BEAM STEERING MECHANISM FOR EARTHCARE ATMOSPHERIC LIDAR INSTRUMENT ATLID – AN ULTRA-STABLE PIEZOELECTRIC TIP TILT MECHANISM

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I. INTRODUCTION

ATLID (ATmospheric LIDar) is one of the four instruments of EarthCARE satellite, it shall determine vertical profiles of cloud and aerosol physical parameters such as altitude, optical depth, backscatter ratio and depolarisation ratio. The BSA (Beam Steering Assembly), included in emission path, aims at deviating a pulsed high energy UV laser beam to compensate the pointing misalignment between the emission and reception paths of ATLID [1]. It requires a very high stability and high resolution.

The BSA core is a 2-axis small range pointing mechanism, supporting a mirror. See Fig. 1. The BSA is composed of 3 main units. The first unit including optics, mechanics and electronics (BSMFE) is made of two sub-assemblies: a Mechanism equipped with the tip-tilt mirror (BSM) and Front End Electronics (BSFE), implemented in the PLH (The pressurized Power Laser Head, the optical UV laser of ATLID. See Fig. 2.). The second is an Electronics Unit (BSME), implanted on instrument panel. And the third part is a Harness (BSH) made of two cables, connecting the two units. Sodern is responsible for designing, manufacturing and testing the Beam Steering Assembly Flight Models (FM); while Sodern and Cedrat Technologies co-developed the Beam Steering Mechanism (BSM) part of the BSMFE.

Both Sodern and Cedrat Technologies were already associated on PHARAO project to develop a similar mechanism. PHARAO is a cold atoms space clock that includes a Laser Source which Sodern was responsible for, under CNES contract. The Laser Source uses 8 mechanisms MEF (Flux Equilibrium Mechanism) similar to the BSM. Their function is to align the laser beam in collimated optical fibers to adjust optical power between different channels [2]. For the BSM, the main basic building blocks were reused such as mechanism push pull architecture and electronic architecture. The most important design differences are the mirror dimension: 27mm diameter for BSM instead of 4mm diameter for the MEF on one hand and the allowable volume, and global layout of the mechanism and electronic on the other hand.

The paper is presenting the main challenges of the BSA and the choices made by Sodern to meet the multiple requirements. It summarizes the key results of performance and environmental tests, particularly the very good stability performances. The two flight models are now achieved and they were delivered during 2015.

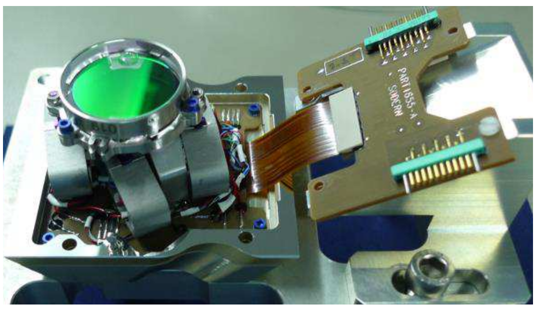


Fig. 1. Pointing mechanism – part of BSMFE

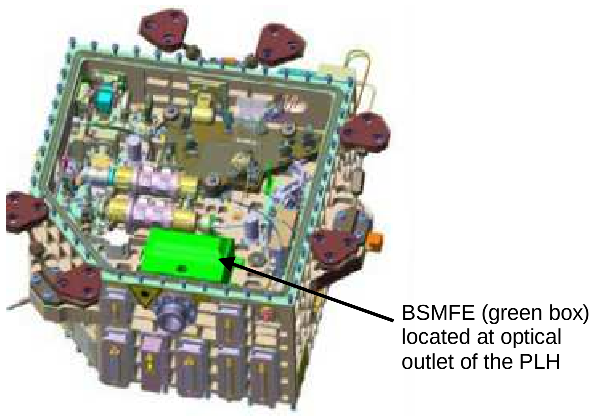


Fig. 2. BSA location inside PLH schema

Tab. 1. Most important improvements of BSA compared with PHARAO MEF

	MEF PHARAO	BSM ATLID
Pointing stability	2 µrad in 20 days	Pointing signal power on [1mHz;10Hz] bandwidth < 0.31µrad² Long term stability: 200 µrad with a goal less than 100µrad
Temperature environment	Regulated baseplate: ~10mK order of magnitude	Operational temperature in [24°C; 40°C] range with following stability : 4K drift on long term 1K on MT2; MT3 see Tab. 2
Long term stability	Not requested	200 µrad
Repeatability	Not requested	70 µrad

II. TECHNICAL CHALLENGES

The direction of the laser beam needs to be co-aligned with the reception path of the instrument to maximize the detection of the LIDAR echo signal. The BSA compensates for the pointing misalignment between the emission and reception paths of ATLID with a high resolution and a very high stability. The BSA design is also compatible with the spatial environmental requirements, including harsh launch conditions and a solar illumination loading case. Moreover, BSA is subjected to severe cleanliness requirements, because of LIDAR specificity.

A. Environmental requirements

The environmental requirements make the design and the validation of the BSA quite challenging.

- Stability requirement is to be reached for thermal variation of ±0.5°C short term and ±2°C long term
- The mechanism is to survive launch conditions – 15,5g RMS random, 100g shocks SRS level.
- Micro-vibration susceptibility requires to be minimised to achieve stability requirements during flight.
- The BSM shall withstand direct solar illumination without damage and shall be able to survive without permanent damage, to a solar input beam of 5,8W during 2 minutes.
- The BSA is located near the pulsed laser resulting in a harsh magnetic environment.
- Due to its position inside the PLH, the BSA contamination requirements on the optical bench are strict and all outgassing materials shall be avoided.

B. Critical performances requirements

The BSM is required to steer the incoming laser beam through a range of ± 3 mrad, optical range, for both axes with a control bandwidth up to 10 Hz. Due to the 45° incidence beam on Ry axis, this performance requires a mechanical rotation of +/-2.12 mrad on the Rx defined axis and +/-1.5 mrad on the Ry defined axis at the BSM level. The critical requirements are the accuracy of the movement, the stability (short term, mid term and long term) and the repeatability.

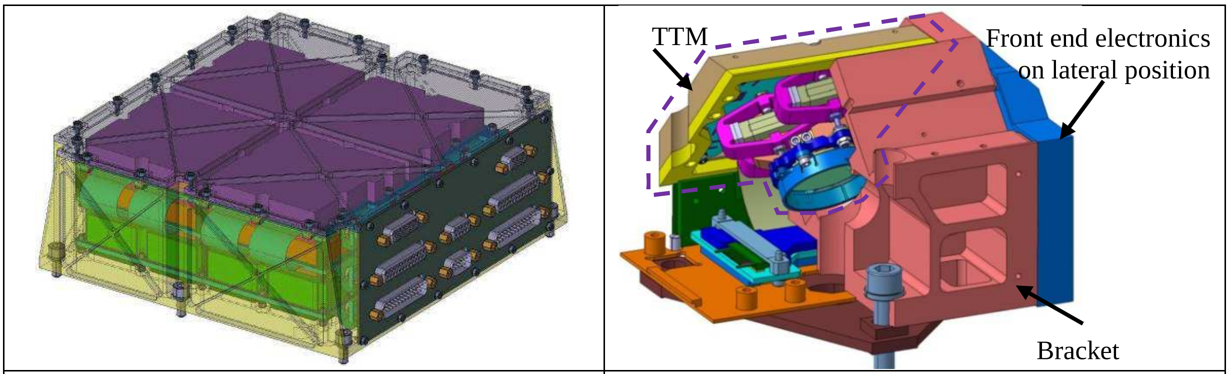
The Tab. 2. lists the time scale and associated instability contributors while Tab. 3. gives the main performance requirements that are compliant for any contributor and for any optical angle.

Tab. 2. Potential contributors to the stability

Contributors to stability budgets	
Time scale	**Contributors**
Long term (LT) Lifetime: in orbit life time 37 months + on ground life time 7 Years	On ground alignment Launch micro setting Gravity release Moisture release LT thermal variations Ageing
Medium term (MT) MT1: One Month MT2: One orbit (~90min) MT3: Co-alignement closed loop (~1000.sec)	Calibrations errors Orbital thermal variations
Short term (ST) 1.5sec	ST thermal variations Measurement noise Laser angular jitter
Dynamics Laser roundtrip period (~3msec)	Spacecraft stability Spacecraft jitter

Tab. 3. BSA performance requirements

General performance requirements		
Description	**Req.**	**Unit**
Optical angular range Rx, Ry Mechanical angular range Rx Mechanical angular range Ry	±3 ±2.12 ±1.5	mrad mrad mrad
Thermal sensitivity: BSM contribution BSFE contribution	 7.5 1	 µrad/°C µrad/°C
Total repeatability	70	µrad
Rx, Ry Linearity @full stroke Realized angle/set point Angle	1 ±5%	µrad/µrad
Power consumption: BSM contribution BSFE contribution BSME contribution	 0.2 1.3 4.5	 W W W



BSME Overview	*BSMFE overview*

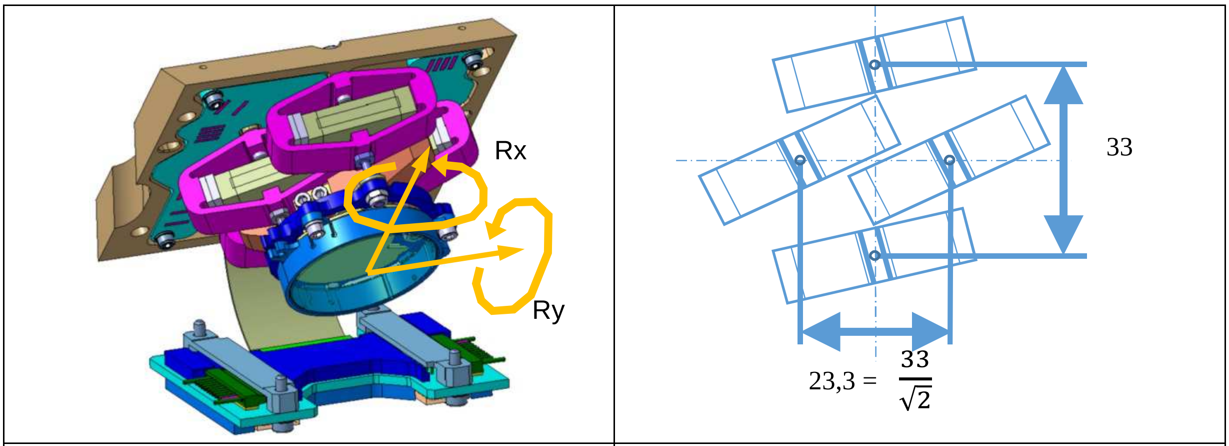
Fig. 3. BSA components overview

III. BSA DETAILED DESCRIPTION

The BSA design tasks were performed to develop the different parts of BSA: the BSME and the BSMFE. Mechanical design main activities were performed on BSA mechanism unit, the BSMFE. Its design shall answer to multiple requirements, particularly; the BSMFE dimension was optimized in order to facilitate its implantation in PLH. System design main activity consisted in studying the close loop optimization, based on strain gauge configuration (see III B.) and its possible environmental perturbation in order to guarantee the stability performance. The electronic architecture was optimized to minimize power consumption and to allow the interchangeability of one unit with respect to the other.

A. BSMFE mechanical design

The BSMFE is a 2-axis Tip-Tilt Mechanism (TTM), mounted on a bracket, supporting the Front end Electronic boards. Based on a two stiff push pull pairs of APA60SM® actuators [3], it produces more than 3 mrad, optical angle, with a bandwidth up to 10Hz with mechanical resonant frequencies above 1.4 kHz thus avoiding the use of a launch locking mechanism and limiting the micro-vibration susceptibility. The position of the piezo actuators was selected to minimize the volume of the BSMFE and to allow a different stroke between the two rotation axes. Such an asymmetric architecture presented on Fig. 4. is proposed to ensure similar range of applied voltage, and corresponding to the same range of optical angle. This choice enables to maximize the applied voltages on the piezo ceramics; it improves the overall sensitivity of the mechanism and then improves the accuracy of the angular movement.



TTM overview showing RX and RY push Pull orientation	*Asymmetric design allowing volume and mechanism sensitivity optimization*

Fig. 4. BSA mechanism architecture description

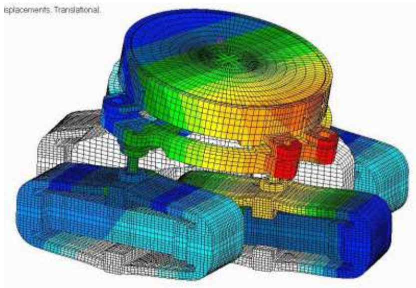


Fig. 5. FEM simulations result: Calculated maximum displacements during RX actuation

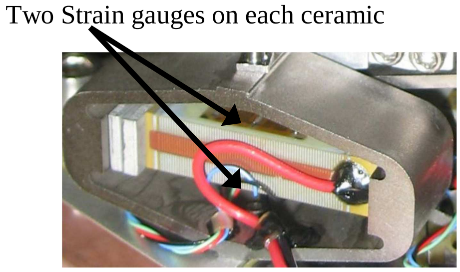


Fig. 6. Strain gauges location

Once the piezoactuators sized, several simulations were performed to validate simultaneously angular range, stress resulting from integration, thermal environment, vibration/shocks environments and micro sliding at screwed links in regards of the thermal and vibration/shocks environments, see Fig. 5. All the stress contributions were summed and complied with the ECSS safety margins for both non-operational and operational modes.

B. Stability and accuracy smart design

This mechanism is controlled by strain gauges position sensors which support the entire stability and accuracy of the mechanism in closed loop, see Fig. 6. The contributors to these performance budgets are long term temperature variation, ageing, and repeatability and thermal noise for short term. BSA does not only require high level of accuracy and stability but also high reliability position sensors for each axis [4].

Consequently, to improve the accuracy and the stability of the strain gauge measurements, several precautions were brought. A full bridge configuration was selected to optimize the sensitivity while limiting the thermal impact and non-linearity errors on its performance, see Fig. 7. The initial sensitivity is given in (1).

$$\frac{\Delta R}{R} = GF_x \times (\varepsilon_{strain}) \tag{1}$$

$$Vout = Excitation \times (\frac{R4}{R1+R4} - \frac{R3}{R2+R3}) \tag{2}$$

With $R_1 = R_3 = R_0 - \Delta R$; $R_2 = R_4 = R_0 + \Delta R$; and GF_x = Gauge constant factor

The full bridge configuration is theoretically insensitive to temperature effect due to the well symmetric bridge. From the previous formulae, we have introduced a thermal coefficient with an apparent strain (3).

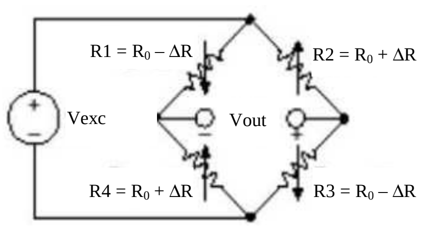
$$\frac{\Delta R}{R} = GF_x \times (\varepsilon_{strain} + \varepsilon_{thermal}) \tag{3}$$

If four strain gauges are applied to the specimen and connected into a full bridge, the thermal component in the total strain has the same sign for all strain gauges; since they are all subjected to the same change in temperature. Based on (2) and (3), we establish the expression (4):

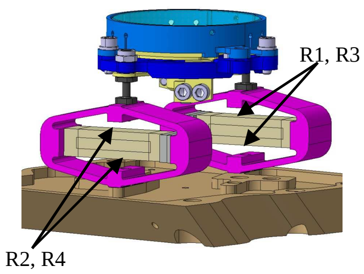
$$Vout = Excitation \times \frac{SG}{4} \times [(\varepsilon_{strain\_push} + \varepsilon_{thermal})_{\_1} - (\varepsilon_{strain\_pull} + \varepsilon_{thermal})_{\_2}$$

$$+ (\varepsilon_{strain\_push} + \varepsilon_{thermal})_{\_3} - (\varepsilon_{strain\_pull} + \varepsilon_{thermal})_{\_4}]$$

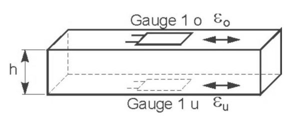
$$Vout = Excitation \times \frac{SG}{4} \times 4\varepsilon_{strain} \tag{4}$$



Standard full bridge configuration

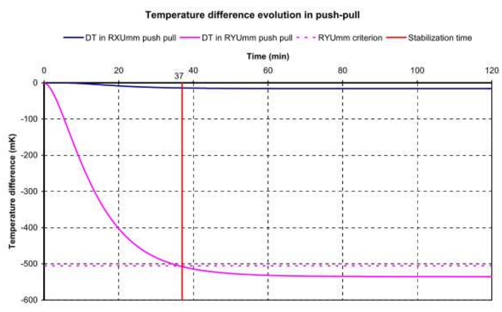


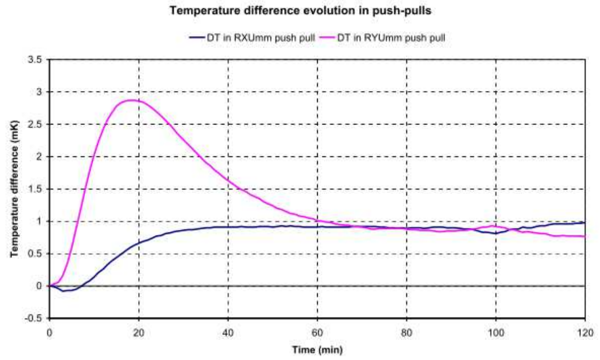
Full bridge applied on push pull



Mounting configuration on one ceramic

Fig. 7. Selected Full bridge configuration and its application on the push pull piezomechanism





Electronic start thermal effect	*Temperature variation under parasite flux loading*

Fig. 8. Transient thermal analyses results in push pull RX and RY

This theory is valid as long as no thermal gradient appears between the bridge components. The degree of the compensation depends on the uniformity of the temperature at the strain gauge level. Balancing the thermal conductive paths at the bracket level is mandatory.
So, the design was optimized for this purpose, particularly choosing aluminum base plate for the mechanism. The temperature gradient in each push pull axis was studied according to each operational thermal perturbation contributor. Fig. 8. gives the result of thermal transient analysis in RY and RX push pull according to electronic start and parasite laser flux loading (corresponding to the non-reflected residual laser flux, i.e. transmitted through the mirror into the mechanism), see Fig. 8. Results are compliant with stability requirements. The thermal gradient in push pull is less than 3mK submitted to parasite laser flux perturbation.
Moreover, in order to minimize the bridges sensitivity to external drifts (thermal effect, thermocouple effect …) the bridge was balanced as much as possible (i.e. to null the residual offset). An adequate pairing of the ceramics + strain gauge couple has been performed and allowed to reduce the initial offset by 99%.
Additional actions were taken to further improve bridge stability: Reduction of the power dissipation, improvement of the strain gauges alignment on the ceramic, balance the lead wires.

C. Beam Steering Electronic

The BSA electronics is split in three flex-rigid PCBs:

- The Interconnection Board (IB) located inside the BSMFE behind and beneath the TTM mechanism,
- The Front End Board (FEB) located inside the BSMFE all around the BSM mechanics
- The Main Electronic Board (MEB) located inside the BSME connected by 3m long cables to the PLH.

BSFE electronics: The Front End Board (FEB) provides the most critical functions of the BSA:

- The strain gauges bridges voltage conditioning
- The strain gauges bridges offset compensation
- The strain gauges signal amplification, which is full differential in input and output with a gain close to 2500

Pharao proximity electronics where thermally controlled within 30mK tolerance, while the BSA proximity electronics are submitted to PLH thermal conditions with some temperature variations up to 4K on long term. Nevertheless, BSA stability performances are better because of electronics improvement and TTM optimized architecture. The PCB outlines and its routing are also particularly complex in order to be compatible with the specified mechanical and electrical interface.
Others particularities or difficulties associated to the FEB electronics are the need of interchangeability and the need of cleanliness, combined with the necessity to be immune to the close high current laser pulses of more than 100A which exist beside the BSMFE.

BSME electronics: The Main Electronic Board (MEB) provides BSA other specified functions which can be put far away from the mechanism:
The first part is the power supply of all the BSA circuits by a single fully shielded dc-dc converter
The second one are the digital functions associated to the management by a FPGA in order to:

- Interface the ATLid Control and Data Management (ACDM) unit
- Configure the BSA operating modes
- Acquire the data of a single multi-channel ADC
- Drive two pairs of DACs for position setting and offset compensation,
- Manage the strain gauge offset compensation process (king of self-calibration mode)
- Increase the command and control resolution by a factor of four by addition of a simple data processing

The third one are the analog functions associated to the mechanism command and control:

- High and low voltage secondary regulations
- High voltage power sparing amplifiers for the command of the piezoelectric actuators
- Damped sinusoid generation for the hysteresis compensation of these actuators during the strain gauge offset compensation process
- Acquisition and reuse inside the MEB of the FEB voltage reference for the mechanism stability optimization
- Acquisition and processing of the FEB amplified strain gauge signals for measurement or comparison with their setting point depending on the operating mode (close or open loop)
- Formatting of the digitalized signals

The outlines of this PCB are far much classical and spacious than the others two. It is simply fold inside the BSME case.

IV. QUALIFICATION, CLEANLINESS AND SYSTEM PERFORMANCE LEVEL

Main performance characteristics of BSA can be separated in 3 categories, cleanliness level, compliance with respect to the harsh environmental conditions and the system performance level.
The cleanliness level was at the center of each activity during the entire BSA project at Sodern and Cedrat Technologies, giving excellent results and compliance with the severe cleanliness specification.
A large qualification tests campaign was performed on BSA product followed by acceptance tests on two flight models. The results validate that BSA is compliant to both environmental and performance requirements. Moreover, the piezoelectric components were first validated through a dedicated LAT sequence, defined during BSA project and being now a reference for the space acceptance of such components.

A. Piezoelectric components LAT

As The Piezoelectric components (or Multi-Layer actuators – MLA) are procured in advance and are standard components, the chosen philosophy is to realize on a part of the batch a Lot Acceptance Test (LAT) to accept the lot before MLA integration on the flight models. The LAT tests validate piezoelectric components procurement of BSM. The BSA LAT sequence is mostly in line with the ECSS draft generic and detailed specification for space piezoelectric components.
As some tests cannot be conducted with piezoelectric components alone, some integration sequences are necessary. Some samples are tested alone and some others were tested in APA shape, integrated in their titanium shell.

Tab. 4. LAT sequence description

Level	Test	Description	Sample Format
level 3	Initial DPA	Destructive Part Analysis to check soldering and gluing quality and have a close look on the internal structure of the piezo stacks on unsolicited MLA	MLA
	Electrical measurement	MLA capacitance, insulation resistance and strain gauge resistance measurement	
	Admittance test	Resonance measurement on MLA not integrated	
	Size control	MLA length verification	
	Stroke test	Measurement of stroke range	
level 2	Thermal cycling	MLA are tested in preloaded configuration. Main APA performances are checked before and after thermal cycling tests	APA
	Life time	MLA are tested in preloaded configuration. Main APA performances are checked before and after Life Time tests	
	Final DPA	The aim is to check soldering and gluing quality and have a close look on the internal structure of the piezo stacks on MLA submitted to thermal cycling and Life Time tests	MLA
level 1	Voltage proof	MLA is submitted to voltage proof test (195V). Main MLA performances are checked before and after voltage proof tests	MLA
	Compressive stress	MLA is submitted to compressive yield load, corresponding to 50MPa stress inside MLA. Main MLA performances are checked before and after compressive yield tests	
	Humidity testing	MLA are powered with 150 V and are submitted to different level of humidity for 2000 hours- 40%, 60% and 85% of relavite humidity. Leakage current is recorded during all the tests and shall remain inferior to 1mA	

All the tests described in Tab. 4. were performed, using all the 25 samples, and the tests results demonstrated the compliance to all criteria. So, the acceptance of MLA batch used for EQM and both flight models was successful after LAT achievement. It is worth noting that this is the first time the LAT sequence has been achieved with piezoelectric ceramics equipped with strain gauges.

B. Cleanliness management and results

LIDAR instruments in general involve high fluence; consequently, to ensure safe operation of the instrument a very careful monitoring of the cleanliness is required. Cleanliness is a generic issue for optical space instrumentation (particulate and molecular contamination requirements) but in the case of active instrumentation trace contaminants, especially as it concerns silicones and other compounds which are not easily removed by oxygen cleaning, cleanliness topic becomes a vital issue [5].

On ATLID project the severe cleanliness specification requires to take into account this matter at each step of the project, starting from the design, naturally during integration and tests, up to the storage. To respect the cleanliness requirement the following parameters were filled by both Sodern and Cedrat Technologies:

- The design respects strict rules in order to obtain the least contamination and to have cleanable equipment.
- A cleanliness and contamination control plan is established to guarantee the cleanliness of the BSA at the delivery
- Facilities of integration and tests are compliant with the defined cleanliness and contamination control plan
- Facilities quality being not a sufficient guarantee, the main contributor of cleanliness is the way of working and the know-how of operators and project team.

Concerning the design optimization, the following design rules have been applied on each part of BSMFE:

- Surfaces accessible for visual inspection / cleaning,
- No blind cavities/holes, low surface roughness,
- Use of low outgassing materials including glues (for strain gauges bonding and wires securing),
- And the electrical connections using an IB board as support to simplify the cleaning of the electrical connection.

Operationally, the BSA was submitted to a severe cleanliness and contamination control plan during all activities of integration and tests. Two cleanliness breadboards were used, at mirror assembly level and at TTM level, representative of APA assembly and electrical connection. The cleanliness breadboards allowed validating design choices with respect to cleanliness requirements.

The cleanliness activities also consisted in repeating interventions with: Visual inspection and cleaning, thermal vacuum chamber blank test and bake out, particular and molecular contamination control, clean room and tools cleaning. Cleanliness tasks were taken into account at each step of the project, giving excellent results with a molecular contamination measurement at $2\ 10^{-8}$g/cm² for FM2 and a successful particular management.

C. System performance test results

The BSA tests campaign, including qualification and acceptance tests, gave excellent performance results, much better than required for some of them.

BSA provides a deviation range of +/-3mrad, optical angle, on each axis, with a typical power consumption of 3.6W taken on a standard 28V power bus. The mechanism response time is less than 100ms for small displacement up to 40µrad, and less than 300ms for larger displacement. The angular resolution is better than 0.4µrad, optical angle. It ensures stability performances of very high quality with long term stability inferior to 100µrad, including repeatability inferior to 30µrad.

Stability performances in different bandwidth and thermal stability are given hereafter:

- Pointing signal power on [0,05mHz;1mHz] bandwidth < 7,3µrad²
- Pointing signal power on [1mHz;10Hz] bandwidth < 0,1µrad²
- Pointing signal power on [10Hz;infinite] bandwidth < 6,1µrad²
- RX thermal stability < 3.2µrad/K
- RY thermal stability < 4.3µrad/K

The measured gap between set point and realized angle also gave excellent results,

- For set point angle > 33.5 µrad Scale Ratio is comprise in the range value of 1 +/-2,5%
  Where Scale Ratio = Realised angle / set point angle
- For set point angle > 33.5 µrad Relative Accuracy is better than 0.98µrad
  Where Relative Accuracy = Realised angle – set point angle

The non-spherical Wave Front Error generated by the BSA mirror is also very good with a value less than 4nm RMS on 7,8mm beam diameter

In conclusion, main system performances are compliant with the requirements, and some like the stability values are even far better than specified.

Tab. 5. BSA worst case environments levels

Environment type	Environment description	BSMFE – PLH environment level	BSME – ATLID electronic panel environment level
Mechanical	Quasi Static	26g	70g max
	Random vibration	15,5g RMS	8,9g RMS max
	Shock	Half sine impulse 75g – 0,27ms – all axes	Half sine impulse 115g – 0,4ms in plane axes
Thermal	Solar illumination	~2,5W towards BSMFE	N.A.
	Non-operational Thermal cycle	[-30°C;60°C]	[-40°C;60°C]
	Operational temperature range	[24°C;40°C]	[-20°C;60°C]
	Cold start	-20°C	-40°C
EMC	Transient Magnetic Field	20µT during 220µs	-
	AC Magnetic Field	120dBpT on [50Hz; 50kHz]	-
	DC Magnetic Field	3mT	-

D. Environmental test results

A large qualification tests campaign was performed on BSA product The BSA was designed and tested according to mechanical, thermal and EMC critical environments. Tab. 5. gives worst case level of each environment requirements with respect to BSA components: BSME and BSMFE.

Both BSMFE and BSME were submitted successfully to shock, vibration, EMC and thermal cycle tests. Results of test campaign show that BSA is compliant to all these requirements without any performance degradation.

V. CONCLUSION

BSA is a high end technology product providing a deviation range of +/-3mrad, optical angle, on each axis. It ensures stability performances of very high quality with long term stability inferior to 100µrad, including repeatability inferior to 35µrad. Both BSMFE and BSME were submitted successfully to shock, vibration, EMC and thermal cycle tests. And cleanliness tasks were taken into account at each step of the project, giving excellent results with molecular contamination measurement at 2 10^{-8}g/cm² for FM2 and a successful particular management.

Both BSA flight models are now delivered, they were supplied during 2015. The BSMFE are currently being integrated into the PLH.

VI. REFERENCES

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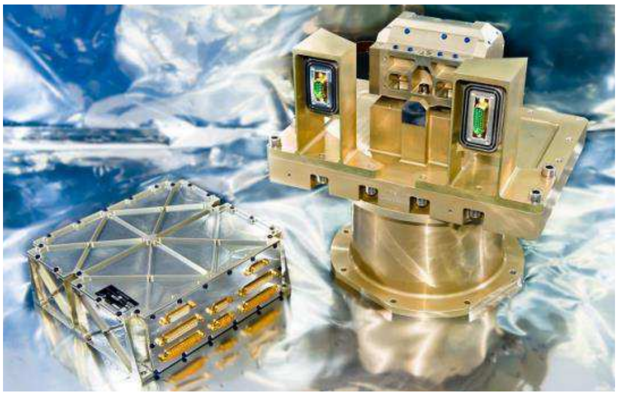

Fig. 9. BSA overview