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## MTG-SCA MICRO-VIBRATION TEST BENCH DEVELOPMENT USING LINEAR INTERFEROMETRY

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### I. INTRODUCTION:

Next generation of high-resolution meteorological satellites for Meteosat Third Generation (MTG) mission comprises six satellites (four MTG-I imagers and two MTG-S sounding satellites) positioned in a geostationary orbit (42,155Km radius). This new generation is expecting to provide meteorological data up to 2035, and includes remarkable improvements on spatial resolution, repeat cycle and signal-to-noise ratio, while maintaining full continuity with current Meteosat program.

SENER is responsible of the development of the following systems:

- The Scan Assembly for The Flexible Combined Imager and the Infra-red Sounder instruments (FCI and IRS SCA) (Fig.1.).
- The Calibration and Obturation Mechanisms (FCI and IRS COM)
- The development, integration, and supply of the Attitude and Orbit Control System, Special Check Out Equipment (AOCS SCOE) for the mission.

The sweeping or scanning mechanisms are strategic elements in terms of optical quality, accuracy and pointing stability. These mechanisms generate high-resolution images through sweeping a mirror mounted on a two-axis gimbal: North/South (N/S) and East/West (E/W), with simultaneous movement of both axes. Each axis include a voice coil motor, a 25-bit encoder and mobile harness.

The combination of improved resolution and geosynchronous orbit involves extremely demanding pointing requirements (in the order of 0,1urad) for these mechanisms integrated in two of the key instruments of MTG mission: FCI and IRS. Reaching absolute accuracies and stabilities of a few tens of micro-radians are an incredible challenge for the mechanical design, manufacturing precision, integration, and calibration/metrology tasks.

This paper describes the metrology concept developed for verification and calibration of the MTG's scanner mechanism designed by SENER. Both functions are complementary in order to achieve the MTG requirements:

- Verification of the MTG pointing requirements (see section II) and dynamics would allow to check their fulfillment. The GSE setup measurements must not must not influence on the SCA behavior.
- **Calibration** of the scanner after integration, performing a mapping of the encoder readings with respect to the pointing direction. This calibration will be performed in two ranges (see section III).

The first part of the paper presents the metrology concept and the main performances, measured during MTG's Phase A-B. The second part of the document describes the improvements performed on the system for MTG's Phase C-D and its applicability. The third part of the document describes one of the applications implemented: a Micro-vibration setup and the performances achieved.



Fig. 1. MTG SCA BBM (left). MTG SCA rotating axis. N/S (±9,7° range) and E/W (±5,4° range)

#### II. ULTRA-HIGH-ACCURACY ANGULAR METROLOGY:

One of the early findings in the project was to assume that, if such an accurate pointing accuracy for the scanner was necessary, an adequate contactless metrology capable of measuring with at least ten times better accuracy than the maximum encoder resolution was mandatory as well. A tradeoff study was performed together with TNO Company during Phase-A to establish the most appropriate measuring method to be applied. Many alternatives were analyzed (optical encoders, autocollimators, magnetic rulers, PSD's, capacitive sensors, etc.), but the conclusion was that using linear interferometry (IFM) to measure distance variations of the mirror surface and obtaining the angular measurement from them, was the best option (See Fig.2.). Linear interferometry was able to cope with long measurement ranges (in the order of meters) with exceptional measuring resolutions (in the order of picometers) and a high data rate acquisition (10MHz). A 10<sup>12</sup> dynamic range is feasible, covering the following MTG pointing requirements defined as per ECSS-E-ST-60-10C:

- Absolute pointing <50µrad
- Pointing drift < 20µrad
- Pointing stability <5urad
- Absolute knowledge <5urad
- Knowledge drift <10urad

#### A. MTG Phase A/B optical metrology concept development and accuracy.

During MTG Phase-B program, SENER developed an optical GSE based in this linear IFM concept. The setup was designed to measure in ambient and one rotational axis, using a 24bits encoder. The scanner angular range was +/- 8°, for the MTG SCA breadboard model (BBM). The optical setup scheme and final GSE implementation can be seen in Fig.2. The overall concept demonstrated to be successful, but two variables rule the final performances obtained: The environmental stabilization/control and the alignment errors.



Fig. 2. MTG pointing GSE concept schematics (left). MTG Phase-B. pointing GSE (right)

**Environmental control:** The setup is especially sensitive to vibration noise and thermal variations. Thermal variations not only modify the refractive index of air (affecting the wavelength of the laser, and therefore the IFM measurement unit and the optical path length), but the thermal expansion of the different components of the setup (affecting the mechanical path length). Using two IFMs per rotating axis instead of only one, allows having a recurrent measurement of the angle (very useful for setup's alignment), and eliminates the dependence on knowing the exact location of the scanner rotating axis. Nevertheless, if environmental changes affects the optical path of each IFM in a different way (due to not perfect symmetry, etc.), this perturbation will be measured by the setup as an angular measurement error, impossible to distinguish from real angular movement. Therefore, thermal variations must be minimized both, minimizing the effect of wavelength variations (vacuum measurements) and minimizing the CTE mismatches along the optical paths. Some of these thermal effects can be calibrated in postprocessing, with the appropriate temperature control (thermistors) on the key elements.

This issue has been handled with care in the actual GSE, where 4 PT100 sensors (0,03 °C accuracy) a pressure sensor (0,1hPa accuracy) and a humidity (+/- 1% accuracy) sensor are acquired synchronized with the encoder and IFMs, monitoring the sensible items along the optical path, and allowing environmental corrections in post processing. Vibrations isolation are equally mandatory. In fact the need of an almost perfect isolation from noise, derived in the development of a complete micro-vibration setup. This setup helped to identify and measure the self-frequencies of the mechanism, and to mitigate and identify the vibrations and noises present in the lab. Proc. of SPIE Vol. 10562 1056256-3

Other important factor to minimize the total environmental error is the measuring time, as thermal drifts are low frequency effects. Their influence can be therefore minimized shortening the measuring duration (As an example, the MTG Phase-B results obtained for stability measurements were 18nrad accuracy during 200msec, and 75nrad accuracy during 20sec).



Fig. 3. IFM1 & IFM2 thermal drift (left). Angular thermal drift (right)

*Alignment errors*: The geometrical conversion from linear to angular measurement in the setup presented is an approximation dependent on the rotation angle. Cosine error is always present on the setup, even assuming a perfect alignment of the components: when measuring directly in the rotating sample mirror (no CCRRs), the IFMs setup is assuming that the returning beam follows the same path as the incident beam, which is not the case, as it reflects with double of the mirror rotating angle. Using retroreflectors (CCRR) instead of direct reflection in the mirror, the incident and returning beam angles are indeed the same, but IFMs setup is assuming that the CCRR apex is making a linear displacement along the IFM beam, which is not the case, as it moves following an arc. Both geometric errors and their contribution with the rotating axis are outlined in Fig.4.

Any additional alignment error (cosine factor on the IFM orientation, accuracy in the measurement of the distance between IFMs, etc.) slightly modifies the equation of the curve shown in Fig.4., but the main dependence remains the same. This dependence was observed during the Phase-B measurements performed, and it was checked that there was indeed a dependence on the equation of the curve with respect to the final alignment of the setup. The same tendency was always observed for every particular alignment. The repeatability of the measurements, once the setup alignment was completed and fixed, was almost perfect, so this allows a calibration of the system to remove this geometric contribution by fitting and subtracting to a second order polynomic.



 Fig. 4. Geometrical error concept for CCRR (top left) and Mirror (top right). Total geometrical error assuming perfect alignment (bottom)

 Performances:
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The completion of this Phase-B allowed validating the metrology concept for measuring a one-axis rotating mechanism, optimizing a fine alignment procedure for the IFMs, and a good control and post-process calibration of the environmental contributors. Figure 5 provides a comparative of the same angular movement measured with IFM setup (1pm resolution), an autocollimator (0,1urad resolution) and a 24bit enconder (0,374urad resolution), illustrating the enhancements in terms of performance of this methodology.



Fig. 5. Angular measurement performed with IFMs (blue), 24-bit encoder (red), and autocollimator (green)

The metrology system is so sensitive that in terms of stability, the figures obtained are very dependent on the mechanical behavior of the measured sample with respect to vibrations. Using a rigid tool, a peak to valley stability of 18nrad during 20sec was measured (still some vibrations pattern was present in the measurement), while using the MTG BBM as sample, the stability lowered to 120nrad for a 20sec measurement due to sensitivity of the scan mechanism to vibrations. The accuracy provided by manufacturer at ambient conditions is better than 0,14ppm (confirmed by PTB institute), and 50 ppb in vacuum.

![](_page_4_Figure_6.jpeg)

Fig. 6. Angular measurement stability of 18nrad for rigid tool (left) and 120nrad for BBM (right)

Regarding the measurement performed for the complete range  $(\pm 8^\circ)$ , the results obtained were as well as good as expected. Four scanner swaths were performed to determine the repeatability of the measurements.

![](_page_4_Figure_9.jpeg)

Fig. 7. Long range angular error between IFM and encoder with respect to time (left) and angle (centre). Zoom near the zero angle (low geometrical errors) shows good repeatability and the encoder harmonics (right). Proc. of SPIE Vol. 10562 1056256-5

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The error between the encoder and the IFMs lecture had the expected second order polynomic fit. Once corrected, the peak to valley error of the encoder measured is in the order of 2secs (which is the error value provided by the manufacturer), and the harmonics can be perfectly distinguished thanks to improved metrology accuracy. The repeatability observed for BBM is below 1urad.

#### B. MTG Phase C-D optical metrology evolution

The objective of this Phase-C and Phase-D of MTG was to develop a metrology system based in the previous Phase-B metrology concept. This concept is to be used to verify the MTG SCA different models.

The main requirements to this new development were:

- Vacuum compatible (Pointing performances during thermal balance tests)
- Two axis measurements (instead of only one axis. Cross-coupled measurements)
- Increased angular range to  $\pm 10^{\circ}$
- Real flight hardware
  - Cleanliness and Qualification levels
  - o No possible attachment of CCRR on SCA mirror without increasing the mass
  - o No contact metrology

The **vacuum compatibility** has been solved changing the linear interferometer supplier, migrating from an interferometer head (not vacuum compatible) to an optical fiber head concept. This change was not initially understood like dramatic, but in practice, there have been several issues associated to it without an easy solution: Apart of the synchronization and interface changes, these interferometers present a saturation to perfectly collimated positions. This saturation involves that the system loses the measuring accuracy (reference) when

aligned perfectly collimated with respect to the sample (for example, with measurements performed in the normal of a mirror). This issue was not considered as a killer when using CCRR, as the GSE can be aligned with a small and known offset tilt, common to all interferometers, avoiding this collimated position. Thanks to the CCRRs, the angle of incidence on the IFMs will be the same independently the rotation of the mirror sample. The problem persists when the interferometer is measuring directly to the scan mirror and a swath of the scanner is performed. In this case, an area around the perfect collimated alignment must be avoided during the scan laws, in order not to lose the reference and obtain an error. A second option has been investigated at SENER and iterated with IFM manufacturers,

![](_page_5_Figure_15.jpeg)

Fig. 8. Collimated and focused beams

and looks very promising, which is using a focusing beam getting through the optical head instead of collimated beam. This will certainly decrease the power of the signal received, but will make it more uniform and tolerant to angular misalignments. SENER understanding is that using this technique, angular range for direct mirror metrology could be increased at the same time than the saturation problems may disappear. On the other hand, due to the quick signal loss, the optical head focusing optics should be designed specifically for each particular setup, as the measuring distance and lens diameter may became a key variable to achieve the needed angular range.

The **two axis measurement** has been the major difficulty to be implemented in MTG project. The problems are not related with a limitation on the measuring concept, but a combination of all the requirements to be fulfilled in this Phase-C-D. The preferred idea was to implement the CCRR linear interferometry metrology for all the

![](_page_5_Figure_19.jpeg)

The MTG SCA mirror is a Sic monolithic piece, with state of the art light weighting and optical performances. In order to be able to attach this structure, some GSE holders were taking into account. Nevertheless, and regarding the fragility of the material, all the GSE operations have been considered extremely risky.

Later measurements on scanner mechanism demonstrator revealed that the weight of the CCRR structure may affect the dynamics of the scanner to be measured. An exercise was performed in order to minimize that weight, reducing the number of CCRR attached to the minimum size (38mm diameter), weight (73gr) and number (three), lightening the structure weight using materials like carbon fiber, etc. To be able to obtain the minimum CCRR size for the increased angular range, and taking into account that the mirror surface is not in the plane defined by the two rotation axis, the best way to optimize the CCRR size was to bend one of the interferometers beam (the three IFM beams will no longer be perpendicular to a common plane). This made the alignment of the setup and the data post-processing much more complex and less accurate, due to cross couplings and the necessity of decomposing the IFM measurements in components to compare them in a common reference frame, being this decomposition dependent on the alignment (mechanical tolerances).

![](_page_6_Picture_4.jpeg)

![](_page_6_Figure_5.jpeg)

Note: The CAD image includes the location of the IFMs with respect to the scanning mechanism, and the CCRR structure has been occulted for clarity (left). The laboratory setup developed to check the performances and refine the alignment procedures.

Regarding difficulties to obtain a very accurate alignment were several alignment jigs were necessary, and the tolerance chain quickly leading into problems, the efforts were focused in obtaining an accurate calibration after the alignment. In parallel, some mechanical tests were performed, that determined that the lightweighted CCRR structure, even for low speed motions, may be not rigid enough to avoid deformations during measurements in the same order of magnitude of the errors that were expected to be measured. Furthermore, the structure was still affecting the scanner dynamic behaviour. Looking at these new findings, for MTG is has been decided to divide the metrology concept in two ranges:

- *High frequency (HF) spatial errors:* Due to the encoder. A short angular range (+/- 1,5°) is measured using linear interferometry concept without using CCRR. The SCA mirror surface is directly used instead. This reduces the total range of the metrology, but enhances the accuracy, making it very convenient to determine the encoder harmonics errors.
- Low frequency (LF) spatial errors: Mainly due to scanner misalignment. A large angular range (+/-10°) is measured using a more conventional method (theodolites) that allows, not only to check the system performances along the whole range, but to determine the rotation axes and link them to alignment aids (optical cubes) and references, in order to minimize the alignment errors during the SCA mechanism integration into the satellite.

The linear interferometry concept for large range measurements continues in development phase at SENER to make it each time more and more versatile.

#### **III. MICRO-VIBRATIONS SETUP:**

One of the applications found for the interferometric angular metrology is to use it for determining the behaviour of a system to micro-vibrations environment. The high frequency and short amplitude movements matches perfectly with high data rate and accuracy of the metrology described.

In the frame of MTG project, and in order to test the MTG SCA performances under micro-vibration environment, SENER has developed a micro-vibration setup which, together interferometry angular metrology, has provided outstanding results.

The microvibraton test facility is capable of measuring the small amplitude vibration environment exported by the SCA during its operation.

On the other hand, the microvibration test facility is capable of injecting controlled low amplitude accelerations to the SCA in different ways: random, sine-on-random, multi-sine and swept sine along the 6DoF.

In order to measure/inject these very low levels of accelerations, the facility is highly isolated from the structureborne and airborne disturbances to achieve a minimum overall background noise. This complete isolation from external disturbances permits high accuracy interferometric measurements on the SCA.

The facility is located inside an ISO 8 cleanliness controlled environment, however ISO 5 level can be achieved by means of a portable laminar flow bench.

![](_page_7_Picture_6.jpeg)

Fig. 11. Microvibration Test Facility.

#### A. Exported Torques/Forces measurement capabilities

The main capabilities of the external disturbances isolation and exported torques/forces measurement are summarized here below:

Mass DUT:	< 50 Kg
• Frequency Range:	0,5 to >500 Hz
• Force Background Noise [0,5 – 500Hz]:	From 1 x 10 <sup>-4</sup> N RMS (bare table)
• Acceleration Background Noise [0,5 – 500Hz]:	From 5 x 10 <sup>-6</sup> g RMS

Graph below shows the background noise force level with bare table (blue) and with a DUT of 40 kg (red), both in Z axis:

![](_page_7_Figure_12.jpeg)

Fig. 12. Background noise bare table (blue) and with 40kg DUT (red).

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#### B. Injected Microvibrations Capabilities

The facility is capable of injecting the vibration levels expected during in-orbit phase. For this purpose the acceleration levels, excitation type and excitation axis are configurable depending on the mission requirement. The main cababilities of the microvibration injection are:

•	Mass DUT:	< 50 Kg
•	Frequency Range:	1 to > 500 Hz
•	Acceleration level:	From $5x10^{-6}$ to $5x10^{-2}$ g
•	Excitation type:	<ul> <li>Swept Sine</li> <li>Random</li> <li>Random on Random</li> <li>Sine on Random</li> <li>Multi-Sine</li> </ul>
•	Excitation Axis:	X, Y, Z, Rx, Ry & Rz
•	Off-Axis acceleration:	< 10%

Graph below shows a Swept Sine from 5 to 100 Hz in Y axis direction:

![](_page_8_Figure_6.jpeg)

Fig. 13. Swept Sine from 5 to 100 Hz a different acceleration levels.