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Planetary Transits and Oscillation of Stars (PLATO) Focal Plane Assembly (FPA): Preliminary Model Philosophy and Prototype test results.

Isabel Vera[a], Ana Balado[a], Miriam Pajas[a], Chiara Cerruti[a], M Ángeles Alcacera[a], Gonzalo Ramos[a], Ángel Luis Valvede Guijarro[a], Laura González Llamazares [a],Irene Catalán[b] , Andrés Manjón[c],Elena Pérez[c], David Muńoz[c], David Barrado[d], Miguel Mas[d]

[a] Instituto Nacional de Técnica Aeroespacial (INTA)
Ctra. Ajalvir, Km 4, 28850 Torrejón de Ardoz, Spain
[b] ISDEFE, as external consultant for INTA
Calle Beatriz de Bobadilla 3,28040, Madrid, Spain
[c] LIDAX
C/ Antonio Alonso Martín, 1, 28860 Paracuellos de Jarama, Madrid, Spain
[d] CAB (CSIC-INTA)
Ctra. Ajalvir, Km 4, 28850 Torrejón de Ardoz, Spain

Abstract

PLATO (PLAnetary Transits and Oscillations of stars) is an ESA mission, which is dedicated to the detection and characterization of terrestrial exo-planets. In the baseline design, it is planned to mount 26 cameras in the same instrument bench. Each camera consists on a telescope, the focal plane assembly (FPA) and the detector electronics. This amount of cameras that has to be manufactured, integrated and tested at the same time makes this mission an industrialization process. This paper explains the approach of the initial model philosophy used and the tests results of the FPA prototype.

1. Introduction

PLATO 2.0 is an M-class mission of the European Space Agency's Science programme Cosmic Vision 2015-2025 planned to be launched in 2026. Its purpose is to find and study a large number of extra solar planetary systems, with emphasis on the properties of terrestrial planets in the habitable zone around solar-like stars. PLATO has also been designed to investigate seismic activity in stars, enabling the precise characterisation of the planet host star, including its age.

The mission architecture can be observed in Figure 1. The Space Segment consists of the Payload Module and the Service Module. There are a total of 26 Cameras in the payload:

- 24 Normal Cameras, each one including:
  - **Telescope Optical Unit (TOU)**: The mechanical structure supports the optical lenses and the baffle with various functionalities (thermal, straylight).
  - **Focal Plane Assembly (FPA)**: Supports the four detectors (CCDs in full frame mode), which also includes the 4 flexi-cables of the 4 detectors, to be connected to the FEE.
  - **Front End Electronic (FEE) box**: Located close to the FPA, including mainly the 4 video chains, the CCDs phase drivers and the temperature sensor acquisition and conditioning.
- 2 Fast Cameras, similar to the Normal Cameras except for a reduced bandwidth of the optics (to provide a chromatic photometry), and use of the same detectors but in frame transfer mode (to provide the position error information).

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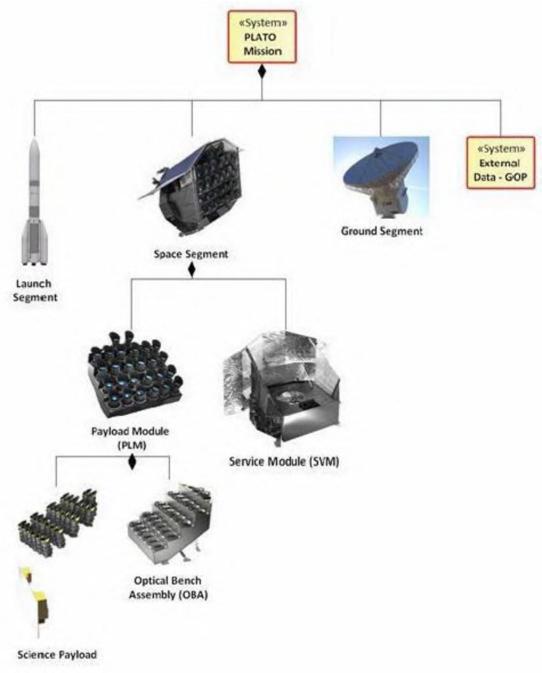

Figure 1: PLATO Mission Architecture

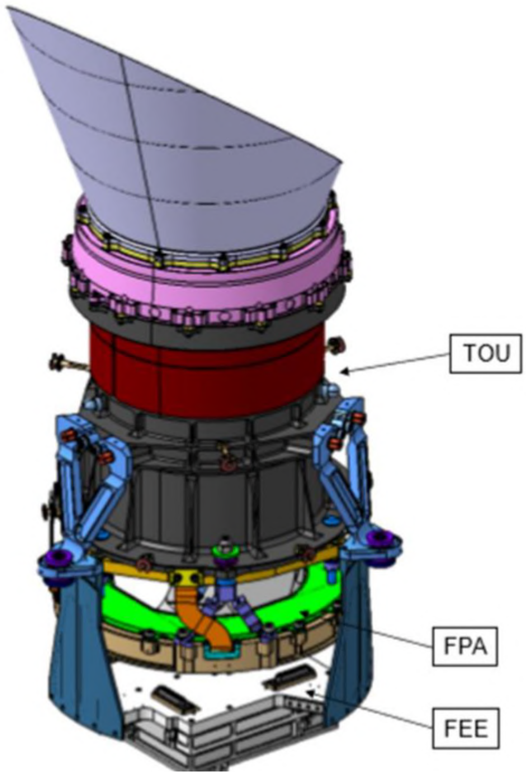

Figure 2: Camera General View

2. AIV Challenges

PLATO mission presents many technological challenges. In particular, the large number of cameras in the payload implies many issues for manufacturing and from the AIV point of view. This impacts the model philosophy, that has to be studied in detail, as there will be a unusual large number of models - not common in most of the space missions. In order to solve this challenge a very developed prototype has been designed, manufactured and tested. This prototype is very similar to a flight model, because it was required that it was very representative. Therefore, the prototype has been used to validate manufacturing, integration and test aspects. Furthermore, this prototype development has allowed the extensive development of Ground Support Equipment (GSE) used at the different stages of manufacturing and AIV, which will be very critical because of the repeatably aspect of the mission development.

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3. PLATO FPA

INTA is in charged of the design development, manufacturing and AIV of one of the three components of PLATO's payload cameras: the Focal Plane Assembly.

The FPA is composed of a support structure with four CCDs and flexi cables, a straylight mask to protect them from radiation and provide stiffness to the plate, the hardware providing the structural I/F to the TOU (bipods, fasteners and shims), the thermal hardware needed to dissipate the CCDs heat and an alignment cube.

The main functions of the Focal Plane Assembly are:

- To provide support to the four detectors.
- To provide protection from straylight and radiation to the detectors.
- To provide mechanical and thermal interface with the Telescope Optical Unit (TOU), being compliant with high mechanical solicitation, alignment and stability requirements, and ensuring temperature dissipation.
- To provide an electrical interface to the Front End Electronic (FEE) box.
- To provide thermal coupling of CCDs to TOU to ensure temperature dissipation.

3.1 FPA Parts

After different trade-offs, the best compromise found was a design solution where the FPA main components can be observed in Figure 3 and are as follows:

1. **CCDs**
   The CCDs (Charge Coupled Device) are a silicon based optical detectors manufactured and delivered by Te2V, with the Sensitive Area bonded to the SiC Package.
2. **CCD Support Structure**
   The CCDs Support Structure consists of a titanium plate which provides support to the CCDs, as well as protection against straylight and radiation. It provides the mechanical interface between the CCDs and the bipods. In order to provide stress relief to the CCDs for the worst case temperatures, CCDs are isostatically supported by means of a fixed support and two flexible supports.
3. **Bipods**
   Three identical bipods made of Ti6Al4V support the CCD Support Plate (and all elements mounted onto it). They provide the required isostatic interface to the TOU.

   After considering other design options, a rectangular section was chosen, as this design has a good modal behaviour, providing an optimal structure. The length and angle of the bipods have been also established in order to comply with the requirements.
4. **Stray Light Mask**
   A Ti6Al4V Mask is mounted on FPA in order to protect CCDs from stray light and from radiation. The mask has a thickness of 1 mm. Shape has been optimized in order to save mass and to comply with eigen frequencies requirement.
5. **Thermal Straps**
   Thermal Straps are used in the FPA as thermal links to guide heat from the CCDs to the TOU. Each Thermal Strap Assembly is a thermal strap made of copper sheets attached to copper terminals; all elements are golden coated to protect from corrosion and minimize thermal losses. Thermal Strap thickness is different for Normal and Fast FPAs, due to the difference in power dissipation by the CCDs in the fast and normal cameras.
6. **Flexi Feedthroughs**
   Eight Flexi Feedthroughs provide a mechanical support to Flexi cables in order to protect CCDs. The Feedthroughs consist on eight Ti6Al4V parts that grasp the Flex cables and are attached to the CCD Support Plate.
7. **Thermal Strap Supports**
   They provide mechanical support to Thermal Straps in order to protect the CCDs.
8. **Alignment optical cube**
   It provides the required alignment functions.

As mentioned above, two models of FPA are foreseen for the PLATO mission purpose, the Normal and Fast FPA.

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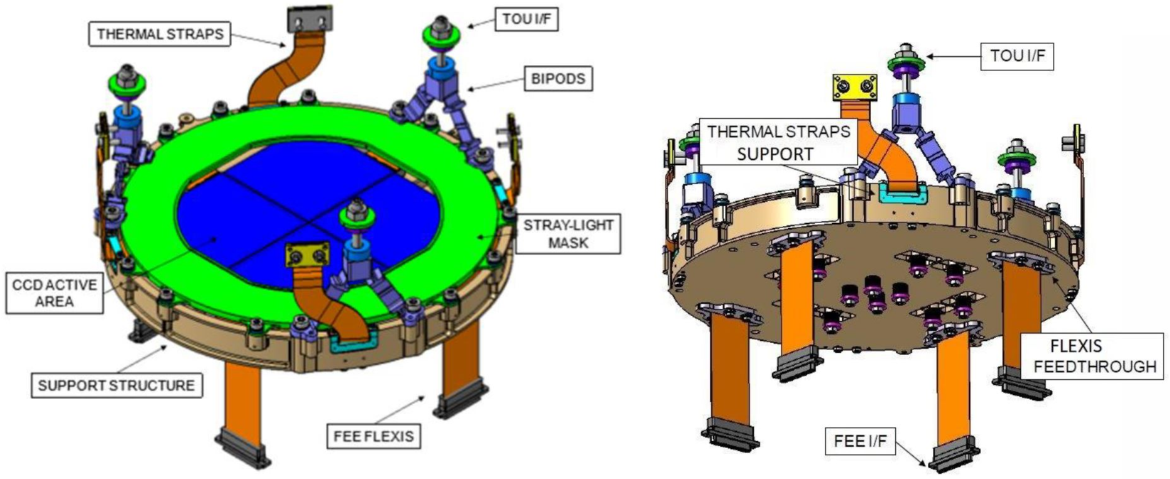

Figure 3: FPA Components

4. Prototype Design

This Prototype is conceived to be as representative as possible of the flight model, to maximize the applicable information obtained from its study. The configuration of the FPA Prototype (Fast) is the following:

- FPA flight design with mechanical representative CCDs (not the operational ones).
- Representative thermal-mechanical IFs.
- The prototype is considered applicable to both the Normal and Fast version of this unit, because the Fast version, that is the one chosen for the prototype, is the most critical one.

The objective of the FPA prototype is to reduce risks and gain confidence in the FPA design and manufacturability. The prototype provides information in the following areas:

- Manufacturability: demonstration that the FPA design is manufacturable with flight materials and obtention of the manufacturing tolerances needed for the alignment requirements.
- Mass budget confirmation.
- CCD/FPA Interface: test of the interfaces agreed with ESA.
- Integration and Alignment requirements feasibility.
- Analysis correlation: complete mechanical/thermal test campaign to correlate the thermal/mechanical analysis.
- Requirements: non-compliance requirements assessment.
- Schedule: information about the process and tests timing.
- Tool confirmation: the prototype design (together with the manufacturing and assembly) has allowed the confirmation of the design of the tools needed.

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5. FPA Protoype Analysis

A set of analyses was performed in order to demonstrate the compliance to the requirements regarding the FPA and to assess the technology readiness. The analysis performed regarding the prototype and the documents generated are the following:

- **FPA Prototype Thermal Analysis**
  The thermal analysis establishes that the corresponding requirements, that concern temperature ranges, margins and power dissipations, are all fulfilled.

- **FPA Prototype Structural Analysis**
  Stiffness, stress, bolted joint and performance of the PLATO FPA Prototype was verified. These analyses conclude that most of the requirements that apply to this analysis are fulfilled.

The prototype analyses are validated with respect to the prototype tests results (described in section 9 of this document). These two types of analyses (thermal and structural) have also been performed for the flight model FPA (normal and fast FPA flight model), together with the corresponding model correlations.

6. Prototype Manufacturing

During phase B, the feasibility of the FPA manufacturing was demonstrated. A fully representative breadboard (Prototype) of a F-FPA was manufactured, following the most conservative approach, as this is the most critical design type.

As a direct consequence of the manufacturability study of the FPA, the FPA prototype was manufactured with flight materials, except flight-like coating. The experience gained in the prototype manufacturing is, thus, directly applicable to the flight models. The prototype fabrication shows that a close collaboration with the manufacturer is required to achieve optimal results.

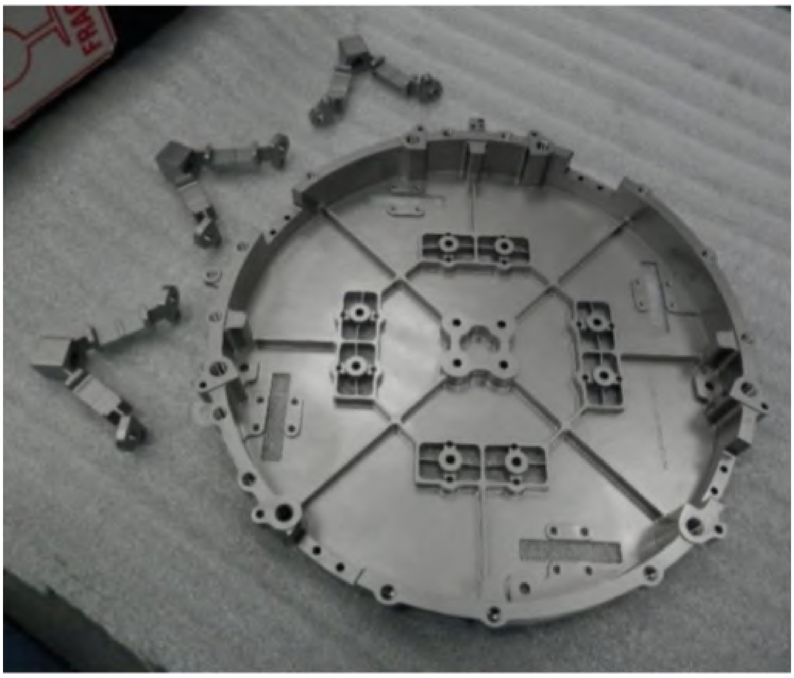

Figure 4: FPA Support Structure and Bipods

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7. Prototype AIV Campaing

The integration and compliance of the requirements in FPA Prototype has been demonstrated performing different measurements and tests in relevant environment. The FPA prototype test campaign consisted in a Thermal Balance and Thermal Cycling Test, Vibration test, Shock Test and Physical Properties Test. Furthermore, several intermediate alignment measurements were performed to check that CCDs and reference systems were in the right place throughout the whole test campaign (optical measurements and CMM).

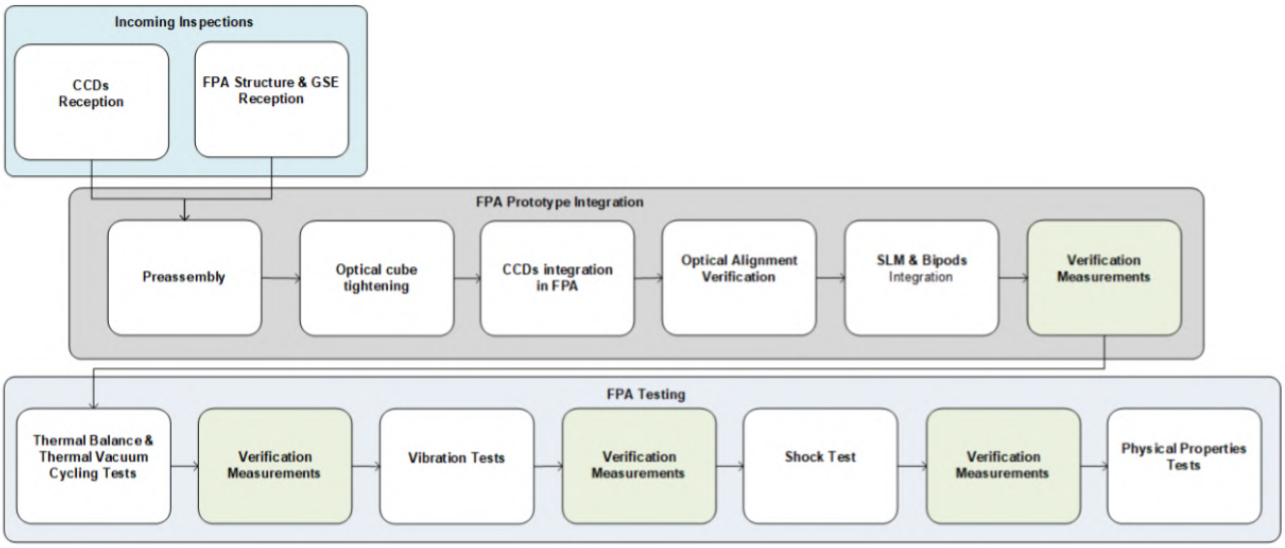

Figure 5: FPA Components

7.1 Test Facilities

The FPA prototype AIV process and the requirements verification collected in this report have been carried out in the following cleanroom and tests facilities:

- Integration and optical activities: INTA clean rooms with cleanliness conditions ISO-7 class 10.000. All under laminar flow cabinet ISO-5 (Class 100) in room conditions.
- CMM and mass measurements, LIDAX clean room area.
- Thermal vacuum cycling test, vibration, shock and MoI physical properties tests at INTA Environment test facilities.

  Room required conditions: Temperature $22C \pm 3C$, Humidity 55 ± 10% RH, Pressure: room ($103mbar$).

7.2 Incoming Inspections

- **CCD's Reception**
  This step took place in the Clean room 100.000 and consisted of four activities: reception, CCDs incoming inspection, mass measurement, and shims identification and studs removal. These steps are needed in order to ensure effective CCDs integration. CCD's reception is a very important activity because they are the most critical component of the camera.

- **FPA Structure & GSE Reception**
  The FPA Mechanical parts Incoming Inspection was performed at LIDAX facilities. It consisted in the Visual Incoming Inspection of all the FPA Mechanical parts (including MGSEs) and metrological reports checking.

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8. FPA Prototype Assemby

8.1 Preassembly

Before the CCDs integration in the FPA, a series of activities had to be performed. These include the thermal strap assembly integration, CCD stack characterization test, PT-100 Mounting, cleaning and a preintegration.

8.1.1 Thermal Strap Assembly Integration

This activity consisted in the assembly of the thermal straps parts.

Figure 6: Thermal Straps after integration

8.1.2 CCD Stack Characterization Test

The main objective of this test was to obtain the relationship between CCD screw disc springs stack total length and the preload obtained at the bolted joint. A first batch of tests performed by ESA showed results with a dispersion higher than desired in order to determine a common length for all the screws that assured the needed preload. Based on these results, the goal of this test is to define a total length individually for each of the screw stacks needed for the PRT integration (12 in total).

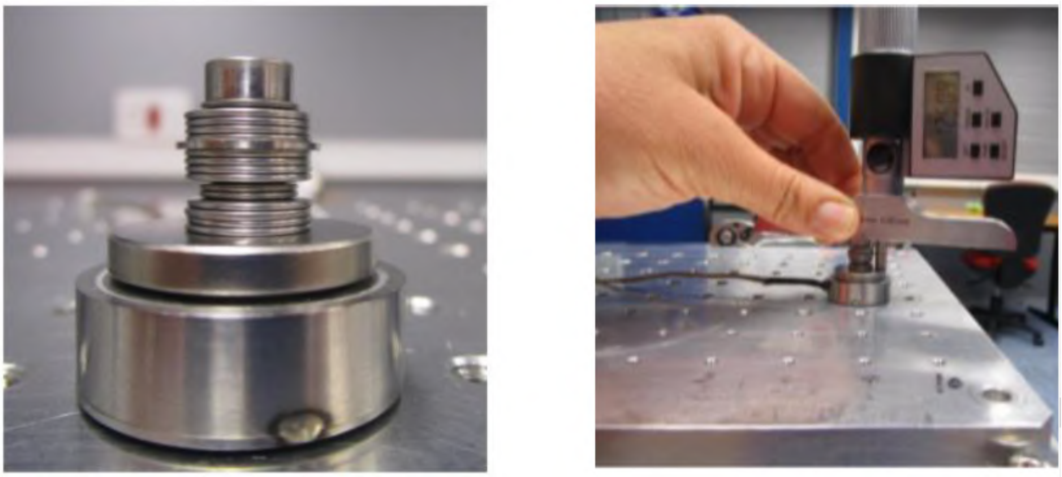

Figure 7: CCDs screw stack specimen

Each IF stack was characterized to obtain the adequate mounting height for each CCD. As a result of the test, a final average length has been defined for each of the screws. During PLATO prototype CCDs integration, each of the screws was tightened until the stack length matched the final average length defined. With this approach, the effects of possible human errors during the length measurement are minimized, as the final length value will be within minimum and maximum values.

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8.1.3 Thermal sensors mounting

In order to collect the temperature information needed during the thermal balance and thermal vacuum cycling tests, thermal sensors were attached to the CCDs before their integration in the FPA. The thermal sensors used in this testing campaign were PT-100. These sensors were placed in different locations in the CCDs and they were attached in the following sequence:

1. Mounting of PT-100 on Thermal Strap Assembly
2. Mounting of PT-100 on CCDs at TRP4 position (on each CCD)
3. Mounting of PT-100 underneath CCDs

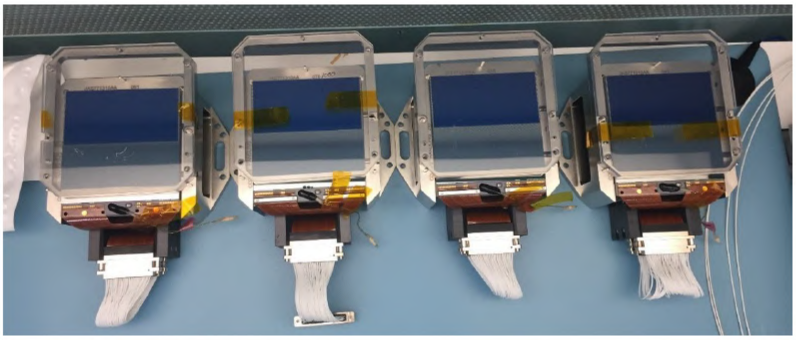

Figure 8: PT-100 Mounting on CCDs

8.1.4 Cleaning

Cleaning of all the parts, components and standards of the FPA Hardware was performed in ISO 5 conditions. It was performed using the ultrasonic bath at the LIDAX flow chamber. The surface of the integration table was protected with kapton tape during all activities in order to avoid scratches of the parts.

8.1.5 Preintegration

A fit check of the integration tools and one CCD (CCD from breadboard) was done prior to integration, to ensure the adequate fitting (Figure 9)

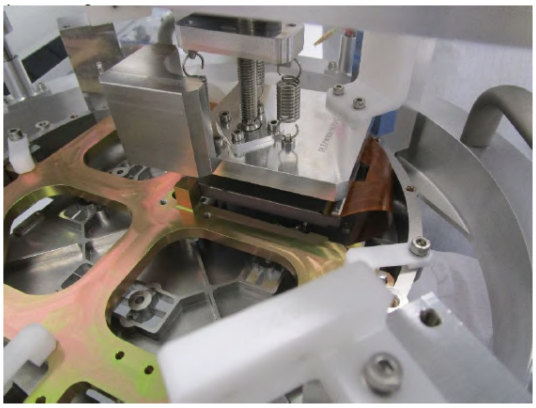

Figure 9: Fit Check

- **Bipods shimming configuration**
  The main objective of this process was to define a shim configuration that meets the flatness requirement for the bipods upper common plane and the parallelism requirement between bipods upper common plane and the CCDs support plane. This is important because after the manufacturing process of the CCD Support Structure and the bipods prototype parts it was found that the flatness and parallelism requirements couldn't be met with the baseline configuration. In order to correct these manufacturing errors the shimming process for the bipods I/Fs was done.

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- **Bipods Parallelism repeteability test**
  A repeteability test (mounting and dismounting the bipods on the CCD Support Structure) was performed. The objective of this test was to evaluate the repeatability of the bipods assembly process, including the shimming process defined in the previous section. To perform the test the bipods were completely mounted and dismounted a total of 8 times. CMM measurements of the Bipods upper common plane and the CCD support plane were taken after each assembly. Once the measurements were taken, a comparison of both planes parallelism and angle difference was calculated.

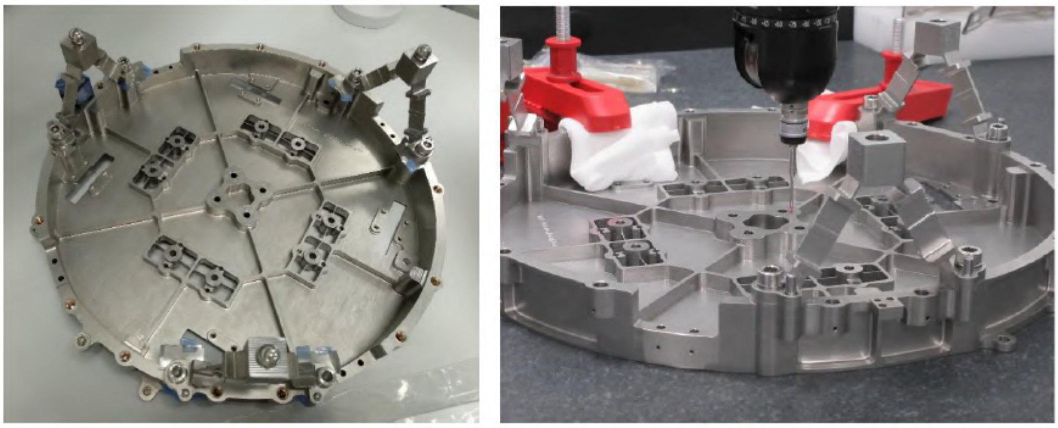

Figure 10: Bipods mounting(a), CMM Measurements (b)

8.2 FPA Assembly

Optical cube alignment was performed using a theodolite. After the thermal straps were integrated onto the CCDs, the CCDs were assembled in the FPA. Next, the optical alignment verification was performed, in order to ensure the compliance to the requirements.

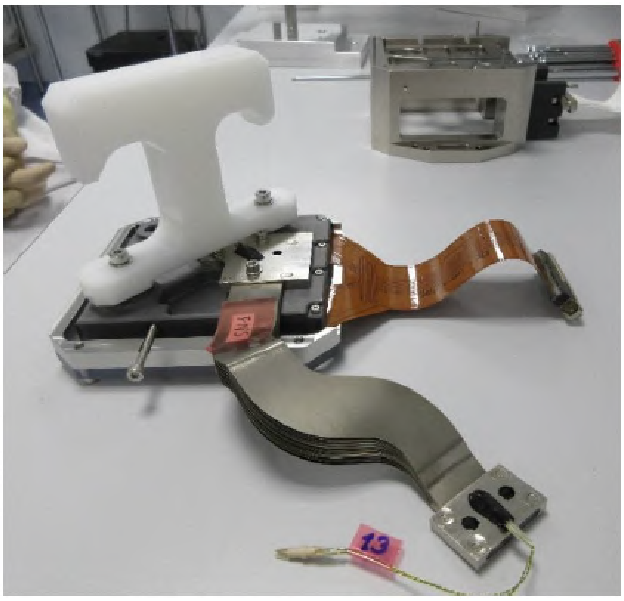

Figure 11: Thermal straps in CCDs.

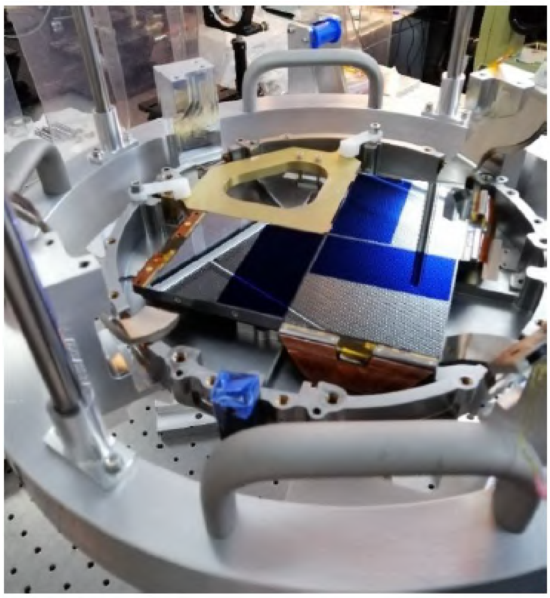

Figure 12: CCDs mounting in FPA

After the optical verification (without bipods and Straylight mask), the flexi feedthroughs and thermal supports were mounted. The Bipods were mounted on the CCD Support Structure with the final shimming configuration obtained after the bipods mounting repetability activity detailed in section 8.1.5. In the following picture the FPA Prototype with the bipods and straylight mask can be observed.

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8.3 Verification Measurements

The Verification Measurements consisted of two parts: CMM measurements and Optical measurements to be able to compare both results. These two activities are repeated throughout the whole testing campaing, in order to verify CCD alignment parameters, so that the results can be compared. The measurements were taken after the FPA PRT integration, after submitting the FPA PRT to the thermal tests, after submitting the FPA PRT to the vibration tests and, finally, after submitting the FPA PRT to the shock tests. The main objective of the test was to characterize the different reference frames of the PLATO FPA Prototype and to study their stability all throughout the test campaign after being submitted to the expected environmental loads.

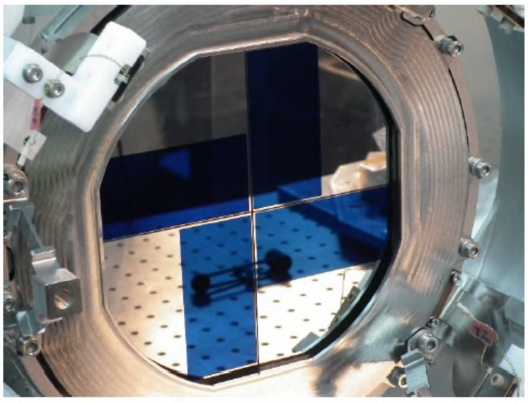

Figure 13: FPA with Straylight Mask and Bipods

9. FPA Prototype Testing

9.1 Thermal Balance & Thermal Vacuum Cycling Tests

The objectives of Thermal Vacuum Cycling Tests (TVCT) and Thermal Balance (TB) test were to evaluate and demonstrate the correct behavior of the PLATO FPA Prototype at maximum/minimum non-operating and operating temperatures and Vacuum Environment. In addition, the Thermal Balance Test Campaign provided measured data that it was used to correlate the temperatures of the PLATO FPA Prototype with its corresponding Thermal Model. During this test, particle and molecular contamination witnesses were used (MOC 15 and PFO).

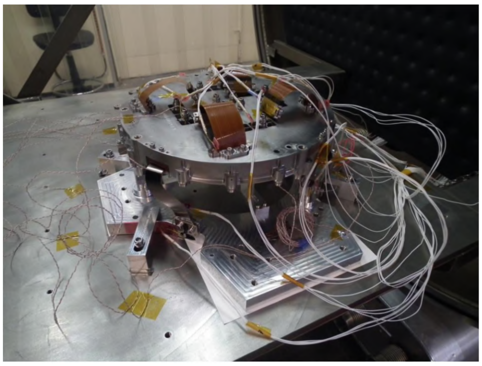

Figure 14: PLATO FPA Prototype inside the chamber

TVCT and TBT on PLATO FPA Prototype was considered successful, as the results are compliant with all thermal related requirements. It is important to notice that CCDs positioning in cold are not measured, so the CCDs displacement between ambient and operative temperatures have been not checked. One aspect to be remarked is that depending on the cooling speed, a thermal gradient can appear between the CCDs and the bipods. It was checked that the gradient obtained is in the thermoelastic deformation range of the material, higher cooling speeds could produce higher gradients.

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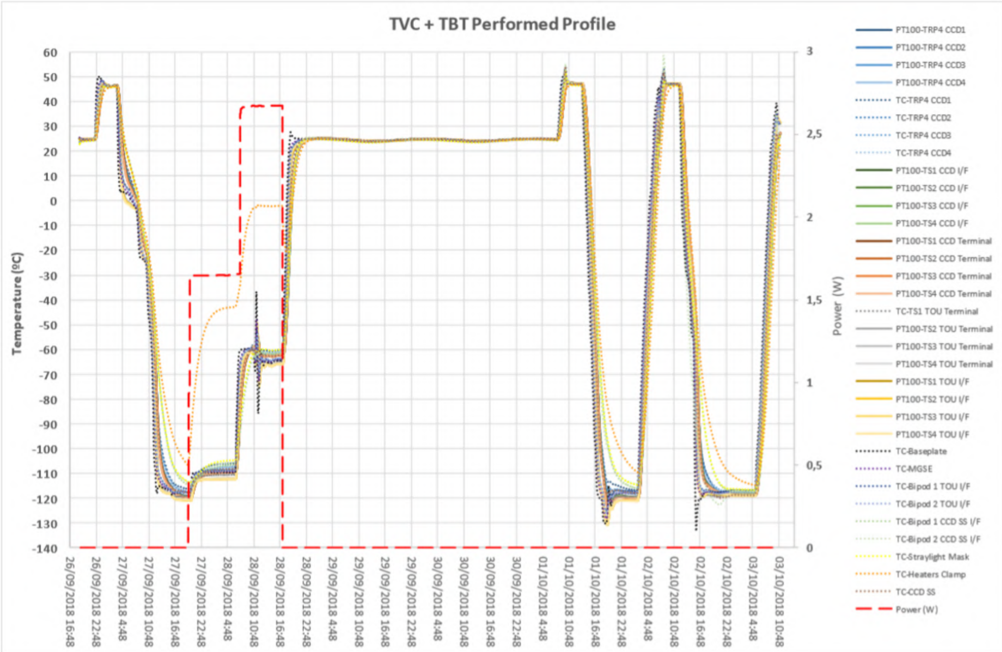

Figure 15: TVCT + TBT Performed Profile

The thermo balance cyling test was successfully passed with minor anomalies in the test. The main objective of thermal correlation of the model was achieved and three thermo vaccum cycles were successfully performed.

9.2 Vibration Tests

The objective of the vibration tests campaign was to verify all the requirements referred to the structural performance of the PLATO FPA Prototype according to system requirements. Furthermore, this test campaign provided measured data that was used to correlate the behavior of the PLATO FPA Prototype when submitted to the required loads with its corresponding Structural Model.

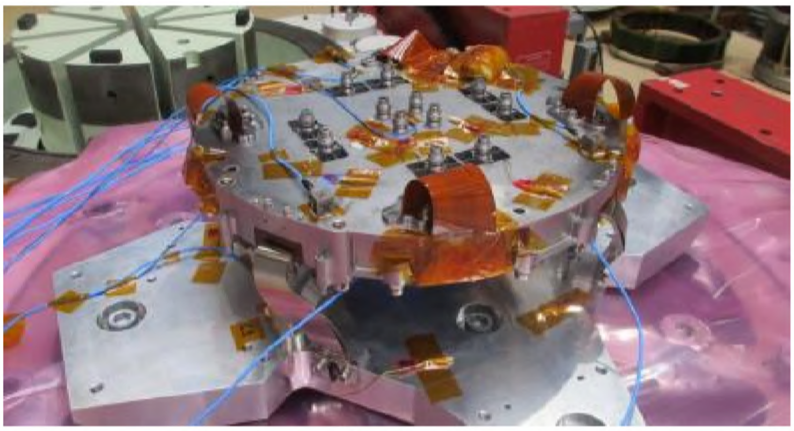

Figure 16: Vibration Tests Set Up

The following tests were performed:

1. **Low Level Sine Test**
   Prior and after submitting the test specimens to vibration tests (sine and random, all directions), a low-level sine sweep was applied on each axis with the objective of demonstrating that the test specimen has not been degraded.

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LOW LEVEL SINE TEST (X, Y & Z axes)			
Frequency (Hz)	Amplitude (g)	Speed (Oct/min)	Tolerance (dBs)
5-2000	0.2 & 0.4 (*)	2	+6dB / -6dB

Figure 17: Low Level Sine levels

2. **Qualification Quasi-Static & Sine Vibration Test**
   The following Sine full levels were applied for each axis. It should be noted that:
   - Specification levels needed to be limited to those listed in the following table, as the maximum CCD qualification load is 50g.
   - An automatic notching was performed to not surpass the limits of the following table.
   - Final submitted profile was adapted to the shaker displacement and speed limitations.
   - An intermediate level (-6dB) was applied before the full level test.

Case	Range (Hz)	Level			Sweep Rate
		X Axis	Y Axis	Z Axis	
Max. Input Level	5 - 120	45 g (*)	50 g	47 g	2 oct/min

Figure 18: QS and Sine Vibration Test Levels

3. **Qualification Random Vibrations Test**
   A first Random Test at -18dB was performed applying the baseline inputs, to obtain a first real equipment response when submitted to the random environment. Afterwards, Intermediate Level Random Tests were performed at -12dB, -6dB and -3dB to have more confidence on the expected Structural Integrity of the Test Specimen and secondary notching were recalculated as needed, based on the equipment obtained responses.

   The following table and figures 20, 21 and 22 show the notching evolution for each axis from the baseline inputs to the final version applied at the 0dB level.

	X Axis	Y Axis	Z Axis
Baseline Level Overall g_{RMS}	24.13 g	24.13 g	22.68 g
0dB Level Overall g_{RMS}	12.48 g	11.32 g	15.93 g

Figure 19: Full level random notching overall gRMS

The following images represent the loads applied in each of the vibration tests.

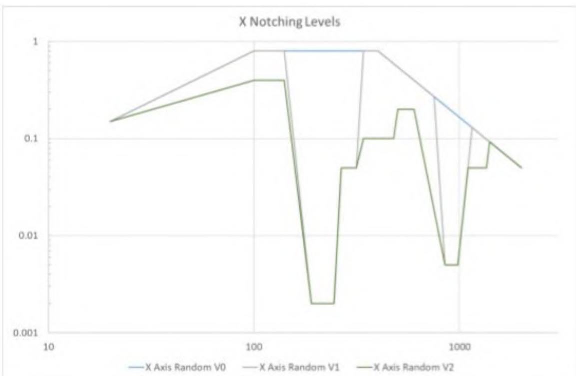

Figure 20: X Axis Random Notching Evolution

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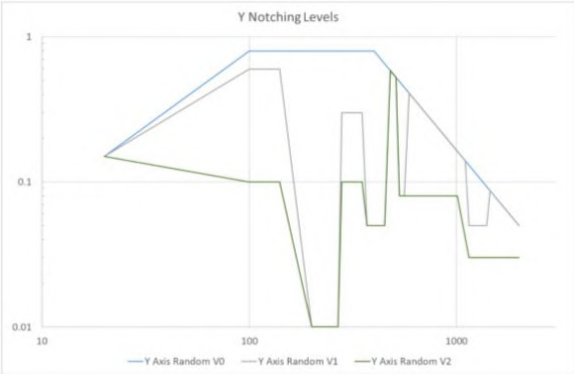

Figure 21: Y Axis Random Notching Evolution

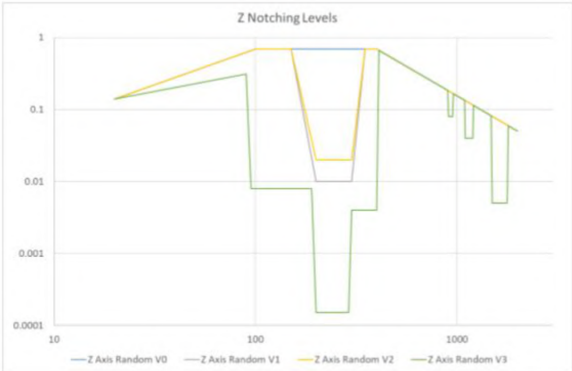

Figure 22: Z Axis Random Notching Evolution

The vibration test execution is considered successfully performed, as:

- The FPA has been excited with the specified inputs and tolerances and within the required accuracy.
- All measurements have been correctly acquired and registered.

Regarding the test results, it is considered that the FPA Prototype has suffered no structural change/damage, because:

- Resonant frequency variations as seen by the Low Level Sine tests are below 5%.
- Structural response amplifications of the resonant frequencies are below 20%.
- Mechanical model correlation based on test data is successful.
- No damage can be observed on the FPA Prototype after visual inspections.

Finally, all the requirements applicable to this test were evaluated and it was determined that the results are compliant with them. Therefore, FPA Prototype Vibration Test under Qualification Loads was considered successful.

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9.3 Shock Tests

The objectives of the Shock Tests are to verify the corresponding requirements referred to the Mechanical Design performance of the PLATO FPA Prototype. A total of 12 accelerometers, 3 control accelerometers and 9 response accelerometers were positioned in the unit. The Shock Test Sequence for the PLATO FPA Prototype was the following: Shock Calibration, Integration and Test Set Up, Sweep (X, Y, Z), Shock Calibration, Y-Z Axis Shock Test, X-Z Axis Shock Test, Sweep (X, Y, Z)

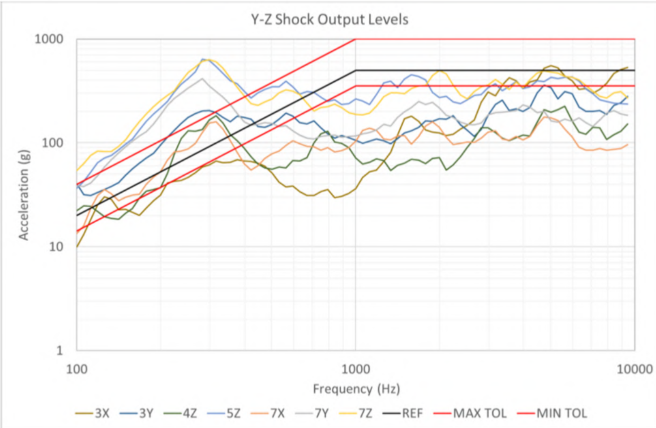

Figure 23: Shock Output Levels Y-Z

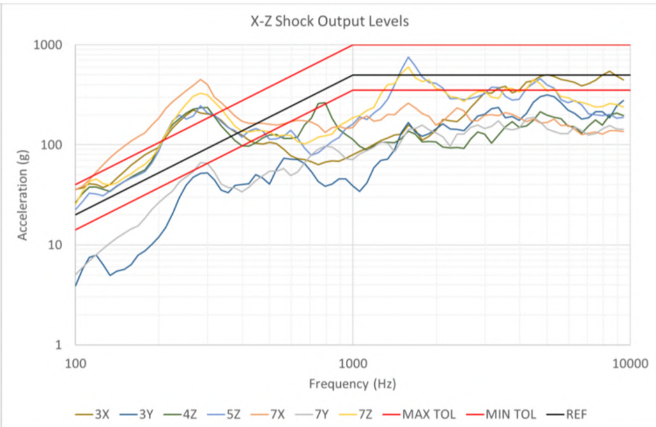

Figure 24: Shock Output Levels X-Z

9.4 Physical Properties Tests

The objective of the test was to measure the physical properties and dimensional requirements for the PLATO FPA prototype. These measurements included mass measurement, moment of inertia, envelope check and LTSM position definition. All the obtained measurements are within the margin determined by previous calculations and analyses.

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10. Conclusions

In this paper all the prototype design activities have been described, and the environmental test campaign results are shown. The following conclusions can be extracted from Prototype Integration and Test campaign:

- Using the learnt lessons during first integration, a second FPA prototype AIV round will be carried out in order to improve integration procedure and repeat measurements to confirm the compliance of the requirements.
- Regarding Test Campaign, all test have been performed successfully except shock test (set up will be reviewed to achieve the shock target).
- Intermediate measures (CMM and optical) demonstrate that FPA structure keeps CCDs in place during mechanical and thermal tests.

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