ECSS-E-HB-10-03A DIR1
15 October 2020

Space engineering

Testing guidelines

This document is distributed ECSS community for Public Review.
(Duration: 8 weeks)

Start of Public Review: 16 October 2020
END of Public Review: 11 December 2020

The documents listed in the Bibliograpy will be made available on the same ECSS Website latest where the published the Handbook will be made available for download. Currently they are embedded objects in the Word file of this draft.

DISCLAIMER (for drafts)
This document is an ECSS Draft Standard. It is subject to change without any notice and may not be referred to as an ECSS Standard until published as such.

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Section
Noordwijk, The Netherlands

Foreword

This Handbook is one document of the series of ECSS Documents intended to be used as supporting material for ECSS Standards in space projects and applications. ECSS is a cooperative effort of the European Space Agency, national space agencies and European industry associations for the purpose of developing and maintaining common standards.

The material in this Handbook is defined in terms of description and recommendation how to organize and perform the work of Testing of a space system product, as specified in the ECSS-ST-10-03.

This handbook has been prepared by the ECSS-E-HB-10-03A Working Group, reviewed by the ECSS Executive Secretariat and approved by the ECSS Technical Authority.

Disclaimer

Published by: ESA Requirements and Standards Section
ESTEC, P.O. Box 299,
2200 AG Noordwijk
The Netherlands

Change log

	Change log for Draft development
	Previous step
ECSS-E-HB-10-03A-WG-DRAFT5 21 July 2020	WG Draft received from WG 21 July 2020 (ECSS-E-HB-10-03A-WG-DRAFT5)
Draft from 21Sept2020	Draft "ECSS-E-HB-10-03A-WG-DRAFT6-Klaus(4September2020) Benoit 18 Sept Pietro 21 sept.docx" checked by Klaus and commented. - All revision tracking and comments accepted. - A few minor comments inserted for final resolution by Pietro and Benoit.
ECSS-E-HB-10-03A DFR1 23 September 2020	Draft for Review (DFR) submitted to ES
ECSS-E-HB-10-03A DFR1 2 October 2020	Parallel Assessment: 5 – 16 October 2020. Draft received from WG on 23 September 2020 sent to TAAR for Parallel Assessment.
CURRENT STEP	
ECSS-E-HB-10-03A DIR1 15 October 2020	Public Review
NEXT STEPS	
DIR + impl. DRRs	Draft with implemented DRRs
DIR + impl. DRRs	DRR Feedback
DIA	TA Vote for publication
DIA	Preparation of document for publication (including DOORS transfer for Standards)
	Publication
	Change log for published Standard (to be updated by ES before publication)
	First issue

Table of contents

Figures

Tables

Introduction

Testing is an important part of a Space Project, because of its impact on cost and because is the most effective way to demonstrate a product functionalities and performances.

As such, this Handbook is of outmost importance in defining how the requirements can be implemented into the verification approach and in providing "real life" experience and examples in order to have an effective application into the test execution.

In order to meet this objective, the WG have tried, in preparing this Handbook, to be as exhaustive as possible in providing methods and techniques, as well as examples, in a punctual one-to-one requirement versus guideline approach.

The WG also recognized that this approach, even if punctually exhaustive, provided in most cases an unstructured definition of the tests as a whole giving a leopard spots information which may not be useful in preparing and conducting a test.

As a consequence, the WG have decided to complement the main body of the Handbook with Annexes where a structured and comprehensive test organization has been defined and described.

In those cases, testing people can find how a test is prepared, applied and executed in terms, for example, of test setup, test configuration, used instrumentation and test facilities/equipment, test preparation suggestions, safety rules to be considered, data acquisition and reporting content, together with pictures, tables and sketches of real cases,

This approach has allowed, in particular for Mechanical, Microvibration and Integrity Tests as well as for Alignment and PIM tests, to have in one shot a complete and structured set of guidelines easing the implementation of the requirements of such tests.

It is to be underlined that some of this material comes from the ECSS-E-HB-32-26 "Spacecraft mechanical load analysis handbook", which contained a lot of information about mechanical testing.

<u>It is worthy to pay attention that the Annexes of this Testing Guidelines do not correspond to the Annexes of the Testing Standard.</u>

<u>Moreover, this handbook only applies for the Revised version of the ECSS-E-ST-10-03 Standard (ECSS-E-ST-10-03C Rev.1)</u>

1 Scope

This handbook provides additional information for the application of the testing standard ECSS-E-ST-10-03 to a space system product.

This handbook does not contain requirements and therefore cannot be made applicable. In case of conflict between the standard and this handbook, the standard prevails.

This handbook is relevant for both the customer and the supplier of the product during all project phases.

To facilitate the cross-reference, this handbook follows as much as practical, the structure of the standard even if, as written in the Introduction, some tests are described in the Annexes to allow a better comprehensive view.

Where test material is already covered in other ECSS handbook, this document refers to them instead of duplicating the information, this is the case of ECSS-E-HB-32-25 "Mechanical shock design and verification handbook" and the various parts of ECSS-E-HB-31-01 "Thermal design handbook".

As the Standard applies to different products at different product levels of the space segment, the space segment equipment and the space segment elements. In the testing standard the requirements applicable to each level are addressed in different chapters clearly identified. The standard clearly states that it is not applicable to other segment (launch and ground) as well as software; as a consequence, no pre-tailoring matrix is needed.

Moreover, as per testing standard, this handbook does not contain guidelines for constellation programmes.

Testing aspects are derived from the verification approach covered in the ECSS-E-ST-10-02 and in its corresponding handbook ECSS-E-HB-10-02.

The application of the requirements of the standard to a particular project is intended to result in effective product verification and consequently to a high confidence in achieving successful product operations for the intended use, in this respect this handbook has the goal to help reaching these objectives.

2 References

ECSS-S-ST-00-01	ECSS – Glossary of terms
ECSS-E-ST-10-02	Space engineering - Verification
ECSS-E-ST-10-03	Space engineering - Testing
ECSS-E-ST-31	Space engineering - Thermal control general requirements
ECSS-E-ST-31-02	Space engineering – Two-phase heat transport equipment
ECSS-E-ST-32-02	Space engineering – Structural design and verification of pressurized hardware
ECSS-E-ST-33-11	Space engineering - Explosive subsystems and devices
ECSS-E-ST-35-02	Space engineering - Solid propulsion for spacecrafts and launchers
ECSS-E-ST-40	Space engineering - Software
ECSS-E-HB-10-02	Space engineering - Verification guidelines
ECSS-E-HB-20-01	Space engineering - Multipactor handbook
ECSS-E-HB-20-07	Space engineering - Electromagnetic compatibility handbook
ECSS-E-HB-31-01 (all parts)	Space engineering – Thermal design handbook
ECSS-E-HB-32-25	Space engineering - Mechanical shock design and verification handbook
ECSS-E-HB-32-26	Space engineering - Spacecraft mechanical loads analysis handbook
ECSS-Q-ST-10-09	Space product assurance – Nonconformance control system
ECSS-Q-ST-70-01	Space product assurance – Cleanliness and contamination control
ECSS-Q-ST-70-05	Space product assurance – Non-destructive testing
ECSS-Q-ST-80	Space product assurance – Software product assurance
NASA-STD-7012	Leak test requirement
ATS paper_MATED Improvement (October 2018)	MATED (Model And Test Effectiveness Database) Improvement and Added Value on Industry *(pdf-file embedded in Annex G)*
MTF.AIDT.TN.2168, Issue 1, Rev.1 (3 March 2020)	Dynamited Final Report
ECSSMET 2016 (article)	DYNAMIC TESTS, WHAT'S BEHIND THE CURVES ? *(pdf-file embedded in Annex G)*
MSG-NNT-SE-TN-0742 (28 October 1996)	Notching guidelines for mechanical test *(pdf-file embedded in Annex G)*

TASI-ASE-ORP-0006_Iss.01 (20 October 2014)	Analysis of Spacecraft qualification Sequence & Environmental Testing (ASSET) *(pdf-file embedded in Annex G)*
TASI-ASE-ORP-0009_01 (3 October 2016)	Analysis of Spacecraft qualification Sequence & Environmental Testing (ASSET+) *(pdf-file embedded in Annex G)*

3 Terms, definitions and abbreviated terms

3.1 Terms from other documents

a. For the purpose of this document, the terms and definitions from ECSS-S-ST-00-01 apply, in particular for the following terms:

1. **space segment element**
2. **space segment equipment**
3. **thermal ambient test**
4. **thermal balance test**
5. **thermal ambient test at mission pressure**
6. **thermal vacuum test**

b. For the purpose of this document, the following terms and definitions from ECSS-E-ST-10-03 apply:

1. **dwell time**
2. **temperature cycle**

c. For the purpose of this document, the following terms and definitions from ECSS-E-ST-31 apply:

1. **acceptance temperature range**
2. **design temperature range**
3. **minimum switch-on temperature**
4. **predicted temperature range**
5. **qualification temperature range**
6. **radiative sink temperature**
7. **temperature reference point (TRP)**

3.2 Terms specific to the present document

None

3.3 Abbreviated terms

For the purpose of this document, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	**Meaning**
AC	actuator control
AFT	allowable flight temperature or abbreviated functional test

Abbreviation	Meaning
AIM	active inter modulation
AIT	assembly, integration and test
AIV	assembly, integration and verification
AOCS	attitude and orbit control subsystem
AOCS SW	attitude and orbit control subsystem software
ARF	alignment reference system
AVB	avionics verification bench
CATR	compact antenna test range
C&C	characterization and calibration
CCR	corner cube reflector
CCS	central checkout system
CDR	critical design review
C&CCP	cleanliness and contamination control plan
CFD	(attitude and orbit control subsystem) closed loop functional test - design
CLT	closed loop test
CoG	centre of gravity
CP	common (reference) point
CSW	central software
DC	direct current
DHS	data handling system
DRD	document requirements definition
DM	development model
DML	declared material list
DMS	data management system
DUT	device under test
EED	electro explosive devise
EEE	electrical and electronic equipment
EFM	electrical functional model
EFT	electrical functional test
EGSE	electrical ground support equipment
EIRP	equivalent isotropic radiated power
ELI	electrical integration test
EMC	electromagnetic compatibility
EPT	equipment polarity test

Abbreviation	Meaning
E2EPT	end-to-end polarity test
EQM	engineering qualification model
ESD	electrostatic discharge
ETB	engineering test bench
FDIR	failure detection isolation and recovery
FFT	full functional test
FFT-A	full functional test - acceptance
FFT-D	full functional test - design
FFT-Q	full functional test - qualification
FFT-W	full functional test - workmanship
FGSE	fluid ground support equipment
FM	flight model
FMD	force measurement device
FT	functional test
FVB	functional validation bench
GPS	global positioning system
GSE	ground support equipment
HFE	human factor engineering
HSVF	hardware software verification facility
HVAC	high vacuum
ICD	interface control document
I/F	interface
IPA	isopropyl alcohol
IR	infrared
IS	interface simulator
ISST	integrated subsystem test
IST	integrated system test
ITP	interface temperature point
IUT	item under test
LEO	low Earth orbit
LNA	low noise amplifier
LVDT	linear variable displacement transducer
MDP	maximum design pressure
MFT	mechanical functional test
MFW	mechanical functional test- workmanship

Abbreviation	Meaning
MGSE	mechanical ground support equipment
MLI	multi-layer insulation
MoI	moment of inertia
MOS	margin of safety
MRC	master reference cube
MRF	mechanical reference system
MT	mission test
NCR	nonconformance report
NDI	non-destructive inspection
NEA	non-explosive actuator
NRB	nonconformance review board
NSVB	numerical software validation facility
OBC	on board computer
OGSE	optical ground support equipment
PCB	printed circuit board
PFM	protoflight model
PISA	payload interface simulator assembly
PDR	preliminary design review
P/F	platform
PIM	passive intermodulation
PIMP	passive intermodulation product
P/L	payload
ppm	parts per million (10^{-6})
P/N	part number
PSD	power spectral density
PT	performance test
PTR	post test review
QA	quality assurance
QM	qualification model
QS	quasi static
RE	radiated emission
RF	radio frequency
RFD	request for deviation
RFT	reduced functional test
RIU	remote interface unit

Abbreviation	Meaning
rpm	round per minute
RTB	real time testbed
RTS	real time simulator
Rx	receiver
SAR	synthetic aperture radar
scc	standard cubic centimeter
SDE	software development environment
SFT	system functional test
SMC	space and missile systems center
SP	sensor processing
STM	structural thermal model
RMS	root mean square
S/C	spacecraft
SCOE	special check out equipment
SDE	software development environment
SHF	super high frequency
SMP	simulation model portability
SPL	sound pressure level
RMS	root mean square
S/N	serial number
SRDB	system, spacecraft or satellite reference data base
SVF	software validation (verification) facility
SVFDEV	software validation (verification) facility development
SysTF	system test facility
S/W	software
TCS	thermal control subsystem
TH	theodolite
ThM	thermal model
TM/TC	telemetry/telecommand
TRB	test review board
TRF	theodolite reference system
TPRO	test procedure
TRP	temperature reference point
TRPT	test report
TRR	test readiness review

Abbreviation	Meaning
TSPE	test specification
TT&C	telemetry, tracking and command
TVTB	thermal vacuum thermal balance
Tx	transmitter
UHF	ultra high frequency
VCD	verification control document
VM	virtual model
VP	verification plan

4 General requirements

4.1 Test programme

4.1.1 Test programme basics

The text in this clause 4.1.1 covers requirements 4.1.a to 4.1.e in ECSS-E-ST-10-03.

The set-up of an appropriate test programme for a space mission is a crucial element for the whole project. With a baseline test programme, as usually established during the Phase B of a project, some cornerstones are set, which do have a major impact on costs, schedule and risk. The testing starts on parts level (which is not addressed herein; see ECSS Q-60 and Q-70 branches), is continued at space segment equipment level and finalized at space segment element level with some extensions to space system level (which is not addressed herein). The challenge for the correct establishment of a test programme along the verification plan is to find the right combination of:

- Completeness: no test repetitions if not intended, but no forgotten test aspects. Remark: The VCD is treated to give the baseline number of tests only. Other tests can be necessary for validation purpose.
- Simplicity: do not intend to perform complicated tests, where simple methods provide adequate results.
- Timing: a test can be worthless or increase programmatic risks, even if performed correctly, but at the wrong time in the sequence of tests.
- Meaningfulness: always put in question if the test is meaningful in the way and at the time it is planned.
- Representativeness: Test like you fly serves as a general rule for this.
- Innovation: especially unique designs and instruments require innovative concepts for tests.

The goal in establishing a test plan, developed on the basis of the verification plan (including model philosophy and what tests are planned on which model), is to reach a complete test programme, optimized with respect to cost, planning and risk. In particular, the test plan mitigates the risk of late problems discovery and the risk of in-orbit failures especially during the infant mortality period. Often, there is no perfect solution, hence a compromise is necessary, keeping this approach in mind. The test plan at equipment level usually is straightforward. At space segment element level, the test plan is generally more complex. In particular, at space segment element level major issues to be clarified are typically:

- Is the test programme appropriate to verify compliance to the requirements?
- What is the most appropriate approach (how to inject failures/failure simulations) to test FDIR issues?
- Is the baseline environmental sequence of tests the best compromise for the specific project?
- Are there any tests missing to become confident with the product apart from requirements closure?
- Does the test programme fit to cost and schedule?

- Has the programme been checked for possible overtesting issues?
- How robust is test programme towards late deliveries of items (e.g. instruments, equipment)?
- Retesting or delta-testing: has an approach been defined to deal with these issues in case of failures, sequence changes or redesign/rework/retro-fits?
- Do we need to identify Regression testing?

These questions are addressed during PDR (draft test plan available) and properly answered before CDR (agreed test plan).

The verification plan, establishes a general approach on the verification (not only by test), which puts some boundaries to the development of the test plan. The test plan defines the implementation and the details of the "how-to" (see ECSS-E-ST-10-02 "Verification" and ECSS-E-HB-10-02 "Verification guidelines").

As said above, establishing an appropriate test programme at space segment element level deals with complex interactions between the different equipment and subsystems. Examples for these interactions, which are taken into consideration when setting up the test programme, are:

- Availability of the "right" software at the time of the test: for schedule reasons, software coding is a parallel process to system integration and testing. The sequence of tests takes into account the capability of the software version at the point in time for a specific test, so an alignment between the sequence of tests and the software development schedule is mandatory.
- FDIR is probably the most complex test issue to deal with. The FDIR concept is implemented in software and hardware. The response to each failure taken into account in the FDIR concept is verified. Therefore, you find a way for simulating these failures (different and probably innovative means need to be found!) and you assure that even if the FDIR reaction is either not correctly implemented or if there is a mistake in the concept, that flight hardware is not damaged in any case.
- Dealing with deviations from the baseline: During the testing phase, adaptions and modifications of the baseline test flow becomes necessary for various reasons, like, for example, late deliveries, unavailability of facilities, failures, and NCR´s with impact on the flow. Often it is decided if a test can take place even if the test setup is not as complete as expected before. An agreement between customer and contractor is found, and this is easier if two precautions have been taken: a clear retesting strategy is agreed, and a delta-testing strategy is in place. See also Test Management in clause 4.3.
- The AIT plan is usually produced by the AIT team taking into account several inputs:
  - Type of test required by the verification plan for the various hardware model,
  - Facilities intended to be used,
  - GSE to be used.
- In general, the test specification is produced by the engineering team taking into account higher level specifications (i.e. launcher requirements, environment specification) and detailed technical analysis of the item under test.
- The AIT team derives the test procedure from the test specification in close contact with the engineering team that produces the test specification.
- In some cases, the engineering team defines test requirements and the AIT team generates a detailed test specification to be reviewed by engineering.
- The test preparation and execution do take into account safety aspect as defined in the project safety plan to ensure protection of the personnel, facility and flight hardware.

4.1.2 Specific tests

Some tests are specific for the mission. Depending on the payload and the mission, and especially applicable for scientific missions, test methods are developed to verify the function and performance of the spacecraft. Examples for such tests are Thermal Balance tests with sun simulation of several solar constants for mercury or solar missions (Bepi Colombo, Solar Orbiter), specific deployment tests (James Webb Space Telescope), planetary environment tests for probes sent to a planetary or Moon surface, optical instruments with high temperature stability and high dimensional stability, landing tests… Common for all these tests are a high grade of innovation, usually high effort in preparation and high costs, and they are often a crucial element in the verification process. In the beginning of a project these tests are hard to calculate in terms of hours and costs. Therefore, a special focus is put on the identification and the proper preparation of such tests early in the project.

Identification: In fact, such tests are identified during a phase B of a project and treated in sufficient detail during the proposal preparation for the phases C and D. Sufficient detail means to establish a baseline for the "how to", to identify the test facilities (and needed upgrades, if applicable), the test duration and therefore a good estimation for expected costs. Otherwise, such tests can run out of control during the project execution. Preparation: achievement of early agreements with the test facility, supervision of the test in the project risk register, early identification of long lead items and time estimations for facility upgrades and developments, and a proper milestone planning are mandatory. However, once these tests are performed, they are usually followed by a big audience and treated as a cornerstone of the project.

4.1.3 Risks during testing

Even for tests meant as non-destructive, each test is putting a risk on the item under test. Therefore, tests without gaining more confidence are avoided. If the test article does not pass the test or, in extreme, is damaged as a result of a non-compliance to the requirements, then the test has fulfilled its objective.

But putting a risk on the test specimen means that there is a probability to damage it by not performing the test in the right way. The risks are of different nature:

a. If the test is putting stress on the specimen beyond the required limits, it can be physically damaged (e.g. vibration test, thermal test).

b. If the specimen is not commanded in the right way, the commands can cause a damage.

c. If the specimen is handled with MGSE, there is a risk of damage by handling (lifting devices, deployment support MGSE…).

Before performing a test, the risks are clearly identified and proper mitigation actions are implemented. These mitigation actions are:

For a): Ensure that the stress put on the specimen is the lowest possible without putting the verification into question (e.g. vibration levels and notching criteria carefully derived). In no case any qualification levels of units may be exceeded, including test tolerances. Automatic test aborts on facility level are implemented (prepared and rehearsed), if sensors indicate in-situ level exceeding (specifically vibration testing). A manual test abort is possible in cases where damage to the item under test may occur. To ensure the above, the whole control and data acquisition chain is verified by dedicated tests (i.e. dry runs, pre-tests for vibration tests). The overall test approach is validated by predictions derived from analysis.

For b): Pre-testing of scripts on non-flight hardware (e.g. engineering model) is applied wherever possible. Commands known as potentially risky (e.g. check of pyro ignition lines, release mechanisms) require special treatment, attention and a design with proper safe and arm functions embedded in both flight hardware and test equipment.

For c): Assure proper training of the crew. Assure that the MGSE acceptance is done according to applicable standards, e.g. proof load tests. Set up handling procedures, involve experts for specific handling activities where own experience is missing.

These risks during testing can and are minimized. However, they cannot be reduced to zero. Therefore, the whole test program is set up as stringent and short as possible – in line with the verification plan as given above.

4.1.4 Overtesting

There can be different definitions for overtesting, according to the aspect that is emphasized:

1. unnecessary amount of tests w.r.t. what a correct establishment of a test programme requires

    NOTE This definition is related to risk mitigation, since test by definition is a risk per se, while the results of the test aim at increasing the confidence about the behaviour of the item. Ideally, a correct test programme maximizes the confidence while minimizing the amount of tests needed.

2. definition of test specifications that are too conservative w.r.t. what is necessary to achieve an acceptable degree of confidence of the behaviour of the item

    NOTE W.r.t. definition 1, this definition emphasizes the importance of specifying adequate requirements (in terms of pass/fail, algorithms, sequences, set-up…).

3. unintended testing of an item beyond the limits given inside the test specification

    NOTE These limits can be related to the duration of activation and the level of the stimulus applied (for example, vibration levels, temperature levels, electrical levels like inrush current or supply voltage).

In the rest of this clause, only definition 3 is taken into account and the consequences are explained.

Following definition 3, overtesting does not necessarily mean that the test item has been damaged. It means that limits which have been set for the test (usually for a good reason) and which have been considered for the verification programme, were exceeded. Therefore, a careful evaluation treated within an NCR process is carried out once overtesting occurred, following the process stated inside ECSS-Q-ST-10-09.

Overtesting effects can be:

- Damage of the test item: repair or exchange to follow, use-as-is is no option practically in all cases.
- Pre-damage of the test item. Example: due to unexpected high mechanical stress (e.g. by wrongly applied notching or shaker malfunction) the crack growth calculation can be outdated and is updated to check whether the item is still flight worthy or if it can fail during the next stress event (launch).
- Wear higher than calculated. Example: during the test programme, an item which is subject to wear (pump, mechanism, slip ring…) has been used for 300h instead of planned 200h. Depending on the whole lifetime and margins, this can cause degradation of the mission lifetime.
- Loss of qualification status: If out-of-qualification stresses (temperatures, mechanical stresses…) have been applied, the qualification status is lost. Using a qualification model undergoing the extended qualification range is a possibility to retrieve the qualification status.

Once overtesting occurred, the evaluation process of how to proceed is started. This is handled on a case-by-case basis. The countermeasures can be:

- replacement of the item affected,
- repair if damaged,
- refurbishment,
- use-as-is after check.

None of these countermeasures are applied without a specific analysis of the event and its impact. A simple re-check of function and performance is not a viable solution because of the possibility of undetected degradation.

4.1.5 Test effectiveness

The above-mentioned optimization of a test programme with respect to cost, schedule, and risk requires a good understanding of the test effectiveness. The better the understanding of the test effectiveness is, the more efficient the set-up of the test programme is. In particular, the defects detection efficiency by monitoring and the precipitation efficiency of latent infant mortality defects participate to the global test effectiveness. Investigations on test effectiveness have been made and are ongoing, in case the available and up to date information can be checked (e.g. Model and Test Effectiveness Database (MAT€D), Analysis of Spacecraft qualification Sequence and environmental Testing (ASSET) study).

References:

- MAT€D: ATS paper_MATED Improvement
- ASSET: https://exchange.esa.int/asset/ TASI-ASE-ORP-0009_01
- ASSET +: https://indico.esa.int/event/151/ TASI-ASE-ORP-0006_Iss.01

NOTE All the referernced documents are embeded in Annex G and are available for download along with this handbook.

4.2 Development test prior to qualification

The text in this clause 4.2 covers requirements 4.2.a to 4.2.c in ECSS-E-ST-10-03.

The definition of development model can be found in the clause 5.2.5 of ECSS-E-HB-10-02 "Verification guidelines".

It is necessary to clearly distinguish between development and qualification. Development and development tests offer the possibility of design changes, depending on the outcome of the tests. Contrary to this, a qualification test campaign is performed on hardware whose design is not expected to change. Therefore, generally a qualification test campaign only starts after the related development tests have been finished.

However, due to schedule constraints, there is always pressure to start with qualification as early as possible. It is a matter of a risk assessment for the specific case to decide whether the qualification is started even if there are open points out of the development tests. Usually the first step is the decision to build (and how to build) a qualification model. For this, results of the development tests are available which allow having a certain design status "most probably" not subject to change any more. The more the overlap between development and qualification is, the higher the risk – a schedule vs. risk trade needs to be performed before a decision.

Development tests are not formally limited to any operational conditions. They can be used to check for margins and limits, and also to set proper qualification limits (as far as not already given by requirements).

During development tests one can be interested in checking for the real limits of operation, for example, during thermal testing, cooling down to the point where failures occur. This is allowed and can help in an operational failure case to evaluate recovery strategies.

A development model or even parts of it cannot be used for qualification purposes afterwards, because the documentation associated with such model does not allow to properly identify the complete history of the model or the part and, more severe, the stresses put on the item under test during the development tests can have an impact on the results of the qualification tests.

Starting from a reproducible and "clean" status is therefore fundamental not to mix development model parts with a qualification model and, of course, not with a flight model.

Development tests by nature do not have stringent documentation requirements as tests on qualification or flight hardware. Test procedures can be modified during test execution if the item under test does not behave as expected. Or it can be the other way around: running the tests gives insight about how the test procedures can be tuned.

No formal NCR and waiver process is carried out as part of the development process. However, as a minimum, the detailed test configurations, a record of test steps which have been performed and the test results need to be stored to highlight progress in the development process and to allow to conclude on the success of the development. This documentation also is of aid for investigation in case of need later on.

4.3 Test management

4.3.1 General

The text in this clause 4.3.1 covers requirements 4.3.1.a and 4.3.1.b in ECSS-E-ST-10-03.

Unclear assignment of responsibilities can cause major problems during different phases of the test programme. Non-optimal responsibility assignment causes a lot of trouble especially when deviations to the test procedure occur and the responsibilities to deal with them are proved to be unclear.

Some element level tests being particularly complex to organise (thermal vacuum test, static test), it is recommended to organise the test preparation as a project in itself, with specific milestones.

Test definition and specification phase:

> The responsibility for the verification concept, the identification of needed tests for verification, and the test specifications are on system engineering side. The AIT responsibility during this phase is to answer to these requests by setting up a test plan, preparing to select the test facilities, and to check the suitability of the test means with regard to the test requirements. Responsibility does not mean that it is done by this party all alone, but the book captainship is on this side. In fact, engineering and AIT work in close cooperation and complement each other to be able to define and run the test programme – see also test specification and test procedure below.

Test preparation phase:

> In this phase AIT prepares the test procedures in close collaboration with the engineering team. One of the main aspects is to define the role and responsibilities (according to DRD TPRO Annex C of ECSS-E-ST-10-03) during the test. In particular, the process and the responsible that authorize procedure variations are identified.

Test execution:

Test is executed upon approval at TRR in accordance with the procedure. Procedure variation if needed follows the agreed process and responsibility. The post test review decides on the end of the test execution and the release of the item under test and test facility for further activity.

4.3.2 Test reviews

4.3.2.1 Test programme

The text in this clause 4.3.2.1 covers requirements 4.3.2.1.a and 4.3.2.1.b in ECSS-E-ST-10-03.

The text in clause 4.3.2.2 to 4.3.2.4 covers requirement 4.3.2.1.c in ECSS-E-ST-10-03.

Test blocks are useful to release a certain amount of test activities at a time. A full test programme can usually not be released in just one meeting (TRR), as the programme covers a large amount of tests, which cannot be prepared up to the very last detail at the beginning. On the other hand, releasing each and every single test procedure by means of a TRR would require a high number of such meetings including the effort of their organization and preparation. Therefore, an appropriate set of blocks is defined, each of which are released by separate TRR. For each test block, all documentation is prepared and all other preconditions (GSE ready, all open points discussed, availability and role of personnel clarified, facility ready…) are fulfilled to have a successful TRR for this test block.

4.3.2.2 Test readiness review (TRR)

The text in this clause 4.3.2.2 covers requirements 4.3.2.2.a to 4.3.2.2.d in ECSS-E-ST-10-03.

As given in the standard, the most important part of the TRR is to run through a checklist to verify that all preconditions for the execution of the test are fulfilled. In fact, the TRR is a question-and-answer meeting between the project PA, the test responsible. Good preparation for the meeting is mandatory – the checklist is confirmed point by point. To allow for such a smooth meeting, the documentation is reviewed and agreed in advance, not to have major issues unexpected at the TRR. Therefore, if there are open technical issues, they are identified before the TRR and the preparatory technical work takes place in advance in order to reach an agreement during the TRR. It is better to avoid any discussion of the content of documents within the TRR, especially discussions on the test procedure content. Test content as defined by the test specification is agreed with the customer in advance, starting with the development of the verification content and proceeding step by step to test specification release.

The TRR ends with the conclusion whether the test (block) is properly prepared or not, and, in case it is, it releases the start. Open topics can be handled by a delta TRR or can be considered as normal work not blocking the test release. In any case they need to be tracked and closed.

It is strongly recommended:

- to check the readiness of the test hardware by physically inspecting the test HW and the facility as part of the TRR.
- that TRR takes place at the test facility.

4.3.2.3 Post test review (PTR)

The text in this clause 4.3.2.3 covers requirements 4.3.2.3.a to 4.3.2.3.c in ECSS-E-ST-10-03.

The focus of the PTR is to come to a quick formal agreement on breaking the test setup to allow AIT to go on with the planned activities. As long as this agreement is missing, all further AIT activities are stopped. Therefore, within the PTR, the detailed results of the test are not checked and handled.

Deviations from the procedure and failures are addressed and discussed as well as preliminary data assessment to exclude the need of any direct retesting in the current setup. The PTR is scheduled right after test finalization.

4.3.2.4 Test review board (TRB)

The text in this clause 4.3.2.4 covers requirements 4.3.2.4.a to 4.3.2.4.c in ECSS-E-ST-10-03.

Differently from a PTR, the TRB needs a not negligible time for preparation after the test is finished. The test report is prepared. Any open point, including NCRs resulting from the test execution, is addressed. The TRB is the final acceptance board for the test.

During the TRB the major stakeholders are the engineering team supported by the AIT team.

4.3.3 Test documentation

4.3.3.1 General

It is highly recommended to establish a first issue of the AIT Plan even if the System Engineering Plan and the Verification Plan are not available in the final form. The AIT Plan is derived from these documents, but only partly. Identification of facilities and the organization and management of AIT are mostly independent of the engineering input. Also, major parts of the GSE (MGSE as well as EGSE and, if applicable, OGSE and FGSE) can already be defined in an early state.

4.3.3.2 Assembly, integration and test plan

4.3.3.2.1 Overview

The text in this clause 4.3.3.2 covers requirements 4.3.3.2.a to 4.3.3.2.c in ECSS-E-ST-10-03.

During the project the AIT Plan undergoes an evolution process. The level of detail increases from early phases to PDR and CDR. PDR and CDR are usually defined milestones for an updated document delivery. The CDR version is very close to the final issue, where only late modifications are implemented.

The AIT Plan available at the first TRR for a given model test programme is the final issue concerning this model.

Apart from other sections to be addressed in the AIT Plan (see according DRD ECSS-E-ST-10-03, Annex A), the AIT Plan serves as a roadmap for all AIT activities. All information necessary to properly run the AIT activities are found in this document, in particular the integration and sequence of tests as well as the prerequisites for any activities (e.g. identification of the facilities, necessary GSE, general test setup, AIT organization and staffing). The AIT Plan is an applicable document for all AIT documents giving more detailed information: AIT flows, document lists, GSE specifications, test procedures…

In the following, as this document is a testing handbook, we concentrate on the test related issues for the AIT Plan. Concerning testing, the AIT Plan is the answer to the Verification Plan (VP, as per DRD Annex A of ECSS-E-ST-10-02). Generally speaking, the Verification Plan identifies which requirements are verified by test and the AIT Plan states how it is going to be tested. Therefore, the following topics related to the “how” are addressed:

- content of the tests,
- splitting and sequencing of tests,
- necessary GSEs,

- necessary facilities,
- organization and management of the tests.

4.3.3.2.2 Content, splitting and sequence of tests

The Verification Plan defines all the requirements that are verified fully or partially by test. In addition, some interdependencies and the associated verification sequences are detailed. The AIT Plan takes the Verification Plan as a basis to develop the whole and detailed test programme (including test matrix and sequence of tests). In an iterative and communicative way, the test specifications are developed by the engineering staff (again what testing required in a specific test), followed by the test procedures by the AIT team (how this required testing is performed). A good interaction between engineering and AIT is essential for a good result concerning test contents and sequence of tests.

As an illustration, the basic logic of a typical S/C integration and sequence of tests is as follows:

- building the "functional core" of the system by integrating the on-board computer including command ability (direct access) and power supply. Interface and basic functional tests are performed.
- adding the platform subsystems one after another: power subsystem, partly represented by simulators (see clause 4.3.3.2.3 "EGSE", batteries and solar arrays to be integrated in a later stage), TT&C system to allow flight like (at least similar) commanding, followed by AOCS units. Each integration step needs to be followed by the corresponding interface and basic functional tests.
- subsystem and platform level tests are to follow to check functions and performances within the platform level, e.g. open and closed loop tests for the AOCS, tests of mechanisms in the platform level test environment, in-depth on-board data handling testing.
- integration and interface as well as functional tests of the payload.
- system level testing like Polarity Test, Mission Simulation Tests and FDIR.
- finalization of the spacecraft with appendices and MLI, preparation for environmental tests, global leak test.
- environmental tests in a sequence appropriate for the specific mission – no "golden rule", but always an evaluation of pros and cons for a specific sequence of tests.
- transport to the launch site and launch campaign (to be set up in close cooperation with the launch authority).

4.3.3.2.3 EGSEs

The AIT Plan identifies all necessary EGSEs. However, not covered are specific simulators used for on-board S/W validation and verification before implementation of the S/W on the target system.

NOTE S/W validation and verification requirements are covered by ECSS-E-ST-40 and ECSS-Q-ST-80.

The needed EGSEs for a typical spacecraft system level test usually consist of:

- a central checkout system (CCS) as a "backbone" of all EGSE major parts to be connected to the spacecraft, also including data management (AIV/AIT database, SRDB).
- an on-board data handling EGSE, including bus Analyser and data loader.
- a power EGSE, consisting of Solar Array Simulator, Battery Simulator, Battery Management Unit and others, usually several racks.
- an AOCS EGSE, used to simulate and stimulate AOCS sensors and to provide an environment of simulated mission scenarios concerning attitude and orbit control.

- a TT&C EGSE including TM/TC front end to allow communication with the spacecraft, consisting of various ways to do so: via direct data bus connection; hardwired, but with modulation/demodulation; end-to-end version using test caps including damping devices to establish a radio frequency link.
- a payload EGSE, which is mission specific.
- other EGSEs like RF suitcase and umbilical EGSE, TCS simulation, propulsion GSEs.

A typical setup is shown in Figure 4-1.

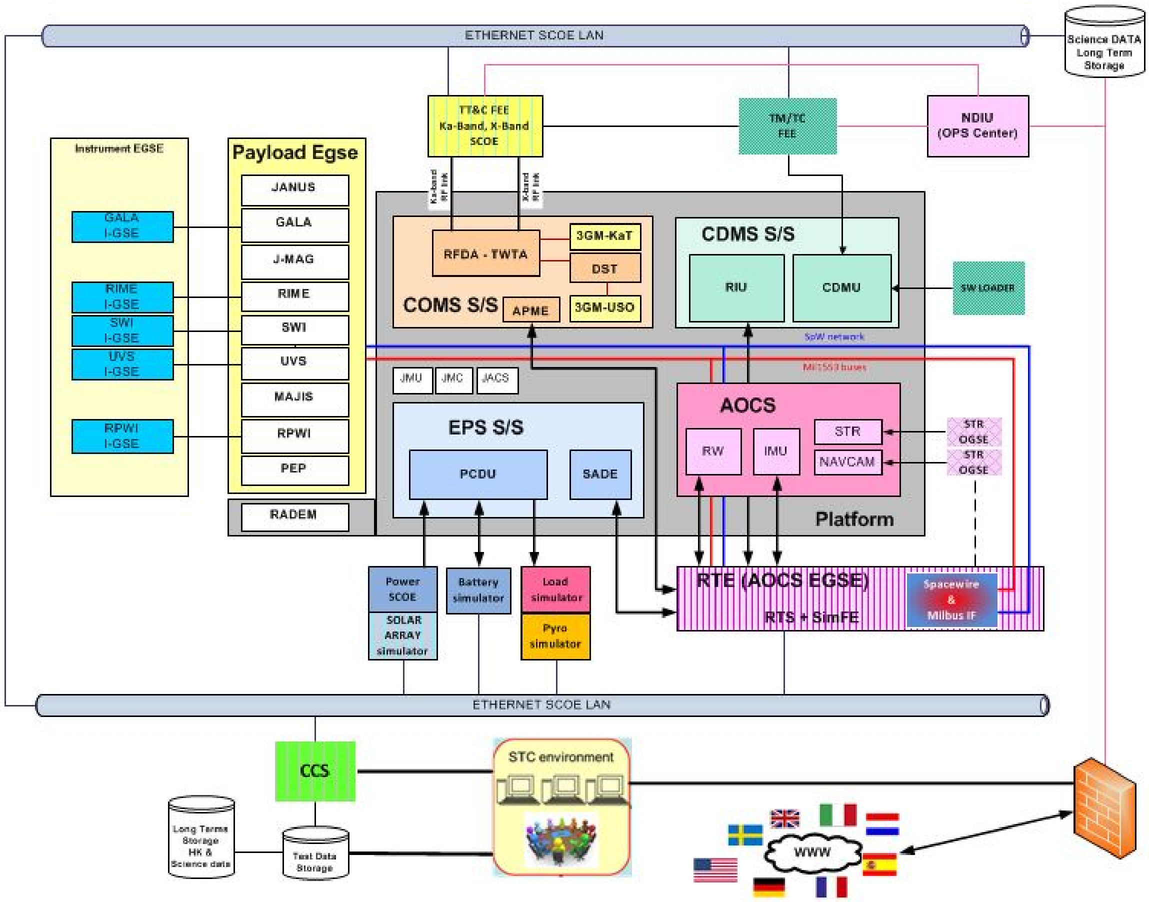


Figure 4-1: Testing at S/C level and example of typical EGSE setup for JUICE S/C (courtesy Airbus Defence and Space)

Apart from the EGSEs needed to run spacecraft tests, other EGSEs are identified and procured or made available in time. This includes facility EGSEs or facility equipment to be procured or rented for the specific project:

- general purpose test equipment like break-out-boxes, multimeters, oscilloscopes, probes, measurement equipment in general: these are either available from a central AIT pool or procured in time.
- small “stand-alone” EGSEs for specific tasks or special tests, e.g. read-out equipment and data storage for thermal test data and sensors, illumination devices for solar array checks, specific measurement equipment for pyro resistance checks…

- facility related EGSEs to support, for example, vibration, thermal vacuum, acoustic noise, shock, EMC and CATR testing, GPS clock reference.

It is important that the EGSE is validated and calibrated before starting the test activities.

The calibration is maintained throughout the ground test activities.

4.3.3.2.4 MGSEs

It is important to identify the MGSEs needed for the integration and test activities. Therefore, it is recommended to go through the whole AIT sequence and to identify, for each step, which kind of MGSE is needed to perform the task. At least MGSE, which is not available off the shelf or not trivial to manufacture, needs to be identified, specified and procured well in advance. Typical "big blocks" of MGSE are transport containers, lifting devices, integration stands and trolleys, module integration aids, test adapters, test and handling clamp band (see hereunder pictures). However, there are also some delicate items to be considered like zero-g devices or deployment rigs. All of these need a procurement process similar to an equipment procurement: issue a specification, select a supplier, agree on milestones like reviews, monitor the detailed development and manufacturing process, witness the acceptance tests (like proof load test, drop test for damper systems, Non-Destructive Inspection tests).

Possible problems during the integration process are anticipated to be prepared with the right MGSE. Also, some flexibility in the concept is anticipated to adapt for late design changes of the spacecraft or its modules.

It is good practice to perform dry runs to become familiar with the MGSEs handling. This is considered in the scheduling.

Small MGSEs are items like diving boards, special tools, scaffolds, fixations, brackets, safety covers and so on.

It is highly recommended to establish a complete list of all MGSEs needed for the project, including small items, but except standard tools, and to track the need date as well as the estimated date of availability.

Figure 4-2: GOCE spacecraft Container

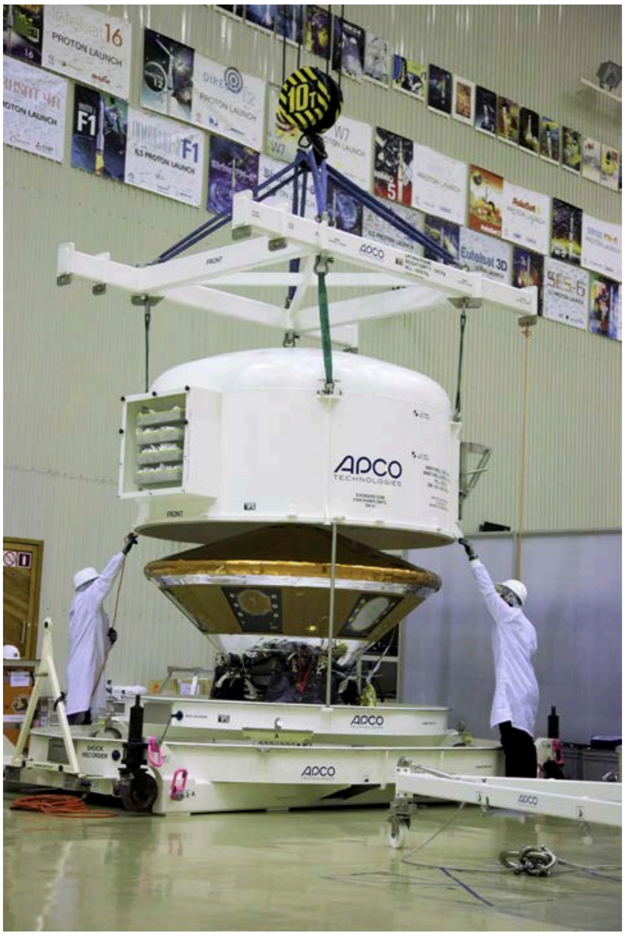


Figure 4-3: Exomars Schiaparelli Descent Module Container

Figure 4-4: AEOLUS multipurpose trolley

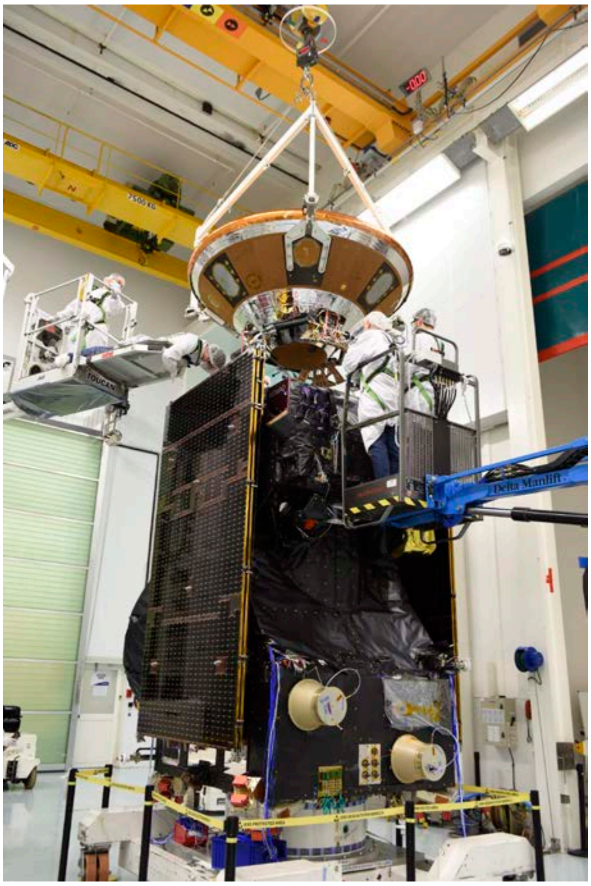


Figure 4-5: Lifting device for Exomars Schiaparelli Descent module

4.3.3.2.5 Other GSEs

Apart from EGSEs and MGSEs, project specific and subsystem specific GSEs are identified. This covers fuelling GSEs, optical GSEs, cooling GSEs (fans or liquid cooling) and more, as applicable.

4.3.3.2.6 Facility infrastructures

The handling of flight items during their lifetime on earth usually requires specific attention with regard to the environment provided by the facilities. To avoid contamination by particles usually a cleanroom ISO class 8 is used for integration purposes. In addition, temperature and humidity are controlled and recorded within limits as given in ECSS-Q-ST-70-01 (RH (55 ±10) %, T (22 ±3) °C in standard cases).

Depending on specific mission requirements other environmental conditions can become applicable. For missions to planets of the solar system the planetary protection rules apply, (see Committee on Space Research – COSPAR PLANETARY PROTECTION POLICY), resulting in more stringent requirements especially on biological contamination. For flight hardware with delicate optics usually higher clean room classes are required (typically ISO class 5).

There are more requirements on the facilities than just the environment (for example, special security requirements can apply). The infrastructure is appropriate for the tasks to be performed: the suitability of the infrastructure is checked against the requirements, for example:

- Fixed facility infrastructure:
    - Crane(s) with necessary load capacity and clearance (lifting height),
    - Facility grounding concept,
    - ESD flooring as applicable,
    - Electrical infrastructure (e.g. power up to three-phase current 330 V / 63 amps),

    - Safety measures for dangerous operations like pressure tests (bunker), if applicable,
    - Illumination according to the needs and legal constraints (brightness, specific working area illumination),
    - Size of access and integration area (see example of floor planning below).
- Moveable facility infrastructure:
    - Cherry pickers,
    - Fork lifts,
    - Lockers / storage means,
    - Clean benches with filters for e.g. gluing activities.
- See also for Safety issues 4.4.1e.

4.3.3.2.7 Integration area planning

Note that apart from the area needed for the spacecraft itself working areas, EGSE, MGSE need to be considered in detail. The working area comprises scaffolds, desks to place tools, desks and chairs for QA and documentation, access areas for alignment activities and more. All floor planning takes into account specific activities, which lead to an increased area need for a limited time: module mating activities, transport preparation involving transport containers and logistics, deliveries of large components.

4.3.3.2.8 Storage area planning

A dedicated non-working area (mainly for GSE) is very often necessary to temporarily store containers, crates etc. that are not continuously used for integration and test activities. Storage conditions need to be identified and taken into account as part of the logistics.

4.3.3.2.9 AIT facilities

Some tests require specialized facilities providing the means to perform vibration and acoustic noise tests, thermal tests, EMC tests, and RF tests. Or facility equipped with adequate test feature for physical properties (Mass, CoG, MoI) determination, appendages deployment, and propulsion test.

For other tests especially for planetary environments, facilities have either to be set up or identified according to the very unique needs of such missions.

To ensure the suitability of the environmental test facilities, the technical data with regard to the applicable requirements are checked first.

4.3.3.2.10 Test Article Instrumentation process

The Design Authority, in agreement with the test conductor or technician (from AIT), approves in a technical meeting on the instrumentation to be utilized to monitor the test performances.

As cooperation activity (co-engineering) before issuing the instrumentation plan, the following main topics are discussed and agreed in detail:

- Instrumentation location to check the accessibility and removability or passivation.
- Instrumentation installation, when and at what time need to be included in the scheduled sequence of tests.
- Instrumentation range and measurement uncertainty in order to use proper standard instrumentation or if strictly needed procure a new instrument.
- Installation procedures (draft) to avoid incorrect installation, Test Article damaging and failure.

- Instrumentation harness routing not to influence the instrumentation readings and test article behaviour (e.g. thermal leaks through harnesses, or issues with deployment/motion).

After the definition of the test instrumentation plan, the whole instrumentation is calibrated checking that the duration of calibration covers all instrumentation activities with also the test execution, with margins.

Dedicated paragraphs of a dedicated instrumentation procedure, or inside the test set-up preparation procedure, describes the instrumentation operations and sequences with also the tables of the main parameters, i.e.:

- instrument type,
- P/N & S/N (if not available in advance a blank range to be filled),
- position/location (with annexed figures),
- directions and axis (for accelerometers, displacement transducers, alignment mirror targets…),
- range,
- measurement uncertainty/sensitivity,
- calibration due date,
- pictures of the installed instrumentation,
- and operator signature and installation date.

Functional check steps are planned, at the end and during the instrumentation process, before and in some case after test execution, in the dedicated installation procedure and they are performed accordingly.

The procedure contains also removal procedures steps.

The instrumentation that is not removed for flight is identified and conditioned as required. An analysis has confirmed that there is no detrimental impact (e.g. contamination, short circuit, mechanical behaviour).

In addition, it is necessary to ensure that the test facility includes proper controls in the final checks with the Data Acquisition system.

After installation of the instrumentation, deviations with respect to the agreed instrumentation plan are clearly identified, e.g. sensors not located or oriented as expected due to unforeseen constraints. It is important to capture the “as instrumented” configuration.

4.3.3.3 Test specification (TSPE)

The text in this clause 4.3.3.3 covers requirements 4.3.3.3.a to 4.3.3.3.c in ECSS-E-ST-10-03.

Test specifications at equipment level and at element level are generally under the responsibility of engineering, not of AIT. Usually, only the developers have a detailed inside view of the equipment which allows defining a proper test specification. However, involvement of AIT in the TSPE preparation is crucial to avoid unfeasible requirements. Early discussions between both parties help to streamline test setups, as AIT is experienced in turning specifications into real test steps.

The DRD for the Test specification is in Annex B of ECSS-E-ST-10-03. It includes the description of the expected and needed content, which are therefore not repeated here, but commented in the following text. The test specification introduction emphasizes two aspects of paramount importance:

- Test purpose (= achievement of test objectives).
- Test limitations (= any open issue, assumption and constraint that does not allow the full achievement of the test objectives).

The Test specification is used as a basis to write the test procedure with all step-by-step activities.

The complexity of a TSPE is directly linked to the complexity of the test.

For a “simple test”, which means, for example, without specific means to develop, and no contribution of many disciplines or sub-contractors, only the TPRO is issued, based on engineering inputs, and it covers the purpose of the TSPE. This is for example the case for physical properties (Mass, CoG, MoI) measurements at equipment level, or derived from a test performed in other projects. For this kind of simple tests, it is acceptable to start directly with the test procedure.

If the test is complex or long to prepare, for example a S/C level EMC test or a S/C level thermal test, at least two issues of TSPE are necessary. A preliminary one is needed to allow for identification of long lead items, booking of the facility, iteration with involved disciplines and similar issues requiring anticipation. A final one captures all requirements to finalize the test procedure.

It is recommended to establish a table containing the requirement identification from the VCD, the requirements text, the verification methods for the requirement as per VCD, and a reference to the point in the test sequence for the planned verification. Discuss the requirements as addressed before as well as the proposed test approach to give rationale for the validity of the requirement verification, if not obvious.

The test description addresses the following topics:

- Test item configuration: required as-built status of the item including S/W version, if applicable.
- Test and operations means: e.g. shaker, vacuum chamber, anechoic chamber, also including description of GSE measurement equipment.
- Test setup including boundary conditions: adapters, interfaces, mounting conditions.
- Ground Support Equipment: mechanical as well as electrical or other GSE necessary to run the test, including test tools.
- Test conditions: specific environmental conditions (temperatures, vacuum, cleanliness…) or other conditions to be fulfilled before running the test.

Requirements on the test facility, either internal or external, need to be addressed. Specifically, for environmental test campaigns, the test facility requirements become part of the contractual documentation with the test house. For environmental tests, usually the following test facility requirements are treated in the TSPE:

- Interface requirements (mounting interfaces, crane interfaces, infrastructure interfaces…).
- Safety requirements (apply for pressure tests, toxic fluids, crane and lifting devices margins).
- Measurement equipment requirements: number of channels, measurement uncertainties, sample frequencies…
- Precise location of sensors, type of sensors selected, measuring range, measurement uncertainty, acquisition frequency, number of sensors. In some cases, this information is captured in instrumentation plans, which can be referenced in the TSPE. Note: some of the instrumentation does not fall under the facility responsibility.
- Facility capability requirements like mass and load requirements or automatic abort capability for vibration, temperature range for thermal testing, frequency capabilities for RF testing.
- Required support means (transport, lifting, nitrogen supply…).

Concerning the test sequence, the TSPE gives a planned test sequence as a frame to establish a TPRO later on. Requirements addressed and verified during specific parts of the sequence are assigned to these parts. The flow of activities is chosen in a way to minimize testing effort without compromising the verification process, i.e. any necessary reconfiguration activities are optimized. The presentation of the flow in the TSPE is limited to the different configurations and major test activities to allow getting an overview of the whole test sequence, but include all necessary information to deduct the step-by-step TPRO later on.

Logical Test sequence: In case of logical constraints to the test sequence (e.g. a measurement value of an activity is needed as input to perform a test step of another activity), these logical constraints need to be identified and described in the TSPE to avoid reshuffling of the sequence during the TPRO preparation.

Pass/fail criteria are defined to allow clear check points between tests steps to decide whether the test is to be continued or stopped.

Test conditions are part of the specification so they are not pass/fail criteria.

Defining the appropriate input pass/fail criteria takes into account the test tolerance bands. Also output pass/fail criteria include test uncertainties to allow for a decision if the test item is reacting or performing as expected.

Responsibilities are essential for successful test performance. Therefore, the roles and responsibilities of e.g. the lead test engineer, the AIT test lead, the project manager and maybe the customer as well are clarified early to avoid discussions about decisions when they are needed urgently.

4.3.3.4 Test procedure (TPRO)

The text in this clause 4.3.3.4 covers requirements 4.3.3.4.a to 4.3.3.4.c in ECSS-E-ST-10-03.

Turning the specification into a step-by-step procedure is a task of AIT. However, as now the developer view is often missing, it is recommended to support the test procedure generation from the engineering side. To make background information available during procedure generation involvement of engineering is necessary. A company structure which allows for some flexibility concerning cooperation of engineering and AIT is beneficial for this. As a general guideline, unproven test procedures are run and checked on engineering models or on a simulator before execution on flight hardware. The step-by-step description needs to exclude any unambiguity. The level of detail is adjusted to the experience and education of the personnel which runs the procedure. This can vary with different company organizations.

The DRD for Test procedure is in Annex C of ECSS-E-ST-10-03. It includes a proper description of the expected and needed contents, which are therefore not repeated here.

4.3.3.5 Test report (TRPT)

The text in this clause 4.3.3.5 covers requirements 4.3.3.5.a to 4.3.3.5.b in ECSS-E-ST-10-03.

Depending on the test purpose (interface test, functional test, performance test…) the test report is issued by AIT or engineering. For interface and functional tests, the focus is mostly on simple pass/fail criteria, verification of requirements in this stage of testing is very limited. Therefore, the test report often consists of a summary of the results, with the as-run test procedure as annex. As long as no deviations occur, no engineering judgment is necessary. Once the phase of performance or environmental testing is reached, engineering produces a test report. In this case, it is often referred to as a test evaluation report. The test results often need a careful evaluation with regard to requirements verification.

Due to the nature of tests, there can be several test reports, for example for thermal tests there are a test facilities report, containing raw data from facilities, an AIT test report, including the operational results of the thermal test activities, and a test evaluation report, issued by the engineering team.

To conclude successfully a TRB, the availability of an issued version of the test report is mandatory.

The DRD for Test Report is in Annex C of ECSS-E-ST-10-02.

4.3.4 Anomaly or failure during testing

The text in this clause 4.3.4 covers requirements 4.3.4.a to 4.3.4.c in ECSS-E-ST-10-03.

Deviations from expected measurement values or unexpected behaviour of the item under test need to be evaluated. To allow for this, recording of the test steps is a necessary precondition for post-test evaluations. Recording is not limited to the failure or anomaly itself, but also clearly describe the test status and conditions. For functional tests, replay of the test steps to verify that either the anomaly or failure has been a single event or is repeatable is often needed to identify the root cause.

AIT and QA check whether a non-conformance is resulting out of the anomaly or failure and in case start the NCR process on the issue. According to the non-conformance processing flow of ECSS-Q-ST-10-09, disposition on corrective and preventive measures including retest activities is given.

4.3.5 Test data

The text in this clause 4.3.5 covers requirements 4.3.5.a to 4.3.5.c in ECSS-E-ST-10-03.

To record test data together with environmental conditions and test setup details (specifically software versions) is mandatory to later on analyse the test results. Missing information, detected during test evaluation, leads to the necessity of test repetition.

Parameters, which are going to be measured several times during the overall test campaign, and which can vary within a certain range, are identified. For these parameters, a specific analysis is performed, aiming on the identification on trends in the measurement results. This allows for a prediction of probably out of range results after a certain lifetime. Typical tests related to the identification of trends are the functional tests before and after environmental testing (System Functional Tests) as well as short functional tests all over the environmental test campaign.

Test data is available in electronic form as far as possible, to streamline processing.

For example, in case of vibration testing, all time histories are recorded for further analysis in case of issue. The availability of the time history is checked with the test facilities.

4.4 Test conditions, input tolerances, and measurement uncertainties

4.4.1 Test conditions

a. The test levels and the test durations that a TSPE require are the main test conditions for the fulfilment of the test objectives.

   If using predicted environmental and interface conditions, the environment specifications or documents managing interfaces between products usually provide the TSPE input information:

   - An environment specification describes the different life phases environmental conditions (ground, launch, in-service and withdrawal from service).
   - Generally, the prediction of an environmental or interface test condition uses in-service data of previous missions, relevant ground or launcher environments, analytical predictions including calculation uncertainties, relevant previous test results including test uncertainties, or a combination thereof. Such test conditions can cover one or more missions.

As an example, if using predicted reliability performances for electronic equipment, the Arrhenius law drives the temperature levels that the TSPE requires. In that case, these temperature levels do not come from TCS (Thermal Control Subsystem) performances predictions.

The predicted environmental conditions can cover either only one mission, for example on a unique LEO orbit, or a set of missions, for example including LEO and non-LEO orbits with interplanetary trajectories.

As an example, in the functional domain, worst case conditions, coming from the specific mission, are taken into account for certain verification activities like test of power profile. This corresponds to the "test like you fly".

For the mechanical domain see ECSS-E-HB-32-26 “Spacecraft mechanical loads analysis handbook”.

b. Deleted requirement.

c. Examples of effects that might induce differences in behaviour due to the testing environment:

- Effects of appendages flexibility during attitude control tests.
- 1g effects or atmosphere effects on mechanisms torque capability or stiffness.
- As indicated in the note in the standard, a typical difference between ambient pressure and vacuum is the absence of convection for the heat transfer and the effect on temperature differences. Note that in some cases, conduction through the gas has significant effects. For example, in cases where there is a thin layer of gas (e.g. gas gap) is present, convection does not happen in this thin layer, but gas conduction changes the heat transfer. This is the case for Multi-Layer Insulation.
- If gas in movement is present around for example a space segment element, effects of heat transfer by free or forced convection on temperature differences between different points of this space segment element.

d. No specific guidelines for this requirement.

e. Safety aspects can be critical, e.g. during pressure tests, static tests, vibrations, tests with batteries, hazardous materials (e.g. Beryllium), pyro devices. Potential hazards are identified and registered and protection means provided (safe unloading during static test, ear protection for vibrations).

Examples for Static tests see A.3, for centrifuge see A.5, for vibration see A.7and for Pressure tests see B.3.

NOTE Test facilities typically have safety procedures to be followed and for which personnel are trained. However, for ad hoc type of tests (e.g. pressure tests, static tests, landing tests), those safety aspects are addressed.

f. Test facilities and GSEs are not the weak part (i.e. do not impact on test performances). GSEs have sufficient margins (in terms of performance and reliability) and redundancy features not to affect the test. MGSE is typically tested before use. Strength tests are performed on a regular basis for items that are re-used (e.g. slings), according to national safety rules. For example, a test heater is sized with derating rules at least as severe as flight ones. It has happened that a thermal test had to be aborted because a test heater started to burn. Similarly, to reduce the risk of a clamp band failure during vibrations or static test, more robust clamp bands can be used, which do not only rely on friction but can also include a mechanical stop on the rear frame of the launcher interface. These topics are addressed early when procuring the GSE and verified at TRR.

g. These topics are addressed early during test preparation and verified at the TRR.

h. It is very important to perform test predictions or test simulations (including as much as possible the effects of the test facility. Example: virtual testing) before the test starts. In case of vibration testing, it is important to begin the test with dry runs and low levels. In some cases, coupled prediction analysis are performed considering simulation models of the facility and of the test article. These topics are addressed early during test preparation and verified at the TRR.

4.4.2 Test input tolerances

a. No specific guidelines for this requirement.

b. This handbook, as the testing standard, does not cover metrology uncertainty budgets and test uncertainty budgets. The guides (JCGM 100 series, EA-4/02 and EA-4/16), in the bibliography of the standard, are the international state of the art in terms of uncertainty of measurement and in terms of uncertainty in quantitative testing. EA-4/02 and EA-4/16 are European guides that apply the JCGM 100 series. A general knowledge of the practice of this terminology and of these fundamental basics is of great help in formulating explicit requirements about these uncertainty budgets in each test specification.

See additional guidelines in the guidelines to the requirement 4.4.3b.

c. No specific guidelines for this requirement.

d. No specific guidelines for this requirement.

e. No specific guidelines for this requirement.

4.4.3 Measurements uncertainties

a. See guidelines to the requirement 4.4.3b.

b. See first considerations in the guidelines to the requirement 4.4.2b.

Metrology and test equipment calibrations are crucial

To support efficiently each test objective and knowing that the engineering team takes care of the accuracy of each test implementation, metrology and test equipment calibrations ensure an accurate value of each test input and output measured parameter.

Repeated calibrations based on approved calibration procedures, with traceability to international standards for metrology and to test standards for test equipment, are the fundamental and primary activity:

- For each test input parameter associated with a test input tolerance, each measured value can vary within the allowable tolerance band. And to do this, the specified allowable uncertainty width (with typically a 95% confidence level), associated to all measurement instruments and test equipment used to control and monitor this test parameter, is a little fraction of the tolerance band width. For this purpose, most of the space programmes international standards require or preconize this width better than one third of the test tolerance band width. Figure 4-6 illustrates the decision rule associated to test input tolerance assessment, as per ISO/IEC 17025:2017, entitled *"General requirements for the competence of testing and calibration laboratories"*.
- For a test input or output measured parameter, the test implementation uncertainty is test dependent and can be much bigger than the metrology and test equipment calibrations uncertainty. Generally speaking, a global measurement uncertainty includes the measurement implementation contribution and the contribution of the calibrations of the complete metrological chain. As an example, for sensors as thermocouples, the uncertainty coming from even good thermal contacts, between a surface near the temperature intended

to be measured and the thermocouple (sensor head and wires), makes negligible the metrological chain calibration contribution to the global uncertainty. For vibrations, the orientation and exact location of the accelerometers are sources of uncertainty. For a static test, orientation and location of strain gauges are sources of uncertainty. For acoustic test, location of the microphones influences the measured sound pressure level, which is never fully homogeneous in the test volume. This is particularly true for direct field acoustic test. For static tests, mounting of the LVDTs might lead to significant uncertainty.

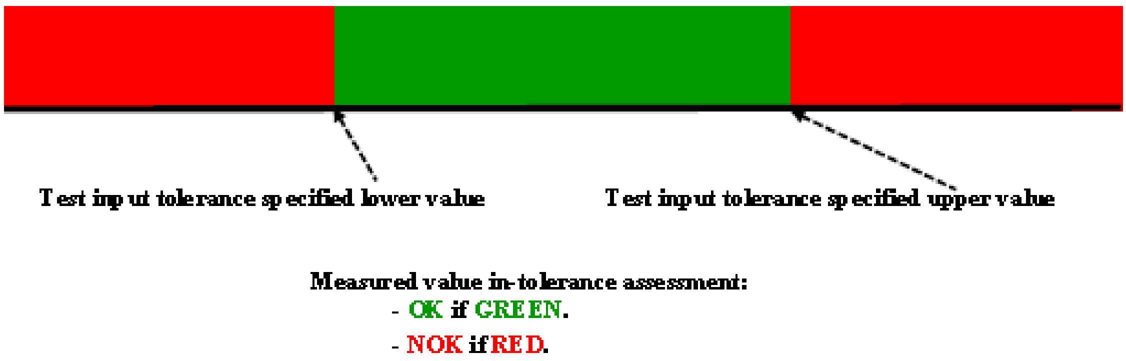


Figure 4-6: Test input in-tolerance or out-of-tolerance assessment (decision rule)

<u>**Test results conformity assessment is performance dependent**</u>

For test output measured parameters participating to the space product verification, the approach of the conformity assessment differs according to two main categories of space product performances:

o For a performance verified by a quasi-direct measurement, Figure 4-7, inspired by the Figure 10 of the JCGM 106:2012 guide, entitled *"Evaluation of measurement data -- The role of measurement uncertainty in conformity assessment"*, illustrates the approach. This figure illustrates the decision rule, as per ISO/IEC 17025:2017, associated to conformity assessment with the guard band approach.

  In case of two (lower and upper) bounds for the specified allowable values, this figure visualizes a range of allowable values (orange and green zones) from lower to upper specified limits and two guard bands (orange zones) defined as the 2-sigma confidence interval (95% confidence level) of the global measurement uncertainty.

  The guarded approach avoids false conformities within the confidence level, but can lead to false rejections and, if the specified interval width is small, to conformities impossible to assess (no green zone). In order to mitigate these two risks, the only way is low global measurement uncertainties. For the second risk and in case of two (lower and upper) bounds for the specified allowable values, the conformity assessment is only possible if the global measurement uncertainty is significantly lower than the specified allowable interval. With a factor superior to two, a green zone appears. With a factor three, the green zone width equals the measurement uncertainty.

  As an example, for a mass measurement with an upper specified limit, the absorbed humidity or another uncertain or unrepresentative test condition can be a mass measurement implementation contribution to the global mass measurement uncertainty much bigger than the calibrations contribution. It is particularly the case if the uncertain or unrepresentative test condition varies between different tests and if the analysis of its impact on the result is uncertain. So, the test specification requires similar conditions (pressure, temperature, humidity) between different mass measurements, in accordance with ECSS-Q-ST-70-01 clause 5.3.

- For a performance verified by a numerical model correlation activity, the TSPE requires each need in terms of uncertainty, including confidence level. Before that, the engineering team ensures the satisfaction of specific needs exceeding the performance of previously available measurement instruments and test equipment. The corresponding decision rule, as per ISO/IEC 17025:2017, is the assessment of the flight predictions results obtained with each validated numerical model.

  Examples: higher than ever dimensional stability to avoid thermo-elastic displacements, lower than ever temperature difference, tighter than ever requirements on temperature stability or variation, or very small displacement to be measured for thermo-elastic stability.

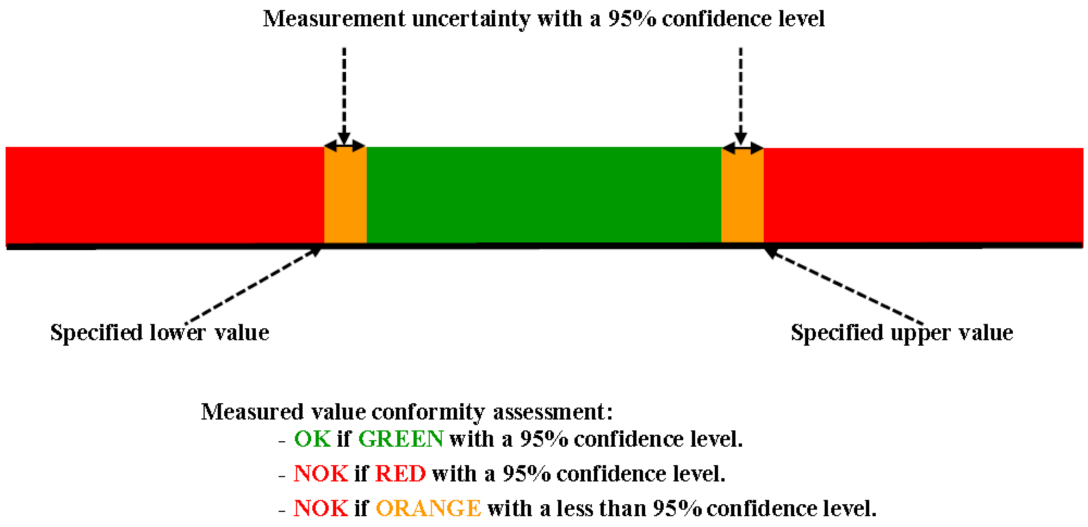


Figure 4-7: Conformity assessment with the guard bands approach (decision rule)

c. No specific guidelines for this requirement.

d. No specific guidelines for this requirement.

e. Deleted requirement.

4.5 Test objectives

4.5.1 General requirements

a. The test programme definition takes into account:
   - verification programme defined in ECSS-E-ST-10-02,
   - model philosophy defined in ECSS-E-ST-10-02,
   - requirements defined in ECSS-E-ST-10-03.

b. No specific guidelines for this requirement.

4.5.2 Qualification testing

a. For functional testing, margins are not systematically applied.

b. The qualification at element level is often spread out over different models.

c. Deleted requirement.

d. Deleted requirement.

e. No specific guidelines for this requirement.

f. No specific guidelines for this requirement.

4.5.3 Acceptance testing

a. For mechanical acceptance testing also makes sure that the flight model behaves as the model on which qualification testing is performed (e.g. dynamic signature). If not, then the qualification can be jeopardized.

b. An important objective of acceptance testing at equipment level is to precipitate by environmental stress screening any latent defect in materials, parts, processes and workmanship that is susceptible to cause detrimental problems or failures during posterior AIV activities at element level and during the in-service infant mortality period. In particular, for temperature cycles, the precipitation efficiency of the thermo-mechanical stresses depends on the amplitudes of the temperature ranges and rates of change. A temperature range limited to the working operational temperature range is not sufficient. Other types of defect, as design defects that escape to qualification stage or as patent defects in materials, parts, processes and workmanship that escape quality control and previous environmental tests, can also cause detrimental problems or failures.

c. Further information about acceptance can be found in ECSS-E-HB-10-02 section 5.2.4.3.

d. No specific guidelines for this requirement.

4.5.4 Protoflight testing

4.5.4.1 Overview

Note that protoflight approach can be performed according to the type of environment. For example, a given project could have a protoflight approach for thermal and perform the mechanical qualification on a structural model (SM) and only mechanical acceptance on the flight model (FM).

4.5.4.2 Requirements

a. See the guidelines for acceptance testing in 4.5.3b with the difference that the protoflight stage has also the objective of detecting design defects.

b. No specific guidelines for this requirement.

c. No specific guidelines for this requirement.

4.6 Retesting

4.6.1 Overview

No specific guidelines for this overview.

4.6.2 Implementation of a design modification after completion of qualification

a. No specific guidelines for this requirement.

4.6.3 Storage after protoflight or acceptance testing

The text in this clause 4.6.3 covers requirements 4.6.3.a to 4.6.3.g in ECSS-E-ST-10-03.

If specific needs for testing during storage are foreseen, it is highly recommended to rehearse the procedures before the storage takes place.

4.6.4 Space segment element or equipment to be re-flown

a. No specific guidelines for this requirement.

b. No specific guidelines for this requirement.

4.6.5 Flight use of qualification Space segment element or equipment

a. No specific guidelines for this requirement.

b. No specific guidelines for this requirement.

c. No specific guidelines for this requirement.

5
Space segment equipment test requirements

5.1 General requirements

The space segment equipment testing is key for a comprehensive test and verification program of the whole space segment element. Ideally the same principles are applied on the equipment and space segment element verification levels. This is requested especially for the functional and performance testing described in the clauses below and in more detail in the foreword of equipment level section 5.5.1.1.

a. No specific guidelines for this requirement.

b. No specific guidelines for this requirement.

c. An aspect to consider is the capability to detect defects produced by the other environments. For example, a structural failure due to thermo-elastic stresses during a thermal test can be detected during vibrations later on, while it can remain undetected if vibrations were performed before the thermal test. On the other hand, a defect produced in vibrations, e.g. on a connector, can be detected during a thermal test afterwards, while it can escape if vibrations are performed after the thermal test. Another consideration is that thermal tests include functional and performance tests and monitoring capability in between. This is very effective to highlight flaws and they offer very good perceptiveness because of this functional and performance verification and because of this monitoring (as opposed to vibrations for example). From a programmatic point of view, capability to detect defects as early as possible calls for early thermal tests (especially by temperature cycling for efficient thermo-elastic stress), while from a technical point of view, it can be considered better to perform them towards the end of the sequence of tests to capture any defect caused by the other environments or AIT activities. These guidelines deal with the screening efficiency objective of the testing sequence. Naturally, this global screening efficiency greatly depends on the screening efficiency of each test in the sequence. In particular, for thermo-mechanical latent defects, the precipitation efficiency of temperature cycling varies sharply with the number of cycles and with the amplitudes of the temperature ranges and rates of change. For example, a temperature range limited to the working operational temperature range is not sufficient to reveal during ground testing latent flaws that can appear later in flight after a certain amount of cumulative thermo-mechanical stress.

d. Any critical parameter is identified and subjected to trend analysis (e.g. batteries voltage monitoring).

e. No specific guidelines for this requirement.

f. No specific guidelines for this requirement.

g. No specific guidelines for this requirement.

h. No specific guidelines for this requirement.

i. No specific guidelines for this requirement.

j. No specific guidelines for this requirement.

5.2 Qualification tests requirements

a. Note that usually sinusoidal vibration covers the static load for equipment. Exceptions can be Entry, descent and landing loads.

Static test allows to combine loads on different axes and have dissymmetric loading (traction/compression) while sine vibration excites the test article in one axis only and symmetrically in both directions, for the dynamic part. Note that there is always a constant vertical load due to gravity. For a vibration test in vertical direction, this means that the applied load is decreased by gravity when the test article is accelerated downwards and increased by gravity when the test article is accelerated upwards. As a consequence, vibration in vertical direction never provides a symmetric loading. For horizontal excitation, gravity applies a constant lateral vertical load to the test article.

More generally, it can be important to consider the load due to gravity for all mechanical tests. There is always a 1g vertical component.

Shock: refer to ECSS-E-HB-32-25, clause 12.2.1.

ECSS-E-ST-10-03 Table 5-2, row 7 “Sinusoidal vibration”: For sinusoidal vibration at low level, it is recommended to perform a low level until 2000 Hz for characterisation purpose. This provides a more complete dynamic signature of the test article, and can be used for investigation about the response to random, acoustic or shock loads.

A discussion about the effect of the sweep rate is provided in ECSS-E-HB-32-26, clauses 5.2.3.3 and 5.2.6.5. While a lower sweep rate provides a better characterisation of the dynamic behaviour and usually allows a better shaker control, the fatigue effects on the test article need to be taken into account. A lower sweep rate leads to a longer test and more load cycles applied on the test article.

5.3 Acceptance test requirements

a. The considerations described in 5.2 also apply for acceptance testing. Destructive tests or tests stressing beyond the required limits are forbidden on a Flight Model.

5.4 Protoflight test requirements

a. The considerations described in 5.2 also apply for protoflight testing.

b. Destructive tests or tests stressing beyond the required limits are forbidden on a Proto Flight Model.

5.5 Space segment equipment test programme implementation requirements

5.5.1 General tests

5.5.1.1 Functional and performance tests

The functional and performance tests on equipment level are the foundation of an overall comprehensive, complete and successful space segment equipment & element test and verification campaign. Particular focus needs to be given on performance as the space segment equipment level is the level where the performance usually can be mastered by demonstration in test. This is very often not possible or limited in later stages especially on the Space Segment element level due to many constraints as described further down.

The main concept regarding Full Functional Test (FFT), Performance Test and Reduced Functional Test (RFT) is as follows:

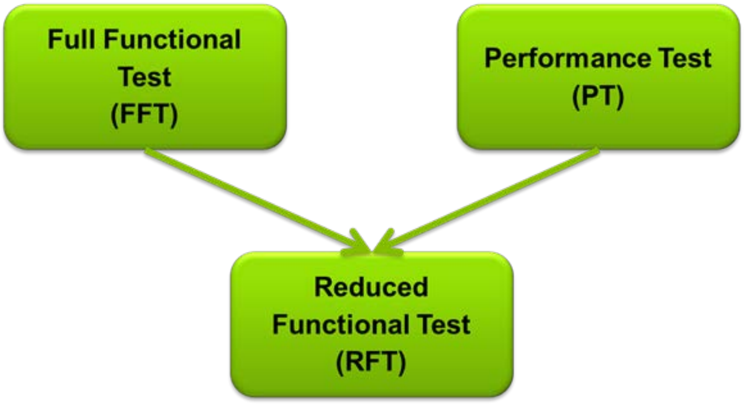


Figure 5-1: Relation between FFT, PT and RFT on equipment level

FFT rationale: The main driver for a comprehensive FFT is to demonstrate the correct functioning of the design as well as the equipment workmanship of the functions. Particular emphasis is required to check all equipment redundancies and including the checking of related operational modes. This needs to include also testing of barriers or protections (e.g. inhibited functions are inhibited if not all conditions are set correctly, like NO firing of a pyro without prior arming) and non-nominal functions like HW failure detection, isolation and recovery. The FFT, together with the PT will provide a substantial part of the equipment VCD coverage. In case of several recurring flight models, a similar concept as described for the space segment element level in section 6.5.1.2 could be applied in agreement with the customer, i.e. to limit testing on flight models concentrating on workmanship tests only after having demonstrated the functional design on the first qualification model, e.g. EQM and/or PFM.

PT rationale: The PT will check on the equipment performance, which requires usually dedicated and sophisticated ground support equipment and test instrumentation. Often performance tests require also access to internal boards or wirings. Due to these reasons, mainly equipment functions but not performance are typically tested on space segment element level. Hence, any performance testing moved from space segment equipment level to space segment element level needs to be discussed and agreed very early in the project to ensure a complete performance coverage.

RFT rationale: The Reduced Functional Test checks that the equipment has not degraded unexpectedly due to test events like environmental testing or transportation. A good test campaign set up will make use of (but is not limited to) health checks which have been defined as part of FFTs. This allows also a trend analysis of identified key equipment parameters across the whole equipment test campaigns. Note please that RFTs are expected to be conducted at least after each environmental test block like for example vibrations. This is not shown in the ECSS-E-ST-10-03C standard in Figure 5-1 Space segment equipment test sequence. Therefore, the equipment Verification or Test Plan should identify explicitly where in the sequence the RFT is executed, starting ideally with a reference test after end of integration and before shipment to or starting of the environmental testing.

The above described concepts are in general also applicable on the space segment element level, as described in section 6.5.1, respectively section 6.5.1.2.

a. Functional tests are as representative as possible of operational modes. When conditions are not testable at system level, elementary tests or analysis are provided.

b. Guidelines in 5.5.5.1 cover also performance tests.

c. No specific guidelines for this requirement.

d. No specific guidelines for this requirement.

e. A recommendation is to select the configurations such that all the interfaces are at least energized once, without testing all possible configurations for cross-strapping verification. This is a trade-off between testing time and exhaustive cross-strapping check. This allows to ensure that all interface circuits are functionally checked.

f. No specific guidelines for this requirement.

g. No specific guidelines for this requirement.

h. No specific guidelines for this requirement.

i. Overall verification of fault voltage is referenced in Table 8-3 and 4.2.4.l of ECSS-E-ST-20. When fault voltage cannot be tested beyond unit level or when tests are potentially hazardous or stressful, the corresponding functions and verification methods are identified and agreed with the customer.

j. No specific guidelines for this requirement.

k. No specific guidelines for this requirement.

l. Flasher test is the baseline. When alternate methods are proposed, it is agreed with the customer.

m. No specific guidelines for this requirement.

n. No specific guidelines for this requirement.

5.5.1.2 Humidity test

a. No specific guidelines for this requirement.

b. No specific guidelines for this requirement.

5.5.1.3 Life test

a. No specific guidelines for this requirement.

b. No specific guidelines for this requirement.

c. No specific guidelines for this requirement.

d. No specific guidelines for this requirement.

e. Life tests apply the temperature conditions expected during actual operation if the test item cannot withstand any acceleration law applicable to temperature effects. Example: If electronic boards defects have a thermomechanical root cause, the most used acceleration laws aggravate only temperature levels (Coffin-Manson law) or also temperature rates of change (Norris-Landzberg law).

f. No specific guidelines for this requirement.

g. No specific guidelines for this requirement.

5.5.1.4 Burn-in test

Burn-in test at EEE component level and at equipment level

These two types of burn-in tests are complementary. As at equipment level, a burn-in test at EEE component level is also a screening test with the objective of reducing infant mortality.

Keep in mind that a burn-in test at EEE component level has by comparison two main specificities:

- A complementary objective of screening EEE component performances drifts.
- The absence of relation to the space mission environment in terms of temperature.

NOTE The European sequences of tests at equipment level never include a burn-in test.

Guidelines concerning a burn-in test at equipment level

When after the temperature cycle the overall ON duration is lower than the specified value a burn in test at equipment level is done until the accomplishment of the specified duration.

The burn-in time is a figure agreed upon with the customer in operating conditions, taking into account the environmental conditions (temperature).

Therefore, the operating time needs to be recorded to assess that the burn-in time requirement was met, and this is reflected in the test specification and test procedure.

The total operating time cumulated during the temperature cycles of the previous thermal vacuum tests and thermal ambient tests at mission pressure can be inferior to the agreed total ON duration. In such a case, space segment equipment suppliers discuss and agree with the customer the specification of a burn-in test on QM, PFM or FM.

NOTE Operating time and ON duration are synonyms.

A burn-in test specification considers the following aspects (non-exhaustive list):

- The only objective of a burn-in test is detecting latent infant mortality defects.
- Monitoring during a burn-in test contributes to trend analysis on key parameters (see 5.1).
- A burn-in test can be a continuation of the last temperature cycling test done at equipment level.
- A burn-in test can be either temperature cycles between acceptance temperature levels or only one long duration hot plateau at the acceptance temperature level.
- In case of internal redundancy, a burn-in test concerns both nominal and redundant chains. It takes into account the type of redundancy (hot, cold…) and an equal division of the agreed total ON duration between nominal and redundant chains.
- The pass/fail criteria of a burn-in test include a failure free duration until the end of the test agreed with the customer. In case of internal redundancy, this failure free duration is equally divided between nominal and redundant chains.

5.5.2 Mechanical tests

5.5.2.1 Physical properties measurements

a. General information is available in A.2.

b. Information is available in A.2.2.

5.5.2.2 Acceleration test (static, spin or sine burst)

General information is available in Annexes A.3, A.4, A.5, A.6.

The complexity of the loads to be applied could influence the choice between possible test methods:

- traditional static test (with application of static loads)
- centrifuge test (with application of unidirectional linearly varying acceleration field)
- spin test
- sine burst test on dynamic shaker (with application of quasi-static loads)

The spin test, used as acceleration test, is very specific to equipment that are submitted to spin loads.

The difference between spin and centrifuge is that spin is a rotation around the test article own axis, while the centrifuge is a rotation around an axis that is far from the test article.

The centrifuge and sine burst tests are sometimes preferred because they are cheaper and shorter in schedule, however they have some limitations:

- for centrifuge test:
  - the centrifuge implies acceleration fields varying linearly with the radius, not always compatible with the required test loading, and imposing a limitation to the size of the test article
  - the test facility capability could impose an additional limitation to the size of the test article
  - The loading is applied in one axis and one direction only
- for sine burst test:
  - the shaker provides a stiff interface, which does not always allow to reproduce interface forces in the presence of a flexible interface in flight configuration,
  - the shaker limitations (e.g. available force)
- the loads are applied in both directions of the excitation axis (symmetric loading) which is not the case at launch in the longitudinal direction (compression loads are higher than traction loads due to the acceleration) or for re-entry loads. All elements have to sustain tension loads and this can be a problem for example for a clampband for both centrifuge and sine burst tests:
  - they are uniaxial, even if the test article might be tilted with regards to the load application direction
  - the combination with other types load (e.g. pressure and temperature) could be difficult

For all those tests, in case of test abort, the specimen can be submitted to an excitation not very well controlled and close to a shock if the test is stopped too brutally.

Static test is generally performed on the structure, rarely on equipment. The static test typically consists of several load cases which are often applied in different directions. A properly designed static test is very effective in verifying strength, as combined loads (directions and application location) can be applied. However statically simulating the launch loads (inertial loads due to acceleration) can be a real challenge. The objective is to develop load cases that envelop the combined effects of the design limit loads using a limited number of points for the loading of the structure (main interfaces, tank interface, ...) with sometimes problems of accessibility preventing to apply the loads in some directions. Due to the high energy involved in those tests (kinetic or elastic energy), it is important to consider the case of accidental unloading (e.g. failure of an actuator for static test) and unloading in case of test article failure.

a. Test fixture is carefully designed to reproduce the interface loads, in particular in case the flight configuration corresponds to a flexible interface.

b. General information is available in Annex A.5.

Be aware that centrifuge can become very destructive in case of failure, as there is no quick abort possible. If an item fails, it can ruin the complete equipment (catastrophic failure) because the applied load cannot be reduced quickly.

5.5.2.3 Random vibration test

General information about the random vibration test is provided in annex A.8.

a. Launch configuration could include connectors and a piece of representative harness, as well as mounting interface and torque. It also includes the functional configuration (ON or OFF, operating mode).

b. Cross axis excitation should be limited to a minimum and considered in the design of the test fixture. Acceptability of the cross axis excitation needs to be assessed. For further information, refer to Annex A.8.3.

c. Refer to A.8.5 for further information.

d. Changes in dynamic responses are carefully assessed, even for modes with effective mass lower than 10%, as they can indicate some degradation.

e. No specific guidelines for this requirement.

f. No specific guidelines for this requirement.

5.5.2.4 Acoustic test

General information is provided in Annex A.9.

a. Launch configuration could include connectors and a piece of representative harness, as well as mounting interface and torque. It also includes the functional configuration (ON or OFF, operating mode).

b. General information is provided in Annex A.9.3.

c. General information is provided in Annex A.9.5. Note that the minimum level depends on the controllability of the chamber.

d. Changes in dynamic responses are carefully assessed, even for modes with effective mass lower than 10%, as they can indicate some degradation.

e. No specific guidelines for this requirement.

5.5.2.5 Sinusoidal vibration test

General information is provided in Annex A.7.

a. Launch configuration could include connectors and a piece of representative harness, as well as mounting interface and torque. It also includes the functional configuration (ON or OFF, operating mode).

b. Refer to A.7.5for further information.

c. Changes in dynamic responses are carefully assessed, even for modes with effective mass lower than 10%, as they can indicate some degradation

d. No specific guidelines for this requirement.

e. Cross axis excitation should be limited to a minimum and considered in the design of the test fixture. Acceptability of the cross axis excitation needs to be assessed. For further information, refer to Annex A.7.3.

5.5.2.6 Shock test

Refer to ECSS-E-HB-32-25 clause 13.

5.5.2.7 Micro-vibration generated environment test

General information on micro-vibration generated environment test is provided in Annex A.13.1.

a. No specific guideline for this requirement.

b. No specific guideline for this requirement.

5.5.2.8 Micro-vibration susceptibility test

General information on micro-vibration susceptibility test is provided in Annex A.13.2.

a. no specific guideline for this requirement

b. no specific guideline for this requirement

5.5.3 Structural integrity tests

5.5.3.1 Leak test

General information on Leak test is provided in Annex B.2.

a. The leak test is a key test for pressurised and sealed hardware. It serves both as performance and workmanship test.

b. No specific guideline for this requirement.

c. Several methods are presented in Annex B.2.3.

d. Typical methods and their applicability are presented in Annex B.2.3.

e. The repetition of leak tests in the test sequence allows to identify possible degradation of the leak rate and to verify that the requirement is still met after environmental tests.

f. The repetition of leak tests in the test sequence allows to identify possible degradation of the leak rate and to verify that the requirement is still met after proof pressure test.

g. No specific guideline for this requirement.

h. Minimum differential pressure across a seal might correspond to the worst case for the seal performance.

5.5.3.2 Proof pressure test

General information on proof pressure test is provided in Annex B.3.

a. No specific guideline for this requirement.

b. No specific guideline for this requirement.

c. No specific guideline for this requirement.

5.5.3.3 Pressure cycling test

General information on pressure cycling test is provided in Annex B.4.

a. No specific guideline for this requirement.

b. No specific guideline for this requirement.

5.5.3.4 Design burst pressure test

General information on pressure cycling test is provided in Annex B.5.

a. No specific guideline for this requirement.

After burst pressure test, the equipment is considered as potentially damaged and not adequate for further use.

5.5.3.5 Burst test

General information on pressure cycling test is provided in Annex B.6.

a. No specific guideline for this requirement.

5.5.4 Thermal tests

By convention, a thermal test involves a temperature variation of at least one test specimen boundary from room temperature, as defined for clean rooms.

Test objectives and precipitation of latent infant mortality defects

A thermal vacuum test or a thermal ambient test at mission pressure can contribute to different testing objectives:

- Functional and performance verification allowed during required temperature plateaux and transitions in between.
- During protoflight or acceptance testing, risks mitigation of problems late discovery before the launch and of detrimental failures occurrence during the in-orbit infant mortality period.

Keep in mind about these different testing objectives:

- Functional and performance tests with continuous or regular monitoring in between have also the aim to detect pre-existing patent defects that are present at the beginning of the test.
- To reduce mission infant mortality to an acceptable level, the risk mitigation objective includes the important matter of latent defects precipitation by exposure to pressure and temperature conditions (or environmental stress screening).

Note: a patent defect is detectable. A latent defect is undetectable. At the very moment it precipitates, a latent defect becomes patent and detectable.

Reminders about the different types of defects:

- Qualification and acceptance stages can detect defects in design, materials, parts, processes and workmanship. Some design defects can escape the qualification stage.
- Each defect can be intermittent or persistent.
- Each defect can be a pre-existing patent (or detectable) defect or a latent (or undetectable) flaw in incremental growth until becoming a patent (and eventually detrimental) defect.

- Pre-existing patent defects can be defects that escape quality control and previous environmental tests.
- Pre-existing patent defects can be pressure and temperature dependent (or environment dependent) and not present at room temperature or at room pressure. For example, a quartz oscillator defect called "activity dip" is present only at a particular temperature.
- Latent defects can become patent during the ongoing and posterior environmental tests, the posterior AIV activities, the launch phase and each in-orbit or mission phase.
- Two main types of latent defects depend on temperature conditions: Arrhenius type and thermo-mechanical type.
- Arrhenius type latent defect precipitation efficiency depends on its exposure duration to a hot or cold temperature level.
- Thermo-mechanical type latent defect precipitation efficiency depends on hot and cold temperature levels, temperature rates of change during transitions and numbers of cycles.

Combined thermal tests at equipment level

A thermal vacuum test or a thermal ambient test at mission pressure can be combined with other tests such as a thermal balance test or a calibration test. For example, it is possible to add:

- A thermal balance phase during one hot plateau of a thermal vacuum test or of a thermal ambient test at mission pressure.
- A characterisation or a calibration test at intermediate temperature plateaux or during transitions between temperature plateaux, if some high level performances are temperature dependent. This is to check for example the dimensional stability, the radiometric, the optical or the RF performances.

The combined tests meet with acceptable and quantified deviation the technical constraints of each individual test:

- The most demanding tests generate the major constraints coming from the different test methods, GSEs or instrumentations.
- See hereunder the guidelines linked to requirements 5.5.4.1b and 5.5.4.1q of ECSS-E-ST-10-03.

Guidelines concerning thermal tests at equipment level

The following guidelines are only for clause 5.5.4 temperature cycling tests at equipment level of ECSS-E-ST-10-03 and concern in particular:

- The elaboration of the test profile.
- The TRP temperature drive during plateaux and transitions in between.
- The definition of the mechanical and thermal test set-up.

NOTE The guidelines of this clause 5.5.4 are self-contained in order to regroup them for end users at equipment level. A guideline can be applicable to both temperature cycling tests at equipment level and at element level. In this case clause 6.5.4 contains the same guidelines.

5.5.4.1 Guidelines to thermal vacuum test and to thermal ambient test at mission pressure

a. When temperature cycling is performed both under vacuum and under mission dependent atmospheric pressure, a single thermal test facility use is more practical and efficient. For example, missions at high altitude within the Earth atmosphere or within the Mars atmosphere or on the Mars surface are good candidates for testing in a single facility:

  - The primary pumps of some thermal test facilities have pressure control capabilities covering both space vacuum and such low pressures.
  - These thermal test facilities can use dry air, dry N_2 or CO_2.

  Be aware:

  - Verify that the chamber pressure pumping capability is in the range of interest.
  - Make sure that the pressure sensors cover the expected pressure range.
  - Verify that the shroud cooling capability can cope with additional heat loads by gaseous conduction or convection coming from the vacuum chamber structure at room temperature.
  - Verify that the test conditions do not present risks of ice-forming on the external side of the chamber structure.
  - If the test is done in different facilities, try to use the same test set-up for testing coherency.

b. At equipment level, a thermal vacuum test (or a thermal ambient test at mission pressure) profile can include thermal balance test phases according to the unit mechanical and thermal configuration:

  - An electronic box can have critical hot points due to important internal temperature differences (in °C). In such a case, waiting longer on a hot operational plateau in order to ensure more stringent stabilisations of internal temperatures can be sufficient.
  - For the example of a unit with internal thermal insulations inducing important temperature differences (in °C), the thermal balance test objectives generally lead to several test phases. Some plateaux (hot and cold, operational and not operational) can contribute by waiting longer in order to ensure the temperatures stabilisations success criteria. Test phases specific to the thermal balance test can contribute to the verification of the sizing temperature differences (in °C) through thermal insulations.

c. For this clause, the guidelines deal with several matters.

Temperature reference point (TRP), conductive ITP and T_{Sink}

Figure 5-2 illustrates a simple case with only one TRP, one conductive ITP and one T_{Sink}:

- If the unit external structure is uniform in temperature, one TRP, located on the unit baseplate, is sufficient to evaluate the heat exchanges with the conductive ITP and with the radiative sink. If not, the unit could need several TRP. This TRP notion is ECSS specific.
- If the unit supporting structure is uniform in temperature, one conductive ITP, located close a unique TRP on the supporting structure, is sufficient to evaluate the heat exchanged by conduction between the unit and its mechanical mounting plane. If not, the supporting structure could need several conductive ITP. In this case it makes sense to define several TRP on the unit corresponding to the conductive ITP. Each conductive ITP is close of its associated TRP.
- If, on each local surface of the unit external structure, the radiative heat exchanges with the surrounding surfaces are uniform and if the external (solar, albedo and IR planetary) absorbed radiations are uniform, one T_{Sink} is sufficient to evaluate the sum of the radiative heats absorbed by the unit. If not, the unit external structure could need several T_{Sink}.

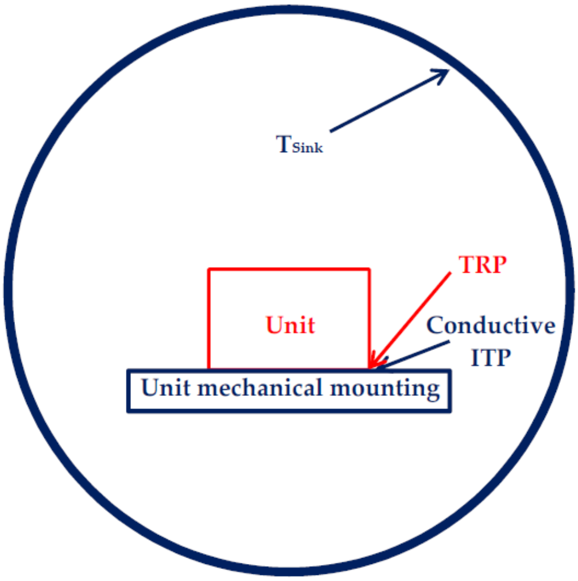


Figure 5-2: Unit TRP and Boundary Temperatures (conductive ITP and T_{Sink})

Keep in mind:

- The initial and only rationale for these notions is I/F management. The aim is insuring, thanks to a proper instrumentation, that the ground testing done at equipment level is coherent with the activities done at higher levels after equipment delivery.
- A temperature point, for TRP and for conductive ITP, allows a precise and reproducible location for each successive implementation of the associated temperature sensors.
- With its associated TRP, each conductive ITP means two temperature sensors.
- In any case, each conductive ITP means two temperature sensors in close proximity one of which on the unit external structure.
- US norms locate, on the equipment boundaries and not on the equipment external structure, the temperature requirements thanks to the conductive ITP and T_{Sink} notions.
- On the contrary, ECSS norms locate, on the equipment external structure, the temperature requirements thanks to the TRP notion.

Test Report

The test report records precisely each temperature sensor position including an exploitable photography demonstrating the proper implementations of the:

- ICD for each TRP.
- Instrumentation plan for any other measured temperature.

d. For this clause, the guidelines deal with several matters.

Definition of space segment equipment temperatures for conditions 1 to 3

As stated by the requirement 5.5.4.1d in ECSS-E-ST-10-03, the conditions 1 to 3 concern respectively the operating modes, the non-operating modes and the switch ON time. The conditions 1 to 3 refer mainly to "type a" equipment i.e. electronic, electrical and RF units, as defined for example in Table 5-1 of ECSS-E-ST-10-03.

For other than "type a" equipment, each unit ICD or user manual defines precisely each mechanical configuration, each functional mode and the temperature conditions for each transition between two mechanical configurations or between two functional modes.

For example, deployment or rotating mechanisms have different mechanical configurations and can have temperature conditions before transitions between two mechanical configurations.

For example, the functional modes of a secondary battery can be charge, trickle charge or discharge.

Operating temperature ranges can have two different meanings:

- A range in which operating the product is safe and without consequence on its intended use.
- A range in which operating the product is with mission dependent required performances.

Reaching some mission performances means:

- Either TRP limited temperature ranges. Example: optical instrument guidance with a star tracker in the control loop. In this case, the performance characterisation in these limited temperature ranges implies the associated tests implementation on additional temperature plateaux or during transitions between existing temperature plateaux.
- Or calibrations during testing. Example: detections of scientific instruments. In this case, each calibration implies specific test environmental conditions.

Obviously, it is not possible to standardise characterisation and calibration (C&C) tests. They are not part of the ECSS-E-ST-10-03 thermal tests even if their implementation is possible with a unique test configuration.

<u>Switch-on Temperature (for "Type a" Units)</u>

"Switch-on" and "start-up" are synonymous terms. As the hot switch-on temperature is always lower than the maximum operating temperature, be aware:

- The switch-on in hot conditions accounts for the fact that the unit dissipation leads to a transient increase of the unit TRP temperature. The test set-up and profile prevent the unit from exceeding the qualification limit.
- To avoid overheating risks at switch-on, it is good practice to start up the unit below the hot qualification or acceptance operating temperature.

e. If a unit TRP temperature range is [-25 °C; +55 °C], the TRP temperature control is successful if the TRP measured value is within:

    - o [+55 °C; +59 °C] during the hot plateau.
    - o [-29 °C; -25 °C] during the cold plateau.

    For temperatures above 80 K:

    - o Table 4-2 of ECSS-E-ST-10-03 requires measurement uncertainty better than ±2 K including the complete measuring chain. When needed, this uncertainty can be better.
    - o Table 4-1 of ECSS-E-St-10-03 requires [Tmin-4 K; Tmin] and [Tmax; Tmax+4 K] as the maximum allowed (peak to peak) temperature test tolerances.
    - o The TRP temperature control band is always 4 K wide.

f. This requirement does not mention explicitly the TRP. Nevertheless, it refers to the TRP. This requirement refers only to a high limit ensuring that testing is really by temperature cycles and not by temperature shocks. In the technical literature, a temperature shock is a temperature cycle with a temperature rate of change superior to values around 30 K per minute

g. For this clause, the guidelines are about dwell time and plateau total duration.

Dwell Time

During a hot or cold plateau, there can be several phases with internal temperatures stabilization. The dwell time is the sum of their durations (see Figure 5-3 and Table 5-2 or see Figure 5-4 and Table 5-3):

- An operating plateau without switch-on verification includes only one internal stabilization phase.
- An operating plateau with switch-on verification as part of functional verification includes at least two different internal stabilization phases: one in the OFF condition and one after the ON command before starting the functional tests with stabilised internal temperatures.
- The first internal stabilization phase starts simultaneously with the plateau when reaching and staying within the TRP temperature control band.
- The other internal stabilization phases (if any) start simultaneously with the OFF or ON command.

For units with a high thermal time constant, an analysis (calculation or previous experience) can estimate the dwell time. If the estimation is too uncertain, adequate test instrumentation can validate each internal stabilization phase duration.

The design team provides to the AIT team:

- Either the needed durations for each internal stabilization phase. By summation, this provides the specified dwell time.
- Or the dedicated instrumentation definition (test or flight) with the appropriate stability criteria (see guidelines about stability criteria in bullet h.).

For units with a very low thermal time constant, the needed dwell time can be inferior to the 2 hours required by this clause g. in ECSS-E-ST-10-03. In this case, the engineering team specifies the dwell time.

Plateau Total Duration

As the dwell time, the total duration of a plateau (Figure 5-5 and Figure 5-6 begins from the start of temperature stabilisation phase:

- The dwell time is only a portion of the plateau total duration.
- The test specification defines the minimum plateau total durations of a non-operating plateau and of an operating plateau.
- The step by step procedure applies these minimum durations according to different situations.
- For example, a minimum plateau total duration can be shorter than the sum of the dwell time and, if any, of the functional or performance tests duration.
- On the contrary, if reducing mission infant mortality is a test objective and if latent defects of Arrhenius type can exist, a minimum plateau total duration can be longer than the sum of the dwell time and, if any, of the functional or performance tests duration.

Note: Non-European standards, as SMC Standard SMC-S-016, use terms like "temperature soak duration" to define the total plateau duration, while other standards use similar terms to define the remaining duration after plateau activities completion. Other standards use the word "dwell" instead of "soak".

h. For this clause, the guidelines deal with several matters.

Test Profile and Tests done at Room Conditions

Test profiles (see 2 examples in Figure 5-3 and Figure 5-4) also include the functional and performance tests done at room conditions, as defined for clean rooms.

These tests are not part of a thermal vacuum test or a thermal ambient test at mission pressure that involves a boundary temperature different than the room temperature. They are checks done just before and after the temperature cycles.

Integration stages and testing at equipment level

Some equipment can undergo some testing at intermediate integration stages before the full integration stage. The two following examples are the most common ones:

- Example 1: some equipment subassemblies, separated by thermal insulations, can have important temperature differences (in °C) between them and very different qualification and acceptance temperature ranges between one subassembly and the other.
- Example 2: structural frames equipped with a functional electronic board and its electrical connections.

Upon program decision, qualification, protoflight or acceptance testing at equipment level can happen at some of these intermediate integration stages:

- Example 1: some subassemblies can undergo testing under their required large temperature ranges, and then extra-testing under much less severe temperature ranges allowable by the test item at the full integration stage. Such extra-testing induces negligible over-testing.
- Example 2: if a third party delivers a functional frame to another integration stage, thermal tests done by the third party are an option to consider and are becoming a common practice.

Test Profile for Combined Cycles (at mission dependent atmospheric pressure and under vacuum)

The test specification tailors the following practical guidelines:

- The cycles under vacuum take place before the cycles at mission dependent atmospheric pressure.
- For "type a" units, the first cycle under vacuum and the first cycle at mission dependent atmospheric pressure include a hot and a cold non-operating plateau and, if applicable, a cold switch-on plateau.
- The minimum number of cycles at mission dependent atmospheric pressure is half of the total number of cycles.

Example of good practice : the number of qualification cycles during equipment level testing is the required number (8) because:

- 2 cycles done under vacuum.
- 8 – 2 = 6 cycles (≥ 8/2) done under mission dependent atmospheric pressure.

Test Profile for "Type a" Equipment (Electronic, Electrical and RF Units)

The test specification defines the functional tests and the performance tests to be done during the plateaux. This specification reconciles the different implementation practices of suppliers and customers, by answering the following questions:

- Is the unit mission only under vacuum?

- If not, what are the cycles to be done at mission dependent atmospheric pressure?
- How many cycles under vacuum after first integration stages (if any) have been done before the unit fully integration?
- How many cycles at mission dependent pressure after first integration stages (if any) have been done before the unit fully integration?
- What are the plateaux and the transitions with functional tests?
- What are the plateaux and the transitions with performance tests?
- What are the plateaux with a hot start?
- What are the plateaux with a cold start?
- Is the unit switched off during transitions to cold operating plateaux?
- Is the unit switched off during transitions to hot operating plateaux?

Example n° 1 (Figure 5-3, Table 5-1 and Table 5-2):

- o Mission only under vacuum: yes.
- o Cycles at mission dependent atmospheric pressure: not applicable.
- o Minimum number of previous cycles after first integration stages: none.
- o Functional tests: hot and cold operating plateaux of first and last cycles with a dynamic and specific functional test during the two transitions of the last cycle.
- o Performance tests: hot and cold operating plateaux of first and last cycles.
- o Hot starts at operating temperature: one during hot operating plateau of first cycle.
- o Cold starts at operating temperature: none.
- o Cold starts at minimum switch-on temperature: one during first cycle.
- o Transitions to cold operating plateaux: no switch-off (no dissipative unit).
- o Transitions to hot operating plateaux: no switch-off.

Example n° 2 (Figure 5-4, Table 5-1 and Table 5-3):

- o Mission only under vacuum: yes.
- o Cycles at mission dependent atmospheric pressure: not applicable.
- o Minimum number of previous cycles after first integration stages: none.
- o Functional tests: hot and cold operating plateaux of each cycle and cold switch-on plateau of first cycle.
- o Performance tests: hot and cold operating plateaux of first and last cycles.
- o Hot starts at operating temperature: two during hot operating plateau of first and last cycles.
- o Cold starts at operating temperature: one during cold operating plateau of last cycle.
- o Cold starts at minimum switch-on temperature: one during first cycle.
- o Transitions to cold operating plateaux: switch-off at each transition (dissipative unit).
- o Transitions to hot operating plateaux: no switch-off.

<u>Test Profile for other than "Type a" Equipment</u>

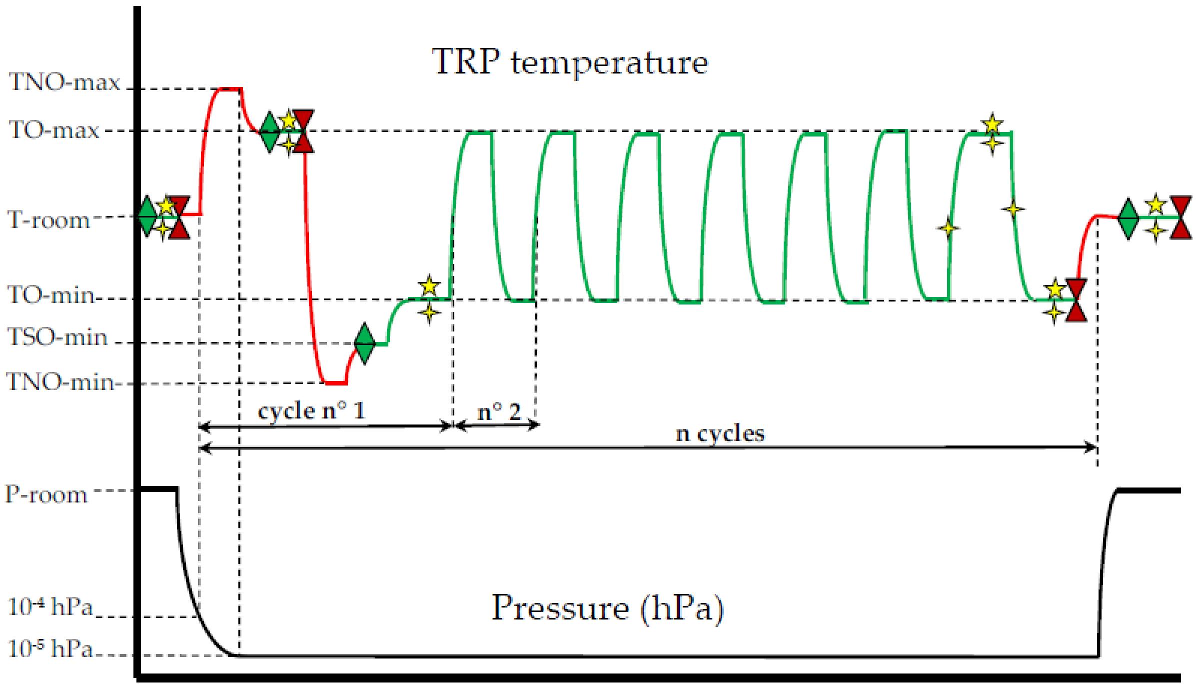
For each (mechanical and electrical) mode and transition in between, the test specification defines:

- If applicable, the functional and performance tests to be performed during the hot and cold plateaux and during the transitions in between.

- The temperature cycling specific nomenclature (as in Table 5-1) and practical implementation, as for "type a" units.

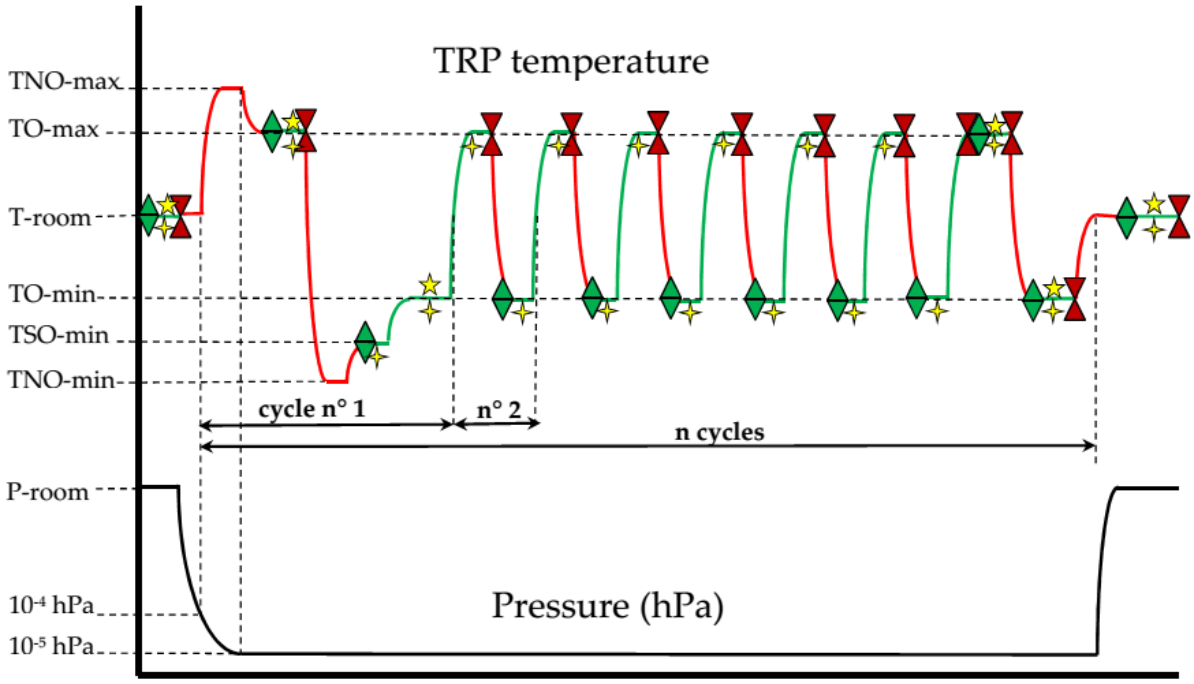
Table 5-1: Nomenclature for temperature cycling implementation on "type a" units

T	TRP temperature
TNO-max	Maximum Non-Operating temperature at TRP*
TNO-min	Minimum Non-Operating temperature at TRP*
TO-max	Maximum Operating temperature at TRP*
TO-min	Minimum Operating temperature at TRP*
TSO-min	Minimum Switch-On temperature at TRP*
T-room	Room temperature at TRP (around +22 °C)
P	**Pressure**
P-room	Room pressure (around 1013 hPa)
✧	Functional tests done during temperature cycling
☆	Performance tests done during temperature cycling
◆	Switch-on
⧗	Switch-off
(*) According to "qualification temperature range" or "acceptance temperature range" standardised terms definitions	



Number of cycles: n = 8 for qualification and n = 4 for proto-qualification and acceptance

Figure 5-3: Thermal vacuum test profile (example n° 1 for "type a" units)



Number of cycles: n = 8 for qualification and n = 4 for proto-qualification and acceptance

Figure 5-4: Thermal vacuum test profile (example n° 2 for "type a" units)

Table 5-2: Thermal vacuum step by step procedure (example n° 1 for "type a" units)

1	Functional and performance tests under room (pressure and temperature) conditions
2	Unit switch-off
3	Decrease pressure (success criteria: $P \leq 10^{-5}$ hPa)
4	If $P \leq 10^{-4}$ hPa, increase of TRP temperatures to maximum non-operating level (TNO-max)
5	Temperatures stabilisation (including internal temperatures)[a, b]
6	Hot non-operating plateau total duration (TBD hours)
7	Decrease of TRP temperatures to maximum operating level (TO-max)
8	Temperatures stabilisation (including internal temperatures)[a]
9	Unit switch-on and temperatures stabilisation (including internal temperatures)[a, b]
10	Functional and performance tests (including power consumption)
11	Hot operating plateau total duration (TBD hours) and unit switch-off
12	Decrease of TRP temperatures to minimum non-operating level (TNO-min)
13	Temperatures stabilisation (including internal temperatures)[a, b]
14	Cold non-operating plateau total duration (TBD hours)
15	Increase of TRP temperatures to minimum switch-on level (TSO-min)
16	Temperatures stabilisation (including internal temperatures)[a]
17	Unit switch-on and temperatures stabilisation (including internal temperatures)[a, b]
18	Cold switch-on plateau total duration (TBD hours)
19	Increase of TRP temperatures to minimum operating level (TO-min)
20	Temperatures stabilisation (including internal temperatures)[a, b]
21	Functional and performance tests (including power consumption)
22	Cold operating plateau total duration (TBD hours)
23	Increase of TRP temperatures to maximum operating level (TO-max)
24	Temperatures stabilisation (including internal temperatures)[a, b]
25	Hot operating plateau total duration (TBD hours)
26	Decrease of TRP temperatures to minimum operating level (TO-min)
27	Temperatures stabilisation (including internal temperatures)[a, b]
28	Cold operating plateau total duration (TBD hours)
29	Repeat steps 23, 24, 25, 26, 27 and 28: five times for Qualification test (to achieve n=8) one time for Proto qualification test (to achieve n=4) one time for Acceptance test (to achieve n=4)
30	Increase of TRP temperatures to maximum operating level (TO-max)
31	Dynamic and specific functional test during the whole transition
32	Temperatures stabilisation (including internal temperatures)[a, b]
33	Functional and performance tests (including power consumption)
34	Hot operating plateau total duration (TBD hours)

35	Decrease of TRP temperatures to minimum operating level (TO-min)
36	Dynamic and specific functional test during the whole transition
37	Temperatures stabilisation (including internal temperatures)[a, b]
38	Functional and performance tests (including power consumption)
39	Cold operating plateau total duration (TBD hours)
40	Unit switch-off and increase of temperature to room temperature
41	Increase of pressure to room pressure and unit switch-on
42	Functional and performance tests under room (pressure and temperature) conditions
43	Unit switch-off
(a) the test specification gives internal temperatures stabilisation criteria in °C per hour (see guidelines about stability criteria in 5.5.4.1h.) (b) before going to next step and if the sum of the plateau stabilisation phases durations is inferior to the minimum 2h dwell time required by ECSS-E-ST-10-03, wait until 2h dwell time (see guidelines about dwell time in 5.5.4.1g.)	

Table 5-3: Thermal vacuum step by step procedure (example n° 2 for "type a" units)

1	Functional and performance tests under room (pressure and temperature) conditions
2	Unit switch-off
3	Decrease pressure (success criteria: $P \leq 10^{-5}$ hPa)
4	If $P \leq 10^{-4}$ hPa, increase of TRP temperatures to maximum non-operating level (TNO-max)
5	Temperatures stabilisation (including internal temperatures)[a, b]
6	Hot non-operating plateau total duration (TBD hours)
7	Decrease of TRP temperatures to maximum operating level (TO-max)
8	Temperatures stabilisation (including internal temperatures)[a]
9	Unit switch-on and temperatures stabilisation (including internal temperatures)[a, b]
10	Functional and performance tests (including power consumption)
11	Hot operating plateau total duration (TBD hours) and unit switch-off
12	Decrease of TRP temperatures to minimum non-operating level (TNO-min)
13	Temperatures stabilisation (including internal temperatures)[a, b]
14	Cold non-operating plateau total duration (TBD hours)
15	Increase of TRP temperatures to minimum switch-on level (TSO-min)
16	Temperatures stabilisation (including internal temperatures)[a]
17	Unit switch-on and temperatures stabilisation (including internal temperatures)[a, b]
18	Functional tests and cold switch-on plateau total duration (TBD hours)
19	Increase of TRP temperatures to minimum operating level (TO-min)
20	Temperatures stabilisation (including internal temperatures)[a, b]
21	Functional and performance tests (including power consumption)
22	Cold operating plateau total duration (TBD hours)

23	Increase of TRP temperatures to maximum operating level (TO-max)
24	Temperatures stabilisation (including internal temperatures)[a, b]
25	Functional tests, hot operating plateau total duration (TBD hours) and unit switch-off
26	Decrease of TRP temperatures to minimum operating level (TO-min)
27	Temperatures stabilisation (including internal temperatures)[a]
28	Unit switch-on and temperatures stabilisation (including internal temperatures)[a, b]
29	Functional tests and cold switch-on plateau total duration (TBD hours)
30	Repeat steps 23, 24, 25, 26, 27, 28 and 29: five times for Qualification test (to achieve n=8) one time for Protoqualification test (to achieve n=4) one time for Acceptance test (to achieve n=4)
31	Increase of TRP temperatures to maximum operating level (TO-max)
32	Temperatures stabilisation (including internal temperatures)[a]
33	Unit switch-off and temperatures stabilisation (including internal temperatures)[a]
34	Unit switch-on and temperatures stabilisation (including internal temperatures)[a, b]
35	Functional and performance tests (including power consumption)
36	Hot operating plateau total duration (TBD hours) and unit switch-off
37	Decrease of TRP temperatures to minimum operating level (TO-min)
38	Temperatures stabilisation (including internal temperatures)[a]
39	Unit switch-on and temperatures stabilisation (including internal temperatures)[a, b]
40	Functional and performance tests (including power consumption)
41	Cold operating plateau total duration (TBD hours)
42	Unit switch-off and increase of temperature to room temperature
43	Increase of pressure to room pressure and unit switch-on
44	Functional and performance tests under room (pressure and temperature) conditions
45	Unit switch-off
(a) the test specification gives internal temperatures stabilisation criteria in °C per hour (see guidelines about stability criteria in 5.5.4.1h.) (b) before going to next step and if the sum of the plateau stabilisation phases durations is inferior to the minimum 2 hours dwell time required by ECSS-E-ST-10-03, wait until 2 hours dwell time (see guidelines about dwell time in 5.5.4.1g.).	

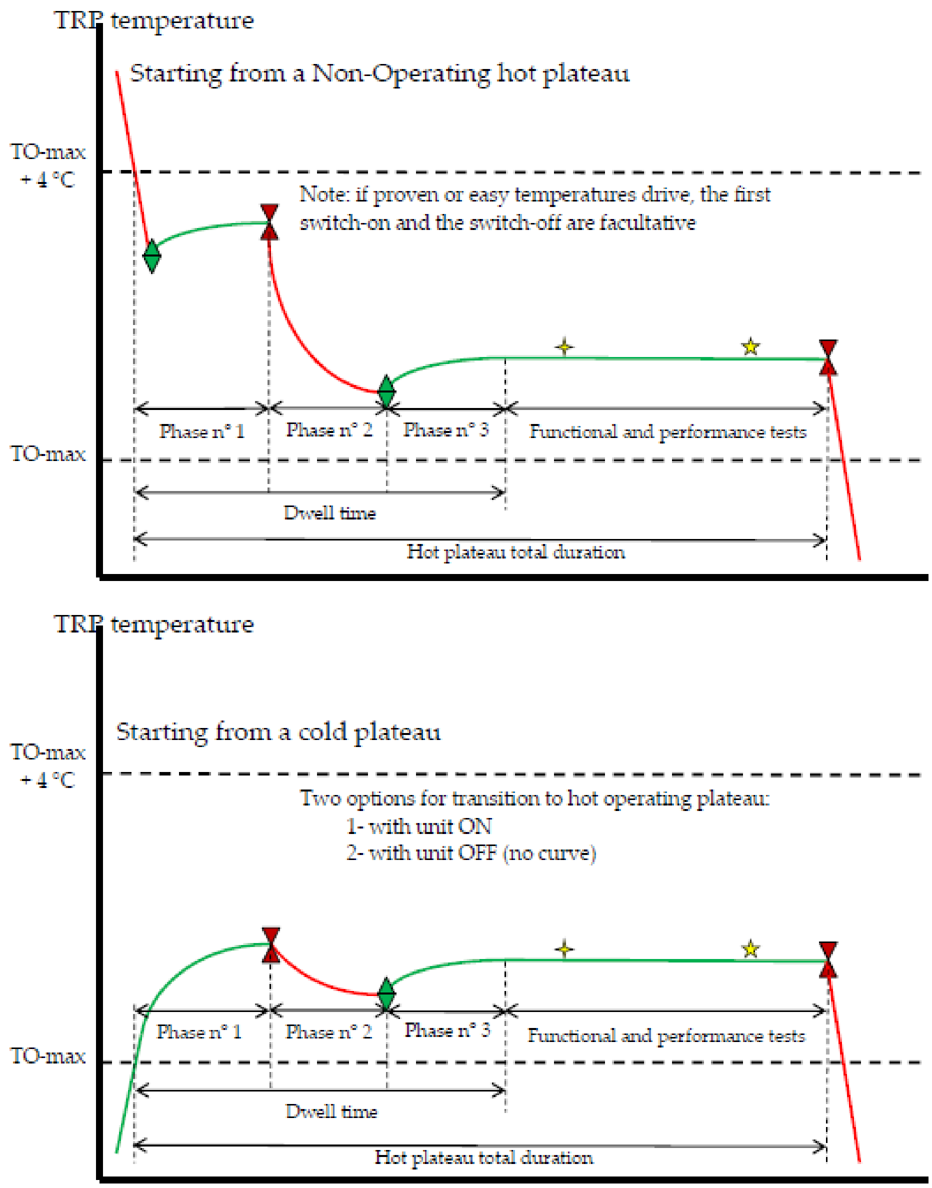


Figure 5-5: Hot plateau TRP temperatures drive (including "type a" units switch-on)

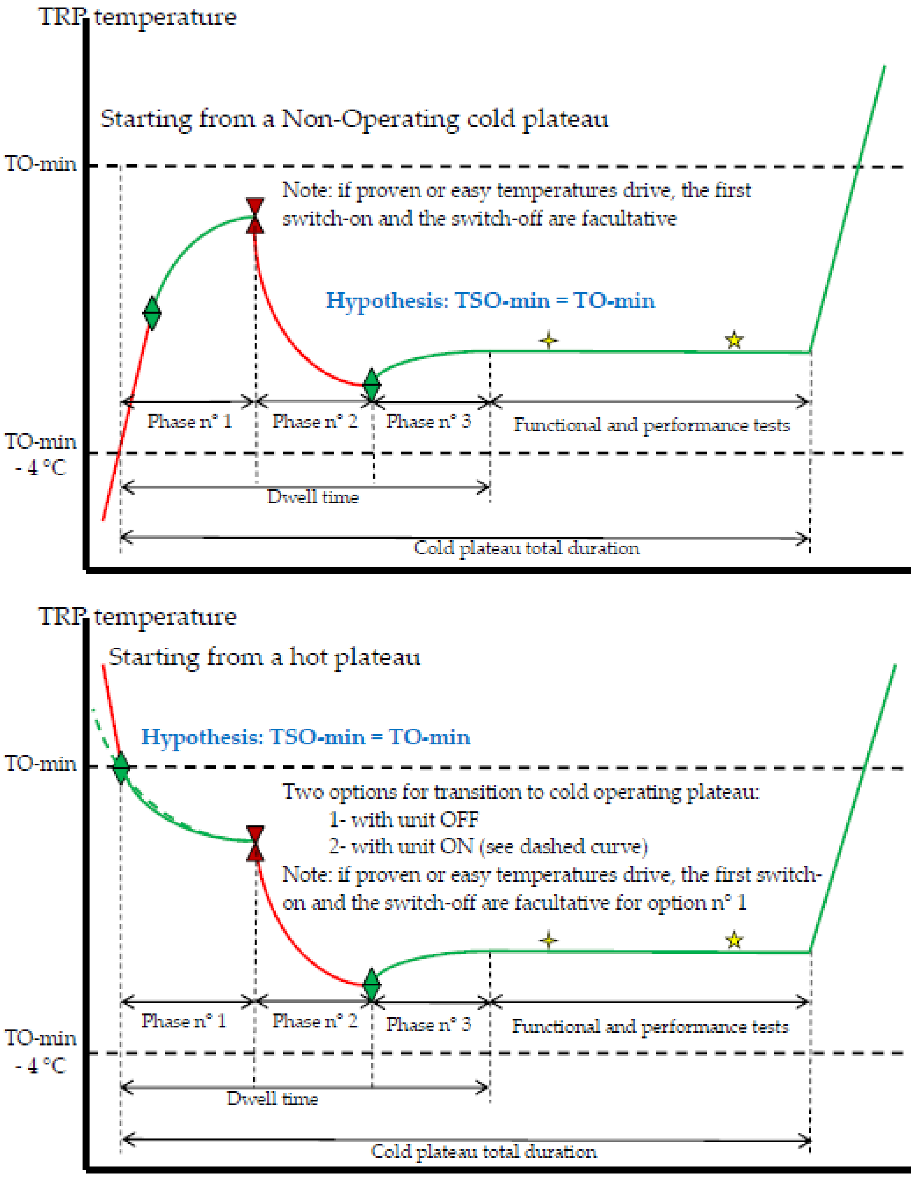


Figure 5-6: Cold plateau TRP temperatures drive (including "type a" units switch-on)

Temperature rate of change

The following considerations drive the TRP temperature rate of change:

- Screening efficiency to precipitate latent defects: the higher the rate, the more effective the screening.
- Duration of the test: the higher the rate, the quicker the transitions.
- Test article integrity: the higher the rate, the higher the thermo-elastic stresses.
- Representativeness of mission conditions.

From experience, the temperature rate of change has a wide range of values:

- A value greater than 3 K or 5 K per minute is commonly obtained.
- For heavy units, the rate of change can be limited to 1 K per minute due to high heat capacity.

- For specific mission like Messenger, the solar panels temperature rate of change was greater than 100 K per minute. Exceptional cases like this implies temperature shocks and are deviations from a requirement concerning temperature cycles.
- At the time of transition to cold plateaux, a dissipative unit is often switched off to speed up its cool down.

Following a compromise integrating the four above considerations, the test specification requires the more appropriate ranges of TRP temperature rates of change.

Stability Criteria

For each phase requiring internal temperatures stabilization (see guidelines about dwell time in 5.5.4.1g.), the stability criteria are fulfilled if:

- The TRP temperatures remain within the required temperature control bands.
- The unit internal temperatures stabilisation meets the test specification requirements (typically, ≤ 1 °C per hour).

Keep in mind to avoid confusion:

- The switch-on verification begins only after the OFF unit internal temperatures stabilisation.
- The TRP temperature stabilization does not mean internal temperatures stabilization.
- These temperature stabilisation criteria are different of the thermal balance test ones (see ECSS-E-ST-31).

TRP Temperatures Drive during a Cycle

Some situations are not favourable:

- Radiative test plates or shrouds are particularly ineffective to drive the TRP temperatures.
- Units with high dissipations, large temperature differences or large thermal time constants are difficult to drive in temperature.

In such situations, proceeding by "trial and error" during the first cycle is the best way to both:

- Better drive the TRP temperatures during the subsequent cycles, and
- Significantly reduce the test total duration.

TRP Temperatures Drive (on a plateau including hot or cold switch-on verifications)

Figure 5-5 and Figure 5-6 displays some examples of such plateaux. They assume that the functional and performance tests duration is sufficient to meet the required plateau total durations.

The adopted strategy maintains the TRP temperature inside its control band (i.e. tolerance band) during the plateau full duration thanks to:

- Adjustments of the test specimen boundary parameters.
- Sufficient TRP temperature control authority even during switch-off and switch-on.

Test Report

The test report records and discusses with regard to the test specification:

- The realised test profile, test configuration and number of cycles.
- The performed functional and performance tests with each test duration and success status.
- The measured temperatures and temperature stabilities for each TRP and for each critical internal point.
- The measured dwell time and plateau total duration on each plateau.
- The temperature rates of change during each transition between plateaux.

To help the assessment, the report visualises time dependent plots of measured data, zooming in on critical areas of:

- The temperatures including TRP rates of change and internal temperature rates of change.
- The dwell time and internal temperature stabilities.

Test Mechanical and Thermal Configuration (for a mission at low pressure)

Gaseous conduction or (natural, mixed or forced) convection can have significant adverse thermal effects. A vacuum facility with pressure control (with dry air, dry N_2 or CO_2) can be sufficiently mission representative. In order to demonstrate this, the test specification assesses carefully differences between mission and ground tests conditions such as:

- The atmosphere composition particularly for gaseous conduction through internal thin layers. For example, dry N_2 can replace Mars CO_2 to avoid frost during cold plateaux.
- The gravity if there is natural convection. For examples, there is no gravity within a space station or only 38% of Earth gravity at Mars surface.
- No wind simulation during cold plateaux particularly for forced convection. For examples, winds at high altitude within Earth atmosphere or at Mars surface.

Test Mechanical and Thermal Configuration (for a simple unit)

Figure 5-2 illustrates a very common set-up in a vacuum facility:

- For units purely or partially controlled in flight by thermal conduction (see Figure 5-8), the mechanical mounting on the temperature controlled support is flight representative (contact area/pressure, bolt size/torque). Supplier and customer define and agree on:
  - The mounting H/W (including filler if any) in the unit ICD.
  - The mounting procedure in the test specification.
- For units purely or partially controlled in flight by thermal radiation (see Figure 5-8) and if the unit housing skin is not thermally insulated during the test, common practices are:
  - The temperature controlled support is black coated (except for contact areas).
  - The chamber shrouds (if any) are black coated.

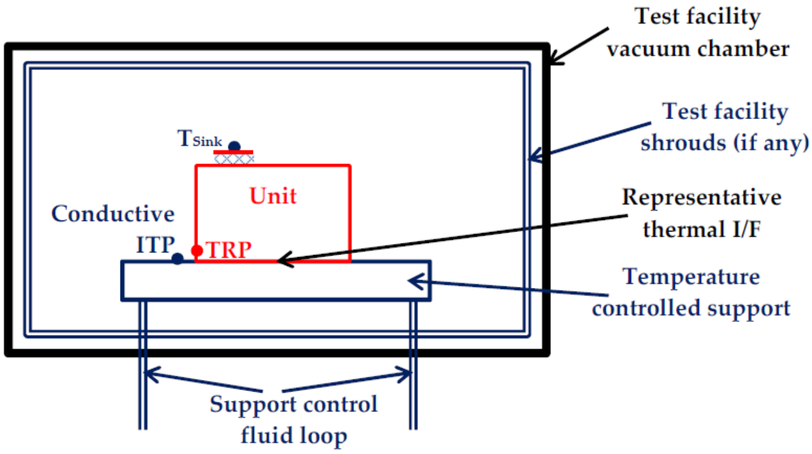


Figure 5-7: Unit temperature cycling mechanical and thermal configuration

<u>Unit Flight Accommodation (for a mission under space vacuum)</u>

The following guidelines are for the engineering teams that require the thermal test configuration:

- In the unit technical specification if done by the customer.
- And in the supplier test specification.

Figure 5-8 illustrates common S/C unit internal accommodations, with indication of the predominant cooling mode of a unit housing. The unit customer, in general the S/C, selects the cooling mode in order to simplify the unit supplier thermal analyses and tests:

- "Pure" cooling mode at supplier level means "predominant" at customer level.
- "Mixed" cooling mode at supplier level means "no predominant" at customer level.

In terms of cooling modes, any unit under space vacuum falls necessarily into one of the following categories: "conductive", "radiative" or "mixed".

The selected criterion to determine the predominant cooling mode is the conductive ratio:

- This ratio considers all heat transfers through all unit boundaries (housing…).
- It is the ratio of the heat transfer by thermal conduction to the sum of all heat transfers.
- In practice, a value around 70% is common. Then, a unit is conductive if the conductive ratio is ≥70%, radiative if ≤30% and mixed if between 30% and 70%.
- If the ratio is not obvious, mathematical modelling or at best test can help to estimate it.
- For multiple missions or off-the-shelf units, the validity of existing thermal analyses and tests requires an explicit agreement between the customer and the supplier.

Figure 5-8 excludes cooling by thermal convection and accomodation of externally mounted units.

For internally mounted units, Figure 5-8 does not address heat transfers among structures, harnesses and units which can induce adverse and cumulative thermal conditions:

- Hot internal units radiating towards other units.
- Closing plates, harnesses and connectors lowering the radiative cooling.
- Masking by internal MLI or big harnesses decreasing the radiative cooling.
- Long distances, poor thermal contacts or poor material thermal conductivity reducing the conductive cooling.

The customer manages such adverse conditions at its level. It takes care of the additional heat coming from other units. And it specifies to the supplier a unit without cooling or heating by radiation hence simplifying the unit level thermal analyses and tests.

Flight or Test Mechanical and Thermal Configuration with Radiative Calorimeters

Figure 5-7 and Figure 5-8 show radiative calorimeters to measure radiative sink temperatures:

- In Figure 5-7, the calorimeter, located on the unit housing, measures a test radiative sink temperature. As the test facility shrouds are not perfect black bodies, this temperature can be rather different than the temperature of the shrouds.
- In Figure 5-8, the calorimeter, located on a radiator, measures a flight external radiative sink temperature.

A radiative calorimeter is a small surface absorbing and reflecting as its location zone the heat radiation coming from all surrounding surfaces or heat sources. Hence, a calorimeter measures the radiative sink temperature of its location zone thanks to:

- Very low heat transfers between the calorimeter and the zone.
- A calorimeter surface finish identical to the surface finish of the zone.

Unit Thermal Management during Testing (Figure 5-7**)**

For units controlled by "pure" thermal conduction (C type units in Figure 5-8), the temperature controlled support drives the unit TRP temperature.

Unit mechanical mounting is flight representative. To make negligible the radiative heat transfer between the chamber shrouds and the unit housing, the chamber shrouds (if any) can be:

- At the same temperature than the temperature controlled support if the unit housing is uniform in temperature.
- At the unit housing radiatively averaged temperature if not uniform in temperature.
- At room temperature if the unit housing is insulated with MLI.

For example, a dissipative unit, mounted on a S/C radiator panel (see Figure 5-8 lower right within the P/F main module), is typically a unit controlled by "pure" thermal conduction.

For units controlled by "pure" thermal radiation (R type units in Figure 5-8), the TRP temperature drive can use:

- Only the temperature controlled support if the unit housing is thermally insulated from the chamber shrouds. Then, the unit is in good thermal contact (as opposed to flight condition) with the temperature controlled support.
- Only the chamber shrouds if the unit is conductively insulated from the temperature controlled support (if present). Supported by thermal analyses, the design team can use one or several shroud zones at different temperatures to impose the relevant radiative sink temperatures around the unit under test.
- Both the temperature controlled support and the chamber shrouds. Supported by thermal analyses, the design team can also use one or several shroud zones at different temperatures to impose the relevant radiative sink temperatures around the unit under test. If the chamber is not able to provide independent shroud zones when the two last options need them, the test configuration can use dedicated GSEs, like IR panels.

For example, a unit mounted internally with highly insulating mechanical fixations (see Figure 5-8) is typically a unit controlled by "pure" thermal radiation.

For units controlled by "pure" thermal radiation, it is common practice to use the temperature controlled support to drive the TRP temperature of the unit under test.

This practice presents advantages with regard to a radiative control with shrouds. It offers an easy way of maintaining the 4 °C TRP temperature control bands. It also allows a much faster temperature transition between the plateaux.

However, this practice works if:

- The unit housing is uniform in temperature (typically, $\Delta T_{max} \leq 5$ °C).
- Or if the unit housing temperature differences are compatible with the required test levels.

During a hot plateau, the unit housing temperature changes induced by different dissipative electrical modes under testing need a validation by thermal analyses comparing the flight and test calculations.

For units controlled by "mixed" thermal conduction and radiation ("m" type units in Figure 5-8), the temperature controlled support (always) and the chamber shrouds (to less extent and not always) contribute to the unit TRPs temperature drive:

- The unit mechanical mounting on the temperature controlled support is flight representative.
- The unit housing can be totally covered by MLI if absence or no use of chamber shrouds.
- Or, on the contrary, the design team, supported by thermal analyses, can use one or several shroud zones at different temperatures to impose the relevant radiative sink temperatures around the unit under test. If the chamber is not able to provide independent shroud zones, the test configuration can use decicated GSEs, like IR panels.

For example, two units accommodated under the P/F ceiling (see Figure 5-8) are units controlled by "mixed" thermal conduction and radiation.

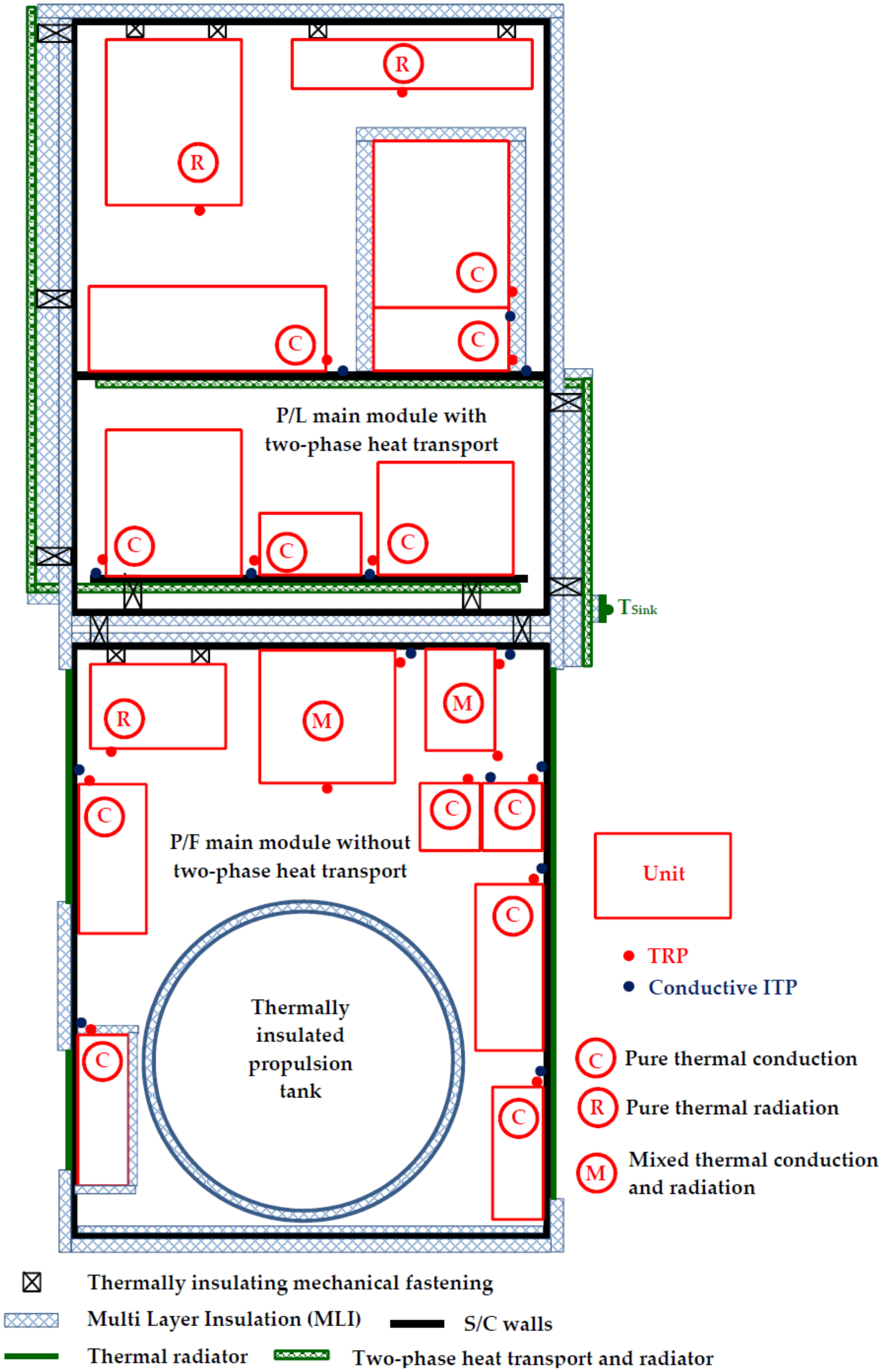


Figure 5-8: Some common examples of equipment flight accomodation

Test Mechanical and Thermal Configuration (for Complex Units)

For thermally complex units, the test specification defines the dedicated and just necessary test GSEs. For example:

- A stellar sensor has subassemblies separated by thermal insulations. Such subassemblies are an optical baffle, optical lenses, a cold detector and a front end electronic board. A stellar sensor test uses a temperature controlled support and can use several IR panels.
- A mechanism with two TRP (for example, one for the stationary part and one for the rotating part) needs, on either side of a gear or a bearing, a temperature difference control.

Overall Test Configuration

- The test specification defines, as necessary and if applicable, all the other aspects of the test configuration (electrical, optical, RF, monitoring, safety…) including testing constraints like material outgassing or offgassing, cleanliness, bio contamination, bake-out, purging, cleaning, venting, grounding (including test MLI), DC and RF corona, multipactor…
- The test report and the inspection reports, written before and after the test, keep a precise record of the overall test configuration including an exploitable photography file.

i. Strictly speaking, the non-operating cycle is not a full-off cycle:
   - In fact, the requirement is to have two non-operating plateaux at extreme temperatures.
   - The more common test profile (see Figure 5-3 and Figure 5-4) aims to reduce the total test duration. To do this, the first cycle includes five temperature plateaux (hot non-operating, hot operating, cold non-operating, minimum switch-on and cold operating). Transitions between plateaux are mainly in OFF mode.
   - With such a test profile, the first cycle counts as one non-operating cycle and as one operating cycle. This first operating cycle includes only two operating plateaux at extreme temperatures with transitions in between in OFF mode.
   - To monitor more frequently the unit behaviour during the first cycle is a good practice (see 5.5.4.1s.).

j. No guidelines (clause specific to functional tests before and after temperature cycling tests).

k. For this clause, the guidelines deal with several matters.

Functional and Performance Tests during Transitions

To run functional and performance tests during transitions between plateaux can be of paramount importance:

- To run functional and performance tests during transitions and to monitor the unit during transitions (see guidelines in 5.5.4.1s.) are two different needs.
- Many units can need tests during transitions. In particular, it is always the case for the active TCS units (fluid loops, cryogenic coolers…) and for units with an internal active TCS.

Functional and Performance Tests for Active TCS

For units including an internal active TCS using temperature sensors, mechanical thermostats, heating lines, thermoelectric coolers or any other active thermal control devices:

- The test specification defines the active TCS functional and performance tests and their occurrences on the temperature cycling test profile.
- Some functional and performance tests require dedicated temperature levels during transitions between hot and cold plateaux.

l. Bullets 5.5.4.1d and 5.5.4.1h. cover switch-on topics.

m. No specific guidelines for this requirement.

n. A recommendation is to select the configurations such that all the interfaces are at least energized once, without testing all possible configurations for cross-strapping verification. This is a trade-off between testing time and exhaustive cross-strapping check. This allows to ensure that all interface circuits are functionally checked.

o. No specific guidelines for this requirement.

p. This clause is only about DC corona. If voltage ≥ 100 V, refer to ECSS-E-HB-20-05 guidelines about high voltage effects and risks. To gain insights about DC and RF corona monitoring and testing at equipment level, refer to clause 5.5.5.6.

q. For this clause, the guidelines deal with several matters about test set-up representativeness. As already seen in the guidelines to 5.5.4.1h the test set-up can be simple or complex with advantages and drawbacks in terms of test implementation and cost.

Test Set-up Representativeness (as illustred by two different examples)

Figure 5-9 shows a unit mounted:

- In the test set-up, on a temperature controlled support with both high heat removal capability and high temperature control authority (thanks to a fluid loop).
- In flight accommodation, on a thermal doubler with limited heat spreading capability.

Comparing flight and test, unit TRPs temperatures and subassemblies temperatures near the thermal doubler can be quite different due to the test set-up lack of representativeness as shown by the two following examples. If temperature cycles on some subassemblies after their integration stages and before the temperature cycles after the full integration stage, the test specification defines the test temperature levels taking into account these temperature differences calculated in flight conditions.

Example n° 1: When a dissipative unit works in static conditions, this test set-up tends to homogenise the temperatures and interface heat flow rate densities on the baseplate. Consequently, it homogenises the inside temperatures of the unit (in particular for central subassemblies). In this example and without compensation of these flight and test differences, the test set-up tends to undertest the unit.

Example n° 2: A secondary battery works in cyclic electrical conditions (i.e. charge, trickle charge and discharge). Electrochemical cells dissipate heat mainly during discharge. A dedicated S/C radiator cools the cells through the battery baseplate. In flight, the baseplate temperature follows the temperature fluctuations of the S/C radiator. During the test, while mounted on the temperature controlled support, the baseplate temperature is constant. Under cyclic electrical conditions, the test set-up tends both to reduce the maximum cell temperature levels and to increase the temperature differences between the top of the cells and the base plate. In this example and without compensation of these flight and test differences, the test set-up tends both to undertest and to overtest the secondary battery.

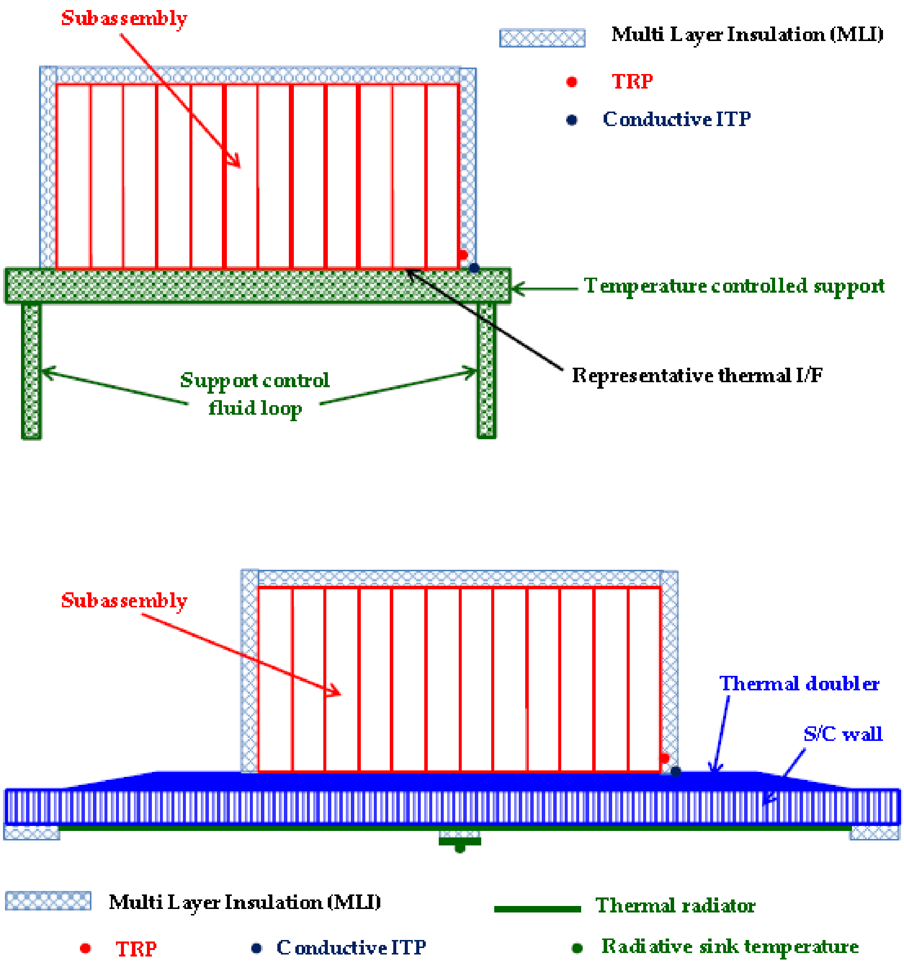


Figure 5-9: Temperature controlled support and test set-up representativeness

<u>**Example - Effect of Residual Pressure on Thruster Thermal Behaviour**</u>

In this example, one test condition, not flight fully representative, can degrade nominal thruster operation. The developments of S/C thrusters and of their thermal mathematical models consider only space vacuum conditions. Nevertheless, a residual low pressure, around 1 hPa, exists in facilities dedicated to thruster firing tests. This residual pressure, a potential source of gaseous conduction, can have significant effects on the thruster internal temperatures:

- It homogenises the combustion chamber temperatures inducing an overheating or undercooling depending on the location.
- The combustion chamber can transfer more heat to the propellant capillary tube hence increasing its temperature.
- A little overheat on a so thin tube can induce an anomalous phenomenon such as a vapour lock or a thermal choke.

Heat transfer within gases at very low residual pressure exhibits peculiar properties:

- A gas layer can be thin enough to prevent free convection start-up and can be thick enough to reach the conduction viscous regime.

- Heat transfer by gaseous viscous conduction is invariant over a large pressure range (typically from ≈1 hPa to 1013 hPa). This is due to the fact that the thermal conductivities of gases are independent of the pressure over such pressure ranges.

Test Methods and Test Set-up for a unit with sbassemblies separated by thermal insulations

A unit can have several subassemblies separated by thermal insulations (see example 1 about integration stages in 5.5.4.1h.) and with important temperature differences (in °C) between them. For example, a star tracker encompasses an optical baffle, optical lenses, a detector and front end electronics.

The test specification and the test instrumentation plan make provision of:

- Additional test instrumentation (temperature sensors, IR thermography...) to monitor hot or critical areas located inside or outside the unit.
- Dedicated test hardware and GSEs with the following objectives:
    - To efficiently drive the temperatures of the TRPs, of each subassembly, either by cooling or heating.
    - To place in front of each test specimen external surface the corresponding radiative sink temperature.
    - To simulate the solar incident heat flow rate densities thanks to the calibrated artificial Sun of the test facility (if any).
    - To control the interface heat flow rates with the test hardware. For example, with conductive or radiative Q-meters.
    - To reduce, using thermal guards, the interface heat flow rates through test harnesses or specific test mechanical fixations. This allows not to consider this heat flow rate in the thermal mathematical model.

The three last objectives are specific to a thermal balance test combined with a thermal vacuum test or with a thermal ambient test at mission pressure. Be aware that in general:

- Combined tests yield conflicting constraints. For example, due to intrusive GSEs or intrusive instrumentations.
- These constraints generate a loss of accuracy of the test results in particular during the thermal balance test.

Interdependent Thermal Behaviour between a Unit and the Space Vehicle

In some demanding or critical testing situations, supplier and customer flight thermal analyses can be inconsistant because of too coarse thermal mathematical models of the unit by the customer or of the space vehicule by the supplier. A reconciliation process can follow different ways:

- Either by performing an iterative cross-verification of the customer and supplier flight thermal analyses thanks to successive exchanges of interface data.
- Or by performing a coupled flight thermal analyses done by the supplier or the customer thanks to exchanges of refined thermal mathematical models.

Thermal Analyses Practical Benefits

If thermal analyses under temperature cycling test configurations at equipment level are often not necessary, they can be of paramount importance when required by the circumstances:

- By running the flight and test analyses to evaluate acceptable test biases or to reduce them. For example, these biaises are due to heat leaks through test harnesses or contacts between the GSEs and the unit under test.
- By comparing the flight and test analyses to validate TRP temperature ranges drifts or deviations during testing.
- By evaluating the radiative sink temperatures due to unit complex external geometry, GSEs around the unit, test facility shrouds singularities...
- By evaluating the impacts on internal hot spots due to any residual low pressure.
- By evaluating the needed dwell times and the expected plateau total durations.
- By estimating the transition durations, in particular from the hot to the cold plateaux, and by investigating ways to speed up transitions.
- By evaluating the allowed responses delays in case of a particular failure or emergency.

r. When the two-phase heat transport unit is horizontal, a practical and efficient test set-up monitors and controls, at every moment during the test, the tilt angles.

s. During a thermal test at equipment level, defects or failures monitoring is not limited to functional and performance tests:
   - For intermittences, efficient detection needs continuous monitoring.
   - For escape or environmental dependent defects present at the beginning of the thermal test, immediate detection avoids confusion with latent infant mortality defects precipitated by the thermal test.
   - The root cause identification of precipitated defects depends often of the ability to determine the time of their apparition.
   - Test instrumentation and telemetry provide the appropriate parameters for a discerning monitoring.
   - Turning power off (if applicable) is necessary only during non-operating plateaux and before switch-on testing.
   - During the cycle n° 1 (see bullet 5.5.4.1i, Figure 5-3 and Figure 5-4), longer ON time improves the detection efficiency of defects.
   - At the start of the thermal test (cycle n° 1), venting constraints (see 5.5.4.2b.) can delay unit powering on.
   - Turning power off (if applicable) can be necessary to reach particular cold plateaux within the planned duration.
   - An equipment unit effective configuration, if powered ON, allows monitoring and maximises observability.

5.5.4.2 Guidelines to thermal vacuum test

a. No specific guidelines for this requirement.

b. For this clause, the guidelines deal with venting durations and with very low vacuum levels.

Venting and Outgassing Durations

The test specification defines the necessary venting and outgassing durations. Differences in the voltage levels between internal cavities combined with cavity dependent low vacuum levels could lead to detrimental electrical phenomenons as arcing:

- For DC and RF corona effects, refer to clause 5.5.5.6 of ECSS-E-ST-10-03.
- For High Voltage effects, refer to section 4.3.4 of ECSS-E-HB-20-05.
- For multipactor effects, refer to clauses 5.5 and 6.2 of ECSS-E-ST-20-01 and ECSS-E-HB-20-01.

Take advantage of the following guidelines:

- Magnetic moments of some pressure sensors can prevent close proximity to some units.
- Depending on the materials and the bake-out history, the outgassing duration can be highly variable.
- During a hot plateau, reaching a pressure of 10^{-5} hPa inside an internal cavity of a unit can be impossible within a reasonable time.
- Prior to the test, negotiate the true pressure limitations and check if other unit electrical modes have less severe pressure requirements.

Very Low Vacuum Levels

Some tests require vacuum levels as low as $\leq 10^{-5}$ Pa or $\leq 10^{-6}$ Pa. These values are one hundred or one thousand times lower than the value required by the ECSS testing standard ($\leq 10^{-5}$ hPa).

For example, such a high vacuum is necessary:

- For the evaluation of space materials, processes, mechanical parts and assemblies and in order to anticipate some under vacuum deleterious effects (see ECSS-Q-ST-70-04; $\leq 10^{-5}$ Pa).
- For technological dependent tribology issues inside mechanisms ($\leq 10^{-6}$ Pa). ECSS-E-ST-33-01 (clause 4.7.3.1) does not require any longer such a very low vacuum level. A mechanism technical specification may require it. Alternatively, a standard vacuum level can be sufficient with a requirement to inspect after the test the surfaces with tribology.

c. To avoid contamination of the specimen under test, of the test facility and test GSE sensitive to contamination and to reduce outgassing risks from test GSE and test facility, the C&CCP (as per the DRD in ECSS-Q-ST-70-01 Annex B):
   - o Refers to the declared material lists (as per the DRD in ECSS-Q-ST-70 Annex A) including all test GSEs DMLs. Examples: test harnesses, test heaters.
   - o And details all the activities, methods and procedures (material selection, protective measures with regard to sensitive areas, instrumentation for contamination monitoring and control, inspections, personnel training, cleaning and decontamination, bake-out, purging…).

   Concerning the test facility and the test GSE and considering the flight H/W with which they interface, to apply the same surface cleanliness requirements is a simple and efficient practice.

Such an interface can be direct by physical contact or indirect by contamination redistribution during AIT activities and, specific to thermal testing, during each pressure transition (rather for particular contamination) or each temperature transition (rather for molecular contamination).

Concerning thermal testing, a pre-test (as per ECSS-Q-ST-70-01 requirement 5.3.2d., e. and f.) includes GSE test equipment and cabling. In addition to pump down and re-pressurization sequences and for a demanding space program, this pre-test can also simulate the critical temperature transient sequences.

The test specification refers to the C&CCP and, if bio contamination constraints apply, to the product supplier PPIP (or Planetary Protection Implementation Plan).

d. The test profile implementation ensures outgassing and trapping of contaminants on cold surfaces of the facility (generally with a cryogenic trap). An efficient practice, often required in test specifications, is to have always the test article surfaces hotter than the chamber shrouds and the part of the test set-up that can trap contaminants during cold phases. Test phases with the higher contamination risks are mainly the beginning of the test and the end of the test. At the beginning of the test, an outgassing phase reduces these risks. Ending the test after a hot plateau is also an efficient practice.

e. No specific guidelines for this requirement.

5.5.4.3 Guidelines to thermal ambient test at mission pressure

a. No specific guidelines for this requirement.

b. Within a planetary atmosphere, gaseous conduction or (natural, mixed or forced) convection can greatly influence the units thermal behaviour. Some specific guidelines to the clause 5.5.4.1-h deal with the presence of a mission atmosphere.

c. For cleanliness and contamination and, if applicable, for bio contamination, see guidelines in 5.5.4.2c. The C&CCP defines the activities, methods and procedures to mitigate the risk of condensation or frost. For Mars atmosphere, this can include using dry N_2 instead of CO_2.

d. The test specification defines the chamber type:

- A mission dependent atmospheric pressure near to room atmospheric pressure (e.g. on-board a space station) can use a temperature chamber.
- Concerning vacuum chambers, see guidelines related to in 5.5.4.1a.

5.5.4.4 Alternative thermal approaches

First alternative approach: two thermal tests in series

In this first alternative approach applicable to space segment "type a" equipment, two thermal tests are present in series in a QM, PFM or FM sequence of tests.

The thermal tests in series are an early thermal ambient test and a later thermal vacuum test or a later thermal ambient test at mission pressure. Such a sequence of tests can allow comparatively less expensive qualification, protoflight or acceptance testing:

- For space vehicles equipment, US literature, standards or handbooks address this point relying on statistical analysis of anomalies and failures during testing and flight.
- By comparison with a test under vacuum or under low pressure (for example, on Mars surface), a test under a pressure around 1013 hPa can significantly increase the rates of change of the unit internal temperatures during transitions between plateaux. This is due to forced convection with quick changes of the inert fluid temperature.

- So, the unit internal temperature rates of change during transitions between plateaux are faster and hence can precipitate quicker latent defects.
- If early detection of pre-existing patent defects or precipitated latent defects, design modifications and retesting (if any) costs are less than if these defects detection is late in the QM, PFM or FM sequence of tests.

Second alternative approach: replacement of the standardized thermal test by a thermal ambient test

In this second alternative approach, a thermal ambient test replaces a thermal vacuum test or a thermal ambient test at mission pressure in a FM sequence of tests.

Without associated risk management, thermal ambient tests cannot replace thermal vacuum tests or thermal ambient tests at mission pressure. A reason for this is that latent defects precipitation efficiency is almost always pressure dependent. Furthermore, some performances are pressure dependent. Concerning this matter, several sources of information are available:

- US literature, standards or handbooks consider this option possible:
  - Only for electric and electronic units (excluding RF equipment) and for mechanical units as structural, moving mechanical, propulsion and heat transport units. Propulsion and heat transport units include tanks, valves and thrusters.
  - Only for acceptance testing on flight models, as in European practices.
- Some ECSS standards discuss deleterious or very specific effects due to a high vacuum:
  - ECSS-Q-ST-70-04 entitled "Thermal testing for the evaluation of space materials, processes, mechanical parts and assemblies".
  - ECSS-E-ST-20-01 and ECSS-E-HB-20-01 entitled "Multipactor design and test".
  - ECSS-E-ST-33-01 entitled "Mechanisms".

Many projects, mainly for cost and schedule reasons, assess the risk of replacing acceptance thermal vacuum tests or thermal ambient tests at mission pressure by acceptance thermal ambient tests. In order to propose this replacement to customer early approval, the electric, electronic or mechanical unit supplier provides in-depth assessments concerning the different acceptance testing conditions with, if any, possible actions to mitigate or to compensate lack of representativeness. Common assessments (not exhaustive list) evaluate the potential acceptance testing gaps related to:

- Internal temperatures homogenisations by gaseous conduction or by free convection that induce, comparatively to thermal vacuum test, lower temperature differences inside the equipment unit. The end of this paragraph discusses possibilities to compensate this lower stress during hot plateaux by increasing the TRP temperature acceptance level.
- If any pressurized internal zone or component, losses of pressure or losses of clearances between the pressurized zone and nearby parts.
- If any high vacuum internal zone, slow losses of vacuum needing representativeness in terms of rate of change of the pressure. Example: an experiment in Mars atmosphere.
- Cracking or fracture risks of materials, parts or assemblies due to sudden changes of the pressure or due to sudden dimensional changes by expansion or contraction.
- Electrical wiring risks (short circuits, losses of electrical continuity…) due to dimensional changes by expansion or contraction or due to other very specific causes.
- Outgassing and creeping of space materials (including lubricants, structural composites, adhesives and harnesses).

- Tribological risks and tribological performances representativeness (friction, cold welding, wear and abrasion).
- Multipactor critical regions.
- Corona (RF and DC) and partial arc discharge (pressure-voltage) domains (in particular, in presence of high voltages).
- Concerning the measured value of each temperature or pressure dependent performance to be tested, updated criteria existence and validity.
- Representativeness of calibrations to be done for flight, if any.
- If any local and demanding internal thermal control (temperature or dimensional stability, precise cooling or heating…) to be verified, representativeness of flight conditions (in terms of pressure and temperatures).
- If temperature cycles under high vacuum (lower than 10^{-5} hPa) done at higher level with proper monitoring, cost and schedule risks.

Note: without clear and agreed technical statements about sensitivity to space vacuum (or to mission pressure), exempting equipment units from flight models temperature cycles under high vacuum (or under mission pressure) is a cost/risk issue. The management of such an issue by an RFD depends on the mission context (for only one S/C, for a S/C or a P/F family, for a S/C constellation…).

Compensation during hot plateaux by increasing the TRP temperature acceptance level implies a particular attention to hottest or critical internal points. A critical point is a point, representing an EEE component, a material, a mechanical part or a process, which temperature is close to its applicable limit. Note that the applicable allowable temperature limit for operation during the mission is typically a derating limit, while for tests the rated temperature limit applies, which can be significantly higher (refer to ECSS-Q-ST-30-11).

The internal hot spots and their reduction due to gaseous heat transfers differ widely according to the unit internal design (geometry, components topology, heat distribution and thermal packaging).

Concerning the possibility and the implementation of this compensation, detailed and valid data are essential to facilitate agreement between supplier and customer:

- Compensation is not possible if the correction of the internal temperature highest difference between the two pressure conditions means:
  - Violating rated temperature limits of any internal point.
  - Or exceeding any internal temperature level seen during qualification cycling. In Europe and for units complying to the ECSS testing standard, qualification margin = 5 °C beyond the acceptance temperature ranges at the TRP.
- Thermal analyses can determine the TRP temperature acceptance level increase before testing.
- If mathematical modelling of gaseous conduction or of free convection is uncertain, internal complementary instrumentation on hottest and critical points can drive during testing the TRP temperature acceptance level increase.

According to common European practices based on experience:

- It is difficult to envisage such a compensation for a dissipative unit, because it often has internal critical points which reach temperatures close to their temperature limit. A thorough review of the temperature levels with respect to the applicable rated limits especially for these points, and for EEE components with small differences between rated and derated limits is necessary to justify the TRP temperature increase.
- A TRP temperature acceptance level increase larger than 10 °C is not recommended, even when qualification margin is superior to 10 °C.

Be aware: US rules or practices, as given in SMC Standard SMC-S-016, are different from ECSS ones:

- The test tolerance of ±3 °C in SMC-S-016 is -4/0 °C (cold plateau) and 0/+4 °C (hot plateau) in ECSS.
- In SMC-S-016, the qualification margin of 10 °C is referring to the allowable flight temperature (AFT) ranges (AFT range = design temperature range in ECSS). In ECSS, the qualification margin is the difference between qualification and acceptance temperature ranges.

5.5.5 Electrical/RF tests

5.5.5.1 EMC Test

a. The rationale for the tests specified in the ECSS-E-ST-20-07 clause 5.4, Equipment and subsystem level test procedures, can be found in the ECSS-E-HB-20-07 clause 4.3, EMC test requirements.

Some specific test methods not specified in the ECSS-E-ST-20-07 clause 5.4 (noted as "specific" in Table 5-3 of the ECSS-E-ST-20-07) are discussed in the ECSS-E-HB-20-07.

Pointers to the ECSS-E-HB-20-07:

- o RE, low-frequency magnetic field: ECSS-E-HB-20-07 clause 7.1.5, Low frequency magnetic field measurements.
- o RE, low-frequency electric field: ECSS-E-HB-20-07 clause 7.3.1, Low frequency electric field measurements.

b. The method for isolating power lines is described in ECSS-E-HB-20-07.

c. No specific guidelines for this requirement.

d. Sniff and spray tests are described in the ECSS-E-HB-20-07. In particular, pointers to the ECSS-E-HB-20-07: Sniff tests: ECSS-E-HB-20-07 clause 7.3.2 with UHF/SHF sniff tests. Spray tests: HB-20-07 clause 7.6.1 and UHF/SHF spray tests.

5.5.5.2 Magnetic test

a. ECSS-E-ST-20-07 requirement 4.2.5.1a. specifies that "The test method described in 5.4.5 providing a dipole model can be inadequate and replaced by a multiple dipole model or a spherical harmonics model".

The relevant test methods are described in the ECSS-E-HB-20-07.

The six points method specified in the ECSS-E-ST-20-07 clause 5.4.5 is further discussed and detailed in the ECSS-E-HB-20-07.

Pointers to the ECSS-E-HB-20-07:

- o Tests for multiple dipole modelling: ECSS-E-HB-20-07 clause 7.1.1, Measurements for multiple dipole modelling.
- o Tests for spherical harmonics modelling: ECSS-E-HB-20-07 clause 7.1.2, Measurements for spherical harmonics modelling.
- o ECSS-E-HB-20-07 clause 7.1.3, "Six points method".

NOTE At the moment of publication of this handbook the activity to create ECSS-E-HB-20-03 "Magnetic cleanliness handbook" was still ongoing.

5.5.5.3 ESD Test

a. No specific guidelines for this requirement.

5.5.5.4 Passive intermodulation test

a. See Annex Annex D.

5.5.5.5 Multipactor test

a. ECSS-E-HB-20-01 covers methods and guidelines concerning multipactor testing and monitoring.

5.5.5.6 Corona and arc discharge test

a. Corona testing concerns DC corona and RF corona:
   - o ECSS-E-HB-20-05 covers methods and guidelines concerning DC corona (and arc discharge) testing and monitoring.
   - o No specific guidelines concerning RF corona testing and monitoring.

5.5.6 Mission specific test

5.5.6.1 Audible noise test

5.5.6.1.1 General

General considerations about audible noise test are presented in Annex C.

a. The audible noise test is specific for manned missions

b. The different operating modes of the equipment are tested to cover the complete operating conditions

c. In case of transient noise, the time history is recorded to provide noise level and exposure time

5.5.6.1.2 Equipment airborne sound pressure measurement

a. no specific guidelines

6 Space segment element test requirements

6.1 General requirements

a. Particular care is taken with the interfaces when splitting space element for test. For mechanical tests, interface flexibility is considered. For thermal tests, heat transfers at the interfaces are representative of the missing element.

b. As a general remark, it is recommended to include the items that are interacting on the element level in the test as much as possible. A typical example of this is the case of a dispenser holding a number of spacecraft's at launch. Because of the hyper-staticity and flexibility of the interface of the satellites with the dispenser high forces develop at the interfaces that could not be reproduced in the test at satellite level, even after increasing significantly the excitation input and so increasing the risk of damaging flight hardware. However, those forces could be easily reproduced if the test is performed with a configuration spacecraft's plus dispenser, and implementing the nominal excitation input. A similar behaviour is found at the interface between a solar array and the spacecraft.

c. No specific guidelines for this requirement.

d. No specific guidelines for this requirement.

e. Note that it is sometimes considered as a risk to stress an equipment unit at element level more than it has been stressed at equipment level. In particular, for thermal tests, it would correspond to limit the equipment temperature during element level test to acceptance levels, if the equipment is a FM from a thermal testing point of view. Concerning vibration tests and provided that it does not prevent a proper qualification of the element, it is recommended to limit the levels on the equipment to their acceptance level in case secondary notching's are needed. This is usually acceptable for the launcher authority provided that there is enough margin with respect to the Coupled Launch Analysis.

f. No specific guidelines for this requirement.

g. It is particularly important, before the test, that a visual inspection is performed by the engineer in charge of the test predictions, to check whether the tested configuration corresponds to the modelled one. Thermal Control examples: MLI, thermal insulation or guarding of harnesses.

6.2 Qualification tests requirements

a. ECSS-E-ST-10-03 Table 6-1 – Static: Note that the structure qualification can be performed in many different ways, not only with a static test. See annex A.3.

ECSS-E-ST-10-03 Table 6-2 – Shock: Discussion about number of activations and firing to firing variability that can be characterised at actuator level. See ECSS-E-HB-32-25 clause 13.1.2.

6.3 Acceptance test requirements

a. ECSS-E-ST-10-03 Table 6-3 – Modal survey: Modal survey can be used to demonstrate that the flight hardware behaves as the qualification model. It can also be used to assess transmissibility in the structure.

Static can be used for acceptance (e.g. re-entry loads), or as proof test of the structure.

Shocks are performed if there are modifications with regards to the qualification model.

6.4 Protoflight test requirements

a. Mechanical qualification example: Mechanical qualification obtained on a STM covers the items that are flight representative on the STM. It cannot cover the items and interfaces that are not flight representative on the STM (flight equipment replaced by structural dummies, piping, tanks, harnesses, connectors…). Hence the levels to be applied on a PFM have to be carefully assessed, even when there were qualification tests on a STM.

6.5 Space segment element test programme implementation requirements

6.5.1 General tests

6.5.1.1 Optical alignment measurement

When the gravity has an important influence on alignment measurement, a Gravity Release test is performed (see A.A.12) to assess the effect of gravity on the alignment.

a. See guidelines in Annex E.

6.5.1.2 Functional tests

The Functional tests section in this HB addresses all testing activities set in place to verify, against customer expressed requirements, the Space segment element from its functional view.

It encompasses all the activities set in place to check that all functions implemented by H/W and/or S/W “fit to requirements” & “fit for mission” (AOCS, DHS, Power distribution, Payload I/F management, Payload functions, TT&C...).

The testing therefore will be executed on various Space segment element models as defined in ECSS-E-HB-02A. A typical set of Space segment element models is given in Table 6-1 below.

Table 6-1: List of typical Space segment element models on which functional tests are executed (Verification Level: Space segment element).

Abbreviation	Description	Paragraph in ECSS-E-HB-10-02	Comment
VM	Virtual Model Also called **Virtual or Hybrid Model**	5.2.5.2.18, page 31	There are several virtual models (or in other word simulation models) of a space segment element. One particular virtual model is the Software Validation Facility or SVF which is a simulated S/C. Another one is typically the AOCS simulation environment, which represents a full Attitude and Orbit Control model of a S/C used for design and verification of the AOCS system.
EFM	Electrical and Functional Model	5.2.5.2.8, page 29	EFM typically consists of EM HW models and in exceptional cases also on DM HW models (BB/EBB) and/or simulated models
PFM	Proto Flight Model	5.2.5.2.13, page 30	PFM consists typically of PFM or FM models
FM	Flight Model	5.2.5.2.14, page 30	FM consists of FM models

New Test Terminology in ECSS-E-ST-10-03C

The C-series of the ECSS testing standard introduced a new terminology on the testing. This was considered necessary especially because of the term IST/ISST which caused a lot of misunderstandings in the past.

Sources for misunderstandings were

- the perimeter of the IST
  - o “Integration System Test”
    - Checking equipment functions when integrating the equipment into the Space segment element.
  - o “Integrated System Test”
    - testing the Space segment element in the context of the mission.
- the purpose of the test IST/ISST, i.e. “sub-system” or “system” but was done on
  - o testing equipment functions after mechanical/electrical integration
  - o testing sub-system functions
  - o testing system functions

To improve this situation, the IST/ISST terms have been replaced by the (Full) Functional Test term to express the correct purpose and content of the test.

A mapping of A-series and C-series terms is given in Figure 6-1.

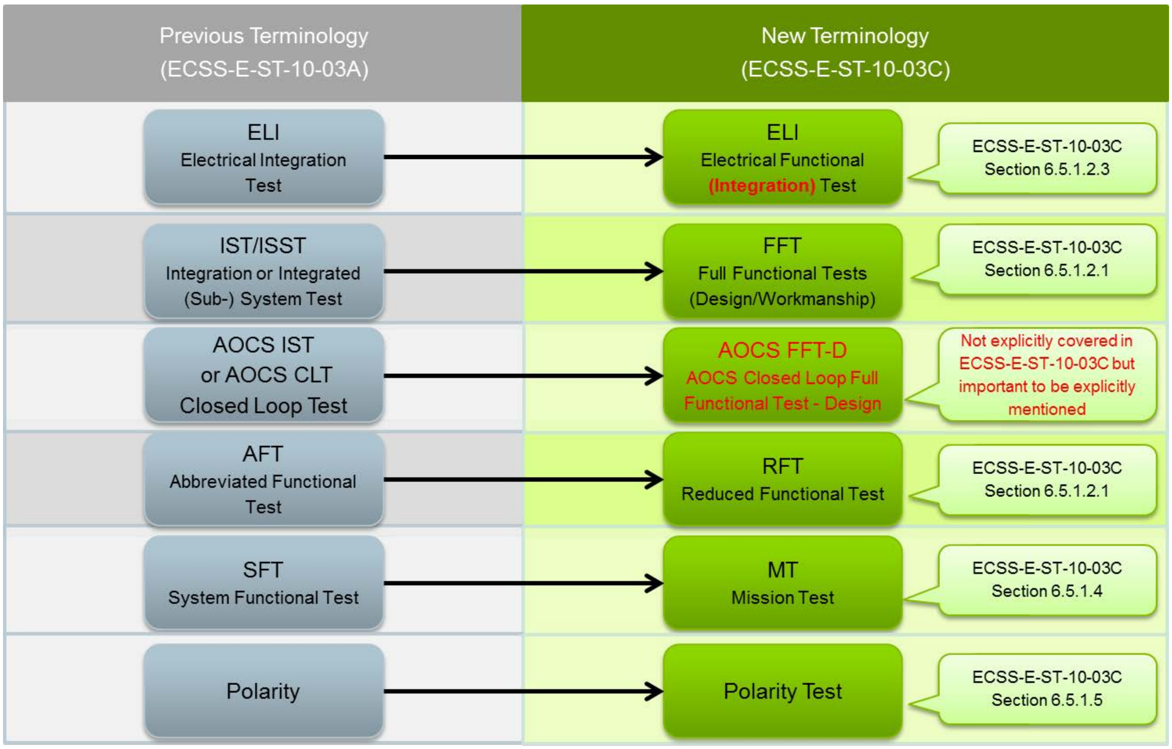


Figure 6-1: Mapping of previous and current test terms in the ECSS-E-ST10-03 standard

Clarification on Functional Test Definitions

The following clarifications especially on model and test bench definitions as well as abbreviations are necessary for a precise understating for functional testing.

Those are:

1. Space Segment Element Model = Test Bench

A major point is that a model is a test bench on Space segment element level, as the models and the test benches own the same name, e.g. SVF, EFM, PFM or FM is a model but also a test bench.

However, a test bench is more than a model, as it consists of additional parts, like MSGE, EGSE, SCOE, additional instrumentation, …

Hence the test benches are an integral part of the model philosophy for verification but each test bench needs also a decent HW and SW configuration control for test execution "on the bench".

A second clarification is that some models consist of other models, i.e. the Spacecraft PFM model is constituted by various equipment PFM models. Therefore, a model philosophy always requires a model flow to present a comprehensive test and verification approach.

2. Virtual, Hybrid & EFM model descriptions in ECSS-E-HB-10-02A cover combinations of simulated & HW models

One key ambiguity in the model descriptions is the grouping of "Virtual and Hybrid Models" as this is misleading.

A second source of confusion is that both Hybrid and Electrical Functional Model (EFM) in ECSS-E-HB-10-02A consist of "real" HW models like "EMs" and (partially) simulated models.

This handbook considers the following clarification:

- EFM is the only "hybrid" model considered in this handbook.
- The Virtual Model (VM) does not include any HW model to comply to its name – virtual or in other words simulation model.

3. SVF abbreviation

The third one is, that the abbreviation SVF in itself is ambiguous, as is can be read as:

- Software **Verification** Facility
- Software **Validation** Facility

Please note that ECSS-E-HB-10-02 defines SVF as Software **Validation** Facility to which this handbook complies to, despite of the fact that the purpose of the model/test bench is considered more verification.

The Functional test clause 6.5.1.2.1 in the ECSS-E-ST-10-03 standard identifies the following test types.

- Functional Test (**FT**) section comprising
  - o the Full Functional Test (**FFT**s),
  - o the Reduced Functional Test (**RFT**) and
  - o the Mechanical Functional Test (**MFT**),
  - o the Electrical Functional Test (**EFT**)where each test has its own purpose.

This handbook develops the definitions of the standard (FFT & Electrical Functional Test) as follows:

- FFT-D, FFT-W to clarify functional testing for design (functional qualification) and workmanship (functional acceptance) aspects.
- AOCS Closed Loop Functional Test – Design (CFD or AOCS FFT-D, sometimes also called CFQ – "Qualification")– which is part of the FFT to test and verify the AOCS modes and control laws in order to demonstrate correct functioning of the AOCS. This is typically done by testing the relevant AOCS modes based on the execution of a selected set of reference scenario on an AOCS closed loop test bench. The superset of AOCS reference scenario is usually developed on the AOCS simulation environment. The AOCS closed loop tests – design are usually performed on EFM test bench. The workmanship verification of AOCS closed loop is part of the FFT-W. The need is to be assessed on a case by case basis.
- Electrical Integration Test (**ELI**) to state more precisely the purpose of the test compared to "Electrical Functional Test". Secondly to confine clearer from (Full) Function Test.

Table 6-2 provides the relation/classification for the test types of the functional tests and includes also Performance, Mission and Polarity tests.

Table 6-2: List of Functional tests, Performance, Mission and Polarity Tests.

Abbreviations of Test Types & Logic			Test Type	Description
FT				Functional Test
	FFT			Full Functional Test
		FFT-D	X	Full Functional Test - Design (Qualification)
		FFT-W	X	Full Functional Test - Workmanship (Acceptance)
		CFD or AOCS FFT-D	X	AOCS Closed Loop Functional Test - Design
	RFT		X	Reduced Functional Test
	MFT			Mechanical Functional Test
		MFW	X	Mechanism Functional Test
	EFT			Electrical Functional Test
		ELI	X	Electrical Integration Test
PT			X	Performance Test
MT			X	Mission Test
POL			X	Polarity Test
	EPT		X	Equipment Polarity Test
	E2EPT		X	End-to-End Polarity Test

The Full Functional Test

The Full Functional Test (FFT), in the perimeter of the Element level testing, is a comprehensive test block that demonstrates the integrity of all functions of the item under test, in all operational modes, including back-up modes and all foreseen transitions.

In this context this means in all mode of the item under test. Please note that the coverage of all mode is not always possible especially for backup or contingency modes.

The FFT is basically set up in two blocks of different nature, run on the VM/EFM or on PFM/FM models, and answering two distinct verification needs, Functional Design Verification sometimes also called “Qualification” and Functional Workmanship Verification, sometimes also called “Acceptance”.

- FFT-D or in some companies also called FFT-Q, are oriented towards a space segment element functional qualification, aiming at proving absence of functional design error, and addressing in particular that the element performs in accordance with its specifications, in all operational modes, including back-up modes and all foreseen transitions. These activities are typically executed on Virtual (VM) or Electrical Functional (EFM) Models assuming model representativeness.
- FFT-W or in some companies also called FFT-A, are oriented towards the verification of as-build or in other words, workmanship, by demonstrating the absence of manufacturing and integration error, and ensuring freedom from workmanship defects and flawed materials in conformance with acceptance needs on PFM/FM.

FFT tests are usually performed for PFM/FM spacecraft models, after assembly and integration phases, before environmental testing. FFT consists of blocks of open-loop tests related for instance to a payload, an equipment or a functional chain.

FFT relates to on-board integrated management of a given equipment or of a set of equipment.

FFT verifies the correct functional behaviour of each functional H/W or H/W paths, respecting the intended operational sequence of the item under test, within the space segment element level operational environment.

FFT functional test coverage is closely linked with item under test physical architecture. FFT tests are performed with only the minimum required spacecraft operating equipment, and the simplest SCOE possible configuration, this means a given equipment management chain (i.e. involving power distribution, on-board computer, central software, data management) or set of equipment integrated into a sub-system functional chain, e.g. AOCS, DMS, Payload stimulated by telecommand or open loop actions.

The Functional design test main objective is to verify the availability and correctness of the space segment element functions (w.r.t design requirements) and exercise the item under test with several, up to all, functional chains processing simultaneously in order to demonstrate suitability for the operational concept of the item under test.

The coverage of all operational modes is achieved here.

This Functional design test consists of blocks of open-loop tests related to a functional chain. For the item under test, the objective is to demonstrate absence of functional design error that would hamper the element to perform in accordance with its specifications.

Functional design tests are performed on space segment element simulators, EFM and PFM on a model based approach, pending the nature of the design verification objective and the representativeness of the used models. The rationale for the model approach is discussed in the verification plan.

The perimeter and content of the FFT-D performed on the space segment element PFM depends on the tests already performed on, and representativeness of, the simulator model (VM) or EFM model versus verification objectives.

The functional design test contributes to verify:

- The consistency of the functional design, through correct functional behaviour of functions and execution on operational modes (nominal and contingency).
- The compatibility of hardware-software and software-software integration with central software.
- The correct functional behaviour of the item under test
- The system database, related to TM/TC addressed during the test phase.

Typical Functional design test examples are:

- packet store management and telemetry routing / download,
- coverage of S/W modes for intelligent terminals,
- coverage of FDIR mechanisms,

For instance, for an AOCS equipment with SW embedded, the FFT test identified can be:

- Equipment switching on and Equipment operational switching,
- Equipment software upload, patch and dump mechanism,
- Equipment Health Check test,
- Equipment -head Temp control,
- Equipment stimulation integration,
- Equipment. Functions

- Equipment switching off

The following figure gives an overview of the functional tests performed during the overall space segment element development and the corresponding verification and validation, typically:

- The AOCS validation and performances test, performed typically on a dedicated AOCS simulation bench, focused on algorithms simulations tests (to prove design solution & performances).
- The S/W verification (against its specification) tests, performed on the SVF (Software Validation Facility). The SVF allows verifying essential parts of the SW requirements (SW-SW integration tests & global tests) in an open or closed loop set-up, based on a simulated on-board time reference.
- The Functional Verification tests on dedicated hybrid benches (so called Flatsat/EFM/Avionic Test Bench).
  - o Note: In case heritage can be demonstrated, e.g. by a product approach, then a full simulated bench (SatSim) could be considered.
- The functional tests on S/C PFM/FM, limited to the test where non-representativeness have been identified on the EFM.

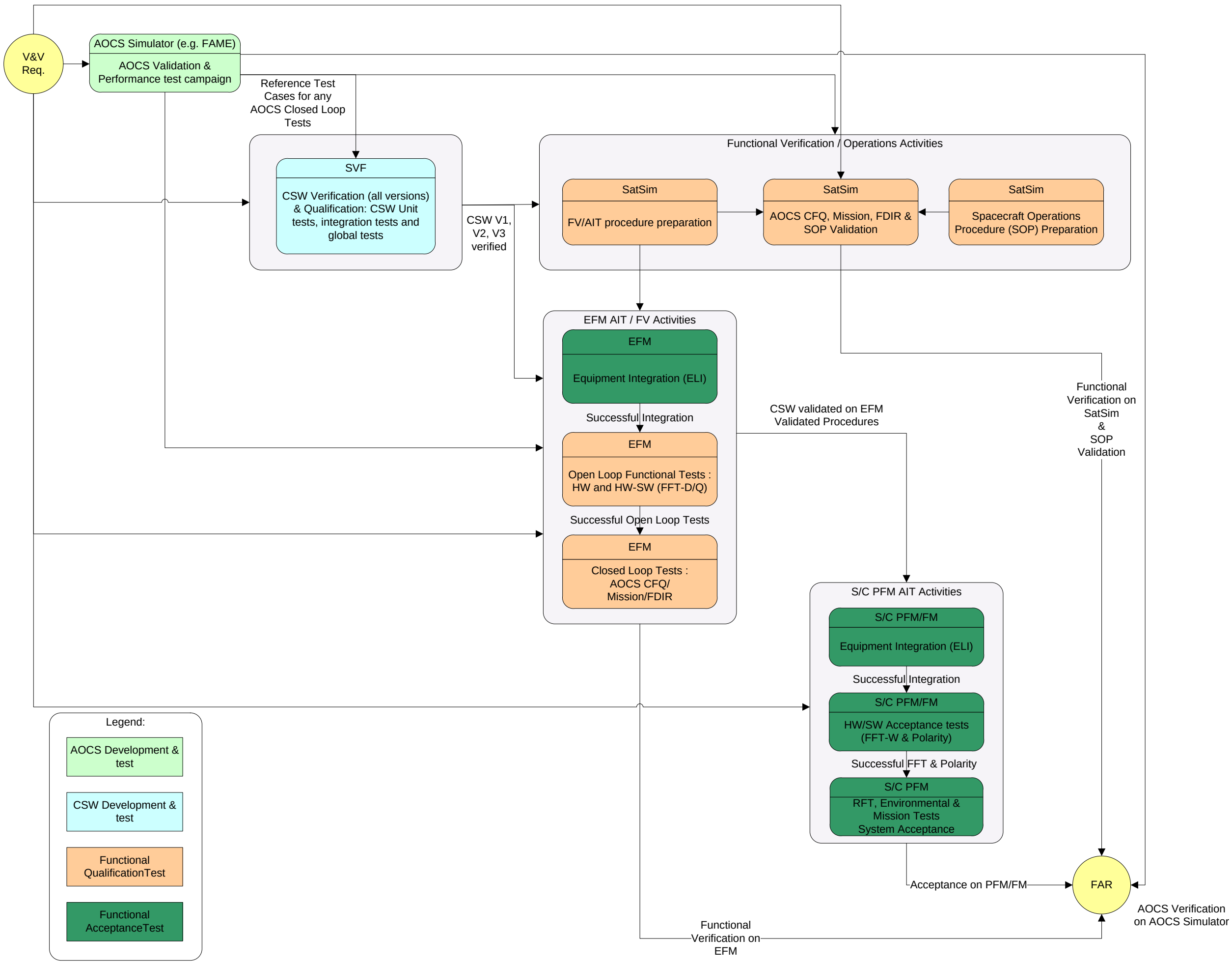


Figure 6-2: Typical sequence of tests for element level functional verification

The identified test configuration and test benches used to typically realize these test activities are recalled Table 6-3. Please note, a mapping of the models/test benches with ECSS-E-TM-10-21A System modelling and Simulation will be given at the end of this paragraph.

Table 6-3: Typical list of test benches for functional verification on Space segment element verification level

Model Category	Test Bench Name	Test Bench Main Purpose	Bench Technology
Virtual Model	**AOCS Simulator (e.g. FAME)** Functional AOCS Modelling & Simulation Environment	• To support the development, verify and validate AOCS algorithms and performance, allowing closed loop simulations with either an image of the AOCS flight S/W application or single modules of the AOCS flight S/W in the loop.	Numerical Bench (Virtual Model)
	SVF Software Validation Facility	• To support the SW development, verify and validate on-board SW.	Numerical Bench (Virtual Model)
	SatSim Satellite Simulator	The SatSim allows to verify essential parts of the SW requirements (SW-SW integration tests & global tests) in an open and/or closed loop set-up, based on a simulated on-board time reference.	Numerical Bench (Virtual Model)
Electrical Functional Model	**EFM** Electrical/Functional Model bench	EFM use case: • To validate the HW/HW and verify the HW/SW compatibility through open and/or closed loop tests • To verify main mission requirements : proof of design • To prepare the (P)FM verification and AIT campaign, including the (operational) validation of EGSE.	Hybrid Bench
(Proto) Flight Models	**PFM/FM** (Proto-) Flight Model bench	• The flight configuration, in the end a 100% hardware configuration • Proof of workmanship (acceptance) • System validation activities • In Orbit Testing	HW bench

Table 6-4 gives a view of the mapping of the functional test phases with regard to test configuration.

Table 6-4: Typical mapping of the functional test phases with regard to test configuration

Abbreviations of Test Types & Logic			Test Type	Description	Virtual Model (Satellite Simulator)	EFM	PFM	FM
FT				Functional Test				
	FFT			Full Functional Test				
		FFT-D	X	Full Functional Test - Design	Debug	"Functional Qualification" = Design Verification	Backup according to representativeness of EFM	N/A
		FFT-W	X	Full Functional Test - Workmanship	Debug	covered by FFT-D	Functional Acceptance	Functional Acceptance
		CFD	X	(AOCS) Closed Loop Functional Test - Design	"Functional Qualification" = Design Verification	Alternative "Functional Qualification" = Design Verification	Backup according to representativeness of Virtual Model or EFM	N/A
	RFT		X	Reduced Functional Test	Debug	Debug	Functional Acceptance	Functional Acceptance
	MFT			Mechanical Functional Test				
		MFW	X	Mechanism Functional Test	Debug or Training	Debug or Training	Functional Acceptance	Functional Acceptance
	EFT			Electrical Functional Test				
		ELI	X	Electrical Integration Test		S/C AIT Preparation EGSE Verification	S/C AIT Activity EGSE Verification	S/C AIT Activity
PT			X	Performance Test	Preparation of performance test	Preparation of performance test	Contributes to performance verification*	Contributes to performance verification*, need of execution or simplification to be assessed
MT			X	Mission Test	Contributes to mission scenario verification	Preparation of mission scenario verification	Contributes to mission scenario verification	Contributes to mission scenario verification, need at this level is to be assessed
POL			X	Polarity Test				
	EPT		X	Equipment Polarity Test	Debug	Debug	Functional Acceptance	Functional Acceptance
	E2EPT		X	End-to-End Polarity Test	Debug	Debug	Functional Acceptance	Functional Acceptance

* Please note: Performance testing on space segment element level (i.e. spacecraft) is limited to necessary performance verification activities, which could not be done on other, especially lower levels of the space segment element.

Reduced Functional Test

The Reduced Functional Test verifies the functional integrity of the Space segment element prior to and after hardware integrity relevant events such as transportation between two test sites or before, during and after mechanical test programme (vibration/shock) and thermal test programme, etc…

These tests, run on the PFM or FM, are designed as a sub-set of FFT-W to verify the integrity of the major functions of the item under test, with a sufficiently high degree of confidence, in a relatively short time.

Figure 6-3 shows the relation between the FFT-D (or FFT-Q), FFT-W (or FFT-A) and RFT test types. In the ideal case FFT-W is a subset of FFT-D and RFT is a subset of FFT-W.

In continuation of the previous FFT example, the RFT can be reduced to the following test:

- Equipment switching on and set to selected mode required to deliver RFT relevant results,

- Equipment Health Check test,
- Equipment -head Temp control,
- specific Equipment. function checks especially for life limited items
- Equipment switching off

Figure 6-3: Logical relationship between FFT-D (or FFT-Q), FFT-W(or FFT-A) and RFT

Mechanical Functional Tests

The Mechanical Functional Tests are testing the correct functioning of any mechanical or electro-mechanical mechanism on-board the space segment element (e.g. valves, mechanisms, pyros, NEAs,…). Detail on this test type can be found in section 6.5.1.2.2.

Electrical Functional Tests

The Electrical Functional Test are describing the activities executed during electrical integration of individual units and equipment, testing the equipment interface compatibility with its system environment, both at on-board and with electrical ground support equipment. Therefore this class is further broken down to the test type of Electrical Integration Test (ELI) which is the pre-requisite for any subsequent functional tests like FFT, RFT or MFW. Detail on this test type can be found in section 6.5.1.2.3.

Mapping of ECSS-E-TM-10-21A and this handbook

Figure 6-4 provides the relation between 6 key elements applied in System Modelling and Simulation technical memorandum ECSS-E-TM-10-21A and this handbook:

- Test bench
- Space Segment Element Model – which is the level corresponding to the "Digital Twin", i.e. the Virtual S/C, being a combination of Digital Mock-Up, S/C simulators and data or documents.
- Test item or Item under Test (IUT)
- Test campaign
- Test infrastructure

- Test environment

These items are building the core of functional test and verification activities on Space Segment Element level.

Test Bench

The test bench is the environment used to verify the correctness of the item under test by test. The test bench context is either HW, SW and/or firmware tests and the tests are supported by additional ground support equipment, which are in general SW and HW tools.

In space business, the test bench is constituted by three elements,

- the Space Segment Element Model (e.g. a satellite PFM), which itself is consisting of HW and SW models and data, all components which are representing functions.
- the test infrastructure and
- the test environment

The Space Segment Element Model

The Space Segment Element Model according ECSS Glossary, ECSS-S-ST-00-01C, is the physical or abstract representation (of a product) used for calculations, predictions or further assessment (i.e. test & verification). A Model can also be used to identify particular instances of the product e.g. flight model.

The Space Segment element model therefore has several levels of fidelity and integration status along the test campaign. In its final configuration, the Space Segment Element Model is corresponding to the (proto) flight model which is the end product, intended for flight. The selection of models is depending on the test campaign, respectively the item under test. The models are selected to ensure optimized and comprehensive test and verification activities. The fidelity level ranging from Development Model (DM) up to Flight Model (FM) is straight forward for HW models. For virtual models there are similar levels of fidelity ranging from Functional Models used in dedicated Functional Electrical Simulators like AOCS Simulators, via more sophisticated models applying for instance the Simulation Model Portability standard (SMP2, refer to ECSS-E-TM-40-07), up to sophisticated simulations models including for instance communication interfaces or modelled physical responses (e.g. temperatures, voltages) as part of a Software Validation Facility. A similar fidelity is seen for SW or database (SRDB) versions assuming the different levels of content across several versions in the development logic. This segregation in levels of fidelity supports the model calibration as the corresponding virtual model can be correlated against the related HW model, e.g. “Virtual EM” against “HW EM” and “Virtual (P)FM” against “HW (P)FM”. This provides the version consistency between SRDB, SW, virtual model and HW model used for testing.

The Functional (Operational) Model is a structured representation of the functions which the Space Segment Element is fulfilling. This is of particular interest as this functional model is the most comprehensive view on the Item Under Test completing pure HW and SW views. Please note that this functional model view is often implicitly established as it is typically distributed in several documents like Space Segment Element (often including subsystem) and Equipment level design descriptions, HW ICDs, Harness Definition, TM/TC or SW ICDs and others.

Item Under Test

The Item Under Test (IUT), sometimes also called Test Item, Device Under Test, test article or Unit Under Test is the manufactured assembled and integrated item which undergoes the test. The Item Under Test will vary across the life cycle of the test campaign and can include (re-)test after repair. The goal is to demonstrate that the Item Under Test is performing in accordance with the specification which is typically the Space Segment Element Specifications (e.g. Satellite Design Specification). The Item Under Test is constituted as part or by the whole Space Segment Element Model, depending on the nature of the test to be performed.

Test Campaign

The test campaign is a defined set of tests which are executed on a selected set of items under test. The Items Under Test are embedded in the test bench through the Space Segment Element Model. The test campaign objective is to fulfil the verification of the Space Segment Element.

Test Infrastructure

The test infrastructure delivers services or support to develop and operate the test bench respectively the space segment element model. The nature of this infrastructure is widespread and ranges from

- mechanical, electrical, optical GSEs and SCOEs
- simulation infrastructure like front-ends connecting HW models with simulation models respectively the simulator infrastructure
- facilities like clean rooms, thermal vacuum chambers where functional and environmental tests are performed
- connection and control items like test harness or Central Checkout Systems (CCS).

Test Environment

The test environment completes the test bench set-up delivering necessary stimuli depending on the tested scenario respectively the needs driven by the item under test.

The following Figure 6-4 and Figure 6-5 are drawn based on UML notation where the dotted line represents a (directional) dependency between the items and the diamond line an aggregation.

The dependency visualizes a semantic connection between the items for instance the test campaign influences the test environment to establish the correct stimulus for the selected scenario of the test.

The aggregation e.g. used to link the test bench with the Space Segment Element Model, the test infrastructure and the test environment expresses that the test bench is more than a model, as it consists of these three items.

Figure 6-5 shows a particular example of the Software Validation Facility using the general UML model of Figure 6-4.

Annex F provides a list of legacy or historical test bench names and its correlation to the applied space segment element models VM, EFM or PFM/FM.

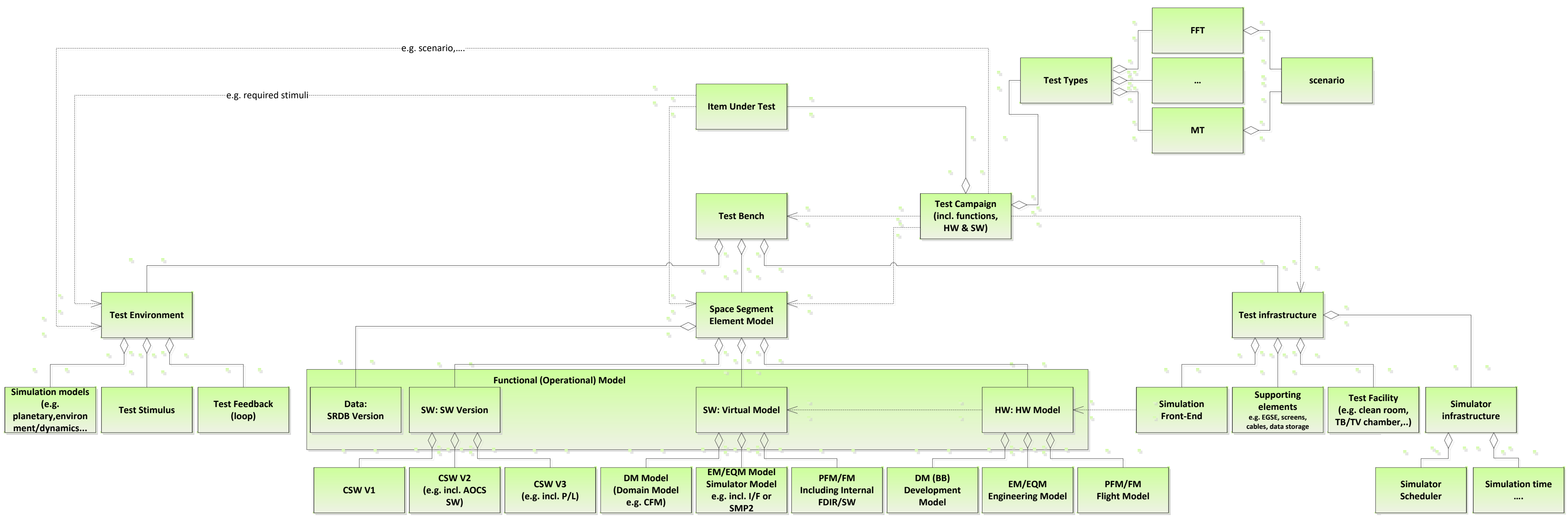


Figure 6-4: Logical relation between model, test bench, test campaign, test item (IUT), test environment and test infrastructure

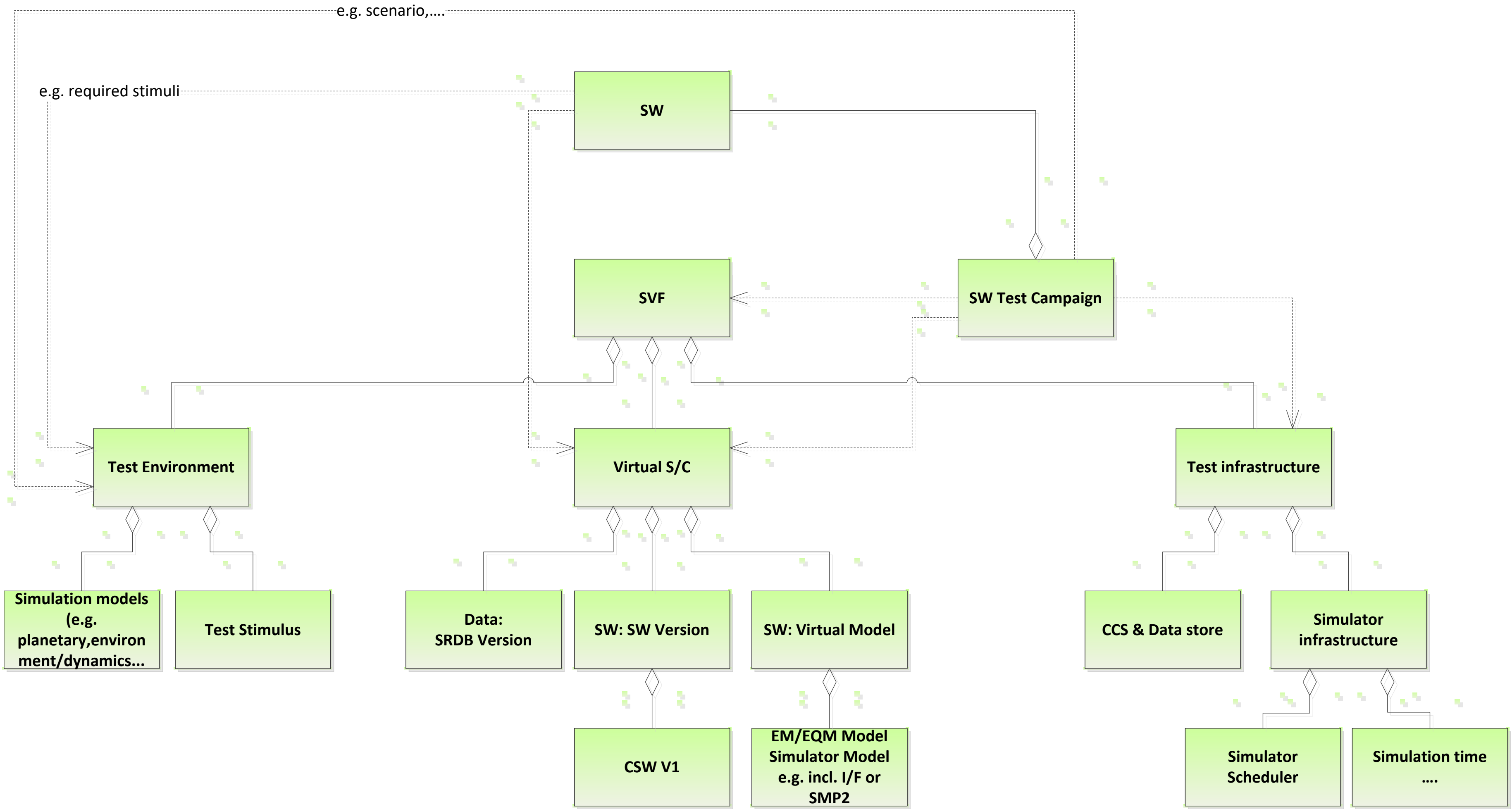


Figure 6-5: Example of an SVF based on the mapping between ECSS-E-ST-10-02C/03C and ECSS-E-TM-10-21A

6.5.1.2.1 General

a. FFT is the most comprehensive test for demonstrating the adequacy of the item under test using minimum required spacecraft operating equipment, and the simplest SCOE possible configuration. Any test restriction, test safety or test like you fly exception is clearly described in the FFT test specification. The test configuration (in particular the item under test redundancies) is fully described as part of the test specification.

Note please: a **test restriction** is a direct answer to the test objective/test scope, i.e. what is not (or not possible) to be tested.

A **test safety** is a human or technical hazards or special safeties which could occur during execution of the test in nominal or failure case where the test engineer has to pay attention to and knowing possible counter measures, i.e. there is a safety procedure in place.

A **test like you fly exception** describes limitations or constraints during ground testing and operation for instance where certain modes or mode transitions cannot be executed due to ground testing environment.

b. No specific guidelines for this requirement.

c. This is achieved by running the FFT (or a subset of FFT, respectively RFT) at the beginning and the end of the test programme.

This requirement aims to demonstrate that the functions are not affected by the environmental testing. However, risk is considered low when performing functional tests also during environmental testing. Therefore, a subset of FFT respectively RFT at the end of environmental testing is considered sufficient

d. Typically, FFT or a subset of FFT test are performed during thermal test. Additional tests like Performance Tests are considered exceptional cases driven by the need of either vacuum or temperature or both for demonstrating the performance.

e. No specific guidelines for this requirement.

f. The FFT ensures the testing of intended operational functions of the item under test. However, operation in the future intended sequence are not possible at all times, hence limitations respectively test like you fly exceptions is clearly identified in the test specifications

g. The need of an on-board or EGSE SW update is caused generally by an NCR disposition. The management of on-board or EGSE SW update, clarification of re-testing needs and customer confirmation is done typically as part of the NRB.

Note: TRR, PTR or TRB anyhow states the test bench configuration where on-board and EGSE SW is part of it.

6.5.1.2.2 Mechanical functional test

The correct functioning of the mechanical functions which are mainly but not limited to mechanism functions needs to be demonstrated as part of the space segment element test campaign. The operation of these functions needs to take into account the ground testing environment. Many of these functions cannot be executed or executed in the full range during ground testing. Also, performance can in general not be tested at space segment element level.

Typical functions that can be tested including during thermal (vacuum) testing are:

- Solar Array Drive Mechanism, without solar array and sometimes only in limited range because of harness.
- Antenna Pointing Mechanism, without antenna or antenna reflector and antenna arms.

- Instrument protections or covers (e.g. shutters).
- Some valve operation but not pyro valve or non-explosive actuators (NEA)

Typical functions which can be tested in clean room conditions with 0g devices if necessary, but not in thermal (vacuum) testing

- Release and deployment tests, e.g.
  - o Solar array deployment
  - o Antenna deployment
  - o Instrument boom deployments
- Rotation of pointing mechanism however usually not on the full range, e.g. Solar Array Drive Mechanism with Solar array attached.
- Pyro or NEA firing.

a. Mechanical function is tested demonstrating the correct mechanism functioning in line with the examples given above.

b. See examples of 0-g devices in Figure 6-6 and Figure 6-7. The friction induced during the mechanical functional test by the 0-g compensating devices should be minimised to allow for a more representative no-gravity condition. Passive gravity compensation solutions using cable suspensions for the moving parts (e.g. solar arrays panels deployment) are widely used. The cable suspension can be implemented by balloons, rails, air cushions, etc. Lately, the implementation of active gravity compensation systems allows to hold the suspension cables in vertical position during the whole deployment motion and to control the force passing through them with high accuracy. This results in a more realistic gravity compensation.

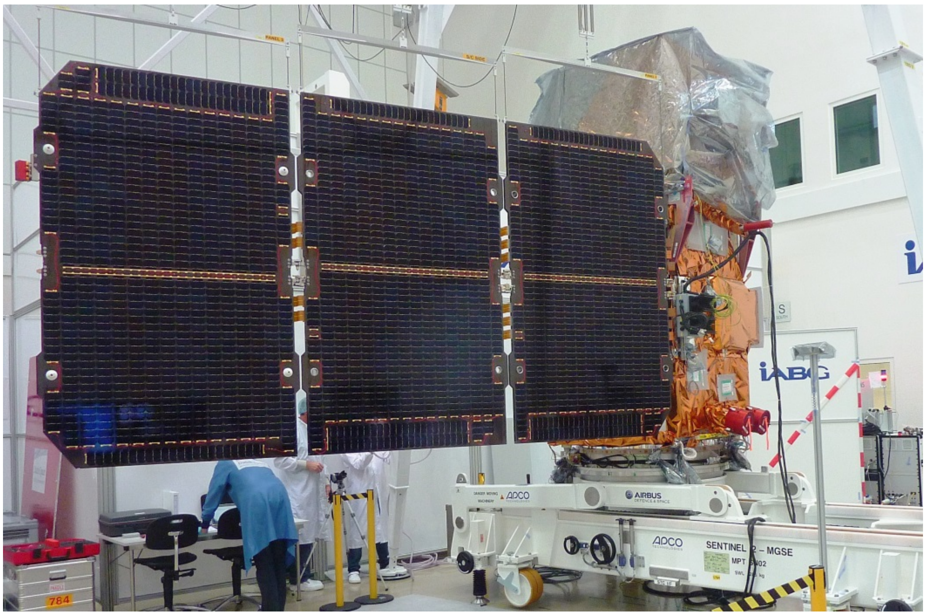


Figure 6-6: Example of solar generator unloading device for Sentinel 2

Figure 6-7: Exomars TGO antenna offloading device

c. This is typically the case for the performance of the mechanism, e.g. motorization margin with respect to resistive torque. The overall verification approach is part of the verification plan. Alternative verification method means that the testing on space segment element level can be for example replaced by an analysis of the testing at lower level to demonstrate the correct functioning.

d. Part of the verification is performed during the thermal (vacuum) testing depending on the mechanical functions. The verification is completed with activities at space segment element integration and selected checks prior launch, depending again on the mechanical function.

6.5.1.2.3 Electrical functional test

The electrical functional test is usually an incremental test approach where activities are distributed across space segment element integration and testing activities, sometimes complemented with lower level testing activities, i.e. equipment.

a. This activity is typically performed during space segment element electrical integration, because it is not possible to have access to some of the electrical interfaces, when the configuration is completed, or due to HW and SW availability.

b. Protection functions are tested at equipment level, as part of the equipment acceptance tests. Testing at space segment element level EFM or flight HW (e.g. PFM/FM) is limited to protection functions when possible:

  - Inducing a space segment element failure when not operative,
  - Whose activation does not require implementation of hazardous operations at PFM AIT level (e.g. implementation of breakout boxes or handling of high voltages).
  - Overvoltage protections are tested only when stimuli exist, as overvoltage injection is hazardous for the tests addressing coverage of all H/W functions and electrical paths.

- Safety routines to protect hazard to humans or item under test are set up prior any operation.

c. A recommendation is to select the configurations such that all the interfaces are at least energized once, without testing all possible configurations for cross-strapping verification. This is a trade-off between testing time and exhaustive cross-strapping check. This allows to ensure that all interface circuits are functionally checked.

d. It is good practice to reach this agreement as early as possible to allow a timely preparation and implementation of the tests.

e. This requirement is interpreted aiming to verify physical measurement such as current, voltages or temperatures during electrical integration. Then a comparison can be made to the TM/TC values received to confirm or initiate correction of the TM/TC calibration as part of SRDB. This is possible at that time of electrical integration since the system is accessible, e.g. via break out boxes.

   A full TM/TC testing is not required during electrical integration as database coverage is subject to a dedicated plan and report which summarizes the incremental TM/TC database verification across all space segment element tests.

f. The verification of autonomous functions is spread across the model philosophy, particularly for S/W implemented autonomous or even HW autonomous functions. Most of the autonomous functions are executed during the functional tests, hence this requirement is covered typically on FFT or MT tests.

g. No specific guidelines for this requirement.

h. Similar comment/approach as for point f. For electrical functions, critical failures are not necessarily verified by test (example: battery voltage below minimum voltage).

i. The subset of the functional test typically demonstrates voltage levels of the main bus in conjunction to battery end of charge levels. This can be done also as part of undervoltage tests demonstrating operation and disconnection of various loads. Besides, min and max bus voltage is tested on supplier level, typically with additional cases.

j. Not expected behaviour is tracked as anomaly, as per requirement 6.5.1.2.3 g.

k. No specific guidelines for this requirement.

l. No specific guidelines for this requirement.

6.5.1.3 Performance test

The performance tests as required in the standard are typically referring to payload performance. The verification of the performance is complex and is specific to the space segment element under test and the mission. This can lead to a combination of analysis and test activities on various models during the development lifecycle of the space segment element(s). The reasons to split these activities across different models can be manifold, e.g.

- Limitations in the size of the test facilities
- Limitations due to operation under 1g
- Limitation due to operation in ambient

The concept of performance test and subsequent verification needs to be clearly identified and described on Space segment element level, typically as part of the Verification Plan.

a. Performance test is the test block for demonstrating the performance of the item under test in operational condition, respecting all limitations introduced due to ground testing In case implementation of performance test is not possible on space segment element level, then alternative test and analysis methods need to be described as part of the overall Verification Plan using relevant models on different verification levels of the space segment element development.

b. Cross strappings are typically part of the FFTs. In case of relevant cross strappings for performance testing, then these should clearly be identified as part of the performance test specification. A recommendation is to select the configurations such that all the interfaces are at least energized once, without testing all possible configurations for cross-strapping verification. This is a trade-off between testing time and exhaustive cross-strapping check. This allows to ensure that all interface circuits are functionally checked.

c. No specific guidelines for this requirement.

d. The baseline is to execute the performance test after environmental testing in order to verify that the environmental testing campaign has no impact on the performance. However, if this is not possible (e.g. due to accessibility as the space segment element will be closed at that time), then this needs to be identified as part of the verification planning.

6.5.1.4 Mission test

The mission tests verify the space segment element functions under nominal and contingency conditions for defined space segment element configurations, applying defined mission scenarios.

Using a LEO Earth mission as example, typical mission scenarios are tested:

- Launch preparation procedure (nominal operation),
- Launch and Early Operational Phase (LEOP) (nominal operation),
- Nominal mission phase (nominal operation), including motor operation or orbit manoeuvre and possibly return operations as far as possible in Earth environment.

For non-nominal or contingency operation the following scenarios are typically tested:

- Long duration & stress test
- FDIR test in AOCS open/closed loop (contingency operation)

The above examples need to be adapted for different mission types like deep space missions or human spaceflight missions where other or additional mission scenarios need to be tested, e.g. interplanetary flight or orbit insertion.

The mission tests are typically based on tests, defined for FFT, but executed in the context of space segment element mission operations (test-like-you-fly).

a. Mission tests demonstrate the conformance of the space segment element to the intended operations. This is not always possible on any space segment element model due to limitations of ground/ambient testing. Hence the mission test approach is clearly identified in the Verification Plan also w.r.t. the models used for mission testing. This means it can be a distributed approach shared across VM, EFM or (P)FM models.

b. The contingency cases can be, as for the nominal mission tests, shared across different models in the overall verification approach. In case of time criticality HW models are preferred unless representativeness of Virtual Model can be demonstrated.

c. No specific guidelines for this requirement.

d. The mission test specification includes any test restriction, test constraint or test like you fly exception which deviate from the final flight configuration (e.g. safeguard memory patching...).

6.5.1.5 Polarity test

The objective of the polarity is to verify the correct polarity of functional chain from sensors to actuators, through a number of interfaces and processing. The main goal is to get the correct sign response based on a defined sign input. See Figure 6-8 for the scheme of the top level Control Chain.

Polarity tests are not limited to AOCS sensors and actuators. The polarity or sign of any other item which has a polarity needs to be tested. Those could be for instance:

- Antenna Pointing Mechanism
- Solar Array Drive mechanism)
- Valves for life control system or thermal control system

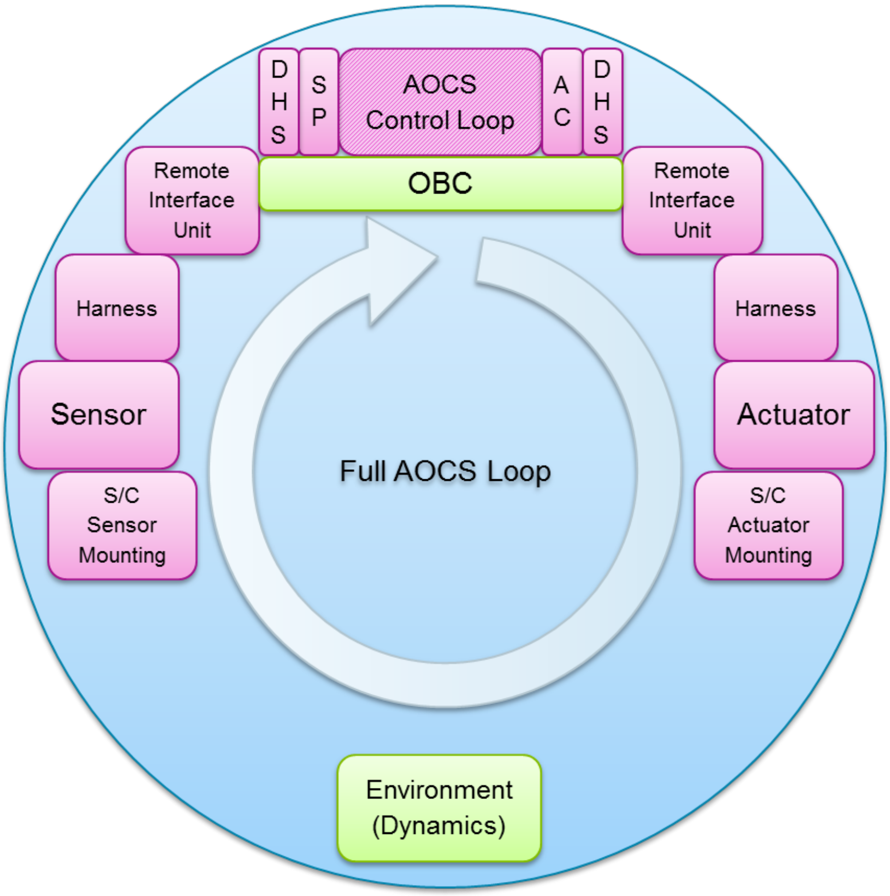


Figure 6-8: Top-level AOCS Control Chain Schematic

The polarity tests are workmanship tests, testing the flight harness connected to the AOCS equipment and AOCS functional chain in order to detect the absence of workmanship errors.

The baseline approach for the polarity test is to demonstrate polarity in an end-2-end test set-up from sensor via AOCS SW to actuator. This is basically to demonstrate test-as-you-fly condition. This test shall be done as late as possible in order to apply the latest CSW and SRDB versions and ideally using a single version for testing.

In case the baseline approach is not feasible, an alternative approach can be proposed, justified, discussed and agreed on a case-by-case basis.

At S/C integration however there is the need to check already sign/polarity on equipment integration, e.g. on integration of the sensor or actuator. This is to demonstrate that all items involved, including the harness is correctly assembled. It is typically done through physical stimulation in open loop and using the simplest possible test set-up. Ideally, there is also minimum SCOE SW interacting in the polarity test to prevent sign/polarity issues caused by (SCOE) test set up.

Please note that also SCOE/SCOE SW are part of the polarity measurements and that the signs of these items need to be verified to exclude double errors.

In consequence equipment polarity tests are essential tests at time of assembly and integration phase of the space segment element where the full accessibility is given, while the space segment element is not closed, as in later stages, e.g. shortly before environmental testing or shipment to launch site.

In general, each polarity test requires the clear definition of the test prediction upfront of the polarity test execution.

In summary, it is essential to define a simple polarity test set up and simple polarity tests which is a direct benefit in correctly measuring sign/polarity and preventing undetected failures.

a. Polarity test approach is mainly implemented on PFM/FM. For instance, polarity tests validate the correct signs of the AOCS control loops on the spacecraft with the real hardware, the real central software and the flight harness.

b. The baseline approach for the polarity test is to demonstrate polarity in an end-2-end test set-up from sensor via AOCS SW to actuator. In case the baseline approach is not feasible, an alternative approach can be proposed, justified, discussed and agreed on a case-by-case basis. A change in the software and/or spacecraft configuration that can be demonstrated not to interfere with the functional chain being verified, may not require the re-run of a polarity check if already carried out.

    1. End-to-End Test(1-Step):

        (a) “Single test” does not mean that no polarity checks are made on lower levels. For risk minimization (to avoid findings in a later stage of integration) such checks and tests on element and platform level are still necessary. However, the “end to end polarity verification” allows the full system polarity verification in a single test setup. For example in science missions, often an end-to-end polarity test between the Sun sensor and thrusters is made where the Sun sensor is illuminated producing a defined polarity input and the correct reaction on the thrusters (opening/closing valves via electrical signal) is checked. Other examples for stimulation are for Gyro measurement polarity can be verified by slowly turning the spacecraft. Earth sensors polarity checks are stimulated by moving a warm plate through their field of view. This test approach follows the “test like you fly” recommendation as close as possible.

    2. Potential alternative approach, distributed polarity tests:

        As a general rule this approach is based on:

        (a) A rigorous decomposition of each control chain into elementary components for which a sign consistency check can be performed, independently of the AOCS control loop but to AOCS control inputs (i.e. including AOCS sensor data processing (SP)) or from AOCS control outputs (i.e. from AOCS Actuator Control. It is essential to demonstrate that the distributed approach covers the full chain as the end-to-end tests, leaving no gaps.

(b) Elementary polarity tests with flight equipment during S/C AIT, when equipment units are accessible, as baseline with the final flight software.

(c) Correlation between telemetry and stimuli at that stage confirming the validity of the stimuli and the measured polarity.

(d) The coverage of the AOCS control loop polarity needs to be defined and agreed as this is an integral part of the overall polarity validation.

c. It has to be ensured that all sign relevant AOCS SW items have been fully covered in the polarity tests. This includes an assessment of which AOCS SW modules are used in which AOCS modes.

d. This requirement states that the polarity checks are carried out as some of the last tests before the shipment to the launch site. Often, they are performed before the environmental test campaign. This is to account for equipment accessibility issues. Final polarity checks can be run after environmental testing. Polarity tests are typically executed before the test campaign as a risk mitigation activity, in order to detect potential issues before running the environmental tests. The rationale for the requirement is to test the complete configuration, please refer also to clause b for clarification on "complete configuration".

6.5.1.6 Launcher interface test

a. It is recommended, even required by most launcher authorities, to perform a fit check early in the development to allow time for modifications if needed. The fit check is performed using a launch adapter provided by the launcher authority. In case of a launch dispenser, the interface is checked between the dispenser and the launcher, as well as between the dispenser and the space element. See example in Figure 6-9. The final fit check is performed at the launch site with the actual flight adapter. Note that the fit check is a verification of the mechanical, electrical and data interface. The fit check can also be used as an opportunity to verify the space element separation system. For example, a clampband installation and release test might also be performed. This is a functional test of the clampband release system, which also depends on the mechanical interface of launcher and space segment side. In that sense, it is also a launcher interface test. The separation test can also be the opportunity to measure the shock levels generated by the separation and transmitted in the space element. See ECSS-E-HB-26.

Figure 6-9: Fit check of Galileo Spacecraft with the launch dispenser

b. The rationale is that the environment at the launch facility is different from the environment in which the AIT took place. Interfaces between GSE and facility are to be checked, and interfaces between space segment element and GSE might also have changed (e.g. length of cables).

c. No specific guidelines for this requirement.

6.5.2 Mechanical tests

6.5.2.1 Physical properties measurements

General information about physical properties measurement is provided in annex A.2

a. Typical facilities to measure physical properties are described in annex A.2.2.

b. Physical properties in launch and orbit insertion configurations are part of the information required by the launcher authority. They are also required for any possible in orbit configuration (partly deployed and fully deployed) to allow the spacecraft control. However, the physical properties in deployed configuration can in most cases not be directly measured. They are derived from measurements of the different constituents (element without appendages and appendages separately).

c. If necessary, to reach the requirements balancing mass are installed on the element to adjust the position of the CoG or the moments of inertias. More details about the balancing are provided in Annex A.4about spin balancing test.

d. This is in particular the case when the element includes large deployable appendages, which cannot be deployed under gravity.

e. Spin balance test is covered by Annex A.4.

f. Note that the gravity affects the fluid distribution.

6.5.2.2 Modal survey test

a. Note that the modal survey test is rarely performed except on crewed modules and payload racks. The dynamic characterisation is usually performed through resonance search on a shaker. It is however a simple and efficient test to characterise the dynamic behaviour of a test article. (see ECSS-E-ST-32-11).

6.5.2.3 Static load test

General information is available in annex A.3.

a. Sometimes the static load test is performed with interface conditions different to the flight ones. For example, the test adapter is different from the flight adapter, or the spacecraft is fixed to the test adapter with a clamp band or a system having a different stiffness than the flight clamp band. The use of a flight or flight-like adapter and clamp band is not always possible. This is not necessarily a problem if the test predictions are performed with the test setup. It is however noted that a different stiffness at the test article interface can modify the load distribution.

b. In general, a test prediction is required with the specific configuration of the test. The static load test differs from the flight loads because a discrete number of load cases is applied on main interfaces and this is different compared to the inertial loading of the whole system under acceleration. The aim of the static test is to reach qualification loads or internal stresses in some critical elements considering the available test setup and the available test configuration. Test predictions performed to adjust the parameters of the test is mandatory.

6.5.2.4 Spin Test

General information is available in annex A.4.

a. The spin test at element level is only performed for spinning spacecraft.

b. As mentioned in Annex A.4.1, the spin test is used for balancing, acceleration loading and possibly functional testing. Each of those objectives are taken into account when alternative configurations are considered. For example for a large deployable boom, the acceleration loading might be tested at boom level while the interface to the element is tested using a mass dummy at element level.

c. The spin test being an acceleration test, it is important that the mass of the propellant is considered to reproduce the corresponding loads. Note that gravity and centrifugal forces affect the fluid distribution.

6.5.2.5 Transient test

Transient test is meant to reproduce the transient acceleration profile at launch or during other events (engine firing, parachute deployment, landing). To reproduce launch loads, facilities exist to impose a transient acceleration in all axes simultaneously at the interface of the element, as the HYDRA at ESTEC for example. Transient tests are rarely performed in practice and agreement of the launch authority is required.

a. Most electrodynamic shakers can apply a transient acceleration in one axis at a time. Hydraulic facilities allow application of transient accelerations in several axes simultaneously.

b. See discussion about tank filling in Annex A.7.3.5 (Sine test). In case tank dummies are used on a structural model, it is important to verify that they do not introduce unrealistic amplifications due to very low damping (e.g. metallic dummy)

c. No specific guideline for this requirement

d. When the appendage size prevents a test at element level in the configuration applicable at the time of engine firing (e.g. deployed solar arrays for in-orbit insertion of a planetary mission), alternative verification is considered

e. Resonance search is covered by Annex A.7.5. Dynamic responses of the test article are compared between the runs to highlight any change in the dynamic behaviour

f. Changes in dynamic responses are carefully assessed, even for modes with effective mass lower than 10%, as they can indicate some degradation

g. No specific guideline for this requirement

6.5.2.6 Acoustic test

General information is available in annex A.9.

a. The test fixture reproduces the interface boundary condition, and the acoustic impingement at this interface. The test article is sometimes suspended using bungee cords. See annex A.9.3.

b. See annex A.9.3. Care is taken to avoid standing waves below the test article.

c. In case tank dummies are used on a structural model, it is important to verify that they do not introduce unrealistic amplifications due to very low damping (e.g. metallic dummy).

d. No specific guideline for this requirement.

e. No specific guideline for this requirement.

f. It is important to avoid unrealistic phenomena like standing waves appearing between the bottom of the test article and the floor or between the panels of the test article and the walls of the chamber. Specific precautions need to be taken like: avoiding the panels of the test article to be parallel to the walls of the chamber and adding a shielding panel between the floor and the bottom panel of the test article.

g. Dynamic responses of the test article are compared between the runs to highlight any change in the dynamic behaviour

h. Changes in dynamic responses are carefully assessed, even for modes with effective mass lower than 10%, as they can indicate some degradation.

6.5.2.7 Random vibration test

General information is available in annex A.8.

a. Each axis is tested separately on an electro-dynamic shaker.

b. No specific guideline for this requirement.

c. See discussion on filled/empty tanks in annex A.7.3.5. In case tank dummies are used on a structural model, it is important to verify that they do not introduce unrealistic amplifications due to very low damping (e.g. metallic dummy).

d. No specific guideline for this requirement.

e. When the appendage size prevents a test at element level in the configuration applicable at the time of engine firing (e.g. deployed solar arrays for in-orbit insertion of a planetary mission), alternative verification is considered.

f. Note that notching in random is less straightforward than in sine. It is recommended to discuss the notching approach and its implementation with the test facility.

Force limited notching is recommended as it provides a simple way to define and implement the notchings. See Annex A.7.3.4.

g. Be aware that the cross axis acceleration can lead to significant responses, which are not covered by predictions performed with one axis excitation only. For this reason, limits (notchings) are also needed in the cross axis directions on the responses, to protect the hardware.

h. No specific guideline for this requirement.

i. Resonance search is described in annex A.8.5. Dynamic responses of the test article are compared between the runs to highlight any change in the dynamic behaviour. Note that transfer functions between the input level and the responses can also be computed for the random test. Real time monitoring of those transfer functions can be used to highlight any change in dynamic behaviour during a run and between runs.

j. Changes in dynamic responses are carefully assessed, even for modes with effective mass lower than 10%, as they can indicate some degradation.

k. No specific guideline for this requirement.

6.5.2.8 Sinusoidal vibration test

General information is available in annex A.7.

a. Each axis is tested separately.

b. See discussion on filled/empty tanks in Annex A.7.3.5. In case tank dummies are used on a structural model, it is important to verify that they do not introduce unrealistic amplifications due to very low damping (e.g. metallic dummy).

c. No specific guideline for this requirement.

d. Notching is covered by Annex A.7.3.4. Force limited notching method is recommended-

e. When the appendage size prevents a test at element level in the configuration applicable at the time of engine firing (e.g. deployed solar arrays for in-orbit insertion of a planetary mission), alternative verification is considered.

f. It is very important to instrument and protect the specimen with some redundancy in case of failure of one accelerometer. Redundancy is recommended for notching and abort channels. It is also important to keep in mind that some channels can be inverted, especially at the beginning of a test campaign. In order to avoid possible issues, protections in terms of notchings and aborts are implemented in all directions. It is also recommended to check the results of the pre-test made in order to ensure that the channels used for notchings and aborts behave as expected. Notching and abort are covered in annex A.7.3.4. Abort can be brutal. It is recommended to systematically implement notching to avoid abort.

g. - Resonance search is described in Annex A.7.5. Dynamic responses of the test article are compared between the runs to highlight any change in the dynamic behaviour. Monitoring of those transfer functions can be used to highlight any change in dynamic behaviour between runs, e.g. change in damping with the excitation level.

h. Changes in dynamic responses are carefully assessed, even for modes with effective mass lower than 10%, as they can indicate some degradation

6.5.2.9 Shock test

Covered by ECSS-E-HB-32-25.

6.5.2.10 Micro-vibration susceptibility test

Reference to Annex A.13.

6.5.3 Structural integrity tests

6.5.3.1 Proof pressure test

General information about Proof Pressure test is provided in Annex B.3.

a. The proof pressure test is a workmanship test and ensures integrity of the pressurised hardware, which can be loaded for the vibration tests. This is why it is performed before the environment tests.

b. This requirement has been deleted in ECSS-E-ST-10-03C Rev.1

c. No specific guideline for this requirement.

6.5.3.2 Pressure cycling test

General information about Pressure cycling test is provided in annex B.4.

The test applies only for qualification and is not performed on flight hardware. Hence, it is rarely applied at element level.

a. No specific guideline for this requirement.

6.5.3.3 Design burst pressure test

General information about Design burst pressure test is provided in annex B.5

The test applies only for qualification and is not performed on flight hardware. Hence, it is rarely applied at element level.

a. No specific guideline for this requirement.

b. No specific guideline for this requirement.

c. No specific guideline for this requirement.

6.5.3.4 Leak test

General information about Leak test is provided in annex B.2.

a. The leak test is very important as workmanship verification of the element assembly from a fluidic perspective. It is also very important from a safety perspective before loading and pressurizing any fluidic system.

b. No specific guideline for this requirement.

c. Annex B.2.3provides a description of some leak test methods.

6.5.4 Thermal test

By convention, a thermal test involves a temperature variation of at least one test specimen boundary from room temperature, as defined for clean rooms.

<u>**Test objectives and precipitation of latent infant mortality defects**</u>

A thermal vacuum test or a thermal ambient test at mission pressure can contribute to different testing objectives:

- Functional and performance verification allowed during required temperature plateaux and transitions in between.
- During protoflight or acceptance testing, risks mitigation of problems late discovery before the launch and of detrimental failures occurrence during the in-orbit infant mortality period.

Keep in mind about these different testing objectives:

- Functional and performance tests with continuous or regular monitoring in between have also the aim to detect pre-existing patent defects that are present at the beginning of the test.
- To reduce mission infant mortality to an acceptable level, the risk mitigation objective includes the important matter of latent defects precipitation by exposure to pressure and temperature conditions (or environmental stress screening).

Note: a patent defect is detectable. A latent defect is undetectable. At the very moment it precipitates, a latent defect becomes patent and detectable.

Reminders about the different types of defects:

- Qualification and acceptance stages can detect defects in design, materials, parts, processes and workmanship. Some design defects can escape the qualification stage.
- Each defect can be intermittent or persistent.
- Each defect can be a pre-existing patent (or detectable) defect or a latent (or undetectable) flaw in incremental growth until becoming a patent (and eventually detrimental) defect.
- Pre-existing patent defects can be defects that escape quality control and previous environmental tests.
- Pre-existing patent defects can be pressure and temperature dependent (or environment dependent) and not present at room temperature or at room pressure. For example, a quartz oscillator defect called "activity dip" is present only at a particular temperature.
- Latent defects can become patent during the ongoing and posterior environmental tests, the posterior AIV activities, the launch phase and each in-orbit or mission phase.
- Two main types of latent defects depend on temperature conditions: Arrhenius type and thermo-mechanical type.
- Arrhenius type latent defect precipitation efficiency depends on its exposure duration to a hot or cold temperature level.
- Thermo-mechanical type latent defect precipitation efficiency depends on hot and cold temperature levels, temperature rates of change during transitions and numbers of cycles.
- Concerning latent defects precipitation by temperature conditions inside equipment units, the thermal tests at equipment level cover better this objective. They are less efficient at element level because temperature conditions (in particular temperature rates of change) are generally less severe at defects locations (PCB, EEE components…).

- Concerning harnesses latent defects precipitation by temperature conditions, the ECSS standard requires 3 (+ 1) cycles at element level mainly for thermo-mechanical type latent defect (in particular, for electrical connectors).

Combined thermal tests at element level

A thermal vacuum test or a thermal ambient test at mission pressure can be combined with other tests such as a thermal balance test or a calibration test. For example, it is possible to add:

- A thermal balance test under the same test configuration than a thermal vacuum test or a thermal ambient test at mission pressure.
- A characterisation or a calibration test at intermediate temperature plateaux or during transitions between temperature plateaux, if some high level performances are temperature dependent. This is to check for example the dimensional stability, the radiometric, the optical or the RF performances.

Obviously, it is not possible to standardise characterisation and calibration (C&C) tests. They are not part of the ECSS-E-ST-10-03 thermal tests even if their implementation is possible with a unique test configuration.

The combined tests meet with acceptable and quantified deviation the technical constraints of each individual test:

- The most demanding tests generate the major constraints coming from the different test methods, GSEs or instrumentations.
- See hereunder the guidelines linked to 6.5.4.1n.

Thermal tests management and planning at element level

Performing an element thermal test requires a thorough preparation and an organisation similar to a space project in terms of test management and planning with:

- Collaborative team organisation.
- Tasks and responsibilities sharing.
- Cost, schedule and risk evaluation.
- Test plan, specification and procedure reviews by all involved disciplines and parties, including approval of requirements validation approach.
- Advanced GSE development, manufacturing and testing.

The preparation of an element test can take advantage of the following guidelines:

- The test (or combined tests) documentation tree reflects without ambiguity the tasks and responsibilities sharing between all the involved actors.
- Each combined test has a separated test specification.
- Preliminary test specification and test instrumentation plan are useful in order to select sufficiently early the test facility. These documents collect the data for the negotiation of the (mechanical, thermal, electrical, RF, optical, FDIR, safety…) interfaces between the test facility and the test set-up.

Guidelines concerning thermal tests at element level

The following guidelines are only for the clause 6.5.4 of ECSS-E-ST-10-03 temperature cycling tests at element level and concern in particular:

- The elaboration of the test profile.
- The TRP temperature drive during plateaux and transitions in between.
- The definition of the mechanical and thermal test set-up.

The guidelines in this clause 6.5.4 are self-contained in order to regroup them for end users at element level. A guideline can concern both temperature cycling tests at equipment level and at element level. In this case, clause 5.5.4 contains the same guidelines.

6.5.4.1 Guidelines to thermal vacuum test and to thermal ambient test at mission pressure

a. When temperature cycling is performed both under vacuum and under mission dependent atmospheric pressure, a single thermal test facility use is more practical and efficient. For example, missions at high altitude within the Earth atmosphere or within the Mars atmosphere or on the Mars surface are good candidates for testing in a single facility:
   - o The primary pumps of some thermal test facilities have pressure control capabilities covering both space vacuum and such low pressures.
   - o These thermal test facilities can use dry air, dry N_2 or CO_2.

Be aware:

- o Verify that the chamber pressure pumping capability is in the range of interest.
- o Make sure that the pressure sensors cover the expected pressure range.
- o Verify that the shroud cooling capability can cope with additional heat loads by gaseous conduction or convection coming from the vacuum chamber structure at room temperature.
- o Verify that the test conditions do not present risks of ice-forming on the external side of the chamber structure.
- o If the test is done in different facilities, try to use the same test set-up for testing coherency.

b. For this clause, the guidelines deal with several matters.

Test Profile and Tests done at Room Conditions

Pressure and temperature room conditions are as clean room conditions. These functional and performance tests are not part of a thermal vacuum test or a thermal ambient test at mission pressure that involves a boundary temperature different than the room temperature. They are checks done just before and after the temperature cycles.

Test Profile

The test specification defines the functional tests and the performance tests to be done during the plateaux for each functional chain (power, AOCS, P/L…) or for each space segment unit. The test specification reconciles the different implementation practices of suppliers and customers, by answering the following questions:

- o Is the element mission only under vacuum?
- o If not, what are the cycles to be done at mission dependent atmospheric pressure?

- o How many cycles?
- o What are the long cycles?
- o What are the short cycles?

One example (see Figure 6-10):

- o Mission only under vacuum: yes.
- o Cycles at mission dependent atmospheric pressure: not applicable.
- o Number of cycles: 4.
- o Long cycles: 1 (n° 3).
- o Short cycles: 3 (n° 1, n° 2 and n° 4).

One other common practise:

- o Long cycles: 2 (first and last cycles).
- o Short cycles: all intermediate cycles.

Test Profile for Combined Cycles (at mission dependent atmospheric pressure and under vacuum)

The test specification tailors the following practical guidelines:

- o The cycles under vacuum take place before the cycles at mission dependent atmospheric pressure.
- o The minimum number of cycles at mission dependent atmospheric pressure is half of the total number of cycles.

Example of good practice: the number of qualification cycles during element level testing is the required number (4) because:

- o 2 cycles done under vacuum.
- o 4 – 2 = 2 cycles (≥ 4/2) done under mission dependent atmospheric pressure.

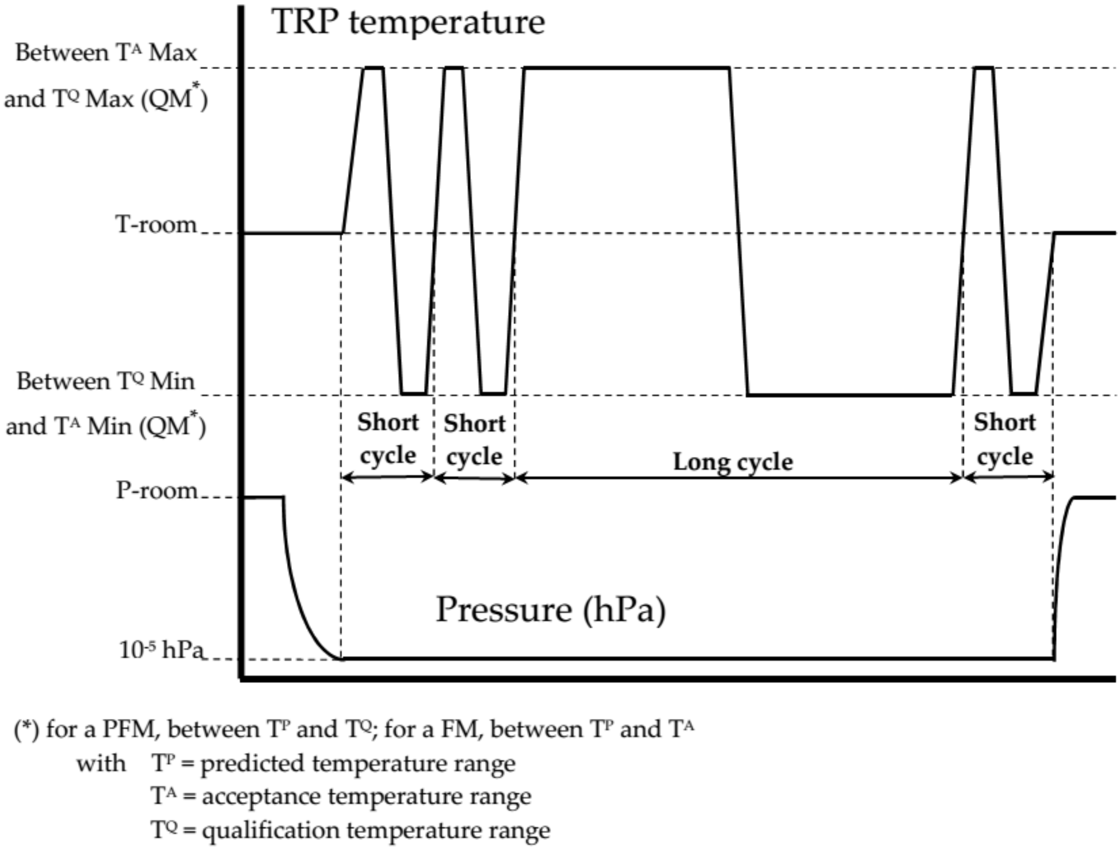


Figure 6-10: Example of a thermal vacuum test profile for a space segment element

Plateau Total Duration

Note: Non-European standards, as SMC Standard SMC-S-016, use terms like "temperature soak duration" to define the total plateau duration. Some standards use the word "soak" only for long cycles. There is no notion of dwell time at element level, which is a difference with the equipment level.

Current practises are very different in terms of plateaux durations:

- The total duration of a plateau is generally the longest of:
  - The short or long minimal plateau duration defined in the test specification.
  - The functional or performance tests duration (if any) including GO/STOP delays.
- For each thermal module of a space segment element, a plateau begins as soon as each unit TRP temperature stays within its control hot or cold band as illustrated Figure 6-11.

  NOTE A thermal module is entirely surrounded with efficient thermal insulations. So, the temperature drive of a thermal module is independent of the temperatures of the other thermal modules.

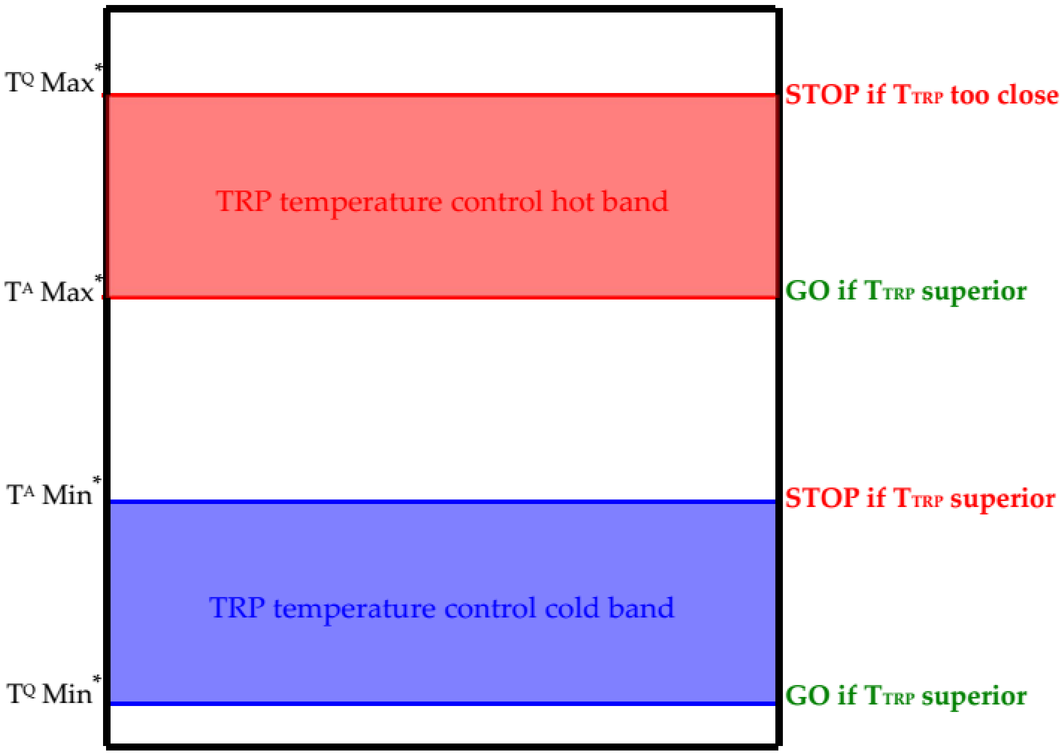
TRP Temperatures Drive on a Plateau

Maintaining the unit TRP temperature within the control bands (see Figure 6-11) asks for:

- A specific attention during the transitions between electrical modes of very dissipative units.
- A proper thermal management of the test specimen boundaries with high thermal response times.
- A sequence of tests avoiding delays before the start of the next test. This can be done by swapping to another more stable thermal module.
- Smart sequence of tests to avoid in particular too long and too dissipative sequences.

Proceeding by "trial and error" during the first cycle is the best way to both:

- Better drive the TRP temperatures during the subsequent cycles, and
- Significantly reduce the test total duration.



(*) for a QM, between T^A and T^Q; for a PFM, between T^P and T^Q; for a FM, between T^P and T^A

with T^P = predicted temperature range
T^A = acceptance temperature range
T^Q = qualification temperature range

Figure 6-11: Unit TRP temperature control bands during space segment element plateaux

Stability Criteria

The only practical stability success criterion is to remain within the TRP temperatures control band (see Figure 6-11). During a plateau, the TRP temperature fluctuates more or less according to the amount of energy dissipated by the units under test.

Keep in mind to avoid confusion:

- The switch-on verification begins only after reaching the OFF unit internal temperatures stabilisation criteria (in °C per hour) as defined in the test specification.
- The TRP temperature stabilization does not mean internal temperatures stabilization.
- These temperature stabilisation criteria are different of the thermal balance test ones (see ECSS-E-ST-31).

Functional and performance tests success criteria

A functional or performance test is successful when the units TRPs stay within the respective control bands during the whole test duration. The decision to begin or to stop a test is illustrated in Figure 6-11. Many practical aspects interfere with such operational decisions:

- Several TRPs and several units can participate to a single functional or performance test.
- Some TRPs temperature control bands can differ according to the operation mode.
- Before testing a unit switch-on capability, the stabilisation of its internal temperatures is necessary between switch-off and switch-on.
- If a particular functional and performance test depends on one or more internal temperatures stabilisations, the functional and performance test definition includes the associated internal temperatures stabilisation criteria (in °C per hour).

As an example, a very dissipative unit can avoid exceeding the control band by:

- Giving the GO close to the coldest temperature of the control band.
- Switching-off unnecessary units.
- Adjusting the test parameters (heaters, cold plates, shrouds…).

Conflicting TRP Temperature Control Bands

Some space segment element zones have good temperature homogeneities. For example, an aluminium alloy structure with several units directly mounted behind shared radiators has good temperature homogeneity. In such a scenario, the individual TRP temperature control bands can come into conflict with one another. This is caused:

- Either by the first unit reaching a limit (STOP) that prevents the testing of units with much wider temperature ranges.
- Or by an avionics bay hot or cold biased leaving little room for fulfilling the success criteria. Figure 6-12 illustrates a difficult TRP temperature management on the hot plateau, but easy on the cold plateau.

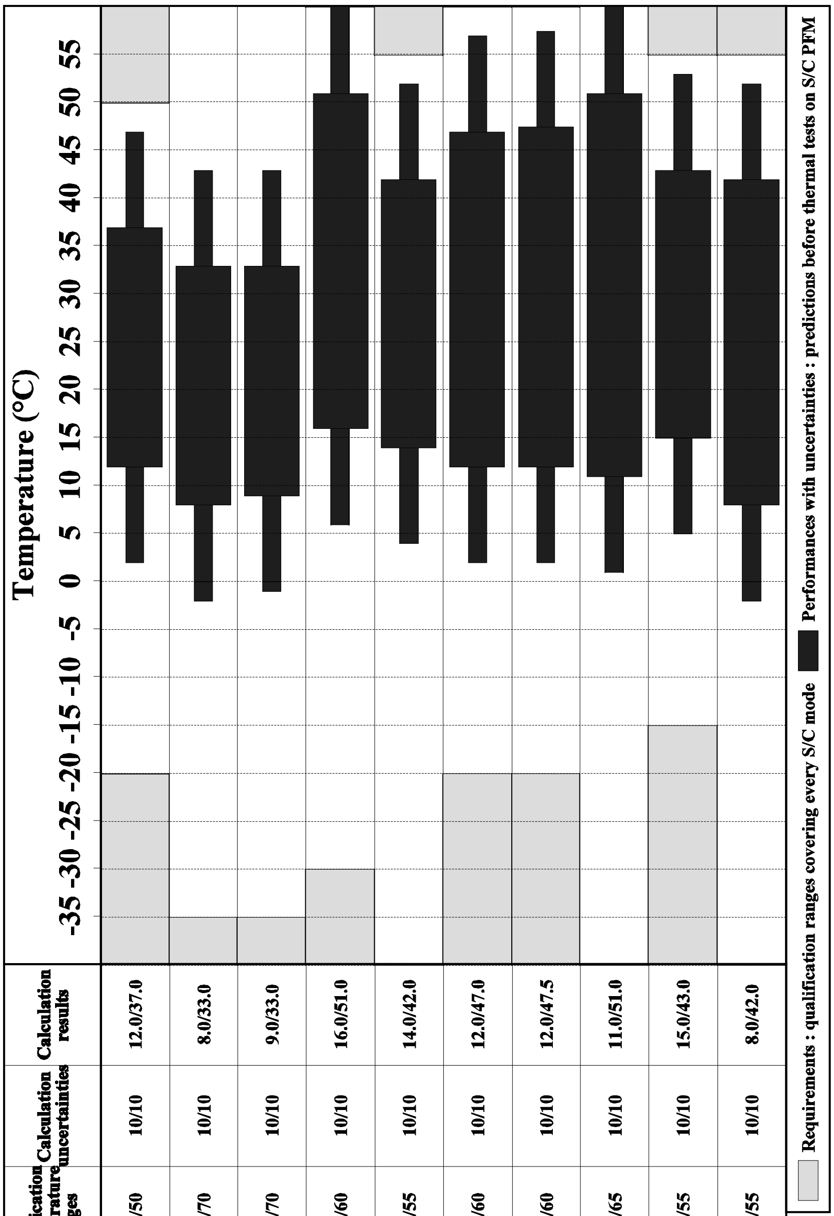
The TCS team can warn the project team about such predictable conflicts at early stage. The conflicts can be alleviated by:

- Developing new units with identical TRP qualification temperature ranges.
- Trying to accommodate off-the-shelf units at suitable locations or with enhanced heat transport H/W compatible with their TRP qualification temperature ranges.
- Using thermal analyses to request for deviation before testing rather than raising a waiver after testing.

PFM S/C testing and temperature cycles under vacuum

P/F avionics module and most temperature control bands during cold and hot plateaux

Unit/thermal zone and temperature definition	Identification of test sensors	Qualification temperature ranges	Calculation uncertainties	Calculation results
P/F -X wall (Nodes 350-353 and 360-363)	Strand n° 7 TC n° 121/122/123/124	-20/50	10/10	12.0/37.0
Magnetotorquer X P/F +Y wall (Nodes 50403/50803)	Strand n° 3 TC n° 42	-35/70	10/10	8.0/33.0
Magnetotorquer Z P/F +Y wall (Nodes 50307/50311)	Strand n° 3 TC n° 51	-35/70	10/10	9.0/33.0
SADA (TRP : node 16)	Strand n° 1 TC n° 12	-30/60	10/10	16.0/51.0
OBC calculator (TRP : node 14)	Strand n° 4 TC n° 73	-40/55	10/10	14.0/42.0
Wheel X (TRP : node 40)	Strand n° 1 TC n° 13	-20/60	10/10	12.0/47.0
Wheel Z (TRP : node 70)	Strand n° 1 TC n° 16	-20/60	10/10	12.0/47.5
Gyrometers (TRP : nodes 6/7/8)	Strand n° 1 TC n° 7/8/9	-40/65	10/10	11.0/51.0
PCDU (TRP : node 23)	Strand n° 5 TC n° 97	-15/55	10/10	15.0/43.0
TM/TC (-Y side) (TRP : node 27)	Strand n° 8 TC n° 157	-40/55	10/10	8.0/42.0



Note: predictions cover all orbital phases with calculations results rounded to the nearest °C

Figure 6-12: Unit TRP temperatures drive feasibility (example of a P/F equipment bay)

Test Report

These guidelines about test report concern only the test profile, the critical TRP drives, the plateaux total durations and the times and TRP temperatures of the functional and performance tests.

The test report records and discusses with regard to the test specification:

- o The realised test profile and number of cycles.
- o The realised plateaux total durations.

The test report details, for each functional or performance test, the time and the TRP temperatures:

- o At the time of each GO or STOP.
- o At the end of the test together with the test duration.

To help the validation, the report visualises time dependent plots of measured data, zooming in on:

- o Some typical temperature plateaux.
- o A selection of TRP temperature evolutions illustrating the different behaviours.
- o The critical TRP drives.

Temperature Rate of Change: see guidelines in 6.5.4.1o.

Test Mechanical and Thermal Configuration

A thermal balance test (see 6.5.4.1n) or a high level (geometric stability, optical, radiometric, RF…) performance characterisation or calibration test requires higher capabilities than a temperature cycling test. Even for a temperature cycling test, the test mechanical configuration, with many (thermal, electrical, optical, RF…) GSEs and harnesses around the specimen under test, can be very complex and critical. It is important to put special attention at the following aspects:

- Take great care of test harnesses routing in the test facility (lengths and radii of curvature, guide rails if needed…).
- Keep comfortable margins with regard to the temperature limits of each test GSE and harness (including connectors).
- Keep comfortable margins with regard to the thermal expansion of each test GSE.
- Keep comfortable margins with regard to the ratings (or the derating rules) of the test EEE components (sensors, heaters…).
- Keep comfortable margins with regard to the thermal control of each test GSE and harness. In particular, install sufficient test heating powers.
- Be careful to uncertainties, errors and failures if harnesses with test heaters under MLI.
- Take care that existing GSE can require modifications for adaptation to the test article.
- Design at the same time the test specimen, the mechanical interface and the thermal interface between every test GSE and the test specimen.
- Take a lot of test GSE spares (including sensors, heaters, MLI…) for test set-up maintenance until the dry run or the functional blank test.

Electrical, Monitoring and Control Test Configurations

A thermal test under vacuum or low pressure is known as being very dangerous for a PFM or a FM and as requiring prompt and reliable actions for recovery after a failure. Some useful guidelines are the followings:

- Perform reliability analysis of the test configuration (including the data acquisition system) and define redundancies.
- Use thermal analyses for evaluating the test specimen time constants and compare them to the facility recovery delays.
- Define redundancy and automatic FDIR mechanism for each critical emergency.
- Define redundancy ensuring no loss and full recovery of data.
- Use well separated test control system and data acquisition system.
- Use a unique database to collect all test data (from facility, from various GSEs and from specimen). This allows the programming of a not limited comparative post-processing (including graphical post-processing).

Overall Test Configuration

- The test specification defines, as necessary and if applicable, all the other aspects of the test configuration (electrical, optical, RF, monitoring, safety…) including testing constraints like material outgassing or offgassing, cleanliness, bio contamination, bake-out, purging, cleaning, venting, grounding (including test MLI), DC and RF corona, multipactor…
- A preliminary test specification can define, at early stage, the interfaces with the test facility in order to be able to select it. For example, it is a question of keeping comfortable:
    - Clearances during specimen handling to go near the test facility and to enter in it.
    - Clearances during specimen movement (if any) within the test facility.
    - Margins concerning sealed feedthroughs capabilities for electrical, optical, RF or instrumentation connexions.
- A blank test of the chamber can be very helpful if the test configuration is complex.
- A dry-run before door closure can exercise the teams to perform specific test procedures.
- The test report and the inspection reports, written before and after the test, keep a precise record of the overall test configuration including an exploitable photography file.

c. The main objective of the Reduced Functional Test before chamber closing (open door RFT) is to validate the test electrical setup and in particular all the physical links going through the chamber feedthrough.

d. No specific guidelines for this requirement.

e. No specific guidelines for this requirement.

f. For this clause, the guidelines deal with several matters.

Operating, Non-operating and Switch-on Conditions

Operating, non-operating and switch-on conditions refer mainly to "type a" units i.e. electronic, electrical and RF units.

For other than "type a" equipment, each unit ICD or user manual defines precisely the conditions and the transitions in between.

NOTE The testing standard specifies twelve equipment types (see for example Table 5-1 of ECSS-E-ST-10-03).

For example, the conditions of a secondary battery can be: charge, trickle charge or discharge.

Switch-on Temperature (for "Type a" Units)

"Switch-on" and "start-up" are synonymous terms. As the hot switch-on temperature is always lower than the maximum operating temperature, be aware:

- The switch-on in hot conditions accounts for the fact that the unit dissipation leads to a transient increase of the unit TRP temperature. The test set-up and profile prevent the unit from exceeding the qualification limit.
- To avoid overheating risks at switch-on, it is good practice to start up the unit below the hot qualification or acceptance operating temperature.

g. For this clause, the guidelines deal with several matters.

Functional and Performances Tests during Transitions

To run functional and performances tests during transitions between plateaux can be of paramount importance:

- To run functional and performances tests during transitions and to monitor the test article during transitions are two different needs.
- Many functional chains can need tests during transitions. In particular, it is always the case for the active TCS functional chain.

Functional and Performances Tests for Active TCS

The active TCS uses EEE components or units like temperature sensors, mechanical thermostats, heating lines, thermoelectric coolers, heat pipes, fluid loops, cryogenic machines or heat pumps:

- The test specification defines the active TCS functional and performance tests and their occurrences on the temperature cycling test profile.
- Some functional and performance tests require dedicated temperature levels during transitions between hot and cold plateaux.

h. See bullet f. guidelines about unit switch-on.

For each unit, the test specification defines the minimum number of switch-on and their locations in the test profile.

i. No specific guidelines for this requirement.

j. A recommendation is to select the configurations such that all the interfaces are at least energized once, without testing all possible configurations for cross-strapping verification. This is a trade-off between testing time and exhaustive cross-strapping check. This allows to ensure that all interface circuits are functionally checked.

k. For this clause, the guidelines deal with several matters.

DC corona monitoring and high voltage risks

This clause is only about DC corona monitoring.

If voltage ≥ 100 V, refer to ECSS-E-HB-20-05 guidelines about high voltage effects and risks.

Multipactor, RF corona and RF power handling monitoring at element level

Multipactor, RF corona and RF power handling testing is at RF component level and at RF equipment level. This testing is not at spacecraft or payload level. This testing at instrument level is not a recommended practice. The risk of permanent damage on RF chain components is high as well as of other instruments contamination.

As assistance in detection and monitoring of potential occurrence of any of these three phenomena at spacecraft, payload or instrument level during thermal vacuum test or during thermal ambient test at mission pressure, the following table gives, in case of unexpected or abnormal behaviours, the phenomena among these three phenomena that can be investigated.

Table 6-5: Multipactor, RF corona and RF power occurrence versus relevant investigations at Element level

Observation: If any…	Investigations can take into account possible damaging effects of…
distortion in the transmitted RF signal	RF power handling or multipactor
permanent degradation in the transmitted RF signal such as high attenuation Note: In the case of RF corona, the transmitted RF power is typically attenuated by 2-3 dB during the first phases of the discharge. If the discharge is self-sustained, the RF chain breaks in short period (less than one minute).	RF power handling or RF corona
sudden low amplitude bursts of reflected RF power (not sustained but occasionally persisting)	Multipactor
sudden reflected RF power (self-sustained)	RF corona
sudden and progressive reflected RF power (and eventually self-sustained)	RF power handling
unusual and sudden increase in the level of the residual harmonics signals	RF power handling, RF corona or multipactor
sudden and progressive increase of temperature detected by temperature sensors (if any) near the suspected area	RF power handling or RF corona
small bursts of released gas detected by the vacuum chamber instrumentation (pressure gauges…)	RF power handling or RF corona
detection by other sensors (if any) of plasma or of light generation due to plasma	RF corona

l. No specific guidelines for this requirement.

m. For this clause, the guidelines deal with several matters.

Unit TRP temperature management

For the temperature cycling tests at element level, the unit ICD defines the position of the temperature sensor representing each unit TRP. This temperature sensor is:

- A test TRP temperature sensor, if no flight temperature sensor at this TRP.
- Or, otherwise, the existing flight TRP temperature sensor.

For a TRP of paramount importance, another test temperature sensor can provide redundancy.

Test Report

The test report records precisely each temperature sensor position including an exploitable photography demonstrating the proper implementations of the:

- ICD for each TRP. In particular, the test report demonstrates that each TRP is a cold point of the unit housing area.
- Instrumentation plan for any other measured temperature.

n. For this clause, the guidelines deal with several matters.

Unique Configuration for Combined Tests:

A thermal balance test or another test demanding high test accuracies can be performed simultaneously. The demanding tests specifications and instrumentation plans make provision of:

- Additional test instrumentations to monitor the thermal behaviour of the tested specimen and of the whole test set-up around it. This thermal instrumentation ranges from standard temperature sensors to more sophisticated IR cameras, heat flow rate sensors or Q-meters, heat flow rate density sensors, calorimeters or mechanical tilt sensors.
- Dedicated test hardware and GSEs with the following objectives:
  - To drive efficiently the temperatures of the TRPs, of each zone, either by cooling or heating.
  - To place in front of each test specimen external surface the corresponding radiative sink temperature.
  - To simulate the solar incident heat flow rate densities thanks to the calibrated artificial Sun of the test facility (if any).
  - To control the interface heat flow rates with the test hardware. For example, with conductive or radiative Q-meters.
  - To reduce to a negligible value, using thermal guards, the interface heat flow rates through test harnesses or specific test mechanical fixations.

The three last objectives are specific to a thermal balance test combined with a thermal vacuum test or with a thermal ambient test at mission pressure. Be aware that in general:

- Combined tests yield conflicting constraints. For example, due to intrusive GSEs or intrusive instrumentations.

- These constraints generate a loss of accuracy of the test results in particular during the thermal balance test.

Overall Test Set-up

The thermal environment characteristics, the TCS thermal design and the space segment element itself imply some constraints in terms of:

- Test representativeness taking into account, if significant, thermal impacts of test GSEs and test harnesses.
- Heat exchange crosstalks between different parts of the test specimen. For example, heat flow rates coming from IR lamps dedicated to a unique radiator can influence too strongly a closeby critical surface.

Thermal Analyses Practical Benefits

Thermal analyses help to understand the driving parameters and trade-off the test configuration. They are of paramount importance:

- By running the flight and test analyses to evaluate acceptable test biases or to reduce them. For example, these biaises are due to heat leaks through test harnesses or contacts between the GSEs and the unit under test.
- By evaluating the radiative sink temperatures due to element complex external geometry, GSEs around the element, test facility shrouds singularities...
- By evaluating the heat exchange crosstalks, for example, between a P/F and an instrument delivered as a black box to a payload level or to a S/C level.
- By evaluating the impacts on internal hot spots due to any residual low pressure.
- By estimating the transition durations, in particular from the hot to the cold plateaux, and by investigating ways to speed up transitions.
- By evaluating the allowed responses delays in case of a particular failure or emergency.
- By consolidating the test thermal margins through sensitivity studies of each critical thermal module. During each test, these margins apply to temperature limits, to heating or cooling capabilities or to heaters deratings.
- By anticipating the test effects of each heating or cooling power change through sensitivity studies giving the main temperature changes in °C/W.

o. This requirement does not mention explicitly the TRP. Nevertheless, it refers to the TRP.

   The following considerations drive the TRP temperature rate of change:

   - Screening efficiency to precipitate latent defects: the higher the rate, the more effective the screening.
   - Duration of the test: the higher the rate, the quicker the transitions.
   - Test article integrity: the higher the rate, the higher the thermo-elastic stresses.
   - Representativeness of mission conditions.

   Keep in mind:

   - At element level, low TRP temperature rates of change are obtainable.

- o Within units (PCB, EEE components…), many internal rates can be significantly slower than TRP ones according to the delay due to each internal point thermal time constant.
- o Due to the rates obtainable at element level, most reliability experts consider this efficiency as generally very low.

Generally, the test set-up offers:

- o Efficient heating GSEs to rise as required the temperatures to the hot plateau.
- o Poor cooling capabilities to lower the temperatures to the cold plateau.

Sometimes, the vacuum chamber pressure control capabilities can accelerate significantly the cooling by adding gaseous conduction at low pressure (in particular, at cryogenic level). At the time of transition to cold plateaux, dissipative units can be switched off to speed up the cool down.

The test report records and visualises time dependent plots of a selection of the measured temperature rates of change illustrating the different speeds and the critical transition durations.

p. Some here above guidelines are about:

- o Temperatures stability (see stability criteria in bullet b.).
- o Transitions durations between extreme plateaux (see temperature rate of change in 6.5.4.1o.).

q. When the two-phase heat transport unit is horizontal, a practical and efficient test set-up monitors and controls, at every moment during the test, the tilt angles.

6.5.4.2 Guidelines to thermal vacuum test

a. To avoid contamination of the specimen under test, of the test facility and test GSE sensitive to contamination and to reduce outgassing risks from test GSE and test facility, the C&CCP (as per the DRD in ECSS-Q-ST-70-01 Annex B):

- o Refers to the declared material lists (as per the DRD in ECSS-Q-ST-70 Annex A) including all test GSEs DMLs. Examples: test harnesses, test heaters.
- o And details all the activities, methods and procedures (material selection, protective measures with regard to sensitive areas, instrumentation for contamination monitoring and control, inspections, personnel training, cleaning and decontamination, bake-out, purging…).

Concerning the test facility and the test GSE and considering the flight H/W with which they interface, to apply the same surface cleanliness requirements is a simple and efficient practice. Such an interface can be direct by physical contact or indirect by contamination redistribution during AIT activities and, specific to thermal testing, during each pressure transition (rather for particular contamination) or each temperature transition (rather for molecular contamination).

Concerning thermal testing, a pre-test (as per ECSS-Q-ST-70-01 clauses 5.3.2 d., e. and f.) includes GSE test equipment and cabling. In addition to pump down and re-pressurization sequences and for a demanding space program, this pre-test can also simulate the critical temperature transient sequences.

The test specification refers to the C&CCP and, if bio contamination constraints apply, to the product supplier PPIP (or Planetary Protection Implementation Plan).

The test profile implementation ensures outgassing and trapping of contaminants on cold surfaces of the facility (generally with a cryogenic trap). An efficient practice, often required in test specifications, is to have always the test article surfaces hotter than the chamber shrouds and the part of the test set-up that can trap contaminants during cold phases. Test phases with the higher contamination risks are mainly the beginning of the test and the end of the test. At the beginning of the test, an outgassing phase reduces these risks. Ending the test after a hot plateau is also an efficient practice.

b. The test specification defines the necessary venting durations. Differences in the voltage levels between internal cavities combined with cavity dependent low vacuum levels could lead to detrimental electrical phenomenons as arcing:

- For DC and RF corona effects, refer to section 5.5.5.6.
- For High Voltage effects, refer to section 4.3.4 of ECSS-E-HB-20-05.
- For multipactor effects, refer to sections 5.5 and 6.2 of ECSS-E-ST-20-01 and ECSS-E-HB-20-01.

Take advantage of the following guidelines:

- Pressure requirements for RF and high voltage equipment can impose local pressure sensors close to those units.
- Magnetic moments of some pressure sensors can prohibit close proximity of some units.
- Due to outgassing and for a temperature increase of about 50 °C, the pressure inside an internal compartment of an element can increase by about a factor 10.
- Depending on the materials and the bake-out history, the outgassing duration can be highly variable, from few days up to several weeks.
- During a hot plateau, reaching a pressure of 10^{-5} hPa inside an internal compartment of an element can be impossible within a reasonable time.
- Prior to the test, negotiate the true pressure limitations and check if other unit electrical modes have less severe pressure requirements.

6.5.4.3 Guidelines to thermal ambient test at mission pressure

a. No specific guidelines for this requirement.

b. Gaseous conduction or (natural, mixed or forced) convection can have significant adverse thermal effects. A vacuum facility with pressure control (with dry air, dry N_2 or CO_2) can be sufficiently mission representative. In order to demonstrate this, the test specification assesses carefully differences between mission and ground tests conditions such as:

- The atmosphere composition particularly for gaseous conduction through internal thin layers. For example, dry N_2 can replace Mars CO_2 to avoid frost during cold plateaux.
- The gravity if there is natural convection. For examples, there is no gravity within a space station or only 38% of Earth gravity at Mars surface.
- No wind simulation during cold plateaux particularly for forced convection. For examples, winds at high altitude within Earth atmosphere or at Mars surface.

Heat transfer within gases at very low residual pressure exhibits peculiar properties:

- A gas layer can be thin enough to prevent free convection start-up and can be thick enough to reach the conduction viscous regime.
- Heat transfer by gaseous viscous conduction is invariant over a large pressure range (typically from ≈1 hPa to 1013 hPa). This is due to the fact that the thermal conductivities of gases are independent of the pressure over such pressure ranges.

c. For cleanliness and contamination and, if applicable, for bio contamination, see guidelines in bullet 6.5.4.2-a. The C&CCP defines the activities, methods and procedures to mitigate the risk of condensation or frost. For Mars atmosphere, this can include using dry N_2 instead of CO_2.

d. The test specification defines the chamber type:

- o A mission dependent atmospheric pressure near to room atmospheric pressure (e.g. on-board a space station) can use a temperature chamber.
- o Concerning vacuum chambers, see guidelines related to the clause 6.5.4.1a.

6.5.4.4 Thermal balance test

a. A thermal balance test (see ECSS-E-ST-31 clause 4.5.3) is dedicated to a TCS qualification if the other methods of verification are not sufficient to obtain this TCS qualification.

An acceptance test programme on a FM (see Table 6-3 of ECSS-E-ST-10-03) does not include a thermal balance test. The TCS functional acceptance on a FM can be part of any other thermal test (thermal vacuum test, thermal ambient test at mission pressure, characterisation and calibration tests…).

The paragraph 6.5.4.1 gives guidelines for interface management between a thermal balance test and any other thermal test done under the same test configuration.

The following text underlines that a TCS qualification is not comparable to the qualification of the space segment element for which it is developed:

- o It is indeed one of many contributions to the qualification of its space segment element.
- o It is a matter internal to the TCS discipline that presents noticeable peculiarities.
- o After development testing, a TCS qualification test programme can use other physical models than qualification model (QM) or protoflight model (PFM). It can use physical models as ThM or STM which can be sufficient to pronounce the TCS qualification.
- o After obtaining the TCS qualification for example on a STM, the verification programme can use testing, as checks at different steps, during qualification or acceptance stages (on QM, PFM or FM) or during commissioning and in-service phases.
- o A TCS qualification test is an environmental test with two types of environmental conditions that are pressure and heat loads. It is important to note that temperature, in one or several of its various forms (level, difference and rate of change), is always an environmental condition except for the TCS qualification.

6.5.5 Electromagnetic test

6.5.5.1 General

6.5.5.2 Electromagnetic compatibility test

6.5.5.2.1 EMC test for stand-alone space segment element

a. Explanation that the ECSS-E-ST-20-07 clause 5.3 is not relevant in full to 10-03, as not all SSE level verification is done by testing.

Pointers to the ECSS-E-HB-20-07 through the ECSS-E-ST-20-07:

- o ECSS-E-ST-20-07 clause 5.3.2 “Safety margin demonstration for EED circuits” -- ECSS-E-HB-20-07 clause 5.3.2.5 “Pyrotechnic subsystem safety margins demonstration by test”.

- o ECSS-E-ST-20-07 clause 5.3.3 "EMC with the launch system"—ECSS-E-HB-20-07 clause 5.3.2.4.1 "Launcher compatibility".
- o ECSS-E-ST-20-07 clause 5.3.7 "Intra-system compatibility":
  - Conducted tests: ECSS-E-HB-20-07 clause 5.3.2.2.1 "Conducted tests at spacecraft level".
  - Radiated tests: ECSS-E-HB-20-07 clause 5.3.2.4.3 "Intra-system margins confirmation or assessment".

b. No specific guidelines for this requirement.

6.5.5.2.2 EMC test for embedded space segment element

a. The rationale for the tests specified in the ECSS-E-ST-20-07 clause 5.4 can be found in the ECSS-E-HB-20-07 clause 4.3, EMC test requirements.

Pointers to the ECSS-E-HB-20-07: clause 5.3.2.2.2, Conducted tests at payload module level.

6.5.5.3 Electromagnetic auto-compatibility test

a. Pointers to the ECSS-E-HB-20-07A: clause 5.3.2.3, Auto-compatibility tests. For point 4, see clause 5.3.2.4.3.

6.5.5.4 Passive intermodulation test

See Annex D.

6.5.5.5 Magnetic field measurements

a. Pointers to the ECSS-E-HB-20-07: clause 5.3.2.6 Magnetic tests.

6.5.6 Mission specific tests

6.5.6.1 Aero-thermodynamic test

a. Considering the complexity of the topic and the very specific domain of application, this topic deserves a dedicated handbook.

6.5.7 Crewed mission specific tests

6.5.7.1 Micro-vibration emission test

a. No specific guidelines for this requirement.

b. No specific guidelines for this requirement.

c. No specific guidelines for this requirement.

6.5.7.2 Human factor engineering (HFE) test

a. No specific guidelines for this requirement.

6.5.7.3 Toxic off gassing test

a. No specific guidelines for this requirement.

b. No specific guidelines for this requirement.

c. No specific guidelines for this requirement.

6.5.7.4 Audible noise test

See Annex C and 5.5.6.1.

a. No specific guidelines for this requirement.

b. No specific guidelines for this requirement.

c. No specific guidelines for this requirement.

d. No specific guidelines for this requirement.

e. No specific guidelines for this requirement.

7 Pre-launch testing

a. Recommended verification is towards workmanship. It is consistent with objectives of RFT.

b. No specific guidelines for this requirement.

c. No specific guidelines for this requirement.

d. No specific guidelines for this requirement.

e. It is consistent with objectives of RFT.

f. It is consistent with objectives of RFT.

g. It is consistent with objectives of RFT.

h. No specific guidelines for this requirement.

i. No specific guidelines for this requirement.

j. No specific guidelines for this requirement.

Annex A Mechanical tests

A.1 Foreword

While the handbook provides explanations for the requirements in the testing standard ECSS-E-ST-10-03, this annex provides additional information and examples for the implementation of the mechanical and structural integrity tests identified in the standard.

A considerable part of this information is extracted from the ECSS Spacecraft mechanical loads analysis handbook ECSS-E-HB-32-26A. That handbook has been developed with the aim to harmonize methodologies, procedures and practices applied for the conduct of spacecraft and payloads loads analysis. It provides well proven methods, procedures and guidelines for the prediction and assessment of structural design loads and for the evaluation of the test loads. In the absence of an ECSS testing handbook it contained also a lot of useful information and examples on test implementation, which are considered to be better part of the testing handbook. The relevant has been extracted, reviewed and updated where applicable, and compiled in this annex to the ECSS testing handbook. The ECSS Spacecraft mechanical loads analysis handbook will be updated accordingly in its next issue.

A.2 Physical properties measurements

A.2.1 Purpose

The purpose of the physical properties measurements is to determine the space vehicle mass, centre of gravity location, and moments of inertia around its three co-ordinate axes.

At equipment level the purpose of physical properties measurements is to determine the equipment physical characteristics, i.e. dimensions, mass, centre of gravity and moments of inertia.

The physical properties measurement is also used to determine the required balancing to reach the specified CoG position or moments of inertia.

A.2.2 General

Generally, only mass and C.O.G. are measured at equipment level, whereas moments of inertia are also measured at element level.

The figures hereafter show a machine for measuring the mass and CoG of an equipment. and machines for measurement of centre of gravity and moment of inertia and product of inertia of elements (satellites).

In case the balancing of the spacecraft element is an important requirement, a spin test is recommended (see A.4).

Before MoI (and CoG) measurements with the specimen are performed, a “TARA” measurement is needed in order to subtract the contributions which are not considered part of the specimen (e.g. interface adapters and other fixation means). When inclined specimen configurations are required for execution of CoG measurements the specimen static deflection should be taken into account and corrected for in order to obtain the most accurate results.

For element level test preparation it is important to understand that the result of the tests is not simply an accuracy, but an uncertainty budget due to additional analysis needed to compute the final result. Important factors for good results are the quality of the test facility and the facility foundation, the accuracy of the test specimen installation, i.e. the quality of the alignment pins, the avoidance of any possible sloshing in the test specimen and possible connections to ground by N_2 flushing lines.

For element level test execution, it is important to avoid any disturbance of the measurements by activities in the area, e.g. lifting and handling operations, and by the infrastructure e.g. air conditioning. It is also important to mention that non-flight items can impact the measurement results and this has to be properly taken into account when processing the measurement results.

If the desired configuration cannot be reproduced on the physical properties measurement machine, or the flight configuration cannot be reproduced on ground, e.g. due to the presence of large deployable equipment like solar panels or SAR antennas, then the most adequate configuration or configurations will be tested and the physical properties of the desired configuration will be calculated by combination of test results and mathematical models.

Figure A-1: CoG measurement along 1st lateral axis

Figure A-2: CoG measurement along 2nd lateral axis

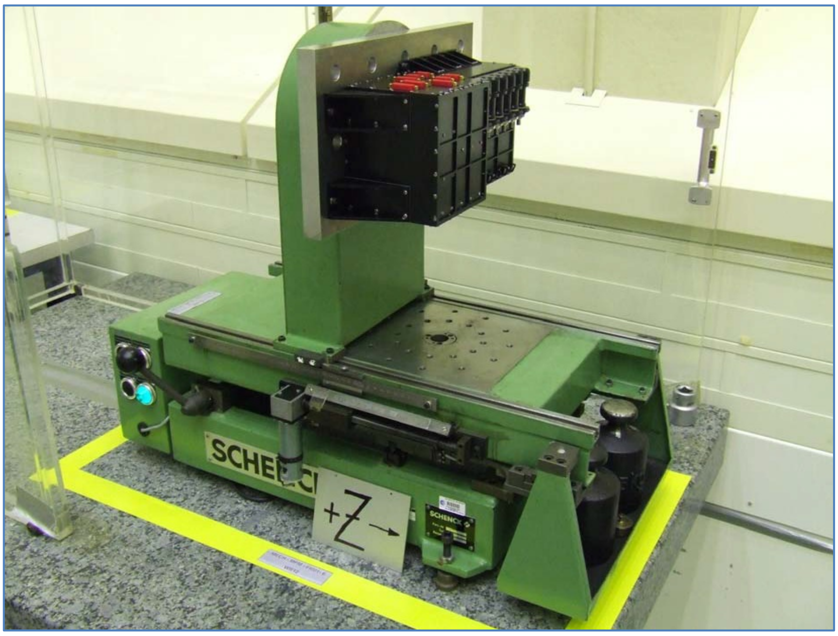


Figure A-3: CoG measurement along vertical axis

Figure A-4: M80 physical properties measurement machine with Bepi-Colombo MCS at ESTEC

Figure A-5: WM50/6 combined CoG and MoI measurement machine with IXV STM

Figure A-6: WM50/6 combined CoG and MoI measurement machine with Goce PFM

A.3 Static Test

A.3.1 Purpose

Static tests are used to verify that the test item can withstand the applied loads. The test can also be used to characterize the test article stiffness.

A.3.2 General

Static test is generally performed on the structure, rarely on equipment. The static test typically consists of several load cases which include application of loads in different directions. A properly designed static test is very effective in verifying strength, as combined loads (directions and application location) can be applied. However statically simulating the launch loads (inertial loads due to acceleration) can be a real challenge. The objective is to develop load cases that envelop the combined effects of the design limit loads.

Static tests are sometimes used for acceptance of flight hardware to demonstrate that no workmanship defect prevents the hardware from withstanding the specified loads. Typical static acceptance tests are:

- proof tests of inserts
- acceptance tests of composite structures, e.g. panel or central tube
- proof test of critical structural interfaces, as the hoisting points (related to safety when hoisting a propellant loaded spacecraft)
- proof test of ceramic structures

Note: those tests are usually referred to as proof tests but in the ECSS terminology they correspond to acceptance tests

It can be noted that static tests are usually not performed until rupture. They serve as verification that the test item can withstand the loads and not as a characterisation of the margin to rupture. This is because there are usually a number of load cases and a characterisation of the strength for each load case would require several test articles.

SAFETY ASPECTS:

Static tests can lead to significant stored energy which in case of failure can have dramatic consequences. It is recommended to consider the case where the test article or any fixation or loading device fails and ensure that the test remains safe. It is recommended to carefully consider the unloading conditions in case of issue. As an example, itis recommended to avoid using actuators compensating loads, i.e. acting against each other, as there is a risk that if one actuator fails, the loading condition becomes more severe.

A.3.3 Definition of static test configuration and load cases

A.3.3.1 Introduction

The following aspects are of primary importance in static tests definition and specification:

- the boundary conditions
- the load application

- the load cases
- the measurement instrumentation

In all cases, it is mandatory to perform a test prediction including the test specimen and also a realistic representation of the test setup. This allows to assess the loads and stress distributions in the specimen and to adjust the parameters of the test in order to reach the objective of the test.

A.3.3.2 Boundary conditions

The test article boundary conditions are particularly important, especially in the case of a structure sub-assembly, but also for the test of the whole structure. The main load paths can be significantly affected by boundary conditions, which are then a fundamental parameter to judge that the test covers the flight conditions. There are two possible choices:

- use a "very stiff" fixture to fix the test article at the interfaces, or
- use a test fixture with calibrated stiffness as representative as possible of the true flight interface.

The first approach requires demonstrating that the test condition is more severe than the flight; the second approach requires careful design of a fixture representative of flight interface. In any case it is recommended that the stiffness of the boundary conditions is always well characterised and that test instrumentation allows measurement of the displacement and reaction forces at the interfaces. The issue of the boundary conditions is particularly difficult for a sub-assembly of the whole structure that is connected in a hyper-static way (i.e. with statically indeterminate constraints to the rest of the structure).

A.3.3.3 Load application

In most cases it is difficult to have a testing load condition representative of the flight situation.

The principle is to reproduce loads that are due to acceleration applied on items with a mass, creating forces. Similar loads can be introduced by applying point loads with a load introduction device (jacks).

In static tests the load application tools are usually jacks or weights, in conjunction with lever systems to introduce forces on attachment points or pressure on surface pads. Alternatively, air bags are used sometimes to represent localized pressure loads.

A.3.3.4 Load cases

The definition of the test load cases includes two major points:

- The selection of the test load cases
- The level of the test loads

Each load case can include several types of loads (e.g. pressure, forces and thermal loads): minimization of the number of load cases and included load constituents is a compromise between cost reduction and representability with regards to the flight loads and also considering the available interfaces and their accessibility for load introduction. Therefore, a test load condition is not always coincident with a specific design load case, but frequently enveloping test load cases are defined to cover with the same test case, as far as possible, the maximum number of the structural items. Nevertheless, this is not always achievable and it is possible that some items are not covered by the defined test load conditions. In this case, examination of acquired measurements and applicability of extrapolation can suffice to cover the required demonstration by test (e.g. structure qualification). "Local" load cases can be considered, in addition to "global" test load cases on a whole structure test article, to test important aspects (e.g. load carrying capability of some interfaces).

A.3.3.5 Instrumentation

In static tests the following instrumentation is commonly used to obtain direct measurements for quantities of interest:

- Transducers for displacements,
- Gauges (mono-, bi-, and tri-axial) for strains
- Load-cell for forces

Note that to achieve the purpose of the static test, the proper monitoring of internal loads paths is an important aspect to be considered when the test instrumentation is defined.

It is important to mention that the accurate measurement of displacements and deformations during the test is not easy and can be affected by mechanical gaps, micro-settlements and small deformations of the test jig itself. As a consequence, there is a risk that the accuracy of the measured displacements is not sufficient to properly assess the stiffness of the specimen.

It is also important to monitor the deformation of the test setup (for example the test adapter on which the specimen is mounted) because parasitic displacements and rotations coming from the flexibility of the setup can appear and can have an important impact on the displacements measured on the specimen itself. For example, small deformations, in particular rotations, of the test jig at the interface of a spacecraft structure that appear negligible can lead to significant displacements at the top of the structure, far from the interface.

Stresses are not directly measured but are evaluated from strain measurements by applying a proper material constitutive law (e.g. the Hooke's elasticity law, the nonlinear material strain/stress curve).

Figure A-7, Figure A-8, Figure A-9, Figure A-10 refer to static test at Rack level, whereas Figure A-11, Figure A-12, Figure A-13, Figure A-14, Figure A-15, Figure A-16, Figure A-17 refer to static qualification test campaign of the Automated Transfer Vehicle (ATV) Cargo Carrier: it is a representative example of traditional arrangement of fixture, loading and instrumentation systems traditionally used in static tests.

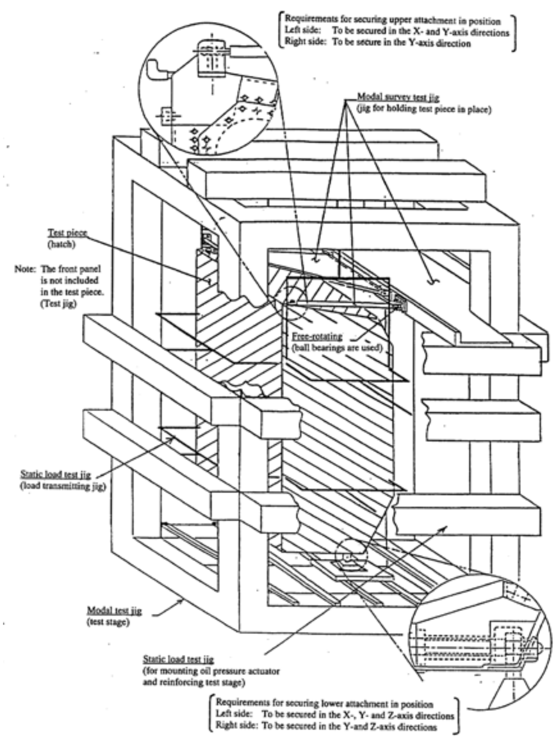


Figure A-7: Rack static test configuration-1/4

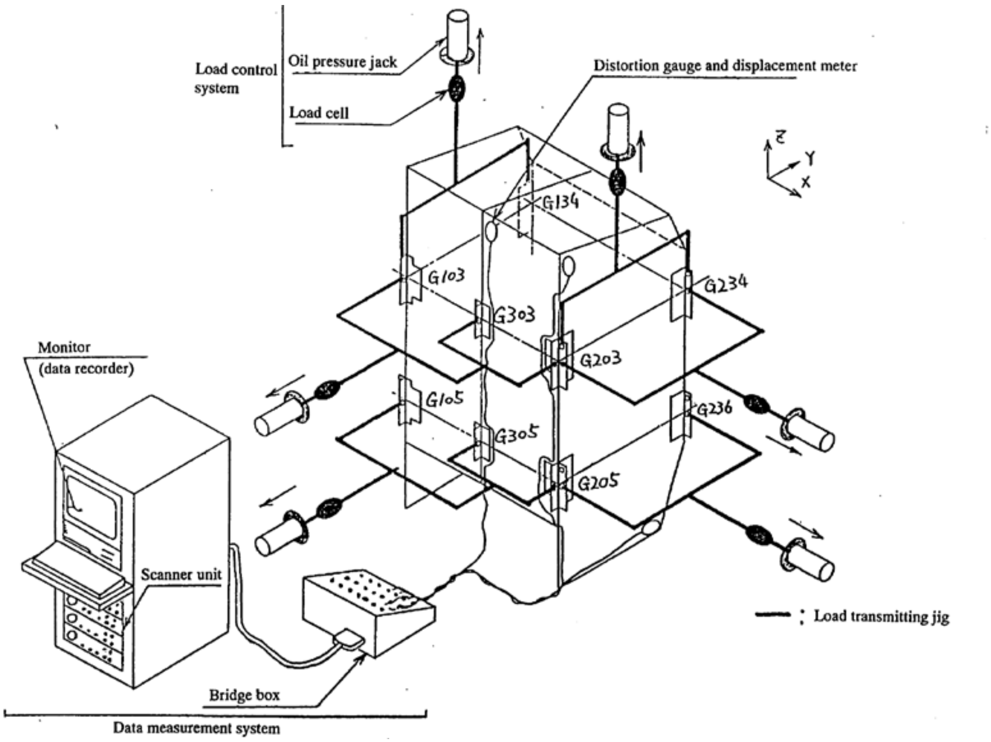
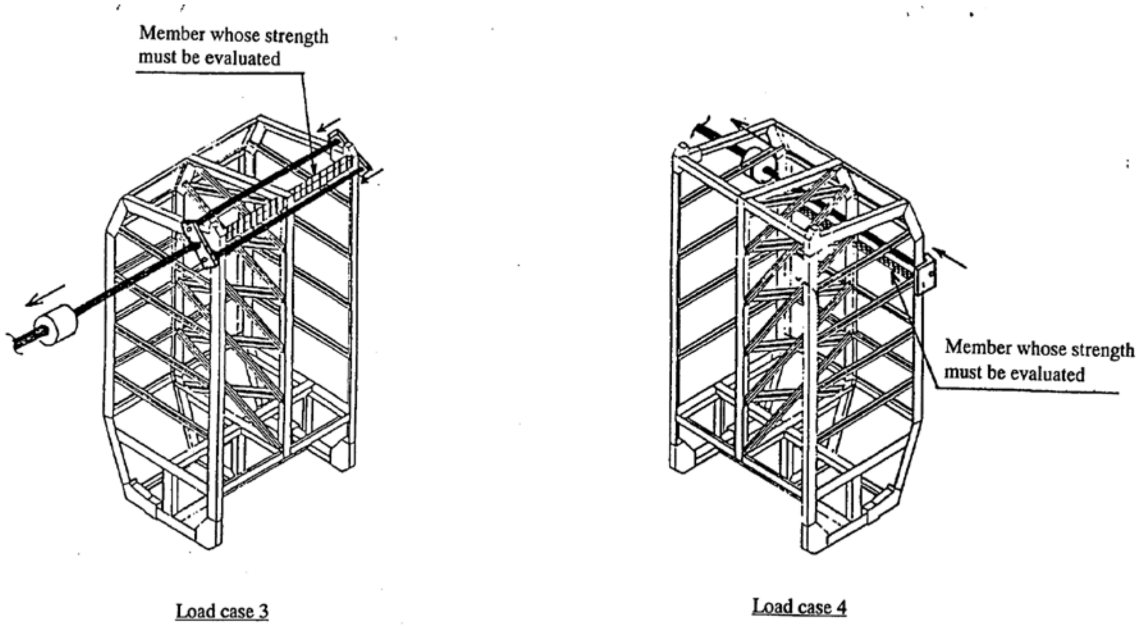


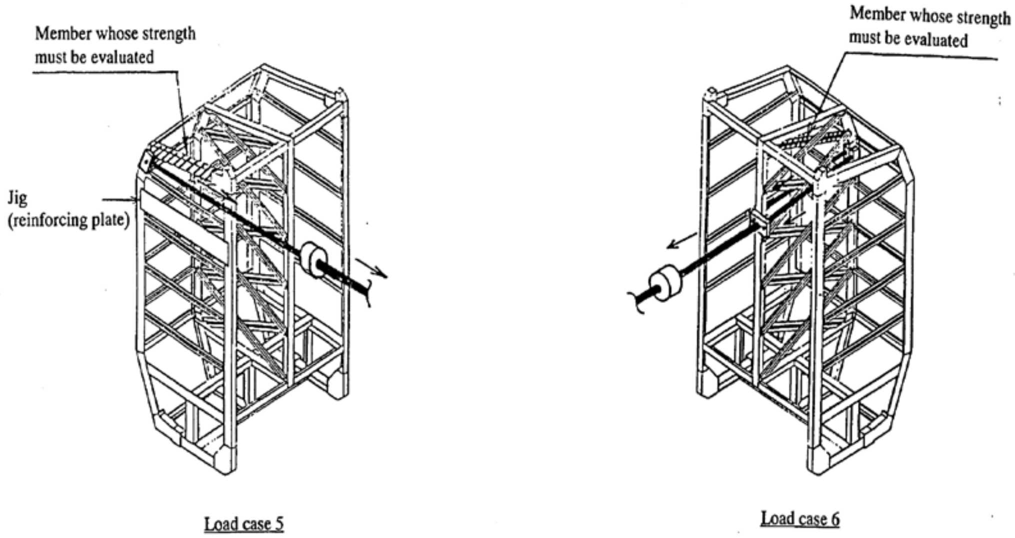
Figure A-8: Rack Static tests configuration-2/4



: Load transmitting jig
: Bracket, tournament
: Load control system
: Direction where load is applied

Note: The descriptions of panel members assembled in the test piece are omitted. The test must be conducted according to the configuration used for actual spacecraft, specifically with all panels mounted, with the exception that part of the front panel that interferes with the test jig in load case 6 must be removed.

Figure A-9: Rack Static tests configuration-3/4



: Load transmitting jig
: Bracket, tournament
: Load control system
: Direction where load is applied

Note: The descriptions of panel members assembled in the test piece are omitted. The test must be conducted according to the configuration used for actual spacecraft, specifically with all panels mounted, with the exception that part of the front panel that interferes with the test jig in load case 6 must be removed.

Figure A-10: Rack Static tests configuration-4/4

Also other instruments and resources are now available, as pressure films for local contact pressure (e.g. pressure under bags, seals or bolted joints), photo-elastic paints, photo/video-cameras, etc. Direct measurements can be used to derive more complex quantities (e.g. several strain-gauges measurements to derive internal load path in a structural item or an interface force), and software packages can be provided to elaborate several measurements to monitor in real time some structural response quantities (e.g. a set of measured displacements to compute rigid body motion components). Properly instrumented and calibrated structural items or devices can convert direct measurements in a quantity to be monitored (e.g. a set of strain gauges on a bracket can be calibrated to recover force component on the bracket).

As an example, digital image correlation or photogrammetry, can be used to measure the full displacement field and deduct the full deformation field, without contact with the test article. While displacement transducers have to be installed on a supporting structure that does not deform, i.e. independently from the loading structure, leading to a double scaffolding, contactless instrumentation, as digital image correlation or photogrammetry, do not require such a complex setup. This is also a good way to measure the overall deformation of the test setup.

A.3.4 Static test evaluation

Two levels of evaluations apply to a static test:

- Test execution correctness
- Test objectives successful demonstration

The test execution correctness relates to the correct implementation of the test according to the test specification. The following are examples of typical criteria:

- Test load are applied within specified tolerances
- The instrumentation measurements are available

All these criteria are preliminarily checked by dedicated pre-test, before final test execution.

The successful demonstration of the test objectives is defined by specific “test success criteria”. Examples of typical success criteria are:

- No permanent deformation occurs at a specified test load (e.g. qualification level, or acceptance proof level)
- No rupture occurs at a specified test load (e.g. qualification load)
- Specified maximum displacement values are not exceeded at tested limit load

Note that final verification of the test item integrity can include Non-Destructive Inspection.

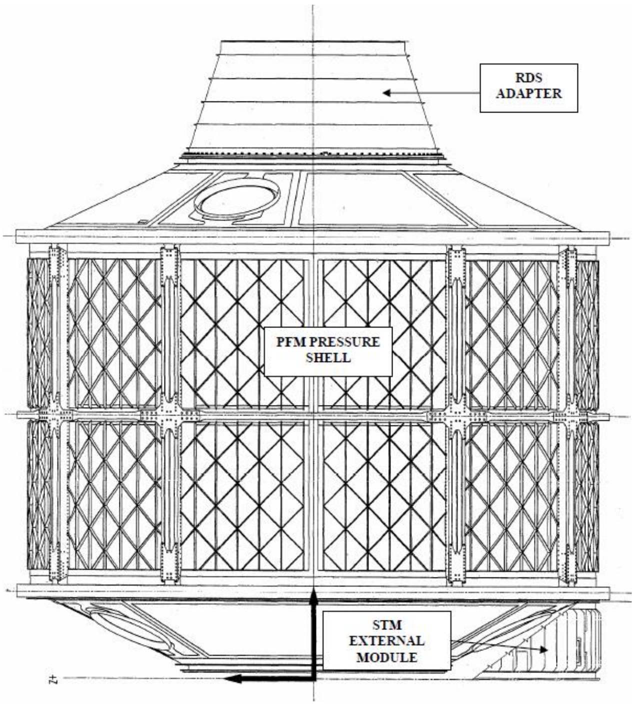


Figure A-11: Automated Transfer Vehicle (ATV) primary structure test article

Figure A-12: Setting of ATV primary structure static test

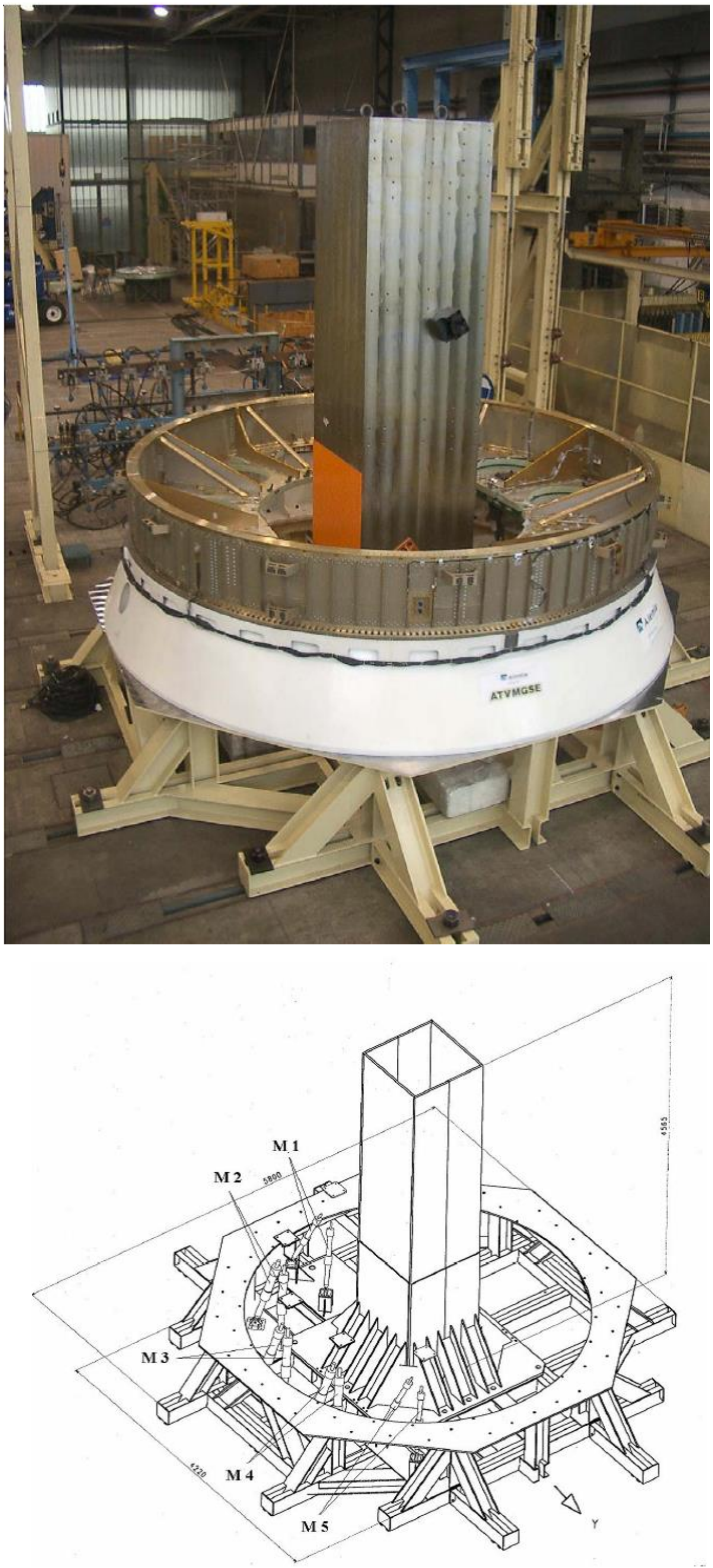


Figure A-13: ATV static test fixtures: “Base” to constrain the test article and “Tower” to support the internal jacks

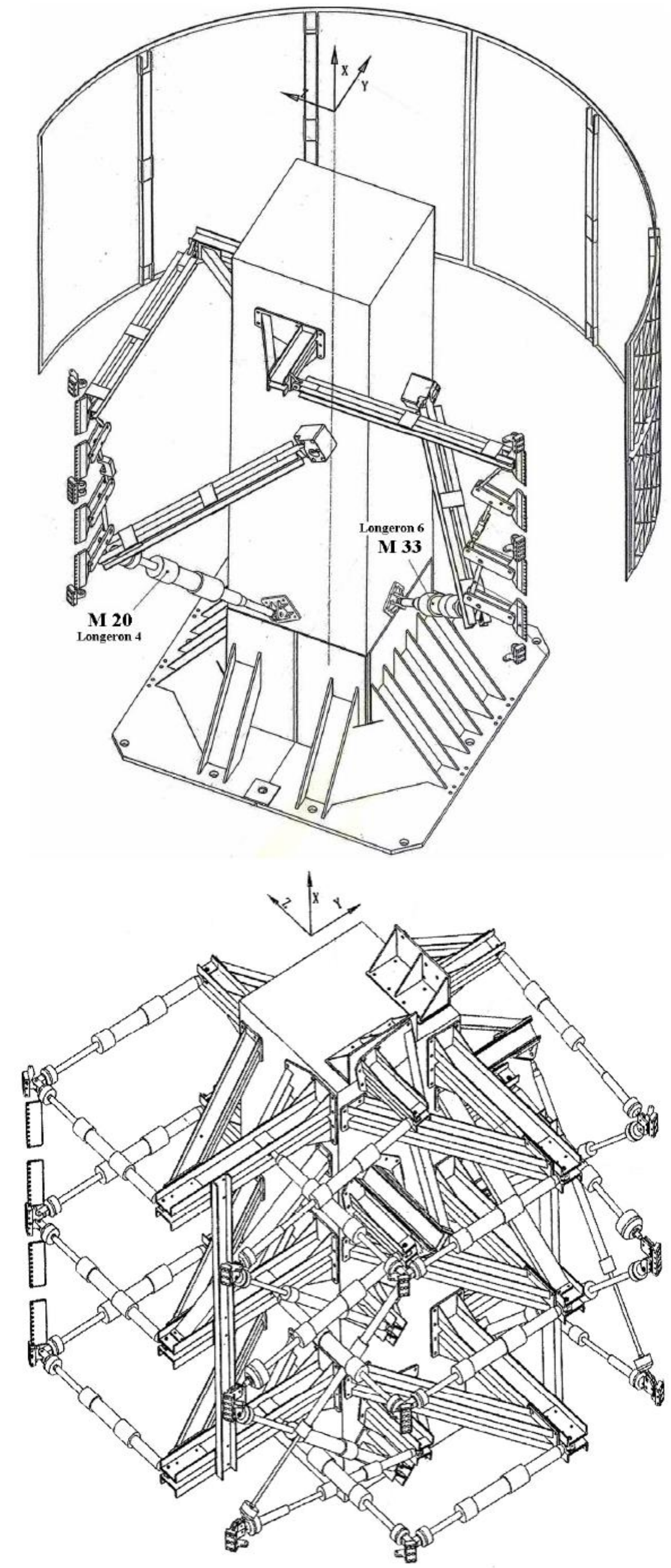


Figure A-14: ATV static test: internal loading jacks arrangement

Figure A-15: ATV static test: internal loading jacks details

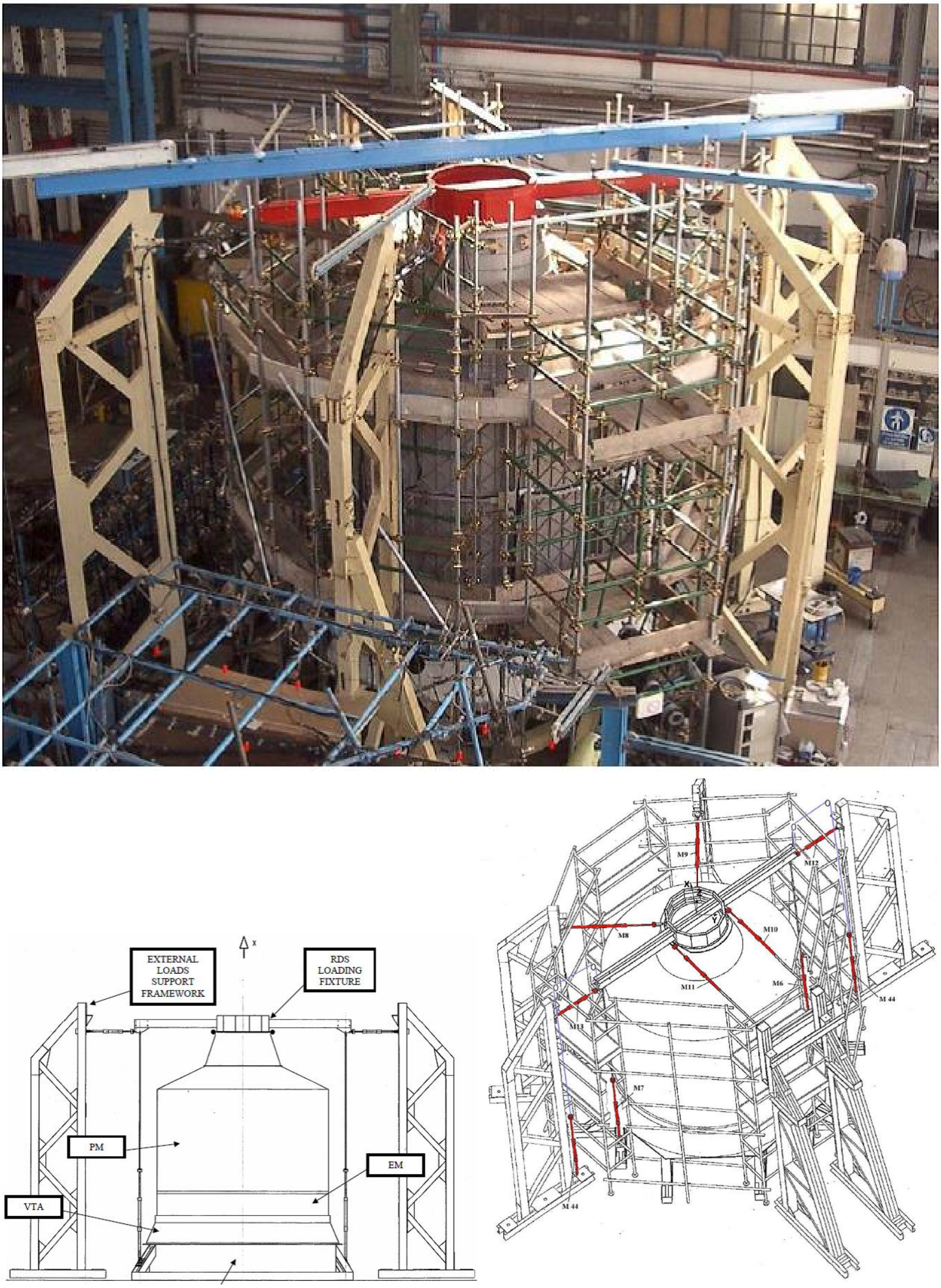


Figure A-16: ATV static test: external view and external loading jacks

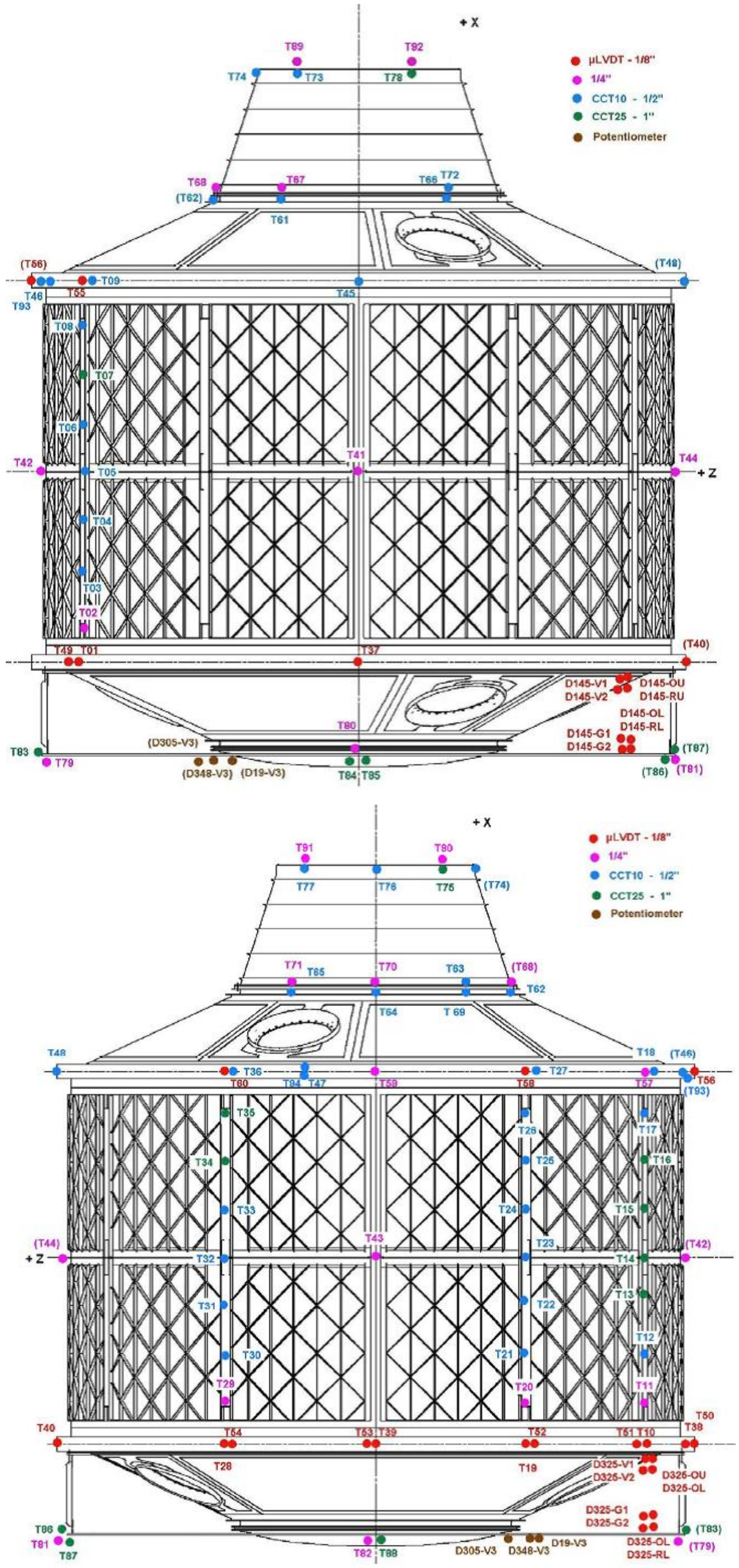


Figure A-17: ATV static test: layout of the displacement transducers

A.4 Spin test

A.4.1 Purpose

The Spin test is performed to verify the mass properties (especially COG and MOI measurement) of the spacecraft, and characterise its balance status. It can also be used to identify corrections to be made (through balance masses) to reach a specified balancing.

The spin test is also performed to verify the strength and functionality of a spin-stabilised spacecraft that will rotate in orbit at significant spin rate (e.g. 100 rpm). The test verifies all functions related to the spin movement of the element (e.g. correct de-spinning of the communications antennae),

A.4.2 General

The Spin test is generally performed at element level, rarely on equipment.

The preferred and recommended baseline configuration is to perform the spin balance test with filled tanks. If the test is performed with empty tanks configuration, then see 6.5.2.1.f of ECSS-E-ST-10-03.

For the strength verification the effects of the fuel mass are to be considered.

SAFETY ASPECTS:

The spin test leads to significant kinetic energy. The spin cannot be stopped quickly. As an example, the failure of a fixation point can lead to parts of the test article being projected.

A.4.3 Test configuration and test aspects

The spin balance test is performed with the element mounted on a specially designed spin-table, usually called spin test facility or dynamic balancing facility.

The dynamic balancing machine are designed to work at ambient pressure or in reduced pressure. Reduced pressure can be used to avoid air drag.

The working principle of the balancing facility is to rotate the test object at a constant rotational speed in order to generate centrifugal forces and moments.

The spacecraft spin test facility is used to test and correct spacecraft balance using either dynamic or static/coupled measurement techniques to force the spin axis to the desired principle axis of the satellite and to measure the moments of inertia.

Figure A-18: Dynamic balancing facility installed in a vacuum chamber (Large Space Simulator at ESTEC)

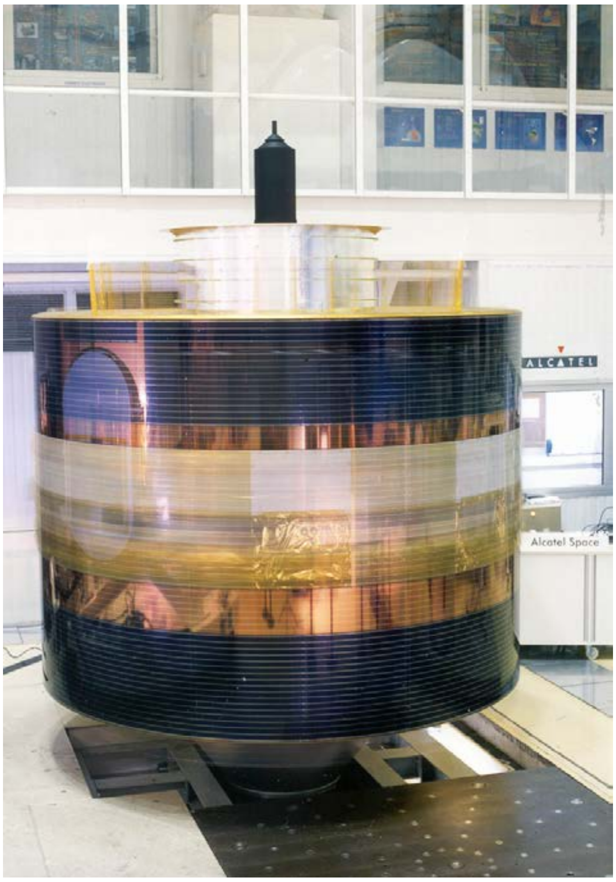


Figure A-19: Meteosat Flight Model during spin test

A.4.4 Test Instrumentation

Force and moments sensors are part of the spin test facility.

Additional sensors to be implemented on the test article (like e.g. accelerometers, strain gauges) require the use of a slip ring, which can be provided by the facility on demand. The same applies if the test requires the implementation of umbilical (e.g. to check functionality).

A.4.5 Test control parameters

The only control parameter during test execution is the rotational speed.

A.4.6 Test Preparation

The criteria to select the spin test facility are the sensitivity and the balancing accuracy which are functions of the rotation speed. Also, the maximum allowable mass, moments of inertia and rotation speed are driving the selection of the facility. The test article is attached to the rotating plate of the spin facility by means of an adapter.

Safety measures are to be considered since the detachment of any part during test execution represents a hazard to the personnel, test article and the test room. The dynamic balancing machines are equipped with an emergency shutdown of the facility to protect the test article during operation. Still, one has to consider that the spin facility cannot be stopped immediately.

A.4.7 Test execution

The spin test is typically run at a rotating speed between 30 and 330 rpm. For small masses, it can go up to 800 rpm. The spin balancing test is typically performed at a speed around 60 revolutions per minute (one revolution per second) for a typical element that will spin at around 5 RPM. Increasing the rotational speed provides a better accuracy for the balancing. However, the loads applied by the centrifugal force need to be considered to avoid over-loading.

Typical test duration is the time needed to acquire the balancing correction data. In case the spin test is performed to verify the strength and functionality of a spin-stabilised spacecraft, it can last several hours.

A.4.8 Test Evaluation

The primary result of a spin balancing test is the measure of the CoG and moments of inertia.

In most cases the spin balancing test is performed to identify the necessary corrections to balance the test article to the levels specified in the requirements.

In case the spin test is performed to identify the corrections to the balance status of the test article, a software routine typically allows to identify possible solutions for the location of balance masses by means of a computed compensation of the unbalance. It is not necessary to physically balance the test article during the test and this activity can be done later on.

The test output can be provided in two ways:

1. Two planes balancing
   - The total unbalance correction mass
   - The total unbalance correction masses at pre-selected locations
2. Static /Couple balancing in two planes
   - Correction masses for CoG offset and the inclination of principal axes of inertia are provided separately

In case the spin test is performed to verify the strength and functionality of a spin-stabilised spacecraft, the test evaluation considers the analysis of the measured parameters (stresses, accelerations, functional, etc.) w.r.t the related specification.

A.5 Centrifuge test

A.5.1 Purpose

The centrifuge test is performed to verify that the test item can withstand the applied loads.

A.5.2 General

The centrifuge test is usually applied to equipment and element level (from small equipment to large elements).

With respect to a static test, the advantage of the centrifuge test is that it is a real acceleration test creating inertial loads, meaning that all non-structural masses present in the test article will create inertia loading into the carrying structure. In this sense, it is a more representative loading than the static test. For a structural model, it requires to have mass dummies installed.

Its main disadvantage is that the inertial loading will be varying over the test article with the varying distance to the rotation axis (see requirement 5.5.2.2. of ECSS-E-ST-10-03C). Also, it is not possible to have a visual observation of the test article during the performance of the test.

SAFETY ASPECTS:

The centrifuge test leads to significant kinetic energy. The centrifuge cannot be stopped quickly. Any failure can propagate to a destruction of the test article. As an example, the failure of a fixation point can lead to the test article being projected.

A.5.3 Test configuration and test aspects

The test set up requires a large amount of space. It is limited, in terms of application, by the radius of the centrifuge and the test article adapter interface. Unidirectional loads can be applied, but application of thermal and pressure loads at the same time is rather difficult.

Figure A-20: GPM spacecraft undertakes centrifuge test at Goddard (courtesy of NASA)

Figure A-21: Centrifuge test of ExoMars Descent Module (courtesy of Lavoshkin)

A.5.4 Test instrumentation

Typical sensors to be implemented are accelerometers, load cells and strain gauges. They require the use of a slip ring which is provided by the centrifuge facility.

A.5.5 Test control parameters

The only control parameter during test execution is the rotational speed.

A.5.6 Test preparation

The test article is mounted, via a rigid test adapter, on the end of a rotation arm of a centrifuge

Safety measures are to be considered since the detachment of any part during test execution represents a hazard to the personnel, the test article and the test room. The centrifuge is equipped with an emergency shutdown of the facility to protect the test article during operation. However, the centrifuge cannot be stopped immediately.

A.5.7 Test execution

The centrifuge test is run at the rotating speed corresponding to the testing acceleration loading. Typical test duration is the time needed to acquire the reading of the sensors. Load application duration is usually part of the test specification.

Prior to achieving nominal loading rotational speed, the centrifuge is run at a very load speed (around 3 rpm) to identify the required balancing masses. Once implemented, the test is resumed up to nominal level.

A.5.8 Test evaluation

The evaluation of the centrifuge test considers the readings of the control accelerometer to verify the input loading plus the reading of all other response sensors (accelerometers and strain gauges).

A.6 Sine burst test

A.6.1 Purpose

The sine burst test is performed to apply a quasi-static load to a test article with the aim to verify that it can withstand the applied loads. This is a test to verify the strength of the test article.

A.6.2 General

The test consists in subjecting the test article in each axis to a few (typically five to ten) cycles of a sine wave whose peak level is the specified load.

The sine burst test is seldom performed at element level.

The sine burst test is sometimes performed at equipment level replacing the sine sweep test when the test article does not have resonance frequency in the sine sweep frequency range.

As a means to check strength against quasi-static loads, the advantage of the sine burst test is that it can be combined with other vibration tests (sine and random) test using the same test configuration.

With respect to a static test, the advantage of the sine burst test is that it is a real acceleration test creating inertial loads, meaning that all non-structural masses present in the test article will create inertia loading into the carrying structure. In this sense, it is a more representative loading than the static test. For a structural model, it requires to have mass dummies installed.

For Safety aspects see A.7.2

A.6.3 Test configuration and test aspects

The test is performed mounting the test article with an adaptor to a shaker. Since the test is meant to apply a quasi-static load to the test article, the test frequency is selected well below the fundamental resonance frequency of the test article. It is strongly recommended that the test frequency is less than one-third of the resonance frequency of the test article to avoid dynamic amplification during the test.

If there is a shaker stroke limitation meaning that displacement corresponding to the load is too high w.r.t the shaker capability, it is possible to take advantage of the first mode dynamic amplification factor to achieve the correct loading. This means shaking the test article at a frequency closer to the article fundamental frequency.

See also A.7.3, as the configuration is similar to the sine sweep test.

A.6.4 Test instrumentation

Typical test instrumentation are accelerometers (for shaker control as well as measuring specimen responses), strain gauges and force measurement devices.

See also A.7.3.1, as the test instrumentation is similar to the sine vibration test.

A.6.5 Test control parameters

The test control parameters are:

- the frequency at which the test article is excited
- the profiles of the ramp up and down
- the number of cycles at the maximum load (typically between 5 and 10)

See A.7.3.2, as the test control parameters are similar to the sine vibration test.

Note that for this test sweep rate and notching are not relevant.

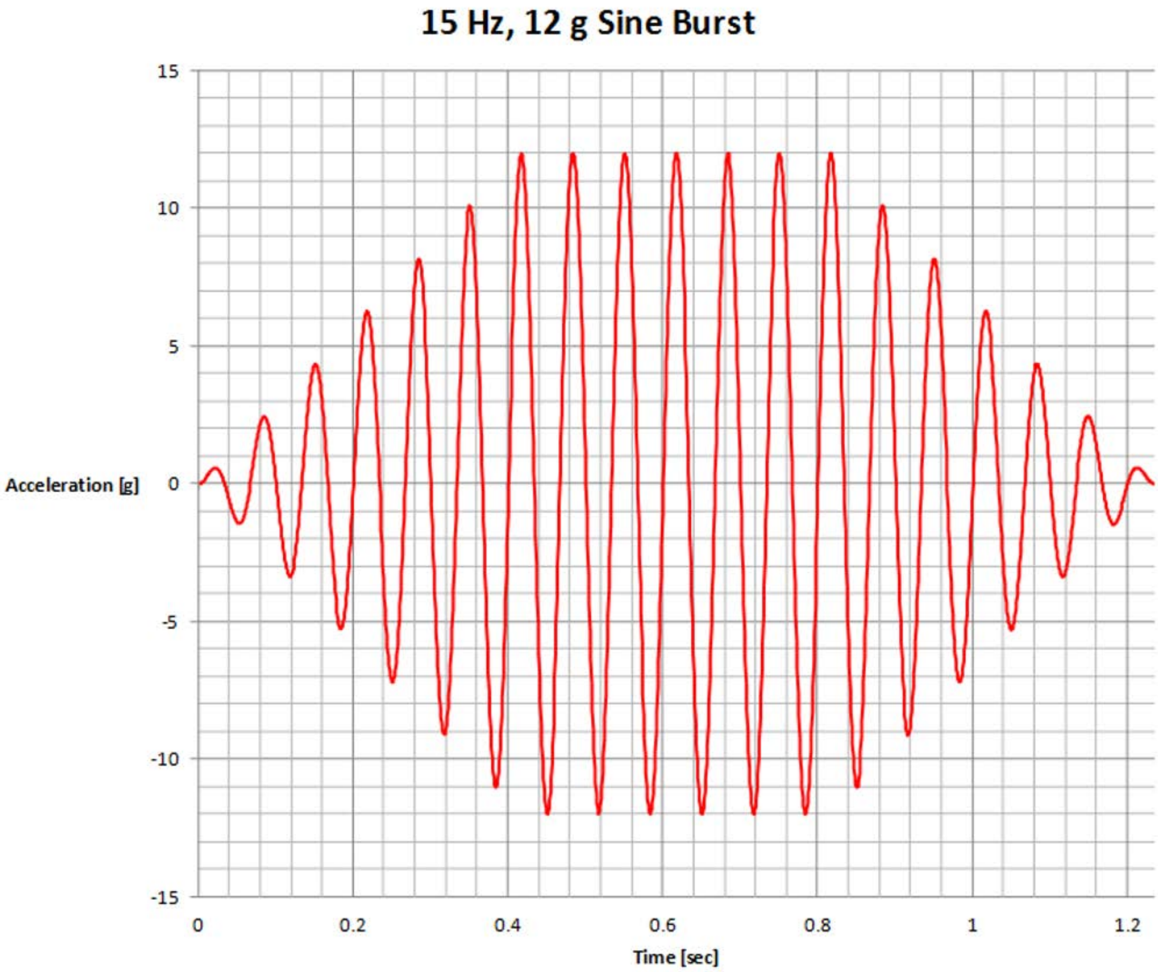


Figure A-22: Example of Sine Burst with a frequency of 15 Hz and 6 cycles at maximum load of 12g (figure taken from NESC Technical Bulletin 15-02)

A.6.6 Test Preparation

The sine burst test specification includes:

- position of the test article on the shaker for all axes to be tested
- instrumentation plan describing identification and location of response and control sensors, including force measurement devices if applicable.
- test sequence and control strategy
- test success criteria

In case the fundamental frequency is excited, test analytical predictions are recommended before the start of the test.

For the facility selection see A.7.4.1.

A.6.7 Test execution

The test is performed, in each axis, in a stepwise manner applying a number of lower level sine bursts at levels that are fractions of the full load.

Before each run is started, it is recommended to perform a pre-test. The pre-test allows to check the proper orientation of all pilots, and the proper functioning of all sensors.

A typical sine burst test sequence consists, as a minimum, of the following test runs for each axis:

- Low level resonance search run – see description in A.7.3
- Intermediate level runs (typical intermediate levels are 1/8, ¼ and ½ of full level)
- Full level run (qualification or acceptance level)
- Low level resonance search run for purpose of structural integrity check

In addition, in case the fundamental frequency is excited, it is recommended to carefully check the evolution of the amplification w.r.t the increasing input level.

Low level run is performed to compare the dynamic signature of the test specimen before and after the test. Changes in dynamic behaviour (frequency shifts and response levels) can indicate structural failure.

A.6.8 Test Evaluation

After each test run following checks are performed:

- that all sensors worked correctly by checking the acquired data
- Check the control (pilot) accelerometers to verify that the input provided is in accordance with the test specification and within tolerances. Check the control accelerometers with the co-pilots (see A.7.3).
- Sensor orientation (first test run)

  During low frequency excitation, the test specimen is expected to behave as a rigid body and therefore the accelerometers on the test specimen are expected to have the same response (magnitude and phase) as the pilot accelerometers in the direction of excitation.
- Piloting quality

  Comparison of magnitude and phase of all pilot accelerometers with each other and with the desired acceleration.

  This includes the determination of excitation in orthogonal directions compared to the excitation direction (cross axis excitation, parasitic motion)
- Check Transfer functions (to confirm no significant amplification)

Comparison between the global and fundamental values allows to detect non-linearities and rattling issues, which creates content at different frequencies than the excitation frequency.

A.7 Sinusoidal vibration test

A.7.1 Purpose

The purpose of vibration tests is to demonstrate that the test item withstands the vibration environment encountered during launch or other high vibration exposures.

The purpose of the sinusoidal vibration test is to subject the test items to low frequency dynamic loads and characterize its dynamic behaviour.

A.7.2 General

The test item is vibrated in three orthogonal directions separately, where the excitation frequency sweeps from a lower limit to an upper limit (sweep up) or vice versa (sweep down). The sweep rate is usually exponential and is expressed in octaves per minute (oct/min). Refer to Section A.7.3.3for a discussion on the influence of the sweep rate.

SAFETY ASPECTS:

It is recommended to check how the abort function is implemented in the control system and test the abort if possible through a blank test, before mounting the test article on the shaker. In vibrations, a test abort can be very severe and lead to damage of the test article. This is considered early in the preparation of the test, and understanding of the abort function is confirmed at the latest at TRR. It is recommended to implement notches to limit the levels in a controlled way as a protection means to avoid abort.

After an abort, the "test restart" function can also create a severe transient acceleration leading to damage of the test article. As a guideline, aborts and restarts are avoided. See also A.7.3.2on the test control parameters.

A.7.3 Test configuration and test aspects

Sine vibration tests are usually performed on single-axis electro-dynamic shakers. A control system energizes the shaker to the desired vibration level. Feedback for the control system is provided by a series of accelerometers or forces, which are mounted at the base of the test item or as responses on the test specimen

Multi axis test facilities provide an advantage by reducing the effort for test reconfiguration and with more flexibility for the test sequence and test direction; low frequency tests can be done in all directions before going to higher level tests, arbitrary direction can be chosen, several axis can be tested simultaneously. Their disadvantage is that the control is more difficult. In case of multi axis hydraulic vibration facilities the frequency range is typically from 0.1 Hz to maximum 150 Hz as compared to electro-dynamic vibration facilities which typically can operate from 5Hz to 2000 Hz. This allows to excite the sloshing modes on tanks.

In general the test article is tested in launch configuration.

For Test article configuration/representativity see ECSS-E-HB-10-02 (Verification) clause 5.2.5.

Typical MGSE are the test adapter for mounting the test article to a Force Measurement Device (FMD) or to the vibration table directly. It also includes a test clampband for a spacecraft level test.

The design of the Mechanical Ground Support Equipment (MGSE) which is used for performing the vibration test is such that it does not influence the dynamic behaviour (i.e. the modal parameters) of the test item and the control of the test. This is an ideal case which cannot be perfectly achieved. If the influence of the MGSE is not negligible it should be taken into account for the simulation of the vibration test.

It is important to keep in mind that the measured dynamic behaviour can be perturbed by the test setup, for example the flexibilities of the shaker and head expanders.

The test adapter must strictly adhere to the requirements imposed by the test facilities and test configuration. Particular important are interface flatness and material when the test adapter is mounted directly to a vibration slip table to avoid the blocking of the slip table due to table deformation caused by insufficient flatness or thermo-elastic deformation during test execution.

A.7.3.1 Test instrumentation

Instrumentation consist of accelerometers, strain gauges, force measuring devices.

It is important to understand how the raw measurements are processed. The measurement is a time history which, for a sine sweep test, is processed to provide a single value for each excitation frequency. This value can be the maximum of the measured signal (peak) over the time window (this is called global response) or the component at the frequency of excitation, obtained by filtering the raw signal over the time window (this is called the fundamental), or a RMS value. Reference to "what's behind the curves".

For each measurement channel, there is the choice to view the global or the fundamental. It is important to know which one is displayed and understand what it corresponds to.

It is recommended to record the time histories of the measured signals. This can be very useful to investigate a particular phenomenon.

As the force measuring device is a specific instrumentation element, it is described in detail below.

Force Measurement Device

The Force Measurement Device (FMD)is a general term naming a device able to measure, between two interface planes, the forces and, indirectly, the moments. Its generic design is composed of two rigid interfaces separated by load cells.

Thus force measurement devices can be designed for different specimen types and interfaces.

For example, the main characteristics of an FMD available at ESTEC are:

Characteritics		
Frequency measurement range:	up to 100 Hz at high level	up to ~300 Hz at low level
Measurement range:	up to 800 kN axially	up to 200 kN laterally
Moment measurement range:	up to 260 kNm in bending	up to 130 kNm in torsion
Stiffness:	Axial: 9,55 x 10^9 N/m	Bending:2,73 x 10^9 Nm/rad
Overall mass / height:	494 kg/40 cm	

The FMD is the best way to determine the interface loads since:

- It provides the direct measurement of the complete interface loads with high accuracy which can be used for direct automatic notching.
- It validates immediately the interface load level achieved,
- It offers a high stiffness, a good linearity and low cross axis excitation.
- The integration in the test set-up is simple and can be adapted to every interface thanks to the modular concept.

For force limited vibration, refer to NASA-HDBK-7004C

A.7.3.2 Test control parameters

The control of the shaker is performed by control accelerometers, also called pilots. Responses of the test article (accelerations and forces) can also be used as limits in the control loop.

Before the start of the sine test, the following needs to be defined:

- Identification of control (pilot) accelerometers:

  The number, orientation (always in the excitation direction) and the position of the sensors used to control (pilot) the test are clearly identified.

  The control accelerometers are located close to the interface of the specimen on the test fixture side, at different locations around the test article. This allows to check the homogeneity of the input to the test article. It is recommended that the control accelerometers are attached with screws and not bonded when possible.

  To ensure that the control accelerometers are working properly, it is recommended to have an accelerometer next to each control accelerometer, called co-pilot, to check the signals of the control accelerometers.

- Identification of limits

  It is recommended to always implement limits on some sensors (pilots, response acceleration, loads), also in cross axis directions. The control of the shaker uses those limits to ensure that the defined values are not exceeded, in order to protect the test article.

  Some of the limits are used for the purpose of notching implementation. See section A.7.3.4

- Identification of aborts

  It is recommended to implement abort values on a number of sensors. When the abort value are reached, the test is stopped (aborted).

  It is recommended to check how the abort is implemented (how exactly the input is affected), as abort can be rather brutal and inadequate (e.g. staying at the same frequency and reducing the levels which can lead to further amplification on a mode).

  It is recommended to implement limits on each channel used as abort, to limit the risk of abort.

Control strategy:

To control the test, it should be decided if the control is made on the maximum or on the average value of the pilot sensors. The average signal being smoother, it can help to ease the control of the test. However the specimen needs to be protected (notching and abort channels) because the failure of one pilot decrease the measured mean level, leading to an unwanted increase in the input level to compensate for that.

It should be also decided whether the control is performed on the global response (that is to say without low pass filter, ensuring that maximum peak-peak acceleration is not exceeded), on the filtered response (or fundamental response, that is to say with a filter at excitation frequency, ensuring that excitation level is reached at this frequency), or on the RMS value. Ref to ECSSMET 2016 article "DYNAMIC TESTS, WHAT'S BEHIND THE CURVES (available as pdf-file in Annex G).

Note that control on global response can be difficult because the global response can be noisy. Most of the time the test is controlled with the RMS level measured by the pilots (average of squared values over a period).

The above parameters are captured in a run sheet, together with the required input spectrum and associated tolerances.

Note that the number of notch/abort channels can affect the shaker control. Increasing the number of channels in the control loop can slow down and degrade the control.

It is recommended to verify that the parameters implemented in the control system correspond to the parameters requested in the run sheet.

The capability of the control for vibrations is assessed with care, especially for notching and abort. There are numerous parameters influencing the control reaction time (e.g. compression factor, sweep rate, number of sensors in the control loop…) and there is possibility to modify those parameters if necessary, i.e. if the control capability is not sufficient. It is important to record the parameters used for each run. If necessary, it is recommended to investigate the effects of the control parameters with very low levels. It is recommended not to change the parameters for high vibration levels if they have not been tested at lower level. It is recommended to check the notching control at intermediate level before applying them at high level.

An emergency abort button is usually available to manually abort the test. The customer usually undertakes this responsibility.

A.7.3.3 Sweep rate selection

Typically one uses exponential sweeps expressed in octaves/minute, where R octaves/minute indicates that after each minute the excitation frequency is multiplied by 2^R. The advantage of the exponential sweep is that all modes (with the same damping) are excited for the same number of cycles regardless of their frequencies (1 octave per minute means 8,66 cycles per 0,1 Hz, i.e. a sine sweep test with one octave per minute, from 5 Hz to 100 Hz goes through about 8277 cycles, depending on the start-up and ramp-down phase; at 2 octave per minute the number of cycles is half of it).

The selection of sweep rate is related to the hardware under test. A very low sweep rate (e.g. less than 1 octave/min) is sometimes used for identification of the eigenmodes frequencies and damping, in particular in the presence of closely spaced modes. A high sweep rate (e.g. up to 4 octaves/min) is selected to reduce the number of cycles when the flight hardware is tested.

A possible approach is to perform:

- a low level run in the range 5 Hz to 2000 Hz (can be less depending on the specimen) with a low sweep rate for modal identification (typically 0,5 octaves/minute).
- a second low level from 5 Hz to 100 Hz at the sweep rate specified for the test in order to have a reference at the same sweep rate than the following runs.

A low sweep rate usually makes the control easier and leads to higher amplification on the modes. To solve control issues, it is possible to modify the sweep rate locally around a mode, while carefully considering the effect on the amplification.

For more information, see the reference of study Dynamited, as well as paper at ECSSMT (available as pdf-file in Annex G).

A.7.3.4 Notching process during testing

In this section the practical aspects of notching are discussed. For the definition and theoretical aspects of primary and secondary notching see ECSS-E-HB-32-26.

Notching can be performed based on loads or accelerations.

Each test run prior to the full level run (qualification or acceptance level) is used to adjust the notching. The starting point is the notch assessment based on analysis results. Typically the following procedure is applied during a sine vibration test for each axis separately:

- Perform the low level run (resonance search)
- Scale the results of the low level run to qualification level. Be aware that the system is not fully linear, and that both the control and the response might not scale exactly linearly.

- Compare this prediction with the allowable limits - check possible exceedances and overshoots
- Update the selection for the channels / measurement points used for primary notching and secondary notching, if needed. The initial selection is based on test prediction by analysis, and is covering the most critical measurement locations in terms of expected response versus allowable load.
- Define the notch profiles including automatic and manual notches. Automatic notches are controlled by measured response (forces, accelerations) whereas manual notches are explicitly defined reductions of the input levels (accelerations).
- Make a new prediction from low level to qualification level, this time with the planned notch profile (including automatic and manual notches) and check the prediction results against the allowable limits. This check can involve dialogue with the authorities responsible for the specification.
- Perform the intermediate level run and follow the same steps as above.

Primary notching during sine tests is based on the loads (forces and moments) at the test article interface with the shaker.

It is recommended to implement force limited notching as defined in NASA-HDBK-7004C

The following methods for the measurement or derivation of interface loads are usually applied:

- **Force Measurement Device (FMD):** The most accurate way to measure the I/F loads is the use of a FMD. Either the resulting I/F loads or individual loads at each I/F can be directly measured and used for the control either for automatic or manual notching.
- **Strain gauges:** The I/F forces are indirectly determined by measuring strains nearby the test article I/F with the shaker. The knowledge of the relationship between strains and I/F forces is a pre-requisite of this method. Because the estimation of the interface forces is indirect, through the calculation of the stresses based on the measured strains, this method is less accurate than the direct FMD, and relies on hypotheses for the relationship between strains and forces. Therefore, the direct measurement of the forces is preferred. In addition, the strain gauges method requires post-processing. In practice, strain gauges can be used easily using the following approach: - perform a low frequency test with a known acceleration (1g for example), monitor the results of the gauges and also of the accelerometers to check if the specimen is already subject to some amplification due to a mode. Use this information to establish the link between quasi-static (QS) acceleration on the specimen and value provided by the gauges. In this way, notching to reach a given QS can be easily controlled with the gauge. However, it is important to ensure that a sufficient number of gauges is available and that they are installed in such a way to be able to cancel local bending effects that can affect the measurements. For example, gauges shall be mirrored on all sides of a strut or on inner and outer walls of a launch vehicle adapter so that a mean value can be derived to cancel local bendings.
- **Shaker Coil current:** This provides only an estimate of the total force applied by the shaker to the test table or shaker head expander. This method is not considered reliable. It gives only an idea of the load applied on the specimen in the direction of excitation. It requires however some precautions and to know the mobile mass of the system on top of the specimen itself and also the load-current relationship derived from the dry runs without the specimen. It is recommended to use this method only to cross check loads obtained in another way.

Figure A-23 shows an example of primary and secondary notching. The grey curve shows the nominal sine input level without any notching. The frequency of the first lateral spacecraft mode is at about 16 Hz. The I/F loads in this frequency range would exceed the allowable limits. Therefore, a **primary notch** is defined there.

The red curve shows a manually defined notch. The purpose of the manual notch is to avoid any damage of the test item if the automatic notch fails. A manual notch is also recommended if the shaker control is not agile enough to follow the defined input. The manual notch should be less deep than the expected automatic notch. Thus, finally the sine input levels (blue curve) are controlled by the I/F loads.

In order to reduce the risk of automatic notching failure, more than one response channel (pilot) should be used for controlling the shaker, including transverse channels in case of channel inversion on some sensors.

In the example case an overshoot due to the limitation of the shaker control at about 18 Hz could not be avoided. Possible overshoot needs to be considered in the definition of the notch.

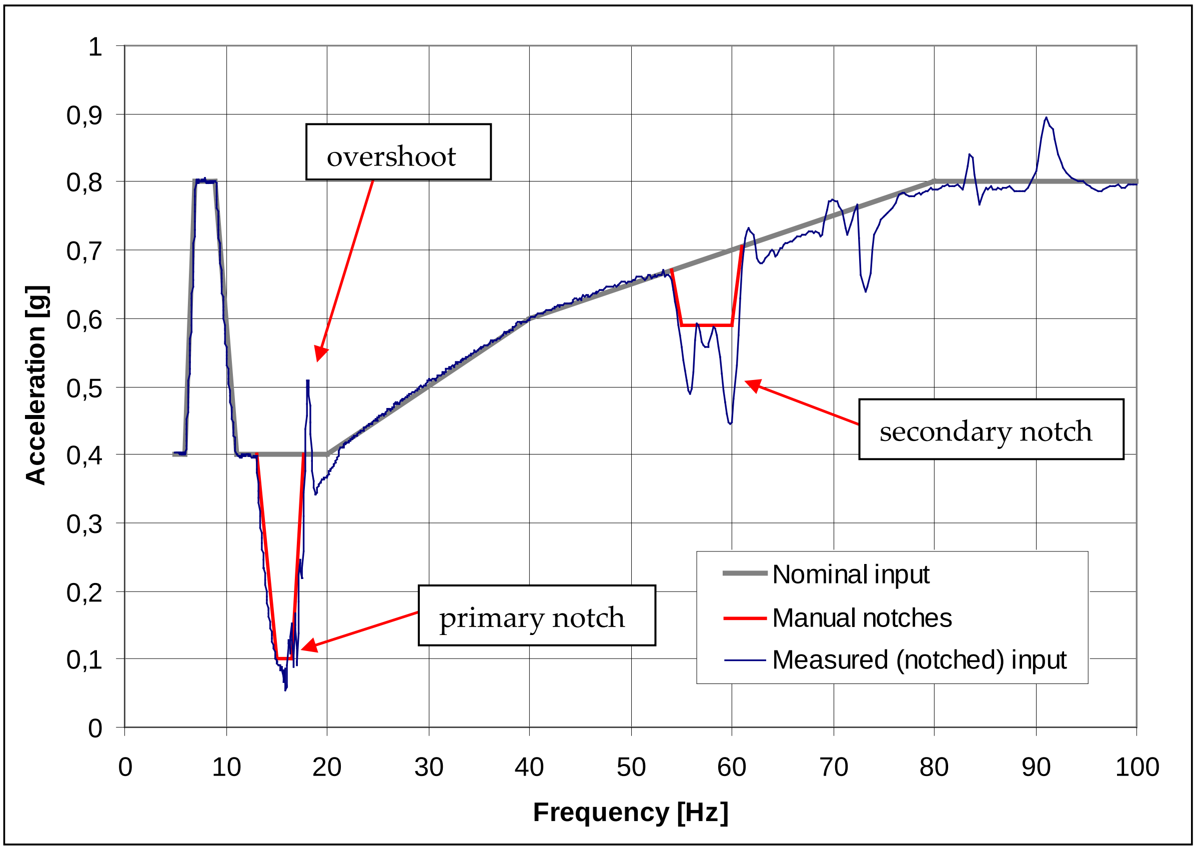


Figure A-23: Example of primary and secondary notching

A **secondary notch** is shown in the frequency range between 54 Hz and 61 Hz. This notch is justified by the maximum allowable accelerations of the propellant tank. It is controlled by the measured accelerations at the tank I/F and on the tank itself. Again a manual notch is defined to reduce the risk associated with an automatic notching.

The number, width and depth of notches should be minimized, avoiding broad-band notches.

More information about notching implementation can be found in Document on notching for MSG (Ref MSG-NNT-SE-TN-0742), available as pdf-file in Annex G.

A.7.3.5 Testing with empty or filled Tank

In general propellant storage tanks are filled to flight conditions during vibration testing, i.e. sine, random and acoustic. The requirements in ECSS-E-ST-10-03 clause 6.5.2.8 “Sinusoidal vibration test” states that testing is to be performed with tanks at least mass and stiffness representative. Since a filled tank has a deep impact on the programmatic constraints, schedule, risk and costs, sometimes vibration tests are proposed to be performed with empty tanks or lower pressure or with equivalent mass dummies.

The impact of that is to be properly assessed during verification approach definition. In particular, it is verified that the tested configuration does not prevent to achieve the objectives of the test in terms of loading of critical interfaces.

If the propellant sloshing is a load case to be tested (leading to significant propellant mass or tank interface force) then equivalent mass dummies should not be used to represent the filled tanks and the test should be performed on a vibrations facility that allows to excite the low frequency sloshing modes.

Due to safety reasons normally the propellant is replaced by a simulant medium, e.g. water or Isopropyl Alcohol (IPA). Depending on the amount IPA used special safety precautions or environmental permits from local authorities might be needed.

For missions with recurrent satellites an approach with testing the first satellite with filled tanks and empty tanks could allow, depending on the engineering assessment, to test the recurrent satellites with empty or partially filled tanks.

A.7.4 Test preparation

The sine test specification includes:

- position of the test article on the shaker for all three axes to be tested
- instrumentation plan describing identification and location of response and control sensors, including force measurement devices if applicable.
- test sequence and control strategy
- notching strategy, including definition of limits and aborts
- test success criteria

It is recommended to perform a dry run test with the empty test fixture mounted onto the shaker. It is also possible to load the fixture with a test dummy representative of the test article.

In addition, test analytical predictions should be available before the start of the test.

A.7.4.1 Test facility selection

The main differentiating parameter for vibration test facility selection is the force a shaker can apply for the excitation of a test item.

The following features are considered in the selection of the vibration test facility:

- Acceleration
- Velocity
- Displacement
- Available force (also considering the need of adapter and the corresponding mass)
- Allowable overturning moment
- Number of available measurement channels
- Frequency range

- Control capabilities (limits, aborts), number of controlling channels, possibility to notch/abort in sine and random (on RMS or PSD)
- Footprint (size of the interface)
- Possibility to record time histories
- Availability of force measurement devices

Other characteristics are important as for any test facility, e.g. handling capabilities in the vicinity of the shaker.

Table A-1presents as an example the characteristics of the ESA/ESTEC Multi-Vibration System (MVS) shaker for system testing:

Table A-1: Performances of the ESA/ESTEC MVS shaker for equipment or element testing

Shaker and amplifier characteristics (QUAD)	
Description	**Vertical**
Nominal maximum thrust	
Sine testing [kN]	640
Random testing [kN RMS]	532
Transient testing [kN peak]	1280 *)
*) *Note: Theoretical maximum. Actual value will depend on payload and pulse width.*	
Frequency range	
Sine testing [Hz]	3 - 2000
Random testing [Hz]	10 - 2000
Transient testing [Hz]	3 - 2000
Maximum displacement	
Sine and random testing [mm p-p]	25
Transient testing [mm p-p]	38
Maximum velocity [m/s]	1,6
Bare table performance	
Sine testing [g]	20
Random testing [g RMS]	16,6
Minimum controllable level [g]	0,05
Fundamental resonance frequency [Hz]	180

Shaker and amplifier characteristics in dual shaker configuration		
Description	**Vertical configuration**	**Horizontal configuration**
Nominal maximum thrust		
Sine testing [kN]	320	320
Random testing [kN RMS]	310	310

Transient testing [kN peak] *)	930	930
*) *Note: Theoretical maximum. Actual value will depend on payload and pulse width.*		
Frequency range		
Sine testing (min - max) [Hz]	3 - 2000	3 - 2000
Random testing (min - max) [Hz]	10 - 2000	10 - 2000
Transient testing (min - max) [Hz]	10 - 2000	10 - 2000
Maximum displacement		
Sine and random testing [mm p-p]	20	20
Transient testing [mm p-p]	38	38
Maximum velocity [m/s]	1,5	1,5
Maximum no-load acceleration		
Sine testing [g]	16	19
Random testing [g RMS]	5	11
Minimum controllable level [g]	0,1	0,1
Fundamental resonance frequencies (bare test facility) [Hz]	250	400
Maximum static vertical load [kg]	4700	10000
Allowable overturning moment [Nm]	100	1300
Mass of the moving assembly [kg]	2000	1600
Shaker and amplifier characteristics in single shaker configuration		
Description	**Vertical configuration**	**Single head expander configuration**
Nominal maximum thrust		
Sine testing [kN]	160	160
Random testing [kN RMS]	155	155
Transient testing [kN peak] *)	465	465
*) *Note: Theoretical maximum. Actual value will depend on payload and pulse width.*		
Frequency range		
Sine testing (min - max) [Hz]	3 - 2000	3 - 2000
Random testing (min - max) [Hz]	10 - 2000	10 - 2000
Transient testing (min - max) [Hz]	10 - 2000	10 - 2000
Maximum displacement		
Sine and random testing [mm p-p]	38	20
Transient testing [mm p-p]	51	38
Maximum velocity [m/s]	2	1,5
Maximum no-load acceleration		
Sine testing [g]	100	20

Random testing [g RMS]	30	30
Sine testing with 100 kg load [g]		27
Minimum controllable level [g]	0,1	0,1
Fundamental resonance frequencies (bare test facility) [Hz]	1700	1100
Maximum static vertical load [kg]	1363	2000
Allowable overturning moment [Nm]	400	600
Mass of the moving assembly [kg]	130,4	369,5

A.7.5 Test execution

Before each run is started, it is recommended to perform a pre-test. The pre-test allows to check the proper orientation of all pilots, and the proper functioning of all sensors.

A typical sine test sequence consists, as a minimum, of the following test runs for each axis:

- Low level run (resonance search) – see discussion on sweep rate in A.7.3.3
- Intermediate level run
- Full level run (qualification or acceptance level)
- Low level run (resonance search for purpose of structural integrity check)

Low level test runs are conducted in order to:

- Identify the test item resonance frequencies and correlate results with predictions,
- Estimate the damping associated to the main modes,
- Establish a basis for resonance frequencies comparison between test runs and allow any interface settling anomaly evaluation,
- Establish first notch prediction for the intermediate and full level run and compare this prediction with the notch assessment based on analyses.
- Verify the structural integrity after the full level run.

It is recommended to have a validated analysis tool at hand to support the extrapolation of the measured data from one level to the next, in particular to support the notch preparation.

Low level run is performed to compare the dynamic signature of the test specimen before and after the test. Changes in dynamic behaviour (frequency shifts or response levels) can indicate structural failure.

Intermediate level test runs are conducted in order to adjust the initial prediction of the full level test run with respect to the following aspects:

Effect of the input level on the Dynamic behaviour:

- resonance frequencies
- mode shapes
- non-linearities
- damping

A typical approach for the intermediate level is to go for a half-level run before full level. Additional intermediate runs can be added before going to full level (3/4 level for example) in case significant evolution of the damping is observed between low and intermediate level. For a flight item, it is recommended to limit the number of intermediate level runs.

A.7.6 Test run evaluation

After each test run following checks are performed:

- that all sensors worked correctly by checking the acquired data
- Check the control (pilot) accelerometers to verify that the input provided is in accordance with the test specification and within tolerances. Check the control accelerometers with the co-pilots
- Sensor orientation (first test run)

  During low frequency excitation, the test specimen is expected to behave as a rigid body and therefore the accelerometers on the test specimen are expected to have the same response (magnitude and phase) as the pilot accelerometers in the direction of excitation
- Piloting quality

  Comparison of magnitude and phase of all pilot accelerometers with each other and with the desired acceleration.

  This includes the determination of excitation in orthogonal directions compared to the excitation direction (cross axis excitation, parasitic motion)
- Check Transfer functions

  Transfer functions are calculated by dividing the test article response by the test article base excitation. The transfer functions are compared between different levels to check for change in dynamic behaviour. Note that the computation of the transfer function can be biased when notching's are triggered. When a notching is triggered due to a mode, the response of the system is the superimposition of the free-response of the system + the response to the remaining notched input level. So, the computation of the transfer functions is perturbed by the notching.
- Global/fundamental comparison

  Comparison between the global and fundamental values allows to detect non-linearities and rattling issues, which creates content at different frequencies than the excitation frequency.

A.8 Random vibration testing

A.8.1 Purpose

Random vibration testing is performed to demonstrate that hardware can withstand the broad-band high frequency vibration environment and to verify structural life and functionality under the loads.

A.8.2 General

The test item is vibrated in three spatial directions separately, where all frequencies are excited at the same time, in a frequency range typically from 20 Hz to 2000 Hz.

Random vibration is mostly applied at equipment level. It is sometimes applied at element level, for example for an instrument.

For Safety aspects see A.7.2.

A.8.3 Test configuration and test aspects

A.8.3.1 Overview

The tests are conducted on an electrodynamic vibration machine or "shaker," which consists of a mounting table for the test item rigidly attached to a drive-coil armature. A control system energizes the shaker to the desired vibration level. Feedback for the control system is provided by a series of accelerometers or forces, which are mounted at the base of the test item or as responses on the test specimen. Similarly to sine testing, adequate control approaches and strategies are used to avoid over testing and to ensure realistic structural responses. In a random test all frequencies are excited at the same time (no sweep).

In a typical random test, the test specimen is mounted onto a test fixture that is bolted to the electrodynamic shaker interface. A set of accelerometers are installed on the test article to control the input and to measure the vibration responses. Strain gages and force sensors can also be used to measure the test article responses.

The test fixture shall be designed to minimize fixture response at resonance within the test frequency range. It should show a variation of transmissibility between test article mounting points not higher than +/- 3 dB between 20 Hz and 500 Hz and +/- 6dB between 500 Hz and 2000 Hz. Additionally, its first resonance should be as high as possible in frequency and should show a limited amplification (e.g. not above 2) in the frequency range 20 Hz – 2000 Hz. Eventually, the cross axis excitation shall not exceed the input and the design of the fixture aims at minimizing the cross axis as much as possible.

The cross axis is considered to evaluate the consequences of this parasitic excitation in terms of:

- Overtesting
- Undertesting
- Test controllability in the full frequency range (20 Hz-2000 Hz)

A.8.3.2 Test instrumentation

Instrumentation consist of accelerometers, strain gauges, force measuring devices.

See also A.7.3.1, as the test instrumentation is similar to the sine vibration test.

A.8.3.3 Test control parameters

The control of the shaker is performed by control accelerometers, also called pilot. Responses of the test article (accelerations and forces) can also be used as limits in the control loop.

Before the start of the test, the following needs to be defined:

- Identification of control (pilot) accelerometers:

  The number, orientation (always in the excitation direction) and the position of the sensors used to control (pilot) the test should be clearly identified.

  The control accelerometers are located close to the interface of the specimen on the test fixture side, at different location around the test article. This allows to check the homogeneity of the input to the test article. It is recommended that the control accelerometers are attached with screws and not bonded when possible.

  To ensure that the control accelerometers are working properly, it is recommended to have an accelerometer next to each control accelerometer, called co-pilot, to check the signals of the control accelerometers.

- Identification of limits

  It is recommended to always implement limits on some sensors (pilots, response acceleration, loads), also in cross axis directions. The control of the shaker uses those limits to ensure that the defined values are not exceeded, in order to protect the test article.

  Some of the limits are used for the purpose of notching implementation. See section A.7.3.4.

- Identification of aborts

  It is recommended to implement abort values on a number of sensors. When the abort value are reached, the test is stopped (aborted).

  It is recommended to check how the abort is implemented (how exactly the input is affected), as abort can be rather brutal and inadequate (e.g. staying at the same frequency and reducing the levels).

  It is recommended to implement limits on each channel used as abort, to limit the risk of abort.

- Control strategy:

  To control the test, it should be decided if the control is made on the maximum or on the average value of the pilot sensors. The average signal being smoother, it can help to ease the control of the test. However the specimen needs to be protected (notching and abort channels) because the failure of one pilot decrease the measured mean level, leading to an unwanted increase in the input level to compensate for that.

The above parameters are captured in a run sheet, together with the required input spectrum and associated tolerances.

Note that depending on the control system, limits and aborts can be defined by PSD curves (as a function of frequency) or RMS value (corresponding to the complete frequency range).

Note that the number of notch/abort channels can affect the shaker control. Increasing the number of channels in the control loop can slow down and degrade the control.

It is recommended to verify that the parameters implemented in the control system correspond to the parameters requested in the run sheet.

An emergency abort button is usually available to manually abort the test. The customer usually undertakes this responsibility.

It is important to understand the processing of the measured data in random. The acquisition system records data in the time domain, which are processed on a given time window to produce the power spectral density (PSD). The size of the window can be tuned and this changes the frequency resolution and affects the peak values. The PSD computed for each time window are usually averaged to compute the response PSD. It is important to understand what the PSD provided corresponds to.

It is important to consider that the PSD does not reflect exactly the time histories, as the data is reduced. There is data loss in the transformation to PSD.

The RMS response measured during short time windows during the test can be quite different compared to the overall RMS level obtained at the end of the test. This means that it can be difficult to drive the test on RMS responses and in particular, abort based on RMS values should be used and adjusted carefully. It is recommended to discuss these points with the test facility and also to measure some time histories to assess the response obtained in practice.

It is recommended to record time histories and to check the maximum values reached in the time domain, as well as the variation of the measured data over time. While it is often considered that the maximum value over time corresponds to 3 sigma, it is very often the case that instantaneous values up to 5 sigma are reached at some point during the test.

[Ref. article What is behind the curves, ECSSMET2016 (available as pdf-file in Annex G).

Some control systems have the option to limit the injected levels to 3 sigma. However, experience shows that this does not always work as expected and it is important to check time histories to verify how efficiently this limitation is applied. While it is possible to limit the input to a max instantaneous value of 3 sigma by clipping, the responses usually reach higher instantaneous values.

A.8.4 Test Preparation

For the selection of the test facility, see A.7.4.1

Note that depending on the control system, limits and aborts can be defined by PSD curves (as a function of frequency) or RMS value (corresponding to the complete frequency range).

The random test specification includes:

- position of the test article on the shaker for all three axes to be tested
- instrumentation plan describing identification and location of response and control sensors, including force measurement devices if applicable.
- test sequence and control strategy
- notching strategy, including definition of limits and aborts
- test success criteria

It is recommended to perform a dry run test with the empty test fixture mounted onto the shaker. It is also possible to load the fixture with a test dummy representative of the test article.

In addition, test analytical predictions should be available before the start of the test.

A.8.5 Test Execution

It is recommended to always start with low levels. Implement notching at intermediate level before going to full level. See A.7.3.4.

It is recommended to check the transfer functions obtained during the random test (square root of the ratio of PSDs) and compare them to the transfer functions obtained during the low level sine. This allows to detect non linearities, or changes in the transfer functions between levels, as a potential indication of a problem. The transfer functions can also be used as health monitoring during the test. If the transfer function changes suddenly, then there is probably something damaged.

Figure A-24 gives the typical test sequence used for the random environment qualification of an equipment.

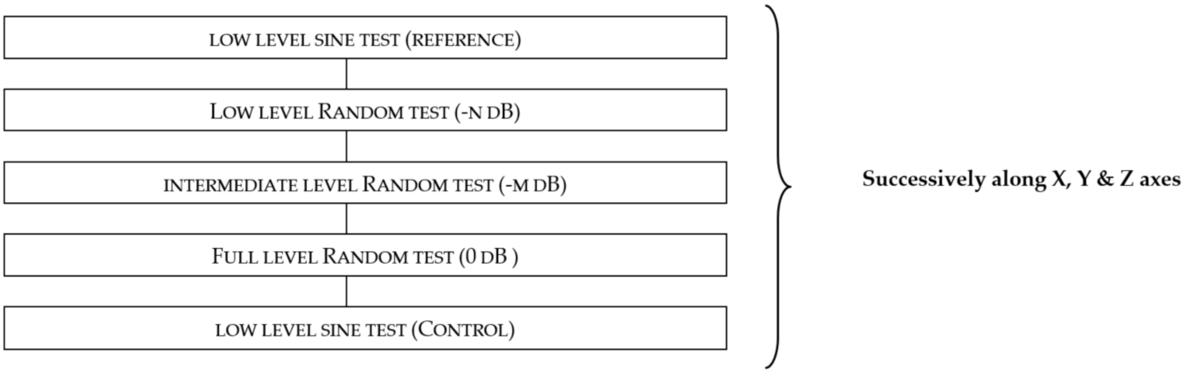


Figure A-24: Example of test sequence for random vibration

- Before starting the test sequence, the specimen is weighted in order to update the Quasi Static resultant interface force criteria.
- The reference low level sine test allows to validate the instrumentation and the entire acquisition chain.

Notching

It is often necessary to limit input acceleration levels during the random vibration tests not to overpass the qualification of equipment or a satellite (over-testing). There are automatic procedures, which are based on interface forces or acceleration measurements, not to overstress the equipment.

Force Limited Vibration

The equipment to be tested is rigidly fixed to a very stiff shaker table and separated from its real mounting structure. The difference between flexible flight mounting (soft-mounted) and rigid test interface (hard-mounted) results in different dynamic response of the component. The application of an envelope of the interface acceleration spectra obtained in flight configuration to the hard-mounted test configuration can generate excessive interface forces at the natural frequencies of the hard-mounted component, leading to undesired over-testing of the hardware.

The Force Limited Vibration (FLV) technique involves the implementation of Force Measurement Devices (FMDS) to measure the interface force during the test and introducing this signal in the control loop to keep these forces below a pre-established limit (the interface forces expected in the coupled, soft-mounted, system). The traditional acceleration specification is used to drive the test, but complemented with the force measurement, used as the criterion to limit the acceleration input at the natural frequencies of the hard-mounted component, so controlling the over-testing (see NASA- HDBK-7004C)

A.8.6 Test run Evaluation

The checks to be performed after each axis single run:

- Check the control (pilot) accelerometers to verify that the input provided is in accordance with the test specification and within tolerances. Check the control accelerometers with the co-pilots (see A.7.3)

- In any case, it is recommended to check the consistency of the control accelerometers and investigate when there is significant discrepancy between them.
- Cross axis acceleration check.
- Check of the stability of the input over time (e.g. using sliding g-RMS values). Note that this check must be requested in advance to the test operator.

The check to be performed after each axis random plus low level sine tests

- Comparison of the pre and post low level sine tests to identify possible changes in dynamic behaviour (eigenfrequencies shifts and amplification variations)

A.9 Acoustic testing

A.9.1 Purpose

The purpose of the acoustic test is to demonstrate that the test article can withstand the acoustic environment encountered during relevant mission phases, in particular the acoustic loads during launch, as specified by the launcher authority.

The acoustic test also allows to validate the random vibration specifications applied to the lower level elements/equipment.

A.9.2 General

Acoustic test is performed at element level. It is applied at equipment level for equipment with large surfaces and low mass, e.g. solar arrays, antenna reflectors…

A.9.3 Test Configuration and test aspects

In a typical acoustic test, the test specimen is positioned in a reverberant acoustic chamber. The chamber is a large room with thick walls and a smooth interior surface that allows high reverberation. The test article is placed on a fixture or suspended from bungee cords. In some cases, the test item can be attached to a supporting structure to simulate actual mounting conditions, thereby creating a more realistic boundary condition. Loudspeakers or horns supply the acoustic energy. Horns are typically located only in one surface of the chamber, whilst loudspeakers are placed around the test article. The control and record of the sound level within the chamber is performed using six or more microphones placed around the test article, including above. Sometimes, microphones are placed below the test article (although not used to control the input) to check the absence of standing waves.

The minimum distance of the microphones from the test article is generally 1 meter. The exact location the microphones with respect to the test article is included in the test report.

The microphones are placed at least 1.5m from the chamber walls.

For a space segment, microphones are typically placed at 2 m height, and for high test articles, at 4 m height, around the test article.

The specification is usually defined in octave band. There is often also a requirement about the homogeneity of the sound pressure field, as measured by the microphones.

Even if the specification and the control is defined per octave or 1/3 octave, it is recommended to check the input levels in fine frequency band and assess risk on the test object (e.g. high peak at a resonant frequency of the test article)

The input acoustic level is controlled in close loop based on the microphone measurements, usually in third octave bands.

The applied input levels are defined as the arithmetic mean of the measurement of the microphones.

It is recommended to check the spatial homogeneity of the acoustic field across the control microphones and adjust position of the test article in the chamber if necessary. It is recommended to avoid placing test article walls parallel to the chamber walls to avoid stationary acoustic waves. Also the bottom panel of the spacecraft should be protected in order to avoid stationary acoustic waves between the ground and this panel.

Sound Pressure Levels (SPL) tables of each microphone and average values of the SPL of all control microphones are provided to judge if specified SPL per octave band and Overall SPL meet the specifications.

In general, the reverberant chambers have large volumes. However, the test items placed in the chamber have an influence on the sound field. The fill ratio is defined as the ration between the volume of the test article and the volume of the acoustic chamber. A fill ratio of less than 10% is recommended.

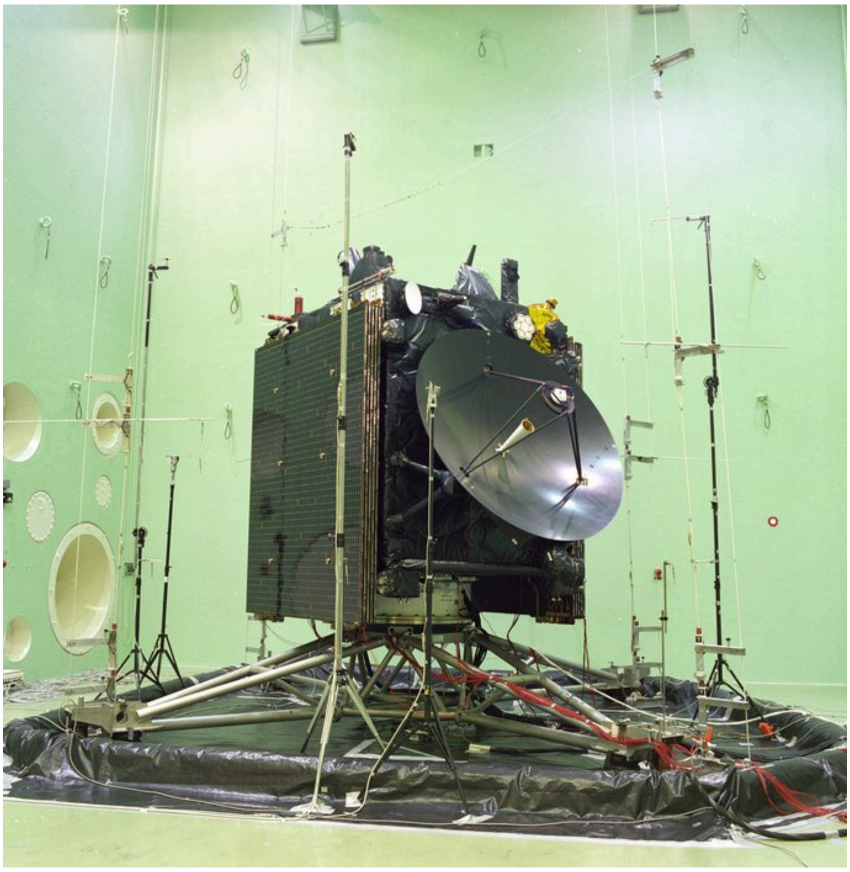


Figure A-25: Rosetta in the ESTEC Large Acoustic Facility

Figure A-26Antenna reflector acoustic test in ESTEC acoustic facility

Instrumentation: Accelerometers are installed on the test article to measure the vibration responses.

Strain gauges and force sensors can also be used to measure the test article responses.

These responses and pressure are measured in the time domain and, in general, presented as power spectral densities in the frequency range of interest (e.g. 20 Hz-2500 Hz, sometimes up to 8000 Hz) and with a certain frequency resolution (e.g. 2 Hz).

It is recommended to record time histories of the responses and to check max peaks values of the time histories as well as the variation of the responses over time

In most cases, the test article is ON during vibrations such that it can be functionally monitored during the test.

As an alternative to performing the acoustic test in a reverberant chamber, Direct Field Acoustic Testing has been developed. Loudspeakers are installed around the test specimen, i.e. not in a reverberant chamber. The acoustic field is different from a diffuse field. Reference to NASA-HBK-7010.

A.9.4 Test preparation

Prior to the test of the article, empty chamber run(s) are performed (without the test article), in order to establish the settings of the control equipment and to achieve the levels as defined in the following sections. The empty runs usually include some runs at higher levels than the ones specified (typically +2 dB or +3dB). This is made to see if the chamber has the capability to inject more energy if necessary to compensate the absorption coming from the specimen itself.

The acoustic test specification includes, as a minimum:

- position of the test item in the reverberant chamber (see Figure A-25 and Figure A-26),
- The test sequence, associated sound pressure levels, test durations, e.g. low level, intermediate level, qualification level and low level again,
- Instrumentation plan describing identification and location of sensors,
- Success criteria.

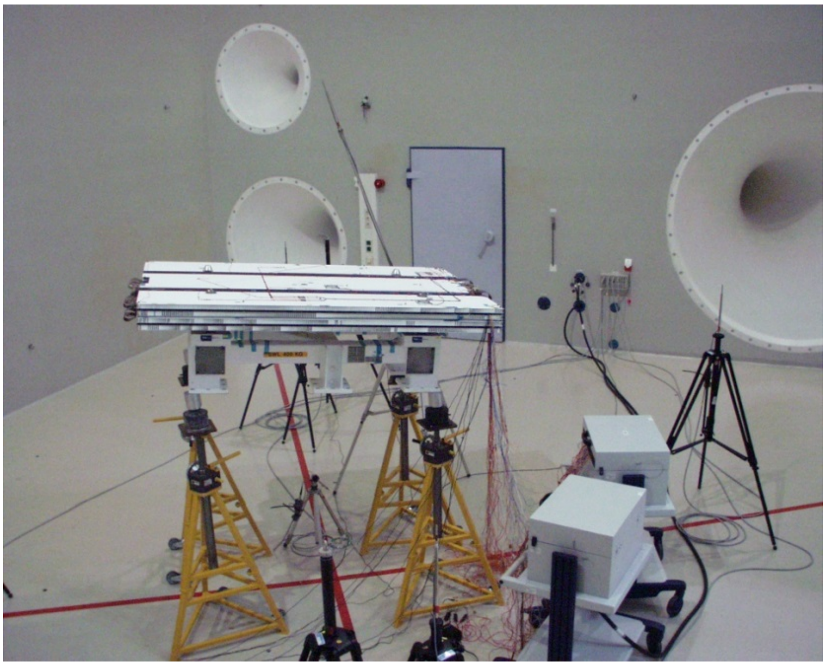


Figure A-27: ATV STM-B Solar array wing in IABG reverberant chamber (Courtesy Dutch Space)

A.9.5 Test execution

A typical test sequence includes low level, intermediate level, high level and low level.

The low levels are also called signature runs and are used to highlight possible changes in the test article dynamic responses.

Between each level run, results of the previous run are evaluated.

Each level run starts with low levels (typically -6 dB/-9dB), increasing progressively (typically -4 dB/-2dB for intermediate level) to the nominal level.

The parameters used to control the acoustic level have to be validated with an empty run. It is highly recommended not to modify the parameters of the control if they have not been validated by an empty run.

A.9.6 Test evaluation

The responses are compared between each run to check evolutions of the dynamic behaviour and ensure that the responses stay within the allowable levels.

It is recommended to check of the stability of the input over time (e.g. using sliding g-RMS values). Note that this check must be requested in advance to the test operator.

A.10 Shock testing

A detailed discussion of shock testing, test methods and test facilities, and of shock test monitoring is found in chapter 13 of ECSS-E-HB-32-25.

A.11 Thermal distortion test

A.11.1 Purpose

Thermal distortion tests are performed to characterise the distortion of a test article under thermally induced loads. It can be performed at equipment (e.g. reflector) or element level.

A.11.2 General

The principle is to apply a controlled thermally induced load to the test article, and to measure the resulting deformation. For prediction correlation purpose, the temperature distribution on the test article is measured as well.

A.11.3 Test configuration and test aspects

In general, the thermal distortion test is performed for the on-orbit configuration. The test article is allowed to expand freely under the thermal loads. In practice this is mostly achieved by kinematic support concepts, see Figure A-28.

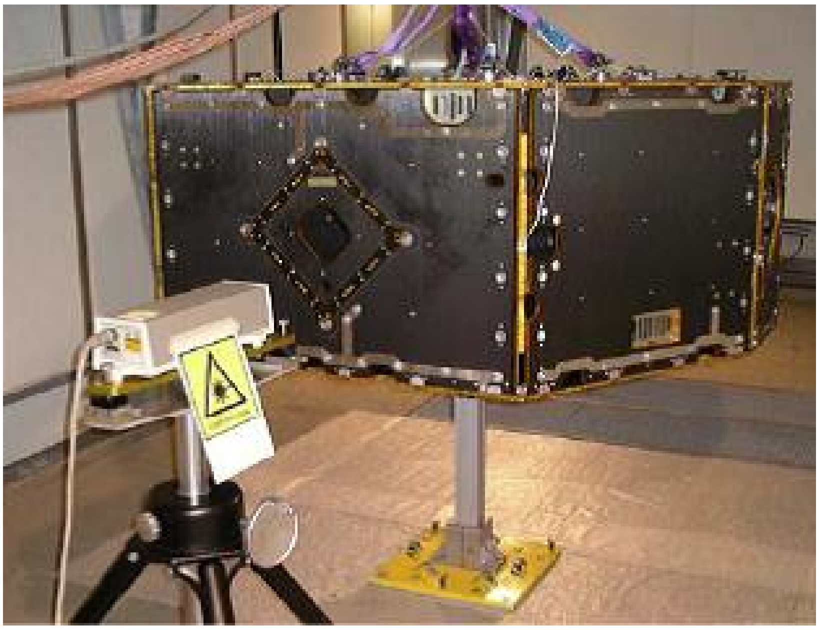


Figure A-28: LISA Pathfinder Science Module structure on kinematic support for thermal distortion test

Alternatively the test structure can be freely suspended by slings. However, problems with such test setup have been experienced due to laser alignment problems caused by small movements of the structure due to circulating air in the test room.

For executing the test the assembled structure is usually placed in a temperature chamber or in a thermal vacuum chamber and then subjected to the temperature variations. Several options exist to measure the structure deformations and to determine the distorted shape of the structure, e.g. laser metrology, videogrammetry, or a combination of both.

Cut-outs in the structure or removal of panels might be needed to provide the required access for the measurement devices or to ensure unobstructed line-of-sight for e.g. laser beams. However, care should be taken to ensure that these modifications do not significantly affect the thermo-elastic distortion behaviour of the test structure.

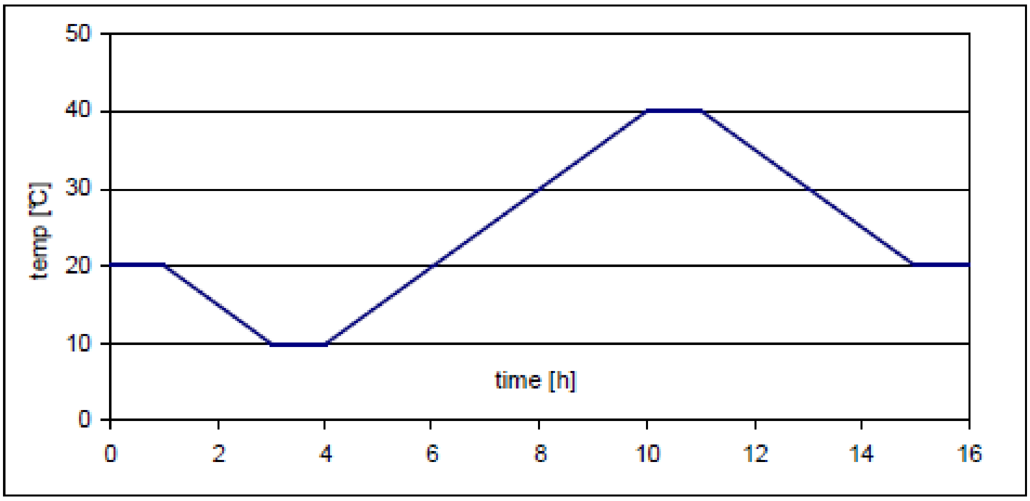


Figure A-29: Typical temperature profile for thermal distortion test

A typical temperature profile for thermal distortion test is shown in Figure A-29. In this case, a uniform temperature was applied to the test article. The distortion of the test article was measured in the temperature range from 10 °C to 40 °C, the heat-up and cool-down rates were 5°C/hour and the extreme temperatures of +10 °C and +40 °C were kept constant for 1 hour in order to equalize the temperature on the whole structure.

The relatively simple thermal distortion test case as shown in Figure A-29 has the advantage that it can be easily conducted in a thermal chamber and has in general a good repeatability.

A.11.4 Test instrumentation

A.11.4.1 Overview

The measurement of the structure deformations can be performed e.g. by laser metrology, videogrammetry, or a combination of both.

A.11.4.2 Laser-interferometric measurements

Laser metrology as illustrated in Figure A-30 is considered the most accurate method to measure distortions of one micrometer or smaller. However, it is not a practical method to determine the distorted shape of a complete structure as only the change of one dimension with temperature can be measured. In addition, the method requires mounting provisions for the interferometer and mirrors.

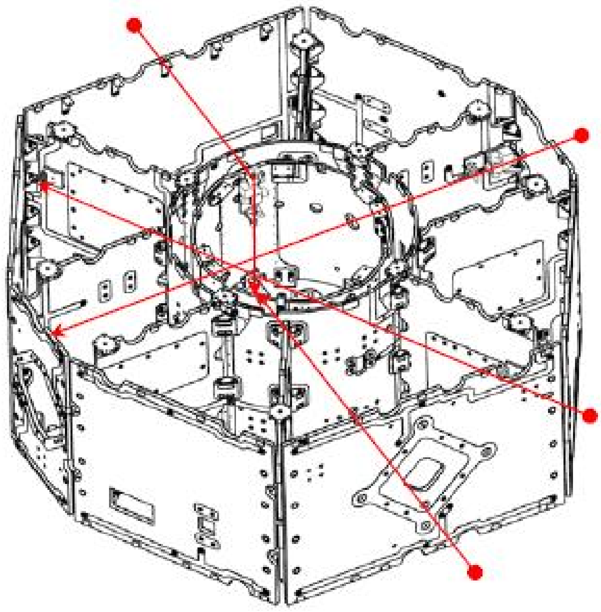


Figure A-30: Illustration of different courses of laser beams for LISA Pathfinder Science Module thermal distortion test

A.11.4.3 Videogrammetry

Digital photogrammetry, also known as videogrammetry, is a well proven method to measure 3D geometry and distortions. Videogrammetry is a measurement technology based on optical triangulation in which the three-dimensional coordinates of points (targets) on an object are determined by measurements made in two or more images taken from different angles. These can be obtained from successive images captured by the same camera with a view of the object.

To perform the videogrammetry measurements the test structure needs to be equipped with an adequate number of self-adhesive optical targets. Calibrated reference scales (yellow bars in Figure A-31) are positioned close to the test article to provide absolute dimensions.

Best results are achieved when the targets are seen from many different angles, see Figure A-32. To obtain the best possible coverage, approximately 250 pictures were taken e.g. during the LISA Pathfinder Science Module thermal distortion test at the minimum and maximum temperatures, respectively (see the temperature profile shown in Figure A-29.

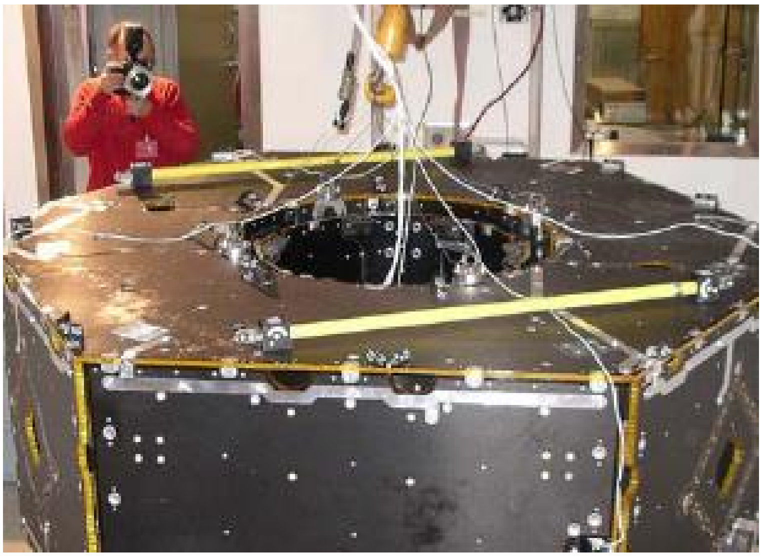


Figure A-31: Videogrammetry measurements during LISA Pathfinder Science Module thermal distortion test

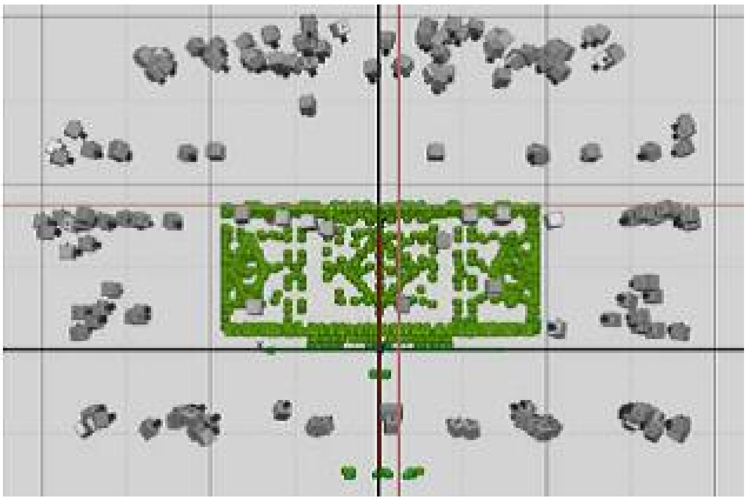
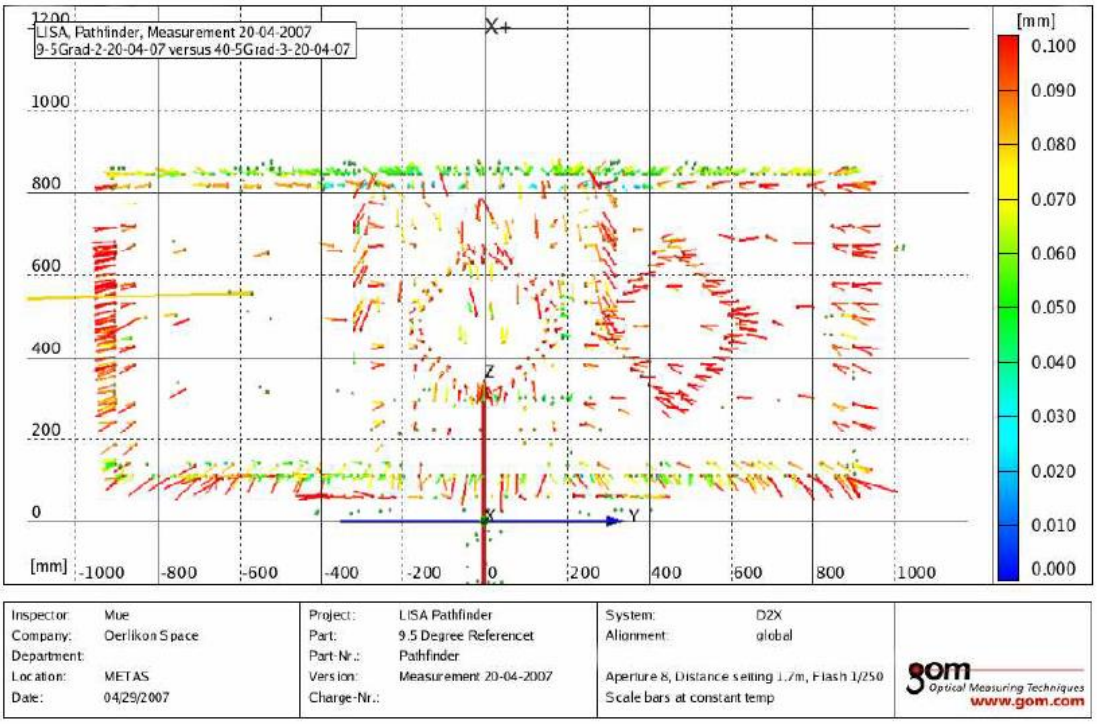


Figure A-32: Overview of camera positions used during LISA Pathfinder Science Module thermal distortion test to generate the images of the test article

Accuracy depends on the size of the field of view. The accuracy of the videogrammetry is typically 10 µm – 15 µm for objects of the size of the LISA Pathfinder Science Module structure (diameter of octagonal structure: about 1,8 m). Although the accuracy of the videogrammetry is at least one order of magnitude less than the accuracy of the laser metrology, it still provides useful information on the global behaviour. The distortion of the external structure caused by a uniform temperature increase of approximately 30 °C is shown in Figure A-33. To increase the signal to noise ratio, thermal loads can be can be increased.



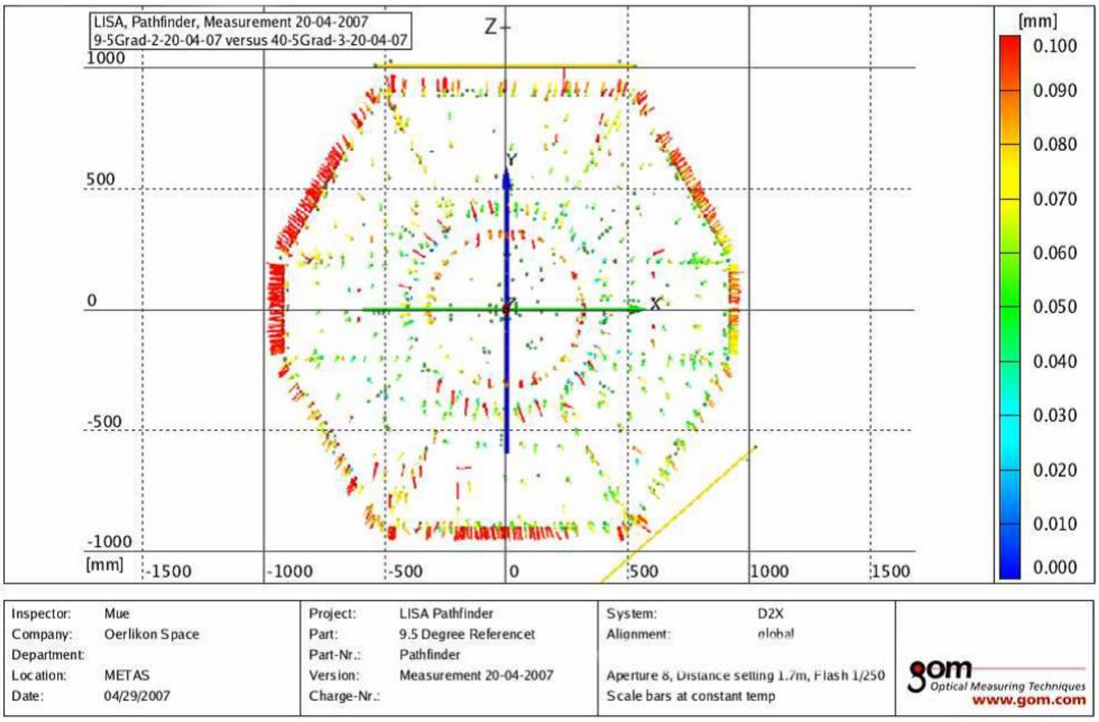


Figure A-33: Displacement of targets mounted on LPF SCM external structure for a temperature variation from +9,5°C (reference temperature) to +40,5°C

A.11.5 Temperature measurement

Temperature measurement can be performed by use of thermocouples or thermistors, as well as thermography. Thermography (infra-red imaging) allows to measure full field temperature maps without contact with the test article.

A.11.6 Test evaluation

The main activities after the thermal distortion test are the following:

- Check that the thermal load was applied according to specification, by checking the temperature measurements
- Check that deformation measurements are recorded and can be used to post-process the data.

A.12 Gravity release test

A.12.1 Purpose

The gravity release test has the main objective to assess the effects of the absence of gravity loads for the on-orbit configuration being in contrast with the measurement conditions on Earth during the AIT/AIV activities. This allows to characterise the potential defocus or decentre of an optical instrument due to the absence of gravity load in space.

A.12.2 General

During the test the alignment is measured with different gravity vector orientations. However, only two integration directions are usually considered: axial and lateral, and as a consequence two loading directions are tested.

A.12.3 Test configuration and test aspects

The test specimen is constrained at its mounting interfaces as applied e.g. for a static test.

There are two ways to characterise the effect of gravity:

- By modifying the relative orientation of the test article with respect to the gravity field and measure the corresponding deformation which corresponds to twice the effect of gravity release. This is the recommended method.
- By applying gravity compensation loads and measure the corresponding deformation which correspond to the unloaded condition.

As an example the gravity-release test configuration for the NIRSpec engineering test unit (ETU) is shown in Figure A-34.

Figure A-34: NIRSpec engineering test unit (ETU) during gravity-release test (courtesy: EADS Astrium)

The measurement of the deformation can be performed by external means, or by taking advantage of the built-in metrology existing in the test article, supported by OGSE if needed.

A.13 Micro-vibration environment verification by test

Four types of tests are performed related to micro-vibrations:

- Characterisation of the disturbance generated by an equipment (addressed in ECSS-E-ST-10-03 clause 5.5.2.7). This is also called emissivity test.
- Characterisation of the susceptibility of an equipment/instrument to micro-vibrations (addressed in ECSS-E-ST-10-03 clause 5.5.2.8)
- Characterisation at element level of a transfer function between a source of disturbance and an equipment/instrument. (addressed in ECSS-E-ST-10-03 clause 6.5.2.11)
- Measurement at element level of the response of an equipment/instrument to a source (End to End test) (addressed in ECSS-E-ST-10-03 Tables 6-1 and 6-2 and in ECSS-E-ST-10-03 clause 6.) and called Micro vibration susceptibility test at element level

Those four types of tests participate in the verification approach, either piece by piece (three first tests) or End to End.

A.13.1 Characterisation of the disturbance generated by an equipment – direct force measurement

A.13.1.1 Purpose

The purpose of this test is to measure the disturbance generated by an equipment in terms of micro-vibrations.

A.13.1.2 General

The principle is to mount the equipment on a rigid fixture, mechanically isolated from the ground, to activate the equipment in its different operating modes and to measure the reaction force at the interface.

It is important to record the time history of all components of the interface forces.

A.13.1.3 Test Configuration and test aspects

The item under test is rigidly mounted on a device (dynamometer) that measures all components of the reaction force. The complete setup is mechanically isolated from the ground to limit the background noise. This can be done by using a seismic foundation, or air bellows.

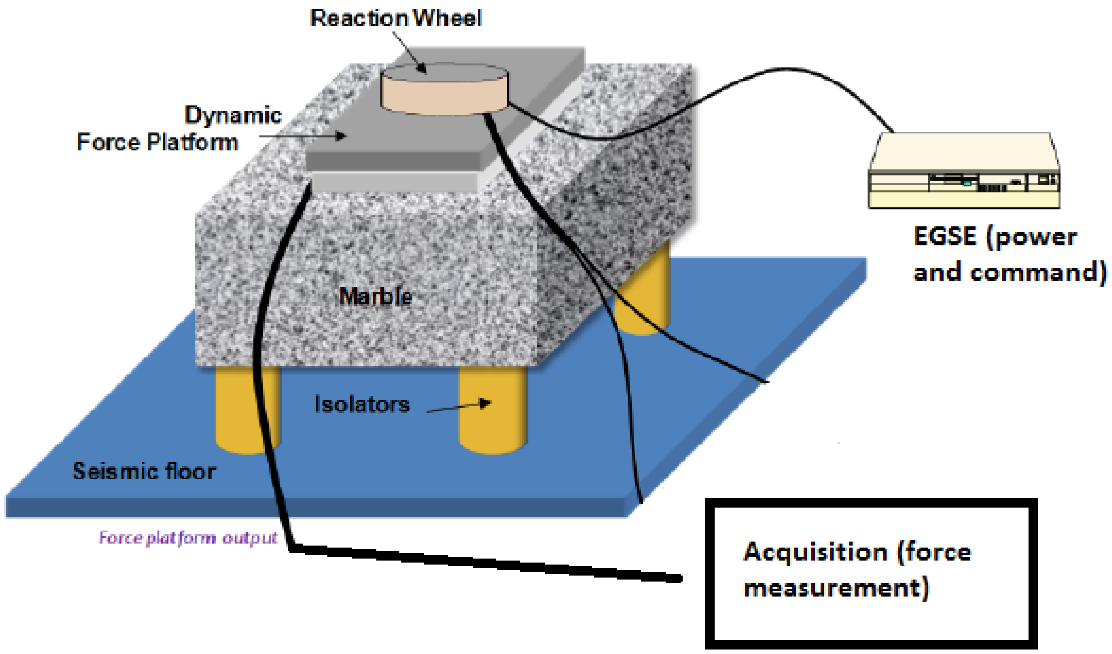


Figure A-35 Principle of measurement of the micro-vibration generated by an equipment

Figure A-36: ESA reaction wheel characterisation facility in ambient conditions and in with vacuum bell (mN range frequency band up to 1 kHz)

Interface forces/moments are measured by piezoelectric force transducers. One of the main drawbacks relies in the possible amplification of measured forces due to resonances of the test set-up, i.e. flexibility of the interface and force sensors, which will reduce the usable frequency bandwidth in which the results can be considered valid. In addition a trade is to be made between the stiffness of force sensors and the required, very high sensitivity.

For this reason it is recommended to acquire not only the background noise levels before each test run but also to determine the dynamic characteristics of the test setup by a modal survey test (see ECSS modal survey test ECSS-E-ST-32-11 by hammer impact or modal shaker excitation. The latter will define the confidence of measurements w.r.t. frequency band.

Instrumentation: high sensitivity accelerometers are used to measure the background noise. The measurement noise (e.g. due to imperfect grounding) is to be reduced. High sensitivity force sensors (dynamometers) are used to measure the interfaces forces.

A.13.1.4 Test Preparation

The test requires an EGSE to drive the equipment in its different operating modes.

It is very important to measure the background noise before and after the measurement. An identification of the sources of background noise will help defining mitigation actions to reduce the noise level, e.g. test by night, stop activities in the surrounding, switch off air-conditioning, improve the electrical grounding. See A.13.6 about background noise.

EGSE and FGSE need to be adequately isolated in order to minimize the transmission of structural and acoustical disturbances to the item under test.

It is also important to consider the effect of harness to the unit under test, which might also transfer micro-vibration from the EGSE. A solution can be to suspend the harness and introduce flexibility through strain relieve loops.

Note that the effect of FGSE (e.g. pump for a cryocooler, of for vacuum) can be difficult to mitigate. Also for a cryocooler, the interface to the cold finger introduces complexity in the setup.

A.13.1.5 Test execution

It is very important to record time histories in each operating conditions, e.g. wheel speed for a reaction wheel.

A.13.1.6 Test evaluation

Measurements are processed to calculate Power Spectral Densities (PSD). It is checked that the measurement can be distinguished from the background noise by comparing the PSD of the measured signal with the noise.

A.13.2 Characterisation of the disturbance generated by an equipment – indirect force measurement

A.13.2.1 Purpose

The purpose of this test is to measure the disturbance generated by an equipment in terms of micro-vibrations.

A.13.2.2 General

When the direct force measurement as described in A.13.1 is not possible or convenient, an indirect method can be used as an alternative (e.g. in the case of Human Space facility payload racks).

This is used when the equipment to be characterised cannot easily be mounted rigidly on a microvibration characterisation facility. It uses an adhoc test setup.

With this test approach the interface forcing functions at the equipment mechanical mounting interfaces are not measured directly at the equipment mechanical interfaces but they are derived by post-processing the experimental data obtained from the following two experimental measurements:

- Acceleration-to-force transfer function measurement,
- Self-induced acceleration spectrum measurement, switching on separately or simultaneously all the potential micro-gravity disturbance sources mounted inside the equipment.

The transfer function experimental measurements is executed acquiring the acceleration-to-force transmissibility from each equipment mechanical interface to all equipment interfaces.

The self-induced acceleration spectrum measurements is executed acquiring the acceleration spectra at all equipment mechanical interfaces in all equipment operational condition.

A.13.2.3 Test Configuration and test aspects

The indirect interface force measurement requires the rigid mounting of the test item to a support structure. Alternatively, it can directly be suspended through its interfaces by air cushion to the ground.

This setup needs to be suspended to ensure a dynamically free-free boundary condition able to filter the mechanical vibration coming from the surrounding environment.

Figure A-37 shows a schematic test set-up for the micro-vibration test by indirect force characterisation.

It is usually possible to realize a suspension system of the test setup having its first resonance frequency between around 1,5 Hz and 3,0 Hz.

The main advantages of this method are that the item under test can be mounted on any convenient test structure (e.g. uniform plate) and the fact that no seismic foundation is required.

Drawbacks are that due to the nature of the test setup, the lowest measurable frequency is limited to approximately from 4 Hz to 8 Hz (2,5x pendulum frequency), thus quasi-static or low frequency interface forces cannot be resolved with this method. Also, additional data processing is required to determine the disturbance force. This data processing might be difficult to apply due to mathematical complications and the knowledge of the accurate dynamic mass of the equipment under test. Another practical implication of the test setup lies in the fact that large supporting test plates are commonly used. These plates, suspended by a number of elastic bungees act like sensitive acoustical surface and result in an increase of background levels when external noise sources are present.

As outlined above this approach is more complex than the micro-vibration test by direct force characterisation and consists in a mix of analysis and test approach.

However, this type of test requires a simpler test set-up because the seismic mass can be replaced by a reference test structure softly suspended capable to isolate the equipment under test from the laboratory mechanical vibration. Care needs to be taken when setting up and executing the test to avoid undesired increase in background noise levels. In addition, the use of high-sensitive accelerometer sensors allows measuring extremely low acceleration levels. Facilities using this measurement principle are often located in basements or bunker and are operated at night to minimize any undesired impact from the surrounding.

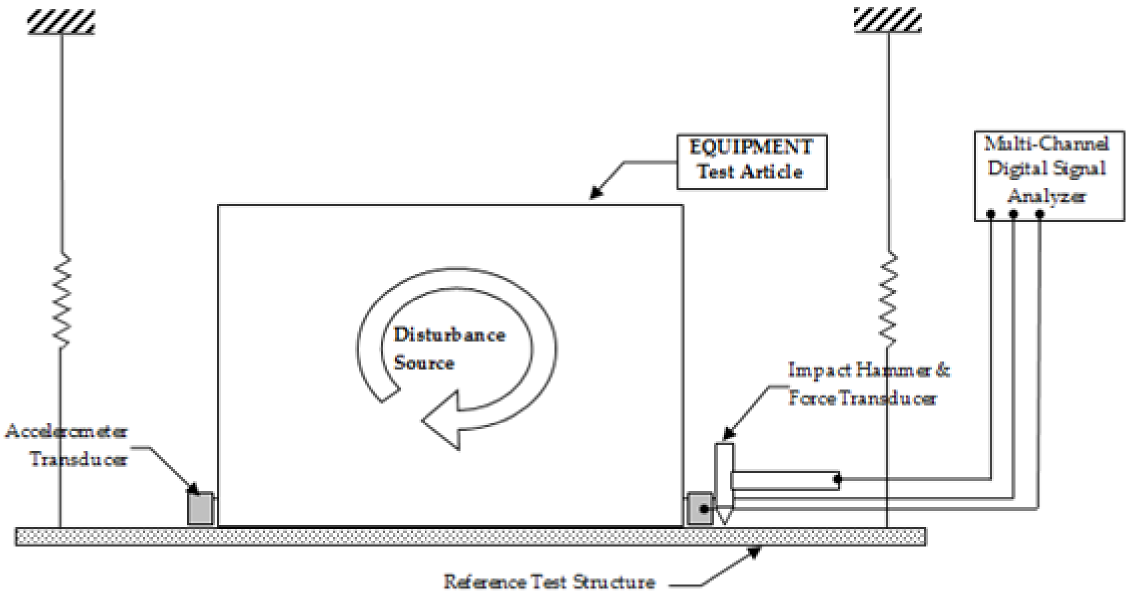


Figure A-37: Micro-vibration measurement test, indirect force characterisation

Test instrumentation:

A set of high sensitivity accelerometers are placed at each mechanical interface of the equipment, on the supporting structure, to measure the acceleration spectrum as illustrated in Figure A-38 and in Figure A-39.

An instrumented hammer with a force transducer mounted is needed to generate and to measure the force applied during the hammer test.

Additional instrumentation is recommended to record the operational parameters of the item under test in its operative conditions.

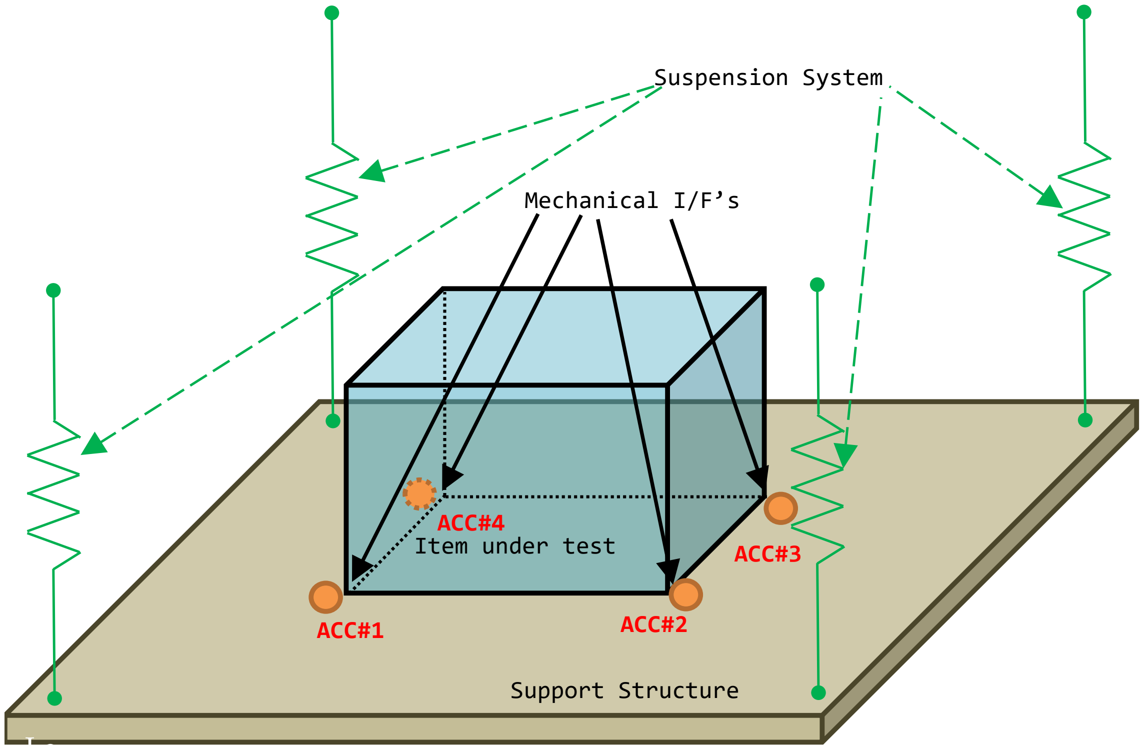


Figure A-38: Example of test instrumentation for micro-vibration test at equipment level using indirect method measurement

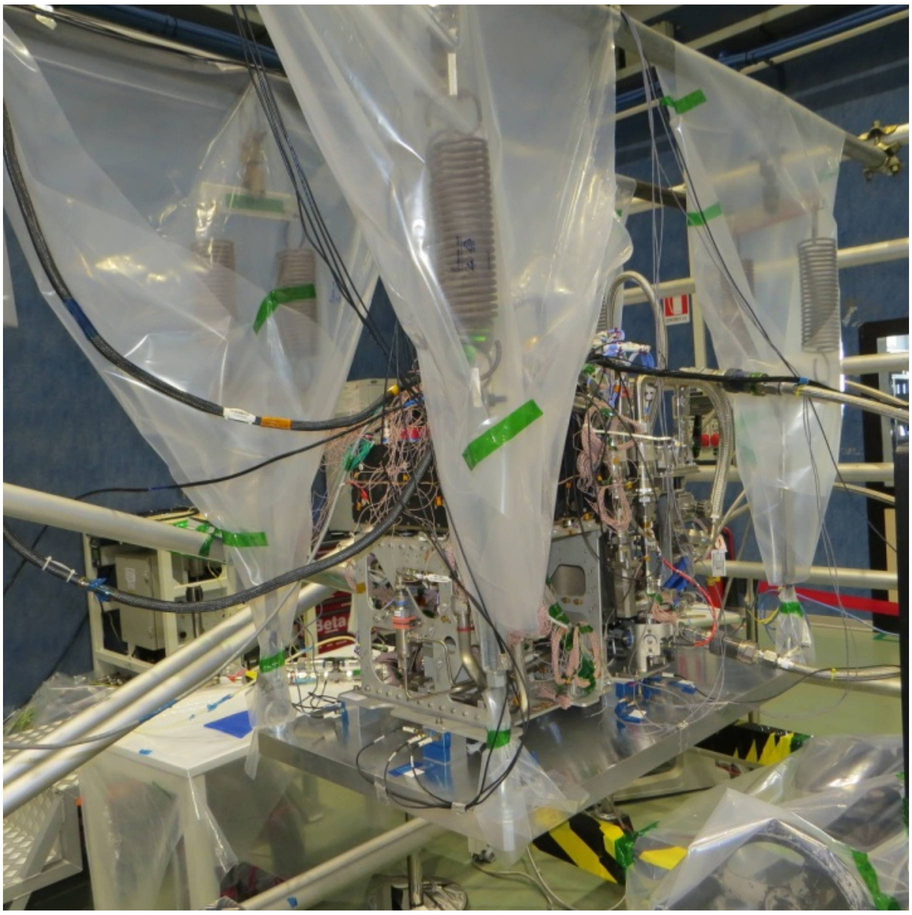


Figure A-39: View of test instrumentation during Water Pump Assembly (WPA) micro-vibration test at equipment level using indirect method measurement

A.13.2.4 Test preparation

The suitability of the test setup should be carefully evaluated and if possible checked by a pre-test. The following points are to be considered in the selection of the test facility:

- Suitability of the location of the test setup (quiet environment).
- Supporting instrumentation cabling and suspension devices can influence the dynamic behaviour of the test setup and therefore affect the results.
- Coupling of unit under test and supporting structure/test facility (i.e. floor isolation).

It is very important to measure the background noise before and after the measurement. An identification of the sources of background noise will help defining mitigation actions to reduce the noise level, e.g. test by night, stop activities in the surrounding, switch off air-conditioning, improve the electrical grounding. See A.13.6 about background noise.

EGSE and FGSE need to be adequately isolated in order to minimize the transmission of structural and acoustical disturbances to the item under test.

It is also important to consider the effect of harness to the unit under test, which might also transfer micro-vibration from the EGSE. A solution can be to suspend the harness and introduce flexibility through strain relieve loops.

Note that the effect of FGSE (e.g. pump for a cryocooler, of for vacuum) can be difficult to mitigate. Also for a cryocooler, the interface to the cold finger introduces complexity in the setup.

Instrumentation: high sensitivity accelerometers are used to measure the background noise. The measurement noise (e.g. due to imperfect grounding) is to be reduced. High sensitivity force sensors (dynamometers) are used to measure the interfaces forces.

A.13.2.5 Test execution

The item under test is in on orbit configuration and is operated according to the mission sequence.

- As a generic test sequence for the micro-vibration source characterization the following steps can be performed:
- Facility characterization: identification of the supporting plate and suspension system resonance frequencies.
- Perform the acceleration-to-force transfer function acquisition runs injecting a force at each interface point (hammer test) of the test article, in each translational direction and measuring the acceleration levels at each test fixture mechanical interfaces. During this test the equipment is switched off and set in on orbit configuration.
- Perform different background noise characterizations, by means of measurements of acceleration levels at the interfaces considering:
  - all the disturbance noise source in the laboratory room switched off,
  - the equipment EGSE and FGSE, if present, switched on,
  - the equipment itself switched on but not operating.
- Before each test case, execute a dry run to optimize the acquisition data chain in terms of measurement duration, and measurement range.
- Execute the micro-vibration source characterization tests. The item under test is operated according to the mission sequence in all possible modes of operation and transitions between these modes as well as, as far as applicable, in different speeds/power levels in order to characterise all possible noise disturbances.
- Before changing to the next following test run perform a quick check on the acquired time history and frequency domain data to ensure that the data is suitable for exploitation and can be distinguished from the background noise.

Background noise level should be at least one order of magnitude lower than the measured disturbances.

A typical characterization test campaign on an equipment goes from few days to around 1 week pending on the complexity of the setup and the required test sequence.

A.13.2.6 Test evaluation

For all test cases, it is recommended to record the responses in terms of:

- acceleration time histories (m/s^2)
- force time histories (N)
- and the following post processing data:
  - acceleration spectrum (m/s^2).
  - acceleration auto-spectrum (m/s^2)^2.
  - force spectrum (N).

- o force auto-spectrum (N^2).
- o Structural TF's (m/s^2)/N.

The measurements are compared to the background noise to ensure they can be distinguished from the noise.

A.13.3 Characterisation of the susceptibility of an equipment/instrument to microvibrations

A.13.3.1 Purpose

The purpose of the test is to characterise the susceptibility of an equipment to the micro-vibration environment.

A.13.3.2 General

The principle of the test is to subject the equipment to a micro-vibration excitation while its performance is measured.

A.13.3.3 Test configuration and test aspects

As for other micro-vibration tests, it is important to characterise and reduce the background noise. For this purpose, the test setup is usually isolated from the ground, on a seismic foundation, or bellows.

In principle, a shaker can be used to generate the excitation.

The measurement of the combined effect of an excitation along different axes or including rotations require the use of specific test facilities able to introduce a 6 degree of freedom micro-vibration environment to a specimen in a controlled manner.

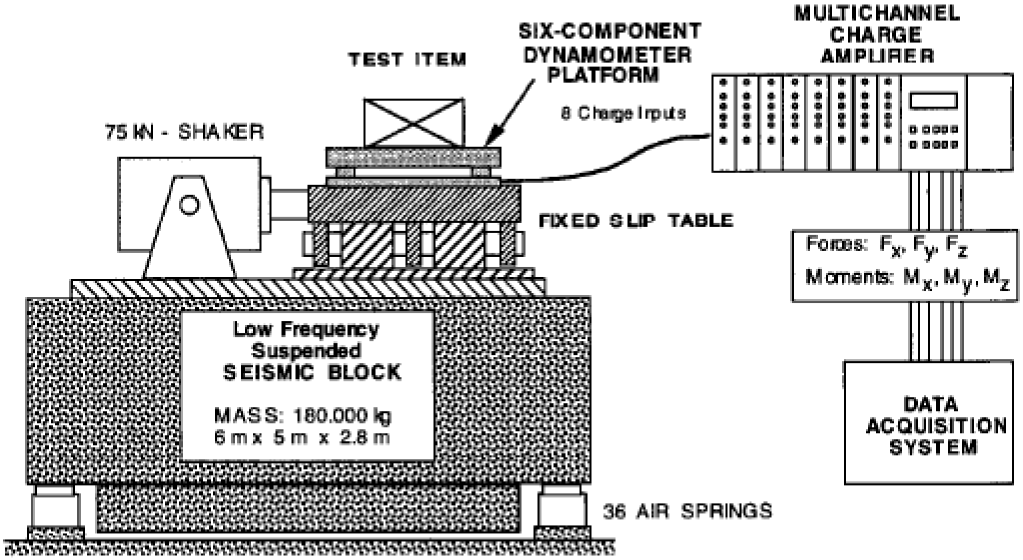


Figure A-40: Test setup for a test of equipment susceptibility to microvibrations

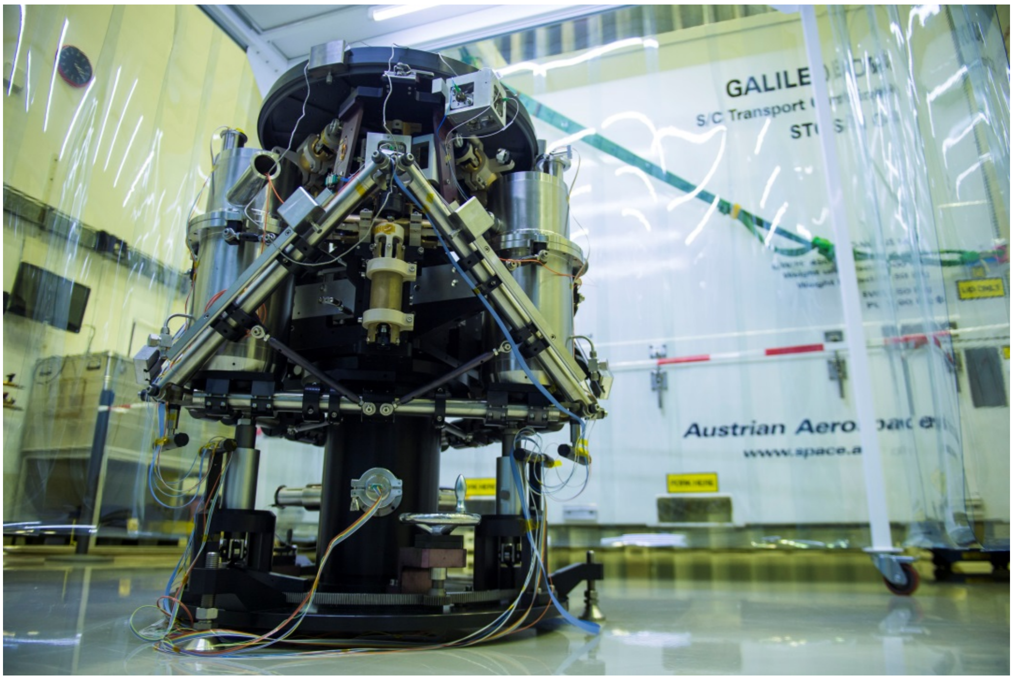


Figure A-41: Micro-vibration measurement system of ESA ESTEC allows 6 Dof excitation and 6 Dof measurement

During a susceptibility test the equipment is rigidly mounted on the test table of a specific 6dof excitation platform that is able to generate a specified micro-vibration to the specimen. The equipment under test is operated in its different modes of operations and its performance is measured while being subjected to (various) micro-vibration environments with the aim to verify related performance requirements. This type of test requires specific testing capabilities since the micro-vibration environment needs to be representative of the one the equipment will experience during its in orbit life.

A.13.3.4 Test preparation

It is very important to measure the background noise before and after the measurement. An identification of the sources of background noise will help defining mitigation actions to reduce the noise level, e.g. test by night, stop activities in the surrounding, switch off air-conditioning, improve the electrical grounding. See A.13.6 about background noise.

EGSE and FGSE need to be adequately isolated in order to minimize the transmission of structural and acoustical disturbances to the item under test.

It is also important to consider the effect of harness to the unit under test, which might also transfer micro-vibration from the EGSE. A solution can be to suspend the harness and introduce flexibility through strain relieve loops.

Note that the effect of FGSE (e.g. pump for a cryocooler, or for vacuum) can be difficult to mitigate.

Instrumentation: high sensitivity accelerometers are used to measure the background noise. The measurement noise (e.g. due to imperfect grounding) is to be reduced. High sensitivity force sensors (dynamometers) can be used to measure the interfaces forces.

A.13.3.5 Test Execution

It is very important to record time histories in each operating conditions, of both the excitation and the equipment performance.

Different levels of excitation are applied to characterise the susceptibility of the equipment in each of its different operating modes. Also different types of excitation can be applied (different frequencies, forcing function types, for different durations – to evaluate the effect of integration time).

A.13.3.6 Test evaluation

Measurements are processed to calculate Power Spectral Densities (PSD). It is checked that the measurement can be distinguished from the background noise by comparing the PSD of the measured signal with the noise.

A.13.4 Characterisation at element level of a transfer function between a source of disturbance and an equipment/instrument

A.13.4.1 Purpose

The purpose of the test is to characterise how the excitation introduced at the location of a disturbance source is transmitted by the structure to the interface of the susceptible equipment, or is affecting the performance (e.g. line of sight).

A.13.4.2 General

The principle of the test is to introduce a calibrated excitation at one location of the spacecraft element, corresponding to a disturbance source, and to measure the response at the location of interest, corresponding to a sensitive equipment.

A.13.4.3 Test configuration and test aspects

The mechanical configuration is meant to reproduce a free-free condition. The element is usually suspended to mechanically isolate it from the ground. Another possibility is to place the element on air bellows or dedicated isolation systems providing low interface stiffness (e.g. the ESTEC VVIS) to simulate free-free conditions.

Note that the large appendages are usually not included in the test configuration, e.g. large deployable solar arrays, deployable booms, large antennas. Those large appendages usually have very low eigen frequencies (typically below 1 Hz). Their influence on the dynamic behaviour need to be considered if there are sources of excitation at such low frequency.

This test does not require the availability of the equipment generating the micro-vibrations, nor the equipment that are susceptible to microvibrations. This allows the test to be performed early in the development, with a structural model. What is important is that the structural path between the source and the susceptible equipment is representative from a dynamic point of view (mass, stiffness and damping).

The load is usually introduced by a portable shaker that is suspended without other contact with the test item than a stinger to introduce the load at the interface point. This means that the load introduced by the shaker does not produce a reaction force on the test specimen. It is an external force on the test item.

The principle is similar to the modal survey test (see ECSS-E-ST-32-11). The idea is to introduce a well defined and well controlled excitation and to measure the response at points of interest on the structure.

Another solution to introduce a load is the use of inertial shaker directly mounted on the interface of the element. This is for example a rotating mass. In this case, there is no external force applied to the item under test. This method leads to a limitation on the frequency range towards the low frequencies.

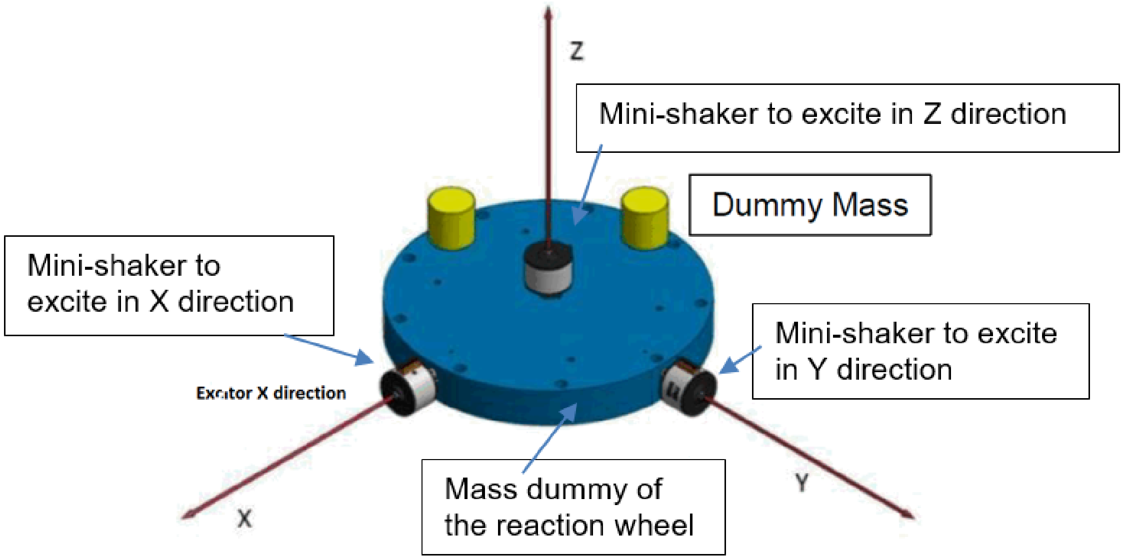


Figure A-42: Example of configuration used for the microvibration test on MTG, by using small shakers (grey) to introduce well defined excitations on a mass dummy of a reaction wheel

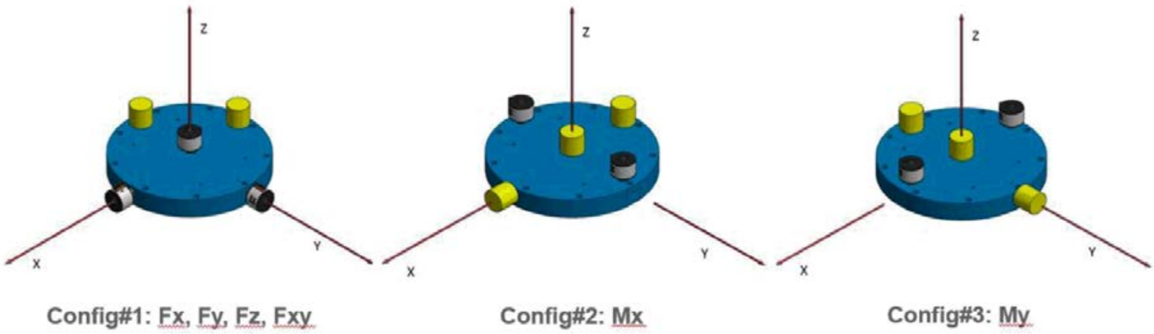


Figure A-43: Example of configurations used for the microvibration test on MTG, by using small shakers (grey) to introduce well defined excitations on a mass dummy of a reaction wheel. Force (left), and moments (centre and right)

Impact hammer can also be used. However, the type of excitation provided by a hammer is limited compared to the forcing functions that can be introduced by a shaker.

For each excitation point, different type of excitation (sine sweep or random) and different excitation levels can be applied. This allows a complete characterisation also as a function of the amplitude of the excitation.

Two basic excitation types could be used for generating the input forces:

- Sinusoidal excitation:

  Sine excitation is useful for examining local details around specific modes of vibrations.

- Random noise excitation:

  Random vibration input should be used if a wide frequency band needs to be excited simultaneously.

Compared to the end to end test, this type of test allows to acquire an increased amount of information, because tests can be performed as follows:

- change of the excitation direction (i.e. along the three orthogonal directions),
- variation of excitation levels to study the linearity of the dynamic response behaviour,
- change of excitation type, delivering forcing functions for e.g. steady state or transient test cases.

The installation of the excitation device and related cabling needs to be done such that the dynamic response behaviour is not influenced by the test equipment.

A.13.4.4 Test preparation

It is very important to measure the background noise before and after the measurement. An identification of the sources of background noise will help defining mitigation actions to reduce the noise level, e.g. test by night, stop activities in the surrounding, switch off air-conditioning, improve the electrical grounding. See A.13.6 about background noise.

EGSE and FGSE need to be adequately isolated in order to minimize the transmission of structural and acoustical disturbances to the item under test.

It is also important to consider the effect of harness to the unit under test, which might also transfer micro-vibration from the EGSE. A solution can be to suspend the harness and introduce flexibility through strain relieve loops.

Note that the effect of FGSE (e.g. pump for a cryocooler, or for vacuum) can be difficult to mitigate.

Instrumentation: high sensitivity accelerometers are used to measure the background noise and control the acceleration excitation. High accuracy force sensors are used to measure the excitation force.

A.13.5 Micro-vibration susceptibility test at element level (End to End test)

A.13.5.1 Purpose

The purpose of the test is to measure, at element level, the effect of a micro-vibration disturbance on an equipment susceptible to micro-vibrations, or on the performance (e.g. line of sight).

A.13.5.2 General

The principle of the test is to operate the sources of micro-vibrations and to measure the response on the performance.

A.13.5.3 Test configuration and test aspects

The mechanical configuration is meant to reproduce a free-free condition. The element is usually suspended to mechanically isolate it from the ground. Another possibility is to place the element on air bellows or dedicated isolation systems providing low interface stiffness (e.g. the ESTEC VVIS) to simulate free-free conditions.

Note that the large appendages are usually not included in the test configuration, e.g. large deployable solar arrays, deployable booms, large antennas. Those large appendages usually have very low eigen frequencies (typically below 1Hz). Their influence on the dynamic behaviour need to be considered if there are sources of excitation at such low frequency.

As a general rule, the satellite should be supported in such a way that the highest natural frequency of the suspension is lower than 25% of the frequency of the first elastic mode in free condition.

This test requires the availability of the equipment generating the micro-vibrations, and the equipment that are susceptible to microvibrations. It also requires the capability to control the equipment generating the microvibrations, i.e. either a functional element (i.e. able to control the equipment) or the use of EGSE. Use of EGSE introduce the difficulty of an additional interface with the test article (harness).

Note that any hybrid solution between the test described in A.13.3and A.13.4is possible, e.g. use of real equipment generating micro-vibrations and measure of the response accelerations, or use of calibrated excitation source while measuring the element performance (e.g. pointing).

A.13.5.4 Test preparation

It is very important to measure the background noise before and after the measurement. An identification of the sources of background noise will help defining mitigation actions to reduce the noise level, e.g. test by night, stop activities in the surrounding, switch off air-conditioning, improve the electrical grounding. See A.13.6 about background noise.

EGSE and FGSE need to be adequately isolated in order to minimize the transmission of structural and acoustical disturbances to the item under test.

It is also important to consider the effect of harness to the unit under test, which might also transfer micro-vibration from the EGSE. A solution can be to suspend the harness and introduce flexibility through strain relieve loops.

Instrumentation: high sensitivity accelerometers are used to measure the background noise and control the acceleration excitation. Any instrumentation necessary for the measurement of the performance, e.g. line of sight through laser tracker.

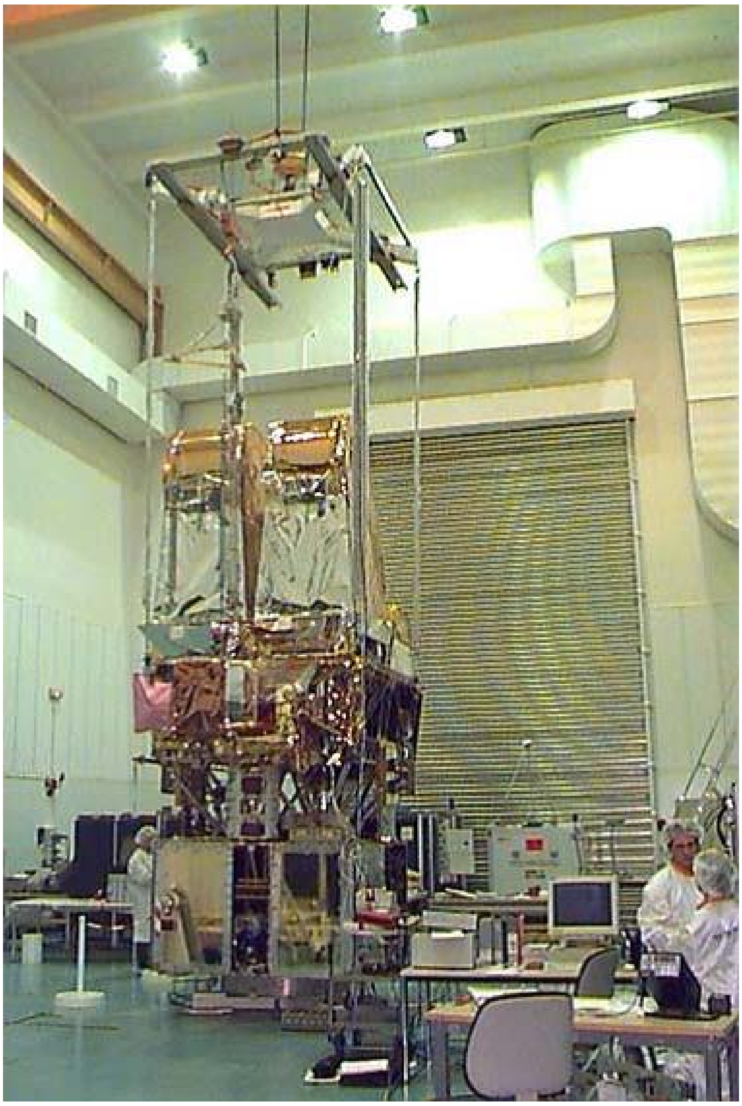


Figure A-44: SPOT4 satellite micro-vibration test

A.13.5.5 Test execution

The different operating modes of the equipment generating micro-vibrations are activated, e.g. the different wheel speeds of a reaction wheel. Each equipment generating micro-vibrations is tested one after the other to discriminate the effect of each equipment and each operating mode. Effect of the combination of different excitation sources can also be tested.

A.13.5.6 Test exploitation

The results are processed to ensure that the background noise is sufficiently low.

A.13.6 Background noise characterisation and reduction

The amplitude levels of acceleration, force or displacement that are to be measured during micro-vibration tests as well as other tests (e.g. thermo-elastic distortion) are usually very low.

There is a risk that background noise covers the levels to be measured.

Background noise is caused by external disturbing sources, e.g. road traffic, air-conditioning noise, people walking by or talking, equipment working etc. A classification of possible noise sources together with the affected frequency range and potential countermeasures is provided in Table A-2.

Note that there is also a noise in the measurement chain.

We can therefore distinguish between the real microvibration levels, and what can be measured with the acquisition chain and its imperfections, in particular the effect of electromagnetic disturbances.

Prior to starting the test activities, the background noise level should be characterised by measuring – with the test item being inactive – the parasitic acceleration levels on the test support structures and the test article itself. An example for the quantification of background noise as acceleration PSD is shown in Figure A-45 where the magenta spectrum indicates the response of the supporting structure whereas the other (lower) spectra are for the accelerometers attached to the test article. The efficiency of the test article suspension system is clearly demonstrated. However, the graph also clearly shows the presence of electrical noise and other high frequency disturbances.

The measured background noise should be compared with the expected level to be measured in order to assess whether the test setup has the capability to provide the expected information regarding the micro-vibration environment.

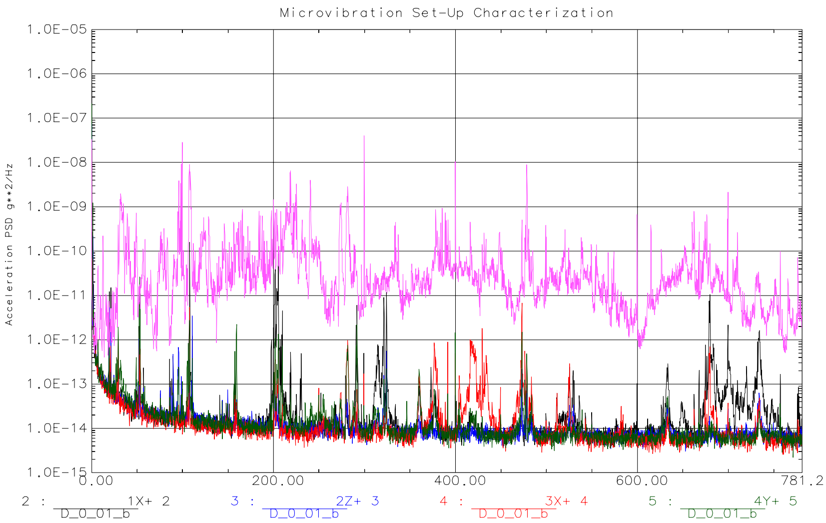


Figure A-45: Typical background noise acceleration PSD

Note that the background noise varies over time, depending on the level of activities around the test article, wind, rain, possible traffic, train, waves from the sea (tide), MGSE, EGSE, FGSE, air conditioning. It is important to characterise the background noise during a sufficiently long period of time to ensure it covers the situation to be expected during the test itself.

Table A-2: Classification of noise sources affecting micro-vibration tests

Noise source	Frequency band	Countermeasures
Electromagnetic noise:		
electrical noise from main supply (50 Hz and harmonics)	narrow band noise appearing as spectral lines	- proper grounding of equipment -use of power filters or run on batteries if possible
tonal noise induced by rotating machinery and illumination systems		- remove light sources - appropriate shielding
internal amplifiers and acquisition system noise	in general 1/f broadband noise, characteristic of equipment	selection of high quality, low noise electronics
instrumentation noise (piezo-electric accelerometers, force cells)		use of high sensitivity sensors, with reduced amplifier volt level
signal conditioning, amplification and acquisition		use of very low noise electronics
Acoustic noise:		
coupling of test article with surrounding air	broadband noise with relevant frequency components in the band of interest for the test discrete frequencies of HVAC systems <30Hz	- test at night without air-conditioning, laminar flux off and reduced human activity close to the test room, -Test under vacuum condition - potential encapsulation of complete test set-up in at for better isolation (while maintaining clean air conditions), - potential use of acoustic enclosure;
acoustic perturbations reaching the satellite structure		
Ground-borne noise (ground vibration input):	low to mid-frequency (250 Hz – 300 Hz) range for transportation noise (e.g. truck or train) low frequency: sea tide	- special seismic isolation devices for noise filtering, use of proper suspension devices for test article - restricted access to test area - test execution during night

Mitigation to reduce background noise

For the mechanical part, the mitigation is by isolating the test setup from the surrounding disturbances.

For the isolation from the ground, this can be done by air bellows, or by hanging the test article.

All sources of disturbances are identified and isolated as far as possible, e.g. by suspending the harness.

Prior to starting the test activities the background noise level should be identified by measuring – with the test unit being inactive – the parasitic acceleration levels on the test support structures and the test article itself.

The mass of instrumentation can influence the dynamic behaviour and unbalance the test setup which can lead to distorted measurements.

At ESTEC a specific, vacuum compatible isolation system exits allow to place the satellite on top and simulating low frequency suspended free-free condition in a clean room, or under thermal vacuum environment.

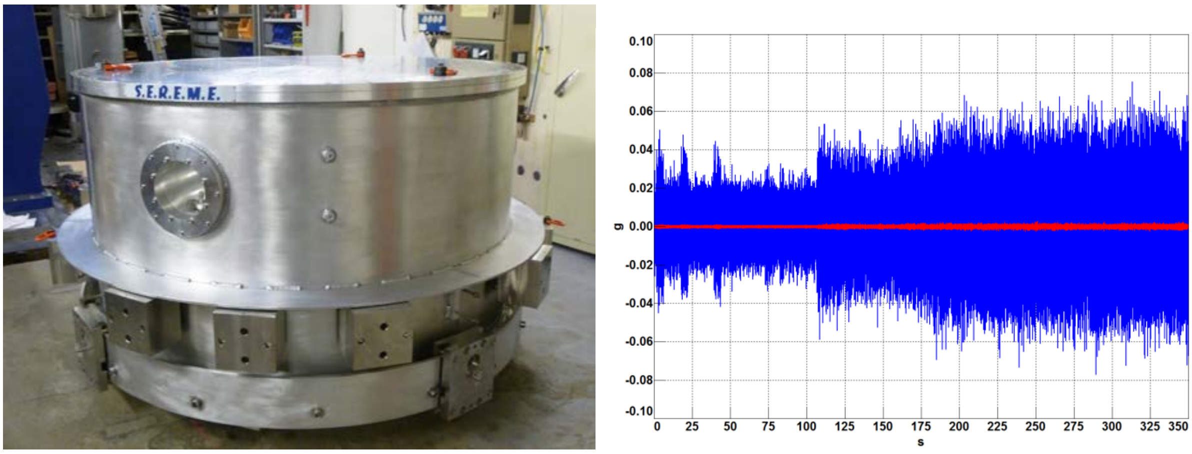


Figure A-46: VVIS acceptance test time history red top surface blue - bottom input

For the electrical part, it is important to use high sensitivity instrumentation, ensure the electrical grounding, and reduce the EMC perturbations. The measurement chain requires particular attention as the measured levels are usually at the limit of the electrical noise.

Examples of existing micro-vibration test facilities are shown in Figure A-47 and Figure A-48:

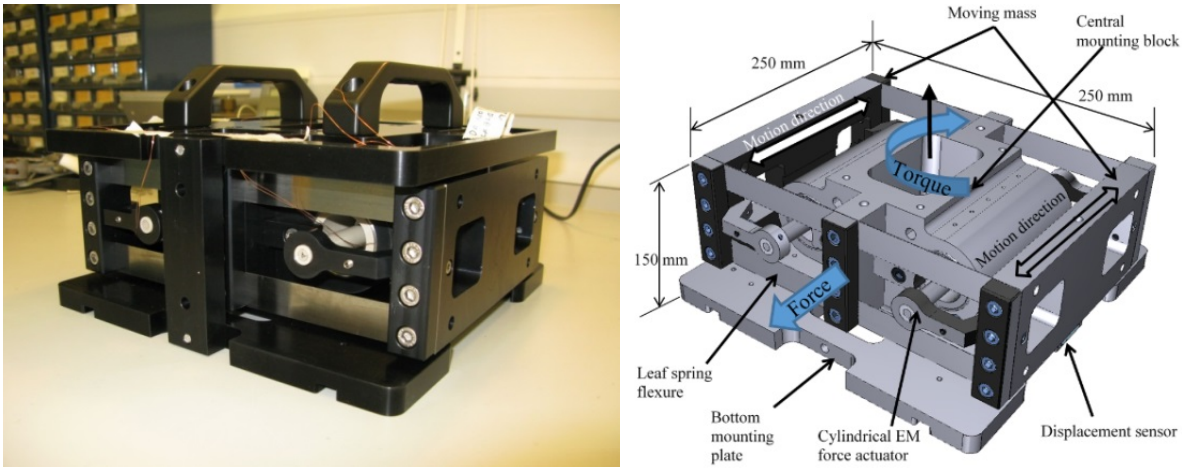


Figure A-47: ESA micro-vibration universal reference excitation unit (0,05 Hz to 10Hz, 10 μN to 5 N, 10 μNm to 1,5 Nm)

Figure A-48: Typical table for microvibration emission measurement (mN range limited frequency bandwidth)

Annex B
Structural integrity tests

B.1 Foreword

Most of these structural integrity tests are related to pressure and the Maximum Design Pressure (MDP) is to be defined. MDP depends on the system design and the way the system is operated, and can evolve during the design process.

For some equipment, as a tank for example, the MDP is clearly defined. It is more complicated for a valve, for which, in closed condition, there can be a difference between the inlet and outlet pressure. Hence there is, for the closed condition, a maximum pressure at inlet, a maximum pressure at the outlet, possibly a maximum delta pressure between inlet and outlet, and a maximum pressure in open condition.

This pressure includes the transient effects on the equipment and is therefore the maximum pressure the unit could see.
One example is the flow control valve attached to a thruster. The MDP in this case covers the transient effects, i.e. the pressure peak at the inlet of the valve due to the priming of the propulsion system.

Note that the testing standard does not specifically require testing to verify the transient effects. However, for items subjected to such transients, specific testing is recommended as per ECSS-E-ST-35-01, clause 4.6.3.7.

It is recommended that the testing approach for the transient effects reproduces the physical phenomena. To keep the example of the flow control valve, a test for the transient pressure peak could be performed with a small tube upstream the valve. This tube is under vacuum conditions and is then primed during test in a similar manner as the tubes during flight.

Also, when several equipment, which can have different MDP, are assembled together (e.g. tank, pipes, valves, regulator), the maximum pressure that can be applied to the assembly is limited by the weakest equipment. This typically limits the ability to apply pressure in an assembly. It is therefore one of the major tasks for a supplier to define the sequence in which the assembly can be tested.

As an example, a pipe going into a propellant tank is, due to the different factors of safety to be applied (ref to ECSS-E-ST-32-02), rated to a higher pressure than the tank. In case of welding of this connection the problem of not being able to test the weld to the maximum pressure of the pipe has to be assessed. One possible solution could be to test before the last weld of the subassembly to the higher pressure without the propellant tank and then testing the last weld up to the maximum allowed pressure of the tank.

The applied pressure level also considers impacts of the specified temperature during nominal conditions of the equipment. For example, a tank containing liquid hydrogen used in cryogenic temperature range is submitted to different stresses and exhibits different strength MOSs when loaded at MDP at the nominal temperature than it would see when loaded at MDP at ambient temperature. This impact is assessed with supportive data from analysis for the equipment and the consequence could be the need to apply a correction factor to the test pressure (see ECSS-E-ST-32-02, requirements 5.4.1c. and 5.5.1b.). In any case, an overstressing of the equipment during acceptance testing has to be prevented for the flight hardware.

A special case for temperature effects is the one of equipment with high temperature differences like thrusters. In this special case, no equivalent pressure can be derived since it is entirely different for each location due to the thermal environment. For this case, the proof pressure test is performed by testing the subassemblies before final assembly. The interfaces load and temperature will then be used to derive the pressure load for testing at assembly level.

Additionally, temperature variations (see ECSS-E-ST-31 for definition) have to be considered as well. This means that either the impact of the temperature has to be considered to calculate the representative worst-case condition for the proof pressure test or that the temperature variation is implemented by additional means under representative conditions. This implies that for some equipment the heating time has to be considered in a similar way than it is going to happen in flight configuration. If this is not possible, a load assessment of the transient effects has to be done and could potentially lead to an increase of the proof pressure level.

Major aspect is the approach of leak before burst, for which a corresponding leak rate must be established prior to testing to distinguish between pure leakage and pressure loss due to other causes. The measurement system has to be designed in such a way to make sure that leak before burst can be evaluated. For example, using helium as pressurant gas will allow to use a helium spectrometer to measure the leakage of the unit. note the use of this measurement set up would then imply a safety concern since the released energy content could potentially be higher if the leak before burst fails. This means that the measurement system, the acceptance criteria and the media belong to each other and should be chosen in an appropriate way.

SAFETY ASPECTS:

High pressure can represent a serious hazard in case of failure. Especially for pressure related tests, safety aspects need to be carefully considered. Risks to the personnel / facility and test equipment need to be identified and mitigation actions taken.

For example, a pressure cycle test of a high pressure vessel is performed in a bunker. This safety assessment also considers the media used for the test. Non-toxic and non-explosive Media are always favoured for the test. The critical aspect for the safety is the assessment of the stored energy inside the equipment. The amount of energy can be calculated with a dedicated formula, mentioned in the definition of “pressure vessel” ECSS-E-ST-32-02C Rev. 1, Definition 3.2.36. Depending on this stored energy, a safe perimeter is defined around the test article and the need for a specific bunker is identified. Those considerations are key for the selection of the facility.
The risk of projections, of a cap for example, is also identified.

Where possible, pressure tests are performed with liquid rather than gas to limit the stored energy due to the compressibility of the gas.

B.2 Leak test

B.2.1 Purpose

The purpose of leak test is to demonstrate the ability of pressurized test article to meet the design leakage rate requirement. This test also allows to check the workmanship of the test article.

B.2.2 General

The principle of the test is to fill the test article with a test medium, apply the Maximum Design Pressure (MDP) and measure the quantity of test medium that leaks. In the case of sealed containers, if the seals are dependent upon pressure for proper sealing, then the Minimum Design Pressure is applied.

The leak test is one of the most important tests to be performed for pressurised equipment/element since a significant leakage of the system can lead to loss of the mission. Because of this, the leak test is performed several times across the test programme of the equipment / element, e.g. before and after the proof pressure test.

As specified in the test standard (requirements 5.5.3.1c. and d. of ECSS-E-ST-10-03), the leak measurement test method used has sensitivity and accuracy consistent with the specified maximum allowable leakage rate. Specifically, the method is checked to have the sensitivity to detect leakage rate of at least half of the specified maximum allowable leakage rate. This sensitivity check is performed before every leak test.

Before defining a leak test, it is advised to review the open literature to check for the state-of-the-art of leak rate measurement.

Best practices for performing leak tests can be found in

- ECSS-Q-ST-70-15 "Non-destructive testing"
- ECSS-E-ST-33-11 "Explosive systems and devices" (clause 4.14.4.2)
- NASA-STD-7012 "Leak test requirements"

B.2.3 Test Configuration and Test Aspects

B.2.3.1 Overview

The leak test can be done in several ways with different measurement and calibration methods.

In all cases, the calibration procedure of the setup is part of the test and is formally agreed during the test readiness review.

The NASA-STD-7012 provides an overview of different methods for leak test and useful references. Parts of this standard are used to describe the most common methods hereunder. Note that the lowest leak rates can only be measured by using vacuum methods.

B.2.3.2 Vacuum Chamber method

A first method is called the "Vacuum Chamber Method" and is used to measure the total internal-to-external leak rate of the pressurized article

- One example of this test method is the measure of the leakage rate of a propellant tank. The tank under test is placed in a vacuum chamber, is loaded with a tracer gas (i.e. a gas that can easily be detected) and is pressurized up to MDP for measuring purpose.
- Additionally, implement a calibration method, mostly a calibrated orifice with a known leak rate, which is introduced in the setup.
- The procedure of measurement therefore includes first the measurement of the calibration orifice to confirm that the setup allows to measure the leakage rate as required (quantitatively less than the minimum leakage rate to be detected in the tank by a factor of at least two to ensure reliability of measurements).. The calibration allows the leak test set up relative sensitivity to be

characterised and used to calculate the tank leak rate. This means that there is a validation of the measurement capability built in in the test setup.

- The MDP is maintained until the readings of the leak detector stabilise The testing time is adjusted to the needed time to detect the leak . The following schematic shows the principle setup:

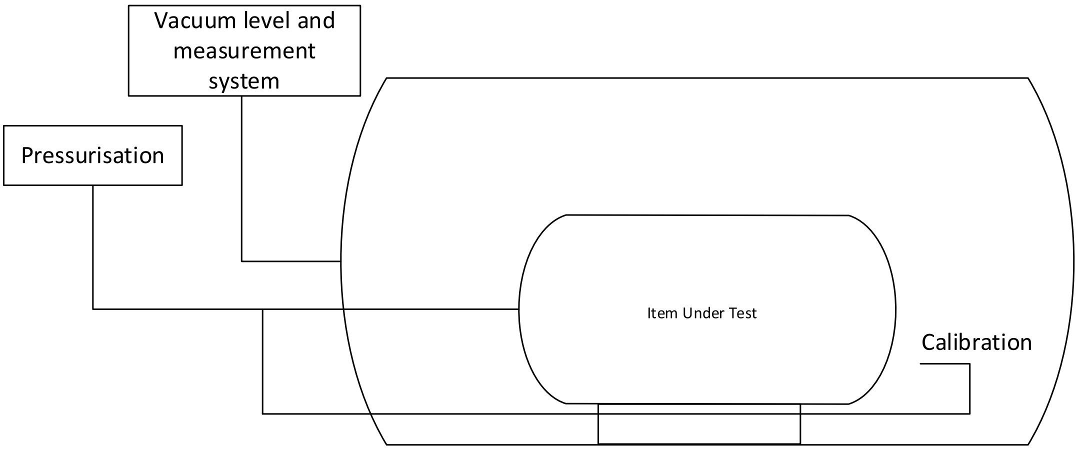


Figure B-1: Sketch of the Vacuum chamber method

B.2.3.3 Accumulation method

A second method is called "Accumulation", and is also used for the measurement of total internal-to-external leak testing of pressurized equipment or elements. The method utilises a helium mass spectrometer connected to a detector probe. It measures local leak rates by concentrating leakage in a containment hood and comparing peak detector probe responses with those of a known leak in the same hood enclosure. This method is used in place of the more expensive vacuum chamber testing which requires removing the test component from the system. The development test set up is shown in Figure B-2 for the leakage rate measurement of a Quick Disconnect mounted in an assembly. A containment enclosure made of plastic and tape is installed over the Quick Disconnect. The helium mass spectrometer is configured for the detector probe operation and the probe is inserted into the bag for initial background measurement. Calibrated sources of various leak rates are inserted into the bag for a pre-determined time period as shown in Figure B-3. At the end of the time period the detector probe is inserted into the bag and the maximum mass spectrometer response is recorded. The sensitivity of the setup is determined from this data.

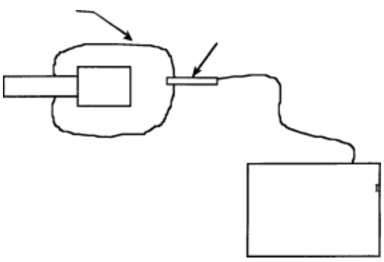


Figure B-2: Accumulation Leak Test set up

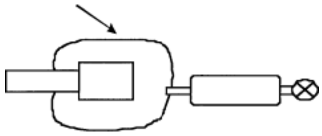


Figure B-3: Enclosure Calibration

The Accumulation method allows the accurate measurement of the leak rate of pressurized articles at ambient test conditions using a helium mass spectrometer configured in the detector probe mode. It has been used to measure leak rates of welds, heat exchangers, hoses, etc. and has substituted other methods in many applications, mainly for large pressurized volumes for which the vacuum chamber and pressure decay methods are impractical (see Figure B-4, Figure B-5 and Figure B-6).

Figure B-4: Cupola Accumulation leak test overview

Figure B-5: Cupola Accumulation Leak Test He capillary leak source

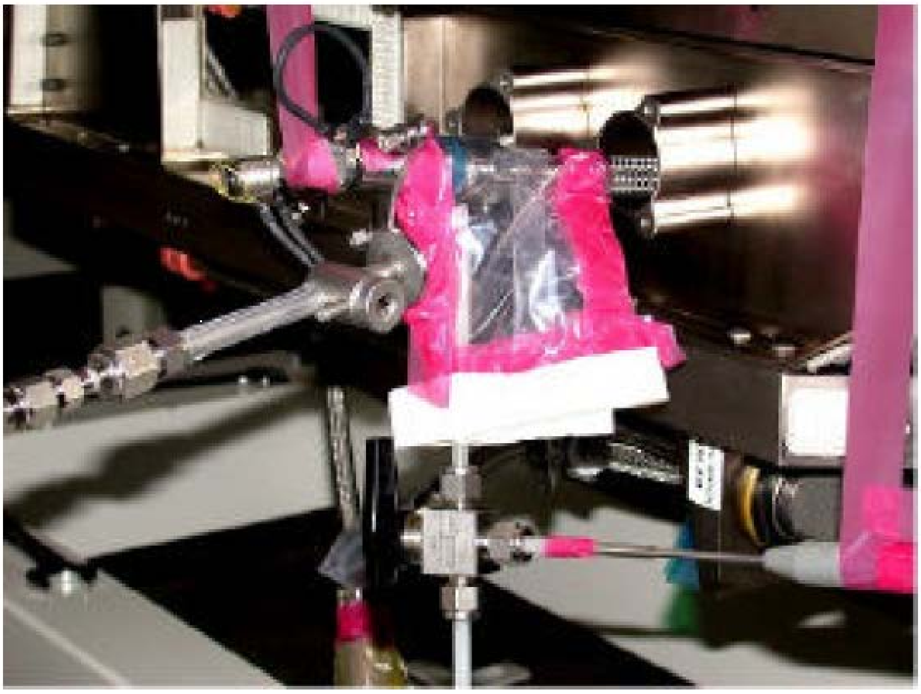


Figure B-6: Node 2 accumulation leak test on a joint _typical set-up

B.2.3.4 Pressure Change method

A third method is the so called "Pressure Change". It is implemented either as a pressure decay or a pressure raise depending on the application. The pressure decay technique can be used for total internal-to-external leak testing of pressurized elements. To improve the accuracy of this technique, a reference vessel connected to the pressurized payload can be used. If ambient temperature changes, the payload and reference vessel volumetric changes are taken into account. The pressure rise technique can be used for total external-to-internal leak testing of sealed elements. The payload internal pressure, barometric pressure, and ambient temperature are monitored for the required time to determine the actual pressure drop or rise and the corresponding leakage rate. The pressure gauge/transducer is selected to have an accuracy adequate to measure the minimum required pressure change. The tolerance/error associated with the total internal volume of the element and the test fixture under pressure used for the leakage rate calculation is taken into account as a maximum positive value. The inconvenient of this method is related to the time needed to have a stabilised pressure change. Besides, leak test measurements for large volumes using the pressure decay method in clean room conditions are not recommended due to the significant variations in pressure due to temperature variations, resulting in long duration tests.

Other leak tests methods can be applied to dedicated configurations, e.g.,

- Mass loss after vacuum exposure method to fluid filled equipment like batteries
- Hood method for total external-to-internal leak testing of sealed equipment
- Volumetric Displacement method for valves, pressure regulators or heat exchangers
- Leak Detector Direct Connection method for valves, pressure regulators or heat exchangers

The test setup for measuring the leak rate has to ensure that the leak rate as specified can be measured in the defined time frame. For example, the volume of the test setup for a valve is chosen in such a way to be able to measure any leakage in the equipment in a short time frame.
The condition to be tested is the one under which the equipment is most probably leaking. In some circumstances and for more complex equipment like valves, this could imply that the leak test has also to be performed at different pressures and at different temperatures, and this applies both to the qualification and acceptance of the equipment.

As the leak rate is mostly dependent on differential pressure, the vacuum condition is not strictly necessary and can be replaced by testing under ambient conditions, compensating the pressure to achieve the required differential pressure for the equipment, as long as the measurement can still verify the leak rate.

The leak test medium is defined according to the specific project objectives and constraints. Two options are possible: test with actual fluid or test with an alternative fluid. In principle, the best approach is to measure the leak rate of the equipment/element loaded with the actual fluid. However, testing with actual fluid might be impractical because of ground safety reasons – e.g. when actual fluid is toxic/explosive - or for accuracy related to the fluid detectability and testing duration.
In fact, in most applications, Helium is used. Helium is easily detectable, and the small size of the molecule means that leak rate is higher and hence test time can be reduced. Leak rate is different when using Helium or the actual fluid – Helium leading to a higher leak rate in most cases. The conversion of the leak rate requirement for the real fluid to Helium one has to be discussed and agreed before testing and is included in the specification. This applies to any other gas (e.g. Hydrogen) in case Helium is not used. In case liquids are used to perform the leak test, special attention is needed concerning the possibility of masking the leak rate due to the molecular size of the medium and the interaction with the material of the unit. For these cases, the preferred solution is to perform the leak test with Helium.

The use of pressure relief valves is recommended to avoid to overstress the hardware under test.

B.2.4 Test Instrumentation

The means used to measure the leakage rate are mainly manometers and Helium leak detector. They are chosen and are located to allow the measurement of the required leak rates. This does not only

impact the sensors to be used and their accuracy (ref. to ECSS-E-ST-10-03C section 4.3), it also affects the set-up of the test to be able to measure the leak rate.
The calibration of the measurement test set up is not limited to the used measurement instrumentation. The entire test set up has to be demonstrated as adequate for the purpose of the test.

B.2.5 Test control Parameters

The test control parameters for the leak test is the differential pressure. This pressure is then controlled throughout the test to maintain the required pressure.

Another control parameter of the test is the time of testing. This time is fixed before testing and the counting of the time will only start when the pressure inside the equipment has reached the stable specified pressure conditions. In case the environmental temperature is also to be considered as influencing factor on the equipment, the test has to start when pressure and temperature are stable.

B.2.6 Test Preparation

An important part of the test preparation is the calibration of the test setup as described in B.2.4.
The unit under test is cleaned as required and inspected. Cleanliness is important as contamination can deteriorate a seal performance, or mask a leak in case the leak path is obstructed by the contaminant.

Safety aspects of the test as per B.1 are checked.

B.2.7 Test Execution

The pressure level to be applied for leak test of the test article is MDP.

In case the test cannot be done at the Maximum Design Pressure due to other limitations, the leak rate measured at a different pressure is converted to the MDP. However, this approach can only be accepted during acceptance testing and the conversion used need to be validated by the measurements performed during qualification of the equipment. The minimum measurement time is defined in ECSS-E-ST-10-3C. The duration of the test is defined in such a way to make sure that the equipment leak rate is measured. For example, using a soft seal within an equipment, the initial leakage of the equipment could be compensated by the seal due to their natural ability to compensate a certain amount of gas. This implies a transient increase of the leakage rate due to the compensation of the gas inside the seal. Only after the saturation of the seal, the leak rate going through the seal is stable and corresponds to the leak rate of the equipment. The duration of the test is therefore defined in such a way to ensure that these masking effects are covered during the testing period.

B.2.8 Test Evaluation

The measured leak rate is compared to the calibration of the test setup to verify that the calibration is adequate, i.e. that requirement 5.5.3.1d. of ECSS-E-ST-10-03 is satisfied.

If needed, correction to account for test fluid vs actual fluid is applied.

For information, typical requirements for leak rate applied to manned missions (in case of release of toxic, biohazardous or flammable material) are:

- Critical hazard: 10-3 Helium scc per second
- Catastrophic hazard: 10-6 Helium scc per second

The NASA-STD-7012 provides the minimum leakage rate expected to be verifiable w.r.t the leak test method used and a table with the conversion rates from Helium to other fluids.

B.3 Proof pressure test

B.3.1 Purpose

The purpose of the proof pressure test is to demonstrate that the pressurized equipment or element is free from workmanship defects. Its main purpose is to verify the structural integrity of the test article under pressure loads.

B.3.2 General

The principle of the test is to apply a pressure, MDP multiplied by a proof factor as defined in ECSS-E-ST-32-02.

Note that the MDP is a differential pressure. Hence, if testing is performed at ambient pressure, the applied pressure has to be increased by 1 bar.

Information about special issues and other important information can be found in ECSS-E-ST-35-02C (see Table 4-4 and Table 4-5). For the case of 2-phase equipment, please refer to ECSS-E-ST-31-02C section 5.6.5 for the approach of testing (proof pressure test and factors).

Additionally, checking the pressure stability over time during the performance of the proof pressure test and comparing it to the specified value is also used as pass/fail criteria.

B.3.3 Test configuration and Test Aspects

Different test configurations might be considered to ensure that proof pressure test stresses are applied at all locations which are critical w.r.t. workmanship defects. For example, the proof pressure test of a valve is done in open condition, otherwise the downstream part of the valve is not going to see any pressure. If this cannot be demonstrated, alternative methods to stress these areas are to be used. For a complex assembly, different configurations w.r.t. valve conditions and different MDPs in different sections of the assembly, might have to be considered. It can also be important to consider additional structural loads (see ECSS-E-ST-32-02 clauses 5.4.2 and 5.5.2) where needed.

It can be practical to use the same media as for the leak test, as it simplifies the test sequence. However, the applied pressure being higher than for the leak test, safety aspects might be limiting, in particular related to the stored energy.

For safety reasons, the use of liquid to pressurize the hardware is often preferred to limit the stored energy. However, this requires filling and draining for the subsequent leak test if a different fluid is used for the leak test.

Use of pressure relief valves is recommended to avoid to overstress the hardware under test.

B.3.4 Test Instrumentation

Manometers are used to measure the applied proof pressure. Strain gauges are used if the measurement of stresses is required.
Use of videogrammetry might be interesting to measure the overall deformation (reference to videogrammetry A.11.4.3).

B.3.5 Test Control Parameters

The test control parameter is the applied pressure, which has to be maintained for the duration of the test. If for some reasons (e.g. seals), there is the need to re-pressurise during the test, it is recommended to evaluate the cause since it can indicate a failure of the equipment.

B.3.6 Test Preparation

Safety aspects of the test as per B.1 are checked.

It is verified that the test setup will not contaminate the hardware under test (pumps, tanks, feeding lines).

It is recommended to check that the pressurization system is able to provide and maintain the required pressure.

B.3.7 Test Execution

The unit under test is slowly pressurised up to the pressure level and then maintained for the test specified duration. The pressurisation process leads to temperature change, which itself influences the pressure. The applied pressure is constantly monitored.

If applicable, the strain gauges are monitored.

B.3.8 Test Evaluation

Proof pressure Test success is achieved when the required proof pressure load is applied and the equipment/element does not show rupture or permanent deformation. Note that final verification of the test item integrity can imply non-destructive inspection.

Use of strain gages and videogrammetry system allow to compare the behaviour of the flight models to the qualification model. Discrepancy can indicate an issue. (see text of B.4.4).

B.4 Pressure cycling test

B.4.1 Purpose

The purpose of the Pressure cycling test is to demonstrate that the test article can withstand the specified pressure cycles, as part of the life cycle testing.

B.4.2 General

The principle of the test is to apply a varying differential pressure between 0, MDP and 0.

Since it is a demonstration of the life testing, it is only applied as part of the qualification on a qualification model, and not on the flight models. One exception is the pressurised space segment element that will experience several re-entries.

Note that the MDP is a differential pressure. Hence, if testing is performed at ambient pressure, the applied pressure has to be increased by 10^3 hPa.

B.4.3 Test configuration and Test Aspects

For the test media to be used for the pressure cycling test, the same considerations as for the proof pressure test apply. See B.3.4.

For propellant tanks for example, usage of water to minimise the risk of the proof pressure test (safety concern of potential burst) is to be considered.

Another consideration about the test media to be used: pressure cycling of the hardware by using clean gas can be beneficial, as this can allow to more easily collect generated particles and identify degradation of the test article. An example is a valve, for which metal to metal contact can generate particles. These particles would then potentially show the degradation of the equipment under test.

One additional aspect for the pressure cycling test is the possibility to monitor functional aspects of the equipment under pressurised conditions. For example, a valve has to work under different pressure levels throughout its lifetime. In case the actuation of a valve is supported by the applied differential pressure, the pressure cycling can imply that functional parameters (e.g. opening and closing times, voltages and currents) are affected during the pressure cycling test. This could imply that monitoring of the functional parameters could be beneficial during the pressure cycling tests.

Use of pressure relief valve is recommended to avoid to overstress the hardware under test.

B.4.4 Test Instrumentation

Manometers are used to measure the applied proof pressure. Strain gauges are used if the measurement of stresses is required.

Use of videogrammetry might be interesting to measure the overall deformation (reference to videogrammetry A.11.4.3).

B.4.5 Test Control Parameters

The test control parameter is the pressure.

B.4.6 Test Preparation

Safety aspects of the test as per B.1 are checked.

It is verified that the test setup will not contaminate the hardware under test (pumps, tanks, feeding lines).

It is recommended to check that the pressurization system is able to provide and maintain the required pressure.

B.4.7 Test Execution

The unit under test is mounted in a facility to enable the pressurisation of the unit up to MDP. This pressurisation of the unit will then be done with a defined pressurisation rate and to the number of cycles specified.

B.4.8 Test Evaluation

Behaviour of the test article along the cycles can be monitored using instrumentation (strain gages and video means).

B.5 Design burst pressure test

B.5.1 Purpose

The purpose of the design burst pressure test is to demonstrate that the test article can withstand the design burst pressure without burst. It is a qualification test to demonstrate the margin of the hardware design with respect to MDP.

B.5.2 General

The principle of the test is to apply a differential pressure to the test article and verify that it does not burst. The design burst pressure test is performed prior to the burst test.
Design burst test is mostly performed at equipment level and seldom at element level. This is the case for the current state of the art of materials and technologies (e.g. metallic modules). However, it is likely that this test is performed for elements built up with new materials and technologies (e.g. inflatable habitat modules). This will meet the safety requirements related to manned space flight.
More information about qualification of pressurized hardware can be found in ECSS-E-ST-32-02.

B.5.3 Test configuration and Test Aspects

For the test media to be used, considering the level of the pressure, safety aspects become predominant.

Also, the next step of testing being the burst test, liquid (water) is most often used.

B.5.4 Test Instrumentation

See B.3.4.

B.5.5 Test Control Parameters

Test control parameter is the applied pressure.

B.5.6 Test Preparation

Safety aspects of the test as per B.1 are checked.

It is recommended to check that the pressurization system is able to provide and maintain the required pressure.

B.5.7 Test Execution

The unit under test is pressurised up to the specified pressure level and then maintained for the specified duration. A pressure decay during the test duration indicates a leak before burst design pressure. A re-pressurisation means can be used to maintain the pressure level.

B.5.8 Test Evaluation

Pressure has been applied without burst.

If deformations are measured (strain gages or optical means), the measured deformations can be compared to the expected ones (through analyses).

B.6 Burst test

B.6.1 Purpose

The purpose of the burst pressure test is to characterise the pressure at which burst occurs on the test article.

B.6.2 General

The burst pressure test is a destructive test which is part of the qualification stage. It can be performed using the QM or using a dedicated model.

B.6.3 Test Configuration and Test Aspects

The test configuration only requires a facility to pressurize the unit up to rupture. An important point is to ensure the capability to measure the maximum pressure before burst.

The test is performed in a bunker (see safety aspects in foreword).

Since the purpose of the test is to increase pressure until burst, the media used for the test is usually water to decrease the released energy content as much as possible. The critical aspect for the safety is the assessment of the stored energy inside the equipment. The amount of energy can be calculated with a dedicated formula, mentioned in the definition of "pressure vessel" in ECSS-E-ST-32-02C Rev. 1, Definition 3.2.36.
One difficulty is that the burst pressure is not exactly known in advance. As a result, the pressure that will be applied is not known in advance, and the adequacy of the facility (maximum allowed energy) has to take this into account (e.g. having margin on the maximum allowed stored energy).

B.6.4 Test Instrumentation

Test instrumentation is a pressure sensor.

The maximum value measured by the pressure sensor is then indicating the burst pressure value of the test article.

B.6.5 Test Control Parameters

The test control parameter is the applied pressure.

B.6.6 Test Preparation

Safety aspects of the test as per B.1 are checked.

It is recommended to check that the pressurization system is able to achieve the required pressure.

B.6.7 Test Execution

The test consists in slowly increasing the pressure inside the unit until burst occurs. The burst value is recorded.

B.6.8 Test Evaluation

Since the unit under test has to burst, the major aspect for the test evaluation is the maximum pressure at which the burst occurred. Another aspect which can be of interest is the location at which the burst occurred. This can be of interest for complex hardware like valves to indicate the weakest points of the unit and to verify the analysis performed for these units. These results can therefore support any detection of anomalies of future production of these units.

See clause 5.3.4 of ECSS-E-ST-32-02.

Annex C
Audible noise test

C.1 Space segment equipment audible noise emission test

C.1.1 Purpose

The purpose of this test is to verify that the audible noise generated by the equipment does not exceed the specified noise rating curve.

C.1.2 General

Audible noise test is performed at equipment level (ref 5.5.6.1) for Crewed Element only measuring the continuous and intermittent noise levels emission generated by items and payloads working in their operative conditions.

Generally, sound pressure levels are measured in several locations around the test article in a frequency range typically from 31,5 Hz to 1600 Hz in octave band center frequency. In some cases, the measurement is in the frequency range from 10 kHz to 40 kHz in third octave band center frequency.

At equipment level, audible noise test is recommended to be conducted in combination with the micro-vibration tests, where possible.

C.1.3 Test configuration and test aspects

In a typical audible noise test at equipment level, the test specimen is mounted onto its MGSE or on its dedicated Integration Stand and it is placed in the test facility as shown in Figure C-1.
The test is normally performed under 1g condition with the test article in on-orbit configuration.

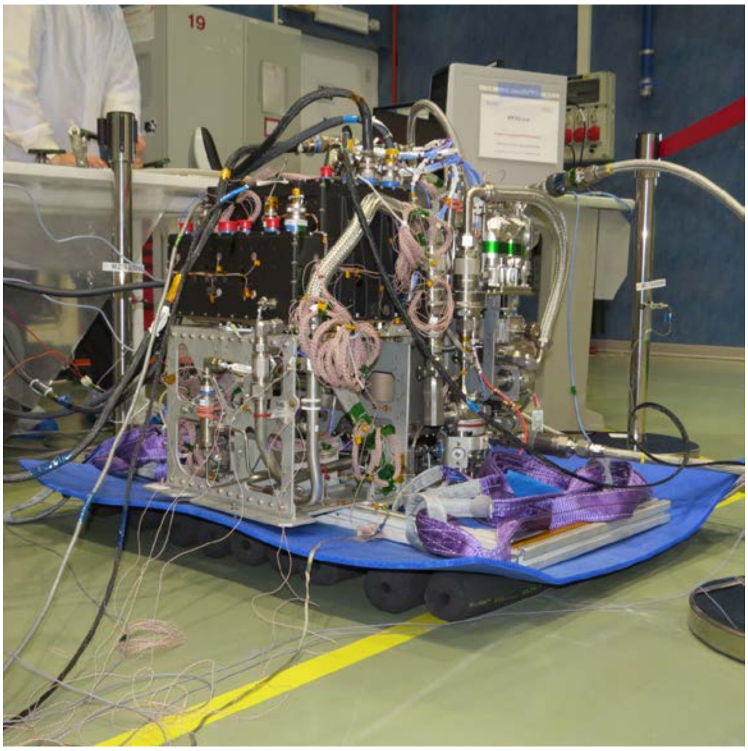


Figure C-1: View of Water Pump Assembly (WPA) test article during audible noise test at equipment level

C.1.4 Test instrumentation

A set of microphones are placed in front of the test article surfaces to measure the sound noise responses as illustrated in Figure C-2and in Figure C-3.

Measurement microphones are usually positioned at 0,6 meter far from the test article.
The same microphones can also be used to control the external background noise levels.
Additional instrumentation is recommended to record the operational parameters of the flight hardware in their operative conditions.

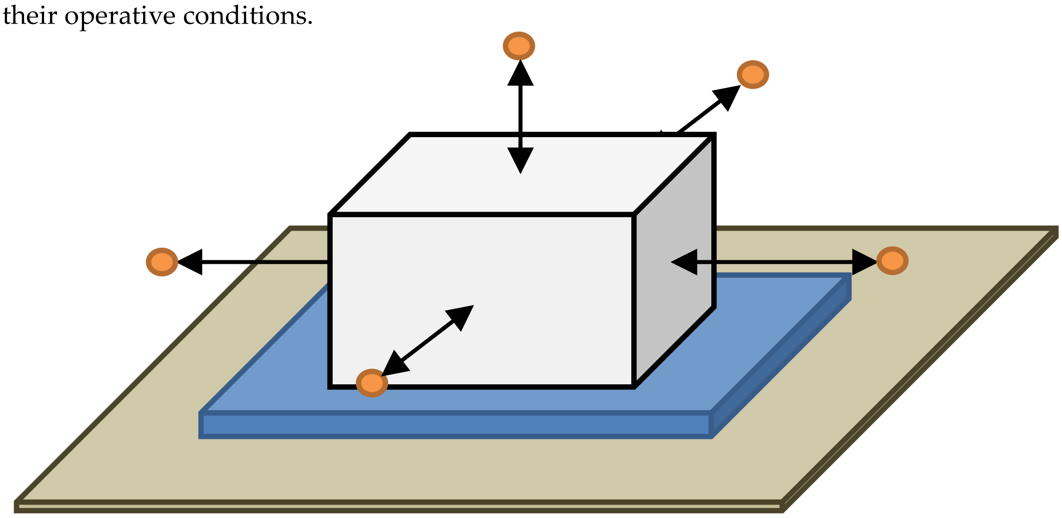


Figure C-2: Example of test instrumentation plan for audible noise test at equipment level

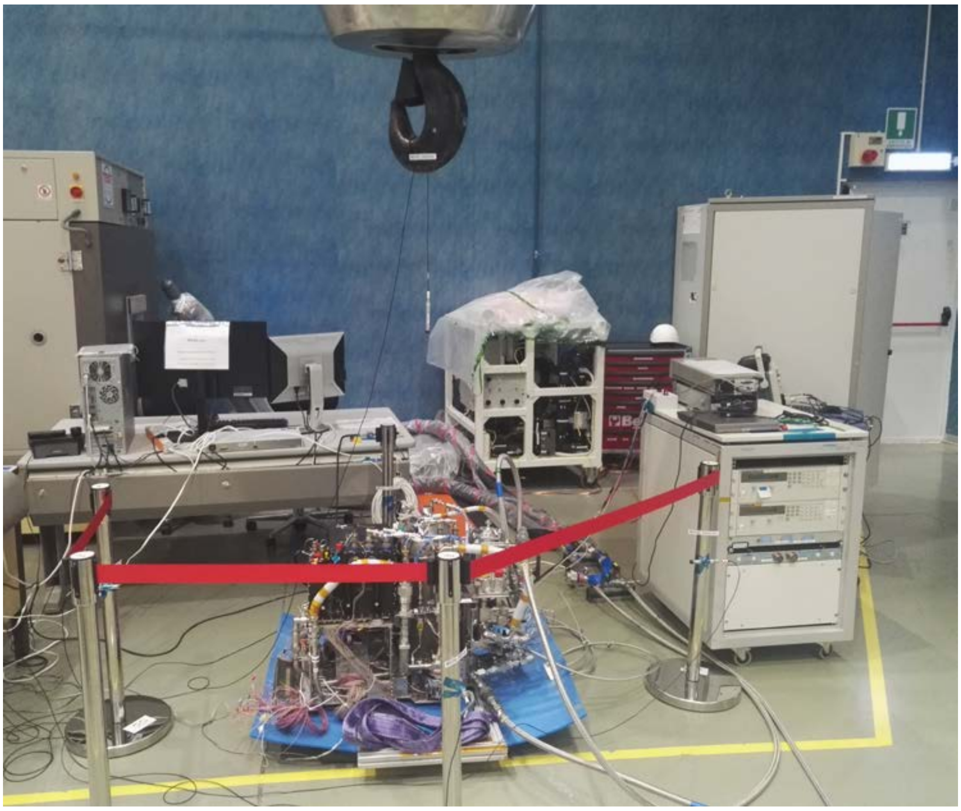


Figure C-3: View of test instrumentation during Water Pump Assembly (WPA) audible noise test at equipment level

C.1.5 Test preparation and test facility selection

A background noise measurement is recommended in order to characterize the behaviour of the test facility, and, in case of high background noise level, identify the disturbance noise source like, for example: EGSE, lights, air conditioning, external traffic that can affect the test results and implement all the possible mitigation actions to minimize the background noise. See A.13.6 about background noise.

The following aspects are considered for the selection of the facility:

- The suitability of the test facility capabilities is carefully evaluated and if possible, checked by a pre-test.
- Suitability of the location of the test setup is assessed (quiet environment).
- Supporting instrumentation cabling and suspension devices can influence the dynamic behaviour of the test facilities and therefore distort the results.

Device to decouple the unit under test from the supporting structure/test facility (i.e. floor isolation) is considered.

C.1.6 Test execution

The test article can be isolated from the ground either suspending it, or resting on air cushion or using a foam layer on the floor, , see Figure C-2.

The item under test shall be in on-orbit configuration and shall be operated according to the mission sequence.

As a generic test sequence for the audible noise source characterization the following steps can be performed:

- Facility characterization: through the reverberation time test with the presence of the test-up in on orbit configuration and in switched off condition.
- Perform different background noise characterizations, by means of measurements of sound pressure levels considering:
  - o all the disturbance noise source in the laboratory room switched off,
  - o the equipment EGSE and FGSE, if present, switched on,
  - o the equipment itself switched on but not operating.
- Before each test case, execute a dry run to optimize the acquisition chain in terms of measurement duration, measurement range.
- Execute the audible noise source characterization tests. The item under test in on-orbit configuration is then operated according to the mission sequence in all possible modes of operation and transitions between these modes as well as, so far applicable, in different speeds/power levels in order to capture all possible noise disturbances.
- Before changing to the next following test run perform a quick look check on the acquired time history and frequency domain data to ensure that the data is suitable for exploitation and does not just show background noise.

EGSE and FGSE shall be adequately isolated in order to minimize the transmission of structural and acoustical disturbances to the unit under test.
Any noise and vibration disturbances generated by items present in the facility room shall be eliminated or minimized to guarantee an acceptable background noise level.

Background noise level should be at least one order of magnitude lower than the test measured disturbances.

A typical characterization test campaign on an equipment goes from few days to around 1 week pending on the complexity of the setup and the required test sequence.

C.1.7 Test data acquisition and evaluation

For all test cases, it is recommended to record the responses in terms of:

- time histories (Pa)
- and the following post processing data:
  - o auto-spectrum (Pa^2).
  - o power spectrum level (Pa^2)/Hz.
  - o sound pressure levels (dB) [dB ref. 20 μPa] in third octave bands.
  - o sound pressure levels (dB) [dB ref. 20 μPa] in octave bands.

C.2 Space segment element audible noise emission test

C.2.1 Purpose

The purpose of the audible noise test at element level is to demonstrate that the flight hardware does not produce audible noise levels that are detrimental to the crew health and safety.

C.2.2 General

Audible noise test is performed at Element level, see ECSS-E-ST-10-03 clause 6.5.7.4 for Crewed Element only measuring the continuous and intermittent noise levels emission generated by items and payloads working in their operative conditions.

In case of intermittent noise emission, the sound pressure levels are measured in term of A-weighted decibel (dBA) and referred to a 24-hour equivalent noise exposure.

After the execution of the audible noise test a reverberation time (T60) test is needed to measure the time required for the sound to decay in a closed space. Sound in a closed manned volume room or in the laboratory chamber will repeatedly bounce off surfaces such as the floor, walls, ceiling. When these reflections mix, a phenomenon known as reverberation is created. Reverberation reduces when the reflections hit surfaces that can absorb sound such as absorbing panels. The reverberation time of a room or space is defined as the time it takes for sound to decay by 60 dB.

Reverberation time is measured from 31,5 Hz to 1600 Hz in octave band centre frequency.

C.2.3 Test Configuration and test aspects

In a typical audible noise test at element level, the test specimen is mounted onto its MGSE or on its dedicated Integration Stand and it is placed in the test facility as shown in Figure C-4.
The test is normally performed under 1g condition with the test article in its on-orbit configuration.

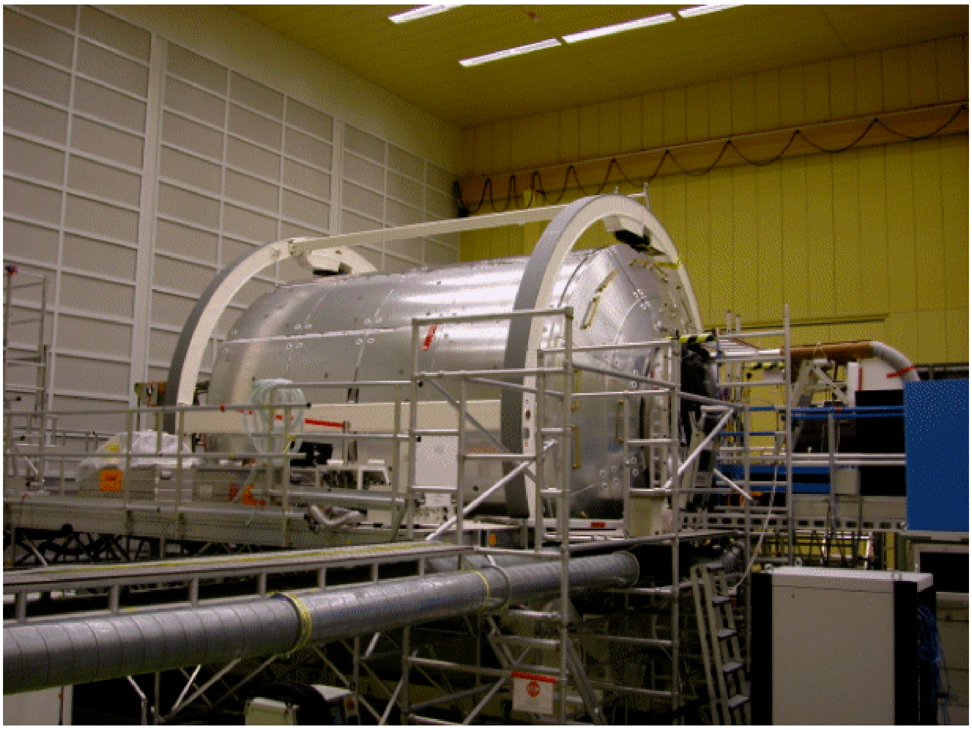


Figure C-4: View of COLUMBUS test article (external view: seen from deck-aft perspective) during audible noise test at element level

Audible noise test at element level is recommended to be executed with the Hatch in closed configuration (using a dummy hatch) because the reverberation time test need to be done in a well-defined closed volume.

C.2.4 Test instrumentation

In case of element level test, as for example on manned module test, a set of microphones are installed inside the test article to measure the sound noise responses and outside the test article, in the test facility, to control the external background noise levels.

Normally internal measurement microphones are positioned along the module centerline, however it is also recommended to install microphones in other representative locations as illustrated in Figure C-5 and in Figure C-6and at expected work and sleep station head locations.
External microphones are usually positioned one meter away from the test article.

Additional instrumentation is recommended to record the operational parameters of the flight hardware in their operative conditions.

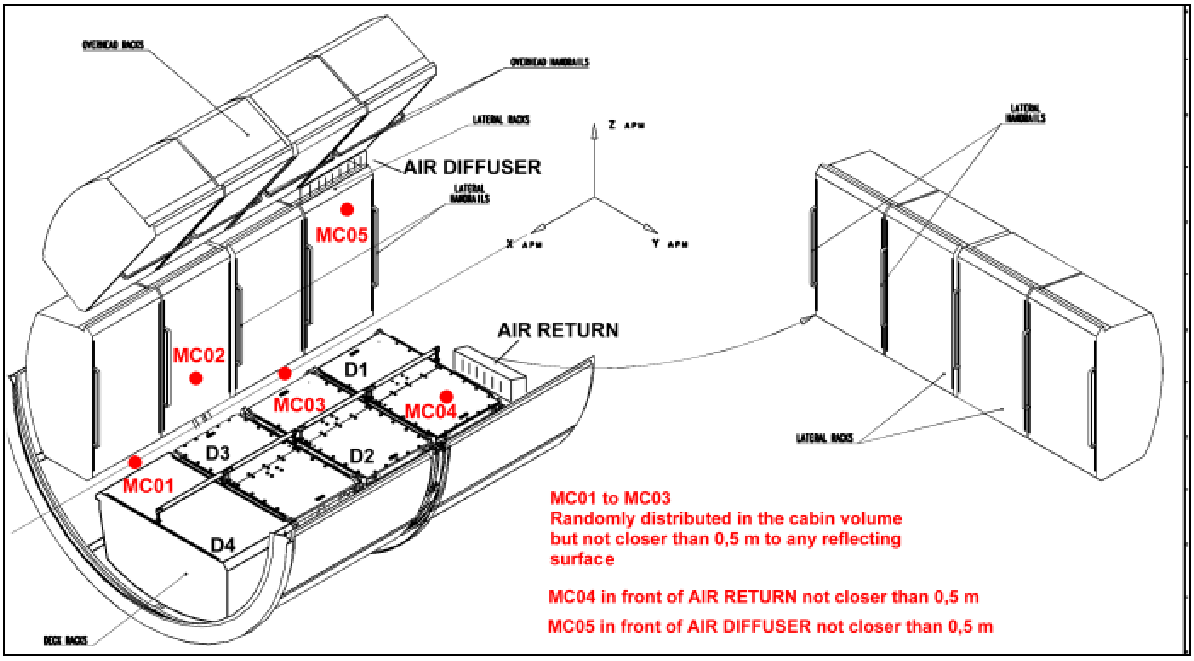


Figure C-5: Illustration of different microphone position inside COLUMBUS during audible noise test at element level

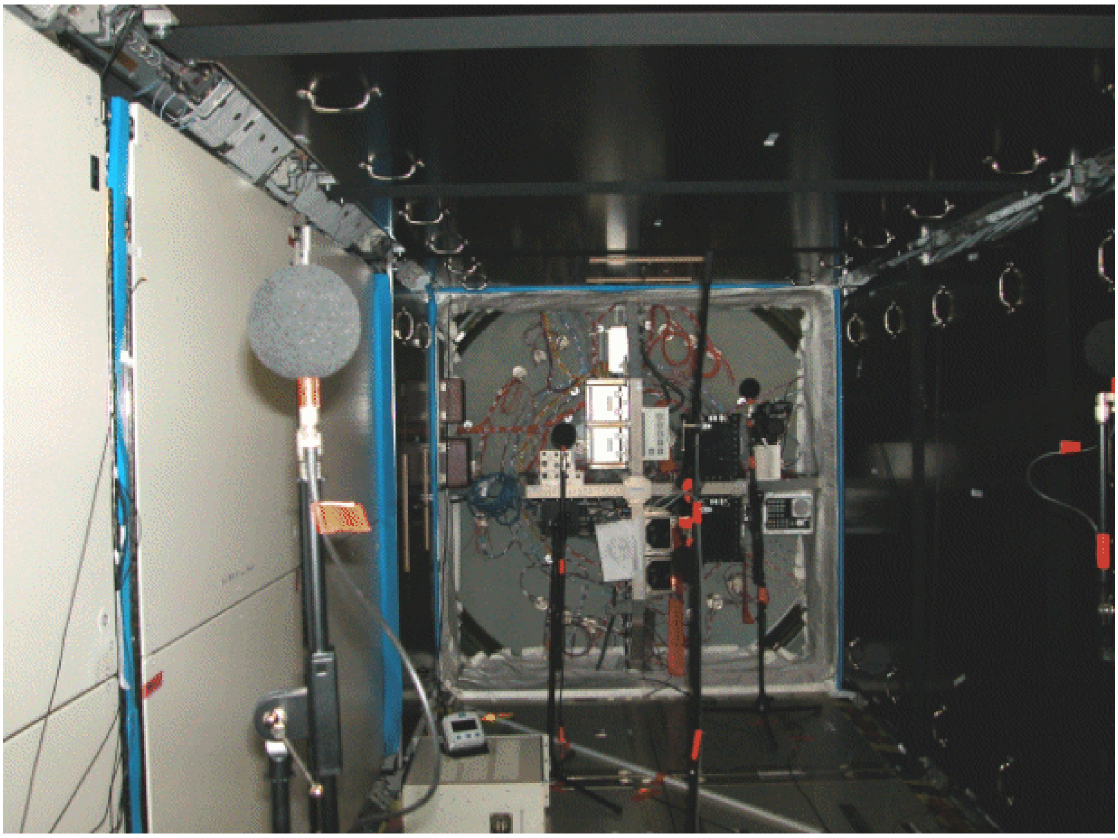


Figure C-6: Picture of COLUMBUS internal microphones during audible noise test at element level

C.2.5 Test preparation and facility selection

The following key aspects are considered for the facility selection:

- The suitability of the test facility capabilities are carefully evaluated and if possible checked by a pre-test.
- Suitability of the location of the test setup is assessed (quiet environment).
- Supporting instrumentation cabling and suspension devices can influence the dynamic behaviour of the test facilities and therefore distort the results.
- Decoupling of unit under test and supporting structure/test facility (i.e. floor isolation).

The background noise is measured. See A.13.6 about background noise.

C.2.6 Test execution

At element level, audible noise test is recommended to be conducted in combination with the micro-vibration tests, where possible.

As a generic test sequence for the audible noise source characterization the following steps can be performed:

- Facility characterization: through the reverberation time test with the presence of the test-up in on orbit configuration and in switched off condition.

- Perform different background noise characterizations, by means of measurements of sound pressure levels considering:
  - o all the disturbance noise source in the laboratory room switched off,
  - o the equipment EGSE and FGSE, if present, switched on,
  - o the equipment itself switched on but not operating.
- Before each test case, execute a dry run to optimize the acquisition data chain in terms of measurement duration and measurement range.
- Execute the audible noise source characterization tests. The item under test in full on-orbit configuration, and under operational conditions, is then operated according to the mission sequence in all possible modes of operation and transitions between these modes as well as, so far applicable, in different speeds/power levels in order to capture all possible noise disturbances.
- Before changing to the next following test run perform a quick look check on the acquired time history and frequency domain data to ensure that the data is suitable for exploitation and does not just show random noise.

EGSE and FGSE are adequately isolated in order to minimize the transmission of structural and acoustical disturbances to the unit under test.

Any noise and vibration disturbances generated by items present in the facility room is eliminated or minimized to guarantee an acceptable background noise level.

Background noise level should be at least one order of magnitude lower than the test measured disturbances.

A typical characterization test campaign on an equipment goes from few days to around 2 weeks pending on the complexity of the setup and the required test sequence.

C.2.7 Test data acquisition and evaluation

For all test cases, it is recommended to record the responses in terms of:

- time histories (Pa).
- and the following post processing data
  - o auto-spectrum (Pa^2).
  - o power spectrum level (Pa^2)/Hz.
  - o sound pressure levels (dB) [dB ref. 20 μPa] in third octave bands.
  - o sound pressure levels (dB) [dB ref. 20 μPa] in octave bands.

Annex D
PIM tests

D.1 PIM – guidelines for equipment testing

D.1.1 Introduction

PIM is a non-linear effect that tends to appear on RF devices operating simultaneously under transmission and reception environment. In these devices, the transmitted multi-carrier signal can generate spurious products which can fall inside the receiving band. As a consequence, the receiving signal can be masked, causing the partial or total jamming of the reception.

For spacecraft communications, PIM can be generated by:

- **Passive devices placed in the main RF transmission chain** (couplers, waveguide harnesses, antennas).
- **Structure devices**. These devices can suffer a radiation from the transmission carriers generating PIM (example: MLIs).

From the testing point of view, the test benches for detecting PIM can be split in two main categories, in concordance with the classification above-mentioned:

- **Conducted PIM test benches**. These test beds are employed to detect the PIM signal generated on devices directly submitted to RF power in their main RF path (example: waveguide harnesses, couplers, antennas). The PIM generated from this class of devices is named "conducted", as it is directly collected via conducted technologies (either coaxial or waveguide based-on).
- **Radiated PIM test benches.** These test beds are employed to detect the PIM signal generated on equipment or parts which are not directly submitted to RF power in their main RF path but that can be radiated by RF power (example: MLIs). The PIM generated from this class of devices is named "radiated", as it is directly collected via radiating elements (antennas).

This handbook includes four main sections:

- **Section 2: Possible test scenarios**. In this section the structure of typical low PIM benches, both for conducted and radiated PIM, is treated.
- **Section 3: Test procedure for evaluating PIM on a generic DUT**. In this section a typical test procedure to conduct low PIM measurements is explained.
- **Section 4: Power Profile and PIM level detected**. In this section typical RF power profiles for transmission carriers to conduct low PIM tests are shown.
- **Section 5: Recommendations to tune properly a PIM test bench.**

D.1.2 Possible PIM test scenarios

Even if PIM is a multi-carrier(1) effect, its study can be simplified to analyse a scenario composed by only two transmitted carriers. A two carriers scenario is the typical trade-off between test bench complexity and the effectiveness of the outcome of the test.

NOTE (1) Multi-carrier is defined as a RF environment in which two or more RF signals are travelling along the same transmission line.

- **Conducted PIM test scenarios**

  This test bench is typically based on a low-PIM multiplexer able to combine two different transmission carriers and collect the PIM signal generated by the DUT.

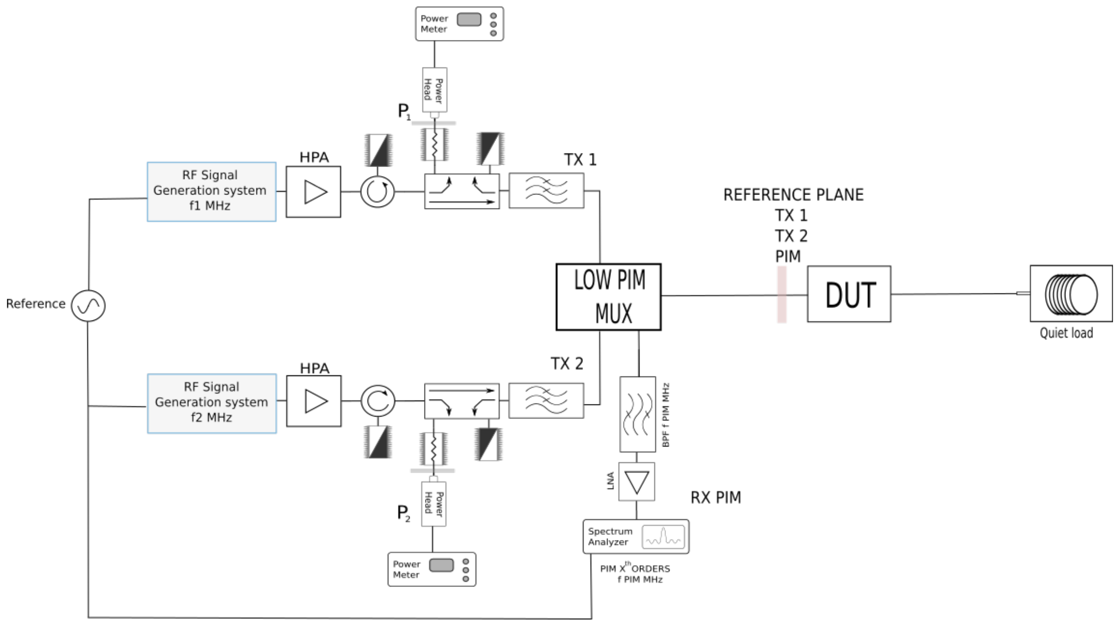


Figure D-1: Sketch from a typical Conducted PIM test bed

- **Radiated PIM test scenarios**

  Two different carriers are generated and combined in order to radiate towards the DUT. The PIM signal generated is collected by means a dedicated channel.

  1. **Foresight (worst case).** Transmissions and Reception have the same angle. The DUT can be inclined with respect to the transmission incident angle (normal incident angle). This scenario can be obtained via two different test benches, as depicted in Figure D-2 and Figure D-3.

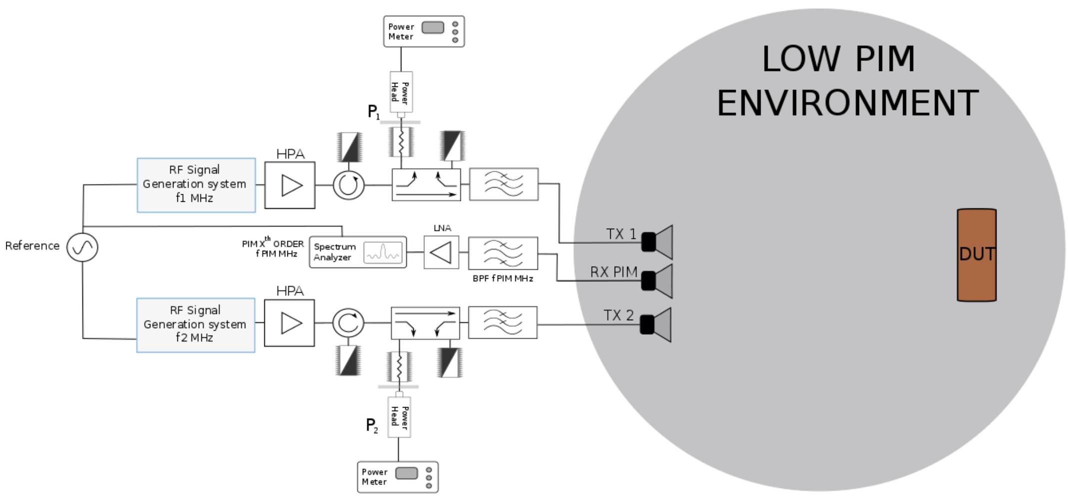


Figure D-2: Radiated PIM test bed: each carrier is transmitted via a dedicated antenna

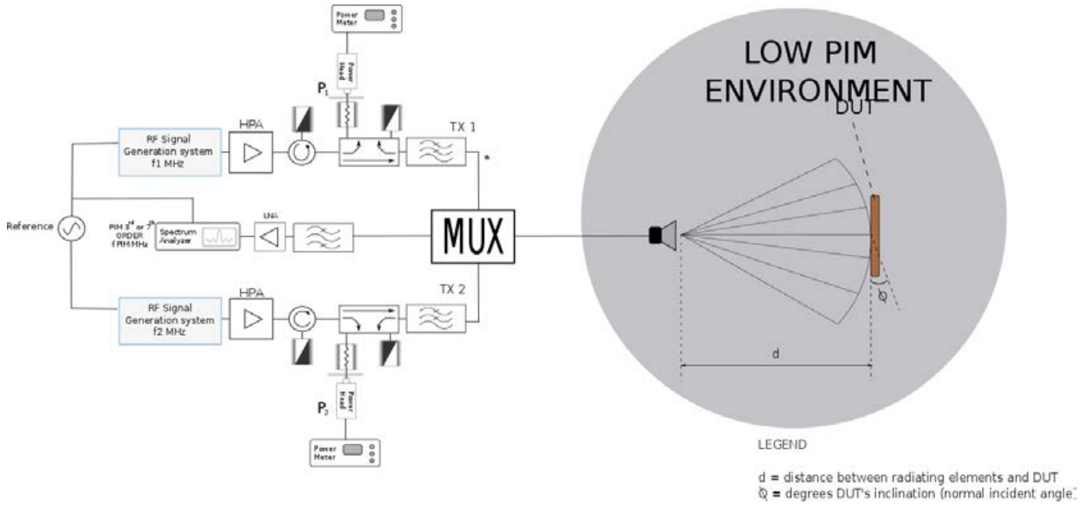


Figure D-3: Radiated PIM test bed: both carriers are transmitted by the same antenna

2. **Different angle between Txs and Rx.** The reception is placed at a different angle with respect to the transmission carriers. The DUT can be inclined with respect to the transmission incident angle (normal incident angle). This bench can be implemented by either radiating the transmission signals towards two different antennas (see Figure D-2) or merging the transmission carriers in a same antenna via a Multiplexer (see Figure D-4).

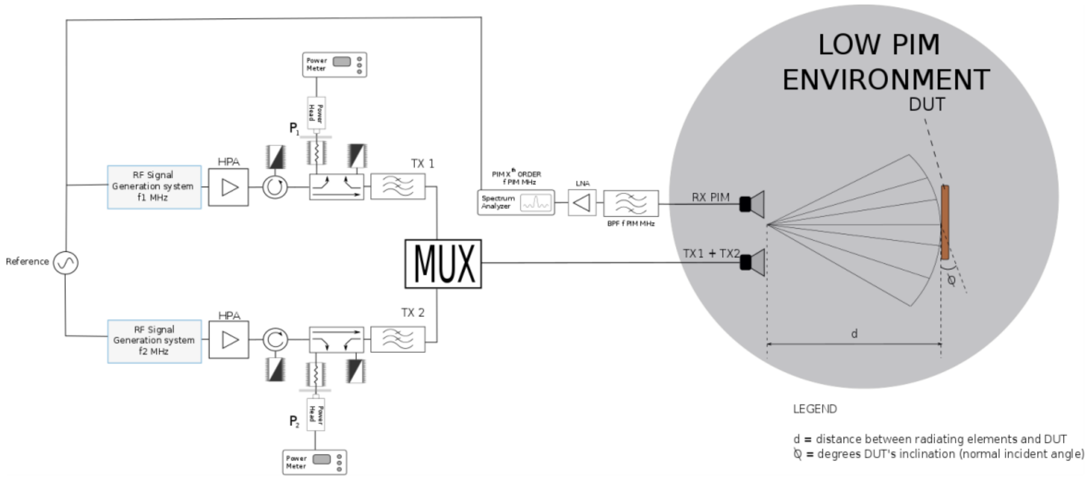


Figure D-4: Radiated PIM test bed: both carriers are transmitted via the same antenna

D.1.3 Test procedure for evaluating PIM on a generic DUT

The following steps are run consecutively during a low PIM test campaign. This procedure is general and can be applied both for conducted and radiated PIM tests on a generic DUT.

Before the start the tests, the requirements indicate the following parameters:

- Transmission frequencies,
- RF transmission power levels,
- PIM order,
- PIM frequency,

- PIM-qualification level which is demonstrated by the DUT.

For radiated PIM scenario, the definition of the maximum amount of transmission RF power required as well as the maximum PIM level is determined considering the flux density calculations. This evaluation is carried out considering several factors, such as the distance between the test bench and the DUT (typically d>>λ[1]) and the antenna's isotropic gain).

NOTE [1] d = distance between the horns and the DUT, λ = waveguide length.

D.1.3.1 Validation of the facility prior testing

The facility or test bed is validated as PIM-free prior testing. The DUT is replaced by a Through-DUT[1]. This Through-DUT is tested under the same conditions as the DUT, in terms of frequencies and RF power levels. The residual PIM level of the facility, if present, is found at least 10 dB lower with respect to the maximum PIM accepted by the customer during the tests on the DUT (example: if the DUT's qualification PIM level indicated by the customer is -115 dBm with 100 W /channel, the bench with the Through-DUT is found to have a residual PIM level below -125 dBm with 100 W/channel).

NOTE [1] Through-DUT = PIM-free transmission line (for conducted PIM tests) or blank scenario (for radiated PIM tests).

D.1.3.2 Verification of the facility prior testing

The facility is verified as PIM-sensitive prior testing. The DUT is replaced by a Sample-DUT[1], whose poor PIM performances are well-known by the test entity. This Sample-DUT is tested at the same frequencies as the DUT and at lower RF power levels. The test bench shows a residual PIM level higher with respect to the maximum PIM level accepted by the customer on the DUT. Example: if the qualification PIM level indicated by the customer on the DUT is -115 dBm with 100 W /channel, the bench with the Sample-DUT detects a PIM level higher than -115 dBm with 50 W/carrier.

NOTE [1] Sample-DUT = PIM generator transmission line (for conducted PIM tests) or object (for radiated PIM tests).

D.1.3.3 Execution of the low PIM tests on the DUT

The DUT is placed inside the bench and tested at the RF power levels and frequencies indicated by the customer. The residual PIM level from the DUT is detected. The time at maximum RF power is enough to guarantee the thermal stabilization of the DUT (typically 1 hour).

D.1.3.4 Post validation of the facility

Post validation after testing is required if during phase 3.3 the DUT has been found having a PIM level higher than the PIM-threshold indicated by the customer. This test, according to Section 3.1, is conducted using a Through-DUT.

D.1.3.5 Post verification of the facility

Post verification after testing is required if during phase 3.3 the DUT has been found having a PIM level lower than the PIM-threshold indicated by the customer. This test, according to Section 3.2, is conducted using a Sample-DUT.

D.1.4 Power profile and PIM level detected

Table D-1 and Figure D-5detail a typical RF power profile applicable for PIM tests.

Table D-1: Typical RF power profile for PIM tests.

Tx1 (W)	Tx 2 (W)	Dwell time (minutes)	PIM level (dBm)
30	30	5	
50	50	5	
70	70	5	
80	80	5	
90	90	5	
100	100	5	
120	120	10	
160	160	60	

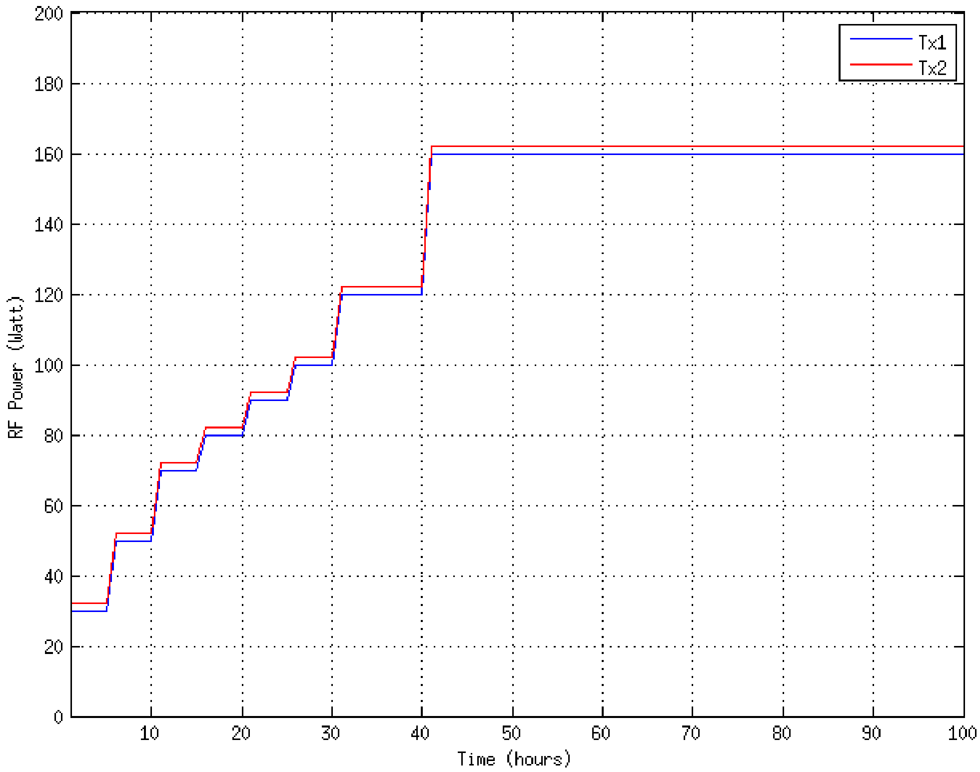


Figure D-5: Typical RF power profile for PIM tests: transmission carriers.

D.1.5 Recommendations to tune properly a PIM test bench

In order to set adequately the PIM detection system (Spectrum Analyser), it is important to enumerate the PIM signal characteristics:

1. PIM is a permanent perturbation.
2. PIM signal is weak in amplitude, typically close to Spectrum Analyser sensitivity (or even lower).
3. PIM signal frequency is expected once the transmission carriers are defined.
4. PIM signal is generated from carriers' amplitudes.

According to the PIM signal characteristics and the test bed configurations (see Figure D-1, Figure D-2, Figure D-3 and Figure D-4), several actions are taken in order to optimize the PIM readings.

POINT 1: PIM is a permanent perturbation.

An eventual PIM signal is permanent, hence the Spectrum Analyser speed reading (sweep time) can be increased in order to enhance the sensitivity.

POINT 2: PIM signal is weak in amplitude, typically close to Spectrum Analyser sensitivity (or even lower than it).

In order to detect an eventual PIM signal, we guarantee both:

- In order to have at the Spectrum Analyser input port a signal greater than its noise floor, a LNA with a good trade-off between high gain and low noise figure is inserted in the receiver (PIM) path.
- The Spectrum Analyser is set to maximize the sensitivity. In order to understand how to do it, the internal block diagram of a Spectrum Analyser is clear. Anyway, please consider the following hints:
  - The Resolution bandwidth is minimized;
  - The Sweep time is minimized;
  - The RF input attenuator is minimized, providing that the internal mixer overloading is avoided (a mixer overloaded can generate distortions);
  - The envelope detector typically is set in normal operation, which guarantees a compromise between the signal and the noise readings;
  - The video bandwidth does not affect the signal reading, but it can only smooth the signal displayed. Typically, it is set as automatic.
- In the receiver path, the PIM filters and the LNA is placed as close as possible to the PIM detection reference plane, in order to strengthen the PIM signal and eliminate the carrier signals at the same time. The LNA is placed always after the PIM filters, to maximize the signal to noise ratio of the PIM.

POINT 3: PIM signal frequency is expected once the transmission carriers are defined.

Have an erratic external reference in the Spectrum Analyser can shift the PIM reading and give erratic PIM evaluations.

The spectrum Analyser has the same external reference as the carrier signal generators. In addition, it is recommendable to set one carrier signal generator as master and the Spectrum Analyser as slave.

POINT 4: PIM signal is generated from carriers' amplitudes.

In a Spectrum Analyser, in order to detect a "true" PIM signal, i.e. generated by the Device Under Test, the following conditions are guaranteed:

- The transmission channels minimize its phase noise at PIM frequency.
- Avoid the AIM (Active Inter Modulation) of the LNA.

D.2 PIM – guidelines for payload testing

D.2.1 Introduction

Elements (payloads) are tested under nominal functioning before their launch, in order to avert the jamming of the communication during their in-orbit operational.
These tests are typically conducted in anechoic chambers whose RF power capabilities and PIM-free behaviour (1) is guaranteed by a test entity, see Figure D-6.

Task of this handbook is to provide guidelines to evaluate the residual PIM response of the test site (anechoic chamber).

NOTE (1) PIM is defined as a non-linear effect typical to appear on RF devices operating simultaneously under transmission and reception environment. In these devices, the transmitted multi-carrier signal can generate spurious products which can fall inside the receiving band. As a consequence, the receiving signal can be masked, causing the partial or total jamming of the reception.

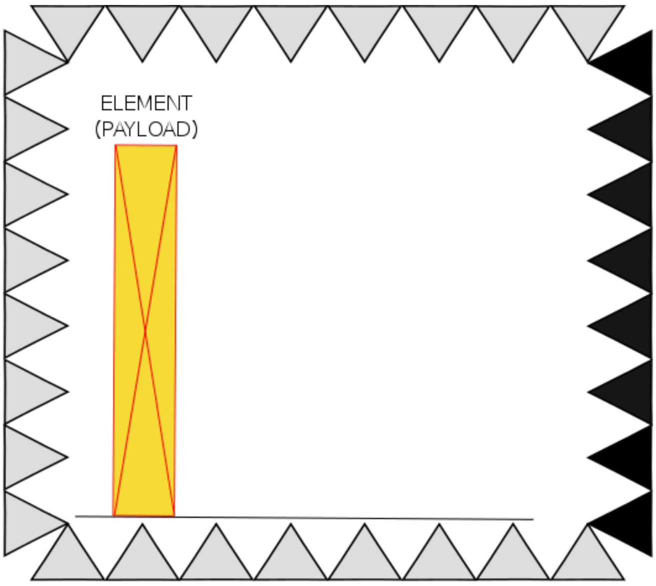


Figure D-6: Typical element (payload) inside an anechoic chamber for validation tests under nominal scenario.

This handbook includes four main sections:

- **Section 2: Test scenario for evaluating the residual PIM level of an anechoic chamber**. In this section the structure of typical low PIM bench to carry out tests to evaluate the residual PIM level of an anechoic chamber is treated.
- **Section 3: Test procedure for evaluating the residual PIM level of an anechoic chamber**. In this section a typical test procedure to conduct low PIM measurements in an anechoic chamber is explained.
- **Section 4: Power Profile and PIM level detected**. In this section typical RF power profiles for transmission carriers to conduct low PIM tests on an anechoic chamber are shown.
- **Section 5: Recommendations to tune properly a PIM test bench.**

D.2.2 Test scenario for evaluating the residual PIM level of an anechoic chamber

Even if the payload is tested under the full operative scenario (multi-carrier(1)), the residual PIM response of the facility (anechoic chamber) can be is typically evaluated considering a simplified scenario.

This reduction, composed by only two transmitted carriers, is the typical trade-off between test bench complexity and the effectiveness of the outcome of the test.
A typical test bench for anechoic chamber PIM evaluation purposes is depicted in Figure D-7. The test scenarios applicable are listed in D.2.3.

As it can be noticed, the test bench is placed in front of the anechoic chamber walls, at a proper distance to radiate the surface with the equivalent flux density as the payload.
It is worth mentioning that only a few surface of the whole anechoic chamber is evaluated, taking into account the payload disposition and the antennas' patterns.

NOTE (1) Multi-carrier is defined as a RF environment in which two or more RF signals are travelling along the same transmission line.

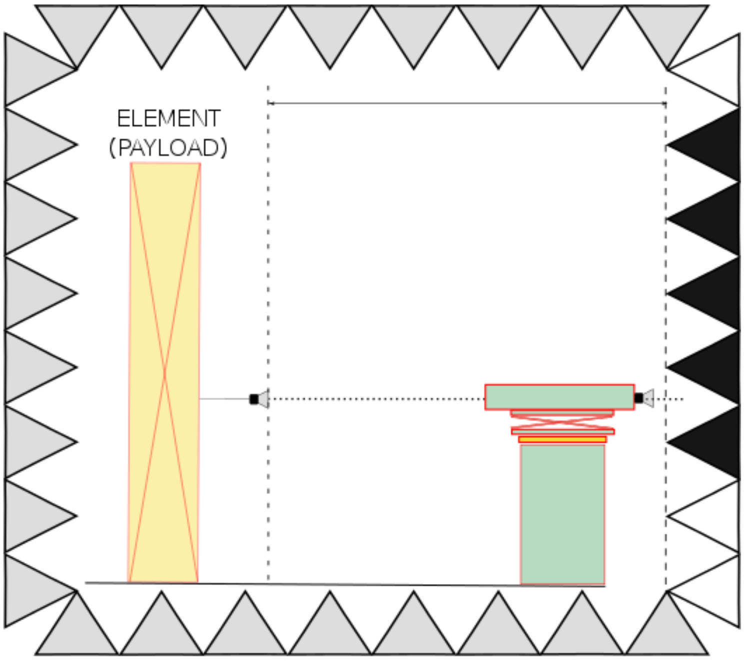


Figure D-7: Test bed placed to radiate the anechoic chamber walls according to payload disposition.

D.2.3 Possible radiated PIM test scenarios

Depending on the frequencies and angle considered, several scenarios are applicable. In all of them, two different carriers are generated and combined in order to radiate towards the DUT. The PIM signal generated is collected by means a dedicated channel.

a. **Foresight (worst case).** Transmissions and Reception have the same angle. The DUT can be inclined with respect to the transmission incident angle (normal incident angle). This scenario can be obtained via two different test benches, as depicted in Figure D-8 and Figure D-9.

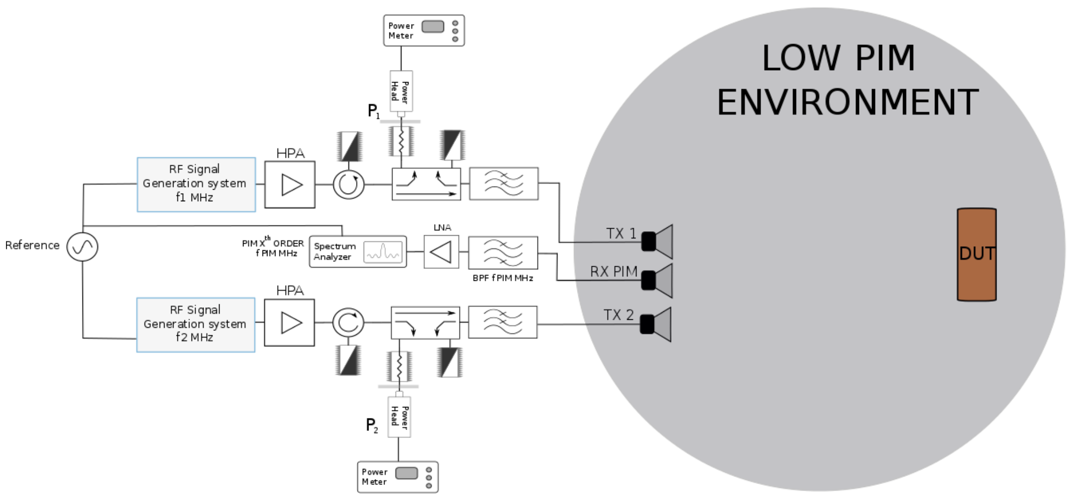


Figure D-8: Radiated PIM test bed: each carrier is transmitted via a dedicated antenna

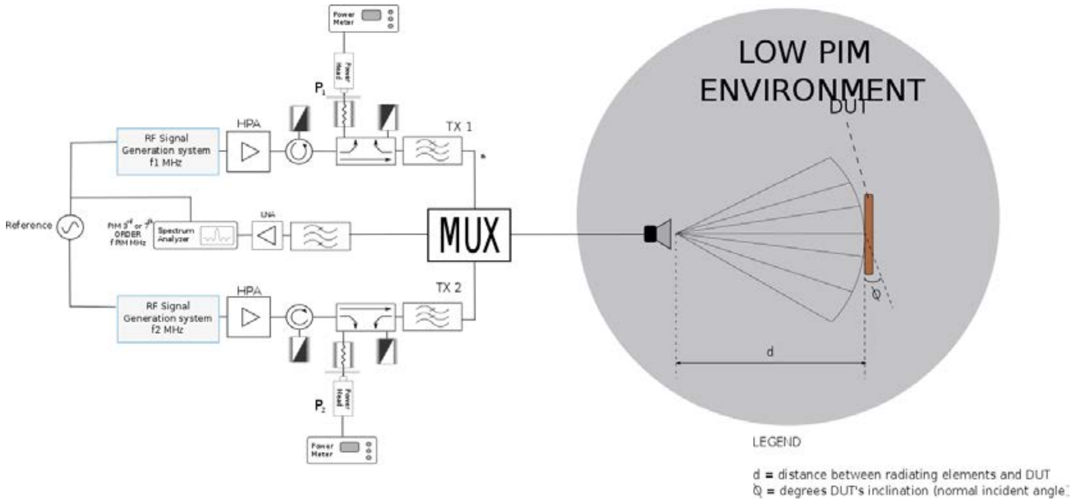


Figure D-9: Radiated PIM test bed: both carriers are transmitted by the same antenna

b. **Different angle between Txs and Rx.** The reception is placed at a different angle with respect to the transmission carriers. The DUT can be inclined with respect to the transmission incident angle (normal incident angle). This bench can be implemented by either radiating the transmission signals towards two different antennas (see Figure D-8) or merging the transmission carriers in a same antenna via a Multiplexer (see Figure D-10).

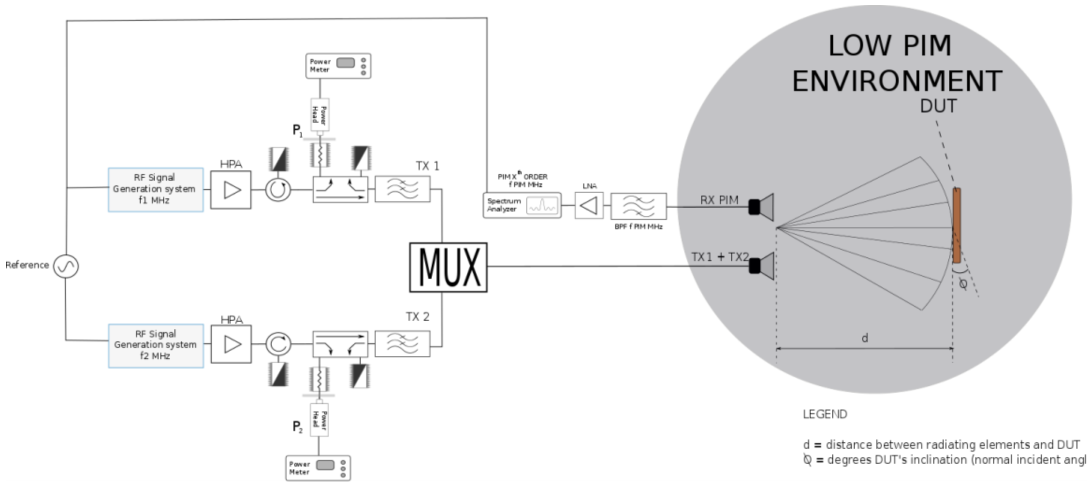


Figure D-10: Radiated PIM test bed: both carriers are transmitted via the same antenna

D.2.4 Test procedure for evaluating the residual PIM level of anechoic chamber

D.2.4.1 Sequence of steps

The following steps are run consecutively during PIM measurement of elements (payloads).

D.2.4.2 Validation of the facility prior testing

The requirements indicate the following parameters:

- Scenarios applicable,
- Per each scenario, transmission and PIM frequencies,
- Per each scenario, transmission and PIM power levels,
- Per each scenario, the anechoic chamber area submitted to testing and its illumination angle with respect to the foresight.

It is worth mentioning that the definition of the maximum amount of transmission RF power required as well as the maximum PIM level is determined considering the flux density calculations. This evaluation is carried out considering several factors, such as the distance between the payload and the anechoic chamber wall, the distance between the test bench and the anechoic chamber wall (typically d>>λ[(1)]) and the antenna's isotropic gain).

NOTE [(1)] d = distance between the horns and the DUT, λ = waveguide length.

D.2.4.3 Verification of the facility prior testing

The facility is verified as PIM-sensitive prior testing. The DUT (anechoic chamber wall) is replaced by a Sample-DUT[(1)], whose poor PIM performances are well-known by the test entity. This Sample-DUT is tested at the same frequencies as the DUT and at lower RF power levels. The test bench shows a residual PIM level higher with respect to the maximum PIM level accepted by the customer on the DUT. Example: if the qualification PIM level indicated by the customer on the DUT is -115 dBm with 100 W/channel, the bench with the Sample-DUT detects a PIM level higher than -115 dBm with 50 W/carrier.

NOTE [(1)] Sample-DUT = PIM generator transmission line (for conducted PIM tests) or object (for radiated PIM tests).

D.2.4.4 Execution of the low PIM tests on the DUT

The DUT is placed inside the bench and tested at the RF power levels and frequencies indicated by the customer. The residual PIM level from the DUT is detected. The time at maximum RF power is enough to guarantee the thermal stabilization of the DUT (typically 1 hour).

D.2.4.5 Post validation of the facility

Post validation after testing is required if during phase 3.3 the maximum PIM level from the DUT has been found higher than the PIM-threshold indicated by the customer. This test, according to D.2.4.2, is conducted using a Through-DUT.

D.2.4.6 Post verification of the facility

Post verification after testing is required if during phase 3.3 the maximum PIM level from the DUT has been found below than the PIM-threshold indicated by the customer. This test, according to Section D.2.4.3 is conducted using a Sample-DUT.

D.2.5 Power profile and PIM level detected

Table D-2 and Figure D-11 detail a typical RF power profile applicable for PIM tests.

Table D-2: Typical RF power profile for PIM tests.

Tx1 (W)	Tx 2 (W)	Dwell time (minutes)	PIM level (dBm)
30	30	5	
50	50	5	
70	70	5	
80	80	5	
90	90	5	
100	100	5	
120	120	10	
160	160	60	

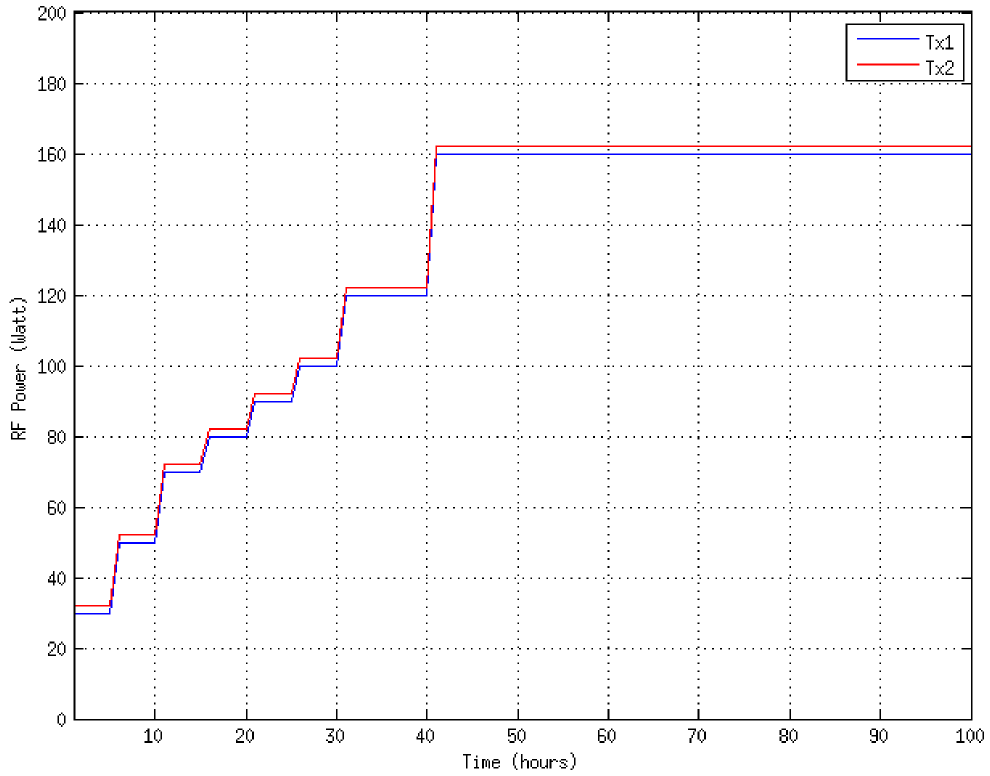


Figure D-11: Typical RF power profile for PIM tests: transmission carriers.

D.2.6 Recommendations to tune properly a PIM test bench

In order to set adequately the PIM detection system (Spectrum Analyser), it is important to enumerate the PIM signal characteristics:

1. PIM is a permanent perturbation.

2. PIM signal is weak in amplitude, typically close to Spectrum Analyser sensitivity (or even lower).
3. PIM signal frequency is expected once the transmission carriers are defined.
4. PIM signal is generated from carriers' amplitudes.

According to the PIM signal characteristics and the test bed configurations (see Figure D-8 and Figure D-9), several actions are taken in order to optimize the PIM readings.

POINT 1: PIM is a permanent perturbation.

An eventual PIM signal is permanent, hence the Spectrum Analyser speed reading (sweep time) can be increased in order to enhance the sensitivity.

POINT 2: PIM signal is weak in amplitude, typically close to Spectrum Analyser sensitivity (or even lower than it).

In order to detect an eventual PIM signal, we guarantee both:

- In order to have at the Spectrum Analyser input port a signal greater than its noise floor, a LNA with a good trade-off between high gain and low noise figure is inserted in the receiver (PIM) path.
- The Spectrum Analyser is set to maximize the sensitivity. In order to understand how to do it, the internal block diagram of a Spectrum Analyser is clear. Anyway, please consider the following hints:
  - The Resolution bandwidth is minimized;
  - The Sweep time is minimized;
  - The RF input attenuator is minimized, providing that the internal mixer overloading is avoided (a mixer overloaded can generate distortions);
  - The envelope detector typically is set in normal operation, which guarantees a compromise between the signal and the noise readings;
  - The video bandwidth does not affect the signal reading, but it can only smooth the signal displayed. Typically, it is set as automatic.
- In the receiver path, the PIM filters and the LNA are placed as close as possible to the PIM detection reference plane, in order to strengthen the PIM signal and eliminate the carrier signals at the same time. The LNA is placed always after the PIM filters, to maximize the signal to noise ratio of the PIM.

POINT 3: PIM signal frequency is expected once the transmission carriers are defined.

Have an erratic external reference in the Spectrum Analyser can shift the PIM reading and give erratic PIM evaluations.

The spectrum analyser has the same external reference as the carrier signal generators. In addition, it is recommendable to set one carrier signal generator as master and the Spectrum Analyser as slave.

POINT 4: PIM signal is generated from carriers' amplitudes.

In a Spectrum Analyser, in order to detect a "true" PIM signal, i.e. generated by the Device Under Test, the following conditions are guaranteed:

- The transmission channels minimize its phase noise at PIM frequency.
- Avoid the AIM (Active Inter Modulation) of the LNA.

D.3 PIM – Guidelines for Element testing

D.3.1 Overview

In the following section the test methods for measuring PIMPs at element level for telecommunication payloads are discussed.

The victim frequency of a PIM is defined as the frequency, inside the receiver useful bandwidth obtained by a linear combination of killer frequencies.

$$f_v = a_1 \cdot f_{k,1} + a_2 \cdot f_{k,2} + \ldots$$

Where *fv* is the victim frequency, *fk, j* is the *jth* killer frequency, and *aj* is an integer.

The PIM order is the sum of the absolute values of the integer coefficients.

The common case is when the killer frequencies and the victim frequencies are not separated by more than an octave of frequency. In this case, the PIM order is an odd number.

The PIM is a memoryless, yet highly non-linear phenomenon: PIM frequencies are easily identified, whilst the associated power levels are almost impossible to predict, due to limitations in EMC SW, presence of contaminants…

Typically, the RF parts (like waveguides), equipment (like the OMUX or the feeder) of the repeater and the antennas forming the antenna farm of a telecom spacecraft are already qualified, at equipment and part level, as being PIM free before they are embarked on a spacecraft. Nevertheless, a spacecraft PIM test campaign can be required at element level to verify that no PIMs are present due to the real structure or to the presence of other real reflectors that could not be modelled perfectly even with the use of full scale mock-up models during the equipment qualification campaign.

A PIM scenario is a pattern that typically includes:

a. Payload RF configuration,

b. Killer emitter antennas,

c. Killer emitter frequencies,

d. Type of modulation of the killer signals,

e. Victim antennas,

f. Victim frequencies,

g. Geometric disposition of the antennas w.r.t the spacecraft (for example the steerable antennas can be orientated in sub- spacecraft point of view).

The payload RF configuration is the set of RF paths from RX antennas to TX antennas, including:

- Status of active units (ON/OFF),
- RF switch positions,
- Gains of analogue amplifiers,
- Frequency shift values for frequency translating devices, (such as down-converters) including vacuum shifts if the frequency pattern contains frequency bins close to the skirts of the filters.

- Others (for example: frequency mapping set for digital frequency translator devices if any, gains of digital sections if any, fine tuning of programmable local oscillators…).

For each victim frequency, a threshold in absolute value (in terms of dBm) is defined in the test specification document over which a PIM is not acceptable, since the spurious signal is likely to jammer the useful signal.

An example of PIM scenario is depicted in Table D-3.

Table D-3: Example of PIM scenario

Payload configuration	TX Killer Antenna	TX Killer frequency [MHz]	RX Victim Antenna	RX Victim frequency [MHz]	PIM Order
Nominal A1	Antenna A1	8323,0	Antenna A3	9386	7
	Antenna A3	8455,0			
	Steerable S2	9052,5			

Possible variations can occur. For example:

a. One or more signals can be modulated, for example FM modulated so to spread out the power over a larger bandwidth and observe the effects.

b. The transmitted carriers can be unbalanced in amplitude so isolate the PIM contribution.

Due to the complexity of a telecom spacecraft (which can embark multiple payloads at different frequency ranges, and multiple antennas, either fixed, including the beacons, and steerable, or beam-forming) a PIM scenario can be either very simple (for example, only two killer signals transmitted by one antenna and impacting only one frequency on the same antenna), or very complex (three antennas transmitting each a signal around 10 GHz and impacting one antenna receiving around 40 GHz, that is two octaves higher, with high PIM order).

Generally, the higher the order the PIM is, the less likely a major PIM in the receiver bandwidth is supposed to be found. PIM testing is eventually aimed at verifying that the isolation amongst the antennas meet the requirements: it is an auto compatibility EMC test.

At space element level, PIMs are mostly a radiated generated issue: nevertheless, in order to stimulate the killer signals and detect the magnitude of the victim signals, whilst coping with on the complexity of PIM scenarios and the geometry of antenna radiators, two PIM testing methods are suggested.

- **First method:** with conducted stimuli and conducted signal detection, that is used when testing the S/C with very complex frequency patterns is required.
- **Second method**: totally radiated, when simple frequency patterns are provided.

In both methods, a preliminary check to ensure that the chamber is PIM free is run, so to guarantee that during the forthcoming tests, any recorded PIM is coming only from the spacecraft itself: this is not a trivial issue, especially at low frequencies, like UHF.

The preliminary check to ensure that the chamber is PIM free is performed in accordance to D.1.3.

D.3.2 First method

In this case, each uplink signal is generated by the EGSE, injected into the correct (according to the payload configuration) repeater RF I/F between the LNA and the downconverter. This signal travels through each RF chain, is down-converted, amplified, transmitted and can combine with the other high power carriers to intermodulate and generate the PIMP victim frequency in a radiated environment.

NOTE When we say "high" power carriers we mean that this is the normal case, in which the range of radiated EIRP is in the order of 40-50 dBW per antenna. Of course, even a beacon or a TT&C transponder can cause intermodulation, whilst the associated EIRP is decades of dB lower.

The victim signal is then amplified by the LNA of the corresponding antenna, and can be routed towards the RF EGSE.

This method has several advantages:

1. It is possible to inject and detect many carriers concurrently, in complex configurations, that can be prevented by the geometrical dispositions of TX and RX chamber antennas;
2. No need for exploiting a perfect alignment of the spacecraft w.r.t. the TX and RX chambers antennas, provided that safety conditions are maintained (the power flow from the reflectors is targeting the anechoic wall and no dangerous hot spots are created);
3. High precision levels of signals can be injected, without relying only on the telemetry information of active units or on the radiated loss estimated for the chamber for each frequency;
4. In case a change of configuration is needed, requiring different transmit and receive antennas (which is likely to occur several times in case of problems for investigating the sources of detected PIMs), there is no need of realigning the spacecraft.

The major drawback of this method is that the repeater is modified after having undergone all the qualification stages till the final RF performance tests: RF connectors after the LNAs are disconnected so to have interfaces through which killers can be injected and victims can be detected by the RF test equipment through metallic transmission lines (typically coaxial cables, but waveguides also are possible if insertion loss is of major concern).

In short, this method has the following disadvantages:

1. It can be difficult to get access to the interior of the S/C to interrupt the RF chain and connect/disconnect only the coaxials to/from the RF EGSE;
2. It is important to make sure that the routing of cables is not a generator of PIM itself, by confining the routing in a zone that is neutral w.r.t. the radiation pattern of the antennas.
3. Most important, qualified flight configuration, after final conducted performance test, is altered.

Some considerations about how to minimize or even eliminate the disadvantage of point 3 are worth to be mentioned.

First, it is possible to take a record of the EIRP before the PIM test is run, and then, using the same configuration, perform the same EIRP test after the PIM testing. The two snapshots are supposed to match, taking into account the contribution of the measurement uncertainty. In addition, a sniff test can be exploited before and after the PIM testing, in proximity of the point where the RF chain is interrupted.

Second, this drawback can be <u>totally</u> overcome if, during the design stage of the payload, a dual directional coupler positioned after each LNA is foreseen. The killer signals and the PIMs can be injected and detected respectively through the coupled ports <u>without</u> breaking the direct path of the RF chains.

D.3.3 Second method

The second method is a radiated one.

As configuration, two transponders radiate in the same transmit section (OMUX or Tx antenna) the two Fk1 & Fk2 frequencies in order to generate the Fv PIM frequency. The two uplink can be hardlined or radiated no difference in the result (only pending optimized S/C configuration of test facility).

As this PIM level is assumed to be low (due to good S/C design ….) it is not necessarily to measure directly this Fv PIM frequency in radiated downlink,

The S/C architecture will be in flight configuration. This generated Fv PIM frequency is automatically radiated and reinjected in one uplink mission of the S/C by design and will perturb a 3rd transponder. The PIM level in downlink of this 3rd transponder is then measured (taken benefit of the transponder gain to amplify the PIM level).

Annex E
Alignment measurements

E.1 Purpose

Purpose of Element and equipment alignment is to set and verify the relative position and orientation of the parts of an Element or equipment.

NOTE Alignment can be limited to a measurement to verify that alignment is within specification. It can also be an integration activity consisting in aligning the equipment such that they comply with the alignment specification, i.e. an iterative process of measuring and adjusting the position/orientation.

E.2 General

Position and orientation of specific parts of the element or equipment need to be measured relative to a reference coordinate system. There are usually one element or equipment reference coordinate system, and specific local reference coordinate system for each part that require alignment. This is typically the case for thrusters, antennas, reaction wheels, gyros, star trackers, instrument line of sight.
Alignment verification is repeated along the test sequence, to track any degradation that can result from the different events like environmental tests, transportation and handling and to ensure that the alignment remains within the specified limits.

In case some equipment need specific positioning and orientation a dedicated adjustment campaign, using shims or other means to adjust position and orientation, is performed in order to set the equipment into defined position/orientation.

Given an equipment mechanical reference system ($MRF_{equipment}$) and the element mechanical reference system ($MRF_{element}$), the final objective of the alignment measurement is to determine the relative position of $MRF_{equipment}$ vs $MRF_{element}$, i.e. the relevant rotation matrix M_{ELEQ} (**M***atrix* **ELement/EQuipment**) which is reported in the Figure E-1. This task cannot be accomplished directly with a single measurement, but is realized step by step with a sequence of measurements and adjustments if necessary. Ref. to ECSS-E-ST-10-09C (Reference Coordinate system) Fig. B-4 for the Alignment Reference Frame and Mechanical Reference Frame concepts.

The alignment sequence, which is not strictly a time sequence but more a conceptual sequence, to calculate the final rotation matrix M_{ELEQ} is reported in Figure E-1. Specific dedicated mirrors (or alignment tools) are installed on the equipment to be aligned in order to materialize the equipment alignment reference frame (e.g. Thruster alignment jig equipped with a mirror, Reaction Wheels with target adaptors for corner cube reflectors, Inertia Measurement Unit with reference alignment cube etc.). In some cases, also, mechanical features on (part of) the equipment can be used to define the alignment reference frames.

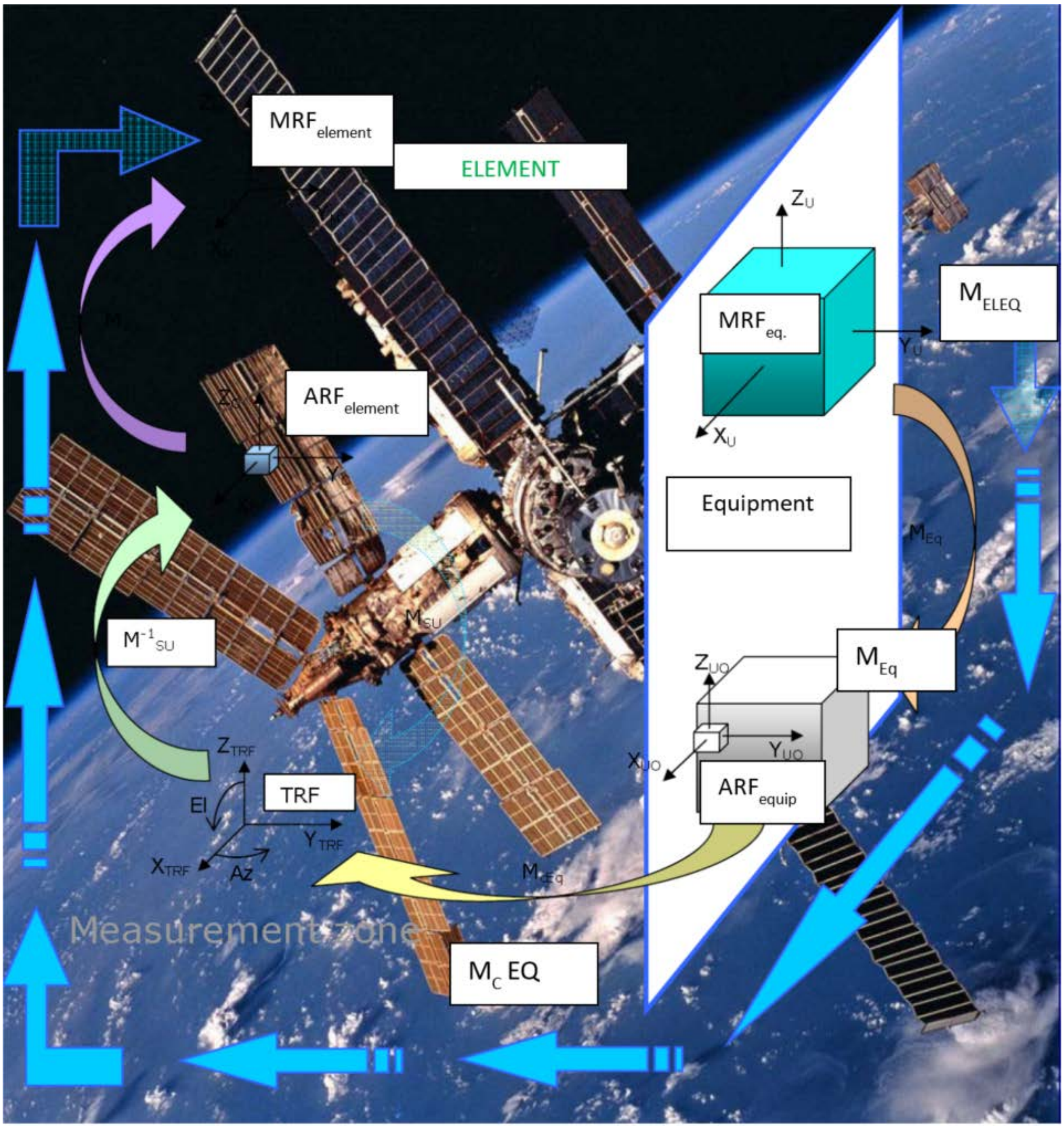


Figure E-1 Coordinate Systems relationship

To obtain the above-mentioned rotation matrices, the alignment is based on 2 inputs from previous activities and a measurement campaign at element level:

- The transformation matrix between the equipment MRF and ARF, provided by the equipment supplier. An example is provided in ECSS-E-ST-60-21 (Gyro) and ECSS-E-ST-60-20 (Star sensors)
- The transformation matrix between the element MRF and ARF, usually provided by the structure supplier

The measurement activity corresponds to the measurement of the transformation matrix between the equipment ARF and element ARF, i.e.:

Element ARF to equipment ARF measurement:

- *$ARF_{equipment}$ (Equipment Alignment Reference Frame);*

- *$ARF_{element}$ (Element Alignment Reference Frame); it is materialized by a Master reference cube*
- *TRF (Theodolite Reference Frame);*
- *M_{cEq} that is the rotation matrix from $ARF_{equipment}$ to TRF;*
- M^{-1}_{su} is the theodolite set up rotation matrix from TRF to $ARF_{element}$.

NOTE The term theodolite is used but it can be changed to measurement instrument if other instruments are used

After determination of the different matrices (ref. to the next paragraphs for measurement techniques) it is possible to use the following formula that allows to achieve the objective of evaluating the relative orientation of an object w.r.t the element reference frame:

$$\overrightarrow{V_{ELMRF}} = \overrightarrow{V_{EQMRF}} \times M_{EQ} \times M_{cEQ} \times M_{SU}^{-1} \times M_{EL}$$

Where:

$\overrightarrow{v_{ELMRF}}$ =	Vector providing the orientation of the vector $\overrightarrow{v_{EQMRF}}$ in the Element Mechanical Reference Frame
$\overrightarrow{v_{EQMRF}}$ =	vector providing the orientation of ARF in the equipment Mechanical Reference Frame. This vector is usually provided by the supplier of the unit
M_{EQ} =	Rotation Matrix which allows to pass from the equipment *MRF* to the equipment *ARF*. This matrix is usually measured and provided by the equipment supplier.
M_{cEQ} =	Rotation matrix from equipment *ARF* to *TRF* (Theodolite Reference Frame); it is obtained as part of the alignment measurement activity (see next paragraph); the *TRF* is usually defined as follows: Z_{TFR}: vector parallel to local gravity X_{TFR}: vector in the plane normal to gravity and in the direction on which the azimuth of the theodolite has been set to zero Y_{TFR}: third vector to complete the right-handed reference frame
M_{SU}^{-1} =	Theodolite set-up rotation matrix from TRF (Theodolite Reference Frame) to Element ARF as defined by the Master Reference Cube (MRC); it is obtained as part of the alignment measurement activity (ref., to E.3)
M_{EL} =	Rotation matrix from Element *ARF* (defined by *MRC*) to Element *MRF*. It is usually provided by the structure supplier. It allows to determine the position of the master reference cube (defining the *ARF*) w.r.t. the *MRF*.

So, the following formula allows to calculate the rotation matrix as previously indicated:

$$M_{ELEQ} = M_{EQ} \times M_{cEQ} \times M^{-1}_{SU} \times M_{EL}$$

E.3 Test configuration and test aspects

The alignment is usually performed with the element or equipment on its supporting fixture during:

- Integration phase on support stands;
- Test phase installed on specific test adapter (Integration stand, TVTB adapter, mass properties or sine adapter etc..)

The supporting fixture needs to be sufficiently stable for the duration of the alignment measurements. No activity that can impact the stability are performed within this time frame.

The test is usually performed in clean room at ISO8 environmental condition or better if required for optical instrument, in accordance with specific cleanliness flight hardware requirements.

When the gravity has an important influence on alignment measurement, a Gravity Release Test is performed, see A.12, to assess the effects of gravity on the alignment.

E.3.1 Measurement devices

E.3.1.1 Overview

Depending on the applied methodology, different measurement devices can be used for alignment, alone or in combination. The classical ones are:

- Laser Tracker;
- Theodolite

Moreover, in the last years the use of photogrammetry is more and more applied but with some limitation and for specific phases. See dedicated chapter in E.7.1.

E.3.1.2 Laser Tracker

The laser tracker is a portable measurement system based on a laser beam. It measures distance and angles (Azimuth and Elevation) of a target, usually corner cube reflector, in its own reference frame.
The laser tracker can determine the co-ordinates of the centre of the corner cube reflector, in the laser tracker reference frame, by measuring the distance with the time of flight of the laser beam and the two angles with two encoders.

A general sketch of a Laser Tracker is shown in Figure E-2.

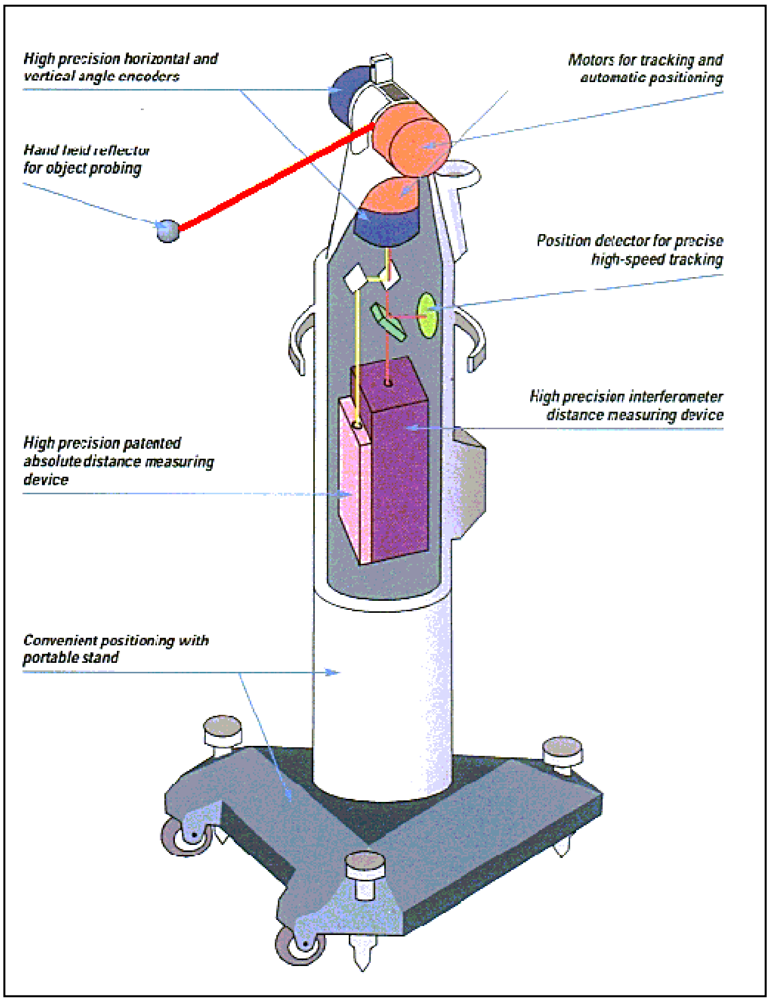


Figure E-2: General sketch of a laser tracker

Figure E-3 shows a typical set-up for alignment measurement using Laser tracker.

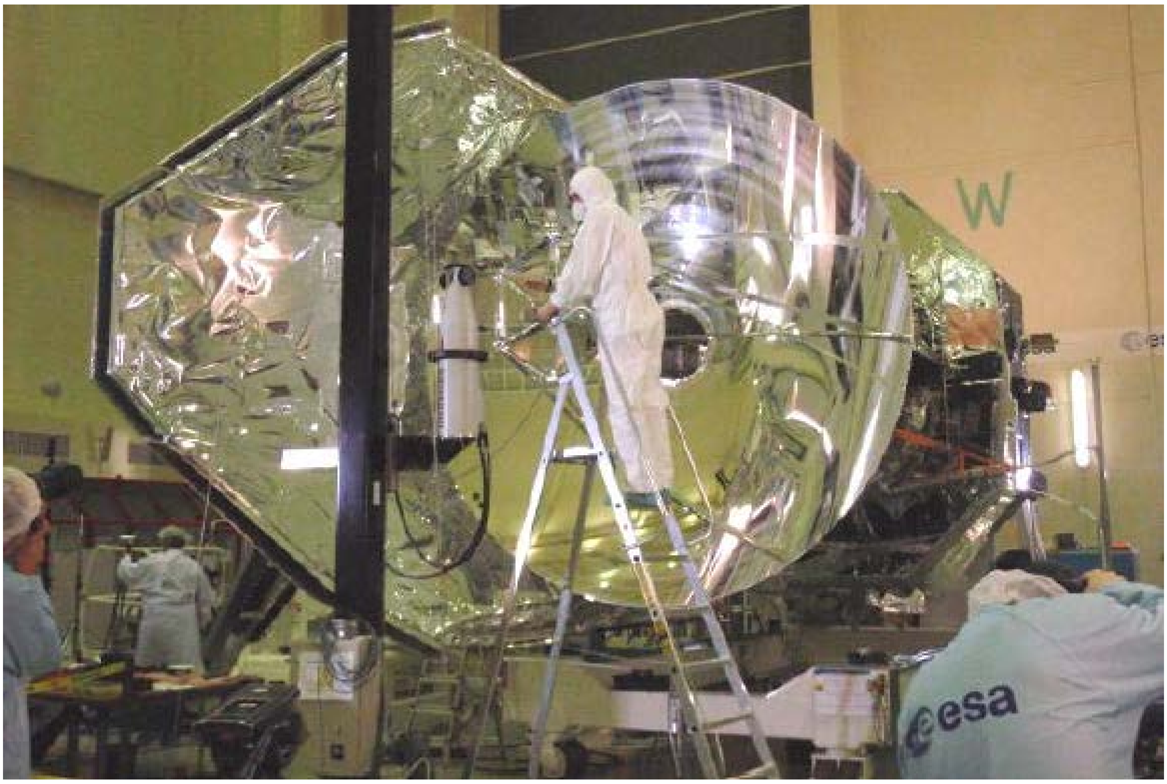


Figure E-3: Typical setup for alignment using laser tracker

The laser tracker measures distances and co-ordinates of points in space using its reference frame which is an ideal reference frame positioned in the middle of his head. This corresponds to the TRF mentioned in previous chapter. The combination of the measurement of several points can be used to derive the element and unit orientation and position within the instrument reference frame.

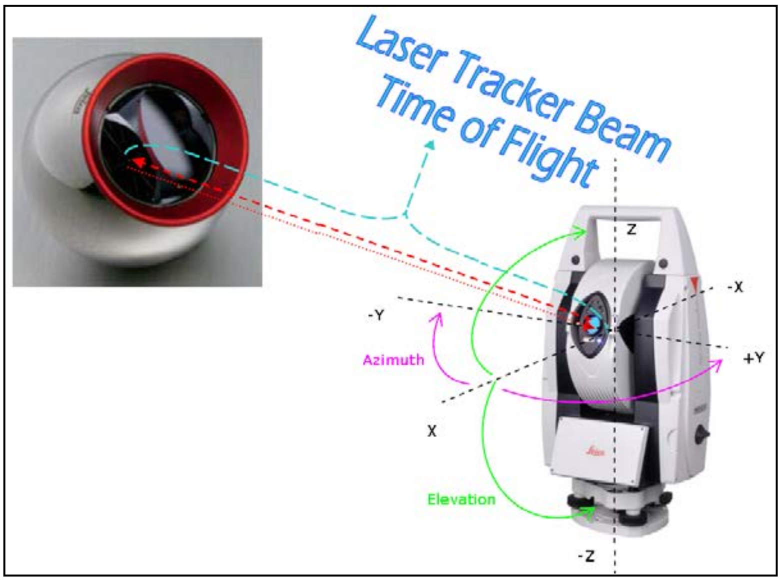


Figure E-4: Laser tracker axis and laser beam

Table E-1: Laser tracker typical performances

Range		
	Linear range	>100 m
System performance		
	Azimuth Range	±360°
	Elevation Range	better than ±60°
	Angular Resolution	better than ±0,07 arcsec
	Repeatability	±7,5 µm +3 µm/m
	Angular Accuracy	±15 µm +6 µm/m
	System Resolution	0,1 µm
	Maximum lateral target speed	6 m/sec
	Maximum acceleration	> 2 g
Accuracy		
	Static measurement (IFM)	±10 µm or 5 ppm (2 sigma)
	Inclination setting Accuracy	±1 arc sec.
Laser		
	Resolution	better than ±0,07 arc sec. 0,08 µm
	Accuracy	better than ±10 µm
	Repeatability	better than ±5 µm
Environmental		
	Dust/water	IP54 (IVC 60529)
	Operating temp.	-10 °C to> 45 °C
	Storage temp.	-10 °C to 60 °C
	Barometric press.	225 mmHg - 900 mmHg
	Relative Humidity	0 %-95 % non-condensing
	Working Range	0 m-25 m Typical
	Field of Vision	30° diagonal

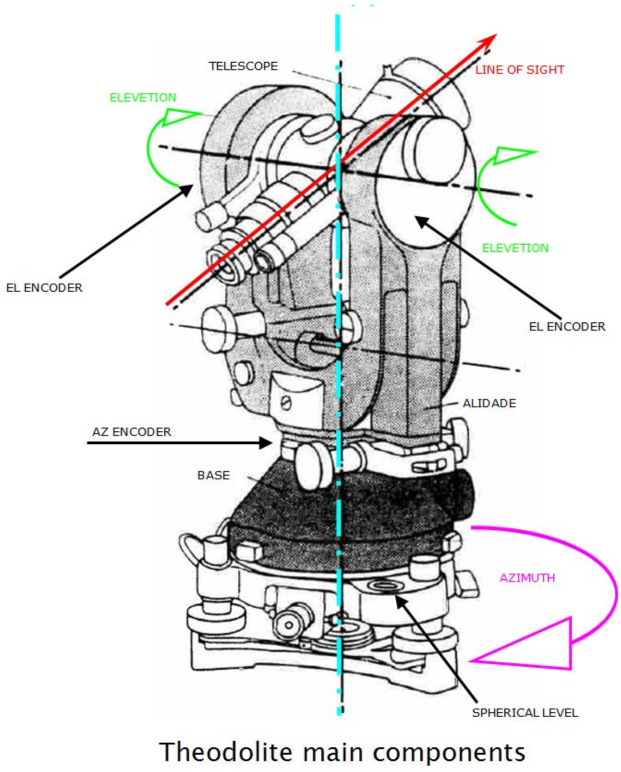


Figure E-5: Theodolites main components

E.3.1.3 Theodolite

During an alignment campaign the capability of measuring angles between cubes reflective surfaces is of fundamental importance to determine equipment line of sight directions. A minimum of 2 theodolites allow angle measurements with a very high precision. The typical instrument resolution is 0,5 arcsec and the typical angle measurement uncertainty (accuracy) is 10 arcsec, 2 sigma.

Figure E-6: Typical Theodolites

The alignment measurement with theodolites requires optical cubes as target. Those mirror cubes are attached to the equipment or element and are used to reflect the laser beam and allow for the measurement. These cubes are polished on five surfaces and coated with a durable protective aluminum mirror coating (sometimes single flat surfaces are used when only one direction is measured).

They are made in Zerodur/fused silica/stainless steel and other thermally stable materials and normally they have size from 10 mm up to 40 mm of edge.

The base of the mirror cubes can be bonded to pre-arranged mounts or equipped with threaded bushings.

Other devices can be used to support the measurement activity depending on the type of equipment to be aligned, like beam splitter (it allows dividing, recombining, and managing the directions of multiple beam paths), corner cube (also known as a retroreflector, which is an optical component with the unique ability to return an incoming beam of light directly towards its point of origin regardless of the beam's angle of entry).

Finally, fixtures to sustain the laser tracker and the Theodolites, tooling bar, tripods are also part of the set up for alignment

E.4 Test preparation

The alignment measurements at element level require sufficient space around the element to place theodolites, Laser tracker tripods and 'reference points' in accordance with the selected method (ref. to next para. 'Test Execution').

Alignment measurements performed using theodolites define angles with respect to the mirror cubes (See E.1). In case the master reference cube position has not been provided by the structure supplier (i.e. it is necessary to determine the element ARF with respect to the Element MRF), the Laser tracker can be used to determine the element Mechanical Reference Frame before the dedicated measurement via Theodolites and Laser trackers can take place. (see dedicated section: 'Cube to structure measurement')

Using theodolites or laser tracker, the test preparation consists in:

- tripod/tooling bar assembly and placement around test article
- mirror cubes or corner cube reflector installation on the equipment and element (if not pre-installed)
- external reference frame stations installation/building.
- Fencing of the measurement area

E.5 Test execution

E.5.1 Measurement with theodolites

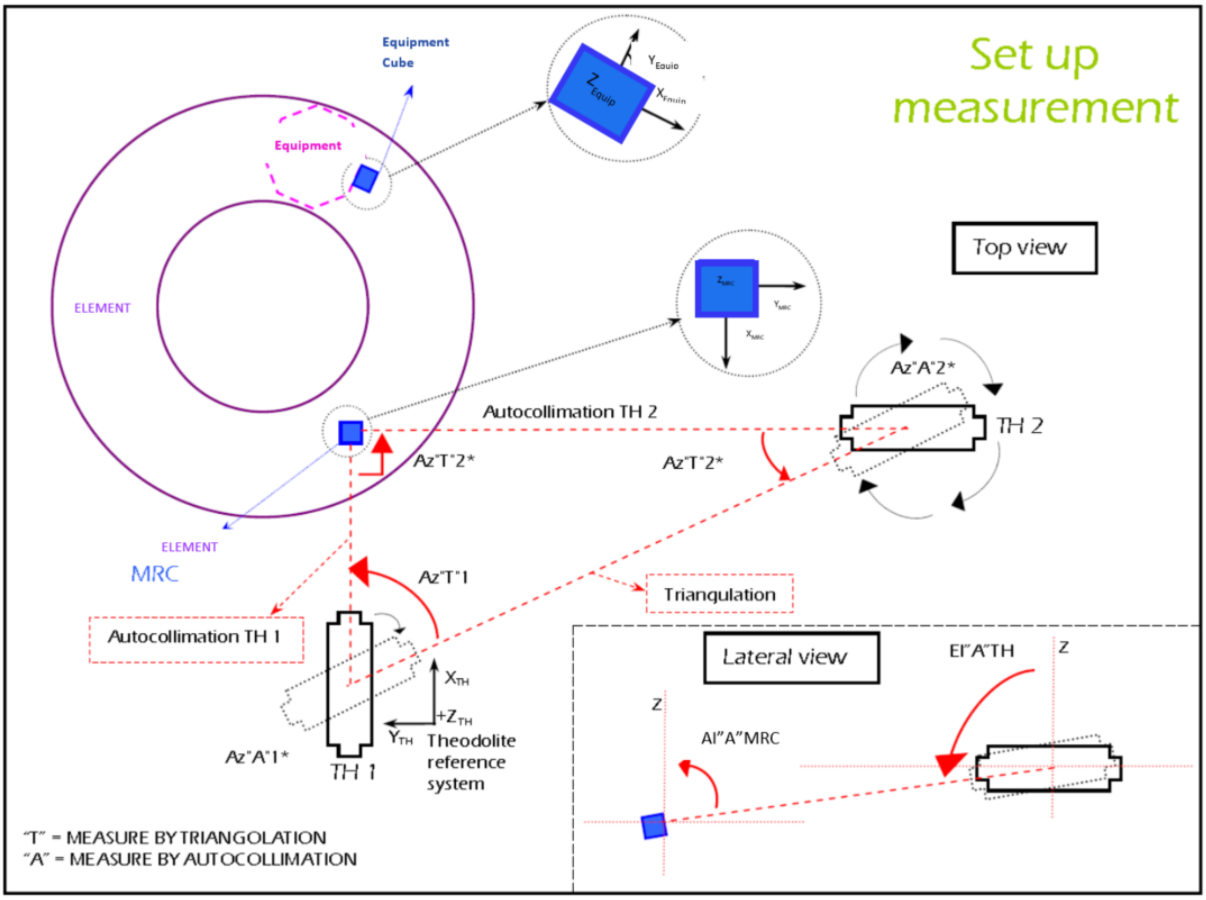


Figure E-7: Measurement setup with theodolites

The measurement is performed with at least 2 or preferably 3 theodolites

All alignment measurement by means of theodolites use the autocollimation method. by triangulation, the rotation matrix between each alignment reference frame is determined (see Figure E-7).

The theodolite identified as TH1 in Figure E-7 is used as reference for measurement and identifies the Theodolite Reference Frame (TRF).

Referring to the above Figure E-7, the following measurements will be performed:

1. Perform TH1 auto-collimation on MRC (including the measurement of the elevation, as per lateral view of Figure E-7)
2. Perform TH2 auto-collimation on MRC (including the measurement of the elevation, as per lateral view of Figure E-7)
3. Rotating TH1 and TH2 perform triangulation measuring AZ"T"1 and AZ"T"2* angles

All the above measurements (using trigonometric considerations) allow to obtain the set-up matrix and consequently its set-up rotation matrix $M^{-1}{}_{SU}$.

The relative orientation of another mirror cube (with respect to the Master Reference Cube) can be determined with the auto-collimation and triangulation method using a third theodolite (e.g. determine the relative orientation of the 'Equipment cube' w.r.t. the 'Element MRC' in the above figure) or properly moving theodolite TH2. Using trigonometric consideration and based on above performed measurement, it is possible to obtain the M_{cEQ} rotation matrix.

E.5.2 Element ARF (defined by the Master Reference Cube) to element MRF (structure) measurement

This type of measurement is used when the element ARF has to be defined with respect to the element MRF. In this case theodolite and laser tracker are used.

Two main steps can be identified:

- Laser tracker alignment with the element MRF
- MRC position determination.

Using a single laser tracker, the first step is to define some reference points (CP) to bound the position where the laser tracker is moved to measure the element structure; these CP's are reference points provided with spherical targets (re. to next paragraph). After this, the laser tracker is moved in dedicated station (STA) to measure the position of characteristic points (known by machining tolerances) of the element structure: Ref to below figure. These measurements allow to determine the Element MRF using the theoretical position of those points in the element MRF.

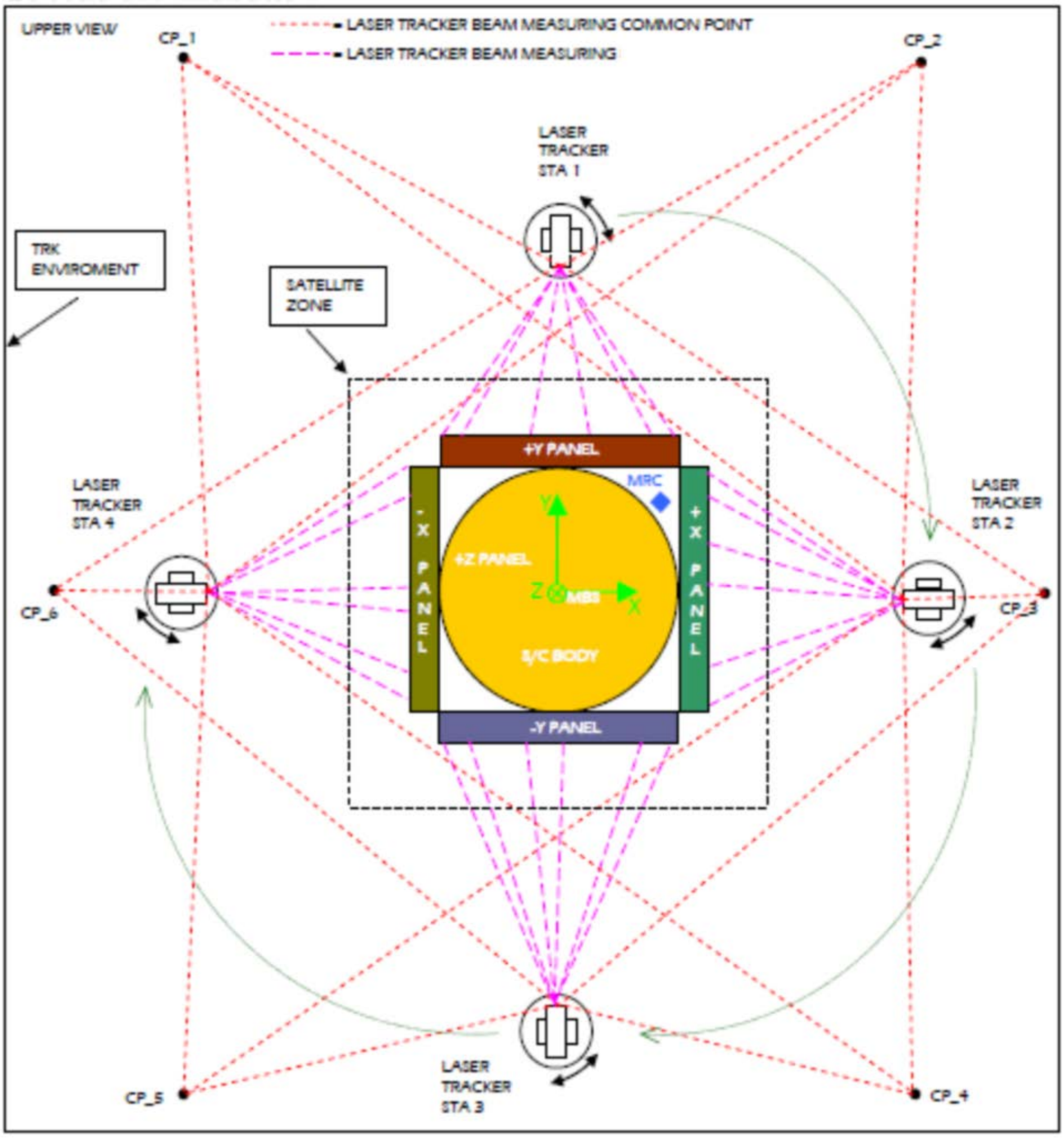


Figure E-8: Laser Tracker environment creation

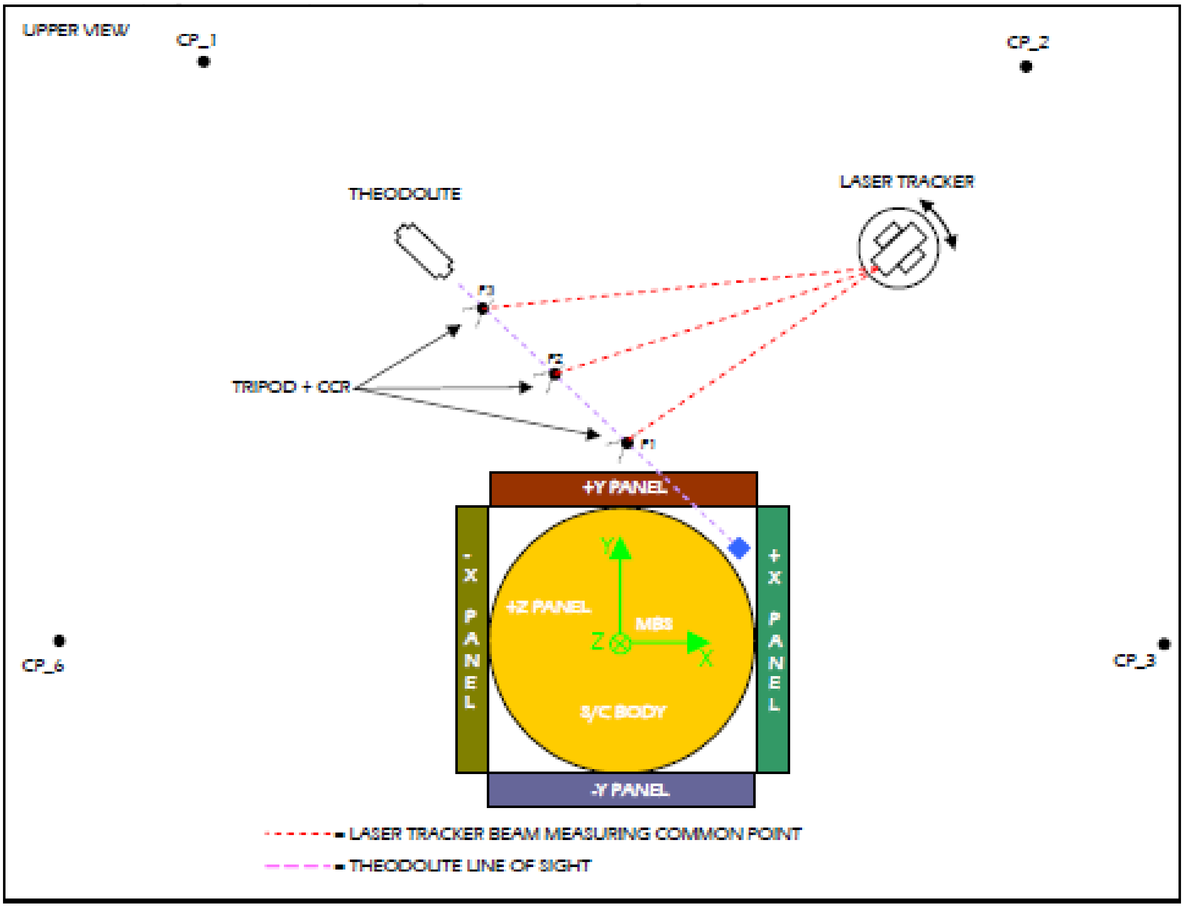


Figure E-9: Laser tracker (Aligned to MBS) measuring theodolite line of sight

After auto-collimation of a theodolite w.r.t the Master Reference Cube (not yet characterized) Y axis, it is possible to measure the theodolite line of sight direction in the element ARF. This is done moving a Corner Cube Reflector (CCR) positioned on a tripod along the theodolite line of site, each time the CCR is collimated to the theodolites and the CCR position is measured by the laser tracker (which position is known w.r.t. to element MRF using previous determined CP points). This procedure is repeated for the MRC X axis and the MCR Z face is determined with vector product, obtaining the rotation matrix MEL.

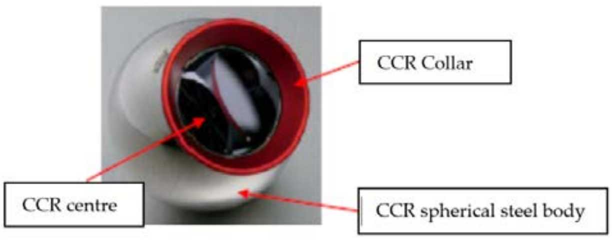


Figure E-10: Corner Cube Reflector

E.6 Test evaluation

As discussed in the previous paragraphs, alignment data from theodolites are reported in a dedicated file where all data acquired are post processed determining rotation matrices.

The rotation matrices allow the equipment orientation verification w.r.t. element reference frame or w.r.t. other equipment reference frame.

For what concern the laser tracker data acquisitions and processing, all inputs are collected by dedicated and validated software.

Either with theodolite or laser tracker, all alignment data are collected and summarized in a dedicated alignment test report.

E.7 Other alignment methodology

E.7.1 Photogrammetry

Photogrammetry can be used to verify alignment as well as shape measurement. Photogrammetry is also used for thermal distortion test and described in section A.11.4.3.

This kind of alignment consists in setting small targets on element to be measured and on reference points. By taking photos around the object, postprocessing algorithm allows to get 3D coordinates of these targets. The typical measurement uncertainties (accuracy) of this Method is around 1 part over 100000, i.e. 0,01 mm. at 68 % of probability (one σ) on a 1 m object.

This method is based on the triangulation principle and can be used for Alignment of equipment, Dimensional Checks, Planarity Tests, Analysis and Study of Deformations, Stability Check as example before and after mechanical vibration or during Thermal test (see dedicated section A.11.4.3).
The advantages using the photogrammetry are mainly the time reduction for stability check and the absence of contact with the article under measurement.

As general set-up, the object under measurement is equipped with optical targets. Camera(s), depending on the measurement to be performed, take pictures all around the object itself.

The instrumentation used is a Photogrammetry Camera + its accessories, Coded Targets and scale bars. A specific software is used for data processing.

Nominally the setup is implemented through the following steps:

- Photogrammetry camera positioning
- Coded target positioning,
- Auto-bar positioning
- Scale-bar positioning
- Measurements around the object
- First elaboration for bundle check.

There are other techniques for 3D scanning like:

Stereo photogrammetry (based on use of two or more high resolution digital cameras) having the following accuracies: single point measurement uncertainties (accuracy) up to 60 µm (2 σ), volumetric measurement uncertainties (accuracy) up to 90 µm (2 σ)
Laser Radars having a 3 D measurement uncertainties (accuracy) of 16 µm at 1 m, 100 µm At 10m and 240 µm at 24 m (2σ - Typical data specifications of Metris Laser radar)

Annex F
List of test bench names

This section provides an unsorted list of legacy or historical test bench names. This list does not imply any guidelines for test benches use during Space Element functional testing and verification. The mapping to the used model definition in this handbook would be:

- Numerical Bench is corresponding to Virtual Model (no HW model)
- Hybrid Bench is corresponding to Electrical Functional Model ("the only" hybrid model)
- HW bench is corresponding to PFM/FM models

Table F-1: List of legacy/historical test bench names

Abbre-viation	Test Bench Name	Type	Configuration	Main Use Case
SDE	S/W Development Environment	Numerical bench	dedicated SW, e.g. Code Development Environment like C++, others	SW development
ADVE	AOCS Development & Verification Environment	Numerical bench	dedicated SW, e.g. Matlab/Simulink	AOCS verification
FVB	Functional Validation Bench	Numerical bench	CCS+RTS+stubbed models+AOCS SW or CSW	AOCS verification
NSVF	Numerical Software Validation Facility	Numerical bench	dedicated (simple) CCS+RTS+CSW	CSW verification
SVF-DEV	Software Verification Facility-Development	Numerical bench	dedicated (simple) CCS+RTS+CSW	CSW verification
SVF	Software Verification Facility	Numerical bench	CCS+RTS+CSW	test development & partially verification
SysTF	System Test Facility	Numerical bench	CCS+RTS+CSW	test development & partially verification
SVF-SAT	Software Verification Facility - Satellite	Numerical bench	CCS+RTS+CSW	test development & partially verification
SatSim	Satellite Simulator	Numerical bench	CCS+RTS+CSW+G/S models, i.e. configuration exceeds the perimeter of the name	test development & partially verification
SimAIT	Simulator AIT	Numerical bench	CCS+RTS+CSW+EGSE /SCOE models	test development & partially verification
HSVF	HW Software Verification Facility	Hybrid Bench	OBC BB/EM+CCS+RTS+CSW	OBC model calibration, OBC HW compared to OBC simulation model
Tracer	I/F Traxer	Hybrid Bench	stubbed CSW+PL HW EMs	early Payload IF verification

Abbre-viation	Test Bench Name	Type	Configuration	Main Use Case
PISA	Payload Interface Simulator Assembly	Hybrid Bench	stubbed CSW+SimFE+PL HW EMs	early Payload IF verification
IS	Interface Simulator	Hybrid Bench	stubbed CSW+SimFE+PL HW EMs	early Payload IF verification
SimEFM	Simulated EFM	Hybrid Bench	TBD HW EMs+CCS+RTS+CSW	test development & partially verification, especially new HW or PL
EFM Light	Electrical Functional Model Light	Hybrid Bench	OBC EM+CCS+RTS+CSW	test development & partially verification
RTB	Real Time Testbed	Hybrid Bench	OBC EM+RIU EM+CCS+RTS+CSW	test development & partially verification
AVB	Avionics Verification Bench	Hybrid Bench	OBC EM+TBD HW EMs+CCS+RTS+CSW	test development & partially verification particularly of the avionics
ETB	Engineering Test Bench	Hybrid Bench	OBC EM+TBD HW EMs+CCS+RTS+CSW	test development & partially verification particularly of the avionics
EFM	Electrical Functional Model	Hybrid Bench	OBC EM+TBD HW EMs+CCS+RTS+CSW	test development & partially verification
FlatSat	Flat Satellite	Hybrid or HW bench	OBC EM/PFM/FM+TBD HW EMs/PFMs/FMs+CCS+RTS+CSW	test development & partially verification
PFM	Proto Flight Model	HW bench sometimes Hybrid Benches	OBC PFM+all equipment HW PFMs+CCS+CSW+EGSE/SCOE+optinal RTS	Verification
FM	Flight Model	HW bench sometimes Hybrid Benches	OBC FM+all equipment HW FMs+CCS+CSW+EGSE/SCOE+optinal RTS	Verification

Annex G
Referenced documents

The following referenced documents will be made available after publication from the ECSS Website along with this ECSS Handbook: *NOTE: embedded files are only available in the WORD file*

ATS paper_MATED Improvement (October 2018)	MATED (Model And Test Effectiveness Database) Improvement and Added Value on Industry	ATS paper_MATED Improvement.pdf
MTF.AIDT.TN.2168, Issue 1, Rev.1 (3 March 2020)	Dynamited Final Report	Dynamited final report.pdf
ECSSMET 2016 (article)	DYNAMIC TESTS, WHAT'S BEHIND THE CURVES ?	ECSSMET 2016 article What s behin
MSG-NNT-SE-TN-0742 (28 October 1996)	Notching guidelines for mechanical test	MSG_MMT_SE_TN_0742_Notching Guide
TASI-ASE-ORP-0006_Iss.01 (20 October 2014)	Analysis of Spacecraft qualification Sequence & Environmental Testing (ASSET)	TASI-ASE-ORP-0006_Iss.01.pdf
TASI-ASE-ORP-0009_01 (3 October 2016)	Analysis of Spacecraft qualification Sequence & Environmental Testing (ASSET+)	TASI-ASE-ORP-0009_01.pdf