SCM ACTUATOR, RE-USE LESSONS LEARNT

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ABSTRACT

The SCM (SCan Mechanism) is a generic compact single axis mechanism developed in the frame of the IASI-NG interferometer, where it drives three axes. It is composed of 3 major components, a brushless motor, a super duplex ball bearing & an optical encoder.
The modularity of this product allows for design options to be developed on demand, ensuring broad adaptability. This document will present the latest additions to the SCM and corresponding challenges, on on-going projects (Earth observation scanners for TRISHNA and LSTM missions) and prospective ones.

1 IASI-NG heritage design

The SCM (SCan Mechanism) was developed for the IASI-NG interferometer: three axes are driven with this unit (with customized mechanical interfaces for each application): the (DSM) Dual Swing Mechanism axis and the Scan Mechanism 2-axes (also covered by a patent for its parallel kinematics configuration). This generic drive unit is composed of our heritage major components:

- A motor, implementing the kinematic profile. It is a DC brushless motor from SOTEREM with 1.3 Nm torque capability.
- A bearing, ensuring rotor motion and sustaining all rotor loads (no need of launch lock). It is a super duplex pair ball bearing from ADR in back to back configuration, with Maplub SH051a lubrication.
- An encoder, monitoring the motion and used by the drive controller, procured from CODECHAMP. For IASI-NG the trade-off for model selection was on maintaining performances even at relatively high speed, but another version with higher accuracy is also available (fully interchangeable: same volume, mechanical and electrical interfaces) used on past projects GOCI-II and MicroCarb.
- Titanium housing and shaft

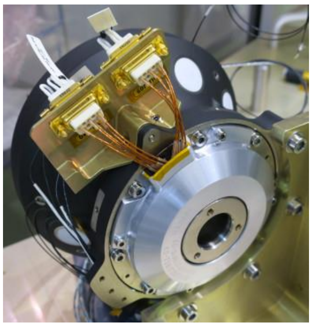


Figure 1. SCM actuator (IASI-NG DSM version)

Characterisation of the SCM during IASI-NG tests campaigns as summarized below allowed for quick performance evaluation of the new applications.

Table 1. SCM major components characteristics

Motor	1.3 Nm rated torque
Friction	Dry ≤0.03 Nm, Viscous ≤0.004 Nms/rad
Cogging	≤ 0.03 Nm, Major spatial harmonics h14,28,42,60,120,180 (h = per rev)
Ripple	H42, ≤ 1.2% of commanded torque
Bearing	
Load ratings	Radial 18031 N, Axial 9391 N
Stiffness's	Radial 223 N/µm, Axial 224 N/µm, Angular 177 000 Nm/rad
Friction	≤0.012 Nm@2rpm, ≤0.045 Nm@50rpm
Encoder	22 bits
Accuracy (uncalibrated)	~100 µrad (encoder option 1) ~50 µrad (encoder option 2)
Hysteresis	≤1 least significant bit

2 TRISHNA & LSTM specificities

2.1 Missions overview

Both missions are similar for the SCM, with a spacecraft cruising in LEO (Low Earth Orbit) and the SCM used as a scanner across the satellite track on ground (mirror in-plane of scan rotation axis)

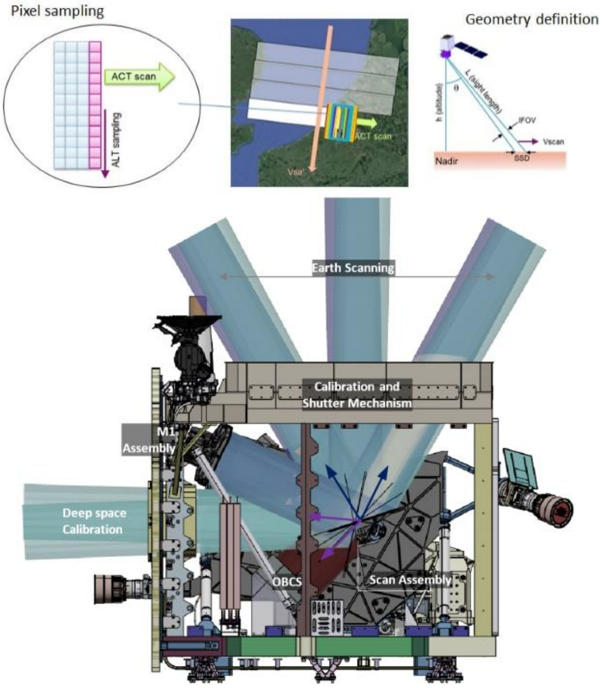


Figure 2. LSTM scan mission (TRISHNA is similar)

2.2 Load path

The load profile on the SCM is different from IASI-NG implementations: the Scan Mechanism consisted in 2 in-line SCM units driving a common rotating mirror shaft (and partially off-loaded during launch with radial mechanical stops) leading to axial and radial loads in the SCM units bearing without bending moment.

For TRISHNA and LSTM, the SCM is a single unit with the mirror payload directly attached to the rotor, leading to high bending moment on the bearing during launch.

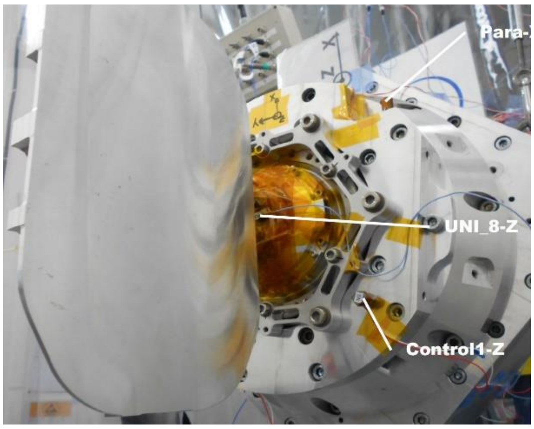


Figure 3. TRISHNA SCM and representative dummy mirror mounted for axial shock tests

2.3 Pointing performance and knowledge

The TRISHNA and LSTM requirements on pointing performance and knowledge budgets are about 2 orders of magnitude lower than the IASI-NG ones.

The performances (realisation and knowledge) budgets for the scan have been derived from instrument needs in overall absolute pointing accuracy and stability requirements for pixels integration: smearing, time delay integration, sampling regularity, scan lines overlapping repeatability, integration channels co-registration. Overall the needed accuracy is in the order of 1 µrad and sub-µrad requirements depending on the timeframe periods considered.

IASI-NG heritage data allowed to evaluate compliance of the SCM design with these budgets. Two contributors have been identified for risk mitigation during proposals phase: bearing wobble and encoder accuracy. State of the art on these 2 elements is addressed in dedicated performance sections of this paper.

2.4 New optional additions

TRISHNA and LSTM programs asked for better performance wrt IASI-NG heritage but also additional functionalities, hence some modular options have been developed and are currently in qualification stage.

ARD (Anti-Rotation Device)

This module developed for TRISHNA adds a mean to passively maintain the rotation axis within ±5° of the launch position. The instrument design has a wide opening towards the Earth for beam scanning, and this module ensures no detrimental stray light can enter the instrument. It is composed of a magnet and flexible blades, whose parameters are adapted to TRISHNA mirror and qualification environments (sinus, random, shocks). It is complemented by shorting the motor phases during launch, hence adding high damping.

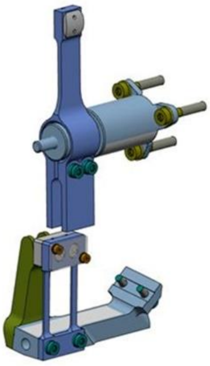


Figure 4. TRISHNA SCM ARD

The ARD limits the available rotation range, but the launch position being outside the nominal operational range, this is not an issue. Escape of the ARD position is achieve by driving out of the position, the motorised torque margins vs. ARD magnet holding torque being high.

Expansion rings

Due to the high performances required and mismatch of materials between the SCM (titanium) and the optical bench ones (e.g. CFRP, AlSi or SiC), interface with the instrument is done through an expansion ring. Several iterations and design have been envisaged like the use of bipods, however for both TRISHNA and LSTM the selected final design is compact, accommodates the thermal expansions difference from non-operational environments via flexible blades, and is compatible of the mechanical environments and performances.

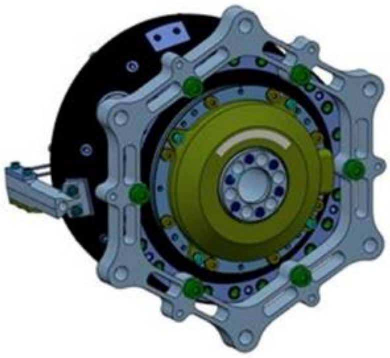


Figure 5. TRISHNA SCM Expansion ring

Backup position sensor

A late requirement from LSTM for a separate position sensor from the encoder has been added to address a possible instrument failure mode. A quick designed option based on a heritage design is now part of the SCM optional modules. At the time of writing this paper the design adaptation to the SCM is being finalised; it consists in REED switches, allowing to confirm whether the SCM axis is at a specific safe location, outside the nominal operational range, within ~15°.

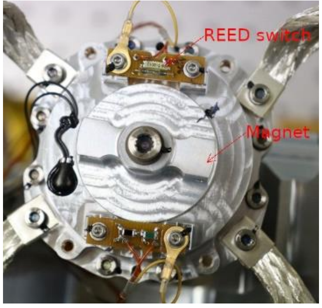


Figure 6. LSTM SCM Backup position sensor

3 Performances

3.1 Verification philosophy

During the proposals phase, thanks to the reuse of the existing IASI-NG design and major components, analyses based on heritage data and experience (as well as early derisking on early breadboards) allowed to identify and evaluate the key contributors to the performances errors.

- Cross-axis angles are not monitored in-orbit and are mainly due to assemblies misalignments and tolerancing (static errors that can be compensated by alignment at instrument level), as well as bearing wobble which is a dynamic error with spatial frequencies (manufacturing tolerances) and noise (rolling contact technologies).
- In-axis angles are monitored by the SCM encoder, adding low and high spatial frequencies errors due to encoder alignments and internal parameters.

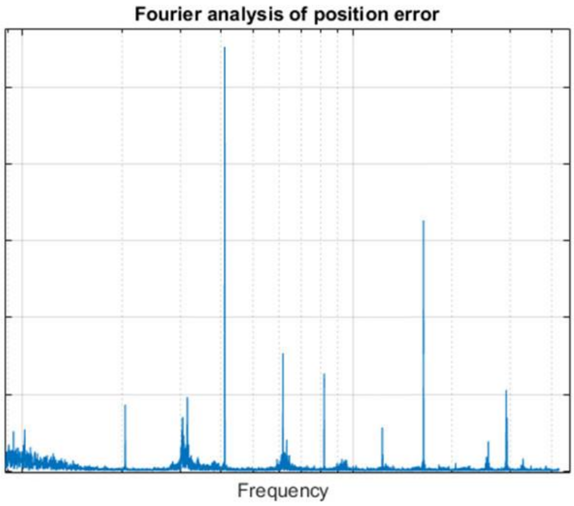


Figure 7. IASI-NG axis high spatial frequencies errors (from encoder) as tested on PFM

Detailed analyses have been performed since, and consolidation of the proposed verification method has been concluded thanks to additional breadboards after SCM Phase B kick-off.

Bearing residual tilt error excluding the circular cone error due to alignment (full revolutions harmonic 1, treated at instrument integration level) is characterised with a wobble test. It directly confirms compliance with bearing wobble allocation budget (both pointing performance and knowledge).

Bearing wobble is further detailed in the next section.

Encoder errors need more work: across track performance and knowledge is verified… with the SCM encoder itself: the needed $\leq 10^{-6}$rad accuracy over a very large across track nominal (BRC Basic Repeat Cycle) range of ~1rad limits the available technologies, and Airbus trade-off + experience led to the proposition of metrology based on the SCM encoder itself.

Low spatial frequencies errors are due to integration alignments only and don't evolve over the mission lifetime, whereas high frequencies are also slowly evolving over the lifetime due to ageing of internal electronics components. Metrology based on SCM encoder only characterises the high frequencies errors (building a calibration table used for post-processing of knowledge data), with low frequencies errors left for characterisation at instrument level + in-orbit (using ground reference points). The metrology process can be reapplied even in-orbit (need for a dedicated calibration mode is still under investigations, nominal operational range may be sufficient for calibration table build-up)

The encoder ~50 µrad rated absolute accuracy is consistent with encoder lot elements repeatability and final alignment tolerances as per supplier requirements. As part of acceptance tests, the supplier perform a calibration against a reference encoder, showing the possibility to improve significantly on the rated accuracy with a calibration process on each installed unit. Early activities with the supplier on a qualification encoder allowed to confirm the accuracy of the calibration table with their reference encoder. Airbus developed with a breadboard a metrology process that achieved similar accuracy, with encoder auto-calibration of high frequencies errors.

The verification metrology chain is based on the reference encoder from the supplier, and build-up of accuracy errors from there with SCM encoder calibration error and calibration repeatability error. The absolute metrology residual error as measured is ~2 µrad@3σ, but to assess the tight requirements in very short timeframes the metrology error is reduced to the relevant harmonics. Encoder error is further detailed in the section after next.

3.2 Bearing wobble

Contribution to pointing performance

Bearings exhibit axial and radial run-out errors. At mirror interface (out-of-beam configuration), radial translations of the mirror are negligible vs. pixels on Earth, while wobble from axial run-out affects the mirror normal direction. Wobble around the perpendicular axis to the mirror plane translate the mirror normal hence negligible (also small, do not increase the mirror surface need to capture the whole instrument beam), while wobble around axis in mirror plane affects the mirror normal hence beam pointing in along track (and negligibly in across track).

Derisking

The bearing wobble impacts the SCM cross axis performance. Derisking activities during LSTM Phase A were conducted with an autocollimator setup

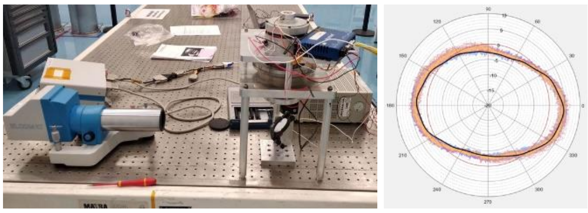


Figure 8. Bearing wobble derisking with autocollimator

Results were promising (3µrad residual wobble after calibration), which allowed to confirm the suitability of the bearing wobble error magnitude and frequencies. Some issues were also identified:

- noisy autocollimator in static mode with mid & long term drift of measurement, already outside the requirements range
- 45° reflecting mirror leading to difficulties of calibration and interpretation of results in 'flight' conditions

A more accurate & repeatable set-up was developed: Trade-off was re-open on measurement set-up (with Optical Lab) and led to the choice of a 3-point interferometer (SIOS), with a direct measurement in front of a plane mirror.

Final setup

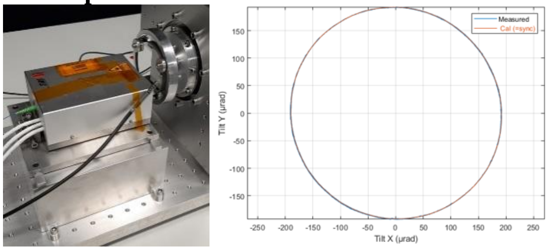


Figure 9. SCM wobble with SIOS test setup

Due to the severe pointing requirements, fine characterisation of the setup was performed.

- SIOS: analysis of the signals in static conditions. Led to the characterisation of a ~525 Hz signal in SIOS channels.
- Test setup frequencies and decoupling from test table also characterised ('tap' tests)
- Best SIOS sampling rate and signal conditioning selected accordingly
- Test mirror WFE (WaveFront Error) characterized, leading to improved attachment and minimized resulting WFE contribution to wobble error: 1.5 µrad 3σ.

The resulting wobble test measurements allow fine review of the bearing wobble characteristics. It confirms the very good performance of the SCM bearing, which does not exhibit a dominant h3 harmonic often cited in literature. We initially planned to characterize a wobble calibration curve and remaining noise, but a calibration curve is now not seen as necessary, considered within noise allocation budget of 10 µrad.

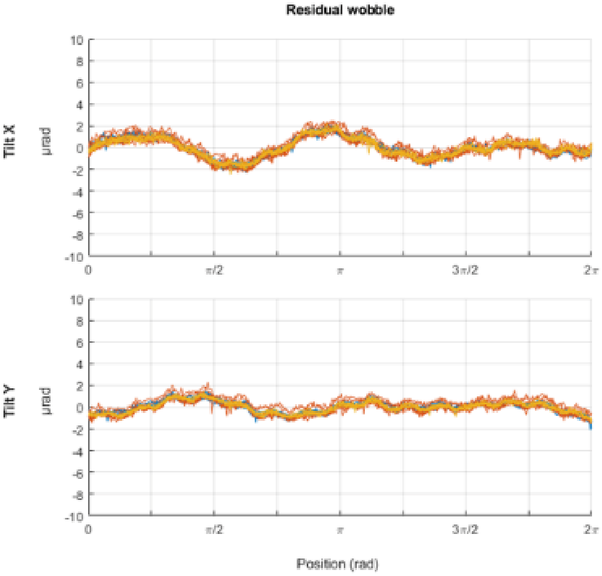
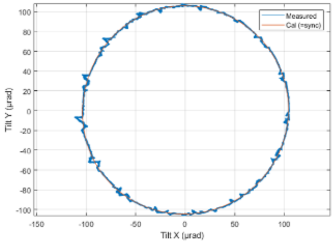


Figure 10. SCM wobble bearing performance, EM

Additional benefit: the detailed wobble measurement allows to detect defaults on the bearing races, which is helpful post-environment tests to confirm whether plastic deformation occurred (happened initially post shocks, cf. this paper lessons learnt section), and even contamination on tracks (with 'moving' small wobble spike).



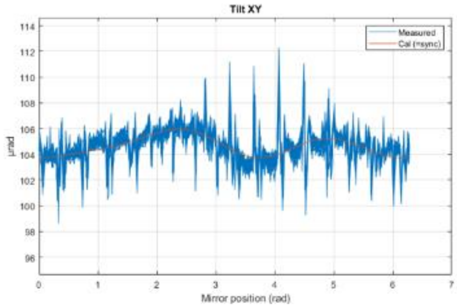


Figure 11. Bearing wobble post shock environment - races plastic deformation visualized

NB: after rework and optimised test requirements with instrument team, the qualification mechanical environments including shocks have been passed successfully for TRISHNA. LSTM in under analysis at the time of writing this paper.

Lessons learnt

It is known that grease lubricated bearing may develop high noise from very low speed and reversal of directions. This has been the case during the tests on initial test models, but with different noise development pattern, which initially confused us whether this was due to the MGSE of the tested bearings.

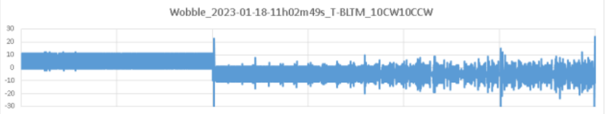


Figure 12. Example of noise developing after change of direction, low speed step & stare drive control

After determining the root cause, it appears this phenomenon is avoided in the flight BRC pattern where Earth observation low speed occurs in one direction, and high speed + high angular range with reversals are performed in the rest of the cycle (rallies to/from calibrations targets). Grease lubrication behaviour could have been a real issue for the mission otherwise.

3.3 Encoder accuracy

Contribution to pointing performance

The encoder exhibits LF and HF ('low' and 'high' spatial frequencies) errors. For our missions, latest analyses show no need for encoder HF error compensation for realised performances, but a need for knowledge performance post-processed on-ground, with a calibration table that can be updated throughout the mission life.

Metrology

The Airbus metrology process (NB: high frequencies only) has been first proved with a breadboard where a high inertia flywheel was attached to the rotor of a test unit with the EQM encoder and a flight representative bearing, but with no motor to avoid pollution of the results with motor cogging affecting the kinematic of the flywheel. The flywheel is motorised by a mass on a string, applying by gravity a constant torque on the rotation axis.

Figure 13. Encoder breadboard with flywheel

Although the kinematic speed with the flywheel was not perfect due to small residual unbalance post flywheel balancing, the encoder data process through adequate filtering allowed to extract the high frequencies error content as expected. Early tests comparison allowed to show that small speed differences or direction of rotation have little impact on repeatability, higher speed of rotation has.

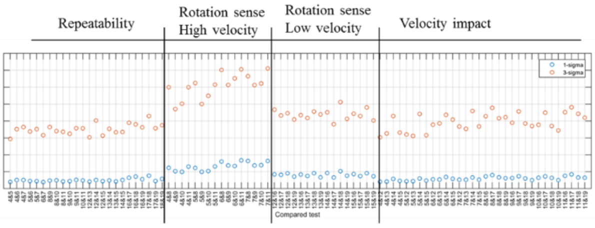


Figure 14. Encoder breadboard, metrology sensibility analysis

Metrology extraction was then also proved with a fully representative motorised SCM, driven at constant speed, with a controller designed to reject low frequencies from e.g. motor cogging, while not altering the high frequencies from the encoder. At the time of writing this paper this subject is still in development with final method (valid also in-flight with real mirror dynamic behaviour) to be tested and validated on an EM model.

3.4 Lifetest

Heritage

TRISHNA and LSTM models benefits from IASI-NG experience, where 8 criteria have been defined in co-engineering with CNES tribology experts to validate the representativity of bearings accelerated lifetests. Several models have been all successfully lifetested, from breadboards for bearing materials and lubricant trade-offs, to qualification of DSM and Scan Mechanism units. Fortunately, one of the breadboards (BB1) lifetest does also cover all the criteria adapted to TRISHNA and LSTM missions, therefore providing good derisking ahead of new life qualification models.

Table 2. SCM lifetest criteria - LSTM and TRISHNA fully covered by IASI-NG BB1

Parameter	IASI-NG BB1	LSTM	TRISHNA
Kinematics			
BRC angular range (°)	28	82.5	85.25
BRC speed range (rpm)	± 80.6	-50 →50	±38
Earth speed range (rpm)	n/a	1.1	1.56
Lifetime			
No of cycles ECSS (x10^6)	236	54.9	44.3
Ball passes on spot (x10^6)	587.4	402.6	335.7
Key parameters			
#1 Oil film thickness:	0-0.58	0-1.6	0-1.99
#2 Hertzian pressure (MPa)	~1000	~1000	~1000
#3 Oil distribution:	Yes	Yes	Yes
#4 Reverse direction (x10^6)	472	109.8	88.6
#5 Balls rolling distance (km):	3 806	2 608	2 175
#6 Acceleration range (rad/s^2)	± 292	± 37	± 41
#7 No of zero speed (x10^6)	472	109.8	88.6
#8 T(°C)-Duration (years)	63-1.83	20-7.75	20-5.5

New lifetime qualification is currently performed to ensure that application of the new mechanical environments including shocks do not alter significantly the IASI-NG lifetest results.

Kinematics

The nominal in-orbit scan BRC (Basic Repeat Cycle) shows a mainly boundary lubrication regime, and an accelerated BRC for lifetest satisfying all criteria above allows to reduce the life duration by a factor 5 on LSTM and 4 on TRISHNA

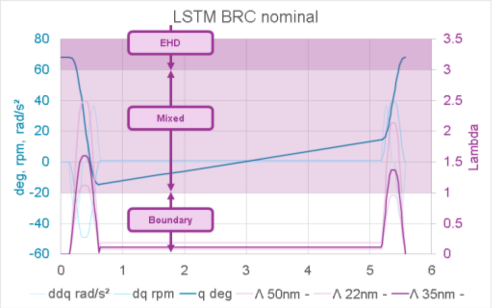


Figure 15. SCM LSTM BRC, nominal

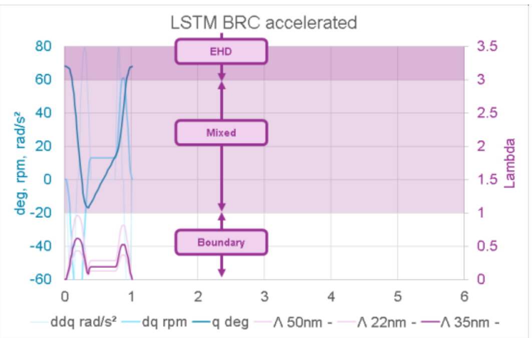


Figure 16. SCM LSTM BRC, accelerated

Planning

Lifetest models are submitted to full qualification mechanical environment including shocks before starting the lifetest in thermal vacuum chamber. At the time of writing this paper, the TRISHNA lifetest model passed successfully its environment tests and is starting its lifetest; LSTM model is under last design options finalisation before starting its lifetest campaign. End of lifetests is expected in 2025.

4 Lessons learnt

Development

The SCM was initially proposed as an off-the shelf unit, with known performances and capacities, adapted to the early requirements. However as the new projects progressed towards detailed definition, both TRISHNA and LSTM projects requested improved SCM performance requirements , changing the design category from B to C and a development program growing accordingly, with wobble breadboard, encoder breadboard, structural model for new environment and shock derisking, new lifetest models where these new mechanical environments are first applied, etc.

For highly customised programs like in Earth observation and science missions, a reuse approach needs to allow for very versatile environments requirements (payload, mechanical and thermal environments, …). This was not fully appreciated when reuse of the IASI-NG actuator was proposed, as this actuator was well adapted to the IASI-NG requirements and constraints. The SCM is now becoming more versatile thanks to the adaptation to TRISHNA and LSTM, which also allowed some derisking activities for future prospect missions (see next section).

Building experience from IASI-NG then TRISHNA and LSTM also helps to identify possible further enhancements or evolution depending on mission requirements. For instance at bearing level, shock tests highlighted design constraints that were not impacting IASI-NG, but with low margins for TRISHNA and LSTM. Small design updates could provide more margins while not affecting the lifetest qualification status.

Shock

The shock environment was not fully anticipated during the proposal phase where only the encoder disk material was identified as a risk. Derisking activities on a structural model cleared the encoder design and qualified it to very high levels (monitoring accelerometers saturated at more than 3000g), but the bearing did not. Following investigations, it occurred that the issue was linked to the herztian contact reaching ellipse truncation at the edge of the bearing races, whereas the hertzian pressure with normal ellipse contact would be compliant. This is due to the high moment load generated by cantilevered mirror, which differs from the load path in IASI-NG configurations load path where moments were very small.

This issue led to better understanding the phenomena occurring during shocks, where we also developed analyses skills for shock environments and predictions, correlated with tests performed on the TRISHNA lifetest model.

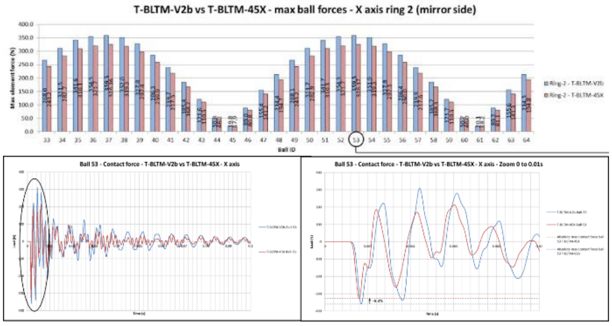


Figure 17. SCM T-BLTM shock test, bearing balls loads, analysis vs. test values

5 Future missions challenges

Having a generic, versatile actuator brings its benefits in optimising our development logic and minimising risks taken. It allows for more accurate simulation and performances prediction, thanks to correlated models, as well as quick derisking tests to demonstrate achievable performances with available hardware in the production line. This sections gives some insights of how such activities were performed for future missions.

5.1 Microwave sounder

A microwave sounder mission requires a scanning mechanism, able to rotate a reflector at constant, and stable, speed during Earth acquisition, and accelerate / decelerate during the non-Earth coverage part to maximise the duty cycle, ie available time for acquisition on the Earth.

The knowledge of our SCM product allowed for quick prediction of performances and supported trade-offs at instrument level, allowing to investigate numerous candidate solutions with limited engineering effort while keeping a high confidence in predicted performances due to the knowledge already acquired.

Table 3. Microwave sounder requirements

Specification	Unit	Value
Earth scan	° / ms	90° / 125ms target
Rotation period	s	0.4s± 1%
APE	°	<±0.01
AKE	°	<±0.01° (1σ)
Velocity stability	%	< ± 5
Mobile inertia	Kg.m²	0.0065
Lifetime	years	3 (obj. 5)

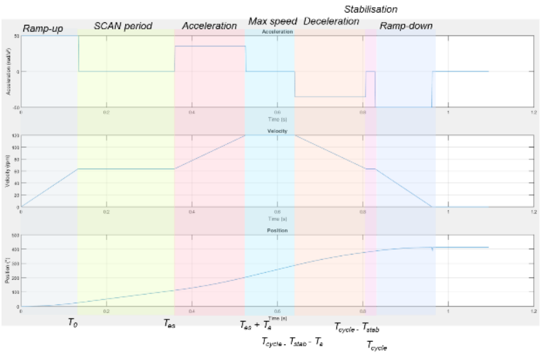


Figure 18. Microwave sounder kinematic

5.2 TRUTHS

TRUTHS is an operational climate mission, for ESA, to estimate the Earth radiation budget through direct measurements. During phase B1, it was quickly identified that one of the mechanisms, the WSM (Wavelength Scan Mechanism) was critical due to the high accuracy expected and very slow scanning speed.

Table 4. TRUTHS WSM Requirements

Specification	Unit	Value
Angular range	°	±2,25°
Scan speed		α = 87μrad/s
APE	μrad	<100μrad 1σ
RPE short term	μrad	< 4μrad 2σ over 0.5 s
RPE long term	μrad	<10μrad 1σ
AKE	μrad	<10μrad 1σ
RKE	μrad	<5μrad 1σ
Scan Mirror mass	Kg	<0,250 Kg
Scan Mirror inertia	Kg.m²	<0,001 Kg.m²
Lifetime in-orbit	/	5000 cycles

Trade-offs quickly identified that the best mechanism solution was using flex pivots with an encoder (calibrated as presented before), but this solution was also more expensive and limited the number of candidate suppliers. The ‘classical’ bearing approach was seen as an interesting alternative, but stick-slip was difficult to assess. A derisking campaign, under ESA funding, was performed on an available unit to evaluate the performances for the TRUTHS kinematics.

It showed that the SCM architecture was a relevant candidate for the WSM, with a sufficiently high TRL (TRL>5 was key criteria for TRUTHS at the end of phase B1), but also identified important lessons learnt:

- Calibration of encoder was required to fulfil the requirements.
- Increased resolution of encoder (above 22bits) was required as the quantization effect was predominating pointing error (as was anticipated, but this was confirmed through testing).
- Accumulation of small strokes quickly lead to high degradation of the performances, with high ‘spikes’ visible. It was assumed this behavior was due to the accumulation of particles, potentially accentuated by the use of grease lubricant. The performances was easily recovered with larger strokes cycles. This was an important finding early in the project as it meant that lubricant could be changed to pure oil to reduce this effect, and instrument design could be designed to accommodate regular larger stroke displacements for ‘maintenance’, should a solution with bearing be used.

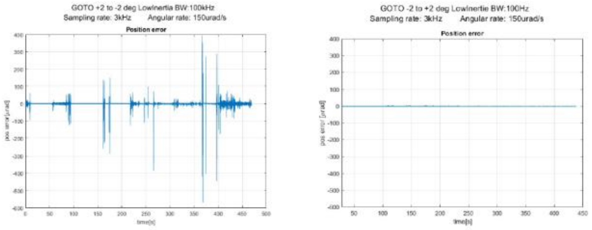


Figure 19. Left: regular spikes due to particles in bearing; Right: recovering performances after a large stroke cycle

5.3 Calibration mechanism

The need for a pointing and calibration mechanism is identified in the frame of an AIRBUS Phase 0 instrument study, leading to the opportunity to reuse the SCM. The mechanism implementation principle is similar to TRISHNA or LSTM, but requirements are different in terms of mass, inertia, stability. Derisking activities with a dummy mass on the SCM have been implemented and demonstrate the adequacy of the SCM with the current instrument baseline.

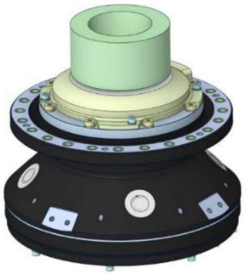


Figure 20. SCM with dummy inertia for calibration mechanism derisking

6 Acknowledgments

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- **All collegues and partners** involved in the development and evolution of the SCM since its inception on IASI-NG

7 References

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