ARIEL PAYLOAD STRUCTURAL ARCHITECTURE: DESIGN, ANALYSIS AND VERIFICATION CHALLENGES

Davide Bruzzi (1), Martin Whalley (1), Sandy Fok (1), Andrew Caldwell (1), Lucile Desjonqueres (1), Georgia Bishop (1), Paul Eccleston (1), Delphine Jollet (2), Robert Knockaert (2), Salma Fahmy (2)

(1) RAL Space, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, United Kingdom, Email: davide.bruzzi@stfc.ac.uk

(2) European Space Agency, ESA-ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, Netherlands, Email: delphine.jollet@esa.int

KEYWORDS

Payload architecture, structural design, model philosophy, thermo-elastic deformation, structural analysis, Finite Element Method, vibration testing.

ABSTRACT

Ariel (the Atmospheric Remote-sensing Infrared Exoplanet Large-survey), the M4 mission for the ESA cosmic vision program, will conduct a large, unbiased spectroscopic survey. It will explore the nature of exoplanet atmospheres and interiors and, through this, the key factors affecting the formation and evolution of planetary systems as explained in [1]. Ariel is planned to be launched on board an Ariane 6.2 in 2029 and the payload is developed by a consortium of more than 50 institutes from 16 ESA countries. The breakdown of responsibilities and national contributions for each functional block of the payload is shown in Figure 1.

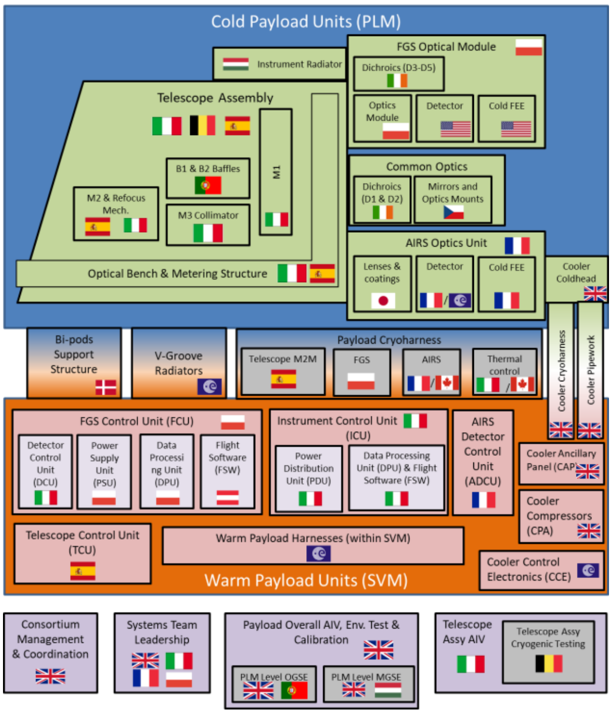

Figure 1: Ariel Payload block diagram and responsibilities

The Ariel Payload has recently approached the Preliminary Design Review milestone and manufacturing of the Structural Model has already started.
After a description of the baseline mechanical architecture of the payload, highlighting the main design drivers, this paper will focus on the structural analysis, test strategies and methodologies defined at Ariel Payload level summarising the significant technical and programmatic challenges of the program together with the proposed approaches and configurations which are to be implemented at the various verification levels and stages.

1. OVERALL PAYLOAD ARCHITECTURE

The baseline architecture splits the Payload into two major sections: the cold Payload Module (PLM) and the items of the payload that mount within the Spacecraft Service Module (SVM) as shown in Figure 2.

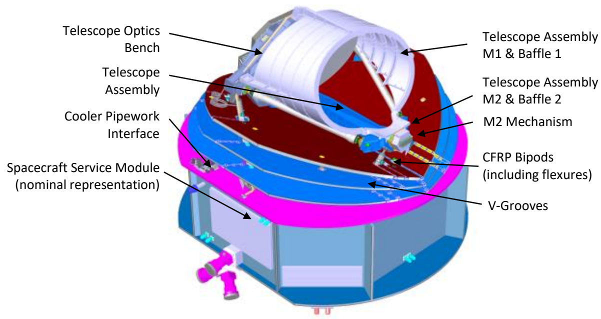

Figure 2: Illustration of the Ariel PLM and SVM

The current mass estimation for the cold Payload Module is currently 414 kg, including design maturity margins, and its envelope is approximately 2620 mm (L) x 2300 mm (W) x 1305 mm (H).
The integrated Payload Module consists of an all-aluminium off-axis Cassegrain telescope (M1 primary mirror 1100 mm x 730 mm ellipse) with a re-focussing mechanism accommodated behind the M2 mirror that allows correction for any misalignment generated during the telescope assembly or launch and cool down. The current design foresees that all the cryogenic components of the Payload architecture, including reflective

optical elements, are manufactured from a common material, aluminium 6061 T651 or T652 (or 6082 T651) alloy. This ensures matched CTEs, allowing warm alignment of the Payload to proceed, with a high degree of confidence that this will be maintained when cooled to operating temperatures. This builds on the significant design heritage within Europe of building all-aluminium space instruments for cryogenic operation.

The Bipods connect the Telescope Assembly to the Spacecraft Module, at the Payload Interface Plate. The (six) struts consist of carbon fibre tubes (which are stiff and have low thermal conductivity) with titanium alloy flexures at both ends (whose stiffness has been tuned to meet both the launch and thermal contraction requirements). To achieve the required operational temperatures, the Telescope Assembly must also be shielded from the thermal radiation emitted and reflected from the Service Module. The V-Groove assembly performs this function as shown in Figure 2 and Figure 3.

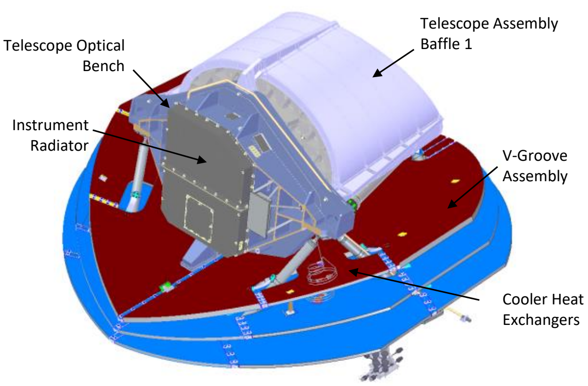

Figure 3: Illustration of the rear of the Ariel PLM

1.1. Mechanical and structural design

The main mechanical design drivers for the structural elements of the Payload Module are to support the optical elements and science subsystems in a sufficiently stiff and strong manner to survive the launch and operational environments, whilst also allowing for the contraction of the Payload as the operational temperature is reached. The optical elements M1 to M4 are mounted to the structural components of the Telescope Assembly (TA), namely the Telescope Optical Bench (TOB) and Telescope Metering Structure (TMS), as shown in Figure 4.

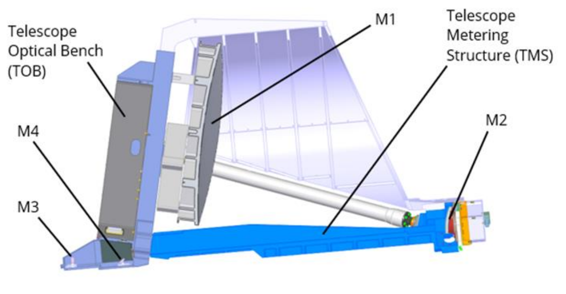

Figure 4: TA structural and optical elements

These structural components are manufactured from grades of Aluminium alloy similar to the mirrors themselves, so that the telescope remains aligned as it cools to operational temperature. The choice of aluminium alloy 6061 and 6082 is due to their almost identical CTE values between room and cryogenic temperatures, good availability, and extensive heritage [2].

To guarantee sufficient dimensional stability and avoid elastic recovery during and after the manufacturing process, the temper T651 (solution treatment, stress-relieve by stretching and artificially aging) has been selected although T652 (solution treatment, stress-relieve by compressive deformation and artificially aging) is also used for large components, such as the Telescope Optics Bench and the Telescope Metering Structure due to the impossibility to procure a 6061 T651 aluminium billet large enough to manufacture those elements as monolithic parts.

Results of the material properties measurement on the first full-size billet of material of aluminium 6061 T652 are expected in Spring 2023 and in the meantime the structural analyses have been performed using de-rated material properties compared to aluminium 6061 T651 typical values (approximately -43% for yield strength and -29% for ultimate strength).

Additional optical elements (in the Common Optics Assembly) and the two science instruments (AIRS and FGS) are mounted inside the Telescope Optical Bench. The structural components of these subsystems are also made from aluminium alloy. The Baffle assembly surrounding the M1 mirror and covering M2 is not structural. It is attached to the Telescope Optical Bench and to the front end of the Telescope Metering Structure. Similarly to other components, the Baffle is also manufactured from aluminium alloy to minimise the stresses induced from the cooldown of the Telescope Assembly structure.

One consequence of the all-aluminium construction of the Telescope Assembly coupled with the cold temperatures required for operation is its large contraction relative to the Spacecraft Service Module. The Telescope Assembly must also be thermally isolated from the Spacecraft for those temperatures to be achieved. The structure supporting the Telescope Assembly must therefore have low thermal conductivity and low stiffness, so that the Telescope Assembly is not significantly distorted by the differential contraction. However, the stiffness must be sufficiently high to avoid the risk of modal coupling between the Payload and Spacecraft during launch, and to reduce the impact of micro-vibration in operation.

These requirements are met by the Bipods; six struts that connect the Telescope Assembly to the Spacecraft Module, at the Payload Interface Plate (PIP). As shown in Figure 5, the struts consist of carbon fibre tubes (which are stiff and have low thermal conductivity) with titanium alloy flexures at both ends (whose stiffness has been tuned to meet both the launch mechanical environment and thermal contraction requirements).

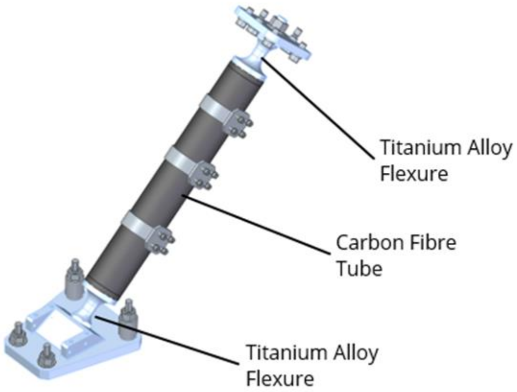

Figure 5: Bipod (front)

The mechanical design drivers for the V-Grooves are similar to those of the Telescope Assembly and Bipods; flexibility to avoid excessive stresses due to thermal contraction, whilst achieving sufficient stiffness and strength to survive the launch environment, within the allocated mass budget. Each of the V-Grooves will reach different temperatures in operation, hence their support structures must also be thermally isolating.
There are no structural connections between the V-Grooves and the rest of the Payload, except via the Payload Interface Plate (to minimise the effects of any structural deformations of the V-Grooves on the Telescope). The V-Groove panels themselves are constructed from aluminium alloy honeycomb with reflective aluminium alloy face skins. The support struts between them are made from glass fibre reinforced plastic (GFRP), to guarantee thermal isolation. The limited accommodation available for the V-Grooves (between the Telescope Assembly and the Payload Interface Plate) restricts the length of the central V-Groove supports, and it was necessary to recess these supports into the Payload Interface Plate to provide adequate length to achieve the thermal isolation and flexibility required. These constraints also pose significant challenges in terms of assembly and integration activities. The V-Groove assembly is shown in Figure 6.

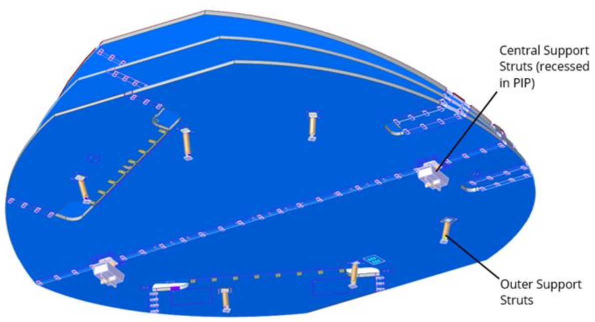

Figure 6: V-Grooves and supports

1.2. Model philosophy

The Ariel Payload level Assembly, Integration and Test programme foresees five models:
1. Spacecraft Structural Model (sSM), structurally representative units delivered for integration and testing at Spacecraft level only
2. Payload Structural Model (pSM), model of the PLM used for mechanical testing at Payload level only to provide verification of the mechanical behaviour of the PLM structure as well as checks of the changes in mechanical alignment
3. Engineering Model (EM), Payload model including parts from the pSM and new subsystem parts, used to assess the Payload performance
4. Avionics Model (AVM), consisting of the warm electronic units (ICU, TCU, FCU and CCE) and PLM cold simulator, for use at Spacecraft Prime only to provide verification of the communications and electrical behaviour and instigate ground test sequences and flight operations
5. Proto Flight Model (PFM)

The approach to testing and qualification of the Payload as a whole is to remove as much of the risk at the higher levels of integration as possible by undertaking verification activities on the sub-systems delivered into first the Instruments then the Payload Module AIV programme. With reference to Figure 7, the experience gained from earlier models (sSM, pSM, EM and AVM) will ensure the PFM design and AIT programme are optimised.

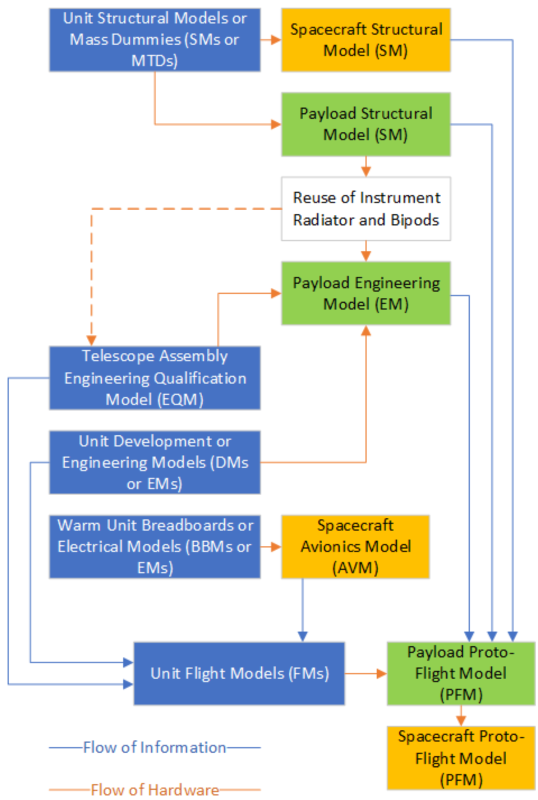

Figure 7: Verification and model logic flow for the Ariel Payload programme

2. THERMO-ELASTIC DEFORMATION CONTROL

One of the critical aspects of the Ariel Payload design is the control of thermo-elastic deformation which is performed at all levels, project phases and verification stages.
Requirements applicable to the Ariel Payload, its subsystems as well as requirements towards the spacecraft are defined to make sure thermo-elastic deformations are minimised by design, verified by analysis and testing, and controlled or compensated as needed during operations.
Control of requirements, interfaces and technical budgets is aimed at ensuring provisions for thermo-elastic deformation control are relevant and up to date.

2.1. Thermal control strategy

As described in [3], the Ariel thermal control is accomplished by a combination of passive and active cooling systems. The Service Module is thermally controlled in the 253K-323K range for nominal operations of all the Spacecraft subsystem units. The function of the cold Payload Module is to shield the scientific instrumentation (the Instruments and the Telescope Assembly) from the warm section of the Spacecraft and to provide it with the required cooling and thermal stability at temperatures < 60K.
As anticipated, the design baseline is that all the cryogenic components of the Payload architecture are manufactured from a common material, aluminium. This ensures that the design has a matched CTE, allowing warm alignment of the payload to proceed, with a high degree of confidence that this will be maintained when cooled to operating temperatures. All-reflective optical elements in the design are also assumed to be manufactured from aluminium for the same reason.
The payload module is passively cooled to ~55 K by isolation from the Spacecraft bus via a series of V-Groove radiators. The V-Grooves system design is a key issue of the Ariel thermal performance as they represent the first cooling stage of the Payload Module. V-Grooves are high efficiency, passive radiant coolers, whose performances in a cold radiative environment such as L2 has been definitively demonstrated by the Planck mission.
At instrument level, the design is once again aimed at minimising the impact of thermo-elastic deformations. For example, where CTE matching is not possible, such as for optical elements or detector mounts, design solutions involving flexures or similar concepts have been implemented.

2.2. Modelling and analysis

The most relevant analysis tool for the control of thermo-elastic deformation is the Structural, Thermal, Optical and Performance (STOP) analysis which involves a sequence of thermal, structural optical and performance analyses aimed at assessing the impact of thermo-elastic deformation. The same model is used for the STOP mechanical analysis and the thermo-elastic analysis.
A set of cases have been agreed between the different disciplines (matching the requirements and planned cases) which will then be individually analysed.
The workflow for the overall STOP analysis is shown in Figure 8. This sequence is repeated at every analysis cycle.

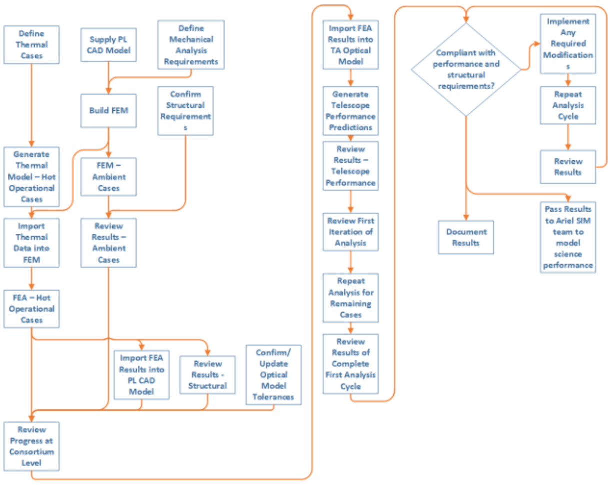

Figure 8: STOP analysis workflow

2.3. Testing

In terms of testing, the thermo-elastic performance is verified at the various integration levels:
- → Spacecraft level on PFM (limited test as operational temperature is not achievable)
- → Payload level on EM and PFM
- → Instrument subsystem level

At instrument level the thermo-elastic performance is verified on:
- → Telescope Assembly on EQM and PFM
- → AIRS on EM and PFM
- → FGS on EQM and FM

2.4. Operations

With reference to the mission profile described in [1], at 1.5 million km from the Earth in the anti-Sun direction, the L2 orbit allows to maintain the same spacecraft attitude relative to the Sun-Earth system, while scanning the whole sky during the mission. Limiting the allowed Solar Aspect Angle (SAA) range, Ariel operates in a very stable thermal environment keeping always in the shade the coldest section of the Payload Module from the Sun/Earth/Moon illumination. The Spacecraft thermal control system will control the Payload Module interface points on the Payload Interface Plate to provide a stable thermal interface.
At payload level, the M2 mirror has a refocus mechanism with three degrees of freedom as a baseline (focus and tip/tilt). The purpose is to correct for one-off movements due to gravity release and

cool-down and potentially to make occasional adjustments (for example to compensate for any long-term drifts in structural stability). As part of Commissioning, the shift in boresight between the payload Telescope and the Service Module star-tracker will be measured and used during science observations.

3. STRUCTURAL MODELLING AND ANALYSIS

3.1. Scope and load cases

As usual structural analysis is performed at all levels, project phases and verification stages. This paper focuses on the analyses performed at RAL Space with the following objectives:

- → Verify relevant mechanical and structural requirements applicable to the Payload Module
- → Create and maintain input level specifications for Payload Module Instruments and Subsystems
- → Validate and cross-check results of analyses performed by other institutions within and outside the Consortium
- → Support mechanical testing at Payload Module level

The structural analyses conducted so far included (but are not limited to):

- → Static analyses, with particular attention to quasi-static load analysis, thermo-elastic analysis, 1g gravity sag analysis, Spacecraft interface tolerance analysis
- → Dynamic analyses, including modal analysis, sine vibration analysis, random vibration analysis

Further dynamic analyses are performed by ESA and the Spacecraft prime:

- → Shock assessment
- → Micro-vibration analysis
- → Acoustic analysis

Additional analyses have been performed to address specific aspects of the structural verification at Subsystem or Payload level.

3.2. Model description

The Ariel PLM FEM is a simplified structural model of the overall Payload Module created by combining together the simplified (or reduced) models of each of the Ariel Payload Subsystems and Instruments with the aim to provide a good representation of the overall structural static and dynamic behaviour while limiting the size of the model. Since the PLM FEM is also used for analyses at Spacecraft and Launch Vehicle level, it has been important to define specific modelling requirements since the early phases of the program.
The current PLM FEM is composed by approximately 420k nodes and 440k elements and it is shown in the following figures.

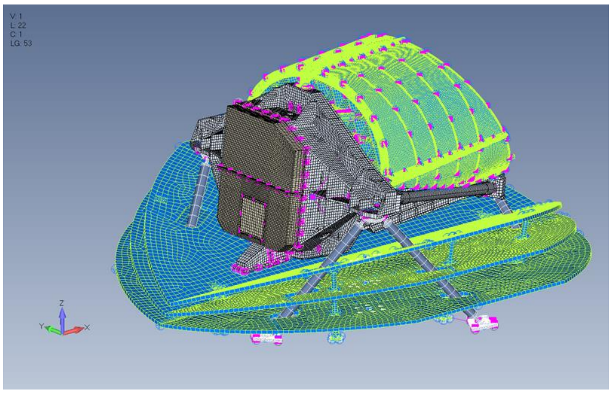

Figure 9: Rear view of PLM FEM

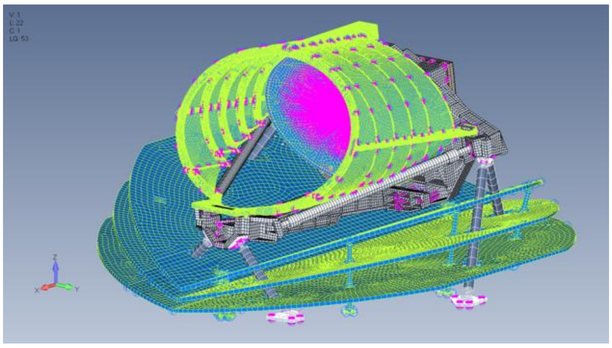

Figure 10: Front view of PLM FEM

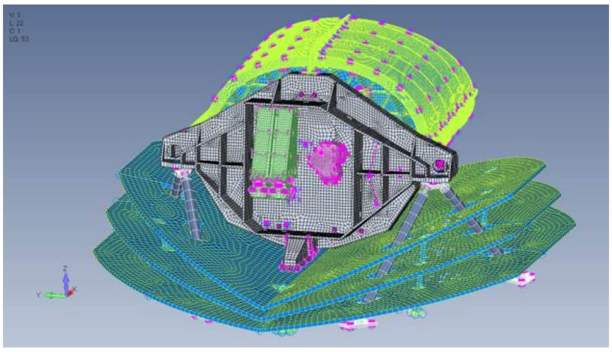

Figure 11: Detailed view of Telescope Optics Bench with AIRS and FGS Instruments

3.3. Analysis results

The results of the structural analyses show overall compliance to the main requirements from the Payload Requirements Document (PRD) including verification of the minimum resonance frequencies as reported later on. Static, dynamic and thermo-elastic load cases have been successfully analysed. Moreover, input levels for the various instruments and subsystems have been generated for comparison with the current specifications.
Where issues have been identified, ways forward have been defined and, in some instances, further investigations and localised design changes have been already proposed and verified in terms of impact (such as the stiffening of the B1-B2 Baffle mounts, proposed improvement of Bipods safe-life design). Therefore, the problematic areas identified are not considered critical.

3.3.1. Modal analysis

The most relevant In-Plane (IP) and Out-of-Plane (OOP) modes of the PLM FEM and corresponding mode shapes extracted from the modal analysis are summarised here below:

- → First Telescope Assembly IP mode (31.99 Hz), twisting of telescope metering structure around the X Axis and bending of the Bipods
- → Telescope Assembly IP/OOP mode (37.02 Hz), bending/rocking of the TA in the XZ plane
- → First V-Grooves IP mode (43.54 Hz), bending/rocking of the V-Grooves in the XZ plane (along the X Axis)
- → V-Grooves IP mode (46.88 Hz), bending/rocking of the V-Grooves in the YZ plane (along the Y Axis) plus local V-Grooves panels flapping
- → V-Grooves IP mode (56.12 Hz), rotation of the V-Grooves around the Z Axis
- → First Telescope Assembly OOP mode (57.61 Hz), bending/rocking of the TA in the XZ plane and vertical compression of the telescope and B1 baffle with coupling in X and Z Axes

Summary plots of the modal effective masses and cumulative modal mass are provided in Figure 12 and Figure 13 respectively.

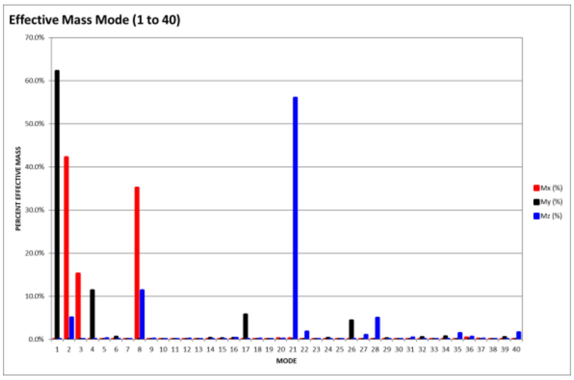

Figure 12: Modal effective mass (%) for the first 40 modes

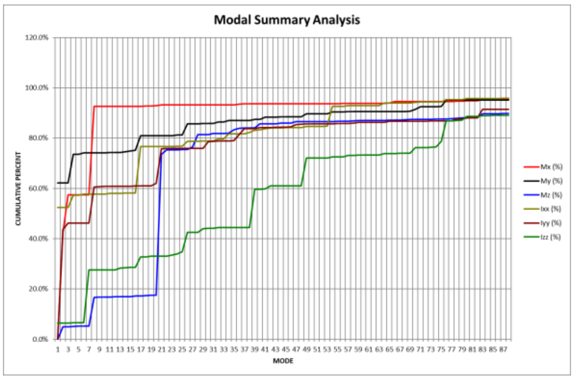

Figure 13: Cumulative modal mass summary

Finally, the three main mode shapes for the Telescope Assembly and the V-Grooves are represented in the following figures.

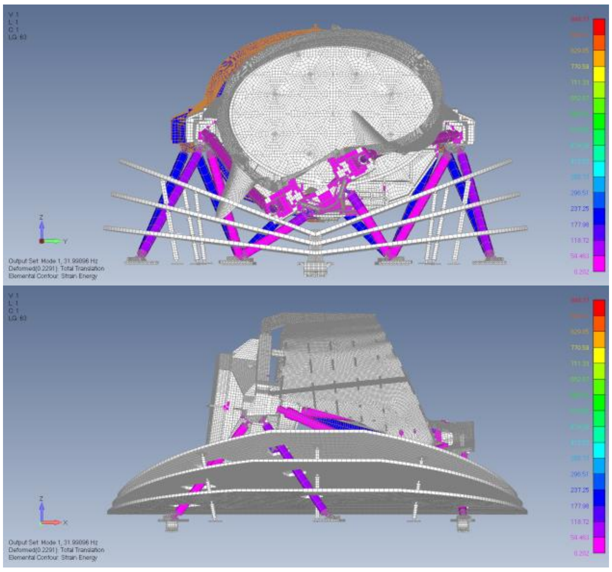

Figure 14: First TA IP mode (31.99 Hz)

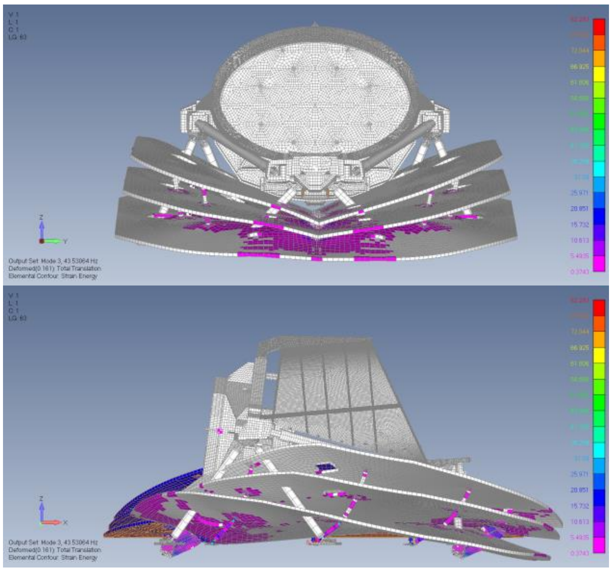

Figure 15: First V-Grooves IP mode (43.54 Hz)

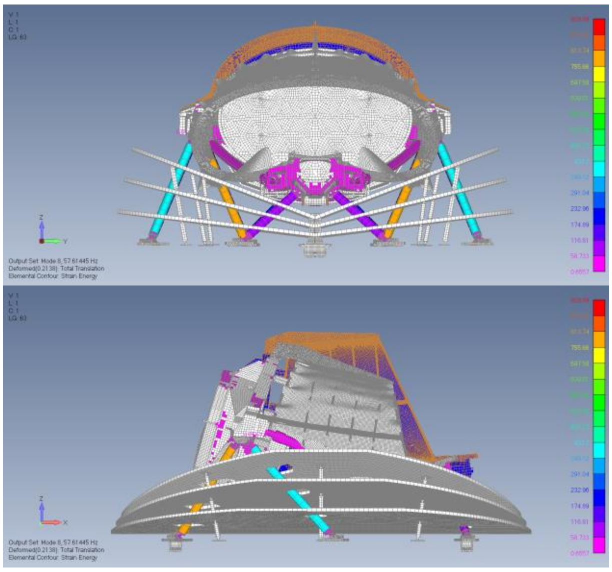

Figure 16: First TA OOP mode (57.61 Hz)

3.3.2. Quasi-static loads analysis

The quasi-static loads (QSL) applicable to the Payload Module are mostly used to define the sine notching criteria. It is foreseen that levels equivalent to QSL will be reached during (notched) sine vibration.

Nevertheless, for completeness, dedicated QSL analyses have been performed with the aim to generate input specifications for the specific subsystems, such as the Bipods and the ACS pipework in terms of displacements and reaction forces/moments.

Moreover, additional QSL analyses have been performed for the overall Telescope Assembly and the V-Grooves.

3.3.3. Sine vibration analysis and Subsystems specifications

Sine analysis is used at Payload Module level to define input levels for the Instruments and Subsystems in terms of quasi-static and sine (harmonic) loads. In addition, dynamic loads in terms of displacements and forces/moments have been extracted to define requirements for specific subsystems, such as the Bipods and the ACS.

For each Instrument and Subsystems accelerations at the mounting interface have been calculated and extracted from:

→ Equivalent accelerations derived from reaction forces at the interface: used to define the quasi-static loads specifications
→ Direct nodal accelerations at the interface: used to define the sine vibration specifications

When calculating accelerations from reaction forces a complex sum (both amplitude and phase) is applied. Moreover, where needed, the QSL specification has been adjusted to match the corresponding sine levels.

Average and maximum values are provided for direct nodal accelerations and the sine vibration specifications are defined considering accelerations maxima and including the necessary uncertainty factors.

An additional aim is to generate simple input level specifications with commonalities between the various instruments where possible and considering reasonable margins at this stage of the project, to avoid frequent updates as design evolves.

In this context, several challenges emerged and had to be addressed.

The definition of input level specifications for smaller units, with a resonance frequency significantly higher than the Telescope Assembly main modes (thus considered to have a rigid behaviour in the sine frequency range between 5 Hz and 120 Hz) is relatively straightforward. Nevertheless, the complexity increases when larger subsystems show a degree of coupling with the Telescope Assembly dynamics. One of the most significant examples is the B1-B2 Baffle which required several iterations of dedicated analyses at both Payload and Subsystem levels to create a suitable set of specifications. The issue became evident when considering analysis and testing at subsystem level assuming, as normal practice, a rigid interface with the shaker compared to the flexibility of the actual interface Telescope Optical Bench. This could easily lead to problems during the verification of the design by analysis as well as under-testing or over-testing at subsystem level.

A similar issue in terms of structural interaction has been observed at the interface between the Telescope Optical Bench and the Instrument Radiator as well. In this case the analyses performed at PLM level highlighted the need for improvement of the interface bolts pattern while the problem wasn't visible at Subsystem level assuming a rigid mounting interface with the shaker.

In some instances, the definition of the input levels and specifications of the Subsystems and Instruments had to take into account the use of components qualified in the context of other missions, most notably Euclid.

Finally, some Subsystems, such as the Bipods, required a totally different approach to the definition of requirements. In this case the specifications included a complete set of forces, moments and displacements extracted at both sides of the Bipods interfaces (with the telescope Assembly on one side, with the Spacecraft service Module on the other side). The process was further complicated by the need to specify the realistic load combinations both in terms of magnitude and signs for the six Bipods interfaces and for all the load cases considered.

3.3.4. Notching

As anticipated, primary notching is applied to sine vibration. Input levels to the Instruments and Subsystems, and the corresponding specifications, are defined assuming that notching is applied individually and separately for the Telescope Assembly and the V-Grooves due to their different applicable quasi-static levels. In general, this is considered a conservative approach as individual notched sine inputs are higher than the combined notched sine input which is expected to be used during vibration testing of the Payload Module. The combined notching for the overall Payload Module is calculated taking the minimum between the Telescope Assembly and V-Grooves notched levels.

The primary notching is calculated comparing the reaction forces and moments generated by the sine loads with the equivalent reactions generated by quasi-static loads at the Telescope Assembly (Bipods) and V-grooves interfaces.

The reactions are directly calculated on independent nodes of Rigid Body elements (RBE) as the sum of the constraint forces and moments on all mounting feet. The constrained node representing the centre of each interface is located at the projection of the CoG onto the interface plane. Longitudinal (F_z) and lateral forces (F_x and F_y) as well as bending moments (M_x and M_y) are calculated in Eqs. 1-5:

$$F_x = 9.81 m_{TA} QSL_{lat} = 16572\ N \quad (1)$$

$$F_y = 9.81 m_{TA} QSL_{lat} = 16572\ N \quad (2)$$

$$F_z = 9.81 m_{TA} QSL_{long} = 43089\ N \quad (3)$$

$$M_x = 9.81 m_{TA} QSL_{lat} Z_{CoG} = 10971\ Nm \quad (4)$$

$$M_y = 9.81 m_{TA} QSL_{lat} Z_{CoG} = 10971\ Nm \quad (5)$$

With m_{TA} being the mass of the Telescope Assembly equal to 337.87 kg, Z_{CoG} being its CoG height equal to 0.662 m, QSL_{lat} and QSL_{long} being the quasi-static accelerations in the lateral and longitudinal direction equal to 5g and 13g respectively.
Notching is applied when the reaction to the sine loads exceeds the equivalent reaction to the quasi-static loads.
The same approach is applied to the calculations of the notching limits for the V-Grooves.
The calculated notching for the X, Y and Z Axes sine vibration levels is shown in Figure 17, Figure 18 and Figure 19.

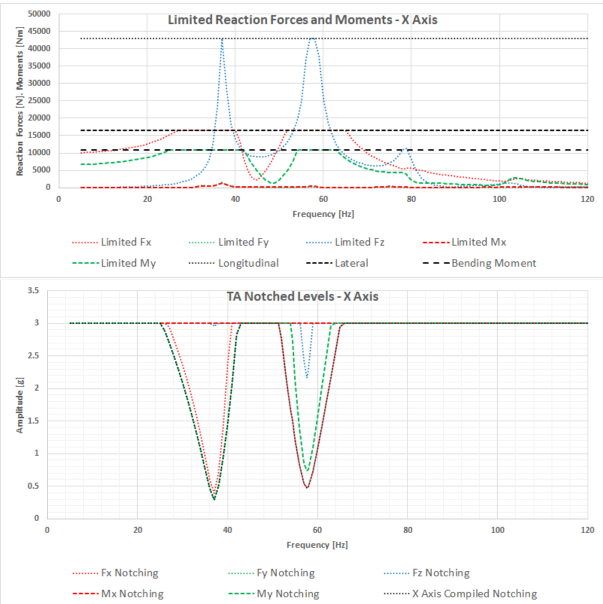

Figure 17: Telescope Assembly notched sine input levels, X Axis

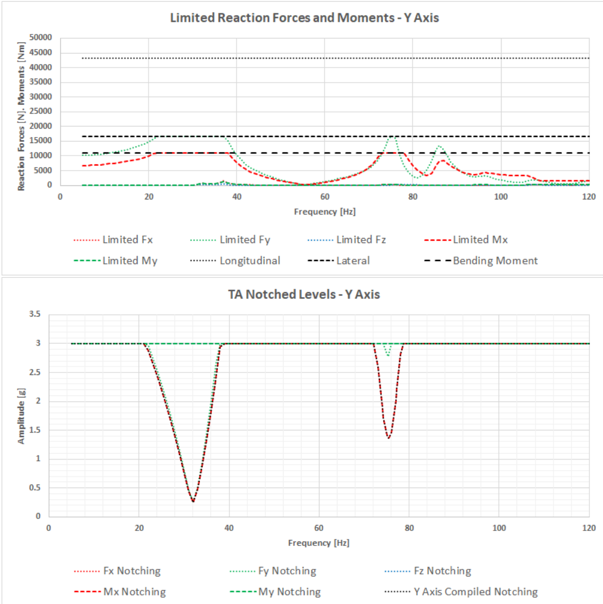

Figure 18: Telescope Assembly notched sine input levels, Y Axis

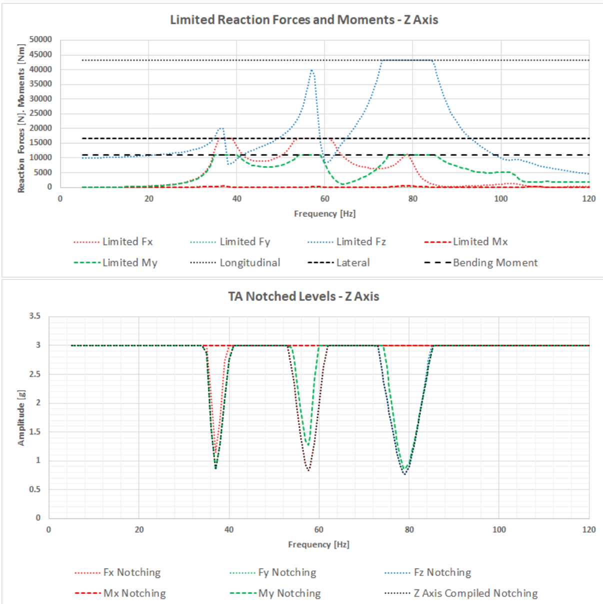

Figure 19: Telescope Assembly notched sine input levels, Z Axis

Finally, the combined notching for the overall Payload Module is obtained by taking the minimum between Telescope Assembly and V-Grooves notching calculated previously.
The current results show that, in principle, it is possible to achieve the equivalent quasi-static reactions forces and moments independently for the Telescope Assembly and the V-Grooves during sine vibration testing in each axis as peaks are not completely overlapping (in other words both curves will define the notching at some frequencies).
Due to the proximity of the second main Telescope Assembly mode and the first main V-Grooves mode in the same direction (X Axis) the evolution of the resonance frequencies for the two subsystems shall be monitored to avoid coupling.

The resulting sine vibration levels for the overall Payload Module in the X, Y and Z axes (in the global PLM coordinate system) are shown in Figure 20, Figure 21 and Figure 22.

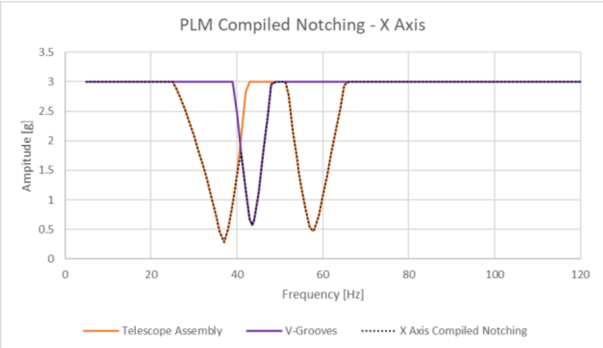

Figure 20: Telescope Assembly and V-Grooves combined notched sine input levels, X Axis

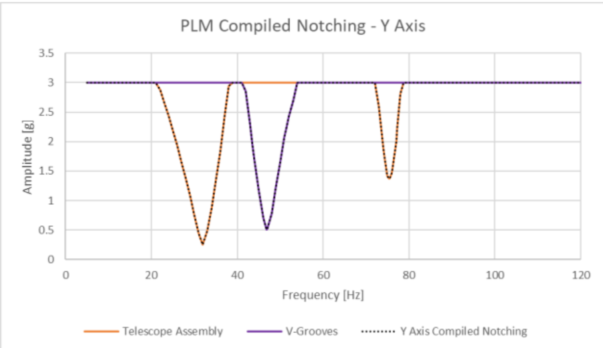

Figure 21: Telescope Assembly and V-Grooves combined notched sine input levels, Y Axis

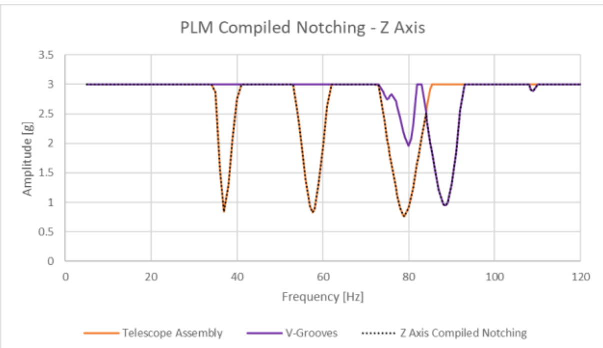

Figure 22: Telescope Assembly and V-Grooves combined notched sine input levels, Z Axis

3.3.5. Thermo-elastic analysis

Displacements, reaction forces/moments and stresses have been calculated for the Payload Module at operational temperatures with the Telescope Assembly temperature set to 50K. The associated average V-Grooves temperatures are 135K for V-Groove 1, 91K for V-Groove 2 and 54K for V-Groove 3.

The maximum absolute reaction forces and moments at the interface between the Payload Module and the Service Module have been extracted for the Telescope Assembly and the V-Grooves. Displacements plots are provided in Figure 23 and Figure 24. The maximum displacement of the Telescope Assembly due to cooldown to operational temperature is approximately 4.26 mm.

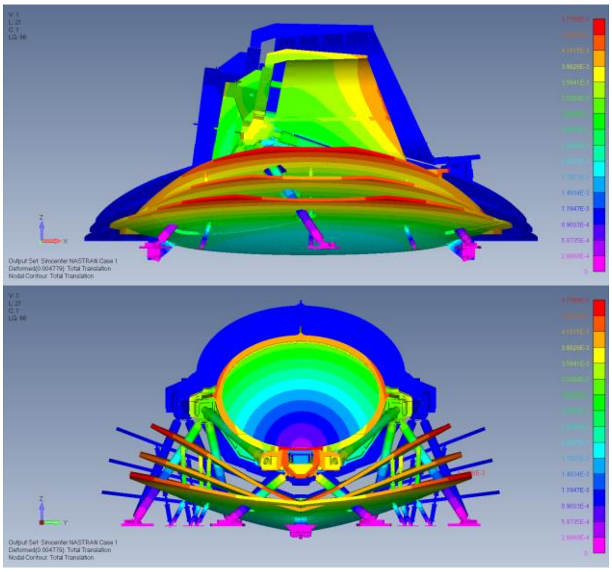

Figure 23: Payload module displacement plot for operational temperature load case

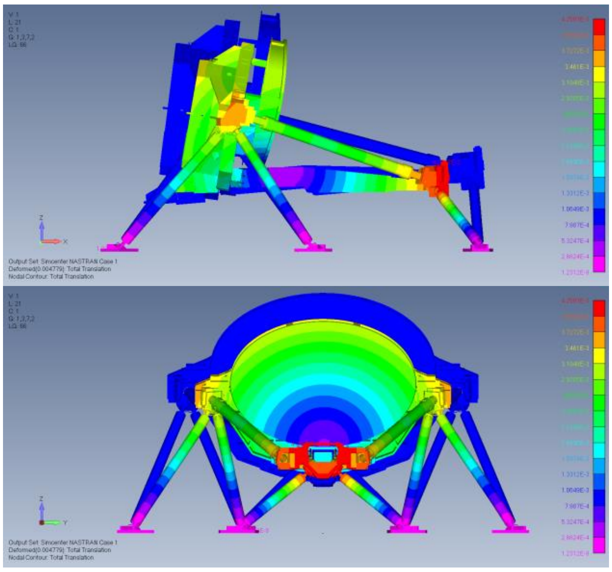

Figure 24: Telescope Assembly displacement plot for operational temperature (50K) load case

3.3.6. Acoustic analysis

Acoustic analysis is performed at Spacecraft level and results are used at Payload level to derive and confirm, or update, random vibration levels to the Instruments and Subsystems.

Additionally, specific load cases have been analysed to understand the impact of the presence, or absence, of the Payload Interface Plate during the acoustic test on the Payload Module and inform the definition and design of the acoustic test setup.

3.3.7. Shock assessment

Assessment of sensitivity to shock levels and the necessary verifications are delegated to each subsystem. For structural non-sensitive equipment (such as the B1-B2 baffle) the 0.8f rule described in Section 12.4.2.3 of ECSS-E-HB-32-25A has been generally used.
With reference to Figure 25, the previous shock specification at PLM interface of 500g at 1 kHz was already below the 0.8f severity criteria. The current shock specification of 350g at 1 kHz adds further margin.

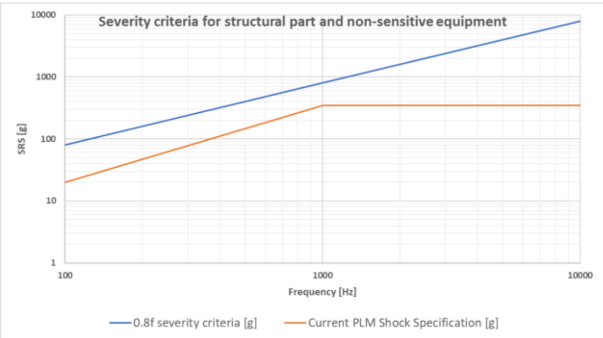

Figure 25: 0.8f severity criteria and comparison with previous PLM shock specification

3.3.8. Bolted joint analysis

Bolted joints are verified following the methods from ECSS-E-HB-32-23A and further corrections and updates agreed with ESA since the release of this ECSS.
Due to the nature of the Ariel mission, the calculations include material properties at cryogenic temperatures, most notably the CTE. NIST cryogenic materials database is used as the main source with additional contributions from the NASA MAPTIS and MMPDS databases.
Reaction forces/moments are extracted from the PLM FEM for each load case and applied to the spreadsheet to calculate the margins of safety for each bolted joint pattern. As usual, fasteners have been modelled with CBUSH and RBEs so that reactions could be easily extracted and used in the calculations.

3.3.9. Fail-safe analysis

Fail-safe analysis for the main internal and external interfaces has been performed as well. The analyses have been run by removing the most loaded bolt from the pattern and re-calculating the margins of safety for the remaining bolts with the methodology previously described.
While uncertainty factors such as the model factor Km and the project factor Kp are maintained, the safety factors are set to 1 in the failure case.
In addition to the interface bolts, front and rear Bipods failure cases have been considered. In particular, a clean cut of Titanium flexure thread is assumed in this scenario, leading to the release of axial translation and torsional rotation degrees of freedom (strut axis) as shown in Figure 26. This has been modelled as line element end released DoFs to simulate the tolerance fit between flexure and mounting brackets.

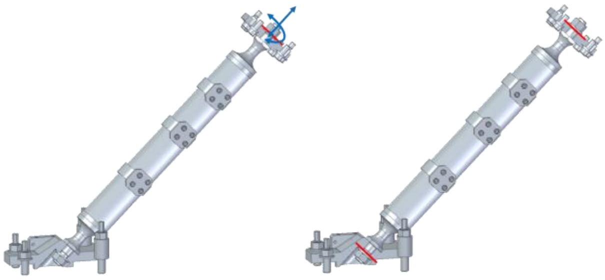

Figure 26: Location of the simulated Titanium flexure (thread) failure and released DoFs

Resonance frequencies, reaction forces/moments, displacements and stresses (for comparison) have been calculated assuming the failure of the Titanium flexures in the front and rear Bipods (not simultaneous). The results lead to the improvement of the fail-safe design of the mechanical interface between the flexures and mounting brackets.

3.3.10. Sensitivity studies

Several studies have been performed in the current design phase to assess the sensitivity of the PLM FEM analysis results to design or parameters changes. As an example, the following studies have been conducted:

- → M1 Mass increase
- → Bipods stiffness
- → B1 Baffle stiffness
- → Telescope Assembly design evolutions
- → Impact of system mass margin

4. PAYLOAD MODULE VIBRATION AND ACOUSTIC TESTS

The Payload Module vibration and acoustic test campaigns will be performed at the National Satellite Test Facility (NSTF) located at the Rutherford Appleton Laboratory in the United Kingdom. Activities are already ongoing to prepare the facility for the upcoming test on the Payload Structural model.
Two models are to be tested:

- → Payload Structural Model, pSM
- → Payload Proto-Flight Model, pPFM

Both models will undergo a series a sine (harmonic) vibration tests, using the notched input levels previously summarised and sine surveys.
Concerning the acoustic test, it is currently assumed that the acoustic environment will be supplied using a Direct Field Acoustic Noise (DFAN) configuration.

4.1.1. Vibration test setup

The PLM will be attached to the horizontal and vertical shakers via force links (load cells), one link at each Bipod and V-Groove interface. Interface blocks will be attached to the top of each force link to provide the required interface bolt patterns and recesses for the V-Groove central struts. The force links will be attached to the slip table/head expander via a vibration adapter. The horizontal and vertical configurations are shown in Figure 27 and Figure 28 respectively.

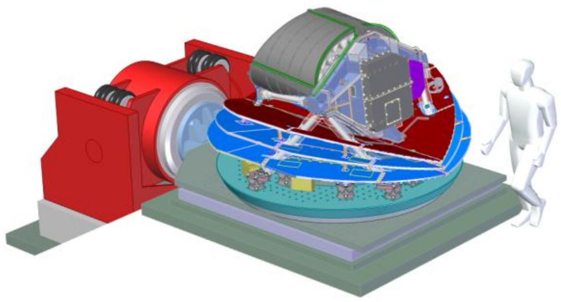

Figure 27: PLM on the horizontal shaker at RAL

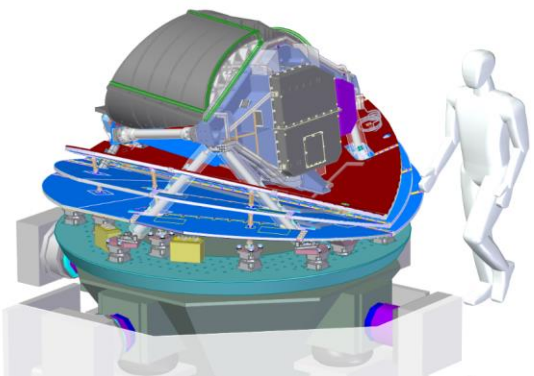

Figure 28: PLM on the vertical shaker at RAL (Flooring around shaker head expander not shown)

The interface between the Service Module and the Payload Module includes shims, to ensure that the Bipod and V-Groove interface points are coplanar. For the vibration test set-up, the thickness of the interface blocks will be machined as required to meet this requirement. The interface blocks are designed to direct the resultant interface forces for the Bipods (which are aligned to the Bipod struts axes) approximately through the centre of the force link; this minimises the moments applied to the force link transducers.

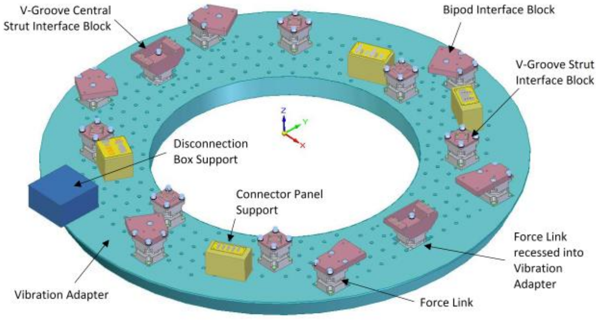

Figure 29: Details of the vibration adapter

Mounting the force links as close as possible to the Payload Module at each interface minimises the mass attached to the upper surface; ideally the total “parasitic mass” should be less than 10% of the test item’s mass. This is difficult to achieve for the Payload Module: the current design has a parasitic mass of about 25kg, approximately 6% of the Payload Module mass.

The vibration adapter is an aluminium alloy ring which is bolted to the shaker slip table or head expander.

The complexity of the test configuration is mostly driven by the need to measure (summed) forces for the Telescope Assembly and the V-Grooves individually so that notching can be calculated and applied in real time as well as the overall footprint of the Payload Module.

From an operational point of view the real-time processing of the force measurements will be challenging. As a matter of fact, with reference to the results provided in Section 3.3.4, the notching at some of the main modes is driven by the moments. Since it will not be possible to accurately measure and calculate the sum of moments at the Payload Module interface, the notching strategy shall be adjusted to make use of force measurements only. It has been observed that, at least for the Telescope Assembly, individual vertical forces measured on each of the mounting feet show a degree of correlation with the calculated summed moments. If confirmed by detailed analysis results, it will be possible to use vertical forces to determine the necessary notching (which is otherwise driven by the summed moments).

In addition to the force links and a set of approximately 80 accelerometers to be installed on the Payload Module, the Bipods flexures are provided with a set of strain gauges which will be used to monitor the forces and moments acting on the Bipods during the test campaign. Each flexure will be equipped with four linear strain gauges. It is expected that this suite of sensors will provide a complete dataset to monitor in real-time the structural integrity of the Payload Module during the test campaign and to allow model correlation and update with sufficient fidelity after post-processing of the test data.

5. CURRENT STATUS AND FUTURE ACTIVITIES

The Payload Preliminary Design Review process started in September 2022. At present, the Structural Models of the Subsystems and Instruments are being manufactured and tested in preparation for their integration into the Payload Structural Model expected in the second half of 2023. The vibration and acoustic test campaigns on the Payload Structural Model is currently planned for the first quarter of 2024. In the meantime, all the Subsystems and Instruments are going through their Preliminary and Critical Design Reviews.

6. CONCLUSIONS

The overall structural architecture of Ariel Payload Module has been described, highlighting the main requirements and design drivers, and summarising the technical solutions implemented to withstand the mechanical environment during launch and guarantee thermo-elastic and functional performance once the required operational temperature is achieved.

The most relevant results of the structural analyses performed on the PLM FEM have been summarised together with the methodologies and the challenges faced during the analysis process. The results show overall compliance to the main requirements and the problematic areas identified so far are not considered critical. Moreover, the results relevant to the definition of the vibration test specifications have been discussed.

Finally, the plans and related setups for the Payload Module vibration and acoustic test campaigns are described including a summary of the most relevant programmatic and technical challenges.

7. ACKNOWLEDGEMENTS

The authors would like to sincerely thank the teams developing the structural elements of the Ariel payload, the members of Ariel Payload Mechanical Working Group and their colleagues at RAL Space and ESA for their collaborative support.

The authors acknowledge the whole Ariel Mission Consortium [4] as well as the Spacecraft team at Airbus Defence & Space and the members of the National Space Agencies for their help and commitment to the make sure the development of the Ariel mission progresses as smoothly as possible.

8. REFERENCES

1. Tinetti, G. et al. (2020). Ariel Definition Study Report, ESA/SCI(2020)1.
2. Mochi, I., Gennari, S., Oliva, E., Baffa, C., Biliotti, V., Falcini, G., Giani, E., Marcucci, G., Sozzi, M., Origlia, L., Rossetti, E. & Gonzalez, M. (2009). High-precision CTE measurement of aluminum-alloys for cryogenic astronomical instrumentation. Experimental Astronomy. 27. 1-7. 10.1007/s10686-009-9172-7.
3. Morgante, G., Terenzi, L., Desjonqueres, L. et al. (2022). The thermal architecture of the ESA ARIEL payload at the end of phase B1. Exp Astron 53, 905–944.
4. Ariel Space Mission - European Space Agency M4 Mission, https://arielmission.space/