IASI-NG SCAN MECHANISM
AN INNOVATIVE ARCHITECTURE TO IMPROVE POINTING PERFORMANCES

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ABSTRACT

Airbus DS and COMAT developed a new concept of 2-axes pointing mechanism for the CNES IASI-NG Instrument (Infrared Atmospheric Sounding Interferometer - Next Generation) that will be embedded on the second generation of Europe's MetOp meteorological satellites. The mechanism parallel architecture supports this new generation with fast mirror movements while keeping smooth transition of the velocity compensation. This reduces the rejected torque disturbance, contributing to the improvement of the instrument performance compared to the first generation.

Airbus DS managed the development of the drive electronics of the mechanism and its control, as well as the flight mirrors. COMAT was in charge of the mechanical and mechanism design and justification, and managed the entire manufacturing, assembly and test activities. An early co-engineering phase allowed deriving the most suitable design for both parties' requirements.

This paper presents the innovation of this parallel architecture concept and highlights the benefits provided compared to a more common series architecture. The flight design, development status and main tests results are presented, then a section is dedicated to lessons learned throughout the development.

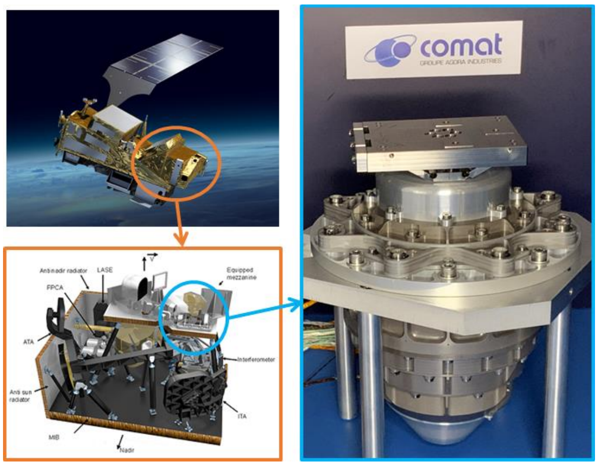

Figure 1: Scan mechanism (SCM) location on IASI-NG instrument and on MetOp-SG satellite (courtesy of EUMETSAT and Airbus DS)

DESIGN DRIVERS

This section details the main requirements that fed the trade-off between parallel and series architectures.

Pointing Requirements

- The Scan Mechanism (SCM) of IASI-NG shall have two axes:
  - One axis for Out-of-Track Scanning (OTS) in order to acquire data around the spacecraft ground track: 240° rotation required (possibly having a specific angular range dedicated to launch phase out of this operational range)
  - One axis for Spacecraft Velocity Compensation (SVC) during interferometer scene integration: 0.37° rotation required (optical angle)
- Pointing accuracy: ≤ 250 µrad (1σ optical)
- Pointing stability over a time horizon of 0.738 s: ≤ 50 µrad (1σ optical)
- Pointing strategy: the mechanism shall operate a classical step-and-stare profile with velocity compensation during stares.

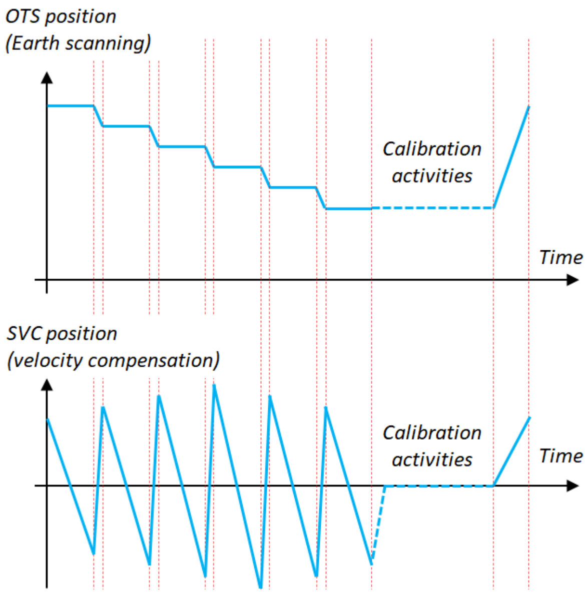

Figure 2: Pointing strategy for IASI-NG SCM

As described on Fig. 2 the scanning only consists in simple step-and-stare motion. There are 14 stare positions in total (the figure is simplified for illustration purpose). The velocity compensation amplitude varies from stare to stare due to the optic configuration.
The stare period is 0.738s and the step is 0.081s long. The accuracy and stability requirements are to be satisfied during stare periods only.
At the end of the cycle, some time is allocated to calibration activities then the first stare position is reached again and a new cycle starts over.

Interface Requirements

- Mass and volume to be minimized
- First mode frequency: ≥ 150 Hz
- Mechanical loads during launch
- Maintain of the angular position during launch: ≤ ±10°
- Low particular and molecular contamination due to nearby optics

Lifetime Requirements

- Storage lifetime: 20 years
- Operational lifetime: 8 years

Other Drivers

At the beginning of the co-engineering phase with Airbus DS, it has been identified that the performances required for the various actuation components of the scan mechanism were close to the performances required for the same components of another mechanism of the IASI-NG instrument. The idea of communalizing these components between the two mechanisms naturally emerged.
In the same logic, the actuation of both SCM axes (OTS and SVC) have been thought to be identical.
Using the same components for different needs was an important design driver but led to a more efficient development.

Another strong constraint was the thermal behaviour. The contribution of this aspect (dissipation capability vs thermoelastic in particular) appeared to be stronger after the Preliminary Design Review (PDR) which induced some design evolutions. The situation would however have been more critical with a series architecture.

PARALLEL ARCHITECTURE PRESENTATION

Two solutions were identified for the development of the mechanism. This section focuses on the innovative parallel architecture that has been selected (the more common series architecture is described later in this document and the comparison between both solutions is made).
The diagram on Fig. 3 illustrates the kinematic principle of the parallel architecture:

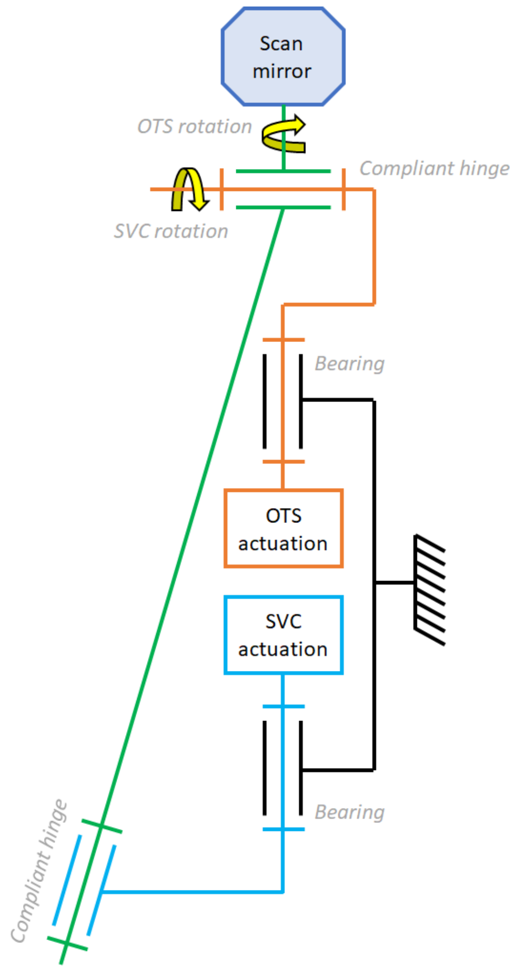

Figure 3: Kinematic principle of the parallel architecture

In this configuration, the OTS axis' motor is in a direct drive configuration (1:1 ratio between command and mirror rotation).
SVC rotation is created by offsetting its actuation with respect to the OTS one (which is nominally stopped during the view), and is transmitted to the mirror through a shaft, imposing a kinematic ratio between command and mirror rotation. This ratio depends on the scan design and more particularly the position of the compliant hinge that is mounted on the end of the shaft opposite to the mirror. For this application, the ratio is close to 1:13 (mechanical angles).
It shall be noted that the resulting SVC rotation is performed around an axis that follows the OTS rotation.

The arrangement of components making this parallel architecture is innovative on its own, but the motion used to operate the mechanism and answer to the pointing strategy required is also quite original.
Indeed, the SVC back-and-forth motion of the mirror (see Fig. 2) is not performed with a back-and-forth actuation.

Instead, the actuation goes in the same direction all along the cycle and only goes back in the opposite direction at the end, in order to start over, just like the OTS axis.
This is possible thanks to the fact that the SVC axis rotates with OTS and the mirror's SVC mechanical angle is proportional to the offset between OTS and SVC actuations. Therefore, the actuation profiles described on Fig. 4 are used to achieve the motion required, with OTS steps performing both the change in pointing area and the reset of mirror's SVC compensation at the same time.

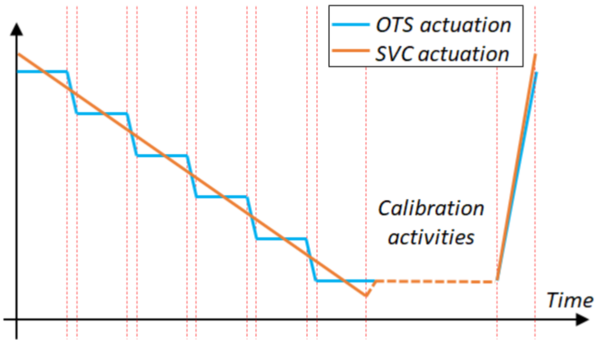

Figure 4: SCM actuation profiles

This actuation strategy brings even more benefits to the parallel architecture as we will explain later in this paper.

RECALL OF THE USUAL SERIES ARCHITECTURE

Before assessing the two solutions, we need to recall the concept of the series architecture, to be compared to the parallel one described earlier.
The following diagram illustrates the kinematic principle of the series architecture:

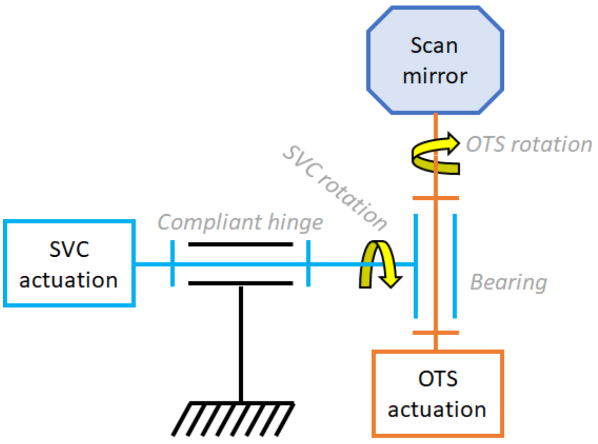

Figure 5: Kinematic principle of the series architecture

The OTS axis is "stacked" onto the SVC one, and both axes are in direct drive configuration (mirror rotation equal to actuation displacement).
In this configuration the SVC rotation axis is fixed with respect to the spacecraft.

One can note that an alternative solution exists where the OTS axis bears the SVC one; the design would be quite different but the architecture is similar.

BENEFITS OF PARALLEL ARCHITECTURE COMPARED TO SERIES ONE

Moving Mass

The proposed parallel architecture comes with a smaller moving mass than for the series one. Indeed, the actuation of both axes are attached to the structure and only a few pieces move (the mirror, its interface part and a shaft), while on the series architecture the actuation of one axis has to be carried by the other.
In order to visualize how much this characteristic is different between the two dispositions, we can provide the rough estimation of the moving mass based on the components selected. Only the SVC rotation is considered since it gathers the main differences.

Table 1: Rough estimation of the moving mass for SVC rotation in parallel and series architectures

Component	Parallel architecture	Series architecture
Mirror	1 kg	1 kg
Bearing	-	0.4 kg
Encoder	-	1 kg
Motor	-	1.3 kg
Structural parts	1.2 kg	1 kg
TOTAL	**2.2 kg**	**4,7 kg**

The moving mass for the parallel architecture is less than half the estimated mass of the series one.
This leads to a low jitter mechanism with a low level of rejected micro-vibrations.
Moreover, this lower moving mass also simplifies the holding during launch, which is made without additional electrical locking device.

Pointing Performances

Another major benefit of the parallel architecture is the kinematic ratio between SVC actuation and the resulting mirror rotation. This reduces the pointing error induced by actuation disturbances, like the encoder accuracy or the motor cogging for instance. As a matter of fact, this was the most important reason we headed toward the parallel architecture. Indeed, the absolute error of the encoder we identified is roughly 100 µrad (end of life). The series architecture being in direct drive configuration, it would not have satisfied the pointing stability requirement by a factor 4, while it only produces about 8 µrad pointing error on the parallel architecture, which is only a third of the stability budget.

Stiffness

As described earlier, the kinematic principle makes the SVC angle being proportional to the relative position of

OTS and SVC actuations. Therefore, the SVC actuation kind of follows the OTS one. This means a large angle excursion for both actuations, while still having small SVC rotations of the mirror. The large displacements allow using bearings for the actuation, unlike the series architecture where SVC actuation goes back and forth with a small amplitude. This would lead to lubrication issue if the rotation was performed with a bearing and the solution would use flexural pivots instead. But these compliant components are necessarily less stiff than bearings and bring a drawback when associated to actuation components. Indeed, the mechanical environment during launch is one of the biggest constraints for optical encoders due to their small distance between optical disks (airgap). And the encoder airgap cannot be increased too much because it would decrease its performance. The electrical motors have the same issue due to the small gap between rotor and stator. The parallel architecture offers a stiffer and better-known mounting on bearings, making the gaps management and justification easier.

This stiffer mounting also makes the mechanism less sensitive to mirror mass increase (in case of new mission). The design would probably need minor modifications compared to the series architecture that would most certainly need an entire remodelling of the flexural pivots and surrounding layout.

Design, Manufacturing and Assembly

The proposed layout offers a compact design where both axes' actuation assemblies (bearing, motor and encoder) are identical. This leads to a simpler design and associated justification. It also implies a more effective manufacturing, as the same parts are used at several places, and a more effective assembly, as both axes' actuation can be assembled following the same procedure and using the same specific tools (parallelization).

Another benefit of having both actuations rigidly mounted on the structure is that there is no moving harness or slip ring needed. All wires are firmly tied to the structure without interfacing with the moving parts. This makes the motorization more reliable and the justification simpler.

Thermal

The mechanism thermal dissipation is due to the actuation components. With the parallel disposition, all these components are directly mounted on structural parts. The thermal path is shorter and less resistive than for the series architecture where it goes through the flexural pivots of SVC axis. Therefore, the components heating is reduced.

Comparison Synthesis

A trade-off was made between the two kinds of architecture, and despite the series architecture flight heritage (first IASI generation for instance), the innovative parallel architecture has been selected in order to match the requirements. This was motivated by the fact that this solution presented better potential on some aspects where the series architecture had drawbacks making it impossible to achieve the pointing requirements.

FLIGHT DESIGN OVERVIEW

After having selected the most suitable architecture for the IASI-NG mission, we implemented it and derived a first design. Some constraints appeared and oriented the definition through lots of evolutions. We only present the final flight design here.

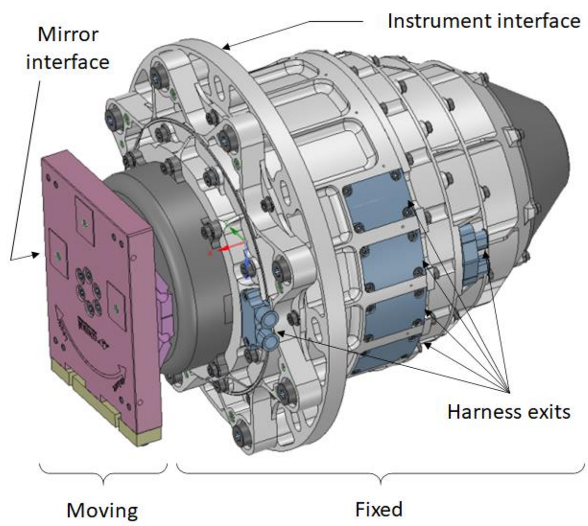

Figure 6: External view of the scan mechanism design

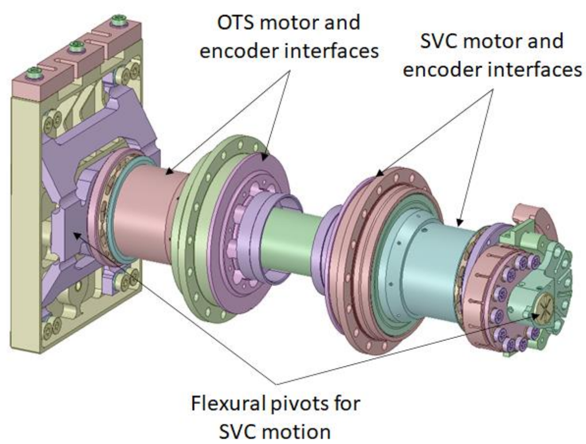

Figure 7: Internal view of the scan mechanism design

Some of the main features are detailed in the following sub-sections.

Flexural Pivots

Two compliant components are required to transmit the SVC angle to the mirror. COMAT developed their own pivots tailored to the project needs.

The compliant pivot near the mirror interface is fully developed by COMAT based on the literature. It is called RCC hinge which stands for Remote Center Compliance because the rotational axis is “outside” the part. This component has been optimized during the early phase of the development with respect to the scan environment. The design selected is presented on Fig. 8.

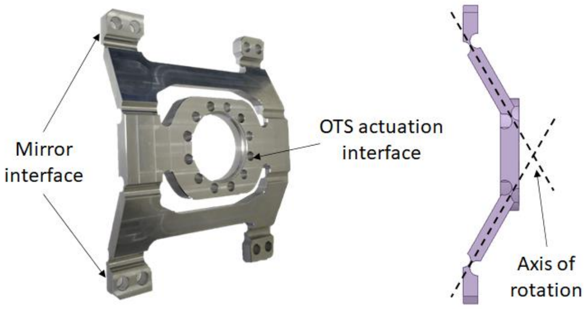

Figure 8: Overview of the RCC hinge

The pivot is made of a single titanium part and as illustrated on Fig. 8, the rotational axis is located at the intersection of the two planes containing the 8 thin compliant sections.

The pivot at the other end of the shaft is based on a former CNES R&T with CLIX company. The maturity level was TRL4 and COMAT helped to reach the TRL8 level.

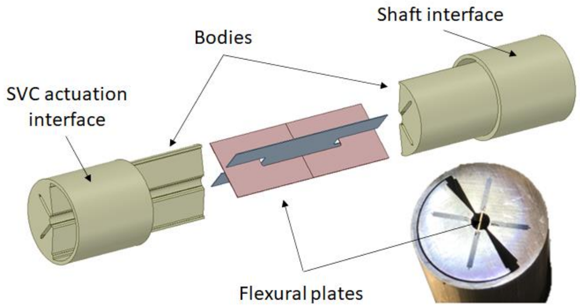

Figure 9: Overview of the flexural pivot

The pivot is constituted of thin beryllium copper plates reported by adhesive bonding into the two stainless steel parts making the body. The rotation is performed around an axis approximated to the intersection of the plates.

Similar Actuation Blocs

The two actuation sub-assemblies have been thought to be as much identical as possible. Except for some structural parts that needed additional or specific interfaces, this was globally achieved and allowed using the same components with the same mounting. They include a 22-bit optical encoder from CODECHAMP, a brushless electrical motor from SOTEREM and an ADR super duplex angular contact bearing. Due to the long storage duration, the bearings are lubricated with MAP SH051a grease in addition of the cage impregnation with Nye 2001a oil.

Structure

The design of the structure was one of the most challenging activities. It was initially planned with titanium in order to match the material of actuation components, but this led to thermal issues due to the small conductivity of this material. The components dissipation could not be evacuated efficiently enough and overheating was constated by analysis. An aluminium structure would have solved this issue but the problem is reported to the compatibility with the actuation components because of thermal expansion (sliding shall absolutely be avoided for this pointing application). The solution identified involved the use of a novel material, AlSi50, which is an aluminium and silicon alloy.
This material was already identified by Airbus DS and under development for other parts of the IASI-NG instrument.

Table 2: AlSi50% characteristics

Characteristic	Value	Unit
Density	2500	kg/m^3
Young’s modulus	110	GPa
Yield strength (Rp0.1%)	130	MPa
Ultimate strength	200	MPa
Coefficient of thermal expansion	11.5~12	10^{-6} K^{-1}
Thermal conductivity	130	W/m/K

The characteristics based on a supplier datasheet are given in Tab. 2. It highlights the compromise made on thermal aspects, with a good conductivity and a thermal expansion rather close to the titanium one. The drawback is a reduced strength but this was not as an issue as thermal aspects. Airbus DS performed a detailed qualification of this material in order to validate these values and assess the manufacturability. COMAT qualified the manufacturing process on its side.

Anti-rotation for Launch Phase

During launch phase, the moving parts shall be held in order to avoid shocks and high stress on the components. The scan mechanism embeds a passive system operated by its own motors (no additional electrical device), and that can be locked and unlocked consecutively without external interaction. This is possible with the combination of a good balancing and some internal “locking” components.
The first elements are end stops mounted on the shaft, at

the opposite end of the mirror. Within operational angular range, they only act as end stops in case of wrong actuation (clearance with the structure). By rotating the mechanism to an angular range allocated for launch, the stops engage on two specific pads on the structure where the SVC stroke is fully limited (adjustment during assembly). At this point, the actuations of both axes are necessarily synchronized since the SVC angle depends on the relative position.
This is combined with an anti-rotation device consisting in a permanent magnet. When the rotor reaches the launch position, the magnet holds the moving parts. The force is calculated to be sufficient to maintain the mechanism in position during launch, but also to be low enough to allow unlocking with the motors torque only.

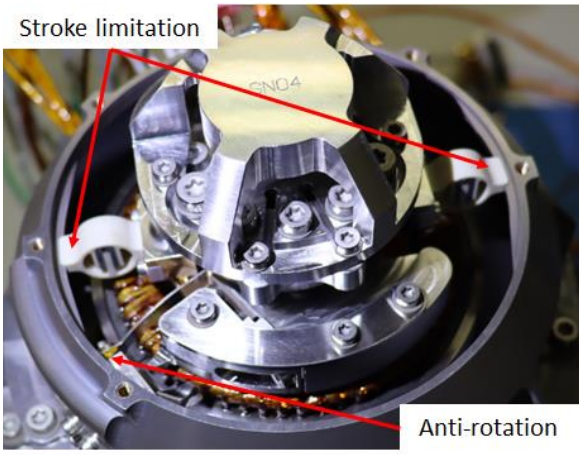

Figure 10: Anti-rotation feature for launch phase

DEVELOPEMENT STRATEGY

The development was organized into two main phases. The first one was a co-engineering phase with Airbus DS, which was responsible for the design. COMAT benefited of Airbus DS knowledge and gained in mechanism design skills. On the other hand, COMAT brought its know-how experience in mater of manufacturing. This ensured that the manufacturing processes and the associated design constraints were taken into account in the earliest phases of design.
The activities included various trade-off, the first one concerning the choice between series and parallel architectures. We also defined together the preliminary design. This shared worked allowed to point out that the performances required for the actuation components were really close to the ones needed for another mechanism of the IASI-NG instrument developed by Airbus DS. It has then been decided to use the same components on both mechanisms which increased even more the development efficiency.

Another activity of this phase was the development of some breadboard models (BBM). Both compliant components have been validated by early functional and life tests (the formal qualification being pronounced after tests at mechanism level). The mechanism kinematic principle was also validated on a breadboard model as it was new. The functional behaviour and preliminary pointing performances (open loop) have been assessed. We also tested this breadboard with mechanical environments as it implemented the actual compliant components.
This phase was concluded by the equipment PDR which marked the transfer of responsibility from Airbus DS to COMAT. Indeed, during the second phase COMAT was in charge of the full justification of the design.
This second phase also included the manufacturing, assembly, integration and test (MAIT) activities of an engineering model (EM). This first model validated functional performances and environments aspects (except for thermal test that was not under vacuum) with a representative design. These activities also provided feedback on the MAIT processes that were updated for further models.
At this point the Critical Design Review (CDR) was held and released the MAIT activities of the qualification and life test model (QLTM) and the three flight models (FM).

MAIN TEST RESULTS

This section presents the main test results of the different models throughout the development.

Early Breadboard Models

The first tests performed were the lifetime validation of the compliant components. We used samples representative of the compliant part of these components and mounted them on a bench with a camshaft imposing the desired rotation to up to 20 samples.

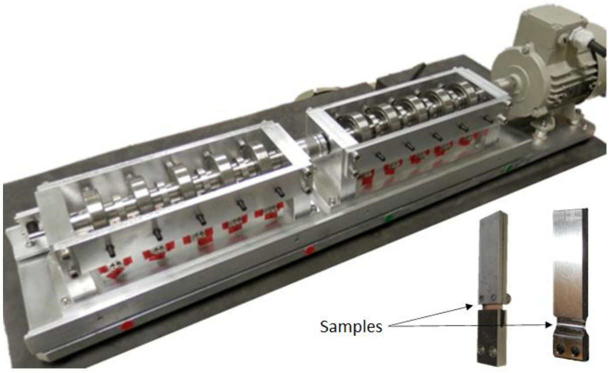

Figure 11: Breadboard for life test validation of compliant components

These tests demonstrated that the samples could withstand the angular range needed (including margin) over a lifetime way larger than required. We even performed tests on voluntarily degraded samples (scratch on the thin section) and they also passed more than the lifetime needed, which showed the design sturdiness. Tests on entire components as presented on Fig. 8 and

Fig. 9 were also conducted on specific benches.
Tab. 3 summarizes the results of all these tests. No breakage of any sample or component was noted.

Table 3: BBM life test results

	Type of test	Stopped after
RCC hinge	Samples	> 1 600 million cycles
	Degraded samples	> 800 million cycles
	Full component	> 680 million cycles
Flex. pivot	Samples	> 1 200 million cycles
	Full component	> 1 000 million cycles

The 8-years mission corresponding to 280 million cycles for the compliant components (including ground activities and ECSS safety factors), the design tested is validated for this application.

Pointing Performances

To adjust the tuning of the control loops and derive the performance budgets, a detailed model of the SCM was developed in Matlab/Simulink taking into account all performance contributors such as motor cogging/ripple and encoder measurement noise.

This model was used to predict the pointing performance in different cases, including:

- A typical, beginning-of-life case (BOL)
- A worst case at end-of-life (EOL)

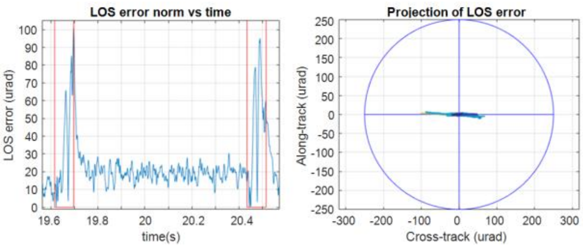

Figure 12: Pointing performance simulation in time (left) and space (right) domains (typical, BOL case)

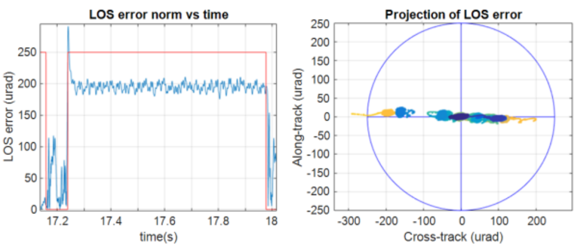

Figure 13: Pointing performance simulation in time (left) and space (right) domains (worst case EOL)

These simulations demonstrate that the performance requirements are met throughout the entire mission.

Consequently, performance validation tests were made on the SCM-EM using the telemetry of the encoders to derive the LOS position. The results are depicted on Fig. 14.

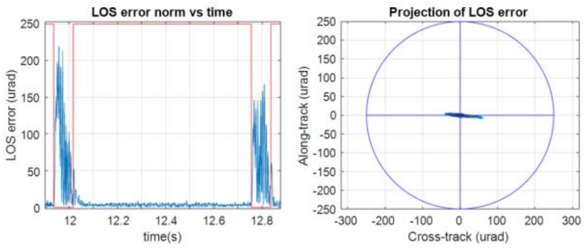

Figure 14: Pointing performance measurement on SCM-EM in time (left) and space (right) domains

The measured performances were in line with the model predictions (the difference being mostly due to the encoder measurement noise).

Qualification and Life Test

A single model is used to perform the entire qualification of the scan mechanism, in terms of functional tests, environments, and life test.
The functional and environmental campaign was successfully achieved at the end of 2019. The performances before and after environments tests are comparable and suitable for the mission.
At the time this paper is written, the life test is still ongoing and has reached ~95% of the objective life (20 million cycles including margins, meaning 280 million cycles for the compliant elements and 320 million zero-speed for the OTS bearing). So far, no degradation has been constated on motorization or closed loop error. The test is expected to be finished by September, which will pronounce the full qualification of the mechanism.

LESSONS LEARNED

Early Testing

When new technologies are involved, early testing with breadboard is a good way to learn. The cost of breadboards may raise some hesitations but some test results often worth hundreds of hours of analysis.

Bending of Flexural Pivots

The early testing of the kinematics raised one design issue concerning the flexural pivots. The functional tests after mechanical environment tests showed a degraded performance. After investigations, we found out that one of the flexure plates of the pivot was broken (see Fig. 15). Further analyses showed that the modal shape of the shaft was such that the pivot had to withstand some bending moment. It was firstly modelled with simple spring elements but a finer analysis with 2D shell elements highlighted that this bending led to very high stress (see Fig. 16). We implemented some design modifications and reduced the maximal stress from 1 480 MPa to 513 MPa (with 1 030 MPa allowable). A new mechanical test was successfully performed afterwards.

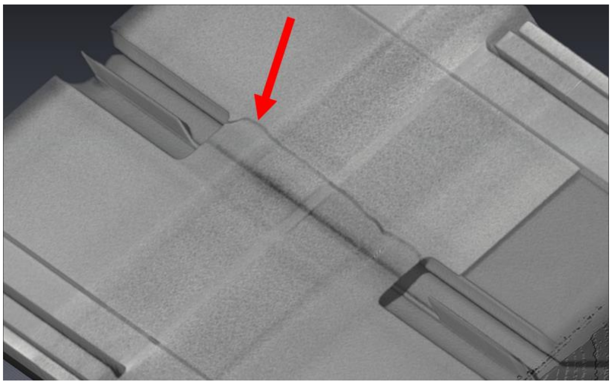

Figure 15: Micro-tomography inspection of the damaged flexural pivot

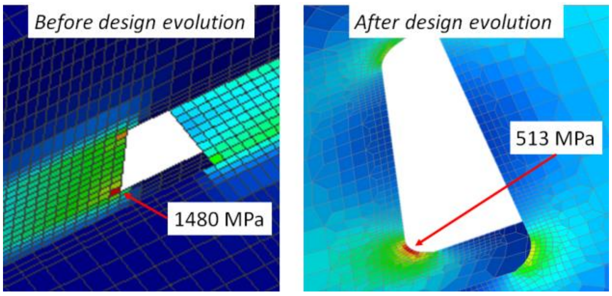

Figure 16: Finite elements analysis of the pivot before and after design modification

The use of flexural pivots often involves a pair, which leads to radial efforts, but sometimes a single component is used like in this scan mechanism application. In this case we recommend avoiding any bending moment in the pivot.

Components Communalization

The co-engineering phase with Airbus DS brought that the SCM components could be the same as the ones in another mechanism of the interferometer. This was eased by the fact that they shared similar environments.
This communalization led to a better cost-effective development for motors, encoders and bearings. This also allowed having similar drive electronics (ground and flight) which was another great benefit.

AlSi Manufacturing

The use of newly developed AlSi material was challenging for the manufacturing activities. The machining processes had to be adapted and several tests were made on dummy parts. In the end COMAT gained a lot in machining experience with this material, and this mastering has been rewarded by new contracts for manufacturing AlSi parts, such as the ones for the Airbus DS interferometer for the same IASI-NG instrument.

Specific Fasteners

Due to the tight volume constraints for the mechanism we had to optimize the fastener sizes. This resulted in high strength material (like titanium or hard stainless steel for instance) associated to solid-lubricated washers. We procured quite soon the fasteners and washers for the entire development and we characterized the assembly in order to optimize the design margins (torque vs preload measurements). Unfortunately, we had to procure some more after a design evolution and we faced some difficulties because the measurements were not as good as the first characteristics that we used to justify the mechanism. Various reasons explained this: the solid lubricant used on the washers was obsolete after new legislations, and the fasteners manufacturing may show dispersion between batches.
The lead time of these specific fasteners being very long we could not make a new procurement, but fortunately we could allocate the weakest fasteners at some places where margins were comfortable and save the first ones for the most demanding interfaces.
We recommend keeping some margin on the fasteners characteristics even if they are measured.

CONCLUSION AND PERSPECTIVES

Thanks to its far-reaching engineering and technological innovations, the IASI-NG instrument will improve the performance compared to its predecessor.
Concerning the scan mechanism, the early co-engineering phase with Airbus DS allowed a more efficient development and helped COMAT to gain in mechanism experience. The parallel architecture, under patent (FR1914747), was the key to reach the challenging pointing performances required.
The mechanism has been qualified, pending the former completion of the remaining 5% of the life test.
The first flight model was delivered to Airbus DS in January 2021 and the FM2 and FM3 are to be delivered in September (acceptance tests are successful).
The next steps are the integration by Airbus DS of the SCM on the IASI-NG instrument and then on the MetOp-SG satellite, which brings us to the first flight foreseen in end of 2023 or early 2024.

This SCM concept has proved its potential for this IASI-NG mission, and can be proposed to a variety of other missions requiring a 2-axes pointing mechanism with one axis having a small angular range.

ACKNOWLEDGEMENTS

We would like to thank Airbus DS and CNES, and particularly their mechanisms teams, for their support along the development of this equipment. We also thank CODECHAMP, ADR, SOTEREM and CLIX for the procurement of some components of the scan mechanism.