MECHANICAL QUALIFICATION OF THE HERSCHEL SATELLITE

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OVERVIEW

The Herschel infrared space observatory is the fourth European Space Agency's Cornerstone mission in the 'Horizons 2000' program. Its main goal is to look at the origins of stars and galaxies, reaching back to when the Universe was only a third of its present age. Herschel will observe at wavelengths down into the far-infrared and sub-millimetre range. This paper gives an introduction to the complex spacecraft design, with highlights on key mission requirements and resulting design challenges. It describes the qualification philosophy for the environmental tests and the extensive mechanical test campaign which was performed at European Test Services (ETS), located at the ESTEC site in Noordwijk, NL. The new Force Measurement Device used for the sine tests is featured. The test results are discussed and evaluated with respect to the qualification objectives. An outline of the current project status and the upcoming Flight Model acceptance test campaign is given.

1. INTRODUCTION

The Herschel spacecraft is approximately 7.5 metres high and 4 x 4 metres in overall cross section, with a launch mass of around 3.3 tonnes. The spacecraft consists of a service module (SVM) and an extended payload module (EPLM). The SVM houses systems for power conditioning, attitude control, data handling and communications, together with the warm parts of the scientific instruments, and a payload module. The EPLM consists of a liquid helium cooled cryostat inside which the instrument detectors sit and are cooled down to a few degrees above absolute zero. It will also carry the infrared telescope, a Cassegrain telescope made of silicone carbide, with a primary mirror at an unprecedented diameter of 3.5 metres. The EPLM is fitted with a sunshield, which protects the telescope and cryostat from solar visible and infrared radiation and also prevents Earth straylight from entering the telescope. The sunshield also carries solar cells for the electric power generation.

In an Ariane 5 dual launch together with the Planck satellite, Herschel will be placed in its operational orbit located 1.5 million kilometres away from the Earth in a direction diametrically opposite the Sun, at the second Lagrange point of the Sun-Earth system (L2). Herschel's operational lifetime is 3.5 years.

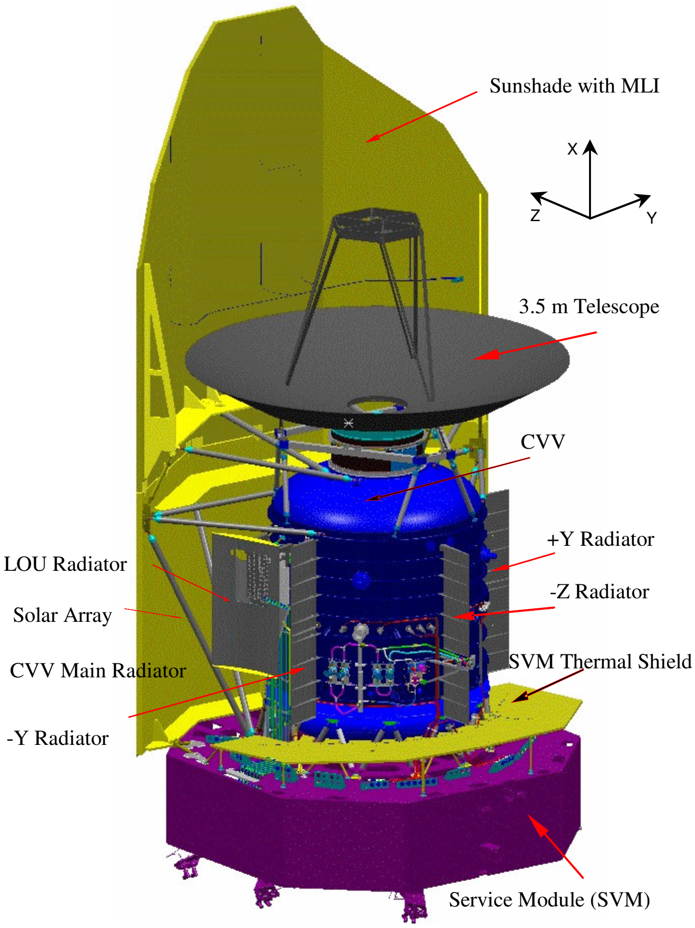

FIG 1 Herschel overview

The Herschel spacecraft was built by an industrial consortium led by Thales-Alenia-Space in Cannes, France, with EADS Astrium in Friedrichshafen, Germany, and Thales-Alenia-Space in Torino, Italy, as the main subcontractors, and more subcontractors all over Europe.

1.1. Service Module (SVM) technical description

The Service Module, as shown in FIG 2, is an octagon-shaped box including a central cone stiffened by shear panels and enclosed by an upper and lower platform all made from carbon-fibre-reinforced plastic (CFRP). The SVM accommodates the units and subsystems providing the essential resources to the spacecraft in terms of: Attitude Control, Command and Data Handling, Power Generation and Distribution, Telemetry and Tracking.

In addition, the SVM provides mechanical interfaces for the launcher, the payload module, Mechanical Ground Support Equipment and accommodates the warm units of the Instruments. A modular approach is implemented. The units belonging to same functional set are accommodated on the same dedicated panels. This approach allows modular and independent integration and functional testing of the various sets.

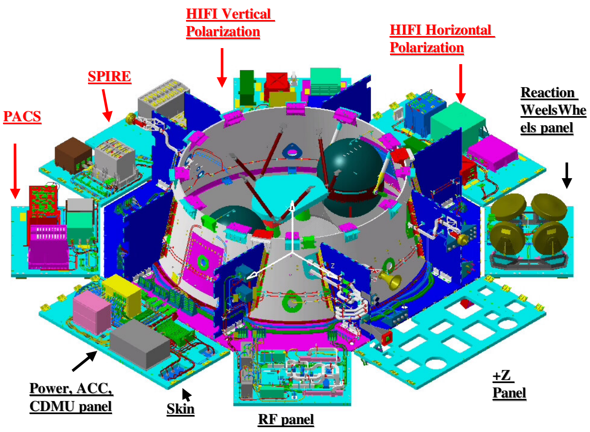

FIG 2 SVM configuration

1.2. Extended Payload Module (EPLM) technical description

The Extended Payload Module primarily consists of a liquid helium cooled cryostat with a cryogenic design similar to the ISO spacecraft. The cryostats primary structure is the Cryostat Vacuum Vessel (CVV), which provides vacuum for ground operation, mechanical support for the internal and external components and finally acts as thermal radiator to deep space. It is made from 5083 aluminium. Inside the CVV, the main helium tank (HTT) contains 2370 litres for superfluid He II at a temperature below 1.8K. In orbit, a passive phase separator prevents that the liquid is venting uncontrolled into space. The cold gas from the Helium tank is venting through the Optical Bench (OB), providing the required temperatures for the focal plane units of the scientific instruments. Then the gas flows through thermal insulation shields in order to reduce the heat load on the Helium tank, until it is released to space through the vent line nozzles. In ambient condition on ground, the amount of helium evaporated per day is about 3 kg or 1% of the HTT content.

Herschel carries three scientific Instruments with their Focal Plane Units (FPU) accommodated on the Optical Bench as shown in FIG 3.

- The Heterodyne Instrument for the Far Infrared (**HIFI**) performs spectroscopy in the range 160 – 600 µm and operates at about 2 K
- The Photodetector Array Camera and Spectrometer (**PACS**) instrument performs imaging line spectroscopy and photometry in the range of 60–210 µm making use of photo-conductors cooled to about 1.7 K and bolometers operating at about 0.3K
- The Spectral and Photometric Imaging Receiver (**SPIRE**) is a direct detection instrument for imaging photometry in the range of 200–670 µm making use of bolometers operating at about 0.3 K

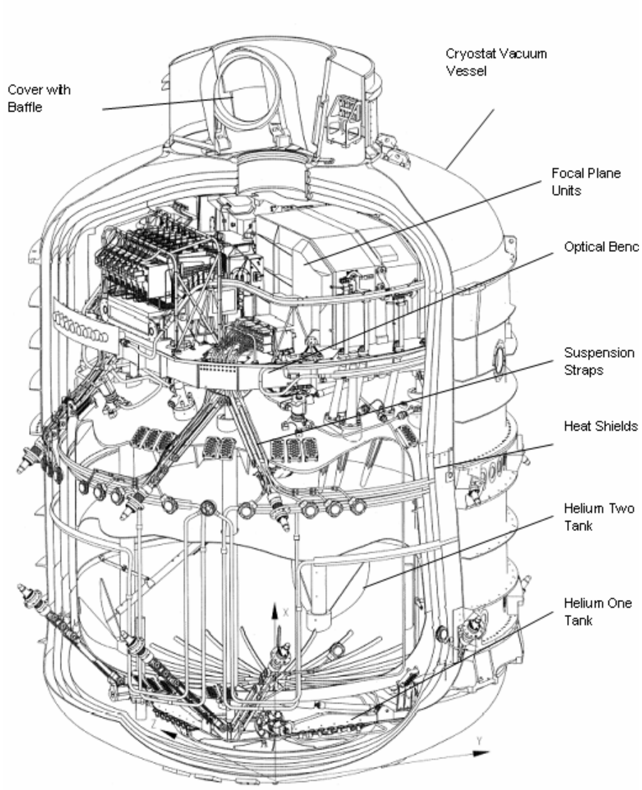

FIG 3 Cryostat internal overview

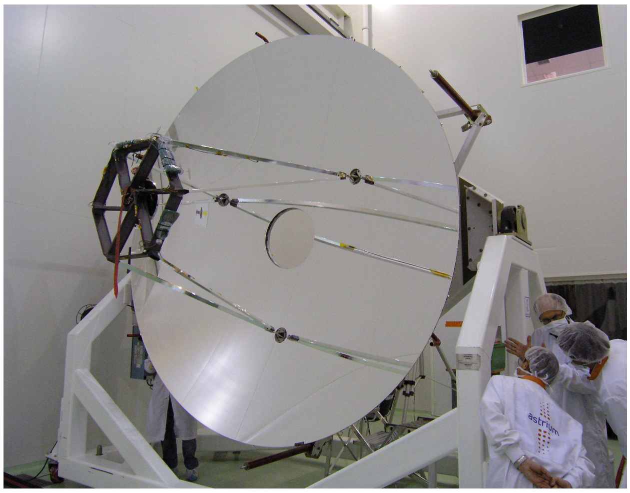

FIG 4 Herschel Telescope

As part of the Extended Payload Module, the Solar Array/Sunshade (HSS) accommodates the solar array and protects the spacecraft against solar radiation. The HSS is a complex CFRP panel structure, which is mounted to the CVV and the SVM by long struts made of glass- resp.

carbon-fibre reinforced plastics (GFRP/CFRP). The struts are designed for mechanical stiffness and thermal insulation.

The Herschel telescope is shaded from the sun by the Sunshade. The telescope is fixed onto the CVV by a telescope mounting structure made of CFRP. The telescopes primary mirror has a diameter of 3.5 metres, which is larger than any previously flown scientific telescope. It is made of silicone carbide segments which are brazed together, and then grind, polished and coated. The telescope mass is 312kg.

A thermal shield between SVM and EPLM reduces radiative heat exchange between the modules. Together with the poor thermal conductivity of the GFRP mounting struts, the cryostat is thermally well insulated from the warm SVM and the HSS.

1.3. Launch and orbit conditions

1.3.1. Orbit

Herschel and its launch companion Planck will orbit the Lagrange point L2 of the Sun/Earth system. This point is located at 1.5 million km from the Earth away from the Sun in the Sun/Earth straight line. A large Lissajous orbit has been selected for Herschel with amplitude up to 800000 km. The selected orbit provides optimum conditions in terms of thermal and radiation environment and straylight effects but imposes constraints on launcher capacity, telecommunication, system autonomy and visibility.

The predicted operational temperatures are ~300K for the SVM, 70K for the exterior of the CVV, 90K for the telescope, 220K for the Sunshade and up to 400K for the Solar Array. The large temperature differences and the material diversity necessitate a thorough design approach to accommodate thermoelastic effects.

The mission lifetime is limited by the amount of helium available for cooling of the detectors. The lifetime requirement is 3.5 years. Recent predictions indicate that the mission duration will be slightly exceeded.

1.3.2. Launcher

Herschel and Planck will be launched by Ariane-5 ECA in dual launch configuration with Sylda5. Herschel will be in the upper position and Planck in the lower position. The launcher capability allows for a direct injection on L2 transfer orbit for both spacecrafts.

2. SATELLITE MECHANICAL QUALIFICATION

2.1. Main objectives & requirements

The main design drivers and environmental requirements to demonstrate by a dedicated mechanical qualification testing program are:

- Resonance frequency requirements in hardmounted condition: 9Hz lateral, 31Hz axial minimum fundamental frequency
- Ariane 5 in-flight steady state accelerations up to 4.55g longitudinal at the end of the solid rocket boost phase
- Sinusoidal (or sine-equivalent) vibration levels at the spacecraft base during powered flight, mainly the atmospheric flight, as well as during some of the transient phases
- Acoustic environment: Acoustic pressure fluctuations under the fairing generated by engine operation and by unsteady aerodynamic phenomena during atmospheric flight.
- Shock environment during launch vehicle stages separation events, mainly fairing jettisoning, and during spacecraft separation.

2.2. Qualification Test Program

The qualification test program was performed on the Structural Thermal Model (STM) with an extensive amount of parts already being proto-flight (PFM) hardware. The test configuration is shown in TAB 1 below (slightly simplified):

TAB 1: STM Model Configuration

Module	Unit	Model	Remark
SVM	Cone & shear walls	STM	
	Propellant tanks	STM	
	Equipment panels	FM	to be refurbished
EPLM	Cryostat incl. radiators	PFM	with dummy instruments on optical bench
	Telescope	STM	Mech. Dummy
	HSS Solar Array	STM	Mech. Dummy without solar cells
	HSS Sunshade	FM	with test MLI
	SVM Thermal Shield	FM	

The mechanical qualification tests performed in the frame of the STM campaign are summarised in TAB 2.

TAB 2: Mechanical qualification tests

Module	Remark	Facility
SVM STM	Static load test on SVM cone	
Satellite STM	Sine vibration test	HYDRA/MultiSh.
	Acoustic noise test	LEAF
	Shock tests (clampband/SHOGUN)	Arianespace
	Microvibration	Minishaker

The individual tests are explained in detail in section 3. Physical properties and alignment stability were also measured on STM but are not detailed here any further.

3. STM MECHANICAL QUALIFICATION TESTS

3.1. Test instrumentation

For all mechanical tests common test instrumentation was used. A total of 410 acquisition channels were foreseen on the spacecraft (but not all were active for all tests):

- 172 accelerometers on the SVM
- 163 accelerometers on the EPLM, 22 of which were cryogenic accelerometers inside the cryostat specifically calibrated at 4 Kelvin
- 75 strain gauges bonded onto the various CFRP and GFRP struts to provide strut force measurements
- Additional sensors for piloting and co-piloting were present for sine test
- Additional sensors on the test fixtures were present for the shock tests

Various types of sensors (piezo, ICP) were used depending on the expected dynamic range, available space and access. All sensors were connected to the LMS Mechanical Data Handling system (MDH) which is in use at ETS since 2003. The systems allows acquisition of a maximum of 512 channels, connected to 4 patch panel racks with 128 channels each, which can be moved around the test facility together with the spacecraft. This avoids time-consuming and error-prone plugging and unplugging of sensor cables.

3.2. The new Force Measurement Device (FMD)

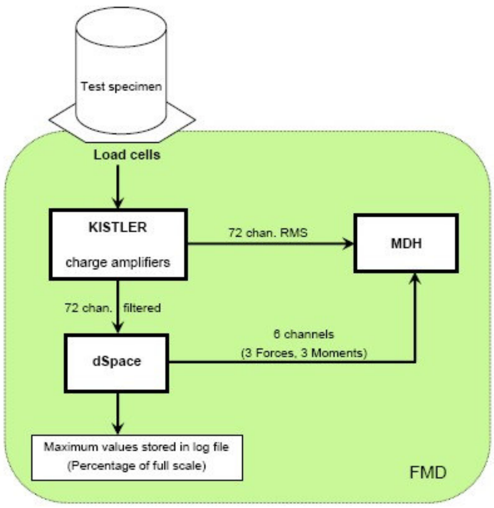

FIG 5 Force Measurement Device

The FMD is a device which measures the forces and moments directly at the interface of the test specimen. The FMD consists of the following four main elements:

- The force links: 24 Kistler 9377B 3-axis piezoelectric force links
- The charge amplifiers: 72 Kistler 5058A400Q01 eurocard amplifiers
- The matrix calculator (visual basic software) defining the input/output relations of the summation unit
- The signal processing unit (SPU) calculating in real time the summed forces and moments

The FMD has a maximum load capability of 10'000 kg per used load cell. The FMD modular design allows to install e.g. only 3 load cells under small (<100 kg) specimens or up to the full 24 load cells distributed on a pattern of 3 m diameter and more. The FMD mass is 240 kg, but additional mass in the test adapter is desirable to provide sufficient stiffness.

As usual the outputs of the SPU were recorded on the MDH and fed back into the shaker control system for notching. It is also possible to connect individual force outputs of the Kistler charge amplifiers to the MDH, but for the Herschel tests this was not done.

3.3. Sine vibration test

Objective: To qualify for the Ariane 5 mechanical requirements in terms of stiffness and low frequency/transient loads, to correlate the S/C mathematical model and to verify the overall dynamic behaviour.

Test facility: HYDRA resp. 320kN Multishaker with FMD. The STM mass was ~ 3300kg including water in the propellant tanks and HTT completely filled with helium. Total mass of the test article including vibration test adapter, clamp band and FMD was 5500kg.

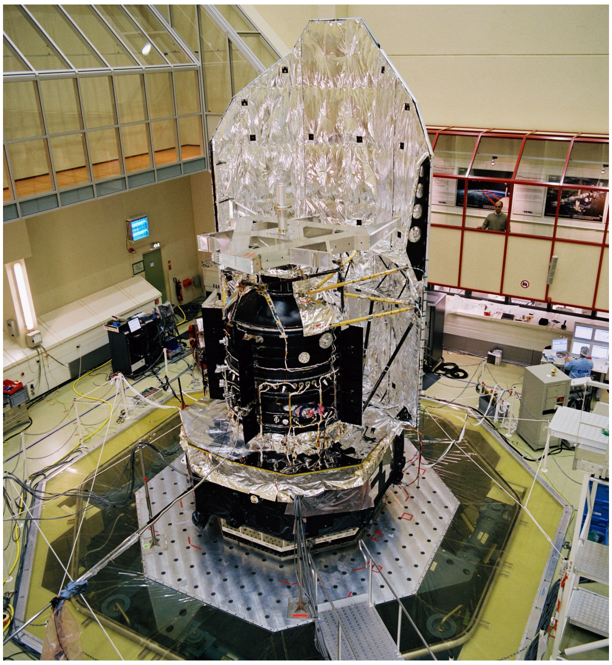

FIG 6 Herschel STM on HYDRA

The original intention was to perform sine tests in 3 axes on HYDRA due to total test article mass above the limits of the 320kN Multishaker in head expander configuration. Extensive simulations were performed beforehand to anticipate cross-coupling and control behaviour. To allow early assessment of correlation and test prediction, so-called "signature-runs" were performed at 25 resp. 50 milli-g input in all 3 axes.

Test execution: As predicted by the coupled dynamic analysis, the HYDRA control system was able to control the sine sweep with good accuracy and reasonable cross-coupling. During the last x-axis post-low-level run, HYDRA control system showed malfunctions which could not be repaired quickly. Luckily, all major data for this axis were collected and testing of the X-axis was declared to be successfully completed.

Thus, the lateral axes tests were performed on the 320kN Multishaker in slip table configuration. The FMD and vibration adapter configuration was retained. All scheduled test runs were performed with a reasonable amount of test execution problems (such as control aborts in the fundamental mode etc.).

For all 3 axes, qualification runs were performed with primary notching on the fundamental spacecraft modes and a number of secondary notches to protect units or sub-systems. Manual notches were defined around the expected automatic notches to avoid big overshoots. All notches were within the range tolerable for the launcher authority to declare successful qualification. As an example, FIG 7 shows the X-axis notch profile with indications of active notch channels.

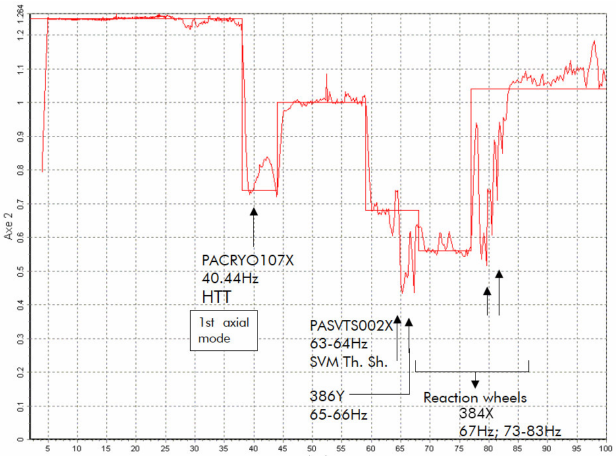

FIG 7: X-axis notch profile

Result evaluation: The table below shows the maximum I/F forces and moments measured with the FMD during the qualification runs (re-calculated from FMD co-ordinate to S/C I/F co-ordinate):

TAB 3: I/F forces and moments

Axis	I/F force	I/F moment	Flux	Requirement
X	179.5kN	n/a	21.8 N/mm	224.2 kN (CLA with static+dyn. part) 34.9 kN (CLA dynamic part only)
Y	47.7 kN	162.7 kNm	30.1 N/mm	117.8 kNm (CLA with static+dyn. part)
Z	47.9 kN	158.7 kNm	29.7 N/mm	117.8 kNm (CLA with static+dyn. part)

The required combined static and dynamic maximum values of the coupled load analysis were reached for the lateral axes. As usually the case, in the axial direction, the combined static and dynamic qualification loads could not be reached; only the dynamic part was well covered. However, the I/F flux reached during the SVM static load test was considerably higher (66.8 N/mm) and covered the required qualification loads. Thus, the primary structure's overall load capability was successfully proven.

As shown in TAB 4, the measured fundamental resonance frequencies are well above the required values and slightly above the predictions. The measured damping values in the first modes are given in TAB 5. It is interesting to note the differences in the two lateral directions both in frequency and damping. The FEM used for sine test prediction did not account for air pressure interaction with the structure, which is more severe in Z-direction compared to Y-direction, where a much larger area of the HSS is effective. Thus it is assumed that natural frequency and damping in Z-direction are more strongly affected by the air pressure effect than in Y-direction.

TAB 4: Fundamental frequencies

Axis	Mode	Measured	Predicted	Requirement
X	First axial mode	40 Hz	38 Hz (on HYDRA) 37.8 Hz (clamped)	> 31 Hz
Y	First lateral mode	16.1 Hz	15.2 Hz	> 9 Hz
Z	First lateral mode	14.9 Hz	14.6 Hz	> 9 Hz

TAB 5: Measured damping

Axis	Mode	Frequency	Damping
X	First axial mode	40 Hz	3.0%
Y	First lateral mode	16.1 Hz	0.9%
	Second lateral mode	29.2 Hz	1.5%
Z	First lateral mode	14.9 Hz	1.7%
	Second lateral mode	29.3 Hz	2.0%

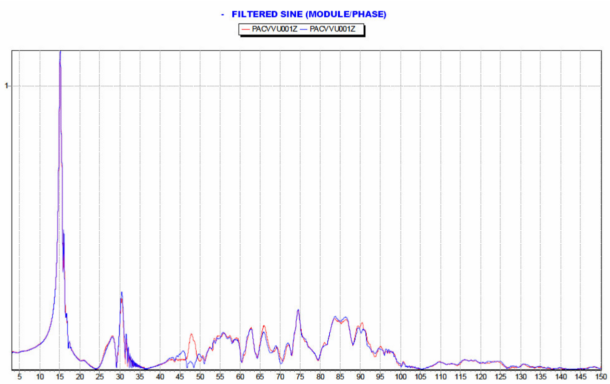

FIG 8: Comparison Pre/Post Sine

As an example, FIG 8 shows an overlay plot of two low level runs pre- (red curve) and post sine qualification runs (blue curve) in lateral Z-direction for a sensor location on the CVV. The small variation between 45Hz and 50Hz is due to the change in helium content of the HTT: During the several days between the first and last run, the amount of evaporated helium was ~12kg. The associated drop in filling level causes a shift to a lower fluid resonance frequency. This fluid dynamics effect was studied in detail prior to the test and the predictions were confirmed nicely by the test results.

The overall system dynamics proved to be fairly complex with strong cross-coupling effects between the telescope dummy and the HSS. However, the dynamics are now well understood and an updated and correlated FEM model was prepared and submitted to Arianespace for CLA analyses.

3.4. Acoustic noise test

Objective: To verify Ariane 5 acoustic environment

Test facility: Large European Acoustic Facility (LEAF). 9 microphones were used for piloting and 3 additional ones for monitoring. The spectrum was controlled in 1/3-octave bands. The overall sound pressure level was 143.5 dB as requested by Ariane 5 Users Manual.

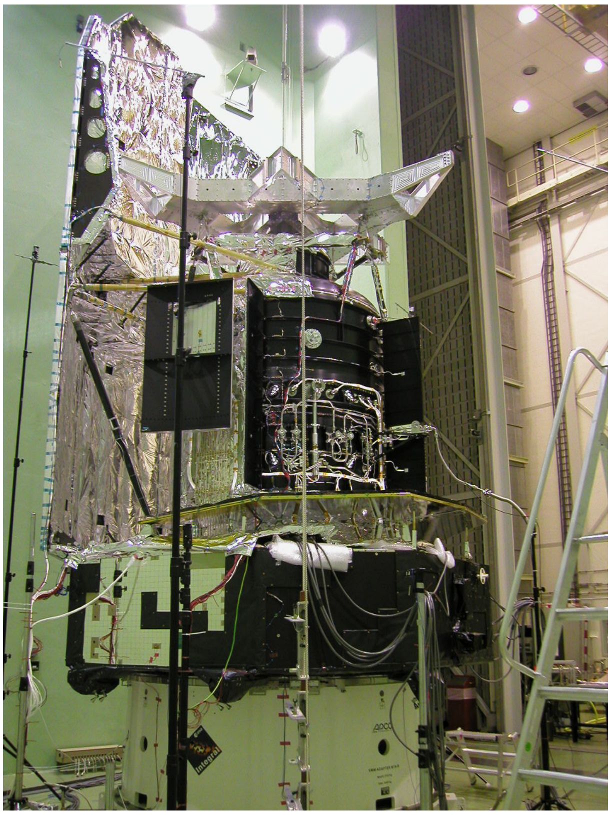

FIG 9 Acoustic test setup in LEAF

Test execution: The homogeneity of the sound pressure field in the lowest octave did not reach the specified value. However, this was to be expected due to the finite size of the chamber.

Result evaluation: Comparison of the control low level plots with the initial low level plots showed that the Herschel structural part successfully withstood the qualification acoustic test.

Some SVM items have seen levels higher than their qualification level during the acoustic test. However, the exceedance was deemed acceptable in all cases and no delta-qualification on unit level was required. The HSS qualification will be completed later on with a dedicated sub-assembly acoustic noise test.

3.5. Shock tests: SHOGUN and clampband release

Objective: The SHOGUN test (SHOck Generation UNit) has the purpose to measure shock transfer functions longitudinally and radially over the spacecraft I/F adapter. The Clampband Release (CR) test intends to verify Ariane 5 shock environment, mechanical I/F compatibility and clamp band separation kinematics. Strictly speaking the CR test is not a qualification test as no +3dB qualification factor is applied.

FIG 10 SHOGUN test setup

Test facility: Arianespace test equipment SHOck Generation UNit (SHOGUN) and Clampband Release (CR). The SHOGUN consists of the EPS cone structure with pyro-charges attached to the bottom side (at ∅3936) and the ACU 2624 on top. The ACU is connected to the spacecraft with a flight compatible clampband.

For the SHOGUN tests, the total assembly Herschel STM, ACU 2624, EPS cone, and SHOGUN is suspended from the crane. The SHOGUN pyros are fired and a shock wave is transmitted via the cone over the ACU into the spacecraft. Shock levels in axial and radial direction were measured at various axial levels to characterise shock attenuation and transfer function.

For the CR test, only the ACU 2624 is attached to the suspended spacecraft. The clampband is released with redundant pyro-technic bolt cutters and the ACU drops to the floor onto a soft cushion. Radial and axial shock levels were measured. A video camera was used to monitor the separation kinematics.

Test execution: Arianespace resp. Intespace provided a separate data acquisition system for acquisition of shock levels on the test adapters. Redundancy of the measurements was improved by routing two Arianespace "Level 28" sensors to the ETS MDH system. For the ETS MDH system, a subset of 130 channels was selected to facilitate acquisition over only one patch panel rack. The MDH measurements were additionally secured by a digital data recording of 36 channels in ETS's TEAC recorder. Thus, at least partial data would have been available in case of a malfunction of data acquisition. For MDH, a manual triggering rather than an automatic one was employed (this is possible due to the large data capacity of the MDH and avoids triggering problems). Full data sets were recorded by both acquisition systems for both tests.

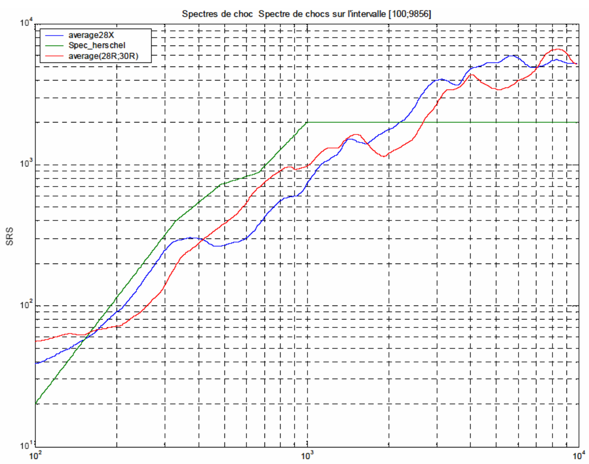

FIG 11: SHOGUN shock response

Results evaluation: FIG 11 shows as green curve the applicable shock environment, as red curve the measured averaged radial shock response spectrum and as blue curve the measured averaged axial shock response spectrum. For frequencies below 2000Hz, the SHOGUN shock levels were lower than desired whereas above 2000Hz they were higher. The transfer functions were then used to recalculate the shock environment for each individual unit location and compared to the unit's qualification shock test level (taking of course 3dB qualification margin on the unit test levels into account).

A slight anomaly around 300Hz gave some doubts on the validity of this method. Exceedance of unit qualification levels in this frequency range was therefore treated as a separate case and the longitudinal interface S/C SRS was used for the transfer function reference.

FIG 12 shows the axial SRS for the clampband release shock, which gives a good confirmation of the CR shock specification.

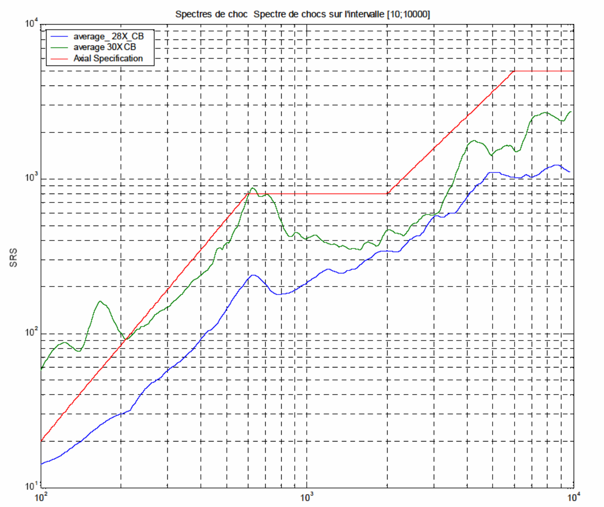

FIG 12: Clampband release shock response (axial)

Comparison of the individual units' shock qualification levels with the updated shock environment showed that several equipments located on SVM panels had to undergo delta-qualification on unit level.

3.6. Microvibration test

Objective: To characterise the transfer function for reaction wheels induced microvibrations between the reaction wheel panel on the SVM to the focal plane units on the optical bench.

Test facility: Suspended electro-dynamic 80N minishaker. The shaker attaches to a load introduction point on the reaction wheel panel as shown in FIG 13 for out-of-plane direction. The spacecraft is suspended from a second crane.

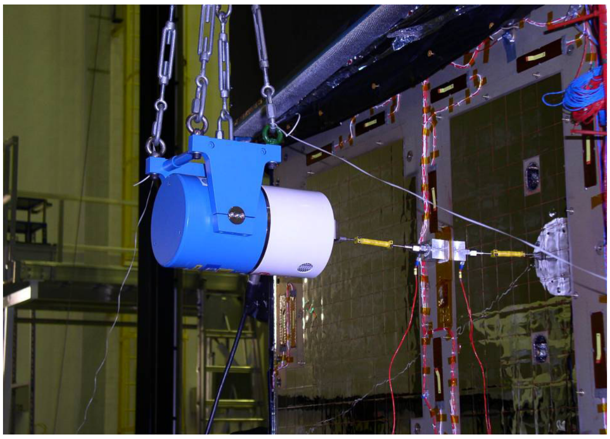

FIG 13 Minishaker for microvibration test

Test execution: Stepped sine sweeps were performed at various force levels in a frequency range between 5Hz and 300Hz for three excitation directions. Acceleration responses were measured on dedicated points of interests on the panel and on the optical bench Transfer functions were directly calculated by a dedicated data acquisition system provided by IABG.

Data acquisition/sensor accuracy: The noise floor of the measurements was very good (≤ 5milli-g for internal cryostat sensors, ≤ 20 milli-g for SVM) due to the fact that the S/C was suspended from the crane and electrically grounded to a clean ground. The lowest tested force level was 0.5N. The corresponding responses were in the range of 10 milli-g. FIG 14 shows an example of a frequency response function for various force excitation levels.

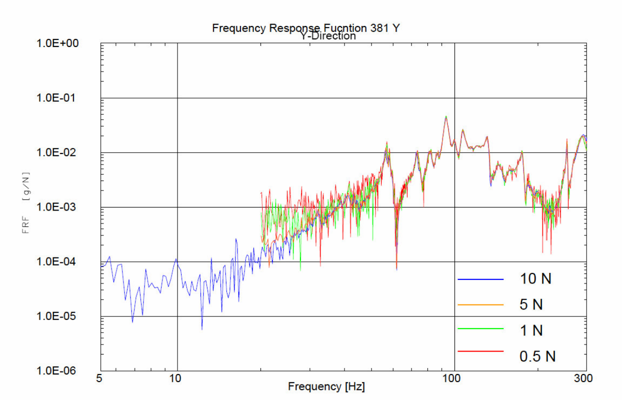

FIG 14 Example for measured FRF

<u>Result evaluation:</u> Responses in the main modes of the optical bench were predicted rather accurately (FEM prediction: 68Hz; measurement 72.1 Hz), see FIG 15. The predicted damping of 0.5% on the OB mode was confirmed by a measured damping of 0.6%. Globally, the measured orders of magnitude are in line with the prediction. The fairly low damping factors were constant over the tested force range between 0.5N and 10N.

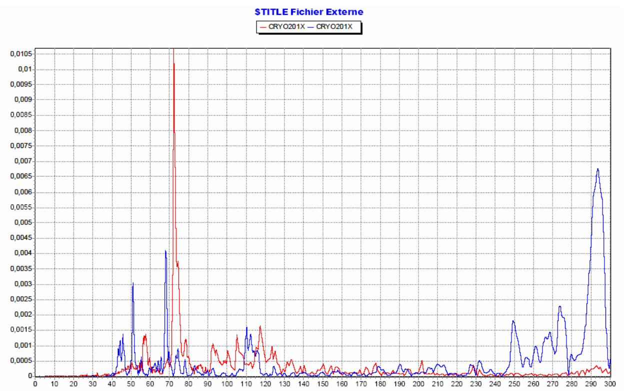

FIG 15: Comparison between predicted (blue) and measured (red) optical bench X response (FRF Hz,g/N)

The test results confirm the validity of the Force Response Function microvibrations analysis which was used to derive the microvibration environment for the instruments.

4. OUTLOOK ON FM ACCEPTANCE TESTING

A dedicated acceptance test campaign of the Herschel satellite will be started after completion of satellite integration in Autumn 2007. The mechanical acceptance testing will consist of sine vibration test in all 3 axes on the 320kN-Multishaker (or possibly the new QUAD shaker), acoustic noise test and a microvibration test. The Flight Acceptance Review is planned for late Spring 2008 prior to shipment to Kourou launch site. Herschel/Planck launch is scheduled for July 31st, 2008.

Main challenge of the sine test is expected to be the dynamic behaviour of the Telescope, which exhibited fairly low damping in the primary mirror modes during unit tests. However, a recent update of the CLA with a correlated satellite FEM indicates that the flight environment in the frequency range of concern is moderate, which would justify notching to relatively low input levels.

5. SUMMARY AND CONCLUSIONS

The main results of the Herschel STM mechanical qualification test campaign are summarized below.

- Sine vibration tests were performed in three axes on two different facilities
- Acoustic noise, shock and microvibration tests were performed
- No flight hardware items were damaged during testing
- All major test objectives were achieved, leading to a successful mechanical qualification of the Herschel satellite

Acknowledgments

The authors wish to thank all the teams involved in the extensive testing & analysis campaign for the close cooperation, their dedication and their hard work.

ABBREVIATIONS

ACU:	Adaptateur Charge Utile
CFRP:	Carbon Fibre Reinforced Plastic
CLA:	Coupled Load Analysis
CR:	Clampband Release
CVV:	Cryo Vacuum Vessel
ECA:	Evolution Cryogenique A
EPLM:	Extended Payload Module
EPS:	Etage a Propergols Stockables
FEM:	Finite Element Model
FM:	Flight Model
FMD:	Force Measurement Device
FPU:	Focal Plane Unit
FRF:	Frequency Response Funcion
GFRP:	Glass Fibre Reinforced Plastic
HSS:	Herschel Solar Array/Sunshade
HTT:	Main tank (Helium Two Tank)
HYDRA:	Hydraulic Shaker
ISO:	Infrared Space Observatory
LEAF:	Large European Acoustic Facility
MDH:	Mechanical Data Handling system
OB(A):	Optical Bench (Assembly)
PFM:	Proto-Flight Model
SHOGUN:	Shock Generation Unit
SPU:	Signal Processing Unit
SRS:	Shock Response Spectrum
STM:	Structure / Thermal Model
SVM:	Service Module
SYLDA:	Systeme de Lancement Double Ariane 5