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SINE TEST PREPARATION & MANAGEMENT INVOLVING LARGE NUMBER OF CHANNEL COUNTS.

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Abstract. *Bepi Colombo represents an ESA corner stone mission in collaboration with JAXA in Space science and exploration. The purpose of the mission is to fly two (2) planetary orbiters to Mercury with the aims of magnetospheric and planetary surface mapping.*

The paper presented here is intended to convey to the wider community considerations and experiences relating to both preparing and conducting a sine test with a large acquisition count. The test specimen comprises of a stack of three Spacecraft modules: a propulsion Spacecraft at the launcher interface and two (2) planetary orbiters stacked one on top of the other. The total test specimen mass was 6400kg comprising 3900kg (structure), 2400kg (test adapter) with the remaining mass allocated to a Force Measurement Device (FMD) and ancillaries. Over 512 channels were instrumented (441 accelerometers, 69 strain gauges, 6 FMD channels) along with a further 49 Virtual Channels combining physical acquisitions to produce angular accelerations, direct force outputs, local bending moment outputs (both from strain gauges) to enable management of sine input levels and monitor integrity of the structure.

During pre-test preparation, activity is focused towards preparation of the test technical management plan whose purpose is to define a justification for sine input levels, how the test is to be managed in terms of technical strategy and collation / establishment of the acceptable upper and lower limits which the test must achieve and not exceed to avoid compromising the structural specimen. The paper also discusses preparation of the test support tool and highlights a number of points including factors such as the need to validate data phase acquisition checks. Simulation (dry runs) of on-test activities is seen as critical to a successful test to ensure that the process is robust, tools/software are adequately de-bugged and ensuring the data analysis team responsibilities are well understood.

For the Bepi Colombo sine test campaign Astrium deliberately maintained the same acquisitions during each axis of sine test, thus trading complexity of data analysis versus improvement in acquisition management. Typically re-configuration of acquisitions between sine test axes is accompanied by a number of re-patching issues which is discussed further in the paper. Using in-house tools written into DYNAWORKS, Astrium confidently managed the large number of acquisitions and data analysis successfully within the tight timeframes imposed during such campaign. The paper concludes with a discussion of the lessons learnt covering both successes and areas for future improvement for the final flight model sine test campaign.

1 INTRODUCTION

Bepi Colombo represents an ESA corner stone mission in collaboration with JAXA in Space science and exploration. Launch is scheduled for 2015 on Ariane 5, the purpose of the mission is to fly two planetary orbiters to Mercury with the aims of magnetospheric and planet surface mapping. Figure 1 shows the Structural Thermal Model (STM) in readiness for longitudinal sine testing at ESTEC within ESA ETS facility. The test specimen comprises of a stack of three (3) Spacecraft modules: a propulsion Spacecraft at the launcher interface and two (2) planetary orbiters stacked one on top of the other. The overall test specimen mass is 6400kg comprising 3900kg (structure), 2400kg (test adapter) with the remaining mass allocated to a Force Measurement Device (FMD) and ancillaries. Over 512 channels were instrumented (441 accelerometers, 69 strain gauges, 6 FMD channels) along with a further 60 Virtual Channels combining physical acquisitions to produce angular accelerations, direct force outputs, local bending moment outputs (both from strain gauges) to enable management of sine input levels and monitor integrity of the structure.

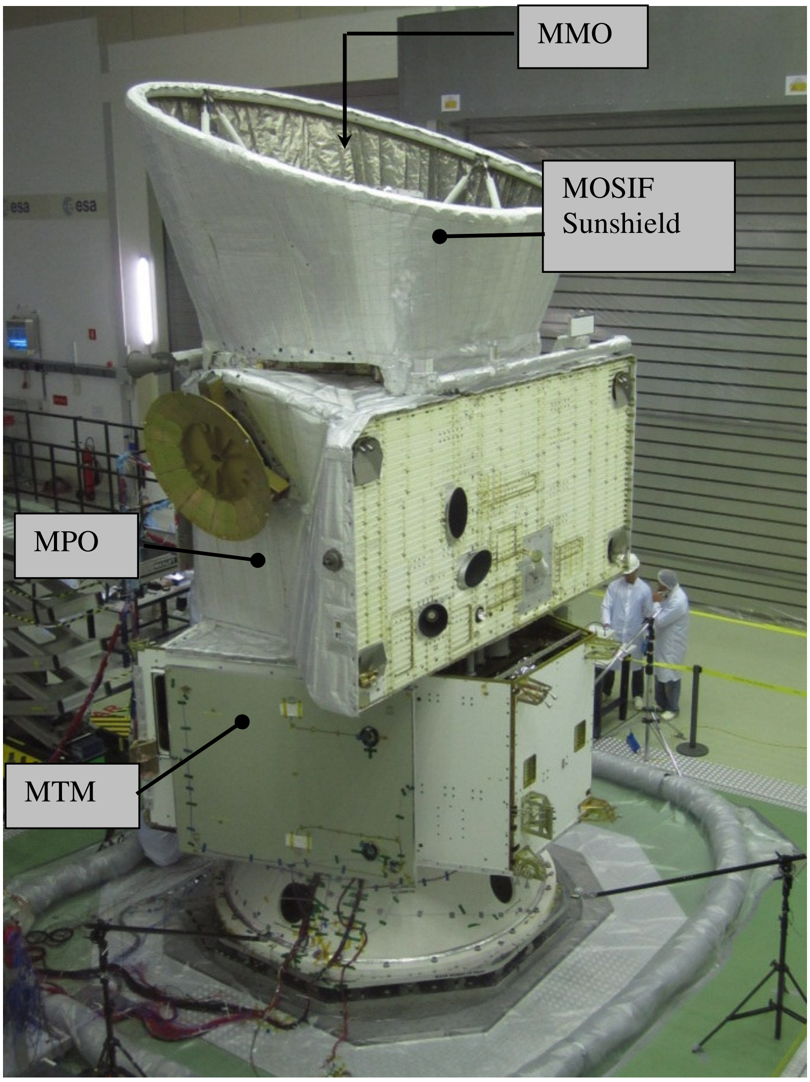


Figure 1. Bepi-Colombo STM stack in readiness for longitudinal sine test on ETS Quad shaker.

Figure 2. Spacecraft integration and stack preparation prior to installation onto ETS QUAD shaker for longitudinal Sine test. MOSIF & Sunshield are shown removed showing MMO STM at top of stack.

Figure 3. MOSIF adapter (right with MMO mass dummy) and sunshield structure with MLI removed. Photographs courtesy of RUAG Space.

2 SPACECRAFT ARCHITECTURAL OVERVIEW.

2.1 Overview.

The composite stack comprises of three (3) Spacecraft modules:

- Mercury Transfer Module (MTM) which provides autonomous propulsion after launch injection by Ariane 5.
- Mercury Planetary Orbiter (MPO): This supports a complement of instruments for planetary mapping.
- Mercury Magnetospheric Orbiter (MMO): that is furnished by JAXA. This module supports magnetic field characterization of Mercury and other science objectives highlighted below.

This section gives a brief overview of the stack complement together with a description of how the Spacecraft modules are coupled together to form a single contiguous structure.

2.2 Mercury Transfer Module (MTM).

The MTM provides the primary interface to the Launch Vehicle Adapter (LVA) through a conventional 1666mm clampband interface through a central honeycomb composite cone. This module contains the fuel tanks for the transit to Mercury after release from the Launch Vehicle. CPS and Xenon tanks are located outside the central structure. The structure is closed by conventional honeycomb panels linked to the central structure via vertical shear walls.

2.3 Mercury Planetary Orbiter (MPO).

The MPO module is located immediately on top of the MTM and is mounted via four (4) point cup and cone separation interfaces. The cup/cone arrangements are geometrically arranged on a square pitch of 870mm with each mating cup/cone preloaded in excess of 160kN to resist launch inertia loads. Separation is achieved by sequential ‘firing’ of low shock separation devices of the NEA fuse wire type. Local coil springs provide motive force to de-mate and separate umbilical connections between the Spacecraft module bodies.

The MPO construction is of aluminium honeycomb panels based on a double H section central structure and contains its own propulsion system for orbital management above Mercury’s surface. This Spacecraft module supports a payload of eleven (11) instrument packages for mapping the surface of Mercury, measuring heights of features, detecting ions and particles in the exosphere and measuring its magnetic field. The instrument complement is:

- BELA (Bepi Colombo Laser Altimeter): a topographic mapping instrument.
- ISA (Italian Spring Accelerometer): non–gravitational accelerations of the spacecraft
- MERMAG: detailed description of planetary magnetic field, its source and interaction with the solar wind.
- MERTIS (Radiometer and Thermal Imaging Spectrometer): global mineralogical mapping (7-14 µm), surface temperatures and thermal inertia.
- MGNS (Mercury Gamma-Ray and Neutron Spectrometer): elemental surface and sub-surface composition, volatile deposits on polar areas.
- MIXS (Mercury Imaging X-ray Spectrometer): elemental surface composition, global mapping and composition of surface features.
- MORE (Mercury Orbiter Radio Science Experiment): core and mantle structure, Mercury orbit, fundamental science, gravity field.

- PHEBUS (Probing of Hermean Exosphere by Ultraviolet Spectroscopy): UV spectral mapping of the exosphere.
- SERENA (Search for Exospheric Refilling and Emitted Natural Abundances): Study of composition, distribution, source and sink processes of the neutral and charged particle environment.
- SIMBIO-SYS (Spectrometers and Imagers for MPO Bepi Colombo Integrated Observatory): HRIC, STC, VIHI Optical high resolution and stereo imaging, Near-IR (<2.0μm) imaging spectroscopy for global mineralogical mapping.
- SIXS (Solar Intensity X-ray and particle Spectrometer): monitor solar X-ray intensity and solar particles in support of MIXS

2.4 MOSIF Adapter and Sunshield.

The MOSIF adapter is located immediately on top of the MPO and provides a structural interface between the MPO and MMO Spacecraft Modules. The adapter is a simple box section cruciform structure manufactured from riveted aluminium alloy sections which is coupled to the MPO by NEA's preloading cup/cones in a similar fashion to the MTM/MPO interface (nominal preload 72kN).

Supported on top of the adapter cruciform is a Sunshield and thermal blanket whose interfaces circumscribe the NEA cup/cone interfaces and the MMO. The Sunshield structure resembles an inverted cone and comprises of thin walled riveted aluminium tubes and end fittings as shown in Figure 3.

2.5 Mercury Magnetospheric Orbiter (MMO).

The MMO Spacecraft Module is provided by the Japanese space agency JAXA. The MMO supports five (5) instruments whose primary functions are plasma and magnetic field measurement.

- MO/MGF Magnetometer: whose function is to establish a detailed description of the magnetosphere and relation and interaction with solar wind and planetary magnetic field.
- MPPE (Mercury Plasma Particle Experiment): to support the study of low and high energetic particles in the magnetosphere.
- PWI (Mercury Plasma Wave Instrument): This instrument provides detailed analysis of the structure and dynamics of magnetosphere.
- MSASI (Mercury Sodium Atmospheric Spectral Imager).
- MDM (Mercury Dust Monitor): whose function is to establish the distribution of interplanetary dust in Mercury orbit.

2.6 Inter Module Hardware (IMH).

The Spacecraft inter-module separation planes at the MTM/MPO and MPO/MOSIF are coupled by a four (4) point mounting arrangement shown sectioned in Figure 4. Each of these device modules are referred to programmatically as Inter Module Hardware (IMH) designed and qualified by Astrium. Each device is consists of single NEAs providing preload to a cup/cone interface through a single tension 'bolt' member with an integrated ejection mechanism. External to the device are ejection devices for Spacecraft module separation.

The four (4) point IMH is contained within the primary load path for launch and has obtained special focus for overall structure qualification as a result of the devices functional criticality. This point of criticality is addressed further in later sections in terms overall load management, sine data processing and critical modes of the structure.

Each of the eight (8) IMHs integrated into the stack were instrumented with two (2) groups of four (4) uni-axial strain gauges as shown in Figure 5. The functions of each group of strain gauges are:

- *Preload stability gauges*: to monitor static preload status and its stability following swept sine loads. Status checks made prior to and immediately after each sine test to confirm no change of preload.
- *Dynamic load gauges:* to establish the external axial force, component bending moments and resultant bending moments exerted during the sine test. In this context each IMH unit was an integrated load cell. Strain gauge frequency response outputs acquired during sine tests were post-processed as Virtual Channels to establish resultant applied axial force and bending moments.

Integration of these load monitoring features was implemented relatively late in the design process hence further improvement to the static preload monitoring could be envisaged if applied early in the design. Prior to stack level STM testing the IMHs were subject to their own static qualification campaign to ensure compliance with specification integrity, stiffness, shock, life test, motorization margins and inertial injection on the stack; such requirements are appropriate to a critical mechanism structural element.

Characterization tests were also performed at IMH level to provide global calibration data for use during the system level sine test campaign thus translating strain output in terms of resultant axial force and bending moment.

In terms of system level preparation activities prior to conducting the sine test campaign, the IMHs received special focus not only in terms of understanding unit level behaviour but also in terms of formulation of test management schemes. An important point of note with respect to establishing a stack level test management philosophy was that at no time prior to test was total reliance on the ability of the IMH integrated load cell adopted. As a back-up strategy in the event of poor strain gauge outputs on test, redundant load management approaches were formulated to provide in essence an ‘over-constraint’ on such limit parameters. These redundant analytical limitations are discussed later. As a general philosophy when developing and testing analytical test control strategies, personal emphasis was always placed on the FEM uncertainty. A philosophy of *the only certainty given to the FEM was its potential uncertainty* provides a good basis for success since the engineer is always working in mode of risk management which maximizes potential for process robustness.

This general philosophy served the test campaign well in that the aim was to apply robust analysis observations and the over-constraint of parameters served to provide a degree of margin on safely conducting a complex test.

A final key message of experience would be relaying the key point of: Redundancy! Redundancy! Redundancy! whether it be a process, individual expertise, computing support hardware or associated networks or sine test control. If every aspect of the test and its process has inherent redundancy then the possibility of a successful test campaign is maximised.

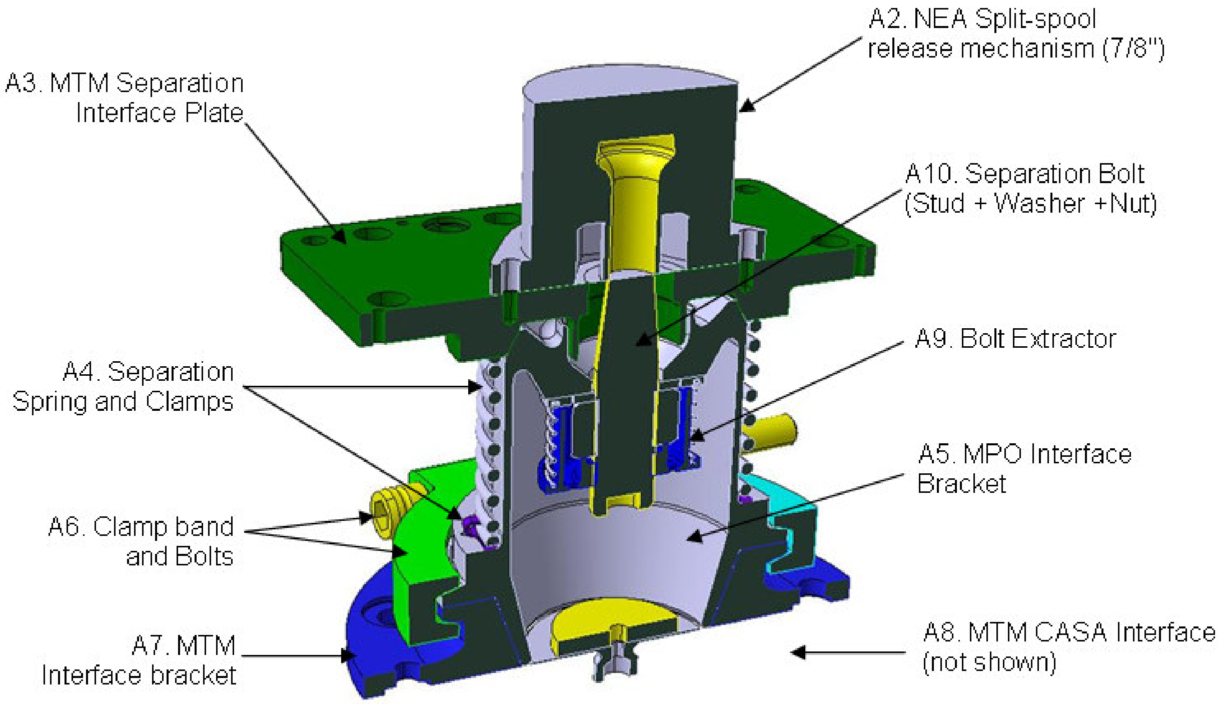


Figure 4. Sectioned illustration of MTM/MPO Inter Module Hardware (IMHs). A similar four (4) point arrangement exists at the MOSIF/MPO interface.

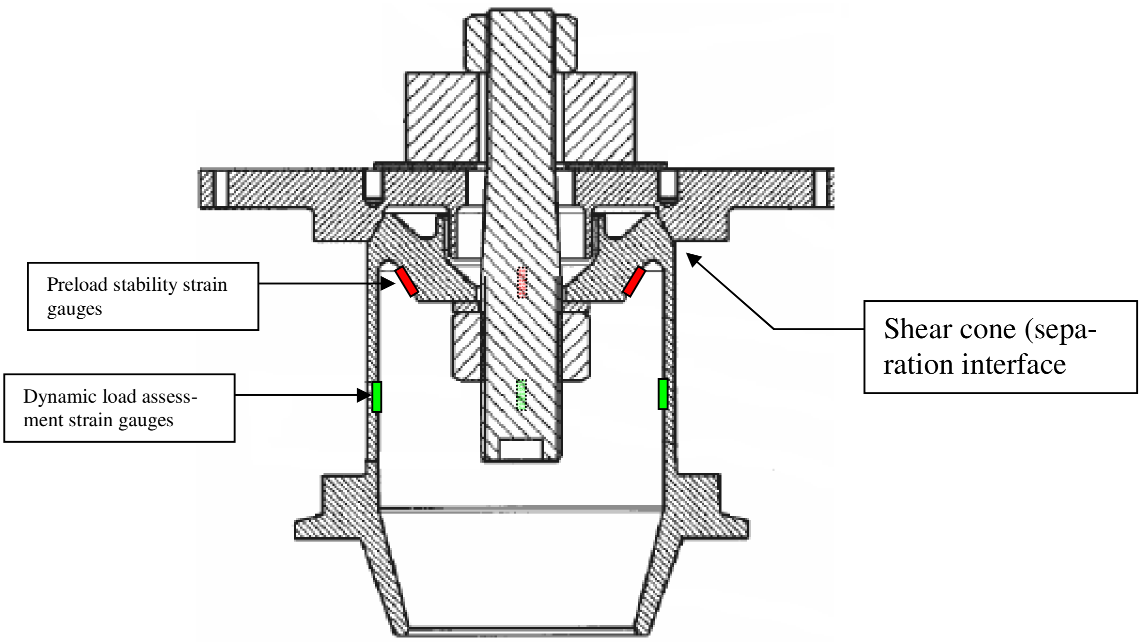


Figure 5. Four point equi-spaced uni-axial strain arrangement for static preload monitoring local to applied preload load path. Gauge purpose is to confirm preload stability pre- and post dynamic loading. Four point uni-axial strain gauge system on external body for external dynamic load measurement during sine testing.

3 DYNAMIC TEST CAMPAIGN.

Bepi Colombo's dynamic test campaign is centered on the needs to fulfill the requirements of an Ariane 5 launch and has been tailored around distinct Structural/Thermal test model (STM) and proto-flight model (PFM) philosophy where only the PFM is scheduled to fly.

In spite of the STM being non-flight, the structure did comprise of certain flight structural elements namely: the MOSIF adapter/Sunshield structure and secondary thermal support structures on the MTM. The JAXA supplied MMO is an STM.

The STM test campaign conducted during July 2012 comprised of sequence tests as dictated by an Ariane 5 launch:

- ***Sine test***: three (3) axis independent at 2 octs/min:
  - Longitudinal:- 5.6-50Hz 1.25g, 50-100Hz 1g.
  - Lateral:- 6.4-25Hz 1g, 25-100Hz 0.8g.
  - Notching both primary and secondary applied.
- ***Acoustic***: Levels [1] +3dB for Qualification
- ***Shogun*** and ***Clampband*** shock tests.
- ***Appendage*** and ***equipment release shock firings:*** characterization shock emission tests.

4 INSTRUMENTATION OVERVIEW.

Subsystem/Module	Instrumentation	No. of Channels for Sine Test	Notes
MMO	Accelerometer	31	
MOSIF	Accelerometer.	35	
MPO	Accelerometer.	219	
MTM	Accelerometer.	153	
FMD/LVA/shaker i/f	Accelerometer.	26	
TOTAL ACCELEROMETERS		**464**	
MMO	Strain gauge	4	Strain gauges on interface ring at clampband to monitor interface loads
MOSIF	Strain gauge	8	Mounted on discrete struts to monitor bending.
MPO	Strain gauge	15	Tank support struts, tank interface brackets, optical bench iso-static mounts.
MTM	Strain gauge	10	
IMH	Strain gauge	32	To assess global axial force and bending moments
TOTAL STRAIN GAUGES		**69**	
FORCE MEASUREMENT DEVICE (FMD)		**6**	24 load cells supporting an interface plate below the VTA.

LVA: Launcher vehicle adapter.
VTA: Vibration test adapter. A cylindrical structure of high relative stiffness with respect to the test specimen. Upper end provides clampband interface. Lower end interfaces to adapter plates on the FMD.

Table 1. Total numbers of channels and types of instrumentation.

5 TEST PREPARATION.

5.1 Recipe for success.

Successful test campaigns are based upon:

- Preparation.
- Test management philosophy supported by back-up test control strategies or "flexible" limitations.
- Pre-agreed limitations and working tolerance defining the safe working perimeter for the test.
- Effective test time management.
- Achievable, measurable & readily identifiable pre-agreed test success criteria.
- Redundancy, redundancy & redundancy! –in ALL elements of the process and support infra-structure.

5.2 Sine test preparation overview.

The typical scope of activities associated with preparation for a major sine test campaign is shown schematically illustrated in Figure 6. Effort is grouped into three principal blocks starting with:

- Establishing and defining test needs.
- Performing analysis to establish a plan for test implementation and management and documenting such process.
- Planning and simulation of the process.

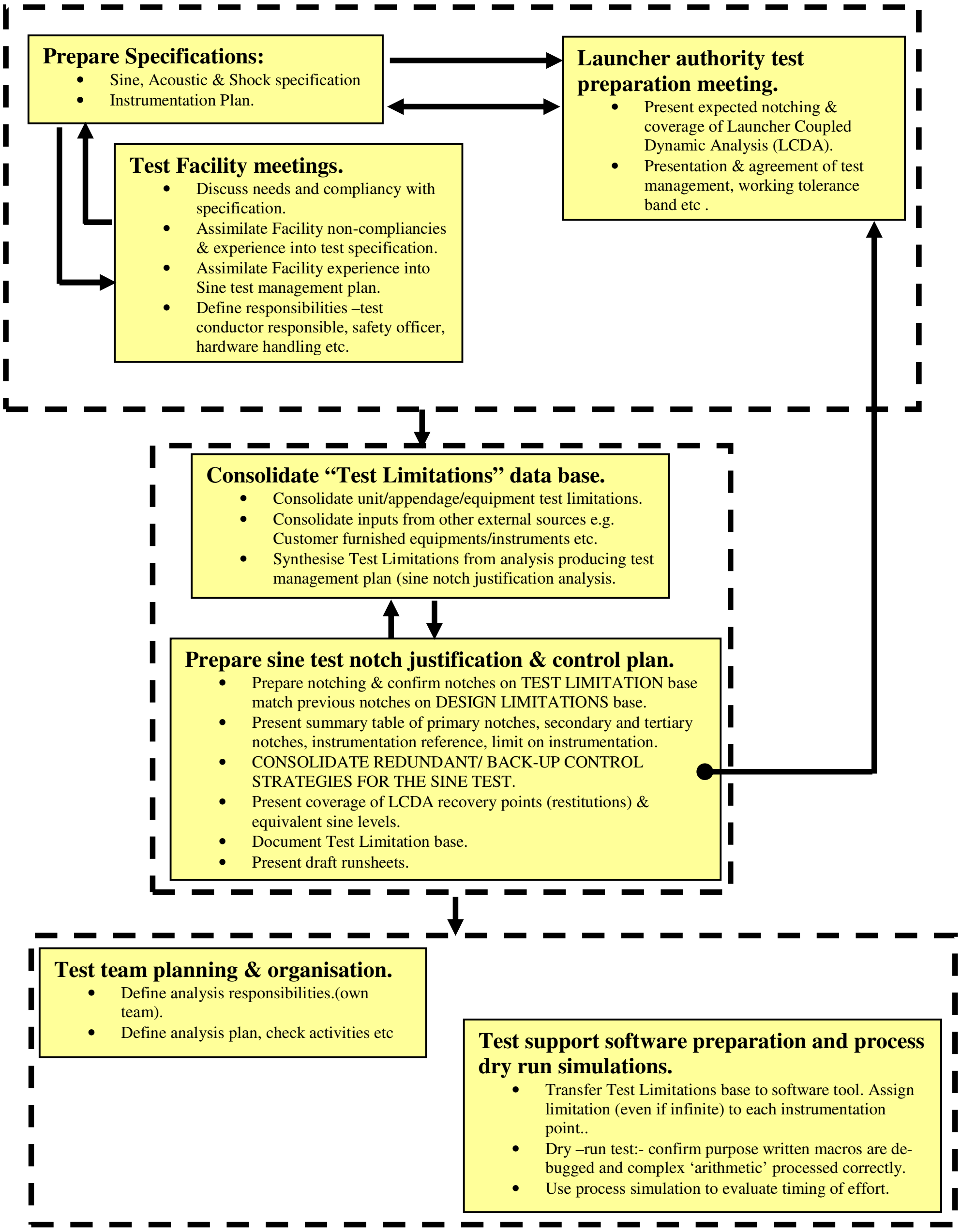


Figure 6. Test preparation activity –schematically illustrated.

5.3 Planning the test.

Experience, planning and effective preparation is of paramount importance in achieving a successful test campaign. This paper has attempted to provide an outline of most of these key points but if these were to be summarized further then principal points which should be focused on can be summarized by a small number of bullet points:

- *Ensure measurable test specific success criteria are in place:* the criteria should be specific to the test and should be closable within the framework of the test activity. Success criteria not specifically linked to the test (e.g. FEM correlation criteria) should where possible be rejected.

- *Ensure all Test Limitations are in place* and every instrumentation point has an assigned limit for its output. Some instrumentation locations may not be critical to the test and may be included for information only, for such locations limits may be assigned to be "infinite".
- *Ensure appropriate endorsements are in place:* from the customer and launcher authority in terms of test tolerance philosophy, predicted notching etc.
- *Ensure the test needs have been discussed with the test facility:* such interface meetings are a two-way process of understanding, provide a means of realizing a rational specification and enable an early understanding of compliancy with the test specification. Include within such meetings (and test specification) needs such as the analysis environment and the means and format of data transfer. For some unknown reason the mechanisms of data transfer always seem to be complicated by political reasons. It is important that a minuted understanding is reached.
- *Ensure all steps of the test support process have been subject to dry runs and the support tools de-bugged.* The aim should be to ensure that all members of the team understand their own responsibilities and are able if necessary to fulfill other member roles. Leave no process to chance and ensure the process is planned and mapped out. For Bepi Colombo this planning process was support by a process flow diagram which was taken and displayed on test.
- *Redundancy, redundancy and redundancy*! This message cannot be over emphasized in terms of its importance. All aspects associated with the test should be reviewed from the point of redundancy or process back-up. This applies to:
    - Personnel expertise.
    - Analysis hardware and software particularly non-reliance on network connections which invariably fail in spite of being "sold" to the test team as robust!
    - Data transfer from the facility to test team computer hardware.
    - Back-up test control strategies and redundant limitations. At the start of the Bepi Colombo test campaign (TRR) it became evident that certain strain gauges would not support management of their associated interfaces. Redundant analytically based limits, established at system level, had been synthesized which were able to address poor instrumentation implementation. Assessment of the second order cantilever mode responses and *applying angular acceleration* limits established during the sine test notch justification and test control plan analysis activity, provided this redundancy in terms of monitoring the interface concerned.

      For purpose of example, other illustrations of such redundant strategies could be catering for correlation errors in boom type structures where an acceleration limit and associated frequency is concerned. In this case of poor advance correlation, such acceleration limits can be corrected to relative deflection limits subject to correcting for frequency and relative response differences.
    - Key non-accessible instrumentation. Invariably accelerometers installed on tanks are typical locations where for various reasons instrumentation function is lost prior to or during a test. Usually tank response limits are critical to the test hence it is recommended that such locations which may be non-accessible for rectification include redundancy or redundant averaging for interpolation to c of g location is required.

5.4 Sine test notch justification and test control plan.

The output resulting from the test preparation analysis activity should be a document or plan (*sine test notch justification and test control plan*) which defines the test control plan, justification of primary and secondary notching and data or perimeters defining limits of response with the instrumentation defined by the measurement point plan.

Content of this notch justification and management plan would normally compose:

- *Definition of predicted notching.*
- *A definition of the test working tolerance band.*
- *A database of Test Limitations providing the perimeter of responses for conducting the test.*
- *Coverage and margins against the LCDA recoveries and equivalent sine inputs.*
- *Support analyses defining test control /management approaches and analyses synthesizing specific Test Limitation base entries.*
- *Summary tables defining governing notch locations, test instrumentation limits, associated frequency bands.*

The test working tolerance band:

For Bepi Colombo the generic working tolerance was proposed as the minimum band based upon experience for managing responses and overshoot of responses (+2.5dB). The generic applied tolerances are shown illustrated in Figure 7. The lower limit provides the target (auto) notch specification given on the run sheet and the upper limit defines the prescribed run sheet abort limit. It should be noted that it is Astrium's practice to contain the abort limit within specification limits compatible with the system's design specification so that any response achieved between notch assignment and abort does not entail justification in terms of imparted load exceedance. On test the low limit may be subject to reduction based upon observations of response overshoot from intermediate levels.

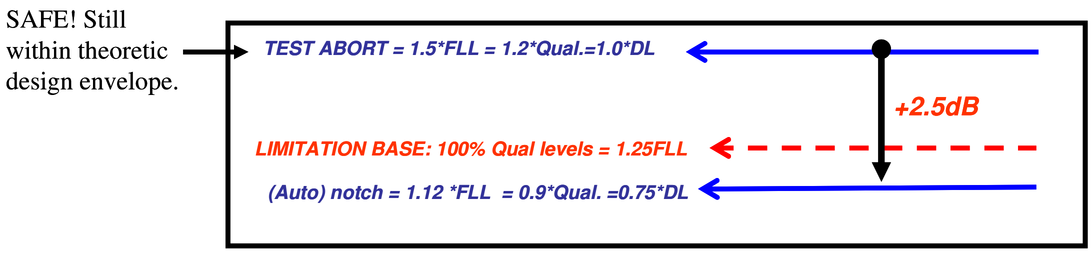


Figure 7. Schematic illustration of the sine test control band between notch specification and abort. The 2.5dB band is based upon experience in terms of management of response overshoots. FLL=flight limit load. DL=Design Limit load (excluding FoS).

A database of Test Limitations providing the perimeter of responses for conducting the test.

Experience has shown that the consolidation effort required to formulate this data base of limits should not be underestimated particularly for subsystems that are not under the Prime's responsibility.

It should be noted that a clear distinction exists between the Test Limitations and the Design Limitations specified in the system design specifications. The majority of the Test Limitations are defined by the design specifications but not all. Some inputs are consolidated from various institutional bodies into one database while others have to be specifically computed from the analysis framework that produces the test control/management plan. In essence the

Test Limitation data base comprises of those limits assigned to the sine test instrumentation and may be an indirect to monitor a Design Limit value.

***Definition of predicted notching*.**

The plan should provide a justification of the notching projected for the test and withstand scrutiny from both the Customer and launcher authority. Since the notching presented is based upon Test Limitations, the notching should be consistent with notching predictions established by application of the Design Limitations. Normally manual notch proposals would be projected on to the computed notching as part of the overall presentation of test control and for forwarding to the launcher authority for endorsement prior to the Test Readiness Review (TRR). The pre-test projected notching for Bepi Colombo is shown in Figure 8 which is shown for one lateral axis and the longitudinal case. These curves show the predicted notch density for the program.

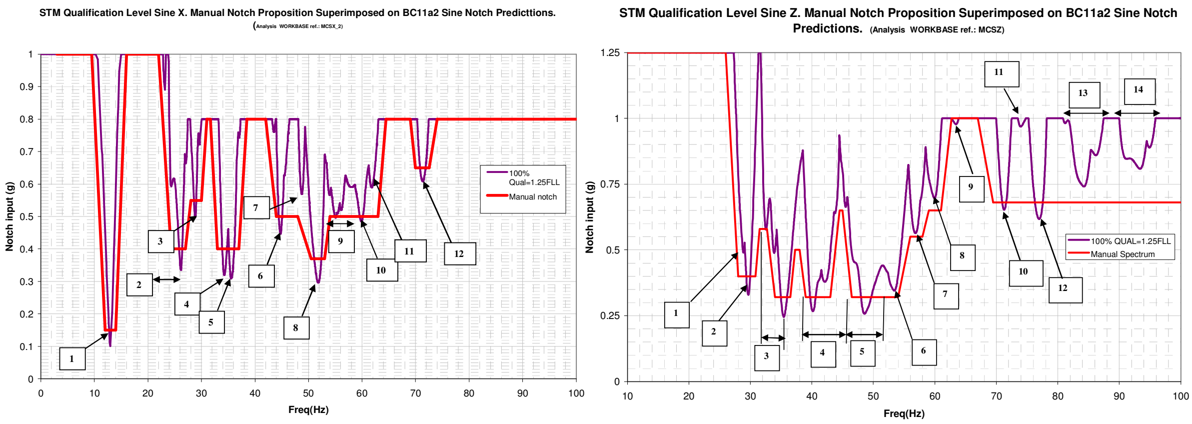


Figure 8. Pre-test predictions illustrate predicted notch density. Notches governed by primary structure main bending modes in the low frequency domain, composite limits suited to virtual channel assignment and single value notch limits are typically at higher frequencies.

5.5 Control of primary modes.

For Bepi Colombo the primary limitations associated with the fundamental cantilever modes and main axial mode are those associated with the Spacecraft interface loads at the LVA derived from the launcher qualification level quasi-static specification [1]. During pre-test sine notch justification/prediction analysis the main LVA longitudinal force limit associated with the main axial mode was predicted to be covered by other internal limitations which generated there own governing notch. For the first cantilever modes the analysis predicted a primary notch governed by the quasi-static interface loads marginally covering secondary notches associated with IMH bending moment limits.

Management of base loads was greatly simplified by use of ETS' force measurement device (FMD) which is shown in Figure 9. This device was installed between the slip table or head expander and the VTA and consists of annular interface plates and twenty-four (24) piezo-electric load cell elements capable of providing six-dof resultant load output on it reference plane. Evaluation of data provided by ETS in advance of the test gave confidence that the gross specimen mass and associated centre of gravity offset would not reduce the fundamental modes or degrade the boundary conditions for the test.

Piloting for all sine tests was specified at the VTA/LVA interface which was of the order of 1.0m above the slip table or FMD reference plane. Due to this height offset two(2) options for interface load management thus existed:

- Generate a DYNAWORKS Virtual Channel (see later for applied Virtual Channel) by transformation of the FMD reference planes *complex* loads to the VTA /LVA reference plane. Such a process would produce 'exact' computed loads at the plane of interest but would need to be transformed to the FMD plane for run sheet specification.
- On the assumption that both the FMD and VTA are rigid relative to the Spacecraft, to *statically* transform the quasi-static LVA interface load limits to the FMD reference plane with a small allowance based upon a small phase angle of the static mass of the VTA and FMD interface plate sprung mass on the load cells. This approach meant that the Test Limitation could be assigned a load limit directly assignable to the FMD and directly assignable to the run sheet. For the Bepi Colombo sine test campaign, this approach was adopted and endorsed by the customer and launcher authority.

As a consequence of incorporation of an FMD into the instrumentation plan, this provided several options in terms of control strategies for managing Spacecraft base loads. During pre-test facility meetings ETS indicated that on a previous program the fundamental cantilever modes were controlled by direct auto-notching on the FMD with no manual notch back-up. Such an approach prior to test was considered by Astrium but it was decided to apply the well trodden path of specifying accelerometer limits on the top of the stack with a manual notch back-up. In addition the FMD limits were also specified on the run sheet with appropriate margin to avoid control hand-overs. This approach of control functioned perfectly adequately and safely on the Bepi lateral sine tests potentially as a result adequate damping on the fundamental cantilever modes (>2% critical viscous). Other programs of similar overall Spacecraft mass but greater centre of gravity height offset (e.g. Metop-A, Metop-B, Metop-C) were more difficult to control on the first cantilever mode's exit from resonance, this was believed as a result of low damping (<1% critical viscous). Hence although initial inspection of the architecture for Bepi indicated a complex structural definition it is believed that multiple interface assisted damping and control during the sine test.

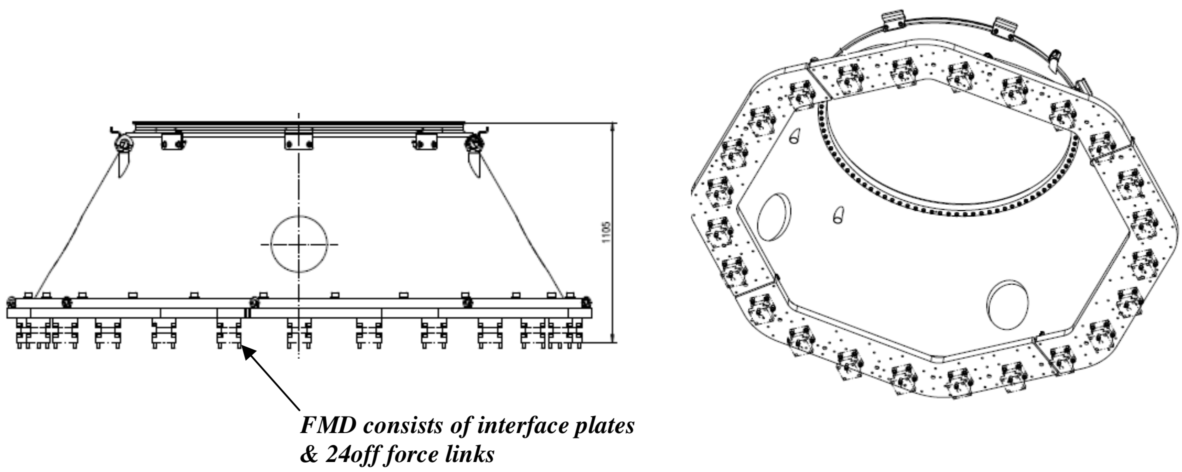


Figure 9. FMD / VTA architecture:- 24off Kistler force links at VTA interface.

5.6 Specific test limitations, management of second order cantilever bending modes and use of DYNAWORKS to formulate constants of proportionality between differing spectral entities.

A powerful feature of DYNAWORKS is its simplicity with regard to application of manipulation of complex variables and its ability to formulate strategies for indirect approaches of managing certain design limits. The "Signal Analysis" window (see Figure 10) is similar to a spreadsheet but with the advantage that a single cell can store a complex quantity such as a complete frequency response function. Thus instead of needing three (3) columns as in a spreadsheet to store XYdata: X, Re(Y) and Im(Y) all of this data can be stored and manipulated within a single cell.

Management of the IMH loads was critical to the success of Bepi Colombo sine test campaign. The primary means for controlling the loads (specifically bending moment components and their resultants) was from strain gauges thus each IMH was an integrated load cell pre-calibrated against IMH qualification static tests.

Prior to test knowledge of the potential quality of frequency response output from the strain gauges was an unknown and as a consequence a redundant strategy for IMH load monitoring was established as a back-up approach to managing their loads. Again in line with robust focus, the strategy needed robust 'physics' and needed to account for FEM uncertainty. The principal modes governing major IMH loads were the first and second order cantilever modes (see Figure 11 for 2nd order mode). To this end the 'firm physics' of the approach is recognizing that the second order cantilever mode is a firm expected outcome from the test, but when relating differing response quantities the uncertainty is the quality of the FEM mode shape to provide links in terms of constants of proportionality between differing response quantities within a frequency band. Since the aim was a redundant back-up to the main means of controlling IMH load, by direct load measurement, then the limited uncertainty is acceptable. Also since the governing modes are associated with lower order modes their predictability in terms of quality of mode shape should be well established from the FEM.

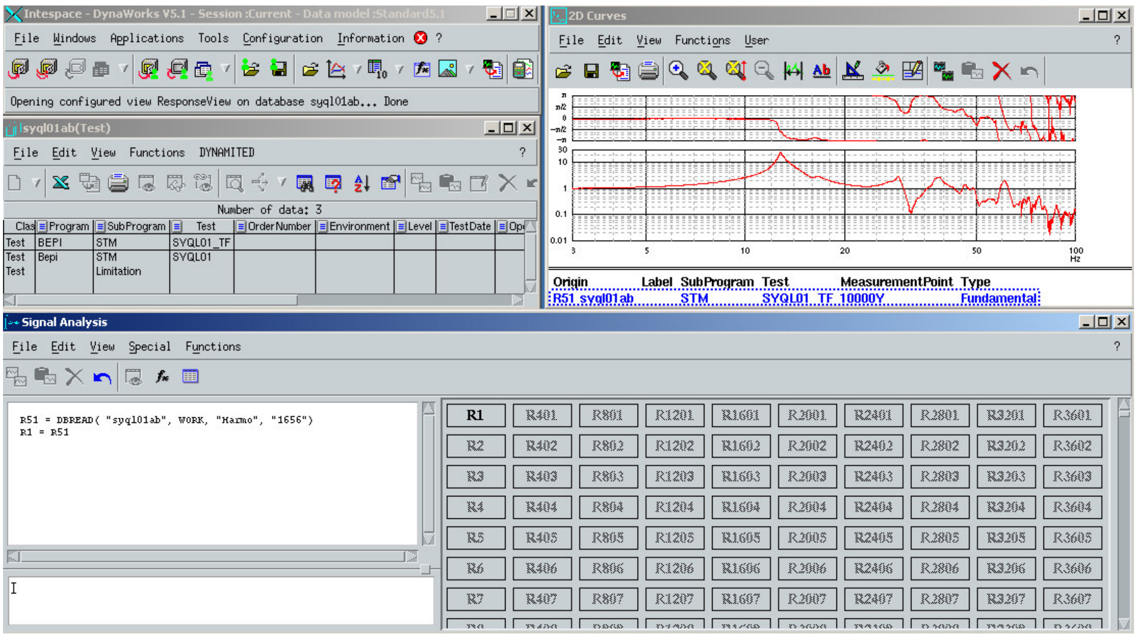


Figure 10. The DYNAWORKS environment.

Figure 11 shows the characteristics of the second cantilever mode. This mode (predicted circa 28Hz for both YZ and XZ planes) shows the upper MMO rotating in the opposite direction to the remainder of the cantilevered structure. Through the assumption that the predicted mode shape quality is adequate to formulate limits, it is possible to link various load quantities that are of interest in the mode to measured *angular acceleration* responses: IMH bending moment, IMH axial force and MMO bending moments for example.

From analysis of the pre-test predictions it was evident that the *angular* response (off axis Z responses) of the MMO was a suitable means to establish these load parameters. An advantage of response differencing in this manner to obtain "scaled" (*) angular accelerations is that the analytical sensitivity is increased, since the difference of out-of-phase responses is amplified, and the differencing approach filters in-phase characteristics.

(*) "Scaled" because the geometry separating these accelerometers can be ignored.

Figures 12 and 13 show example over-plots of the angular accelerations Δ(10001Z,10011Z)(*) Transfer Functions (TF) versus the IMH bending moment TFs and MMO interface bending moment TF.

10001Z and 10011Z denote labels assigned to accelermeters.

Figure 12: *MOSIF/IMH fixation plane result B.M. envelope:*

*MO_IFL*_MXY ≈ 42* (10001Z – 10011Z) -----------(1)*

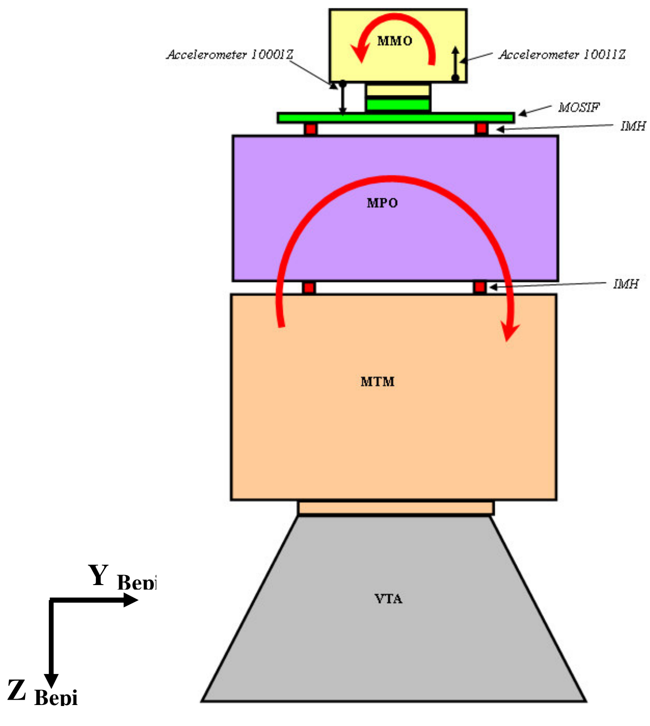


Figure 11. Schematic of 2^{nd} cantilever mode. MMO lower floor accelerometers differenced for angular response characterization of this mode.

It can be seen from Figure 12 that the relation (1) provides a good approximation over the frequency band 20-46Hz except for a narrow band below the main peak of 26.2Hz where the relation is not conservative. To address this, two options exist:

- Modify the constant of proportionality until this region is covered. This will produce a more conservative function but would result in relation which would generate a deeper notch at the 26.22Hz peak.
- Extend the main notch computed at 26.2Hz so that it spans the region not covered by the redundant function.

For test application a combination of these two(2) options was recommended along with a specification of a manual notch covering a region +/- 3Hz centered on the main peak. At 1Hz below the main peak at 26.2Hz the error in correlation of the redundant function with the predicted B.M is predicted as 20%, factoring the constant of proportionality by this factor:

*MO_IFL*_MXY ≈ 50.4* (10001Z – 10011Z) Nm   20Hz*$\leq$ f $\leq$40Hz -----------*(2)*

For an MXY limit of 616Nm:

$\Delta(10001Z - 10011Z) \leq 12.2g$ -------------(3)

The relation and limitations here on the differential Δ(10001Z,10011Z) cannot be directly applied to the run sheet for control purposes. The expressions are therefore on-test analytic and must then be transferred to one or both of the channels 10001Z and 10011Z on the run sheet i.e.:

$10001Z = 0.58 * 12.2g = 7.08g$ -------------(4)

$10011Z = 0.419 * 12.2g = 5.11g$

The previous example linking MMO angular accelerations to IMH bending moments gives some insight to the power of DYNAWORKS to iteratively assess spectral limitations. With raw response quantities such as multiple IMH component bending moments, by a single macro function it is possible to define a new response quantity which is maximum spectral envelope of numerous loads at different IMH locations. From this step it is relatively easy to correct this quantity to a TF and iteratively amend constants of proportionality until the analysis shows good coverage of the measured relation relative to the load entity of interest.

As a point of note, with measured loads obtained the IMH integrated load cells, the above parameters are able to be correlated in “real time” during the test.

Figure 13: *MMO interface bending moment for Sine X excitation:*

Shows a similar process applied for evaluating acceleration limits for establishing MMO interface bending moments generated by Sine X excitation. Such redundant analytical methods compensated for poor MMO strain gauge outputs.

Additional evaluations are presented in Table 2 linking relations between measured IMH axial force ‘Fz’ and different bending moment quantities on the MTM/MPO and MOSIF/MPO IMH interfaces. The analysis here shows that adoption of measured 10kN limitation ensures that all IMH bending constraints remain with the static qualification perimeter established from unit level static tests.

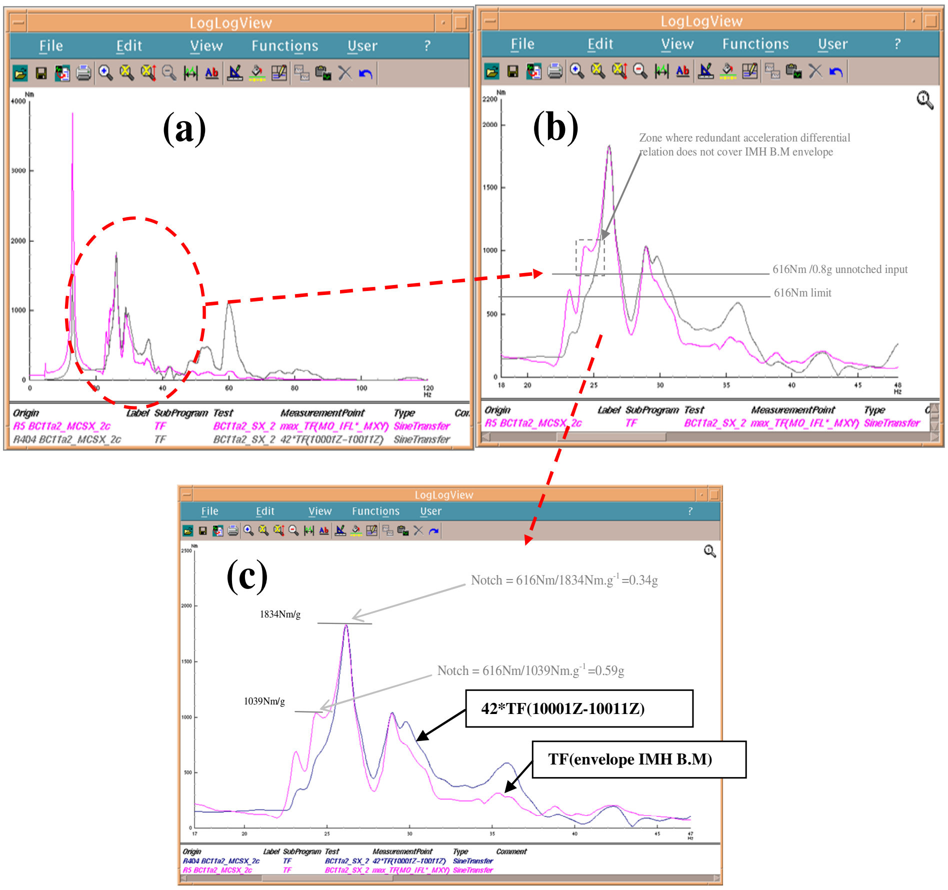
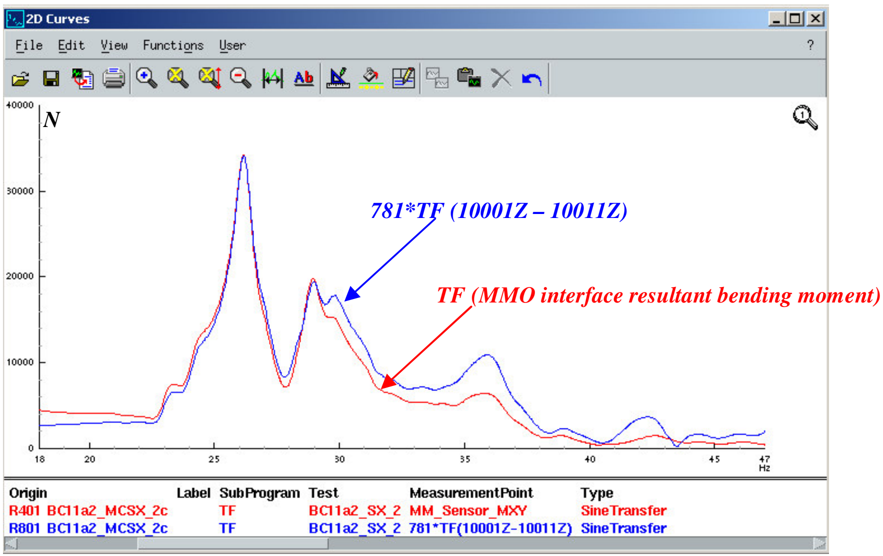


Figure 12. Spectral coverage of IMH maximum bending moment, envelope of four (4) IMH locations, and a synthesized CONSTANT* acceleration differential Δ(10001Z,10011Z) accelerometer references.



$MXY = 781*(10001Z - 100011Z) = 17g$ *for limitation* $= 13322Nm$ $(20 \leq f \leq 47Hz)$

Figure 13. CONSTANT* Δ(10001Z,10011Z) related to MMO interface bending moment T.F. (MM_Sensor_MXY).

Case	Variable	I/F description	Const. proportionality (Nm/N)	Qual. Limitation (Nm)	Qual. Limit Fz (N)	Notes
SINE X	max TF(MO_IFL*_MXY)	MOSIF /IMH fixation	13.9	616	8562.4	max. TF(MP_IFU*_FZ)=13.9*max TF(MO_IFL*_MXY)
	max TF(MP_IFU*_MXY)	MOSIF/ MPO cup/cone	30.2	355	10721	max. TF(MP_IFU*_FZ)=30.2* max TF(MP_IFU*_MXY)
	max TF(MP_IFL*_MXY)	MPO/MTM cup/cone	17.4	861	14981.4	max. TF(MP_IFU*_FZ)=17.4* max TF(MP_IFL*_MXY)
			min. cup/cone=		**10721**	Limitation Fz PER IMH
			min overall=		**8562.4**	
SINE Y	max TF(MO_IFL*_MXY)	MOSIF /IMH fixation	23.7	616	14599.2	max. TF(MP_IFU*_FZ)=23.7*max TF(MO_IFL*_MXY)
	max TF(MP_IFU*_MXY)	MOSIF/ MPO cup/cone	38.3	355	13596.5	max. TF(MP_IFU*_FZ)=38.3* max TF(MP_IFU*_MXY)
	max TF(MP_IFL*_MXY)	MPO/MTM cup/cone	21.4	861	18425.4	max. TF(MP_IFU*_FZ)=21.4* max TF(MP_IFL*_MXY)
	max TF(MP_IFL*_MX)	MPO/MTM cup/cone	21.9	440	9636	max. TF(MP_IFU*_FZ)=21.9*max TF(MO_IFL*_MX)
			min. cup/cone=		**9636**	Limitation Fz PER IMH
			min overall=		**9636**	

Table 2. Summary of narrow band (20-45Hz) constants of proportionality of MOSIF/MPO IMH axial Fz force versus various IMH bending moments.

5.7 Asymmetry of boundary conditions .influencing measurement point locations.

For a limited number of units/payloads, pre-test analysis indicated the sensitivity of the exact assigned location of accelerometers relative to the unit. System architects (may) prefer instrumentation specified at the base of the unit for direct comparison with unit level specifications while the engineer performing the inertial load assessment may conflict with this in terms of preference with a response through a unit's centre of gravity. For flight items, surface coatings or configuration may preclude such a response through the c of g, but instances where the unit is a mass dummy or the boundary conditions are highly asymmetric then sensitivity to accelerometer position assignment may need to be addressed in advance of the test.

One such example was noted on one of the MTM large avionics units. The foot print of this unit is rectangular but the supports on each boundary are significantly different. Depending on which boundary the accelerometer was mounted then the assumed inertia load could be significantly different.

On one foot edge the unit was immediately adjacent to a shear wall hence the out-of-plane response of the unit was propped by this panel. Similarly the next edge clockwise was propped by floor panel while the diametrically opposite edge was a free edge. The final foot edge was remote from any support and tended towards a panel centre type response. For this unit as a mass dummy was defined the only way of confidently establishing the units interface load was instrumentation through the unit's c of g.

5.8 Virtual channels.

In the context of this paper a "Virtual Channel" represents a new channel of data computed by combining or processing of a set physical data acquisitions. Such channels may be embedded into the notching analysis performed on test by expanding the *raw* acquisitions data set prior to TF computation and subsequent notch computation effort. In the previous discussion one such Virtual Channel has already been highlighted namely combining accelerometer differentials to derive an angular acceleration for which a Test Limitation would be prescribed. It should be noted that the Virtual Channel retains the original complex basis in terms of Real and Imaginary content from the physical acquisition from which it is generated.

During the Bepi Colombo sine test data analysis some forty-nine (49) extra Virtual Channels were synthesized by pre-prepared DYNAWORKS macros. On receipt of the frequency response data from the facility, a suite of three (3) macros were run making generation of the Virtual Channels automatic. Table 3 lists the supplementary Virtual Channels created, the list has been condensed by grouping like channels.

*MO_IFL*_MXY*: -see previous section 5.6. Limits are assigned angular accelerations.

*QSL_MT_S*_Z*: average Solar Array dummy panel responses to establish in-plane accelerations effective through the dummy centre of gravity. Limitation is based upon specification quasi-static design limits for the dummy and the structure interfaces.

*QSL_MP_TK*_XY:* resultant accelerations through specific propellant tank c of g's.

MP_MIXS_TY, QSL_MP_OPTB_Z:, QSL_MP_OPTB_Z: responses for one of the MPO instruments and the MPO optical bench equipments. Constants of proportionality established during sine test preparation analysis.

MT_TMY_PXMZ_TXYZ: establishes the resultant (XYZ) accelerations for specific MTM thrusters from a local triax on each thruster.

QSL_MT_TPA3_XY: establishes a response for lateral acceleration resultant through the SEPs thrusters c of g.

QSL_MM_Z: Similar quantity as MO_IFL*_MXY constants of proportionality convert angular acceleration quasi-static equivalent interface bending moment on the MMO.

MP_TK_AUX_*_TRQ: virtual channel computing: *(angular acceleration * polar moment of inertia)* to establish reaction torque on the polar mounted tanks –see Figure 14.

IMH_MO_PXPY_Fz: virtual channel averaging four(4) strains on each MOSIF/MPO IMH. Limits retained as strain but calibration factor for this average strain to resultant axial force Fz = 86.5N/με. 'Calibration' constant derived from local static testing / qualification of the IMHs

IMH_MO_PXPY_M:* three Virtual Channels per IMH covering two (2) component bending moments and resultant at the MOSIF/MPO interface. Bending moment components established from differential strains in diametric opposing strain gauges. Calibration constant =1.86Nm/με.

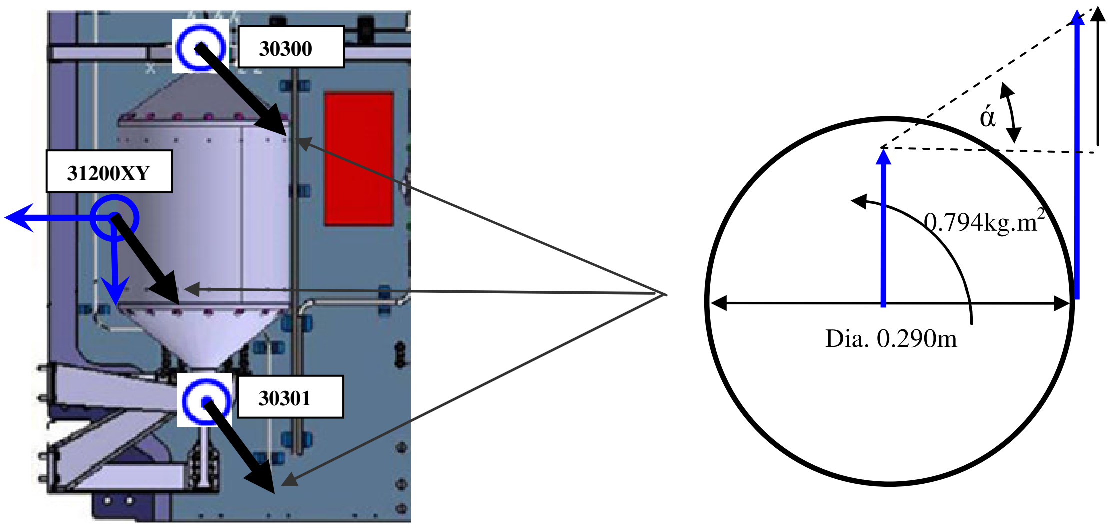
IMH_MT_PXPY_*: IMH virtual channels monitors but for MPO/MTM interface Fz and Mx,My and Mxy loads as MOSIF/MPO.

In terms of implementing these differential limits and other virtual quantities to the sine test run sheet, the compound spectra of combined responses must be prescribed to a single physical channel. For angular acceleration based limits this not a problem as this entails selection of one of the pair channels used for differencing while the other channel may be used as a redundant back-up.

5.9 Preparation of test calibration support data.

Irrespective of certification, engineers always perceive it to be good practice to validate information against a quantifiable reference i.e. "*the back of envelope approach*". Load cells typically fall into this domain, armed with basic mass information and low frequency responses (*tending to quasi-static*) it is possible to establish a level of confidence in the data acquired.

For transducer sets such as the FMD such basic calibration can be made during bare fixture tests. For integrated load cells such as the IMHs preparation of mass property data of Space-craft modules or pre-test 1g load distributions fulfill the quality check.



$\Delta a_1 = ((0.5*(30300Y+30301Y)) - 31200Y)$
Test management parameters:
Tank diameter= 0.290m
Tank mass dummy Polar Moment of Inertia= 0.794kg. m^2

$Torq = I \,.\, \acute{\alpha} = 0.794 \,.\, \Delta a_j / (0.290 * 0.5)$

Torque Limit (100% Qual Limit) = 158Nm
100% Δa_j Limit = 2.94g (ALL sine cases X,Y,Z)

Figure 14. Virtual channels for complex computational assessment of propellant tank reaction torques evaluated by differential responses for angular accelerations. 30300Y,3030Y and 31200Y define accelerometer labels from the measurement point plan.

Virtual channel ref.	No. channels	Location	Unit	Limitation	Calculation
MO_IFL*_MXY	2	MO IMH MXMY OP	g	**12.2, 10.4**	=(10001Z – 10011Z) & (10006Z-10007Z) range of validity: *20Hz*≤ f ≤40Hz
QSL_MT_S*_Z	2	MTM SA PX IF IP	g	12.5	=(AvZ^2+AvY^2)^0.5 , AvZ= (40601Z+40602Z)/2 AvY=(40601Y+40602Y)/2
QSL_MP_TK*_XY	2	MPO Hyd. Tank QS IP	g	5	=(31000X^2+31000Y^2)^0.5
MP_MIXS_TY	1	MPO MIXS Ave. OOP	g	9	=(1.7*30706Y+30752Y)/2.7
QSL_MP_OPTB_Y	1	MPO OPTB QS IP Y	g	13.7	=(30150Y+30152Y+30153Y)*1.23 / 3
QSL_MP_OPTB_Z	1	MPO OPTB QS IP Z	g	10.38	=(30150Z+30152Z+30153Z)*1.3 / 3
MT_TMY_PXMZ_TXYZ	4	MT TMY PX MZ RXYZ	g	28.7	=(40114X^2+40114Y^2+40114Z^2)^0.5
QSL_MT_TPA3_XY	1	MTM TPA3 QS IP	g	6.25	40106XY=(40106X^2+40106Y^2)^0.5
QSL_MM_Z	1	MMO/MPO IF QS OP	g	11.25	=(10001Z+….+10011Z) *0.7 / 11 f ≤ 60Hz
MP_TK_AUX_*_TRQ	2	MY Tank reaction torque	Nm	158	(AVG(30401Y,30400Y) - 31202Y)*9.81 *0.794/(0.145), Tank moment of inertia I = 0.794 Tank radius r = 0.145
IMH_MO_PXPY_FZ	4	MO/MP PXPY FZ	uStrain	116	Refer to chapter 11.2 µS1(-X) = S50002 , µS2(+X) = S50000 µS3(-Y) = S50003 , µS4(+Y) = S50001 Strain limit = av(S50001,S50002,S50003,S50004) Fz= 86.5N/µέ
IMH_MO_PXPY_MX	4	MO/MP PXPY MX	uStrain	191	Refer to chapter 11.2 µS3(-Y) = S50003 , µS4(+Y) = S50001 MX=1.86Nm/uE * (S50003-S50001) /2 Nm
IMH_MO_PXPY_MY	4	MO/MP PXPY MY	uStrain	191	Refer to chapter 11.2 µS1(-X) = S50002 , µS2(+X) = S50000 MY=1.86Nm/uE * (S50002-S50000) /2 Nm
IMH_MO_PXPY_MXY	4	MO/MP PXPY MXY	uStrain	191	= (MX^2+MY^2)^0.5
IMH_MT_PXPY_FZ	4	MT/MP PXPY FZ	uStrain	983	Refer to chapter 11.2 µS1(-X) = S50033 , µS2(+X) = S50031 µS3(-Y) = S50034 , µS4(+Y) = S50032 Strain limit = av(S50031,S50032,S50033,S50034) Fz= 86.5N/uE
IMH_MT_PXPY_MX	4	MT/MP PXPY MX	uStrain	237	Refer to chapter 11.2 µS3(-Y) = S50034 , µS4(+Y) = S50032 MX=1.86Nm/uE * (S50034-S50032) /2 Nm
IMH_MT_PXPY_MY	4	MT/MP PXPY MY	uStrain	272	Refer to chapter 11.2 µS1(-X) = S50033 , µS2(+X) = S50031 MY=1.86Nm/uE * (S50033-S50031) /2 Nm
IMH_MT_PXPY_MXY	4	MT/MP PXPY MXY	uStrain	272	= (MX^2+MY^2)^0.5

Table 3. Summary of Virtual Channels (49 channels total)

5.10 Test support software preparation and 'dry run' process simulations.

Software preparation, de-bugging and process simulations should enable a level to be reached by the data analysis engineer where usage of the tool within a planned process is second nature. Experience has shown most tests that 'fail' in terms of perceived inefficiency of management usually as a result of complex analysis processes or lack in depth familiarization of the tool at hand. The aim of any preparation is to ensure that test focus is directed to considering the information that is presented by the test and that mental effort is *not* expended in the demands of driving the software or data analysis tool.

The principal elements associated with preparation of the data analysis software are:

- *Transfer the Test Limitation base into the software*: for Bepi Colombo a Test Limitation was defined for every instrumentation channel. For some instrumentation 'infinite' limits were assigned when the channel was included for information only, post test correlation support etc. The Test Limitations defined in the software are the reference limits to which the computed *TFs * un-notched base sine input* are compared so that a notch curve is produced for each instrumentation point. The overall predicted notching is then the minimum of each curve at each discrete frequency point. For Intermediate sine levels i.e. sine inputs between the first low level and qualification, scaled limits may be defined so that Intermediate responses may be directly (automatically) compared with the factored limits. This analysis provides a check to confirm no limits have been exceeded by this preparatory run before qualification.
- *Generate program specific macros to compute Virtual Channels*: such channels have been discussed previously in some detail.
- *Test the macros functions and Test Limitations base:* during Bepi Colombo test preparation activity, two(2) tests were designed to ensure Test Limitations and their labeling were free of errors and to confirm the arithmetic operations of the macros:
  - *Test 1:* simulated test data was generated by converting NASTRAN data into a test format. This was achieved by simply changing FE related identifiers from grids or element I.Ds to the actual instrumentation identifier.
  - *Test 2*: to modify existing sine test data so that instrumentation identifiers matched those for the forth coming test. The complex data operated on here was not intended to produce notch simulations but test operation of macros and that the 'arithmetic' on the complex data was performed correctly.

The value of these tests was only apparent when the actual Bepi Colombo sine test was performed, no data bugs manifested during the test data analysis. The value of dry runs cannot be over emphasized. A 'killer consequence' in terms of effective analysis management is managing analysis time. All Spacecraft test campaigns are subject to progress chaser activity and time constraints lead ultimately to pressure on the analyst. For Bepi Colombo process tests on site prior to test enabled a good understanding of the turn-around time on analytical support.

5.11 A key trade-off: reducing the effort of data acquisition check.

The sine test involves acquiring a significant amount of data, much of which is for downstream information, but the objective is to narrow this large amount of data to a relatively small number of channels to those critical for managing or monitoring the sine inputs and specification on the run sheet. Normally this process of data analysis and criticality filter is achieved by purpose written software to project notch needs controlled by a select number of channels.

Historically tests were often pressed to perform with the minimum amount of acquisition which often meant acquiring different channels on different axes of test. Such an approach has two(2) main disadvantages:

- Re-patching of channels and incorporation of new channels often brings with data management issues relating to repeated validation of data and instrumentation disturbance resulting in data channels becoming defective or providing data of uncertain content resulting in exhaustive and repeated patch checks.
- If a channel whose response is initially evaluated in an off-axis context then full validation is often only possible if that channel is ultimately checked as an on-axis response i.e. X response for X direction of sine input.

Experience from previous sine test campaigns has shown that defective channel management should not be underestimated in terms of time and effort required to rectify such bad data.

The first activity the mechanical analyst is responsible for when receiving new data from the facility is to confirm the data as received is acceptable in terms of:

- On axis responses are clearly on-axis and no errors in orientation assumptions are evident.
- There are no defective channels.
- The quality of the frequency responses is acceptable i.e. free of noise/spikes.
- The data is of the correct level confirming correct charge sensitivity settings on the acquisition.

The management process here involves recording observations or ‘bad’ data log deficiencies, generating appropriate non-conformance reports, performing rectification, validating the fix and tracking; this entire activity is a time consuming process.

On Bepi-Colombo Astrium were confident that a high channel could easily be managed analytically by the DYNAWORKS tool set, hence this conventional approach of dedicated channels per axis was disposed of and consistent acquisitions were specified for each axis of sine input. As a consequence it was accepted that some channels would be of very low order response for certain directions of sine excitation but the resulting high channel count was traded-off against the benefits of potential reduced channel management. As result of reduced disturbance to the patched channels it was found during the Bepi Colombo sine test campaign that management effort rapidly diminished after the first rectification exercise and that the decision to adopt such a philosophy was vindicated.

A secondary advantage of maintaining consistent acquisitions through the X,Y and Z axis tests was that ultimately an on-axis response check was able to be performed which might not be the case for different acquisitions on different test axes. For post-test data processing and FEM correlation this ability to validate accelerometer bonded orientation or labeling can be important.

5.12 Test axis sequence planning.

The sequence that tests are performed must be considered where Virtual Channels are computed. When inter-data phasing is important, such as computation of angular response variables, then data phase validation with respect to macro summations is important. Generally data can only be validated when it is known to be an ‘on-axis’ response. As a consequence the sequence that tests are performed can be important in this respect.

5.13 Team planning and organization.

Time management on test and individual understanding of responsibilities is a key element for success. A clear danger during any test campaign is failure to correctly plan for parallel analysis activities or redundancy in roles of individuals. As a general policy, test redundancy not only applies to control strategies and instrumentation but also to personnel roles. Most test analysis activities fail primary as a result of poor planning, preparation of tools and analysis of test data being processed by a single individual who treats the activity as one long in-series process. Every effort must be made in the planning stage to define roles and responsibilities within the team and to parallelize effort within the team. Astrium advocates a planning flow-chart showing the analysis focus through the sine test campaign. The core main stream process can be regarded as generic irrespective of the project while off-line parallel activities may be project specific involving detail data acquisition checks.

5.14 Sine test data analysis planning.

Analysis planning is critical to test success. The goals of the plan should be to:

- Ensure that the test support analysis does not become a serial process through a single individual.
- To establish a plan for parallel activities to offload effort on any single individual and to define clearly understood domains of responsibility on each person in the test data analysis team.
- To obtain a 'time and motion' understanding of effort associated with the data analysis activity.
- To capture program specific data checks and assign them to a given individual. Examples of such data validations have already been discussed e.g. data phase checks to confirm accelerometer bonded orientation (mechanical installation phase) to ensure correct 'sign' of response are programmed into macro computations. Other program specific checks included FUNDAMENTAL /GLOBAL response comparisons on accelerometers adjacent to the IMHs. The purpose of such checks was to establish if the IMHs were structurally stable in terms of no noise/shock source indicating global slippage or gapping of the devices (*highly undesirable*).
- To provide visual reference or process refresher to team member during the test. On the Bepi Colombo sine test campaign, the process flow charts were pinned on the office wall as source of reference.

5.15 Facility pre- test meetings.

The propose of these meetings is to ensure a number of key aims are understood by all parties involved in the test campaign:

- The industrial and institutional teaming responsibilities are understood on all sides. During such meeting identification of test conductor, test hardware interfacing constraints, safety person etc is some of the key responsibilities that have to be understood and specified prior to test.
- Such meetings ensure status of compliancy against the test specification are understood and that the needs on both sides have been discussed and properly recorded.
- Through such meetings the specification may be subject amendment or update.

5.16 Launcher interface meetings.

During this meeting the Prime contractor would normally present the sine notch justification including the proposal for test control, working test control tolerances on the Test Limitations base and the specific limitations governing requested notches. As part of the sine notch justification effort the Prime contractor would normally demonstrate to the Launcher Authority that their flight predictions through the LCDA are covered. From the Prime contractor's side, the main outcome from such meeting is a provisional endorsement or sanctioning of the test management approach and expected notches.

6 TEST ANALYSIS INFRA-STRUCTURE.

The analysis infra-structure for the Bepi Colombo test campaign is shown in Figure 15 with the aim of reinforcing the point on redundancy consideration. Notching is performed by designated team members on one lap top, the remaining lap top provides redundancy and data back-up potential. The principal lap top has a node locked license capability so that further redundancy from the local network is provided in the event of network or connection to home site loss.

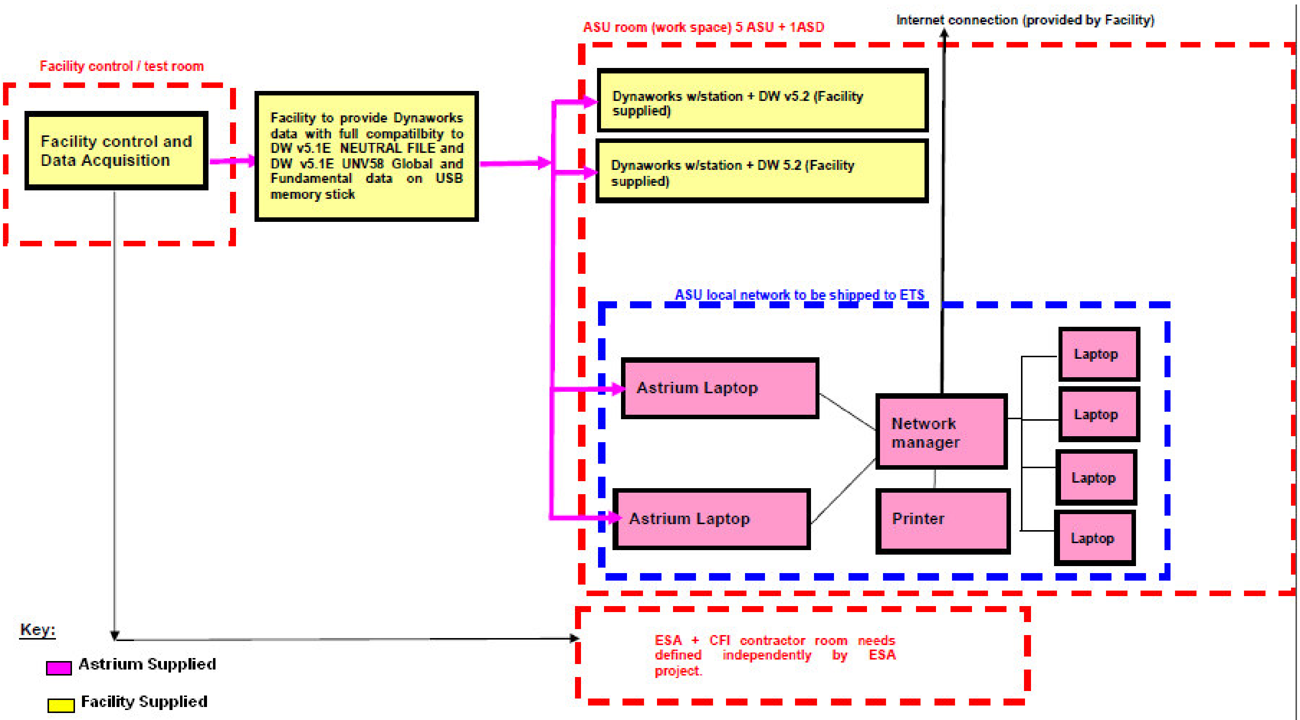


Figure 15. The analysis environment and infra-structure.

7 THE DATA ANALYSIS PROCESS DURING TEST.

The test analysis that is conducted is as result of the necessary trade-off between risk, analysis robustness, confidence in the process and data at hand and most importantly time. A sufficient amount of analysis of the test data has to be performed, prior to committing to the next level of input, to avoid compromising integrity of the test specimen. An early trade-off must be made with allocated time to conduct this analysis and the time need to progress testing. As a consequence the analysis must be focused and effort must be directed solely to data evaluation and *not* mentally applying thought to driving any support tools.

Experience has shown that poor time management has direct affect on success or perceived success outcome. Time pressures force mistakes, undermine external confidences and reflect badly on the industrially responsible team.

The basic philosophies behind successful test management are very simple: knowledge of specimen's perimeter of loading (Test Limits) and to establish where and what frequencies the limitations are most prevalent. On the latter point it is the function of the notching analysis software to provide this filtered focus, the transducer set (*both physical and virtual*) may be large (>500 channels) but its purpose of the notching software to filter this set to small set of critical locations that can be selected to manage the test or specify on the run sheet.

In general analysis effort diminishes during any given axis of test after evaluation of the first low run data and becomes more efficient through the test campaign as confidence in the structures behaviour increases. Figure 16 *schematically* outlines the process of analysis of the Bepi Colombo sine test for any given axis. This schematic is a simplification of the analysis plan (flow chart) discussed previously and forms the basis of the test analysis process plan. Certain data checks clearly diminish through the overall test campaign, for example, certain phase checks implemented to validate summation assumptions in specific macros performing the Virtual Channel calculations may only need to be performed once and not repeated for each axis of test.

The general core process is based upon experience and trade-off on efficient test time management. For Bepi Colombo the process was expanded and further analysis was conducted in support of test abort margins. The decision to conduct this additional analysis was vindicated by the time saved resulting from no abortive sine runs.

The schematic shown in Figure 16 comprises of the following elements:

- Parallelised check / validation effort within the team.
- Data checks, recording and tracking of bad channels requiring rectification.

Low level sine:

- Notching analysis based upon the first low level Sine data operating on the *Test Limitation* base. Notching is "mapped" and this map is critically evaluated to establish if deep notching can be elevated by exercising known stress margins of safety. Mapping involves transferring to the notch diagram labeling for each feature providing the notch along with notches hidden by these primary notches.
- Establishing a draft control plan and test the run sheet by repeating the notching analysis on the *run sheet values*.
- Assessing abort margins based upon pilot inaccuracy.

Intermediate and Qualification data review:

- Analysis is focused on confirming the acceptability of the previous control philosophy in terms of confirming no responses exceedances and confirmation of overshoot allowance where necessary.
- For the Qualification data the analysis aim is to principally confirm that all response were maintained within the agreed limits ideally avoiding the need to justify acceptability of responses that exceed advise limits.

Final low level comparisons:

- A dynamic comparison of final low level signatures with the initial responses recorded at the start of testing on a given axis.

Confirm IMH preload strains (stability check)

OK?

STOP

Yes

Start Low Level Sine

Prepare 'blank' DYNAWORKS bases to receive data.

Receive data from Facility

CHECK FORMAT
- **Check format compliant with specification.**
- **Format data for import into DYNAWORKS.**

DYNAWORKS (DW) IMPORT DATA & ACQUISTION CHECKS.
Bad data channels?

DYNAWORKS (DW) IMPORT DATA & ACQUISTION CHECKS.
Bad data channels?

BAD CHANNEL LIST PROFORMA
- **Complete proforma listing bad data channels. Action remedy / check/track**
- **Supply list to Facility /AIT.**

RUN DW MACROS GENERATE VIRTUAL CHANNELS

Global/Fundamental data comparisons:
- **ALL data**
- **Accelerometers adjacent to IMHs. (to indicate gapping)**
- **All virtual channel inputs.**

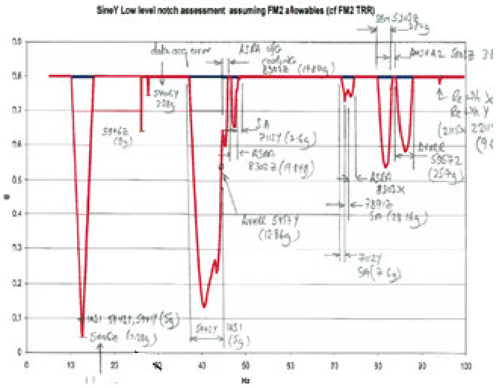
Export data to other analysts for parallel evaluations.

Virtual Channel checks:
- **ALL input acquisitions—check low freq. phases for correct 'sign' assumptions in macros.**
- **Calibration (confidence) checks – IMH low freq (q-static) loads versus known mass properties.**

RUN ASTRIUM TEST SUPPORT MACROS.
- **Generate TF on selected control strategy (MAX PILOTS)**
- **Compute notches on TEST LIMITATIONS data-base.**

CONFIDENCE CHECKS ON IMH LOADS.

MAP NOTCHES:
- **Notch minima and those covered notches.**
- **Critique notches and limitations – evaluate scope for limitation increase based upon known margins**

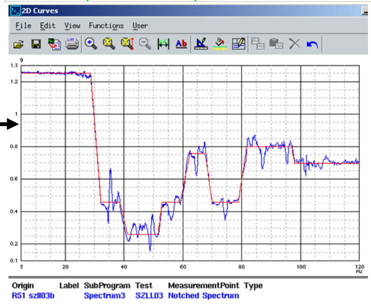


DRAFT RUNSHEET & PROPOSED MANUAL NOTCH PROFILE

Continued next page

RUN ASTRIUM TEST SUPPORT MACROS.
- **Compute notches based on DRAFT RUNSHEET specification..**
- **Confirm notching is in-line with notching based upon TEST LIMITATIONS**

RUN ASTRIUM TEST SUPPORT MACROS.
- **Compute notches DRAFT RUNSHEET specification –INCLUDE PILOT INACCURACY.**
- **Assess ABORT margins.**



PREPARE PROPOSED RUNSHEET & CONSOLIDATE WITHIN INDUSTRIAL TEAM.

PRESENT RUNSHEET PROPOSAL TO CUSTOMER, DISCUSS,AGREE, JUSTIFY CONTROL APPROACH. Consolidate inputs from AGENCY & AGENCY CONTRACTORS.

NOTCHES & RUNSHEET PROPOSAL PRESENTED TO THE LAUNCHER AUTHORITY BY THE AGENCY/CUSTOMER.

Confirm IMH preload strains (stability check)

OK?

STOP

Yes

INTERMEDIATE SINE RUN

Prepare 'blank' DYNAWORKS bases to receive data.

Receive data from Facility

CHECK FORMAT
- **Check format compliant with specification.**
- **Format data for import into DYNAWORKS.**

DYNAWORKS (DW) IMPORT DATA & ACQUISTION CHECKS.
Bad data channels?

DYNAWORKS (DW) IMPORT DATA & ACQUISTION CHECKS.
Bad data channels?

BAD CHANNEL LIST PROFORMA
- **Complete proforma listing bad data channels. Action remedy / check/track**
- **Supply list to Facility /AIT.**

RUN DW MACROS GENERATE VIRTUAL CHANNELS

Global/Fundamental data comparisons:
- **Accelerometers adjacent to IMHs. (to indicate ga**

COMPARE RESPONSES WITH TEST LIMITATIONS AT 50%QL
COMPARE RESPONSES WITH 0.8* 50%QL TEST LIMITATIONS
- **Generate assessment for presentation to Customer.**

UPDATE PROPOSED RUNSHEET & CONSOLIDATE WITHIN INDUSTRIAL TEAM.

PRESENT RUNSHEET PROPOSAL TO CUSTOMER, DISCUSS,AGREE, JUSTIFY CONTROL APPROACH. Consolidate inputs from AGENCY & AGENCY CONTRACTORS.

NOTCHES & RUNSHEET PROPOSAL PRESENTED TO THE LAUNCHER AUTHORITY BY THE AGENCY/CUSTOMER.

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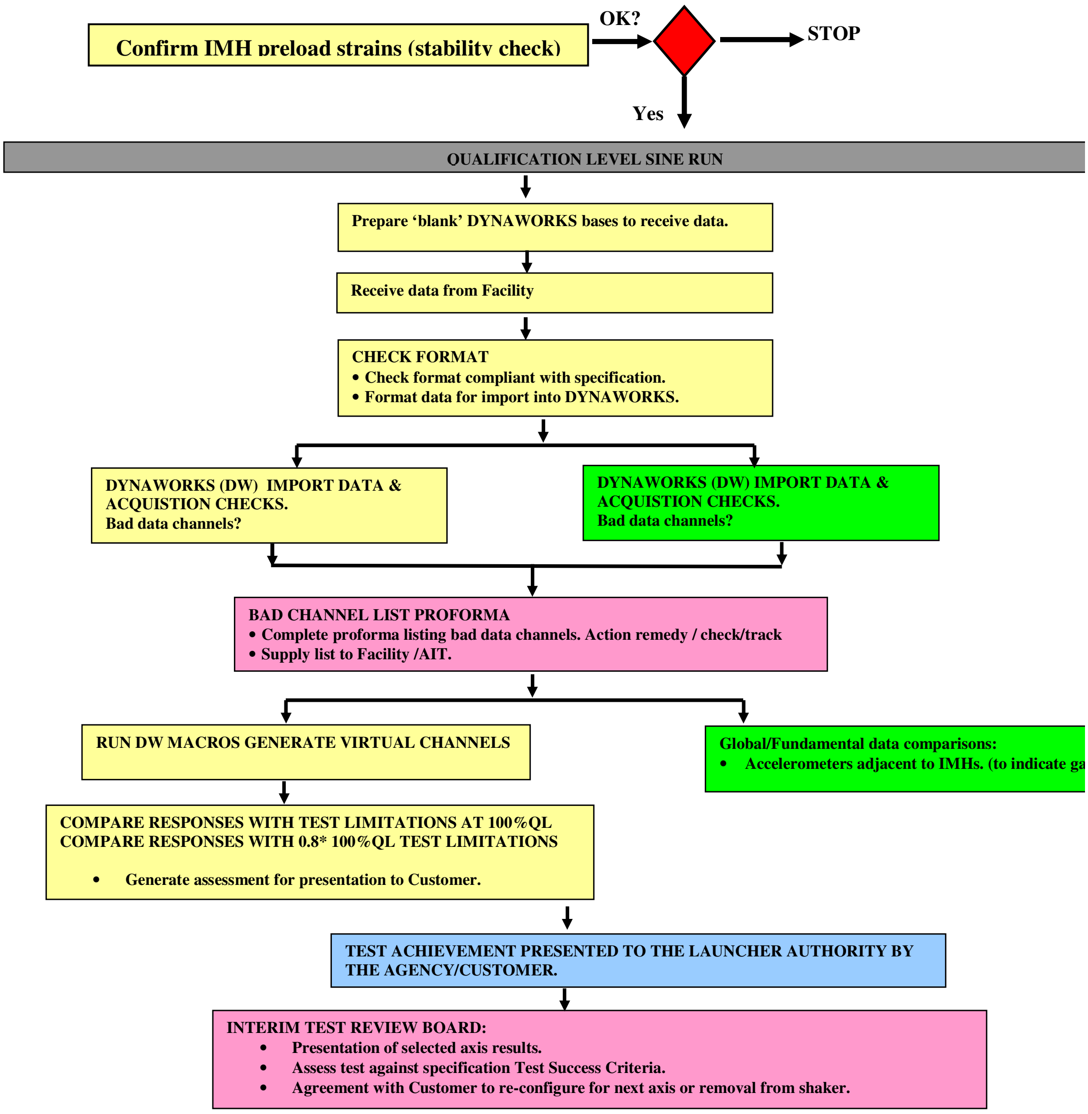

Figure 16. Schematic outline of test analysis and management. Note visual inspections and feedback from 'bad' acquisition tests/checks not shown.

8 LESSONS LEARNT.

Irrespective of an individuals experience all test campaigns provide a new set of lessons learnt. The principal lessons learnt from Bepi Colombo's sine test campaign are summarized below:

Instrumentation:

- A key part of the lessons learnt process reflection on decisions made during the program. On reflection the decision to integrate static and dynamic load cell capability into the IMHs in advance of the Spacecraft stack test was of paramount importance to both management and structural qualification. By incorporating the strain measurement systems into the STM stack test this provided an element of closure to concerns associated with the functionality and endurance of the IMH system. The IMH systems have been subject, rightly, to close scrutiny during unit level design reviews. The STM test campaign has demonstrated that:

- *The static preload state* was stable in terms of comparison of state prior to and subsequent to dynamic loading. No relaxation in load was observed across the whole sine campaign.
- *The dynamic response of the strain gauges (and associated virtual load channels)* yielded frequency response outputs of high quality in spite of relatively low strain outputs. Confidence in data quality from the integrated IMH load cells was established from the analysis of the first data outputs from the sine test campaign. High quality low noise FRFs along with good low frequency correlation of output load with respect to predicted static load distributions from the known support module masses on each interface gave early confidence in the integrated IMH load cells-see Figures 17 and 18. A key lesson learnt here was that of effective screening of the strain gauge cabling which is in contrast to a selected few strain gauges pre-installed elsewhere. At these other locations gauge outputs were not usable due to high signal / noise resulting from interference from lack of screening.
- *Global and Fundamental comparisons:* comparisons of the Fundamental (narrow band pass FRFs) with the unfiltered Global FRFs of accelerometers in the vicinity of the IMHs were made to obtain confidence that no gapping or gross slippage was evident in the IMH system. Polar mounted propellant tank instrumentation is often characterized by noise generation from tank mounting interface and this is evident by such comparisons. This phenomenon was used not necessarily as a definitive means of confirming the structural stability of the IMHs but indicative. It should be noted that no Global / Fundamental anomalies were evident on IMH local transducers.

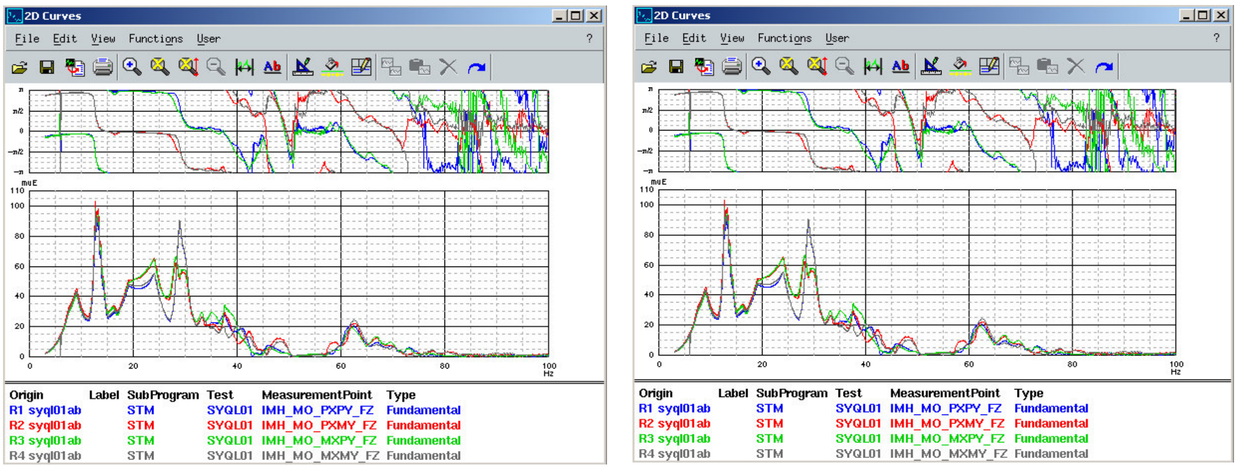

Figure 17. IMH Virtual Channel output for IMH axial force (in terms of µstrain sum) for MOSIF/MPO interface (LEFT) and MTM/MPO interface (RIGHT). Data shown for notched lateral qualification sine Y.

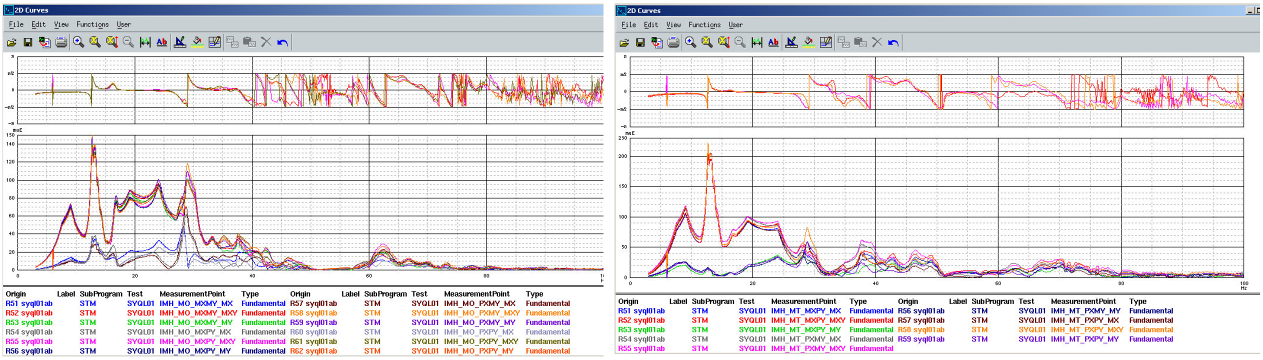

Figure 18. IMH Virtual Channel output for IMH bending moment components and resultants. (in terms of µstrain) for MOSIF/MPO interface (LEFT) and MTM/MPO interface (RIGHT). Data shown for notched lateral qualification sine Y.

Working practice:

- Prior to conducting one of the Intermediate level sine runs, following self / control loop check but before data acquisition was active, the shaker was subject to a transient voltage spike which introduced as a short duration transient motion. Since no data acquisition was active then input into the Spacecraft was not measured. Limited peak hold data was available along with video footage of the motion which enabled estimates quantifying response input.
  As a consequence of this 'non-quantified' anomaly, Astrium has modified its generic test specification policy to ensure that some form of data acquisition is maintained at all times when the shaker drive amplifiers are active.
- Previous discussion has highlighted that in advance of the test campaign it was decided to minimize channel re-patching to minimise corrective effort in rectifying and validating defective channels. The trade-off with respect to increased channel count versus potential reduced effort associated with such management was deemed validated and is expected to be applied during subsequent PFM testing.
- A notable success attained during the sine test campaign was that there were no test aborts recorded during the whole campaign with the exception of a sweep down run on a low level sine survey that was included for information only. For a complex stacked structure such as Bepi Colombo this was deemed a testimony to the planning and management. Repeated control aborts are undesirable because they introduce time management pressures on the analysis team and often detract from team credibility in terms of technical management. Success in terms of lack of aborts can be attributed to the factors below:
  - The analysis effort was extended by assessing abort margins using purpose written macros in DYNAWORKS centered on accounting for pilot dispersion or inaccuracy with respect to base manual notch profile. By extending the amount of analysis the team traded-off this extended analysis effort against the cost of abortive runs, repeated set-up and re-presentation of strategy to the customer. The tool and results were used to support judgment as opposed to provide definitive margin assessment but were deemed of sufficient value to warrant some limited extended effort in analysis.

- Maintaining a credible margin between the notch specification and abort so that some no response overshoots triggered an abort. As rule of thumb a minimum margin of 2.0-2.5dB has been found from experience as adequate to cover uncertainty in output response.
- Characterising overshoots from Intermediate sine runs. To some extent testing entails trust and confidence in the known limits or the perimeter of integrity within which the test is to be conducted. To this end it is possible to introduce a healthy margin or tolerance between the run sheet notch prescription and abort at Intermediate levels compared with the final qualification run. Specifying the run sheet auto-notch limits to be compatible with the Intermediate level at hand but maintaining ABORTs at the qualification limits increases the effective tolerance for the Intermediate run and enables the qualification strategy to be fully tested. In addition by replicating fully the desired qualification level control strategy, it is possible to obtain the best estimates for overshoot when the tolerance between notch and abort is reduced for the qualification run. A key philosophy when considering an intermediate run is maintenance of the control philosophy between the lower level input and the subsequent higher level input which is the next target. On Bepi Colombo only one Intermediate level was applied per axis hence effectively each axis consisted only of: a low level swept sine survey, Intermediate (50% Qualification level), Qualification sine followed by the final low level sine survey. An Intermediate level of 50%QL was specified in advance of test as this was deemed compatible with 2.5dB margins or possible expected overshoot of response. Post Intermediate sine analysis confirmed there were no unexpected exceedances relative to 50% QL limits by direct comparison of each measured and virtual response versus the 50%QL spectral limit profiles and by comparison of 0.8*50% QL limits to indicate if any other limits approached limits and were worthy of note. Overshoot characteristics in terms of 'X'dB overshoot were noted and incorporated as reductions for subsequent auto-notch specification on the following Qualification Level run sheet.

- This paper has emphasized the need during pre-test preparation to establish redundant strategies in all aspects associated with the test. During the Bepi Colombo sine test campaign this preparatory focus was vindicated when it was found the strain gauges monitoring MMO interface loads were not operable. To cover this interface management the analytical preparation discussed earlier with respect to management of the second order cantilever mode of the stack were used with effect.

Management and planning effectiveness:

- The test planning, preparatory de-bugging of the process and software, personnel planning and definition of individual responsibilities was a "*one-hundred percent*" success. No macro errors were evident and the use of tools and implementation of the process was instinctive due the repeated dry runs simulations of the process prior to test. During the test a white board was useful means of providing a visual record to the team of analysis findings that needed further consideration or a prompt to provide reminders for activities to be completed before committing to the next crucial runs.

Test control:

- Prior to test the complex stacked nature of the Spacecraft system was anticipated to bring with it complexities of test management in terms of control related issues. Stacked (tandem) Spacecraft of smaller overall size have been previously tested by Astrium where configurations such as a Science spacecraft stacked on top of a single propulsion module have been recently tested, but no experience exists where a stack of four(4) major modules (MOSIF and Sunshield considered here) has been tested. On reflection the stacked nature actually assisted management of the test in that due to integration of a number of major structural bodies the structure was acceptably damped in all of main primary structure modes. In comparison with another large Spacecraft such as Metop-A, -B and –C; these Spacecraft exhibited relatively low damping (<1% critical viscous) in their first-cantilever modes and this presented control issues even at 2-octaves/minute sweep as the structure passed through resonance of the first main bending modes.

- During the final lateral axis tests, control of one local 10N thruster (panel corner response) was the only the only area were notable control issues were observed. No active auto-notching was initiated during this run for this location but subsequent notching analysis on this low level data indicated potential criticality with respect to assigned response limits. For the Intermediate sine run auto-notch limits were prescribed that resulted in active auto-notching for the 10N thruster location. The depth of the notch generated exceeded that projected from the low level analysis. As a consequence of the deeper notch finding on the Intermediate it was decided to remove the auto-notching on this channel and prescribe an abort only limit on the run sheet (*this is implemented by a notch specification at -0.1dB relative to abort*). The test was passed successfully and the resulting notch depth was significantly less than that which would have introduced by assignment of an auto-notch. It was clear after the Qualification Level run that controlling an off axis channel (*Z response for X sine input*) for local mode that was very lightly damped the control system was not able to react sufficiently to manage such characteristics. This observation will be carried forward in due course for the PFM test.

Cross talk observations at the piloted interface during longitudinal sine tests :

- Sine test piloting was implemented at the VTA/LVA interface plane which was approximately 1m above the FMD interface plane. For the longitudinal test the lateral cross talk (*lateral responses on the piloting plane)*is shown in Figure 19. The cross-talk above 35Hz can be seen to be significant i.e. the off-axis response at the LVA approaches or even exceeds input. In terms of managing the longitudinal tests the cross talk generally did not present any technical difficulties in terms of conducting the test safely. The issues resulting from this phenomena were expected to arise in later sine test correlation effort and filtering out the influence of these responses to obtain a pure fixed base understanding.

  In terms of a lesson learnt relative to pre-test statements of compliancy against the dynamic test specification, confirmation of lateral stability of the header expander and test fixture could be given in advance of the main test campaign by early blank fixture tests. The practicality on future programs for this early confirmation will be considered in the future by Astrium.
- The previous point highlighted for the longitudinal test the boundary condition for the Spacecraft was potentially removed from that of a pure encastre condition. Further evidence of this was found in the small degree of coupling between the fundamental cantilever modes and the axial excitation. Lateral sine tests confirmed that the first bending modes were circa 13Hz for both XZ and YZ plane cantilever modes. Low level coupling between these modes and axial excitation was predicted and is not sole consequence of the lateral cross talk. The test TFs for the longitudinal sine in terms of FMD bending moments (Mx,My) and certain lateral responses at the top of stack showed this coupling to exist at circa 10.5Hz which indicates that the boundary flexibility, lack of base inertia or clearance in the longitudinal guidance system has resulted in relatively significant drop in frequency. Such an observation is readily apparent but less apparent is influence of the boundary condition on higher order modes for the longitudinal case. The implications are as stated previous and mainly affect post test correlation effort.

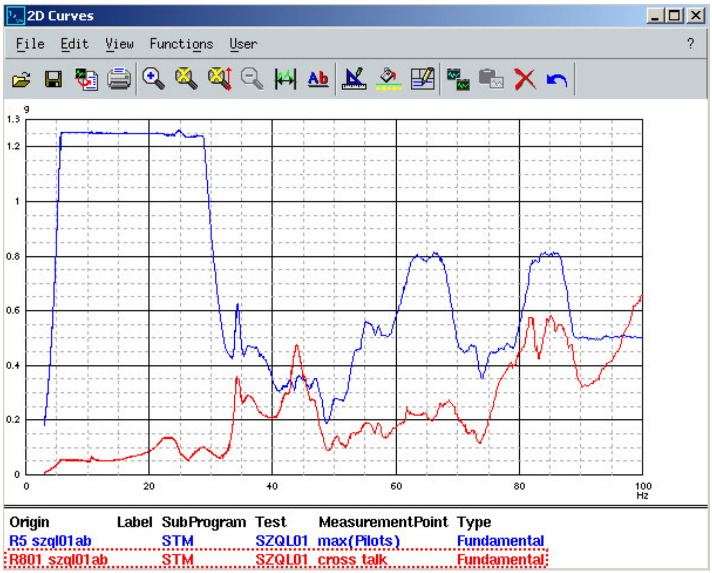

Figure 19. Qualification level Longitudinal Sine Z. Pilot maximum [envelope of four (4) pilots] versus cross talk [off axis response on pilot plane-maximum envelope of eight (8) channels].

Test support infra-structure (redundancy):

- Information technology is invariably sold to engineers as a robust and reliable commodity. One of the key messages this paper has tried to convey is that the concept of redundancy should be considered or applied to all domains of the process, infra-structure, personnel, control strategies etc. In support of the Bepi Colombo test campaign, the Astrium test support team utilized an in-house designed secure portable network solution providing an off-site office capability. This network capability provided the capability to access tools, including DYNAWORKS, by remote connection to the Astrium home site. The redundancy in-built into this infra-structure was the ability on at least one PC to run stand alone with no network using local software licenses. This capability was used when a short duration network failure manifested.

Test specimen hardware:

- Propellant tank mass dummy design has historically provided sources for lessons learnt. On Bepi Colombo a degree of geometric representation was made in that the tanks were designed essentially diametrally representative. For the polar mounted tanks (no internal baffling), the tank dummy polar moment of inertia introduced non-representative reaction torques relative to a fluid filled tank. This characteristic was recognized well in advance of the test and was managed by specific monitoring –see Virtual Channel listing Table 3.
- Astrium's sine test specification required that specific checks should be made to the interface flatness of the Vibration Test Adapter (VTA) as result of lessons learnt on previous test campaigns. Such checks were made but checks were omitted on the interface plates between the adapter and FMD. Delay to the test was incurred when it was found that these plates did not meet flatness needs. Consideration should therefore be given to early fit-checks to ensure advance inspections are completed to avoid impact on test delay.

9 CONCLUSIONS

By virtue of the complex structural nature of the test specimen in terms of stacked module arrangement the test management and outcome was a resounding success. The fundamental reasons for this success are governed by the principles reported in this paper: careful preparation and planning, process simulation and mapping, the software tool supporting data analysis (DYNAWORKS coupled with Astrium's purpose written macros) and of course redundancy, redundancy and redundancy!

It is hoped that the messages and experiences detailed here will support the wider community in terms of their needs and preparation.

REFERENCES

[1] Arianespace. Ariane 5 User Manual Issue 5 Rev.1.

[2] Background and further information relating to the Bepi Colombo--see www.esa.int and search Bepi Colombo.