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Abstract— **Gaia is the European Space Agency's cornerstone mission for global space astrometry. Its goal is to make the largest, most precise three-dimensional map of our Galaxy by surveying an unprecedented number of stars.**

This paper gives an overview of the mechanical system engineering and verification of the payload module. This development includes several technical challenges. First of all, the very high stability performance as required for the mission is a key driver for the design, which incurs a high degree of stability. This is achieved through the extensive use of Silicon Carbide (Boostec® SiC) for both structures and mirrors, a high mechanical and thermal decoupling between payload and service modules, and the use of high-performance engineering tools. Compliance of payload mass and volume with launcher capability is another key challenge, as well as the development and manufacturing of the 3.2-meter diameter toroidal primary structure. The spacecraft mechanical verification follows an innovative approach, with direct testing on the flight model, without any dedicated structural model.

***Index Terms*—Optical instrument optimized development**

I. OVERVIEW

A. Mission features

Gaia primary science case is devoted to the understanding of our Galaxy's composition, structure and evolution.

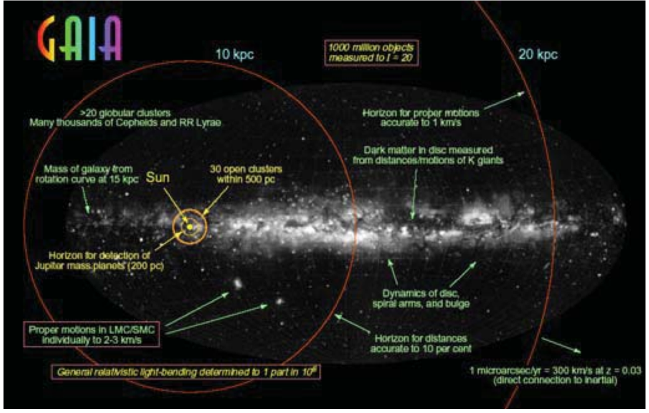

Fig. 1. Some features of Gaia science objectives

To this aim, objects belonging to the Milky Way, or at its vicinity, will be probed for both spatial location and velocity as well as for luminance and chrominance. The relative high distance between these objects and the Gaia spacecraft leads to parallax of up to 100 kparsec (i.e. parallax angle of less than 1/100.000 of arcsecond), the required spacecraft angular stability between the two telescope lines of sight (so called Basic Angle, see Fig.2) shall be commensurate with these values, to about 10 micro-second of arc, and the actual Basic Angle value known to an even better accuracy. Hence, beyond the strength and stiffness performances commonly required in space missions, utmost thermal and dimensional stability is clearly a mechanically dimensioning factor.

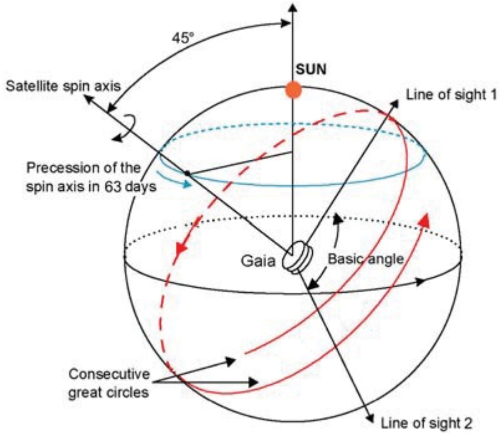

Fig. 2. Gaia scientific measurement principles

The Gaia spacecraft will be launched by a Soyuz-Fregat 2-1b launcher from the Centre Spatial Guyanais in 2013. Gaia will be injected onto a one million kilometre high elliptical orbit so that, when reaching the apogee, it can be stabilised on a Lissajous orbit around the second lagrangian point of the Sun-Earth/Moon system (L2).

As part of the early operations phase just after launch, the launch bipods maintaining the instrument are released, so is the large deployable sunshield, which is then unfurled so as to stabilise the thermal environment and to provide energy through its solar array panels.

En route to its final destination at L2, the spacecraft will be commissioned, and will eventually be stabilised on a Lissajous orbit around L2 with a fixed solar aspect angle of 45° so as to provide the required environmental stability mandatory for the scientific mission.

B. Spacecraft overall description

The Gaia spacecraft has a size of 3.8 m diameter and a height of 3.5 m. Its mass at launch is of 2100 kg, among which about 400 kg are devoted to the propulsion propellant (chemical and gaseous Nitrogen). Its operating electrical power is of about 1300 W, and it has a 5 year lifetime.

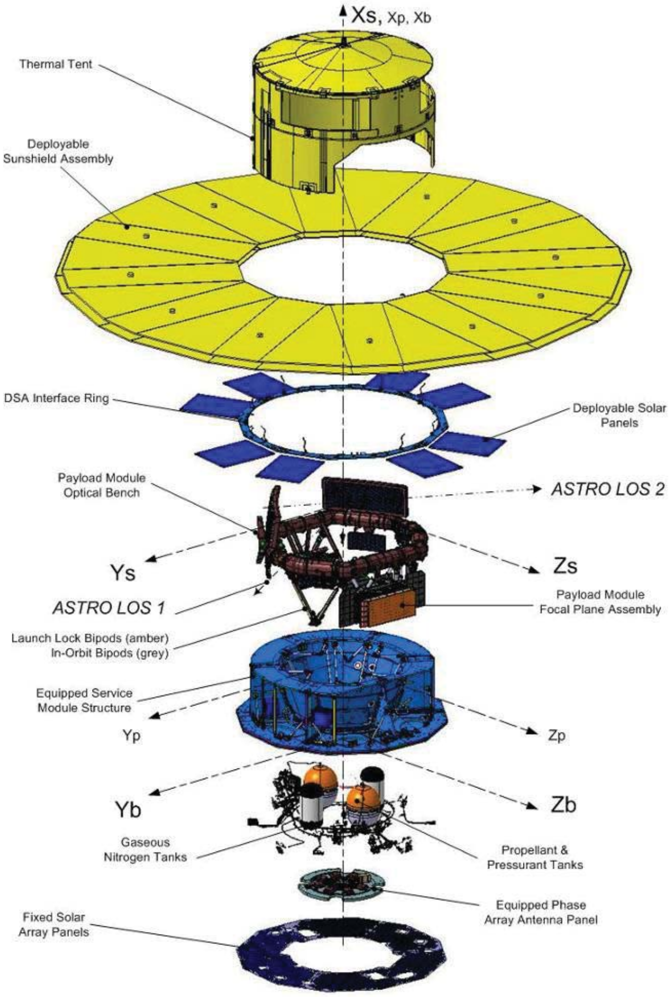

Fig. 3. Gaia spacecraft exploded view

In order to cope with mission stability needs, the Spacecraft (S/C) has been separated in two modules:

- The Payload Module (PLM), mainly composed of :
    - an opto-mechanical bench in Boostec® SiC, with a toroidal structure and a set of mirrors,
    - a large size Focal Plane Assembly (FPA),
    - the Radial Velocity Spectrometer and the Basic Angle Monitoring Opto-Mechanical Assemblies,
    - two sets of three launch (resp. in-orbit) Bipods and Release Mechanisms (BRM), maintaining the PLM atop the SVM during ground and launch (resp. in orbit) operations.
- The Service Module (SVM), mainly composed of :
    - the spacecraft structure, harness and thermal control on which are assembled the electrical equipment from service and payload modules,
    - the chemical & micro propulsion systems,
    - The service module appendages (the Deployable Sunshield Assembly (DSA) for stabilising the thermal environment of both modules, Solar array panels, the Thermal Tent Structure (TTS), and antennae)

II. PAYLOAD MODULE (PLM) OVERALL DEVELOPMENT

A. Introduction

Among the main factors identified as strongly influencing the Gaia spacecraft design and development, two are directly applicable for the PLM:

- Mass and volume resources limited by the Soyuz-Fregat fairing volume and launch performance,
- Stringent thermal and dimensional stability, requiring strong thermal and mechanical decoupling of the PLM instrument from the rest of the spacecraft.

Taken advantage of the integrated industrial team (Spacecraft and Instrument), the design iterations were kept as short as possible in order not to increase the quite long time necessary for such demanding instrument design and manufacturing files consolidation, driven by paramount stability requirements and mass/volume constraints applying on a complex 3-D structure.

B. Payload Module features

The main design drivers are very stringent: basic angle stability (i.e., mastering of potential variation of relative telescope Line Of Sight (LOS) to less than 7 µas), stiffness and mass (about 20 Hz min and 700 kg max), together with the accommodation of 2 large 3 mirrors anastigmatic telescopes, with an aperture size of 1.5m², and a large focal plane of about 1 Giga pixels. The low operating temperature of 120 K is another key characteristic.

Silicon carbide (Boostec® SiC) stands out as the best choice for the structure and telescopes: this single phase material, homogeneous and isotropic, with a very high specific rigidity, has also a high thermal conductivity, a low CTE and is not sensitive to moisture neither to radiation. The use of this material is the essential key to meet the requirements. Another key element is to decouple the instrument from the thermal and thermo-elastic perturbations through high efficiency MLI and through glass fibre composite (GFRP) bipods, which have to be mounted in parallel to carbon fibre composite (CFRP) bipods necessary to withstand the launch environment.

The mechanical architecture features a large torus structure, supporting the two large three mirrors telescopes of 35m focal length, with combining and folding mirrors, optical devices, and the FPA. It interfaces with the SVM through 3 bipods subsystems (BRM). The overall envelope is a cylinder of about 3.2 m in diameter and 2 m high.

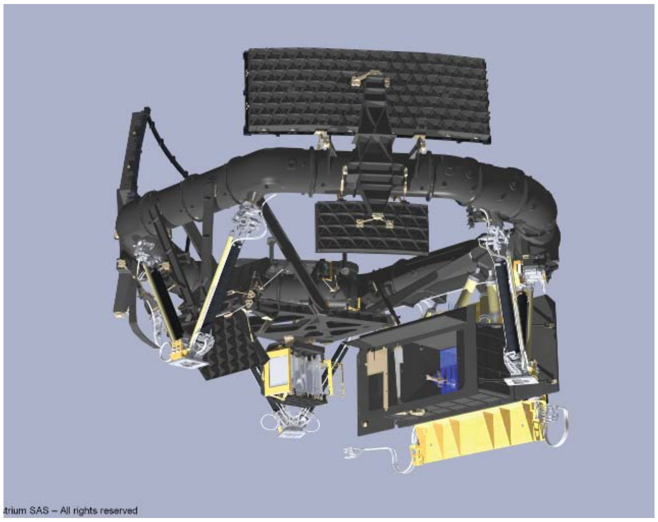

Fig. 4. Payload module overview (DMU)

Since the distortions at payload interface cannot be tested with affordable effort, high value has been set on the accuracy of the mathematical thermo-elastic models. A detailed stochastic analysis has been performed in order to assess design robustness.

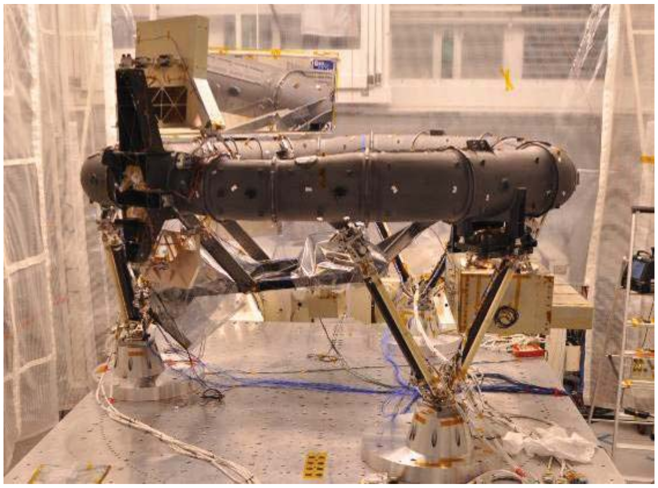

Fig. 5. Payload module SM on the shaker

The overall mechanical accommodation, together with the selected interfaces design, allows parallelizing several developments of subassemblies, with the constraint of implementing a strict follow up of mass and interface loads and capabilities.

The modularity offered by the design is directly applicable to the development phase, therefore securing the schedule.

C. Overall Mechanical Design Consolidation

The mechanical design consolidation phases (B & C) have classically been divided in several sub-phases, with intensive exchange of finite element models and digital mock-up databases within the industrial team:

During the early design phase, performance of Spacecraft system analyses led to settle apportionment of mechanical resources (e.g. mass & stiffness during launch, mechanically and thermally induced distortion during in-orbit phase) and to derive the related specifications as an input to structure preliminary and detailed design to follow. These specifications have in turn been flown down to the instrument subsystems. In parallel, the instrument mechanical accommodation is detailed.

During the subsystem and system preliminary, then critical design review (PDR, CDR) cycles, an advanced Launcher Coupled Loads Analysis (CLA) at S/C PDR was the key to refine the applicable mechanical environment. Associated to an early freeze of major interfaces and mass allocation, it led to tailor the PLM applicable sine and quasi-static environment, which was then derived down to the PLM subassemblies. The Instrument CDR provides the associated design justification files, to confirm performance level and compliance to above defined requirements, then freeze manufacturing files. Finally system analyses using SVM and PLM structure modelling from previous phase are repeated, so as to confirm overall system performance and specification apportionment, authorising modules and spacecraft assembly.

D. Overall Mechanical Assembly and Verification

The Payload Module follows the Spacecraft mechanical assembly and verification approach:

Once the bottom-up CDR process is completed, the assembly and verification phase (D) is undertaken as depicted in Fig. 6, and detailed in the following sections.

In order to cope with the constraints mentioned in section II. A and B within the programmatic limits set to the project, a specific thermo-mechanical verification approach has been selected so as to ensure a safe, but efficient, development throughput, characterised by:

1. Deletion of standard structural and/or thermal models, to avoid duplication of effort and schedule,
2. Systematic advanced proof-tests on structural individual parts, before assembly of the flight structure.
3. Implementation of dedicated PLM mechanical test campaign (sine and quasi-static) on an intermediate configuration based on the structure flight model (including the bipods), together with a full set of flight combining and folding mirrors and a flight telescope (3 mirrors). The remaining subassemblies, mainly the other telescope, the FPA and the RVS are dummies.
4. Risk mitigation of the FPA development through the same approach, leading to the delivery of a fully qualified FPA PFM for the PLM PFM
5. Acceptance of the PLM PFM (full flight standard) through a reduced mechanical test campaign, before integration on the full spacecraft proto-flight model,

6. Performance of PLM thermal balance & vacuum tests at PLM level, taking benefit of the strong thermal decoupling with the SVM, and considering that there it no facility large enough in Europe to perform a TB/TV test of the full S/C flight configuration with deployed DSA.

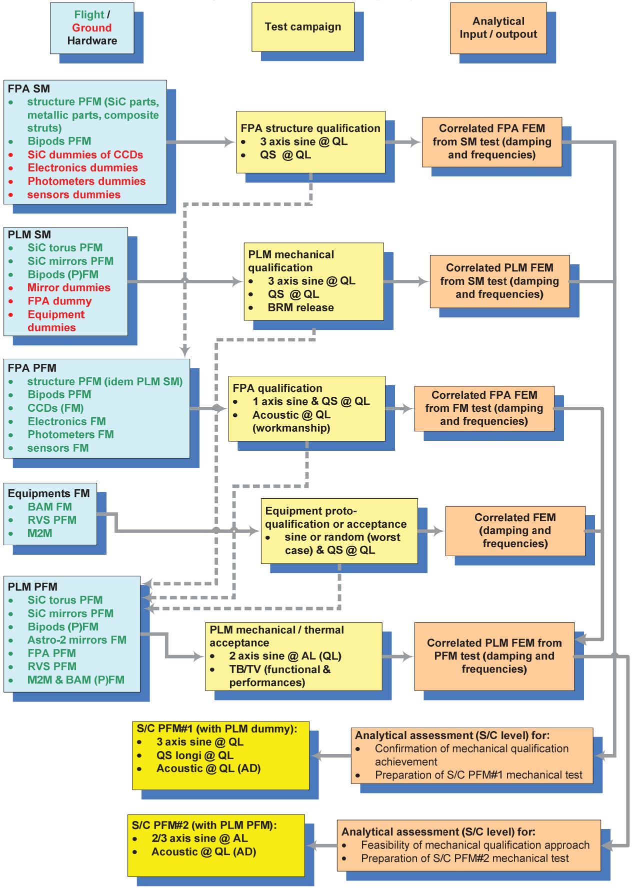

Fig. 6. Payload module mechanical development flow

The above scheme enables a modular and incremental verification of the relevant mechanical and thermal performances, for the sake of mission performances prediction and validation.

In order to ensure robustness of this one shot, streamlined approach, a sensible margin philosophy has been ensured throughout the mechanical design phases. This secured in particular the mechanical qualification, so that its validity is only a matter of confirmation once the final launcher coupled dynamic analysis is done.

In addition, the mechanical specification apportionment was facilitated by the coverage of all related mechanical design and verification by the spacecraft industrial team, with a clear and streamlined approach following the modular construction of the spacecraft.

The thermoelastic stability requirements are so challenging that an extensive on-ground verification by test is impossible. Performance is then mainly verified by analysis, with thermal and stiffness correlation /characterisation to the maximum affordable extent.

III. OPTICAL BENCH

A. Structure

One challenge was to imagine a very large quasi monolithic, isotropic, light and stiff structure (*i.e.*, made of Boostec® SiC), compatible with the optical design, but also with the analysis tools and manufacturing capabilities:

As a result of the optical layout, the supporting structure features a torus like structure with a diameter of about 3.2 m, in the middle of which is lying a large tray supported by long struts. Each mirror or subassembly is fitted to the structure through iso-static mounts, so as to master interface loads / displacements and therefore to authorize the performance of the structure, mirrors and subassemblies developments in parallel.

The applicable mechanical environment is defined in terms of quasi-static and sine excitations, random and acoustic. The quasi-static and sine environment is covering the mechanical inputs and is therefore used for the instrument dimensioning.

It is quite common to use enveloping quasi-static levels at sub-assembly or parts level, which include sine effect, in order to simplify the development. This approach implies however to have margins in terms of strength or mass so that it is possible to define enveloping dimensioning cases. Despite several attempts, it was not possible to define a quasi-static dimensioning environment for the structure, because of the complexity of loads fluxes. Therefore, the structure dimensioning was based on both quasi-static and sine analysis, impacting directly the overall volume of analysis to be performed, hence the development schedule.

On another hand, the PLM structure (mainly the torus and the folding optic structure) is very complex in terms geometry, load distribution and interfaces. Because of its size, a full 3D finite element model cannot be envisaged. For system analysis, as far as stiffness is concerned, a simplified 2D model is sufficient. It needs however to be correlated with the outcomes of the detailed design phase, for which a 3D model is required due to the needed optimisation and the complex geometry and interfaces (at least for the most stressed elements: segments of the torus and the large tray). Furthermore, the detailed design phase has to be consolidated at system level, meaning that models used for one or the other type of analysis shall be homogeneous or their transfer/modifications validated. In front of these major issues (size of the model, handling of a 2D and a 3D model in parallel with question marks on representativeness, consolidation of the detailed design phase) and because of the need to have a step by step manufacturing sequence, it was decided to select an original approach based on the multi-excitation enforced motion method:

The torus structure is designed as the assembly of several parts, so called segments. The segments boundary is based on the accommodation of, and interfaces with, sub-assemblies, and associated load fluxes. The interface loads and displacements of the segment to be designed are computed in a global torus FEM: the model of this segment is fully detailed for its interfaces (the brazed joint geometry is well known and modelled in 3D) and made of 2D elements for the remaining geometry. The remaining segments of the torus are either simplified, i.e., 2D models, or condensed 3D models of already designed and dimensioned segments. Thanks to the computed boundary conditions (for each load case), the detailed design of the segment is performed individually on a full (and large) 3D model, including necessary iterations to comply with the required margins of safety. At the end, the 3D model of the segment is condensed and included in the instrument structure FEM, before the dimensioning of the following segment.

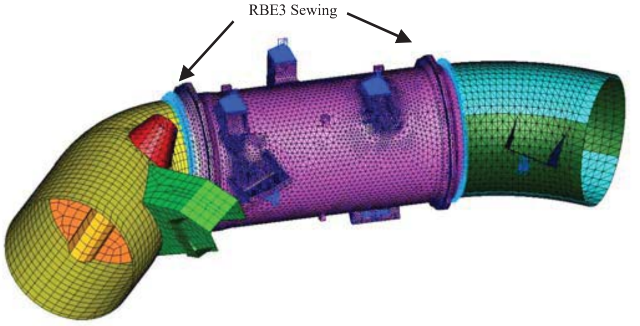

Fig. 7. Segment modelling

Such method is very efficient and flexible for both system and detailed design activities:

- It allows to perform the detailed dimensioning of several structural parts in parallel, with different teams. Emphasis can be put on one segment without impacting the sizing of the other segments, whatever the number of iterations is needed.
- Path and exchanges between system level and detail design level are very simple and ensure a very good traceability of potential evolutions.
- Validation of each detailed design is performed at system level
- Manufacturing files of each segment or mechanical part can be established quasi-independently from the other segments,
- Manufacturing can start well in advance of last segment sized, reducing the overall manufacturing duration (manufacturing is no longer in series with the end of the design) the manufacturing and associated proof-testing can be performed part by part, reducing the overall schedule.

The statistical nature of the strength of the Boostec® SiC is taken into account in the detailed design phase through the use of a Weibull distribution. Specific routines have been defined and implemented in the analysis tools, in order to assess the probability of failure of the segment, as well as the definition of the proof-test, which will enable the reduction of this probability to acceptable levels.

On regular basis, as necessary, the instrument FEM is run with the torus being composed of condensed models of the dimensioned segments. Interface loads and displacements are computed again at each segment interface, allowing to check the stresses inside the segment (with its full 3D model). This allows to verify that the (even small) discrepancies between the final system FEM (2D) built with all segments condensed 3D models and the detailed design 3D models are of negligible effect on the sizing.

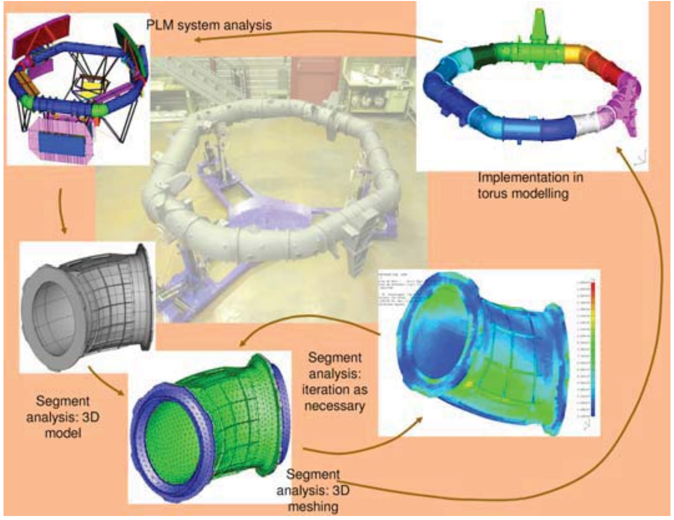

Fig. 8. torus dimensioning logic

The final step is performed with all the very detailed FEMs used to validate the detailed design and sizing of the different elements and sub-assemblies: an instrument level FEM is built with the latest up-to-date sub-assemblies or equipment FEMs. It takes therefore into account both the detailed design of the structure and the detailed design of the equipments and subassemblies.

The detailed design phase coverage is checked at 2 levels: the first one is obviously the maximum stress seen by the segment (a discrepancy of some percent may be observed due to the FEMs evolutions). The second one is the ratio at element level of the stresses computed during the 2 phases. The first one allows to confirm the compliance with the safety margin requirements, the second one allows to confirm the outcomes of the proof-test, which have been defined to cover the qualification loads plus some additional margins.

The same approach was successfully used for the Folding Optics Structure, even if the tray is monolithic, in order to assess in detail stresses in specific local areas under flight environment and also under proof-test loading.

The assembly of the torus is performed by brazing the segments together. The margins in these joints are also verified with the system model.

At the end, the final instrument model allows to recover the stress restitution at any location of the torus or of the folding optics structure, if needed at a later stage (for the mechanical and thermal test prediction for instance).

B. Bipods & Release Mechanisms (BRM)

The interface of the optical bench with the service module (SVM) top floor is ensured by 3 identical assemblies: specific in-orbit Glass Fibre Reinforced Plastic (GFRP) bipods provide the required mechanical and thermal decoupling from the service module, leaving the stiff support function to releasable Carbon Fibre Reinforced Plastic (CFRP) launch bipods. The latter are the load path between stiff SVM top floor pattern and the torus neutral fibre. Their layout (upside-down with respect to usual configuration) allows a better load introduction in the torus. The separation mechanism uses a non explosive actuator, to minimise shock at opening.

The BRM's are subcontracted, with classical follow-up activities. Each of the sub-assembly is characterized in terms of stiffness before delivery to the instrument.

One of the BRM experiences a qualification campaign, and the final qualification of the full sub-system is achieved during the PLM SM testing (with the PFM torus).

C. Mirrors

Because the mirrors lead time is very long due to polishing activities, their manufacturing was released very early in the programme. This was made possible because the design drivers of such mirrors made of Boostec® SiC are the optical performances (mechanical performances being achieved with large margins), and also because they are attached to the structure through dedicated iso-static mounts, which interfaces have been frozen at that time.

The iso-static mounts have then been dimensioned in a second step, with due consideration of the interface loads from the system analysis.

IV. FOCAL PLANE ASSEMBLY (FPA)

The FPA is very large (1.9m x 1m x 1.2m, 180 kg) and complex, featuring a lot of charge coupled device (CCD). Its design benefited from a comprehensive ESA Technological Development Activity.

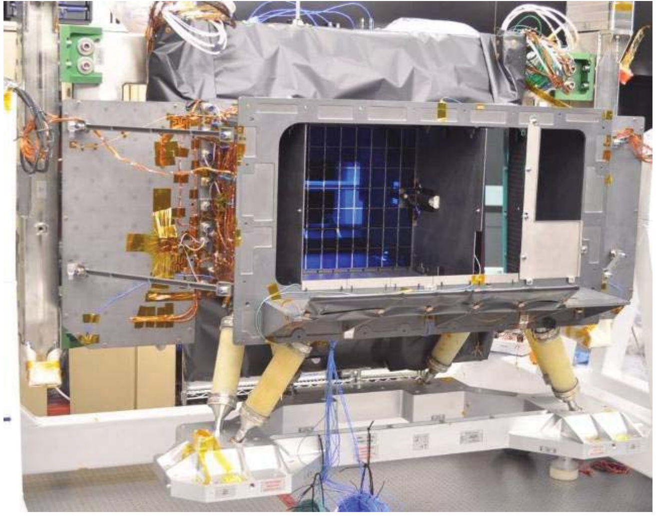

Fig. 9. FPA on its MGSE (upside down)

The FPA is composed of one open box-like structure of Boostec® SiC fitted with 106 CCD in the bottom panel, and one other metallic box like structure which accommodate all the proximity electronics, this last one being iso-statically attached close to the CCD plane.

These 2 parts have to be strongly thermally decoupled (electronics are working at about 293K while CCD's need to be kept at about 150K), through specific thermal shields and insulated bipods.

This focal plane assembly is so large and complex that it constitutes a project on his own. Its mechanical development encountered very delicate Boostec® SiC dimensioning such as a thin and lacy baseplate for the CCD interface, and its bolted assembly to the large box, acting both as a support structure and as a radiator.

Again, based on an early freeze of interfaces and geometrical characteristics on one side, and on an early definition of the applicable mechanical environment, the FPA development is performed in parallel of the optical bench development, with the same analysis tools and database. Such approach is enabled by the integrated industrial team (FPA and Instrument), allowing design iterations and model exchanges as frequent as necessary, with a reaction time as short as possible.

The FPA follows the same approach as the PLM: the qualification of the structure is performed on a structural model (i.e., flight structure fitted with dummy CCD and electronics dummies) passing through 3-axis sine and QS tests, then a full proto-qualification campaign (sine test for the worst axis only and acoustic for workmanship) applies to the flight model.

V. PAYLOAD MODULE VERIFICATION

Analytical verification is performed in synergy with the integrated industrial team with timely payload / FPA FEM deliveries, so that any evolution can be anticipated as necessary.

The payload development is secured from proof-test up to the proto-qualification model, with intermediate qualification of the structure and major subassemblies. It can be highlighted that the effect of the statistical behaviour of the Boostec® SiC is vanished at the completion of the qualification test.

Also, extensive characterisation test campaign have been performed to define bonding and braze allowable, so that the assembly level qualification is well secured.

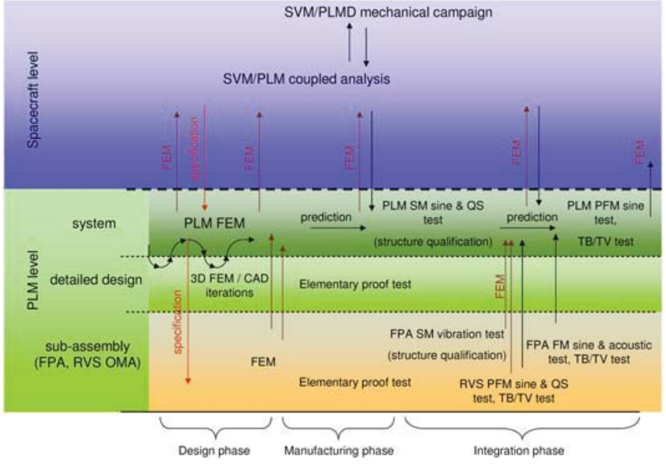

Fig. 10. PLM verification approach

When possible, verification by test has been prioritized. The enhanced structural model of both FPA and instrument were dedicated to the mechanical qualification of the flight structures, when submitted to quasi-static and sine environment. The full demonstration of mechanical acceptance will be finally given with the PLM PFM mechanical campaign, which will only include transverse axis vibration test (these 2 axes covering the vertical axis needs).

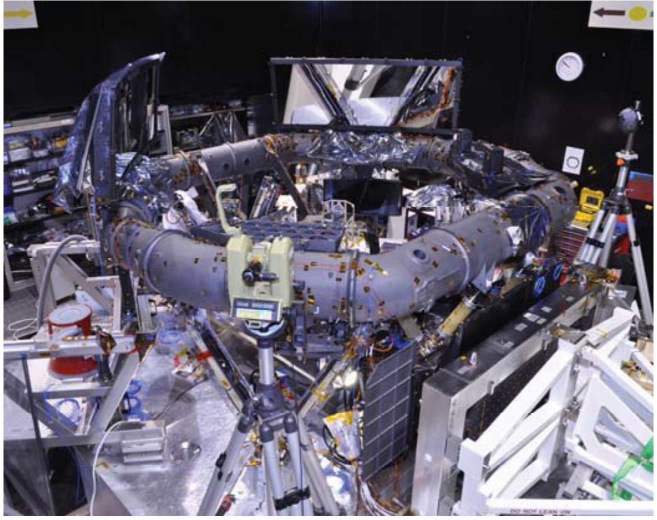

Fig. 11. PLM PFM during final step of integration

Together with a thermo-stable environment, the PLM interface distortions have been minimised in order to reach the very demanding basic angle stability. In terms of design, this is achieved through the selected material and through the accommodation. Because the contributors to the PLM stability are mainly external to the PLM, and because the related displacements are so small, it is extremely difficult to verify such performance, even with a mixed analysis/test verification approach. This is why such important performance is assessed at the higher level, in order to provide the most accurate value. The basic angle variation as a function of thermal environment and as a function of interfaces displacements are delivered in the form of matrices, implemented in the spacecraft model for computation of the consolidated basic angle stability.

Specific improvements and developments of the analytical tools and methods were necessary to cope with the accuracy required for the very tiny basic angle variation, and validated through e.g. stochastic analyses.

VI. SPACECRAFT MECHANICAL TESTING (CONSOLIDATION)

The used approach for the instrument is made affordable by the spacecraft approach, leading to the following optimized test campaign sequence:

- the first S/C model (PFM#1 with a highly representative PLM dummy) allowed to qualify the Gaia S/C with regard to acoustic levels, S/C interface flux including over-flux, and SVM structure interface loads to PLM, propellant tanks and unit interfaces. Fundamental frequencies as required by launcher have also been checked and fulfilled.
- This step allows to confirm or refine the qualification levels to be achieved through the instrument qualification test.
- the main objective of the S/C PFM second test (PFM#2, including also the PLM PFM, but no DSA) is to apply acceptance loads to S/C, PLM and SVM interfaces and to confirm their dynamic coupling. Sine and acoustic environment will be applied.

For all the different configuration test preparation, modelling of three S/C configurations have been established i.e. Flight, PFM#1 and PFM#2, taking into account latest mathematical models from modules and assemblies, updated with regard to latest mass measurements and global/local stiffness test results, up to final flight predictions.

VII. CONCLUSION

Through the Gaia spacecraft and instrument mechanical development, it is being demonstrated that a streamlined approach can be implemented as a meaningful compromise between:

- affordable throughput time and programme costs on one hand, thanks to use of one-shot flight structures for qualification and acceptance testing,
- exhaustive testing verification with coverage of the quasi-static, sine vibration and acoustic noise environment on the other hand (with an optimized testing level at spacecraft or instrument), thanks to concurrent engineering tools now extensively deployed, and to robust strength and stiffness margin policy which is the guarantee of stable mechanical environment and of strength/stiffness performances.

This is done with due respect to the project management phases and rules traditionally but efficiently followed during development of ESA science missions.

Specific analysis tools have been extensively validated and are now in place within Astrium for developing large and very stable Silicon carbide (Boostec® SiC) structures and instruments.

The optimized approach implemented for Gaia represents an optimum response to challenging ESA science programmes using single shot platforms and very stable instruments.