From PYSCHE PAM30 to Large Scale Free-Space Optical Communication

Gérald Aigouy[*], Etienne Betch [*], Augustin Bedek[*], Nicolas Bourgeot[*], Anthony Baillus[*], Hugo Grardel [*], Pierre Personnat[*], Jean-Marc Nwesaty[*], Xavier De Lepine[*], Thomas Maillard[*] and Frank Claeyssen[*]

Abstract

New space giant constellations based on Free-Space Optical Communication are a new challenge from many perspectives. Considering the mandatory cost efficiency, with repeatability of performance, and reliability with no defect at customer integration, this requires an upheaval in space production and acceptance test methods when the quantities are beyond several thousands of units. Starting from the former PYSCHE PAM30 flight project heritage for Deep Space Optical Communication, CEDRAT TECHNOLOGIES (CTEC) presents the new design and test results of the P-FSM150S Fine Steering Mirror (FSM) Engineering Models developed under the ARTES project TELCO-B for future Free-Space Optical Communication constellations. The specific cost-efficient hardware design is presented, dedicated to very large quantities to be manufactured together with the performance test results over a preliminary batch of Engineering Model's production. The environmental test campaign for space qualification was passed and is presented, which includes launch vibration and shock tests, thermal vacuum tests, and high-frequency accelerated lifetime fatigue tests.

Introduction

The new P-FSM150S fine pointing mirror mechanism is the result of former CTEC space heritage in the field of mirror tilting piezo mechanisms and SiC substrate mirror design. The TELCO-B project was the opportunity to re-define the PSYCHE PAM30 design to future new space applications that require very high cost efficiency and very large quantities for giant constellation programs. A strong effort was applied to the design not only for achieving performance requirements, but also in the concept simplification for fast and reliable assembly processes, as well as qualification of a mirror supply chain with two different substrate technologies, i.e., SiC and SiSiC.

Figure 1. PSYCHE PAM30 (Left) and P-FSM150S (Right)

[*] CEDRAT TECHNOLOGIES, Meylan, France; gerald.aigouy@cedrat-tec.com

SiC Mirror Design and Manufacturing

One of the main design constraints of an embedded optics mechanism is to keep the mirror surface deformation to a minimum to limit the induced optical wave front error below the requirements. In this case, a maximum of 40-nm rms RWE at 0° mirror surface flatness is the target (corresponding to a 20-nm rms optical surface flatness). To ensure that the specification would be reached, CTEC used tools developed for previous space optical mechanisms projects. Specifically including evaluation of induced surface deformation caused by mechanical biases, thermal deformation, as well as optimization of mirror shape and dimensions.

The design optimization process included not only the mirror, but also an equally important part, the mirror support. The mirror support is the part providing the mechanical link between the actuators and the mirror. A specific mirror with flexible support design was performed. The support design aimed at reducing the operational optical surface deformation, while keeping the assembly stiff enough to withstand (mechanical stress considerations) environmental conditions (temperature, vibration) and mechanisms forces.

The mirror deformation induced by the mechanism was targeted to be under 20-nm rms RWE (at 0° angle of incidence), the mirror manufacturer was requested to deliver a coated mirror also under 20-nm rms RWE.

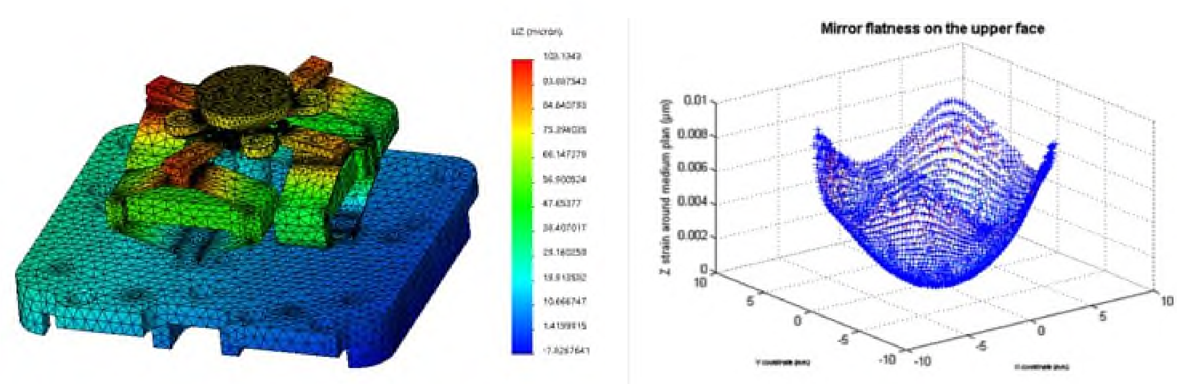

Figure 2. P-FSM150S WFE Simulation For a +60°C Temperature

Two mirror types were manufactured to be integrated onto the engineering models, i.e., SiC substrate with silver coating and SiSiC substrate with gold coating, from different suppliers and optical verifications were performed. Figure 3 shows the two mirror types and the RWE (reflected wave front error) measurement Zygo interferometer at CTEC laboratory.

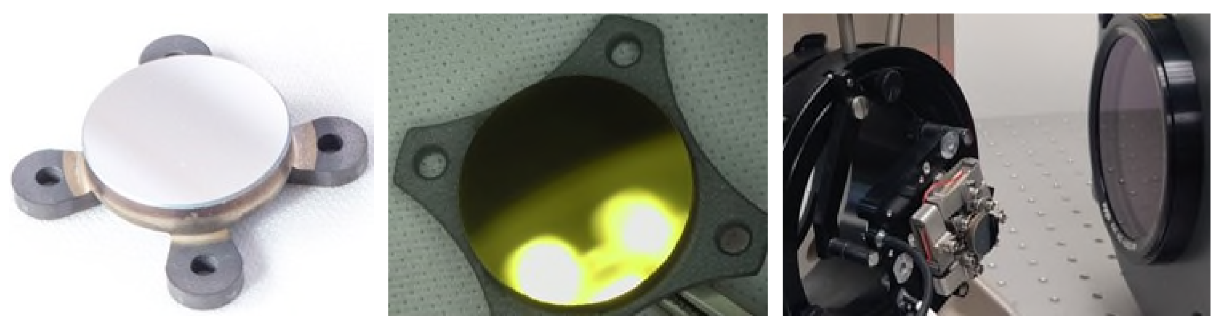

Figure 3. SiC Mirror (Left) SiSiC Mirrors (Middle) and RWE Test After Integration (Right)

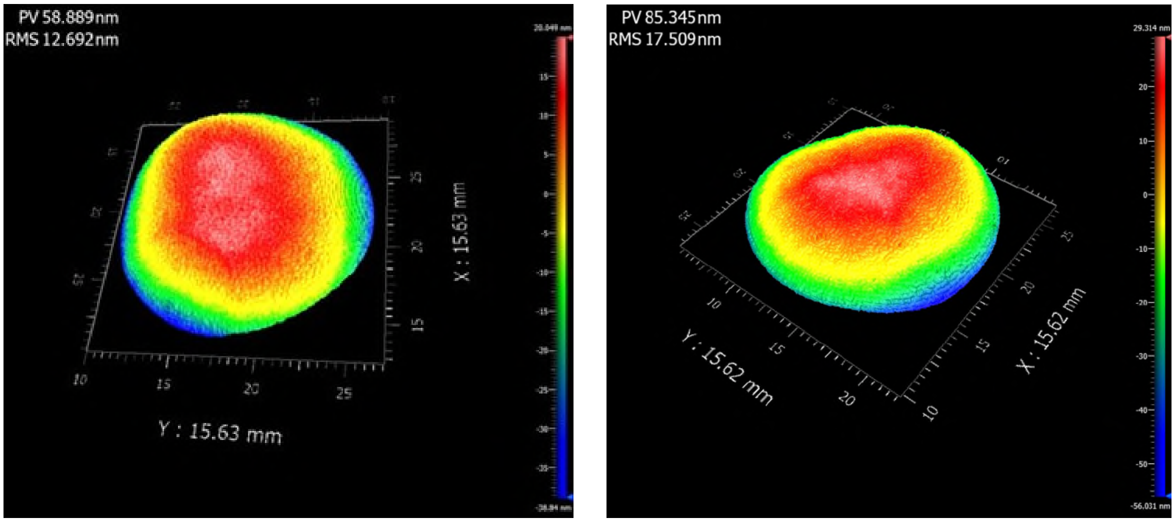

Figure 4. Mirrors RWE at 0° Test After Integration, Type1 (left) and Type2 (right)

The optical verification indicates that both mirror types are compliant with important margins in both free state and after integration (<40-nm rms was targeted).

Table 1. Mirror Optical Control Results (Specification: RWE < 40-nm rms at 45°)

	Type 1	**Type 2**
Mirror RWE at 0° before integration (nm rms)	10	14.2
Mirror RWE at 0° after integration (nm rms)	12.7	17.5

P-FSM150S Mechanism Design and Manufacturing

The main requirements for this mechanism were to ensure an angular stroke of ±7 mrad throughout the full operational temperature range of the mission (-10/+60°C) and a mirror surface flatness under 40-nm rms RWE (Reflected Wavefront Error) while remaining inside a very limited volume (especially less than 30-mm height) and surviving launch vibration.

Four P-FSM150S Engineering Qualification Models (EQM) have been assembled (EQM1 to EQM4). The integration process and assembly tooling were constantly improved as the operations were progressing. Even for prototypes one of the focus areas was to keep the time required to assemble the model as low as possible in anticipation with the plan to have this mechanism compatible with serial production.

Hence the number of steps, especially highly time-consuming ones like gluing, were reduced to the minimum required without impacting required quality. With that in mind, each integration step duration was monitored and the overall process time was analyzed in order to identify critical steps and room for process optimization.

P-FSM150S Piezo Mechanism Design

The piezo actuators are cabled in two push-pull configurations (one per axis) to allow a direct mirror rotation control, inheriting from PHARAO and ATLID tip-tilt mechanisms [3,4]. The P-FSM150S itself is composed of the following parts:

- A bracket baseplate (in aluminum): The APA® (Amplified Piezo Actuators) are fixed on it with screws.

- Four APA® (in stainless steel): They provide the required displacement and are fixed to the baseplate and to the mirror support. The APA® are equipped with SG sensors by a gluing process
- A flexible mirror support (in stainless steel) which holds the mirror. It includes flexible parts in order to ensure the limitation of the mirror deformation after integration (insulate the mirror surface from the mechanism bias)
- A flexure bearing (in stainless steel) soldered onto the central cylinder that stiffens the assembly.
- A Silicon Carbide (SiC or SiSiC) substrate-based mirror with either silver or gold coating.

The mechanism is composed of four APA®, deriving from CTEC standard APA120S. The existing CTEC actuators were either slightly too short in stroke or not stiff enough to ensure the mechanism survival during launch. Therefore, APA150S have been specifically designed for the application needs. A total of 25 APA® were assembled and tested; the measurements are detailed in Table 2.

Table 2. P-FSM150S Custom APA Measurement Results

	Full stroke (-20/+150V)	**1st coupled resonant frequency**
Units	µm	Hz
Average (measured)	187.3	4892.0
Standard deviation (measured)	0.9	22.9
Design value (worst case)	152.8	4783
Difference measurement/design value	+23%	+2%

<u>P-FSM150S Strain Gauge Position Sensors (SG)</u>
In order to be able to monitor the mirror angle, an indirect solution using strain gage placed on each piezo actuator is selected based space heritage from other projects, especially ATLID [4] on this matter, which enabled an important development on the SG assembly process.

The project used constantan, 350-ohm SG. There is one SG per piezo stack, mounted in one full Wheatstone bridge per rotation axis to maximize the sensitivity while minimizing thermal drift. All SG wires and PCB traces are the same length to limit offset drift.

<u>Expected Reliability from OPTRONICS Recurrent Manufacturing CTEC Heritage</u>
CTEC has a long heritage in the Optronic domain with the delivery of 3430 XY piezo stages based on similar push-pull piezo-mechanism and with fluctuating production rate from 200 to 500 per year (i.e., 20 to 50 per month).

Since 2005 this production has been delivered to several customers, with custom designs for each on interfaces, connectors, and optical components.

The production rate and test acceptance approach are based on this heritage to guarantee a zero defect at the customer level and 100% testing before delivery.

Over this historical quantity delivered, only one failure was observed and led to a customer service, which concluded the cause of failure to be a customer mistake at integration and not a hardware defect. The piezo stage was sent back to customer without modification.

Considering nonetheless this single event as a failure to be conservative, the following reliability analysis can be performed:

- Cumulated operational hours = 1.33 x10^7 at 20°C and average voltage @ 65 V
- Failures in Time (FIT) = 75 over 1 billion hours
- Reliability R= 0.992

P-FSM150S Test Results

Angle Stroke Test Results

As it was anticipated based on the good piezo actuator stroke performance (see Table 2), the P-FSM150S mirror tilt angle range is compliant with the requirements with notable operational margins. Hence the target stroke of ±7 mrad can even be reached (at ambient temperature) when supplied with a limited voltage range of 0/+130 V instead of -20/+150 V (23% less voltage).

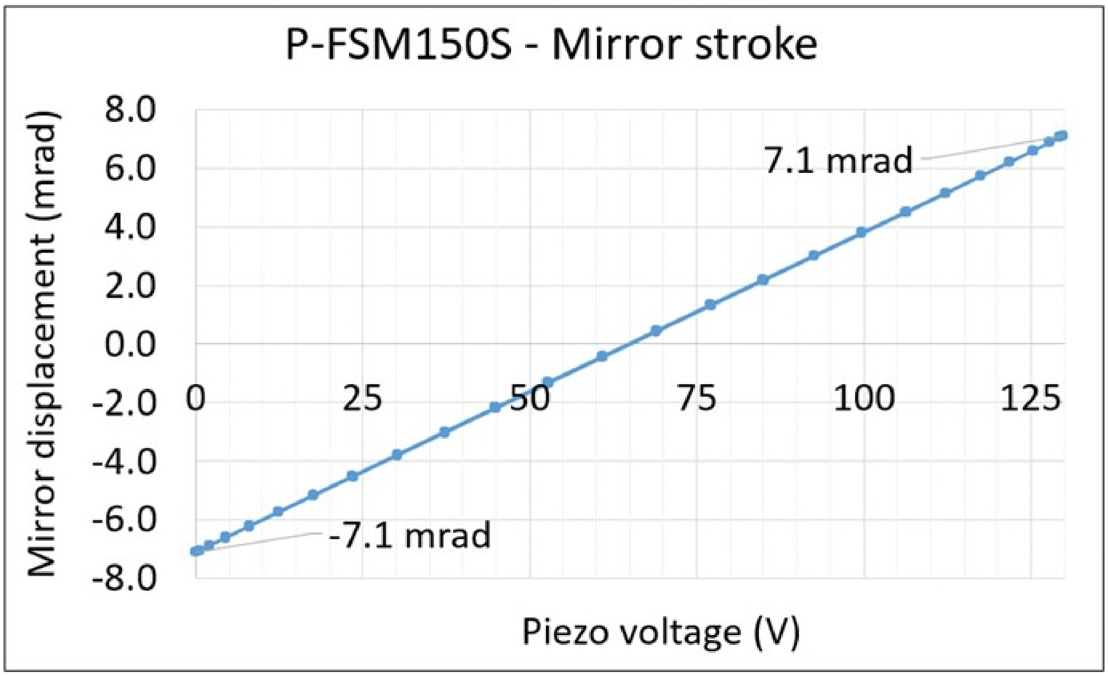

Figure 5. P-FSM150S Stroke Results with a 0/+130 V Supply

The actual full operational stroke could not be fully tested due to the limited range of the autocollimator instrument, but we can extrapolate that the P-FSM could reach a ±9.6-mrad stroke with a -20/+150 V supply, which should cover the slight stroke loss expected in cold operational temperature (around -5%) and the mirror integration offset compensation.

Modal frequencies test results

The mechanism stiffness and associated modal landscape is evaluated with an admittance sweep. With that method, only the piezo coupled modes are visible, hence the vertical pumping mode (cancelled from piezo point of view) is not visible.

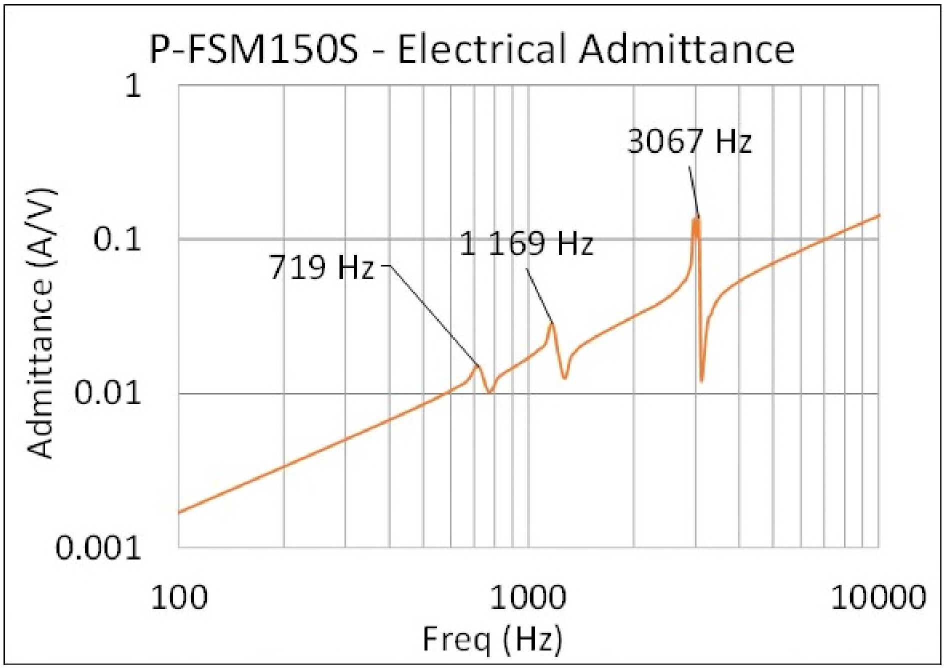

Figure 6. P-FSM150S EM1 X-axis Admittance Sweep

<u>Pointing accuracy test results</u>

The tests reveal a 0.1% cross coupling: ±10-µrad cross axis displacement with a ±7-mrad stroke which is a good result given the high amplification of the mechanism.

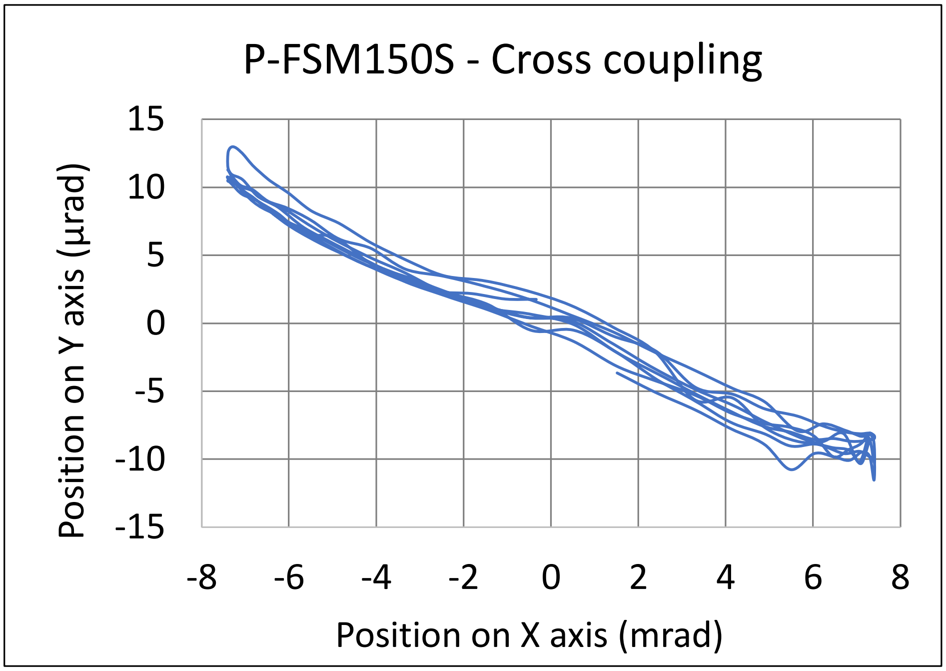

Figure 7. P-FSM150S Cross Coupling Measurement

With another test, it is demonstrated that the mechanism can generate ±1-µrad steps (0.01% mechanical resolution) using an external measurement for the mirror angle (autocollimator). The share of errors due to instruments measurement has still to be determined (especially for cross coupling) but measured resolution is already compliant with the ±1-µrad requirement.

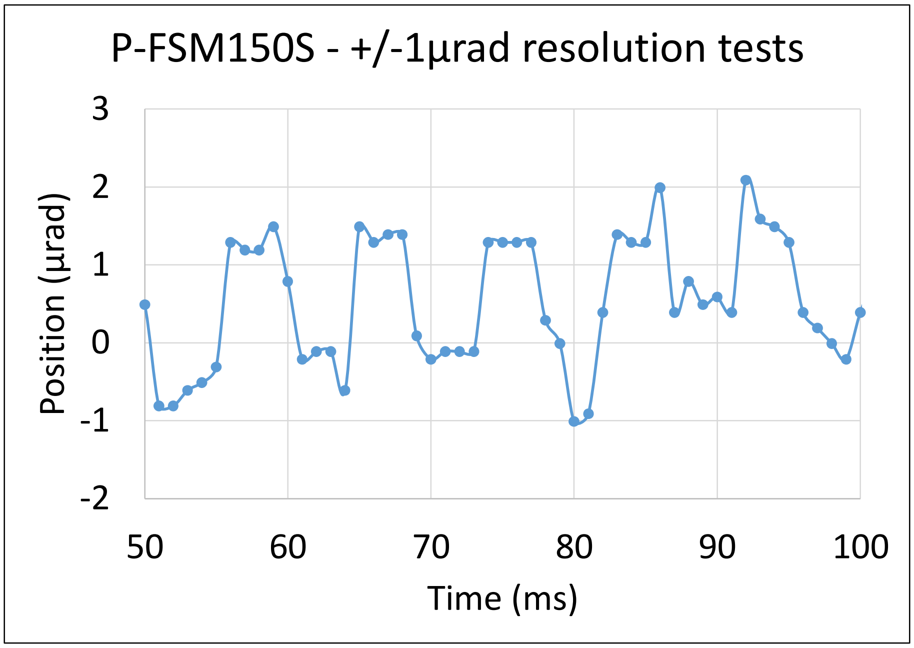

Figure 8. Mechanical Resolution Test

<u>Fatigue lifetime tests</u>

The EM1 is currently going through a lifetime test. The mechanism is actuated at full stroke (±7 mrad) in a diagonal direction (45° along X and Y axes) to excite both axes in fatigue. With a frequency of 100 Hz, 2.6e8 cycles are performed each month so the first billion cycles have been reached after the first four months of test. After that period, the test frequency was accelerated to 400 Hz, which has allowed to achieve at publication 4.7×10^9 cycles, with the test still ongoing. The lifetime test shall be continued up to failure and will be regularly interrupted to perform stroke and SG verification, to detect any deviation linked to lifetime evolution.

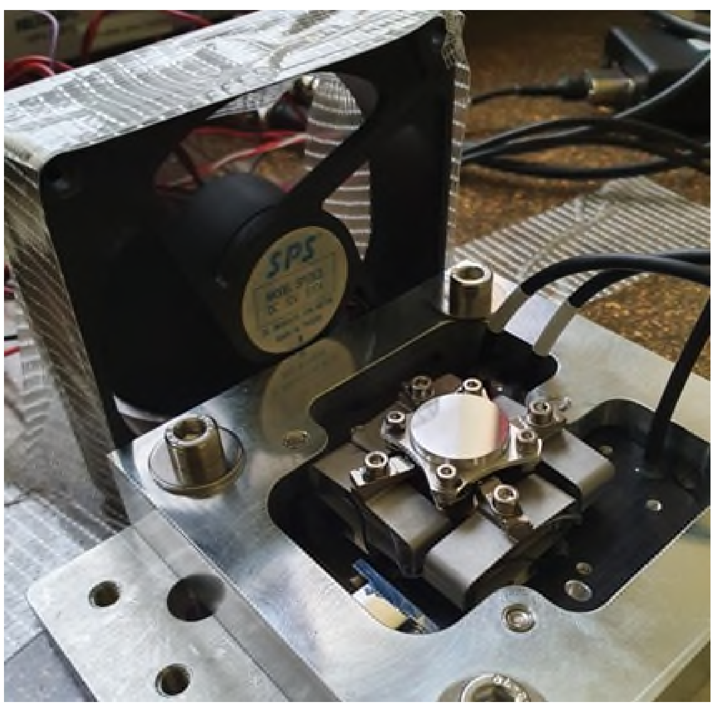

Figure 9. Lifetime Test Setup for P-FSM150S EM1

Vibration and shock tests

The P-FSM150S was tested in random vibration at 0.65-g²/Hz maximum level at its first structural resonance frequency at 720 Hz and with ISO8 clean condition packaging.

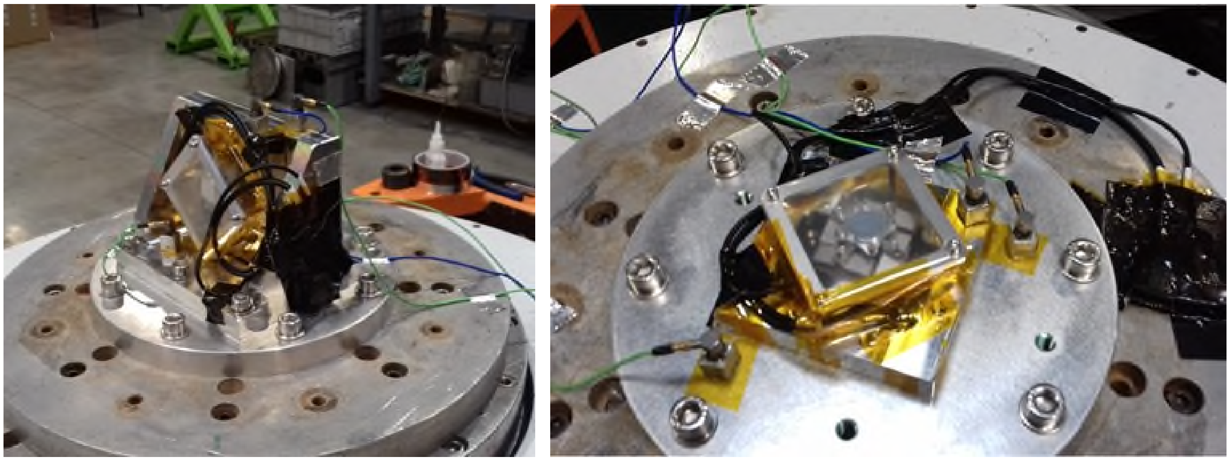

Figure 10. Random Vibration Test Setup in Clean ISO8 Condition

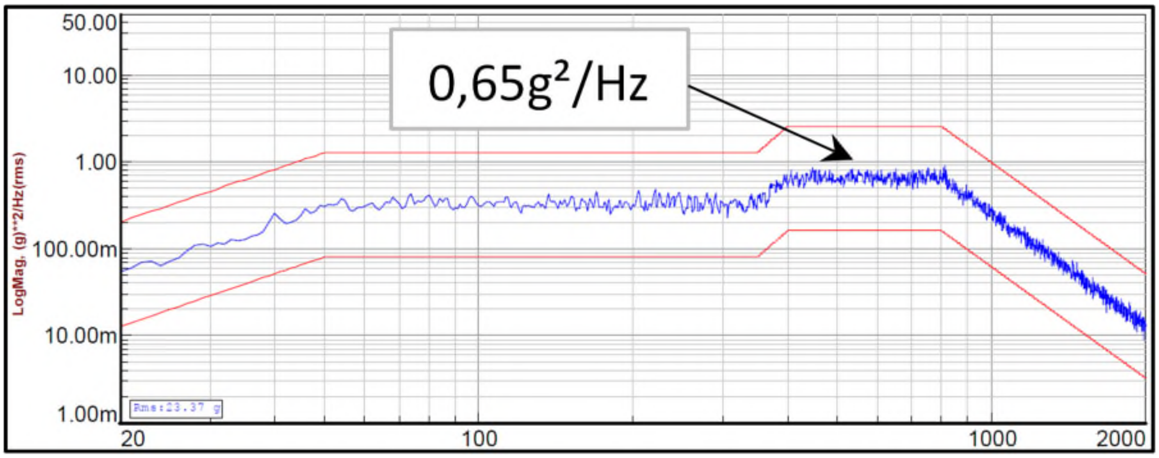

Figure 11. P-FSM150S 0.65-g²/Hz Random Vibration Test

The P-FSM150S was shock tested with a drop machine in order to test a 1000-g SRS shock input level at 800 Hz. In order to achieve the targeted test input all along the specified SRS frequency spectrum, the level was exceeded up to 1500 g at drop impact, as can be seen in shock the transient measurement at interface as shown in Figure 14.

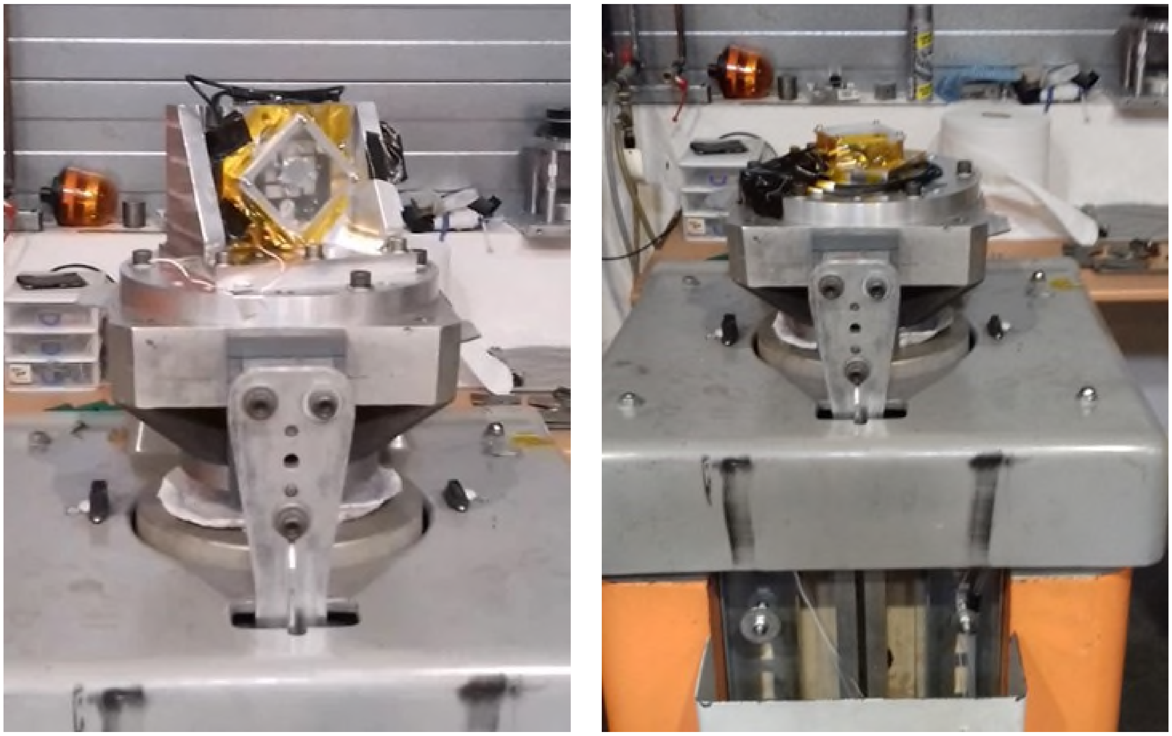

Figure 12. Shock Test Setup in Clean ISO8 Condition

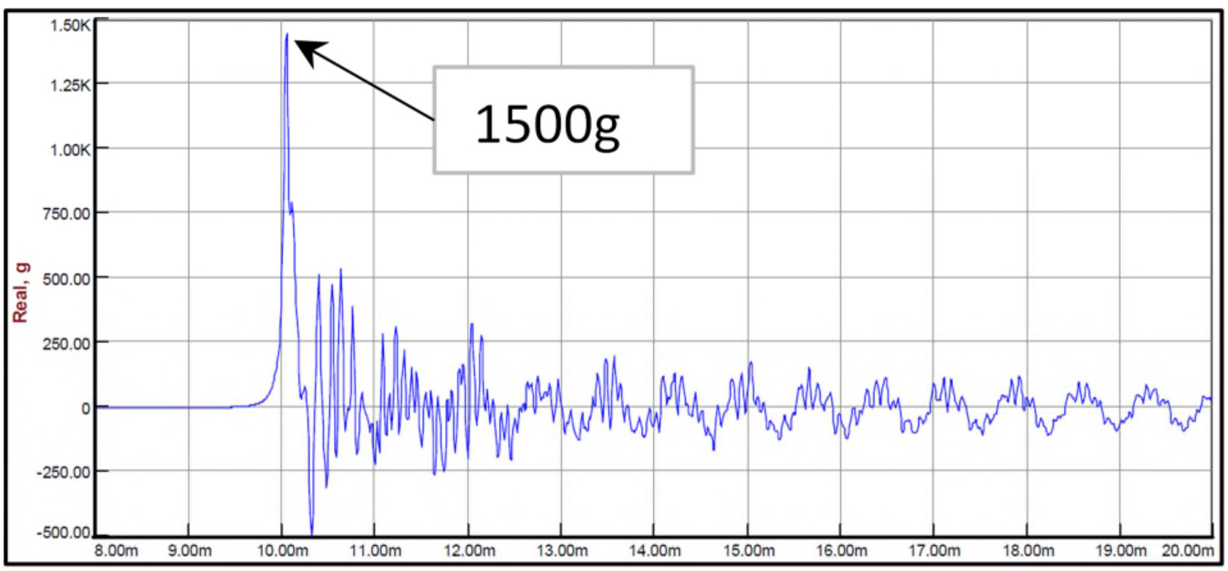

Figure 13. P-FSM150S 1500-g SRS Shock Test - Transient Measurement

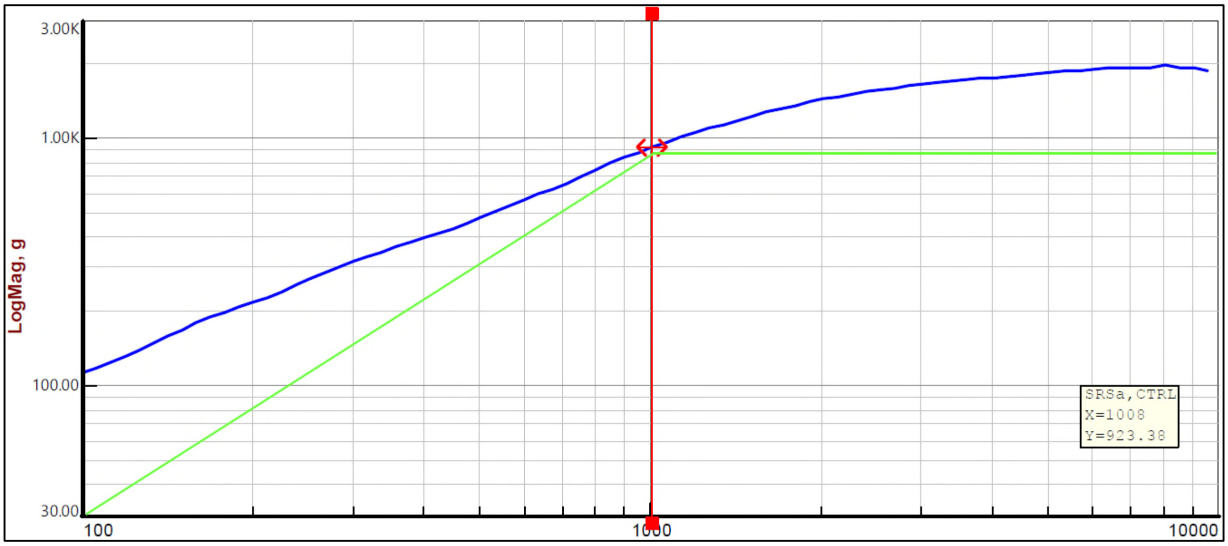

Figure 14. P-FSM150S 1500-g SRS Shock Test – SRS Analysis

Performance Summary Table

Table 3 summarizes the P-FSM150S performance as verified by test.

Table 3. P-FSM150S Design and Performance Summary Table

P-FSM150S	
Dimensions	65 mm x 60 mm; Height 30 mm
Mass	150 g
Stroke at [0V- 130V] voltage range	±7 mrad
Stroke at [-20V- 150V] voltage range	±9 mrad
Resolution with cots drive electronics (non space)	±1 µrad
Accuracy with cots drive electronics (non space)	±10 µrad
Embedded position sensors	Strain gauges
1st resonance frequency (Actuation)	720 Hz
Closed loop position control Frequency bandwidth	> 200 Hz for low speed fine pointing operation (*)
Mirror size	Ø17 mm with Ø15 mm clear aperture
Mirror substrate and coating (**)	SiC with Silver coating or SiSiC with Gold coating
Mirror mechanical interface onto support	Fastening (***)
Mirror RWE after integration on flexible support	< 20 nm rms @ 0° angle of incidence
Operational temperature	-10°C / +60°C
Random vibration level	0,65 g^2/Hz from 100 Hz to 800 Hz
SRS shock level	1000 g from 1000 Hz to 10000 Hz

(*) With basic proportional integral controller tuned for low frequencies fine pointing operation. Much higher frequency bandwidth is achievable with other tuning for fast steering operation.

(**) The mirror flexible support is compatible, with respect to WFE after integration, with other alternate metallic substrates, with same usable mirror mechanical drawing applicable

(***) Mirror gluing processes was avoided for fast and reliable assembly processes

Conclusion and Acknowledgments

The authors specifically thank CNES and ESA for the funding of TELCO-B project as well as THALES ALENIA SPACE for the close collaboration on requirements definition and performance evaluations.

References

1. G. Aigouy "P-FSM150S & M-FSM45 For Large Scale Free-Space Optical Communication", Proc. OPTRO 2022
2. A. Guignabert, Point Ahead Mechanism for Deep Space Optical Communication for PSYCHE mission, Proc. ICSO, February 2021
3. A. Guignabert, Point Ahead Mechanism for Deep Space Optical Communication – Development of a new Piezo-Optical Tip-tilt mechanism, Proc. 45th AMS, Houston, May 2020
4. R. Le Letty, Miniature Piezo Mechanisms for Optical and Space applications, ACTUATOR Conf, Messe Bremen (G), June 2004, pp 177-180
5. F. Claeyssen, Beam Steering Mirrors from space applications to optronic solutions, Proc. OPTRO Conf, Paris, Feb. 2018
6. F. Claeyssen, Large-stroke Fast Steering Mirror for space Free-Space Optical communication, OPTRO 2020, n°0062, 28-30 Jan 2020
7. A. Guignabert, E. Betsch, G. Aigouy, Large stroke Fast Steering Mirror, Proc. ICSO, February 2021
8. W. Coppoolse, Dual-axis single-mirror mechanism for beam steering and stabilization in optical inter satellite links, Proc ESMATS conf, 2003
9. Y. Long, Design of a Moving-magnet Electromagnetic Actuator for Fast Steering Mirror, J. of Magnetics, Vol. 19 (3), 2014
10. JC Barriere, Qualification of Euclid-near infrared Spectro-photometer cryomechanism, Proc. ESMATS 2017