GOCI II POINTING MECHANISM DEVELOPMENT

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ABSTRACT

The Geostationary Ocean Color Imager II (GOCI-II) is the next generation of GOCI, which is one of the main payloads of the Korean COMS satellite. GOCI was the first ocean color sensor in the world operating on the geostationary orbit. Since COMS launch in June 2010, GOCI is monitoring ocean color around the Korean Peninsula in order to detect, monitor, quantify, and predict short term changes of coastal ocean environment for marine science research and application purpose.

GOCI-II has improved functional, radiometric and geometric performances in comparison with GOCI. It acquires Earth images in 12 visible and near-infrared narrow spectral bands between 380 nm and 865 nm with a spatial resolution of about 300 m over the Korean sea (250 m at Nadir). It provides a full Earth Disk coverage as well as Moon and star imaging capabilities.

As GOCI instrument and COMS satellite, GOCI-II is developed by AIRBUS Defence & Space in close collaboration with the Korean Aerospace Research Institute (KARI) and Korea Institute of Ocean Science and Technology (KIOST). It will be delivered in 2017 and launched in 2019 on the Geostationary Earth Orbit Korea Multi-Purpose Satellite: GEO-KOMPSAT-2B simply called GK2B. It will be operated on a geostationary orbit located at 128.2°E. Three Mechanisms were developed by Airbus DS operate on GOCI: a shutter and calibration Mechanism (SCM), a Filter Wheel (FWM) and a Pointing Mechanism (POM). Refer to ESMATS 2009 paper “GOCI (GEOSTATIONARY OCEAN COLOUR IMAGER) MECHANISMS)

The major consequence of improved GOCI-II performances is a larger optical aperture with respect to GOCI, resulting in a larger mirror on top of the POM. **Therefore a major redesign of the POM has been successfully performed for GOCI II.**

This paper presents a comparative assessment of major GOCI & GOCI II POM requirements, the GOCI II POM main design features, together with the major test related lessons learnt, focusing on the POM kinematic model, which is specific to GOCI II POM architecture.

THE GOCI-II MISSION [1]

The mission

Main mission is to observe in 13 spectral bands ocean color around the Korean peninsula in continuity of GOCI mission with enhanced capabilities and performances and also to cover full Earth disc.

Most of the applications concern:

- monitoring of marine environments around Korean peninsular,
- production of fishery information (Chlorophyll, etc.),
- monitoring of long-term/short-term change of marine ecosystem

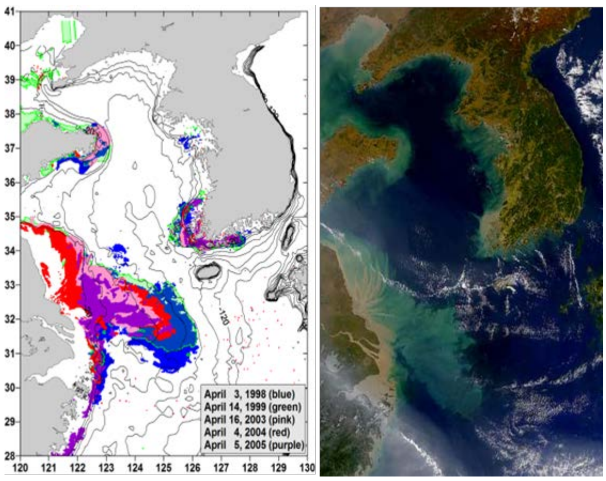


Figure 1. Example of GOCI images for monitoring of turbidity

Main evolutions from GOCI to GOCI-II

The following table summarises the major evolutions between GOCI and GOCI-II, with focus on evolutions impacting the POM design:

Mission Life Time Extended from 7 to 10 years
Duty Cycle (Local Area : LA) Extended from 8 to 10 times/day
Addition of duty Cycle (Full Earth Disk : FD) 1 time during day time
Spatial resolution (GSD) improved from ≤ 500 m @ center of Ref. (130°E, 36°N)LA to ≤ 250 m @ Nadir (Ref. LA : 2.500 km x 2.500 km)
MTF @ Nyq freq from 0.3 to >0.25

Table 1. Major GOCI-II evolutions with impact on POM mechanism

Impact on POM requirements

The impact of the increased radiometric performances can be summarized as follow for the POM: increased optical instrument aperture leads to a larger mirror. The mobile mass characteristics are strongly dependent from this fact: Mobile mass was 1.1 kg on GOCI POM and becomes 2.15 kg on GOCI-II POM ➔ Assuming identical mechanical environment, the loads on ball bearings are multiplied by a factor 2. Mobile inertia around actuation axis was 0.011 kg.m² on GOCI POM and becomes 0.024 kg.m² on GOCI-II POM ➔ Assuming identical kinematic profile, the mirror shaft motorisation torque will be multiplied by a factor greater than 2. As a consequence, the GOCI POM would need the addition of a launch locking device (LLD) to fulfil GOCI-II requirements.

An architecture trade-off has been carried out, to choose between to design architecture:

- The GOCI POM "serial" architecture, with additional LLD
- A novel POM architecture for GOCI-II, able to bear launch loads without LLD. This architecture, called "parallel" architecture, re-uses as an elementary brick the POM actuator module, recurrent from GOCI design.

FROM GOCI POM TO GOCI-II POM

GOCI POM main design features [2]

The GOCI POM includes 2 stages, assembled in a "stacked" or "serial" configuration. The first stage interfaces with the GOCI structure, the second stage interfaces with the mirror frame. A coupling flange links mechanically the rotor of the first stage to the stator of the second stage. A slip- ring provides signal and power transmission for the downstream axis. Each stage is composed of a "standard" actuator module. The actuator module contains a SAGEM 35 PP Stepper Motor, a pair of preloaded ball bearings from ADR, an optical encoder from CODECHAMP, mounted into a titanium structural housing.

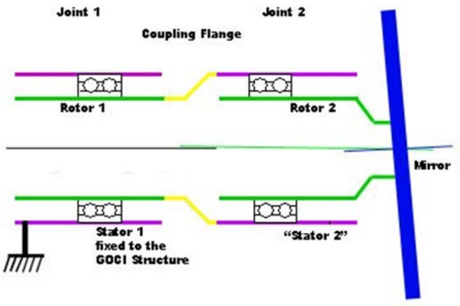


Figure 2. Architecture of the GOCI "serial" POM

POM GOCI main features are summarised into the following table:

Materials	Titanium
Mass	8.8 kg (POM alone) 1.3 kg (Support-POM)
Size	length ~ 240.mm, diameter ~ 180.mm (without the I/F flange)
Electrical I/F	- Step Motor 28.V - Optical Switch 5.V
Power dissipation	Holding mode : 2.86W Moving mode : 11.02W
Frequency	100.Hz (when mounted on Support-POM)

Table 2. GOCI POM main features

Figure 3. QM Model GOCI "serial" POM

GOCI-II POM concurrent architecture: a "parallel" architecture to overcome increased mobile part

The major motivations of this alternative architecture are:

- to re-use POM GOCI basic actuator module
- to obtain improved POM GOCI-II performances
- to avoid the design, development & implementation of a LLD

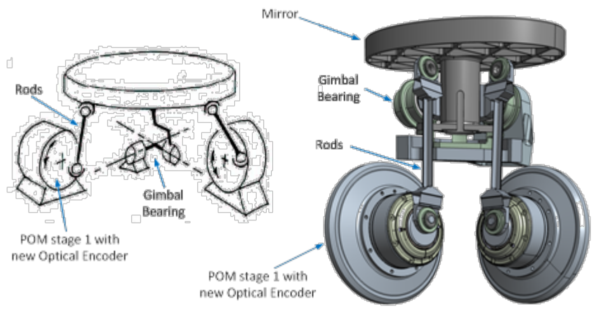


Figure 4. GOCI-II "parallel" two-axis POM architecture principle

Trade-Off Criteria and Results

Nine criteria were studied and compare to conduct this trade-off. **The discriminating criteria are marked in bold characters**

C1: Strength due to launch case: The mechanism shall withstand 30 g QSL without degradation.

C2: Restitution of optical angle better than 6 µrd.

C3: Speed and response time. Speed shall be greater than 20°/s, a stability better than 2 µrad peak to peak shall be achieved after 15 s including stabilisation & motion, and simultaneous activation of both axes shall be possible.

C4: Optomechanical range shall be at least ±6.5 deg. (mech. angle) at mirror level.

C5: Volume shall be minimized

C6: 1st mode during launch shall be greater than 120 Hz on rigid interface conditions, including POM support flexibility.

C7: Minimisation of mass

C8: Simplicity of command

C9: Development constraints (non recurring efforts)

The POM "serial" architecture was discarded for the following reasons:

C1 (qualification strength) and **C6** (launch frequency) will imply the **implementation of a LLD**, considered too heavy, very complex and risky for the development.

C3 (Response time and stabilization), will require either the **adding of a damper** or **closed loop command**, to ensure the performance of pointing stability.

C9 New H/W: New motor will be needed to provided needed torque

Therefore the selected baseline is the "parallel" POM architecture: this architecture has the capability to provide the required performance. It is based on the re-use of POM actuator module, and allows a simple profile command recurring from GOCI-1. The performances are ensured without any additional device.

Figure 5. CAD view of GOCI-II POM

THE GOCI-II POM REQUIREMENTS AND DESIGN

The POM Architecture

The GOCI-II POM is a mechanism composed of one gimbal allowing two rotations in I/F plane of the pointing mirror and two actuators linked to the gimbal by rods with the reduction ratio r/R.

The optomechanical angle motion is the product of the actuator angle by the reduction ratio:

+/-αr/R

The kinematics is illustrated by the schematics of figure 6. At launch, POM is placed at Top Dead Point (TDP) and actuators are energized with reduced tension, LLD is not needed.

1 – Initial Position 2 – Command on actuator 1 3- Command on actuator 2

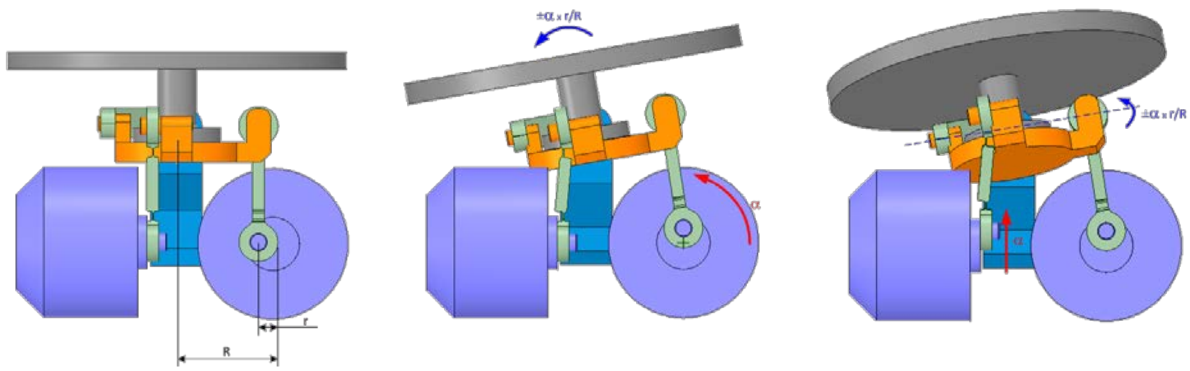


Figure 6. GOCI-II POM kinematic principle

The GOCI-II POM is composed by a mirror bracket holding the Pointing Mirror Assembly. A gimbal bracket link the mirror bracket to the fixed support-structure with two paired ball bearings. The mirror bracket is actuated by two rods whose end is fitted with small ball bearings.

The two actuators are identical and re-use GOCI-1 components (same motor and ball bearing). For EEE obsolescence, the optical encoder is replaced by a new one on GOCI-II. The shaft is modified to interface the eccentric crank pin and housing is adapted to new encoder and support-structure interfaces.

The rigid support-structure is positioned by three bipods in order to prevent thermo-elastic distortions and to give a high mechanical first frequency.

The GOCI II POM requirements

The following table summarizes major POM requirements, focusing on major evolutions between GOCI and GOCI-II POM mechanisms. One has to consider that optical angles are to be converted into actuator angles by taking into account kinematic ratio of POM rods and Opto-Mechanical Gain (OMG) of the mirror.

	POM GOCI	POM GOCI-II
Mobile part	Mobile mass1.1kg, Mobile Inertia around rotation axis 0.011m²kg	Mobile mass 2.15 kg Mobile Inertia around rotation axis 0.024m²kg
Actuation Voltage (Vnom)	7V	10V
Holding Voltage (Vhold)	28V	40V
Speed	1st stage : 12°/s 2nd stage : 20°/s	20°/s
Pointing Stability	Better than 30µrd during 8s (mechanical angle equivalent to ~4µrd LOS)	Better than 2 µrd. p.p after 4s motion completion (1s Vnom + 3s Vhold) (LOS)
Pointing Accuracy	Better than 150 µrd.	Better than 100 µrd. optical angles
Pointing knowledge	7 µrd.	7 µrd. optical angle
Stiffness	1st mode higher than100Hz support	1st mode higher than 120Hz on rigid b/plate
QS load	20g	30g
Cycles	172 000 rev. 688 000 stop/start per actuator	1 450 000 rev. per actuator 1 450 000 stop/start per actuator
non-op Temperature	[-40°C / +65°C]	[-20°C / +55°C]
Operational Temperature	[+5°C / +62°C]	[+5°C / +45°C]

Table 3. GOCI & GOCI-II POM Compared requirements

The GOCI II POM design

In order to provide two rotations to the Pointing Mirror, The POM is based on 2 rod levers and actuators systems moving a barrel guided by a central gimbal (2 axis ball bearings). The Pointing Mirror is fixed on the barrel. The gimbal and actuators are attached to the main structure. Bipods guarantee the thermoelastic stability.

The design allows re-using **recurrent actuator modules from GOCI POM**, composed of:

- a Stepper Motor 35 PP from SAGEM
- a pair of preloaded ball bearings from ADR
- a stator structure mainly in titanium
- An optical encoder from CODECHAMP for angular position. The encoder is not fully recurrent from GOCI (some EEE obsolescence).

The new items with respect to GOCI POM are:

- Mechanical parts (rods, barrel, gimbal ...)
- Small ball bearings at rods joints to maintain the isostaticity of the mechanism
- The gimbal ball bearing
- The encoder mechanical interfaces
- The mirror Assembly

See figures 7 and 8.

As for the GOCI POM, no LLD are implemented, the GOCI II POM ball bearings and structural parts withstand the launch loads (30g Q.S). Launch configuration corresponds to TDP position associated with a 10V holding voltage on full motor step.

The POM command is similar from GOCI to GOCI II:

- Ministep command (32 ministeps/step) with increased voltage (40V instead of 28V) to obtain maximum motor torque of SAGEM 35PP
- Holding voltage (10V instead of 7V) on a full step / Top Dead Point (TDP) position

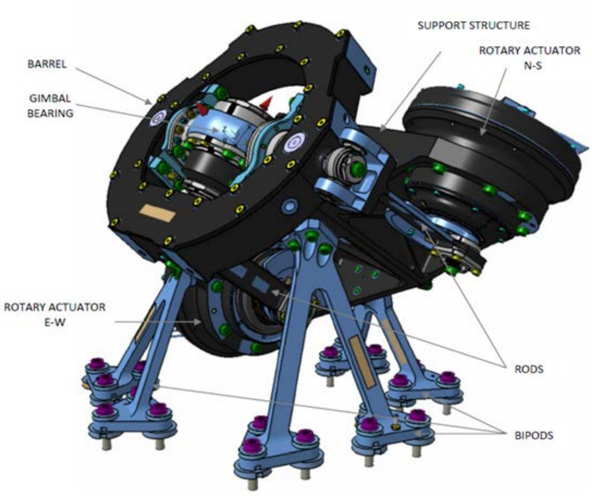


Figure 7 The POM design (mirror not represented for clarity)

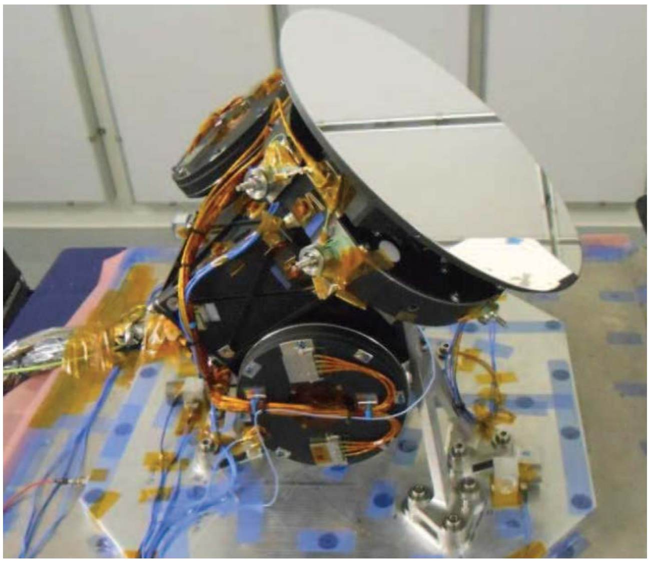


Figure 8 the POM during tests

THE GOCI-II POM KINEMATICS

Kinematic law:

Contrarily to GOCI, where the actuation angle was directly applied to the shaft, a complex kinematic chain exists on GOCI II between actuator angles and mirror rotation.

In order to derive mirror pointing LOS from actuator angles (commanded, and measured by optical encoder), a mathematical model has been developed. Considering all mechanical parameters, such as coordinates of actuators centre of rotations, axis misalignements, eccentric radius… 27 parameters are defined for this model.

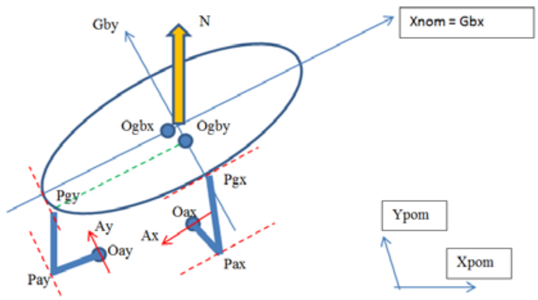


Figure 9 from actuator angles to mirror rotations

Kinematic model parameters determination

A pointing test has been carried out to determine the 27 parameters of the model. The basic method is the acquisition of a large set of points N = f (ax, ay) where N is the mirror normal (unit vector expressed in a reference frame) and (ax, ay) are the POM encoder angles.

The measurements are done with a **laser tracker** aiming at a fixed target. A reference measurement is done by directly measuring the target position with the laser tracker. The other measurements are done by reflection on the pointing mirror. When the mirror moves the laser tracker follows the motion. A simple processing of the laser tracker measurements allows determining the mirror normal.

The test has been done three times:

- Before POM vibration test in +1G configuration
- After POM vibration test in +1G configuration
- After POM vibration test in -1G configuration

The test configuration is illustrated in figure 10.

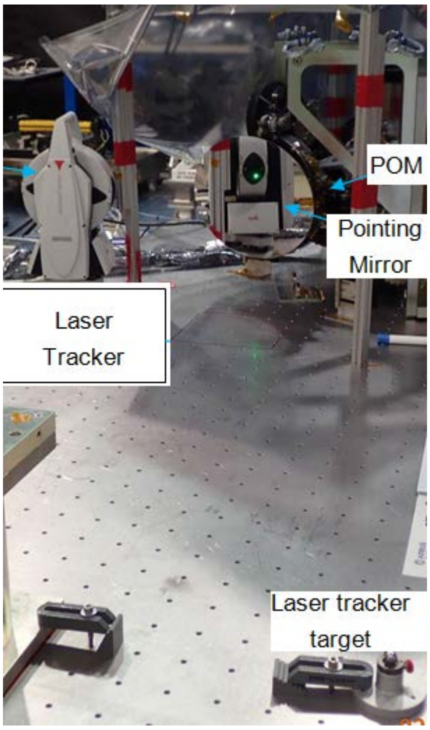


Figure 10 – Pointing Test configuration

Test before vibration - +1g

The 27 model parameters are determined by best fitting between the measured mirror normal angles and the predicted ones from the measured encoder values.

The residual error after this fitting is around or below 8 µrad rms. This is deemed very satisfactory and well in line with expected measurement accuracy.

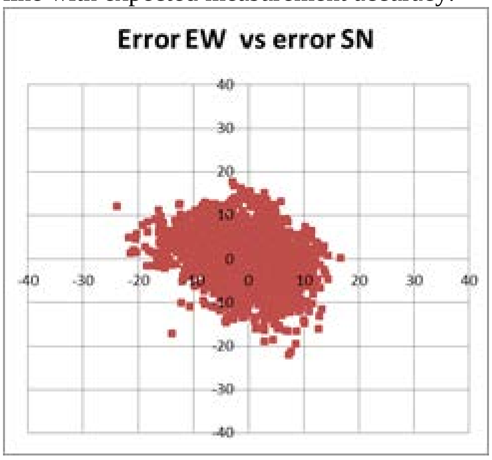


Figure 11 – Residual error after fitting, before vibration.

Test after vibration - +1g

The same fitting set of parameters is used, but with a different laser tracker configuration. The results are equivalent to the "before vibrations" case which shows that the POM model was not affected by the vibration test. The slight degradation in E/W in particular is not deemed significant and may be due to the different test configuration. A group of points seems to be "out of family"; this may be a consequence of the test configuration limits, because the mirror is used in limit of field of view

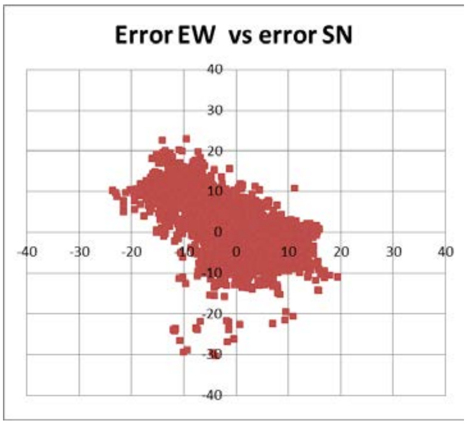


Figure 12 – Residual error after vibration test

Test after vibration - -1g

The test has been done in opposite gravity configuration than the previous tests. Consequently the laser tracker configuration is also different. The same fitting set of parameters is used, with exception of some rotations angle (different configuration thus different reference frame).

The results are different than the previous ones although still quite satisfactory and consistent with the measurement accuracy. Nevertheless the errors show a residual "shape" which means that the residual error is not a pure noise but the indication of a model error. It is not clear whether this difference wrt. the previous cases is an effect of the gravity or of the test configuration. In any case, the largest errors are out of the useful range.

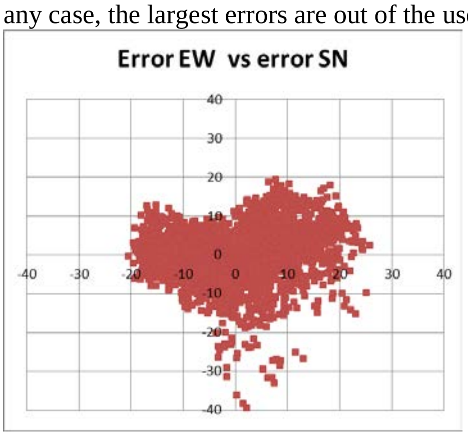


Figure 12 – Residual error after fitting, before vibration.

Kinematic model parameters verification

The objective is to verify the accuracy of the POM model by dedicated measurements within the useful angular range. These measurements are done with a theodolite. The results are similar with the previous one, roughly 8 µrd. rms, however, the residual shape in the

error plot shows that a better modelling is probably possible.
In order to check this hypothesis a dedicated parameter optimisation is done on the set of measurement points. The results are strongly improved.

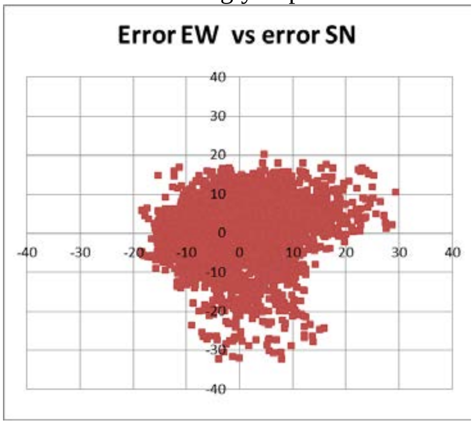


Figure 13 – Model verification with initial setting of parameters

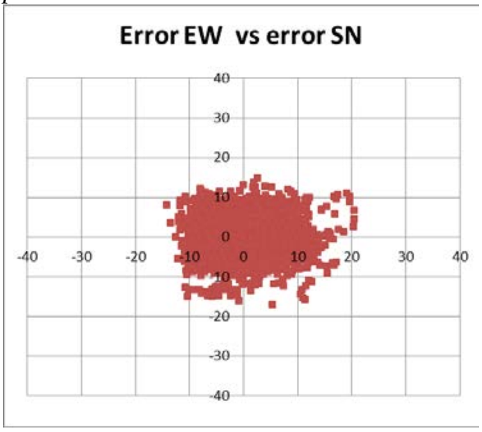


Figure 14 – Improved result after model optimization.

The optimized parameters have been applied to the previous 3 sets of measurements available, and give satisfactory results. This confirms that there no significant variation due to vibration, and that gravity effect exists, but remains small.

<u>Major outcomes</u>

- The results in the useful range for the 4 sets of data are very similar with a rms error around or better than 7 µrad rms in both S/N and E/W directions and better than 10 µrad rms for the combined angle. The maximum error is below 25 µrad in all cases.
- These results in the useful range are also equivalent or a little better with this second parameter set than with the first one.
- The new parameter set is therefore as good as the initial one within the useful range or even a little better.
- However results over the full range are strongly degraded, especially in the S/N directions which, according to the test configuration let think that there is significant gravity impact.

As a conclusion**, the POM model is good and adapted to accurate retrieval of the POM mirror normal direction, within the useful angular range but also over the full range.**

MAJOR LESSONS LEARNT FROM QUALIFICATION

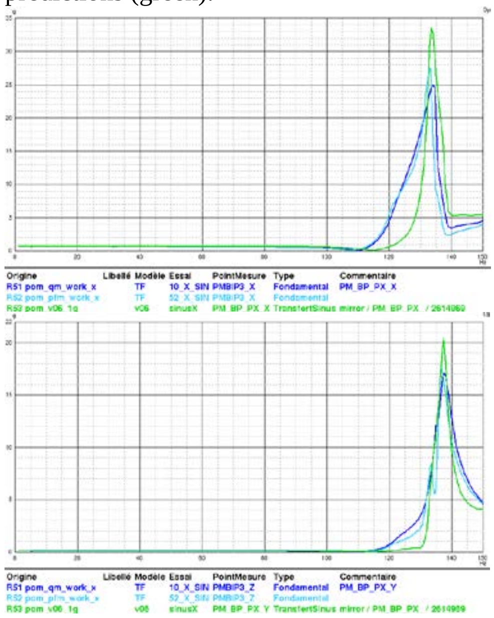
A classical qualification campaign of the POM has been carried out, including performance, environment, and life-test.

Launch configuration

The configuration decided to withstand launch effort without LLD is to set the POM in the Top Dead Point and to energize actuators with a constant voltage of 10V. Associated with balancing of rotating part, this has turned to be very efficient. This configuration (without actuator energisation) is also used for POM storage and transportation

Vibration tests – Modes prediction – Non linearities at low levels

Tests show a good correlation between tests and FEM model, and a good repeatability between QM and PFM. The following figures show a comparison under X axis of the transfer functions between qualification level sine test on QM model (blue curves), qualification Level sine test on PFM model (light blue) and FEM predictions (green).



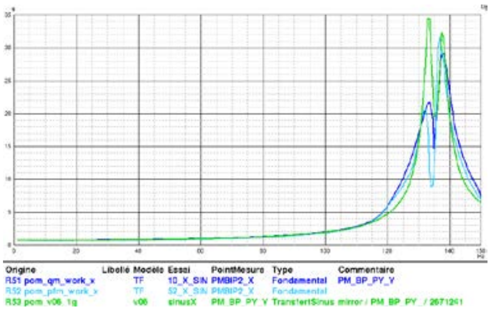


Figure 15 – Examples of POM modes identification (QM qualification level, PFM qualification level, F.E.M. predictions

However, some non-linearities on transfer functions have been observed on some accelerometers particularly between low level sine and sine tests between 10-150Hz with high levels. This is explained by the several ball bearings directly participating to the 2 first modes, which show usually some non-linear behavior

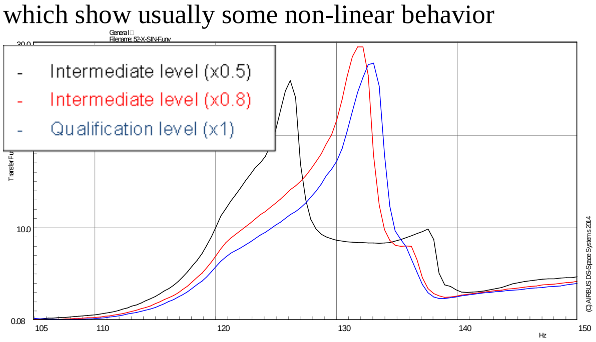


Figure 16 – Examples of non linearities observed at low and intermediate levels

Life-Test

A typical motion profile, with duration of 92s has been defined

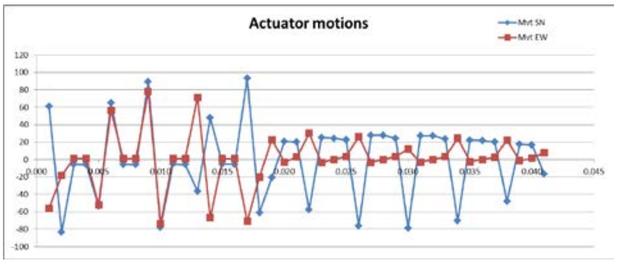


Figure 17 – Life-Test POM motion profile

48 800 profiles, representing 2.06 Million actuations have been executed; the life-test duration was 55 days excluding monitoring tests.
The life-test has been done in air, at a temperature corresponding to bearings minimum operating temperature.
The life-test was successful -

CONCLUSION

The POM mechanism is a **two axis mechanism with medium/large mirror** (optical size approx. 35*25cm²).
The POM **accuracy after calibration is better than 10 µrd.** The POM is very well adapted for **static pointing** performances. It would require closed loop operation to be used for dynamic pointing performances.
The POM has been qualified, and PFM delivered. The major outcomes of this development are:

- POM GOCI II relatively complex **architecture** is balanced by **the re-use of POM GOCI actuator modules, which significantly simplifies development efforts**. Moreover, the **avoidance of a LLD** due to this architecture is an outstanding advantage.
- A valid **mathematical model**, with 27 parameters implemented into the command logic, allows achieving required in-orbit LOS, with measurement data at actuator shaft level.
- The selected architecture requires 13 pairs of ball bearings, (compared with 2 pairs for GOCI POM). This induces particular mechanical behaviour. Although the F.E.M. model has turned out to be sufficiently accurate – showing good correlation at qualification levels – the **non-linearities of POM mechanical behaviour at low and intermediate levels** generated a lot of engineering and analyse effort, to clearly understand the nature of this fact, and its harmless effect with respect to POM qualification.

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