International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

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International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127772R · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2690301

Thermal and dynamic qualification test results on PLATO optical mount groups based on lenses made of brittle materials (CaF2, S-FPL51)

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ABSTRACT

Thermal and dynamic qualification loads on spacecraft are usually very high and the design of space components requires to use strong material to withstand them. However optical payloads usually mount brittle materials for optics and lenses. Two of them are the crystal CaF2 and the OHARA glass S-FPL51. Allowable design values for this kind of materials are hard to define, also considering that the numerical values for strength are low and the safety factor to use for design of brittle materials are really high. These two optical glass/crystal shall be used for three of the six lenses mounted on each one of the 26 Telescope Optical Units (TOU) of PLATO (PLAnetary Transits and Oscillation of stars), an ESA satellite that will be launched in 2026 to discover exoplanets. These brittle lenses, together with the mounts on which they are bonded, have been tested on a breadboards campaign checking their resistance to cryogenic temperatures (down to -115 °C), random loads up to failure and their behavior under shock loads. The results presented in this article show an unexpected and very high performance of each lens and its mount considering both thermal and dynamical behavior.

Keywords: PLATO, glass, crystal, CaF2, S-FPL51, brittle materials, random, shock, cryogenic temperature

1. INTRODUCTION

PLATO (PLanetary Transits and Oscillations of stars) is the Cosmic Vision Program M3 mission organized by the European Space Agency (ESA) for launch in 2026. The main goal of the PLATO mission is to detect terrestrial exoplanets in the habitable zone of solar-type stars and to characterize their bulk properties.

The spacecraft will operate in the orbital Lagrangian L2 point at 1.5 million km from Earth, permitting the long-term observation of the Space.

The payload concept is based on a multi-Camera approach involving a set of 24 “Normal” Cameras (N-CAM) monitoring stars, plus 2 “Fast” Cameras (F-CAM) observing extremely bright stars for fine guidance. The 24 N-CAM are arranged in four sub-groups of six cameras, having exactly the same Field of View (FoV). The PLATO spacecraft model is shown in Figure 1 where the 26 Cameras are visible in the upper part.

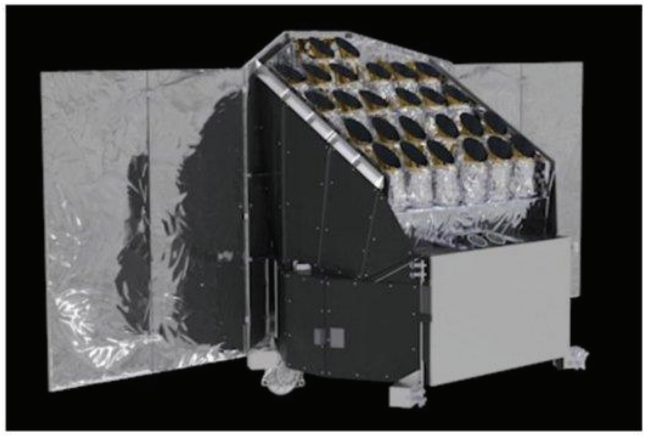


Figure 1. The PLATO spacecraft model: the payload concept is based on a multi-Camera approach. (Copyright: ESA/ATG medialab)

The TOU – Telescope Optical Unit – is a refractive optical system with one aspherical surface and five fully centred spherical lenses, as shown in Figure 2. A front window in quartz protects the inner lenses from the thermal and radiative environment; moreover, it hosts a filter coating that selects the operative optical bandwidth of the TOU. The design complexity of the telescope and the demanding requirements for its performance characterization have led the project team to develop particular approaches for manufacturing, integration and alignment of optical elements, and the overall test process.

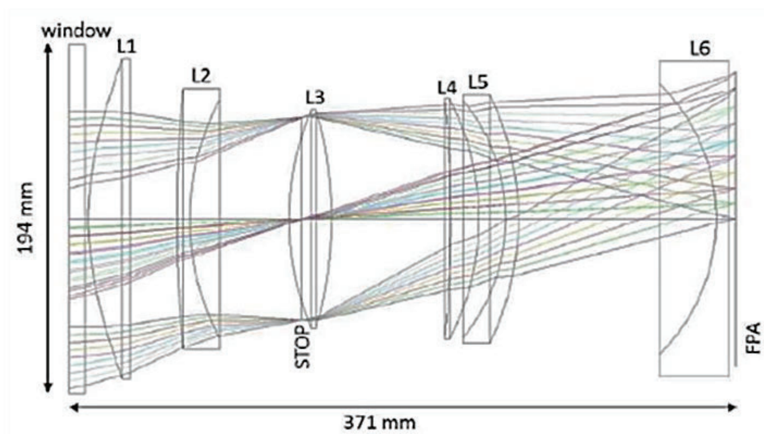


Figure 2. Optical scheme of PLATO Telescope Unit (TOU)

Figure 3 shows the full telescope, with detail of the opto-mechanical elements.

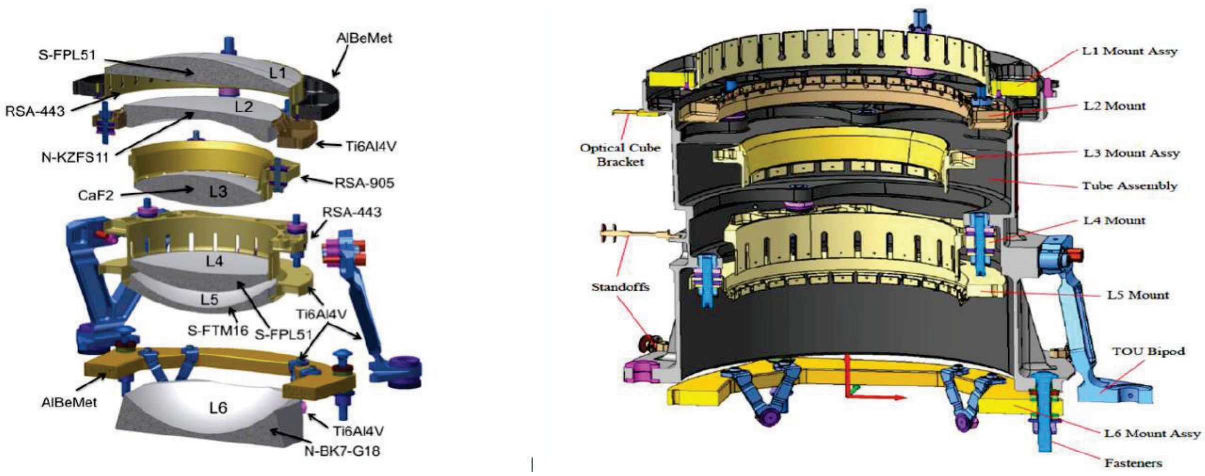


Figure 3. Left: an exploded view of a PLATO's TOU with a focus on the materials used for the glasses, their mounts, and for the interface components. Right: Details of the mechanical structure with subcomponents highlighted.

1.1 Opto-Mechanical Groups (OMGs) design load

Each lens, together with the metallic support where it is bonded, forms the six Opto-Mechanical Groups (OMGs) that are integrated in the telescope barrel, made in Aluminium - Beryllium alloy. Such OMGs are shown in Figure 4.

Figure 4. Optical-Mechanical groups (OMGs) of the Telescope

Considering that the telescope will operate in the orbital Lagrangian L2 point and that it will be oriented always toward the deep space, the operative thermal environment is very stringent. The operative temperature of the TOU is -80 °C, and it will be adjusted between -70 °C and -90 °C to better adjust the focus on the FPA. However, the OMGs shall withstand to the not-operative temperature, that reaches -115 °C, including also the qualification margins.

The Coefficient of Thermal Expansion (CTE) of each lens material matches exactly the CTE of the metallic alloy chosen for the mount. In this way the thermo-elastic load induced by the mount on the lens will be minimized. On the other hand, the lens is bonded to its mount by means of many epoxy adhesive pads. This structural adhesive, even if it is characterized by a strong strength to maintain the lens in position despite the dynamic load at launch, it has also a high CTE, that usually is ten times higher than the glass ones. The CTE mismatching between the lens material and the adhesive induces on the glasses a peak of strength that becomes a design limit for the OMG design.

The best way to proceed to limit the strength on the glass induced by this CTE mismatching is to reduce as much as possible the dimension of the adhesive pad. The limit of the pad area shall be determined by the dynamic load at launch to which the OMG is subjected. In particular, all OMGs have been designed to withstand a design limit load of 55 g.

This means that the total number of adhesive pads that sustains the lens – each pad has a diameter of 3,5 mm – has been determined in order to sustain a shear load equivalent to the mass of the lens multiplied for the 55 g of design limit load.

The bonding procedure has been setup foresees the use of a centering machine, in order to have the best control of the adhesive pad diameter and of the position of the lens with respect to its mount, in terms of centering, axial position and tilt. Figure 5 shows respectively the alignment and the bonding phases for the OMG5.

Figure 5. Alignment and bonding of Optical-Mechanical Groups (OMGs) under centering machine.

1.2 Issues in OMG Margin of Safety determination

The strong thermal load to be considered, the very small diameter of the bonding pads and in general the assumption used in a Finite Element Model (mesh size, bonding modeling, material properties definition at cryogenic temperature, etc) make the determination of the strength on the lens hard to be calculated with good accuracy. Moreover, the applicable ECSS defines strong safety factors to be used for brittle materials in the Margin of Safety calculation, and on the same time the allowable strength for glasses at cold temperature are hard to find.

The lens materials used on the TOU are listed here below, together with the mount material to which it is coupled.

Table 1. TOU OMG materials

OMG	Lens Material	Mount Material
1	S-FPL51	RSA-443
2	N-KZFS11	Ti6Al4V
3	CaF2	RSA-905
4	S-FPL51	RSA-443
5	S-FTM16	Ti6Al4V
6	N-BK7 G18	Ti6Al4V

In particular, two of the materials used on the TOU, the CaF2 of OMG-3 and the S-FPL51 used on OMG-1 and OMG-4, are characterized by a very low value of allowable strength, therefore, for these materials was very hard to choose a design confirmed by an analytical approach that includes all the safety factors defined by the space normative.

Another issue that cannot be solved with a simple analytical approach is the definition of the failure mode in a bonded junction. In general, three different failure modes can be observed on a bonded junction:

- A failure of the cohesion of the adhesive pad, that means that the adhesive is separated into two parts, one attached to the lens and the other one attached to the mount;
- A failure on the adhesion of the adhesive to the lens or to the mount;
- A failure of the lens or of the mount (usually very improbable being the allowable of the metallic alloy higher than the others).

Sometimes a combination of different failure modes can be observed on a dedicated test campaign. In addition, the failure load and the failure mode are strongly dependent from the bonding procedure and operator, therefore it is very hard to determine with a FEM model the system allowable.

1.3 BreadBoards (OMGs BB) Test Campaign

To solve this issue, a dedicated test campaign on OMGs BB have been setup to qualify the design of the six OMGs and to validate the procedures used for their bonding and alignment.

For each OMG, two identical BBs have been produced. To reduce cost, each lens was polished but uncoated, the L1 was a spherical lens, in place of the aspherical one adopted for the nominal design, and the L6 glass was in not rad-hard version. All the mounts were representative of the design and the coating, with particular attention to the bonding interface. With these assumptions all the bonded interfaces between each lens and its mount were flight-like.

All the OMGs BB have been subjected to thermal cycles at cryogenic temperature before doing the vibration test. After thermal cycles the first set of BBs (BB1) have been subjected to random vibration in order to validate the bonding design against the 55 g design limit load, while the second set of BBs (BB2) have been used to check the bonding design when subjected to shock environment.

Next chapters present the results obtained in particular for the OMG-3 and OMG-4.

The OMG-3 (Figure 6) has a lens made by CaF2 and bonded on a RSA-905 mount. The STOP, always made by RSA-905, is mounted on the mount through six countersunk screws. A section view of the OMG-3 is shown below.

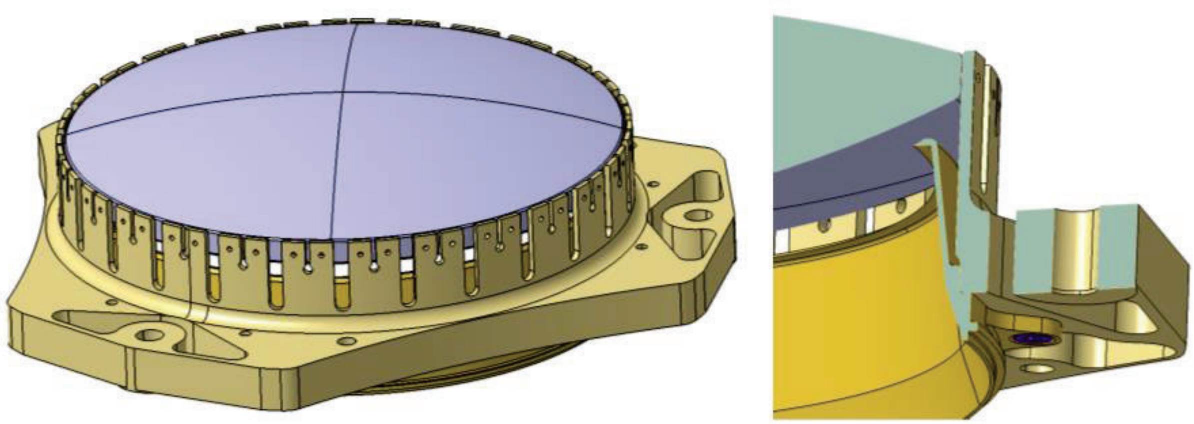


Figure 6. OMG-3 design.

The OMG-4 instead is composed by a mount in RSA-443 and a lens bonded on it in S-FPL51 (Figure 7).

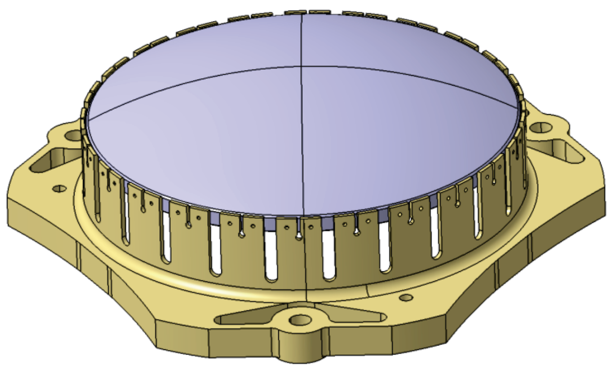


Figure 7. OMG-4 design.

2. OMG THERMA VACUUM CYCLING (TVC)

2.1 TVC Test setup

The TVC test has been performed in the CRV thermal vacuum chamber facility at Leonardo premises in Campi Bisenzio (Figure 8),

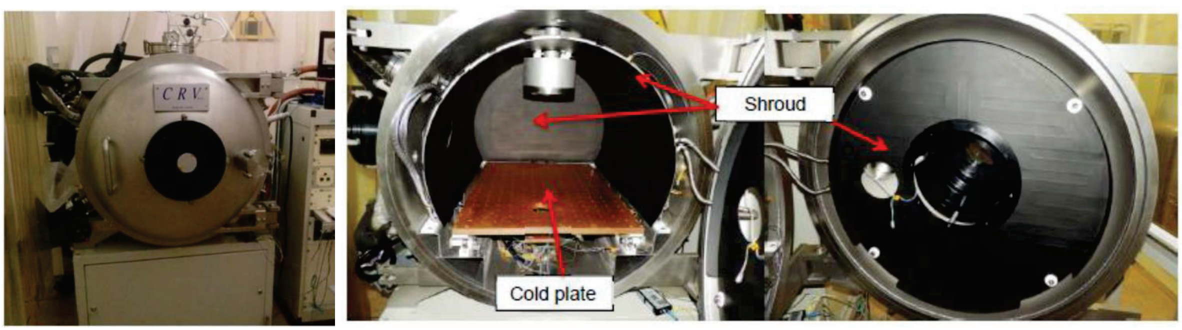


Figure 8. CRV front view (left) and internal view (right).

All the OMG BB1 and BB2 has been subjected to 8 cycles between -115 °C and 45 °C, i.e. the qualification not-operative temperatures. The maximum temperature has been covered also during the bake out cycle done on each OMG after adhesive curing at 65 °C.

As shown in Figure 9 (left side), two thermistors were mounted directly on the glasses, on the center of the lens and near the edge, and one thermistor was mounted on the OMG mount. The temperature was monitored and controlled in order to avoid overstressing the glasses and possible failure for thermal shocks. For this reason, the OMGs were simply leaning on the cold plate without any preload that could increase the conductivity, limiting the temperature gradient on the lenses, CaF_2 of OMG-3 in particular, to 0.2 °C/min maximum. The duration of each complete thermal test has been about 11 days.

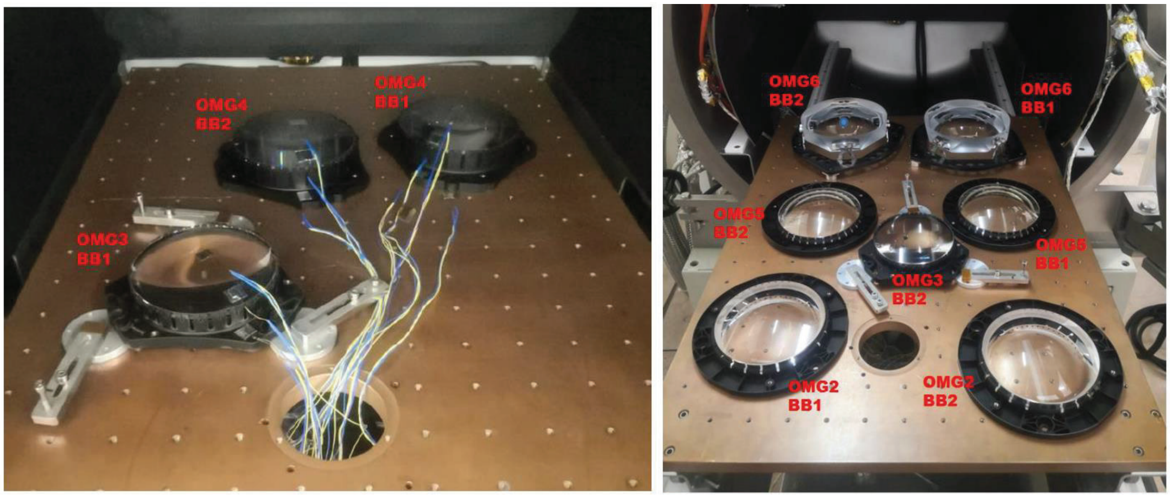


Figure 9. OMG TVC test setup.

OMG4 BBs have been tested with the same TVC, whilst OMG3 BBs have been tested with two different TVCs: OMG3 BB1 has been cycled together with the OMGs-4 (Figure 9 – left side) while OMG-3 BB2 has been cycled together with OMGs-6 OMGs-5 and OMGs-2 (Figure 9 – right side).

2.2 TVC temperature profiles

The different boundary condition given by the position inside the chamber and the different interface on the cold plate of the OMGs lead some variation on the minimum temperature reached by each OMG. In particular, the minimum temperature measured by OMG-4 thermistors on the lens is -115.3 °C, whilst the temperature on the OMG-3 was higher than the one measured on the other OMGs. After some adjustments and optimizations of the thermal cycle, the minimum temperature reached by the OMG3 was -105.2 °C on the BB1 and -109.1 °C on the BB2. For this reason, only for OMG-3 BB2, an additional thermal cycle has been done to verify the bonding design against the qualification minimum temperature of -115 °C.

The following figures show the plots of the temperatures vs time measured by means the reference thermistors mounted on the shroud, on the cold plate and on the OMGs.

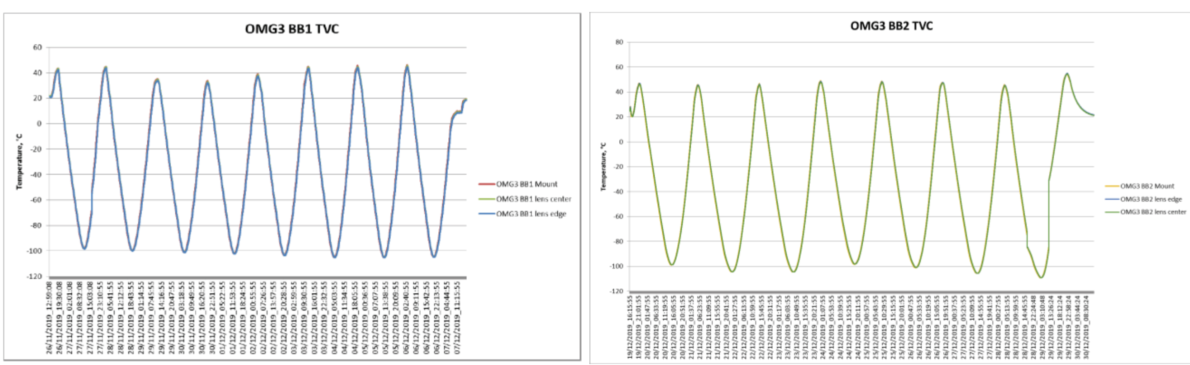


Figure 10. OMG-3 BB1 and BB2 TVC temperature profile.

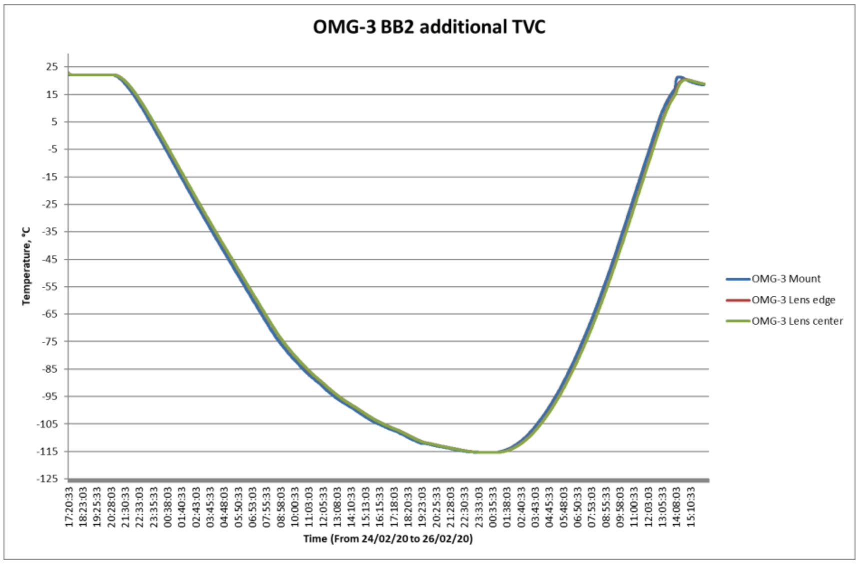


Figure 11. OMG-3 BB2 additional TVC temperature profile.

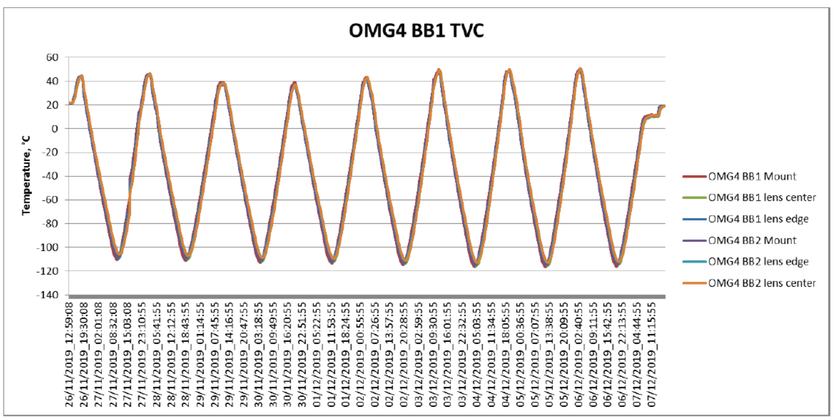


Figure 12. OMG-4 BB1 and BB2 TVC temperature profile.

The visual inspection of the OMGs performed at completion of each TVC confirmed that the OMG passed successfully the thermal cycling without any degradation.

3. OMG BB1 RANDOM VIBRATION TEST

3.1 Vibration Test setup

The vibration test performed on the OMG-3 and 4 BB1 has been subdivided in two phases:

- The first phase was aimed at validating the design at its qualification load on X, Y and Z axes.
- The second phase consisted in repeating the random test in the Out-of-Plane direction until the failure of the OMG is reached. The random load was increased by adding to the plateau in correspondence of the first resonance frequency of each OMG+3dB for each run.

The random tests were performed on the shaker LDS V964LS/DPA110-140K DC located in Florence at the site of Leonardo. Figure 13 shows the shaker in the Out-Plane configuration (left side) and in the In-Plane configuration with the slip table mounted (right side).

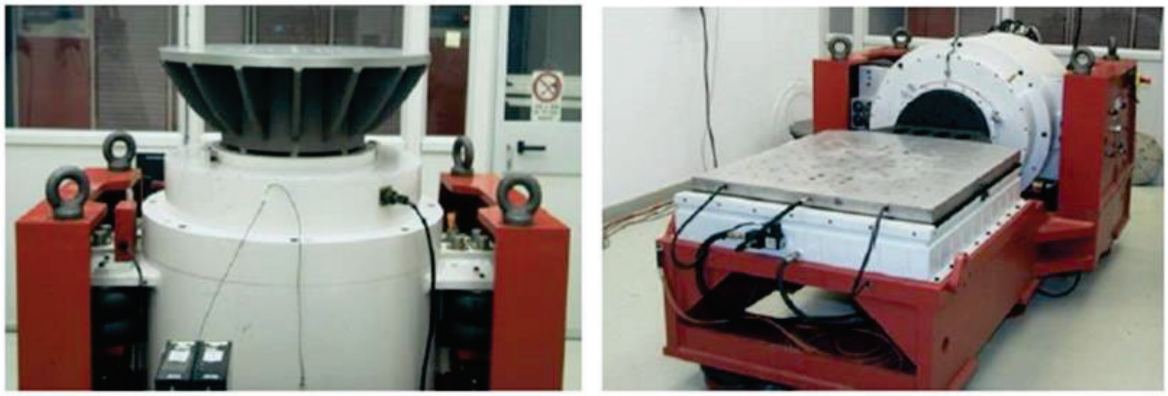


Figure 13. Shaker used for vibration test on BBs.

For each run the OMG3 was rigidly attached on a reference fixture and two mono-axial accelerometers were attached on it to control the vibration input. The control has been done using the mean value of these two accelerometers during the resonance search and the maximum value during the random vibration.

Other two tri-axial accelerometers have been used for the control response and the resonance research on the lens and on the mount. The positions of the accelerometers are reported in Figure 14. The position on the lens was chosen in correspondence of the point at maximum acceleration in order to guarantee that the notching based on the response of this accelerometer leads to a load on the lens always under the 55g limit load in the first phase.

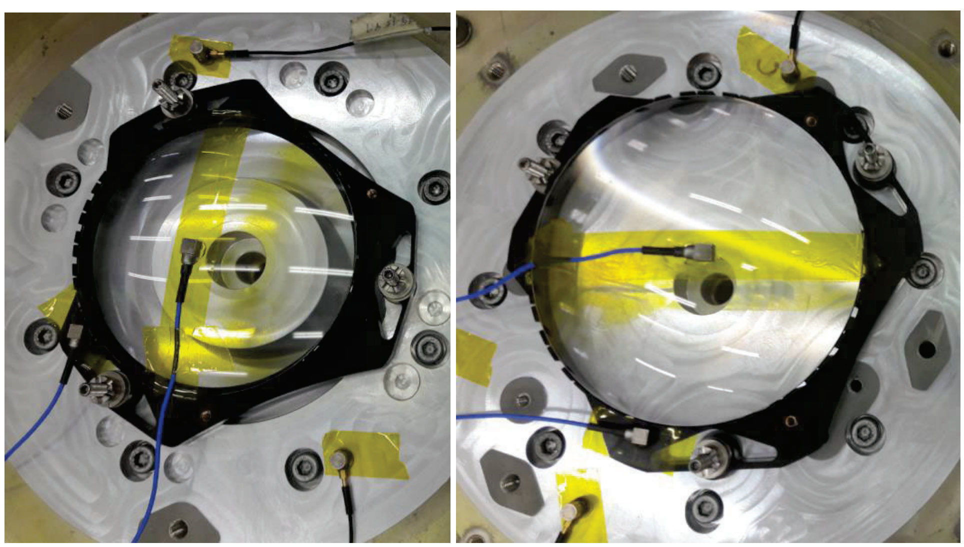


Figure 14. OMG-3 (left) and OMG-4 (right) test setup

3.2 Qualification test and resonance verification

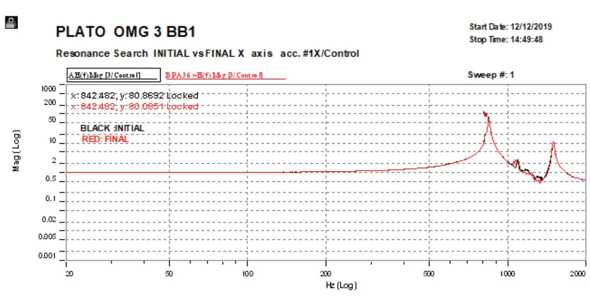
A sine vibration in the frequency range from 20 to 2000 Hz with a sweep rate of 2 oct/min (one sweep up) has been performed before and after each random run. Resonance frequencies have been measured during the whole resonance search test to verify that they are higher than 140 Hz and that no frequency shift greater than 5% is observed between first and last modal survey. The level of the resonance search was chosen considering the amplification factor, in order to avoid to exceed the qualification load.

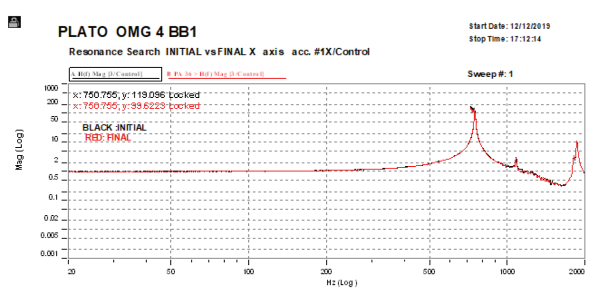
Table 2 shows the summary of the resonance search, in terms of main frequency of each OMG and relative amplification factors. The Transfer Function measured with the initial resonance search has been used to evaluate the notching profile.

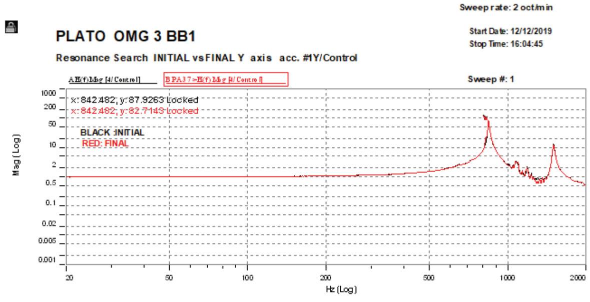
Table 2. OMG-3 and OMG-4 resonance search summary

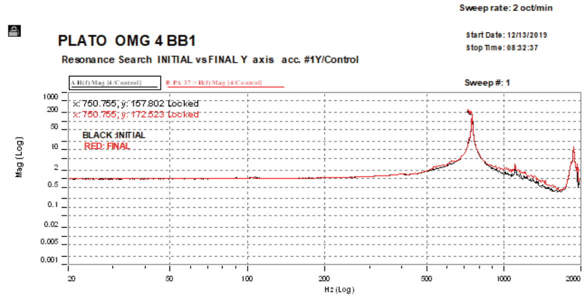
OMG	Axis	Resonance freq.	Amplification factor
3	X	842 Hz	85 @0.5g
3	Y	842. 5 Hz	85 @0.5g
3	Z	603 Hz	90 @0.2g
4	X	746 Hz	120 @0.2g
4	Y	746 Hz	155 @0.2g
4	Z	642 Hz	200 @0.2g

The initial TF for all axes are plotted in the following figures together with the TF measured during the last run after random test with qualification level on the center of each lens. When comparing the resonance search at the start and at the end of the qualification campaign, one can observe the absence of any dynamic changes in the whole frequency range.









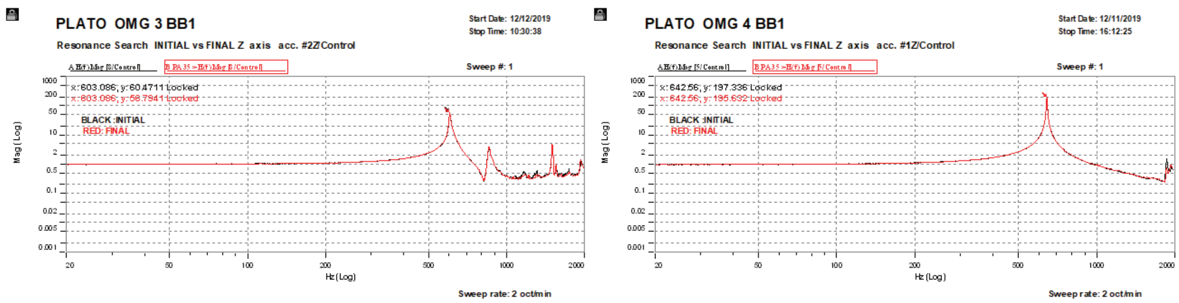


Figure 15. OMG-3 (left) and OMG-4 (right) resonance search comparison

3.3 Random test till failure

Starting from the full level random load given to each OMG at the end of the qualification campaign along the Z axis, the plateau of the notching has been increased by +3dB for each run, until failure was reached. Before and after each random run, a resonance search and a visual inspection was done to verify the status of the lens and of the adhesive pads.

For OMG-3 and OMG-4 the failure of the lens happened respectively with an input load of 15.6 gRMS and 22.43 gRMS, which corresponded to a load measured on the lens of 190 gRMS and 199 gRMS. Instead, the last load sustained by the lens without any failure was 137 gRMS, given by an input of 14.3 gRMS, for OMG-3 and 163.5 gRMS, given by an input of 18.44 gRMS, for the OMG-4.

The following pictures show the input given to the OMG-3 and OMG-4 for each run (black curve), together with the response on the lens (red curve), for the last successful run without failures and damages. On each picture it is also indicated the gRMS reached (input at the I/F written in black and output on the lens written in red) and the maximum PSD (y value written in red at the frequency x) reached on the lens.

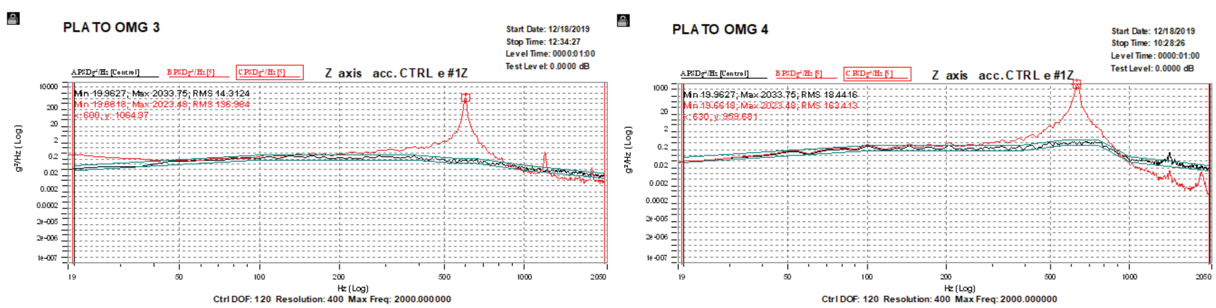


Figure 16. OMG-3 and OMG-4 successful random run before failure

3.4 Visual inspection after random test

The following pictures show the OMG at the failure of the lens. The crystalline structure of the CaF2 leads a mode of breaking into multiple parts. In particular, it can be noted two main planes along which the glass is broken. The adhesion of the adhesive on the lens and on the mount do not present any sign of degradation or detachment.

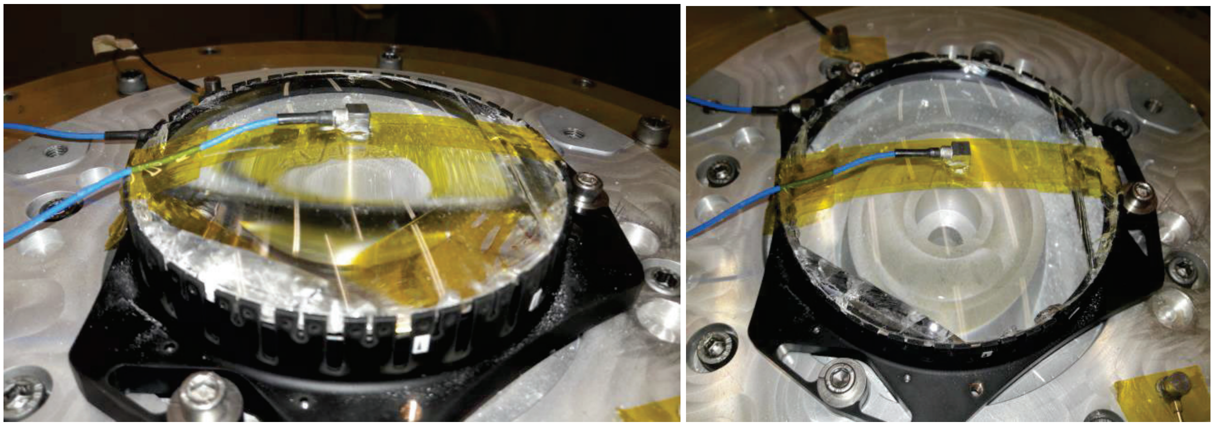


Figure 17. OMG-3 visual inspection after failure.

The failure of the OMG-4 shows the breakage of the lens in correspondence of the edge. The adhesion of the adhesive on the lens and on the mount do not present any sign of degradation. The following figures show the photo of each area after the failure of the lens.

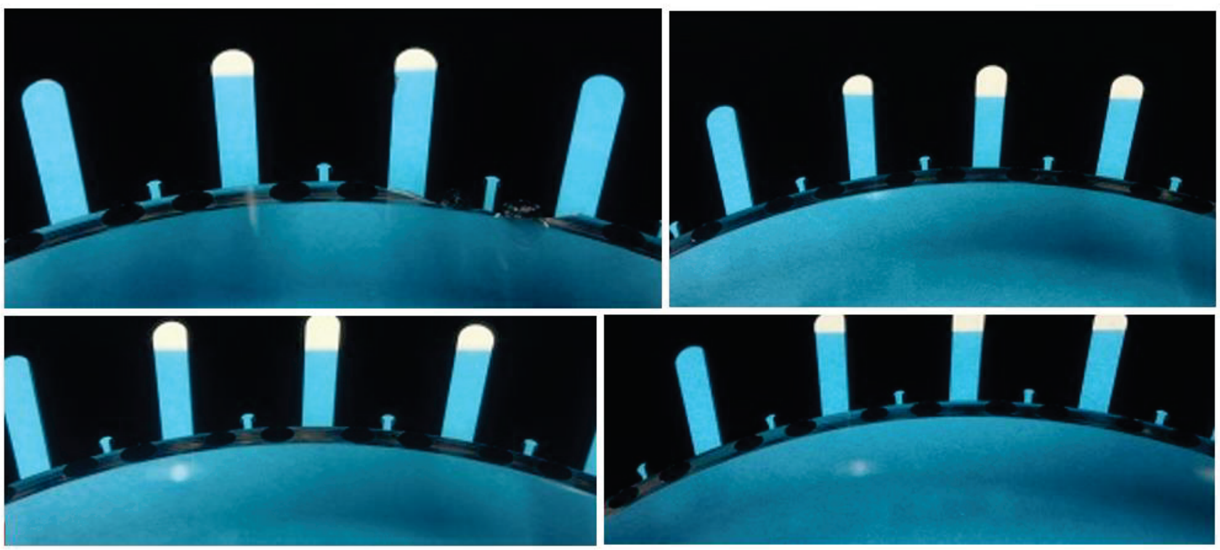


Figure 18. OMG-3 visual inspection after failure.

4. OMG BB2 SHOCK TEST CAMPAIGN

The shock test on the BB2 has been performed along out-plane axis (the most critical for the OMG design in terms of stress on bonding pads and on the lenses). The goal of this test was to demonstrate that the design of the OMG is able to withstand to a SRS load on the lens of 500g. Starting from 200 g SRS, the load has been increased run by run up to reach the desired load on the lens.

Before and after each run, a resonance research and a visual inspection were done in order to identify possible failures. All other OMGs reached the qualification level without any damages, therefore only the final resonance search comparison is shown in paragraph hereafter,

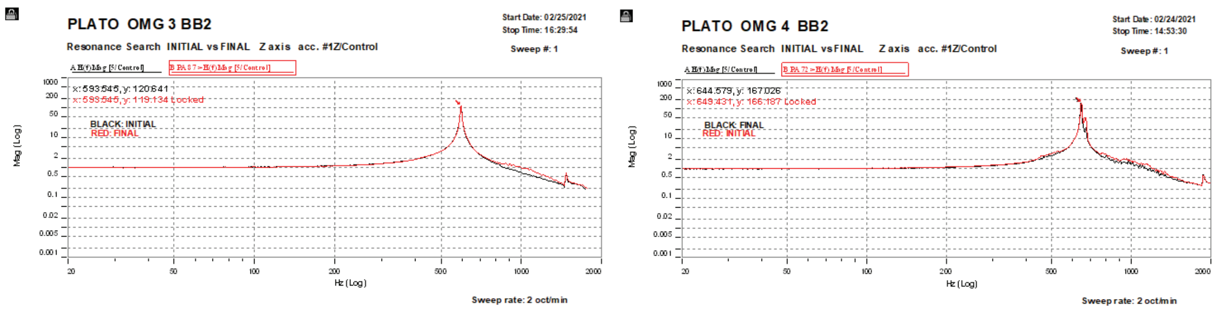


Figure 19. OMG-3 (left) and OMG-4 (right) resonance search before and after shock

OMG-3 has been tested increasing the SRS load from 200 g to the 500 g. The OMG-3 has been successfully subjected without any kind of damages and degradation. The SRS input load and the response on the lens are shown in Figure 20 and 21, both in the time and frequency domain.

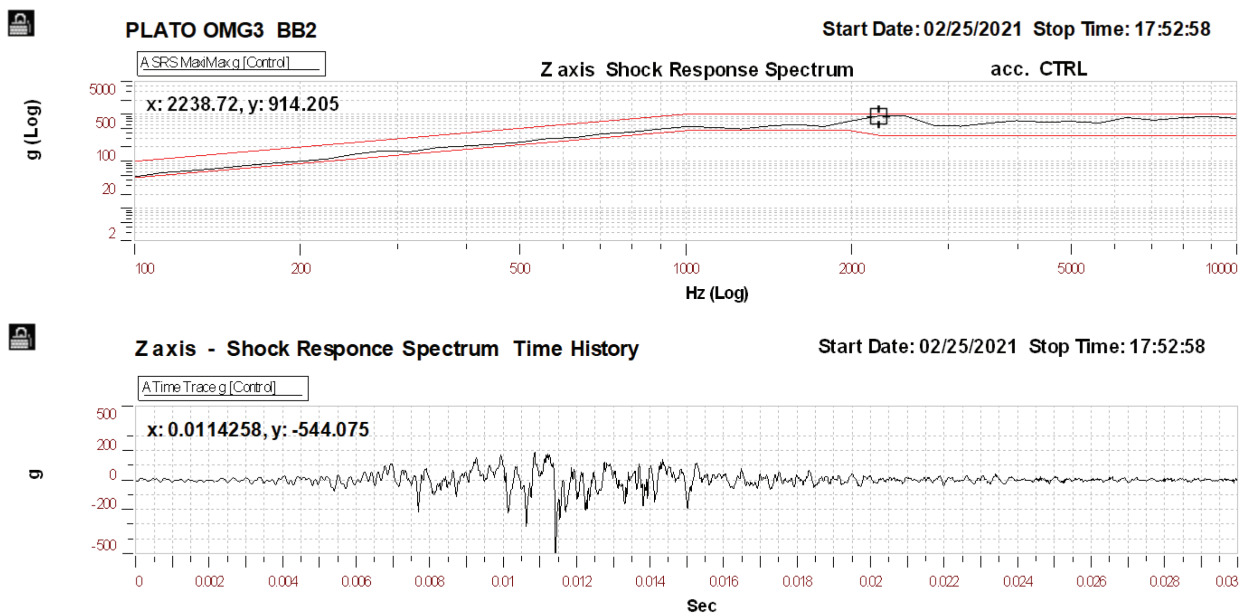


Figure 20. OMG-3 BB2 Shock Z axis 500g - Input.

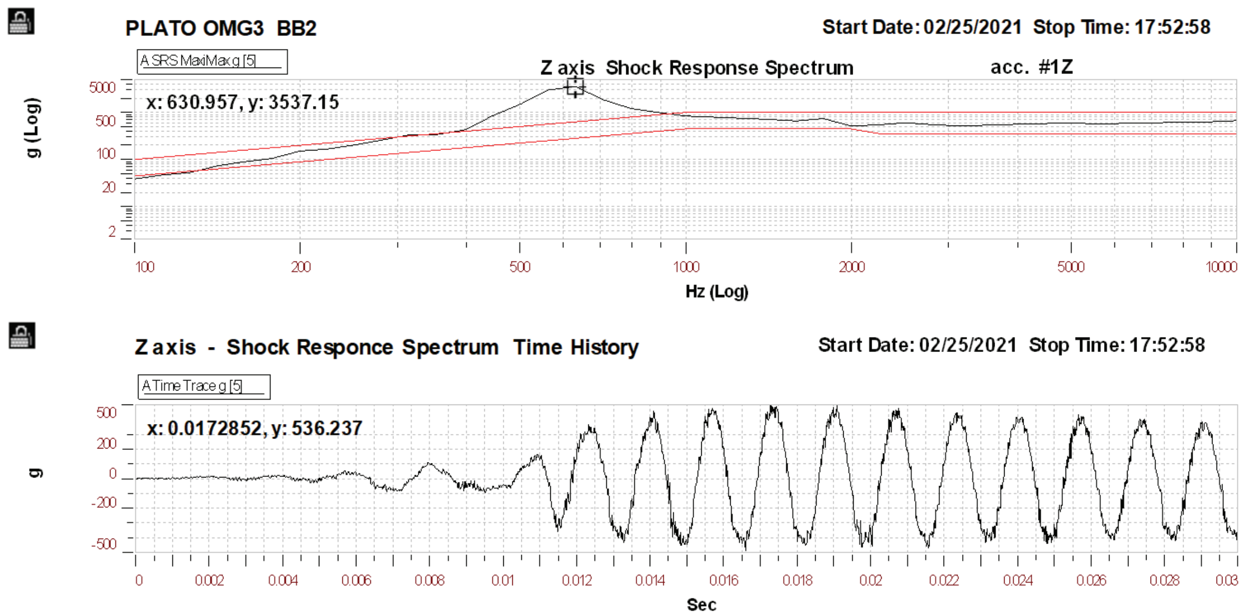


Figure 21. OMG-3 BB2 Shock Z axis 500g – Lens response.

Also the OMG-4 has been successfully subjected without any kind of damages and degradation, reaching 500g SRS on the lens with an input at the OMG interface of 450g. Figures 22 and 23 show the data measured at the final stage on the fixture and on the lens, both in the time and frequency domain.

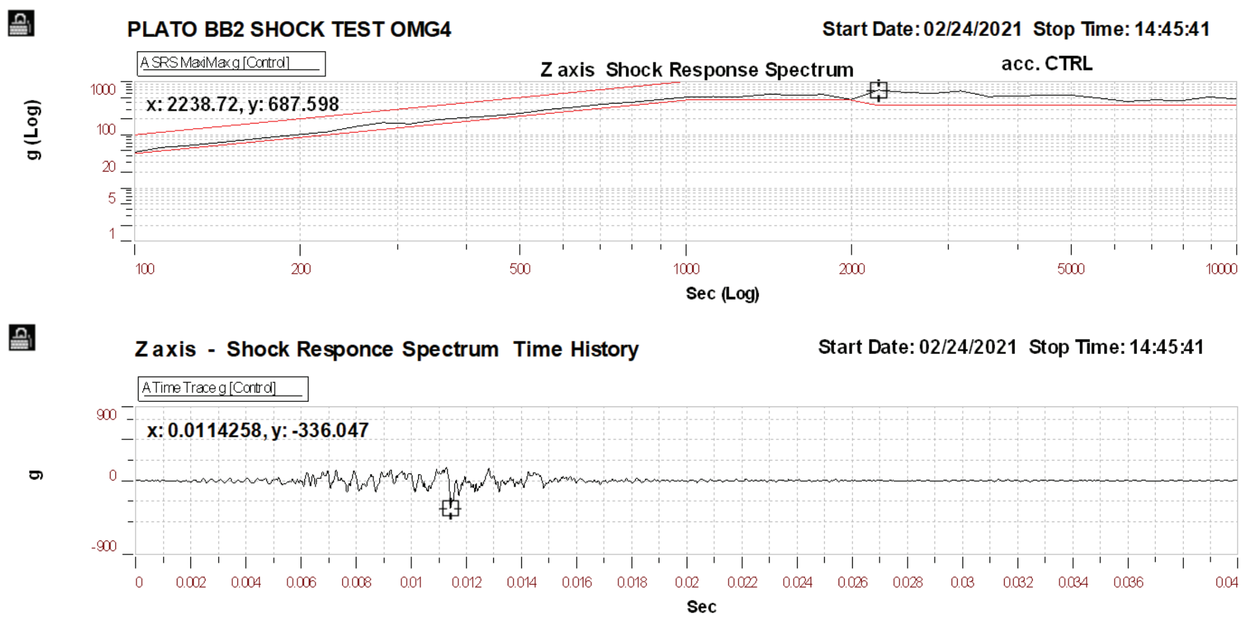


Figure 22. OMG-4 BB2 Shock Z axis 500g - Input.

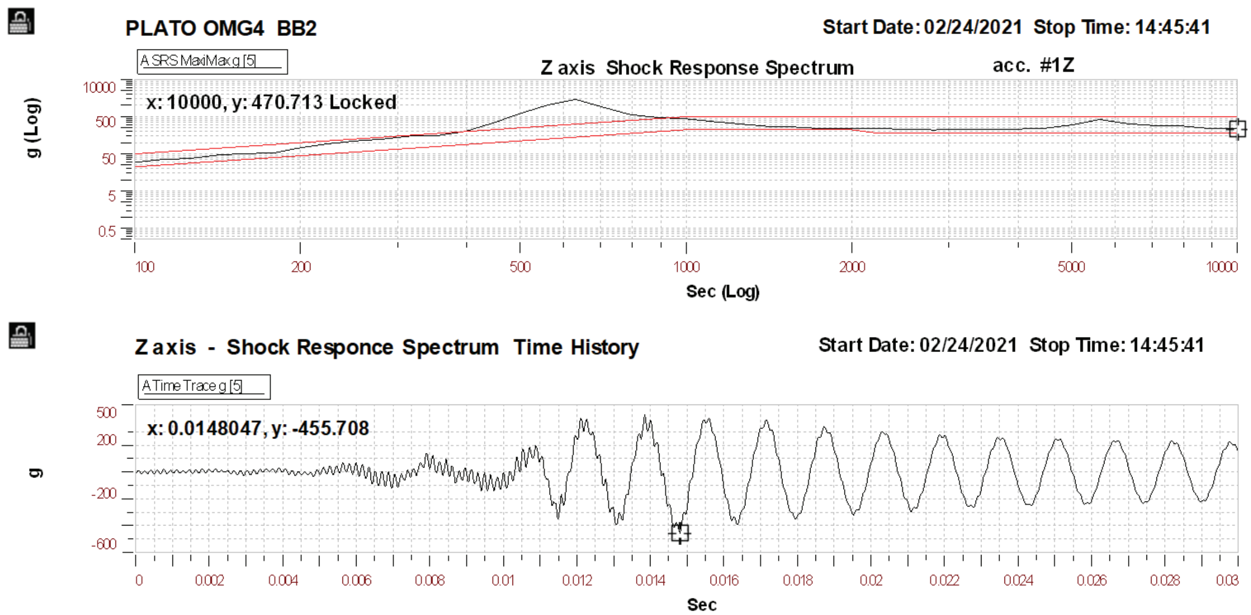


Figure 23. OMG-4 BB2 Shock Z axis 500g – Lens response.

5. CONCLUSION

All these test results demonstrated that it is possible to use brittle materials in the frame of space environment, even if these materials have a very low ultimate strength and an analytical approach does not permit to recover good margins of safety. In fact, when the design is such that does not induce stress on a glass, and also the gluing process is well done and controlled, it is possible to sustain very high loads or strong cooling down without any damages on the glass.

6. ACKNOWLEDGEMENT

Authors gratefully acknowledge the financial support of the Italian Space Agency in the framework of the contract N. 2016-16-I.0 of PLATO Phase B program. A special acknowledge for the very good co-engineering approach goes also to ESA, UBE and INAF teams involved in the development of PLATO TOU project.

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