-2, reference measurements acquired right after the light bulb replacement have been considered for the final polarimetric performances reported in Table 2.

While the observed drift of the PS of channel 3MI-2 was ultimately linked to the calibration source rather than to an intrinsic degradation of the instrument, the analysis highlights the coupling between the channel out-of-band response and the spectral distribution of the observed radiance. Since in-flight observations encompass scenes characterized by a broad range of spectral signatures, including ocean, land, vegetation and cloud targets, further investigations are ongoing to quantify the potential impact of this effect under representative Earth-observation conditions and to assess its contribution to the overall polarimetric performance budget in flight.

5. INITIAL IN-FLIGHT PERFORMANCE ASSESSMENT

The EPS-SG A1 satellite was launched on the 13th of August 2025 carrying, among others, the 3MI instrument. After a de-contamination period and a first in-orbit verification period, it was handed over to EUMETSAT for Calibration and Validation in January 2026.

The 3MI processor generates three different L1 products: L1B1, corresponding to the acquisitions of the instrument, after radiometric corrections, L1B containing the Stokes Vectors triplet (I, Q, U) resampled on the grid of the second polarizer, and L1C, corresponding to co-registered and geolocated Stokes Vectors co-located on a fixed geographical grid.

At L1B it is possible to observe the different behaviour of the glint of the Sun on water bodies. The glint is a highly geometry-dependent phenomenon and the light is strongly linearly polarised.

Figure 18 illustrates this example using L1B1 products for one representative in-flight scene observed by 3MI FM2. The polarisers P1, P2 and P3, oriented at -60° , 0° and 60° are depicted left to right. The dashed line is the principal plane, containing the Sun-glint-Sensor. Through the amount of light received from the glint area it is possible to derive the

orientation of the polarisers in orbit with respect to the scene. The light from the glint is perpendicularly polarised to the principal plane. Therefore, the polarizer whose orientation is closest to the principal plane should receive the smallest amount of light.

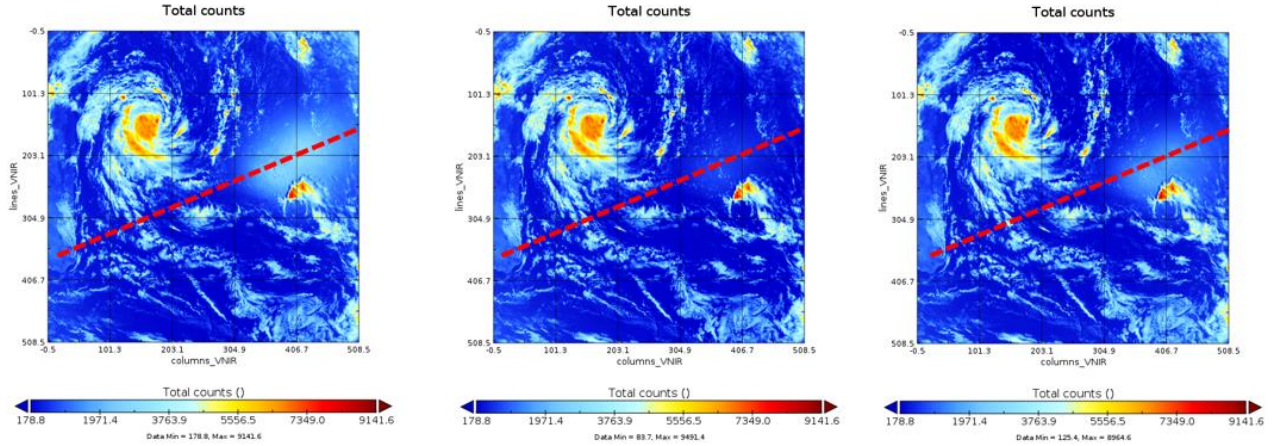


Figure 18 L1B1 products for one representative in-flight scene observed by 3MI FM2 on board of EPS-SG A1 satellite. Maps are related to polarised slots -60° (left), 0° (center) and $+60^\circ$ (right), respectively

Based on this analysis using multiple sunglint observations, it was possible to derive the effective orientation of the polarisers in orbit. This was used to detect and correct an anomaly in the projection of the Mueller matrix into the proper reference frame, leading to an updated implementation of the corresponding calibration parameters.

More generally, the first months of in-flight observations have provided an important opportunity to validate the readiness of the calibration knowledge derived from the ground campaigns. While several aspects have already been successfully consolidated, additional refinements and investigations are still ongoing as part of the Cal/Val activities. The in-flight performance assessment is therefore not concluded at the time of writing of this paper, as the Cal/Val phase is still in progress.

6. CONCLUSIONS

This paper presented a comparative assessment of the polarimetric performance of 3MI instrument from early analytical predictions to on-ground calibration campaigns and the first in-flight observations acquired during the In Orbit commissioning and Cal/Val phase.

The optical design developed during the OPD phase successfully anticipated the main polarimetric features of the instrument, including the spatial distribution of polarisation sensitivity, throughput uniformity effects induced by optics polarisation, polarisation angle variations across the field of view and the dependence of Mueller matrix elements on exposure time. The subsequent OPD, PFM and FM2 characterization campaigns provided extensive experimental validation of these predictions while also revealing several instrument signatures not fully captured by the initial models.

Dedicated investigations performed during and after the flight model calibration campaigns enabled the identification and understanding of additional effects, including the influence of source spectral variations on the measured polarisation sensitivity of the shortest wavelength channels. These analyses contributed to consolidating the as-built calibration knowledge and to improving the physical understanding of the instrument polarimetric response.

Finally, the first months of in-flight operations demonstrated the value of polarimetric observations for the verification of the calibration chain and the validation of key instrument parameters in operational conditions. Although the Cal/Val activities are still ongoing, the results obtained so far confirm the overall consistency between analytical predictions, ground calibration data and in-flight measurements, providing confidence in the capability of 3MI to deliver the high-quality polarimetric observations required for its scientific objectives.

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