IMPRS Lectures on SPACE INSTRUMENTATION

25-29 October 2010

MPS , Katlenburg-Lindau :

Space Instrument Development

(based on lecture by Hermann Hartwig, Dec. 2006)

Reinhard Meller, MPS

After winning the proposal selection

it usually takes about 8 years for a major instrument up to launch .

Examples :

SOHO (ESA solar cornerstone mission)

instrument selection : 1988 ⇨ launch : Dec 1995

ROSETTA (ESA planetary cornerstone mission)

instrument selection : 1995 ⇨ launch : Mar 2004

W H Y ?

Commercial off-the-shelf (COTS) instruments usually will not work for space because they

- are too heavy
- will not survive the launch loads
- will stop functioning under space conditions:

space is a very hostile environment !

A closer look at :

- **mass :** why it is important

SOHO :	scientific instruments accumulated	= 610 kg
	spacecraft mass at launch	= 1850 kg
	launcher mass	= 237 500 kg
	launch cost ATLAS II AS	= 72 000 000 €
	specific launch cost for instrument :	118 000 €/kg
ROSETTA:	scientific instruments accumulated	= 186 kg
	spacecraft mass at launch	= 2900 kg
	launcher mass	= 760 000 kg
	launch cost ARIANE 5	= 100 000 000 €
	specific launch cost for instrument :	537 634 €/kg
	[for comparison : price of gold (Au) :	17 500 €/kg]

A closer look at :

- **total launch support mass / scientific payload mass ratio:**

SOHO : (237 500 + 1850 - 610) kg / 610 kg = 391

ROSETTA: (760 000 + 2900 - 186) kg / 186 kg = 4101

ratio depends on space mission trajectory

=> Scientific instrument mass saving is an important issue!

A closer look at :

- **launch loads :** why they are important

  for smaller instruments the Design Loads can be as high as 60 x gravity (60g)

  for larger instruments (> 50 kg) still 25 x gravity

  => Design must have : low mass ; high strength !

- **hostile space environment**
  - high vacuum
  - zero-g
  - radiation (electromagnetic & energetic particles)
  - very low temperatures to dark space background
  - extremely high thermal loads on sun illuminated side (e.g. Solar Orbiter)

examples for unusual effects, occuring in space environment :

- high vacuum cleans metallic surfaces ⇨ cold welding of moving part
  design shall avoid metal-to-metal contacts !
- usual liquid lubricants evaporate in vacuum ⇨ bearings seize
  use vacuum-compatible dry lubrication films !
- energetic particles passing through semiconductor devices create charge clouds ⇨ bit flips in memory cells (SEU single event upsets)
  implement hardware error correction function into design !

  or –worse- create conductive channels in insulating layers between power conductors ⇨ self-sustaining short circuit (latch-up effect)
  implement latch-up protection circuits into design !
- high vacuum : no convective cooling for electronics ⇨ electronics overheat
- zero gravity : gravity assisted heatpipes don‘t work ⇨ “
  careful design of conductive/radiative heat transfer !
- high vacuum : outgassing of organic materials; EUV “cracking“ of molecular deposits on cold surfaces (detectors, optics) ⇨ carbon black blinding
  careful material selection ; cleanliness control program !

For all these reasons

- space instruments are custom-designed one-of-a-kind items
- building these unique instruments follows a universal pattern :
  - staged development with milestone peer reviews
  - succession of models with increasing complexity and level of detail

Instrument Development Cycle : overview

- **Preliminary Design (Phase A), ends with:**

  Preliminary Design Review (PDR)

  hardware delivery : STM Structural / Thermal Model

- **Detailed Design (Phase B) , ends with:**

  Critical Design Review (CDR)

  hardware delivery : EM Electrical or Engineering Model

- **Flight Hardware Manufacturing (Phase C)**

- **Assembly/Integration/Verification - AIV (Phase D) ,**

  optional with mid-term Test Readiness Review (TRR); ends with :

  Flight Acceptance or Pre-Shipment Review (FAR / PSR)

  hardware delivery : FM Flight Model(s) + FS Flight Spare Model

A : Preliminary Design Phase :

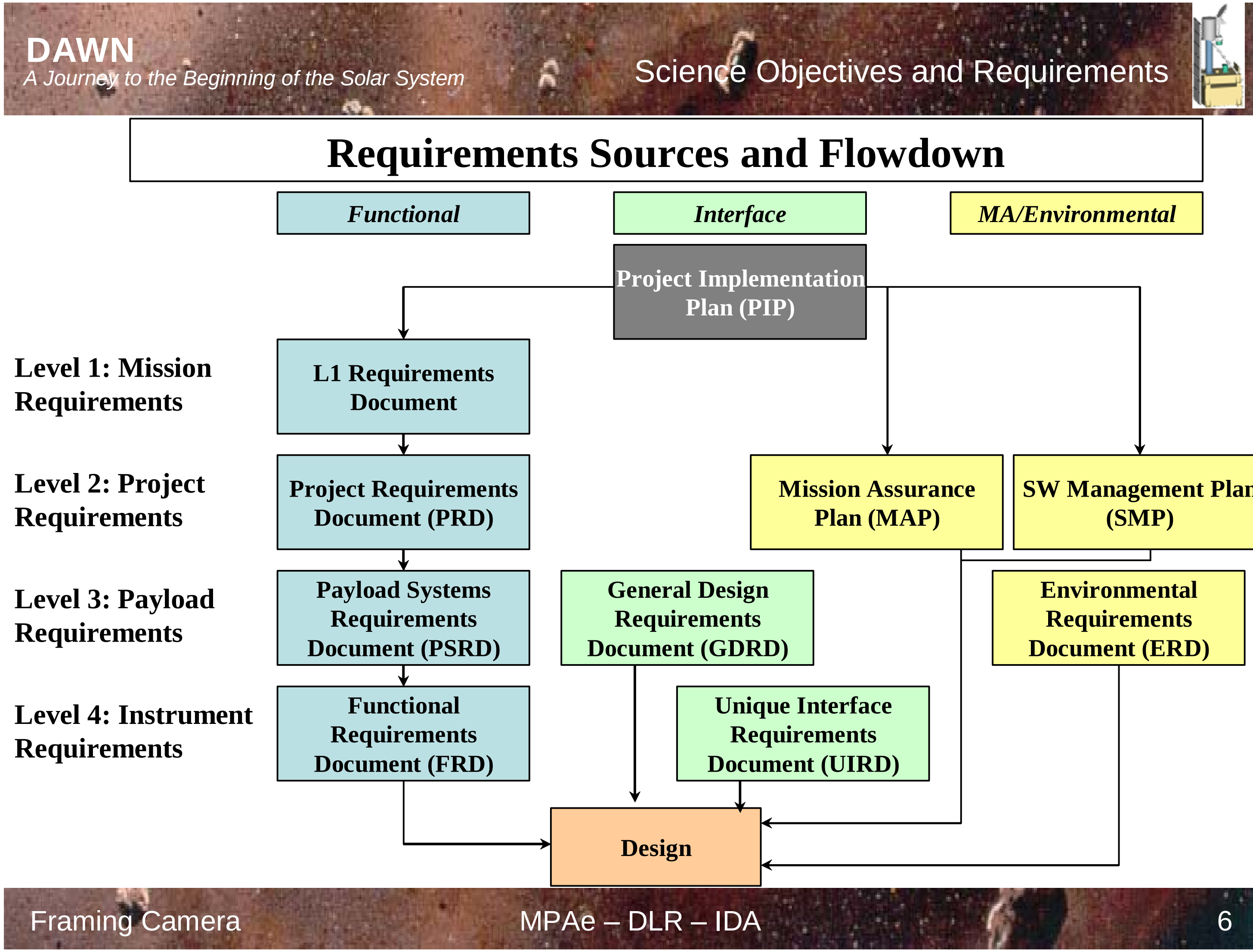
- **establish requirement flowdown : from mission requirements to payload requirements to instrument functional requirements to instrument specification**
- **allocate mass and power budgets to subsystems**
- **define mechanical and electrical interfaces between subsystems**

  (e.g. form factors for PCBs, connector types and arrangement etc)
- **determine dimensions, volumes, shapes**
- **write specifications for subsystems, that will be subcontracted to industry**
- **assemble STM (form, fit, no functions) = mass and thermal “dummy“**

- ⇨ **Preliminary Design Review ; STM delivery**

example:

requirement flowdown diagram for DAWN Framing Camera

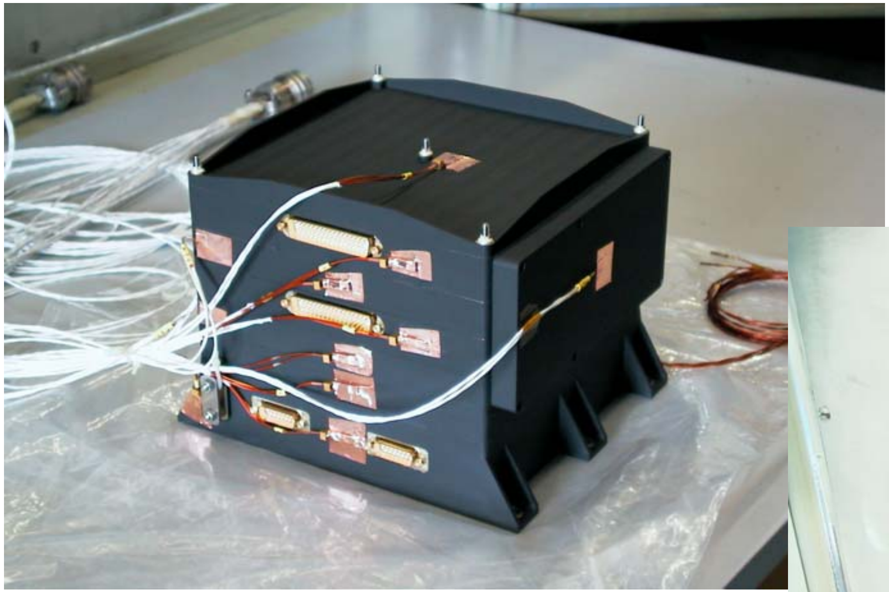


A : ROSETTA / OSIRIS STM examples:

- Electronics Unit & CRB Unit assembly

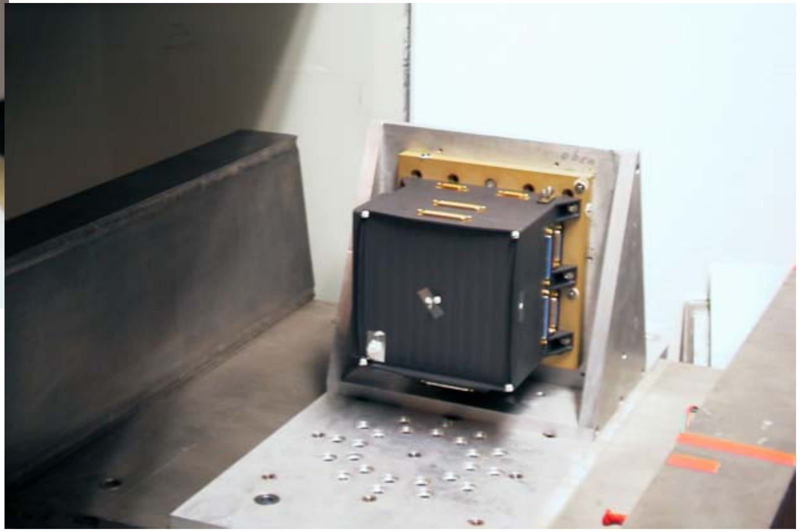
cont. A : ROSETTA / OSIRIS STM examples:

- Electronics Unit prepared for thermal balance test



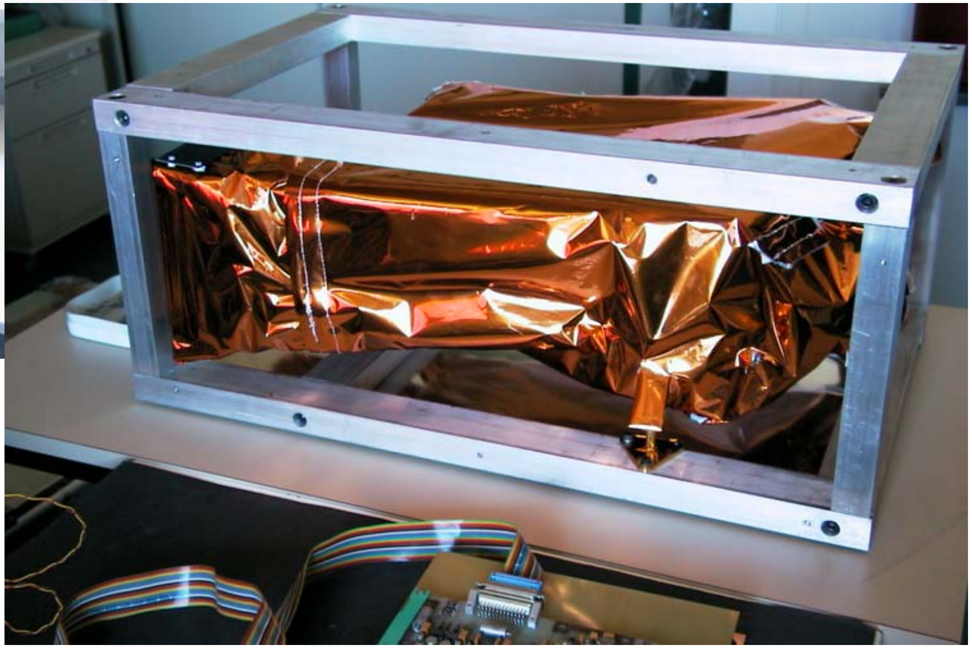
cont. A : ROSETTA / OSIRIS STM examples:

- **Electronics Unit sine vibration and static load test**



cont. A : ROSETTA / OSIRIS STM examples:

- **NAC & WAC STM delivery preparation**

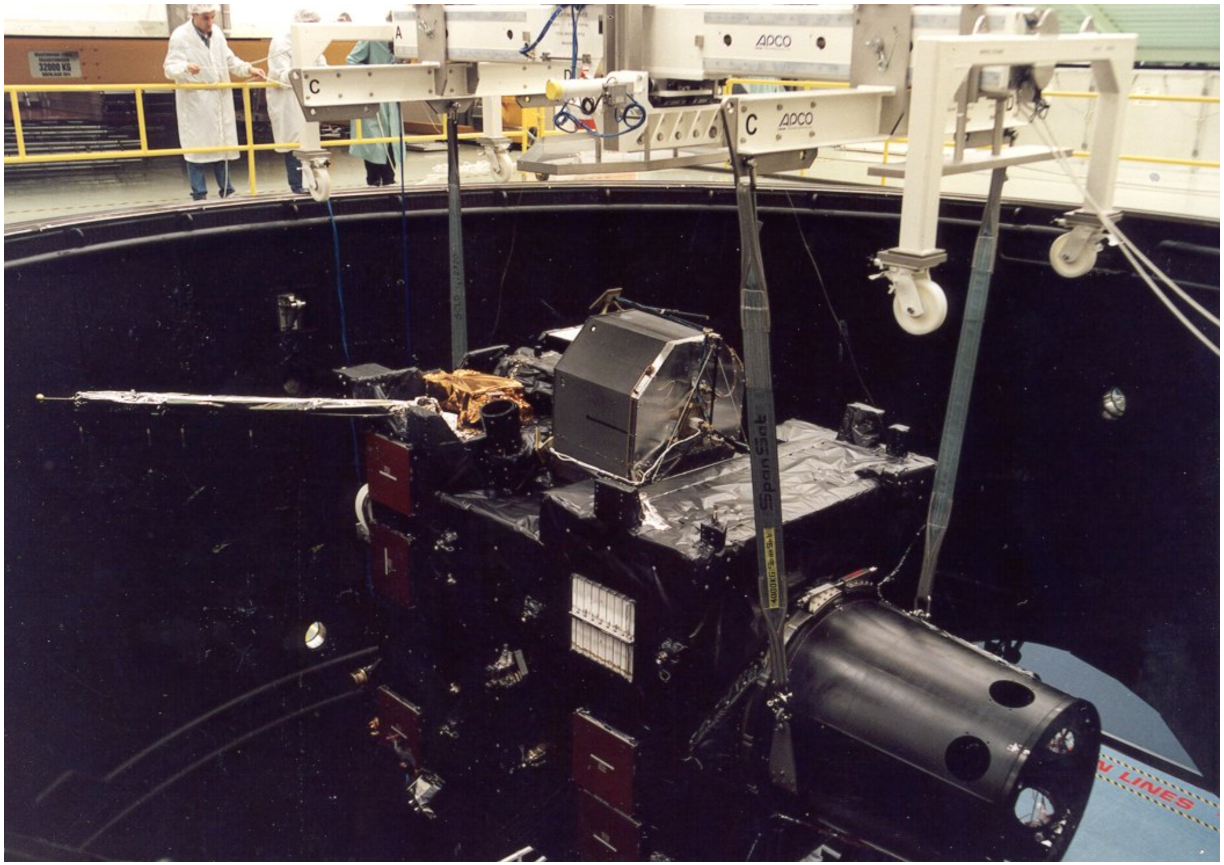


cont. A : ROSETTA / OSIRIS STM examples:

- **NAC STM delivery to ESA and integration onto ROSETTA STM S/C**

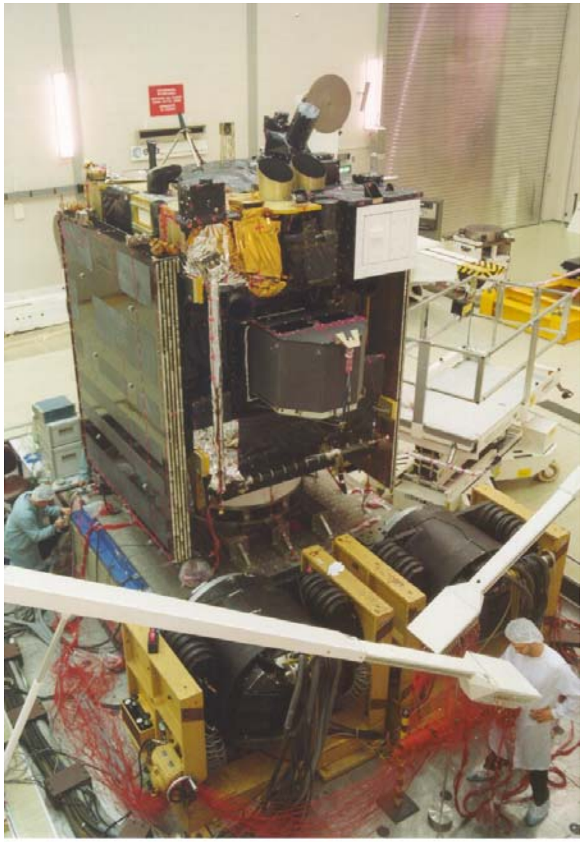
cont. A : ROSETTA / OSIRIS STM examples:

- OSIRIS STM integrated on ROSETTA for thermal verification test



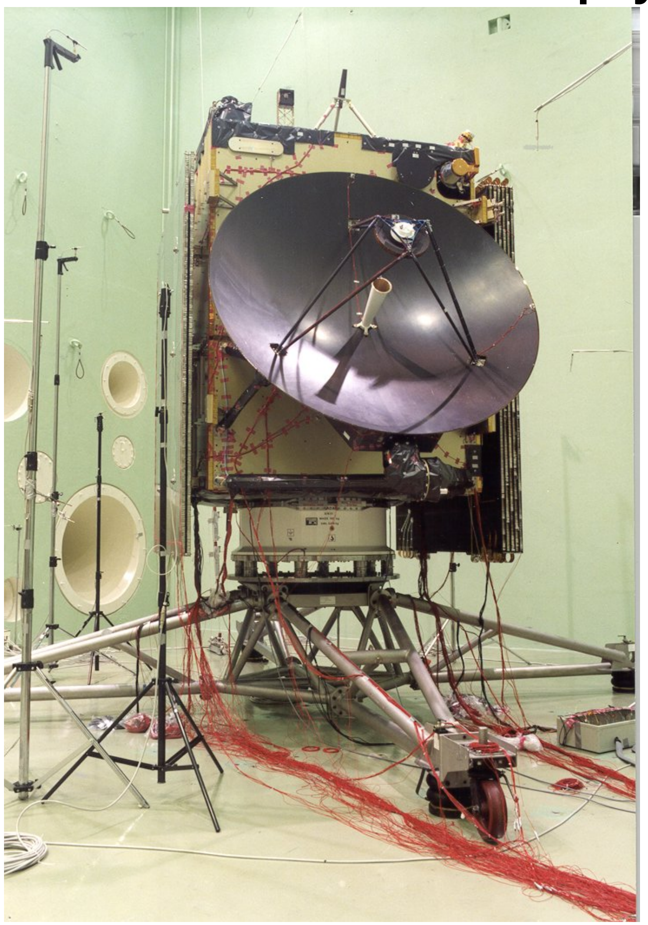
cont. A : ROSETTA / OSIRIS STM examples:

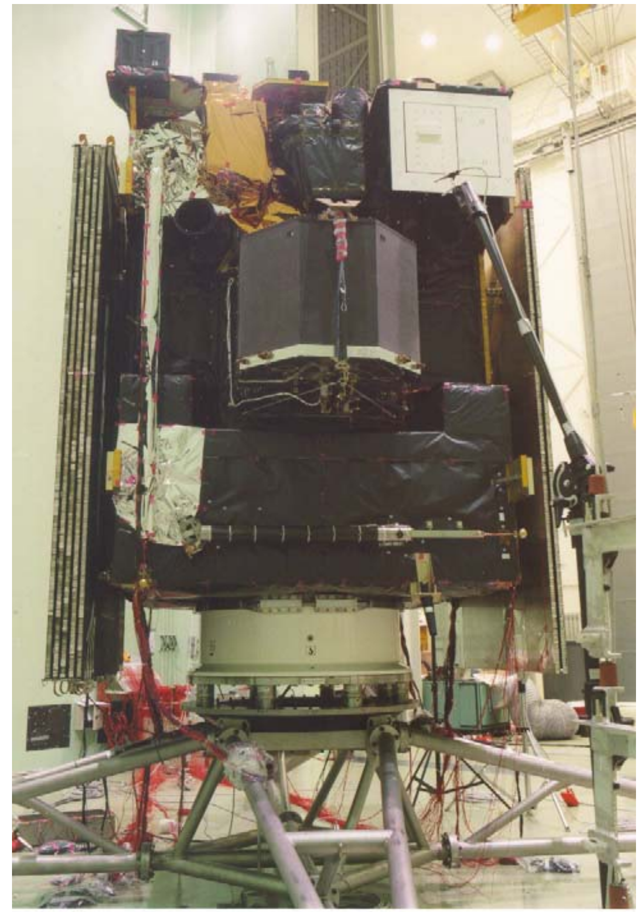
- ROSETTA STM S/C incl. STM payload instr. prepared for vibration testing



cont. A : ROSETTA / OSIRIS STM examples:

- **ROSETTA STM incl. STM payload instruments acoustic noise test setup**





B : Detailed Design Phase :

- define / select materials and processes
- design parts , select components
- write basic operational code / software
- generate mathematical models for:
  - structural analysis (Finite Element Model)
  - thermal analysis

  validate models and pass on to S/C contractor (to be included into their global model)
- perform Failure Modes, Effects and Criticality Analysis (FMECA)
- assemble EM (form & fit as good as possible, all functions; components not space rated); verify functionality and interfaces (power / command & telemetry)
- ⇨ Critical Design Review ; EM delivery

Example :

Design reviews :

Agenda for the

Critical Design Review

Framing Camera DAWN mission

DAWN
Framing Camera (FC)
Critical Design Review - CDR
May 18 & 19, 2004

MPAe, Katlenburg-Lindau, Germany

Tuesday May 18, 2004

09:00 Welcome and Introduction – H. U. Keller

09:10 Goal of the Meeting – D. Norris

09:20 DAWN Project Status – C. Russell

09:30 Overview FC – Science Objectives and Requirements - H. U. Keller

09:50 FC Team Organigram and Top Level Workpackages – H. Sierks

10:00 Instrument Concept and Implementation – H. Hartwig

10:15 **Coffee Break**

Camera Head
10:30 Optical Design – H. Mosebach/K-T
10:45 Lens System, Filters, Baffle and related Analysis – H. Mosebach/K-T
11:00 CCD and Front End Electronics – S. Mottola
11:20 Front Door Mechanism and Fail Safe Mechanism - H. Hartwig
11:30 Filter Wheel Mechanism – H. Hartwig

11:45 Discussion

12:00 **Lunch Break**

Electronics Box
13:00 Electrical Interfaces Block Diagram & Grounding Concept – I. Hejja
13:10 Data Processing Unit and Mass Memory – H. Michalik/IDA
13:30 Power Converter Unit – R. Enge
13:45 Mechanism Controller Unit – W. Kuehne
14:00 Housekeeping Data Acquisition – I. Hejja

14:15 FC Heater Concept - H. Sierks

Resources
14:30 Power Breakdown – H. Sierks
14:40 Mass Breakdown – H. Hartwig
14:50 MICD & Accommodation – H. Hartwig

15:00 **Coffee Break**

Instrument Modelling
15:15 Structural Design – H. Hartwig
15:30 Thermal Design – H. Hartwig with H. P. Schmidt/DLR

Software
16:00 Low Level Software - H. Michalik/IDA
16:10 Operation Software – H. Michalik/IDA

16:30 EGSE Configuration and Software – H. Michalik/IDA

16:45 EM demonstration run in room S1-49

Wednesday May 19, 2004

09:00 Model Philosophy and Schedule – H. Sierks

09:20 Qualification Approach and Environmental Test Matrix – H. Sierks

09:30 QA Approach and Status – M. Richards

09:45 Operations Plans – P. Gutierrez

10:00 Calibration Plans – K. Schneider

10:15 **Coffee Break**

10:30 FC Data Processing Approach – R. Jaumann

10:50 Risk Mitigation Plan – H. Sierks

11:00 Review of PDR RFAs – H. Sierks

11:30 Discussion

12:00 **Lunch Break**

13:30 Board Summary, Action Items, and Wrap-up

17:00 Adjourn

Splinter Meetings as required.

Board Members:

Dave Norris (Chairman)
Fred Vescelus
John Schlue
F. Gliem
K. Wilhelm

Attendees List:

UCLA
Chris Russell
Steve Joy

JPL
Ed Miller
Betina Pavri
Khanara Ellers
Paul Hesse
Carol Polanskey
Jerry Dalton

Orbital
Mike Violet

MPAe

Example :

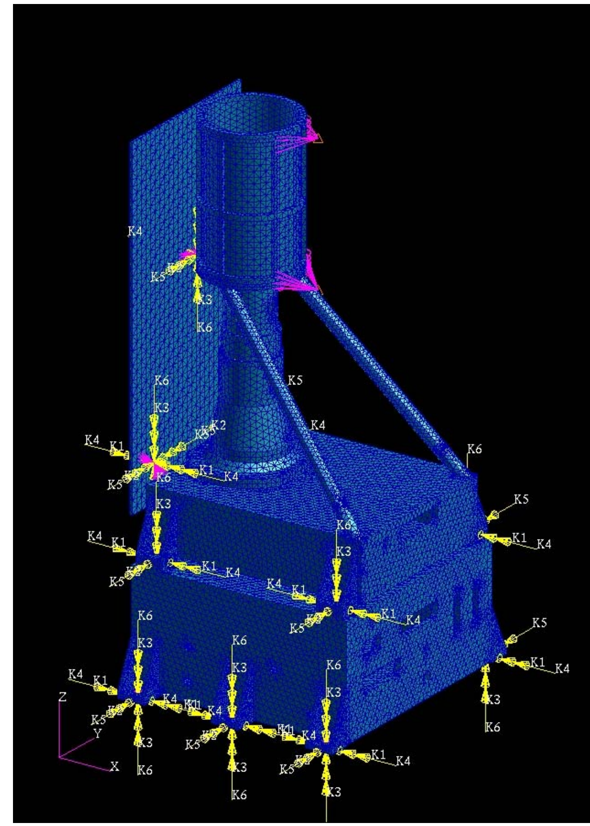
structural mathematical model

Finite Element Analysis

Framing Camera on the DAWN mission

Finite Element Analysis : Modelling

model anlyzed with :
  MSC NASTRAN
pre-/post-processing with :
  MSC PATRAN
element type used :
  TET10(3D)
element size :
  4mm global edge length,
  smaller in critical areas
model size :
  153 715 elements
  288 605 nodes
  78 spring elements
  22 multi-point constraints

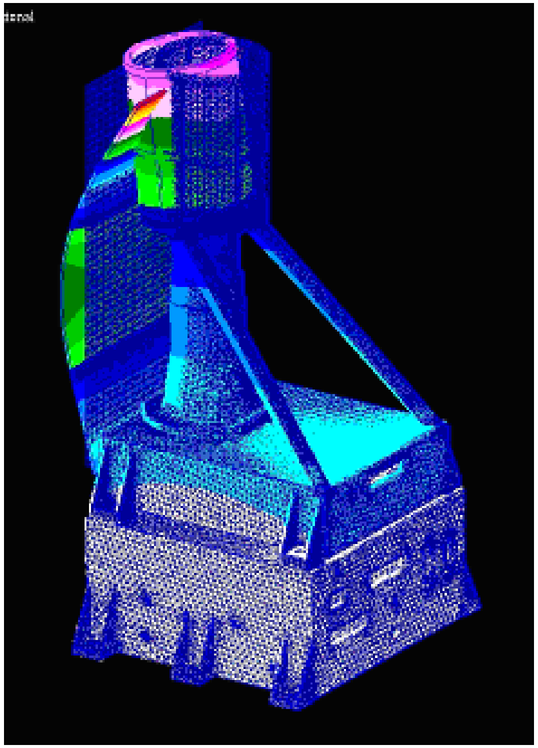


Example:

Finite Element Analysis cont‘d:

Finite Element Analysis : Dynamics : 3rd Eigenmode

Mode Nr.	Frequency in [Hz]	Remarks
1	353.48	bending of mainly the radiator but also the baffle around y-axis
2	377.18	swinging of tubus/baffle in y-direction (and bending around x-axis)
3	414.42	swinging of tubus/baffle in x-direction (and bending around y-axis)
4	447.40	bending of the radiator around z-axis
5	670.00	longitudinal vibration of the structure in z-direction
6	737.16	bending of the baffle around y-axis
7	813.82	local vibrations
8	937.80	2nd mode for swinging of tubus/baffle in y-direction
9	990.14	longitudinal vibrations in z-direction
10	1049.16	bending of radiator around y-axis



Example :

thermal mathematical model

Finite Difference Analysis

(ESATAN/ESARAD)

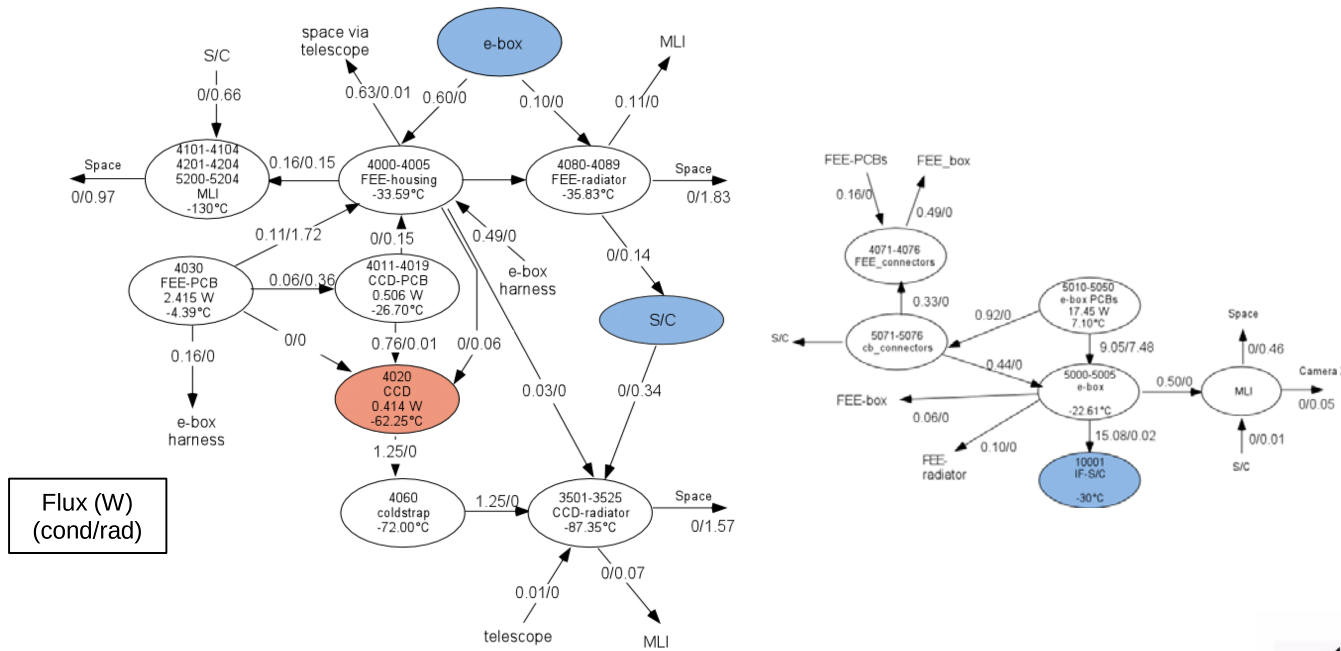
Framing Camera on the DAWN mission

Dawn Framing Camera

Thermal Control Subsystem

Steady State Analysis - Operations (continued)

- Results : cold case heat fluxes from CCD and adjacent nodes to space



H.P. Schmidt, DLR, Institute of Space Simulation - DAWN FC CDR, 2004-05-18 & 19

16

DLR

Example :

Delivery reviews :

Documentation to be ready before instrument H/W delivery

- **Preliminary Design Review (STM)**
- **Critical Design Review (EM)**
- **Flight Acceptance Review (FM, FS)**

OSIRIS Camera System on ROSETTA

OSIRIS

Reference: RO-RIS-
Issue: Rev.:
Date:
Page:

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C / D :Assembly / Integration / Verification :

- Controlled and documented flight parts production & procurement; population of Printed Circuit Boards; in Clean Room ; ESD protected etc
- Testing at subsystem and system level:
  - Functional tests , including S/C interface verification (with S/C simulator)
  - Performance Tests / Calibration
  - Environmental tests :
    - Vibration
    - Pyro-Shock
    - Thermal-Vacuum / Thermal- Balance
    - Mechanism Lifetime
    - Electro-Magnetic Compatibility (EMC)
  - Physical properties
    - Interface Metrology
    - Mass
    - Center of Gravity
    - Moments of Inertia

Example: OSIRIS E-Box Module Test Philosophy and Test Matrix

Test item	*QM*	*STM*	*EEM*	*FM*	*FS*	*responsible*
Physical Properties (COG, Mass, Dimensions)	**M** / X	X	**M** / X	**M** / X	**M** / X	All / MPAE
Vibration	Q	Q	---	A	A	All / MPAE
Shock	Q	(Q)	---	---	---	All / MPAE
Acoustic Noise	tbd.	(X)	---	---	---	All / MPAE
Thermal Balance	**M** / X	X	X	---	---	All / MPAE
Thermal Vacuum	Q	---	---	A	A	All / MPAE
Mechanical Functional	**M** / X	**M** / X	**M** / X	**M** / X	M / X	All / MPAE
Electrical Functional	**M** / X	---	**M** / X	**M** / X	**M** / X	All / MPAE
Optical Functional	---	---	---	---	---	---
Electrical Test (Grounding, Bonding, Isolation)	**M** / X	---	**M** / X	**M** / X	**M** / X	All / MPAE
EMC (Conducted and Radiated Interference)	**(M)** / X	---	---	X conducted only	X conducted only	All / MPAE
DC Magnetic Properties	**(M)** / X	---	---	X	X	All / MPAE
Alignment	---	---	---	---	---	---
Calibration	**M** / X	---	**(M)**/(X)	**M** / X	**M** / X	All / MPAE

Models:
- QM: Qualification Model — not delivered to ESA
- STM : Structural Thermal Model
- EEM : Electrical Engineering Model
- FM : Flight Model
- FS : Flight Spare Model

(STM, EEM, FM, FS: build by MPAE, delivered to ESA)

Module Tests, to be performed at the responsible institutes or manufacturers prior E-Box integration:
- M : Required, no specific test level
- ( ) : Desirable

Instrument Tests (Modules integrated in E-Box), to be done at MPAE or testhouse, supported by the responsible institutes:
- Q : Qualification Level
- A : Acceptance Level
- X : no specific test level
- ( ) : Desirable
- --- : Not Required

Vibration testing :

simulates launch loads (structural and acoustic)

power of ARIANE-5 at launch = 30 million h-p ; acoustic pressure level ~145 dB !

Test :

on electrodynamic shaker systems: giant “loudspeaker“ coil drive , w/o membrane

sine test : swept single frequency ; control = peak acceleration

random test: wide-band random “noise“ spectrum; control = power spectral density profile

SIR-2 Sine qualification levels (TBC by ISRO)
for O-Box ; on ASS panel extension

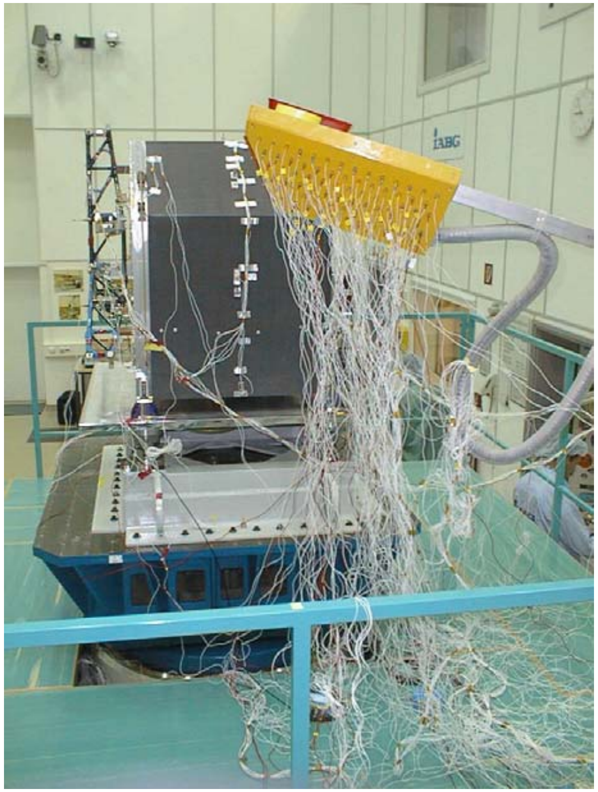
frequency	in-plane (X and Y)	frequency	out-of-plane (Z)
5 Hz to 20 Hz	9.3 mm(0-p)	5 Hz to 18 Hz	11.5 mm(0-p)
20 Hz to 70 Hz	15 g const.	18 Hz to 50 Hz	30 g const.
70 Hz to 100 Hz	8 g const.	50 Hz to 70 Hz	20 g const.
		70 Hz to 100 Hz	15 g const.
sweep rate	2 oct/min		2 oct/min

SIR-2 Random qualification levels (TBC by ISRO)
for O-Box ; on ASS panel extension

frequency	in-plane p.s.d. (X and Y axis)	out-of-plane p.s.d. (Z axis)
20 Hz to 100 Hz	+ 3 dB/octave	+ 3 dB/octave
100 Hz to 700 Hz	0.1 g^2/Hz	0.3 g^2/Hz
700 Hz to 2000 Hz	- 3 dB/octave	- 6 dB/octave
RMS level	11.8	18.2 g

Example : **ROSETTA Lander STM** on shaker at IABG, Munich

measurement accelerometer wiring



Thermal Vacuum / Thermal Balance Test :

tests thermal behaviour in special test chambers under space conditions

(high vacuum ; cold space ; solar illumination / planetary thermal emission)

passive protective systems:

- Multi-Layer Insulation (MLI) ;
- thermal radiators / absorbers
- second-surface mirrors (reject heat against solar irradiation)

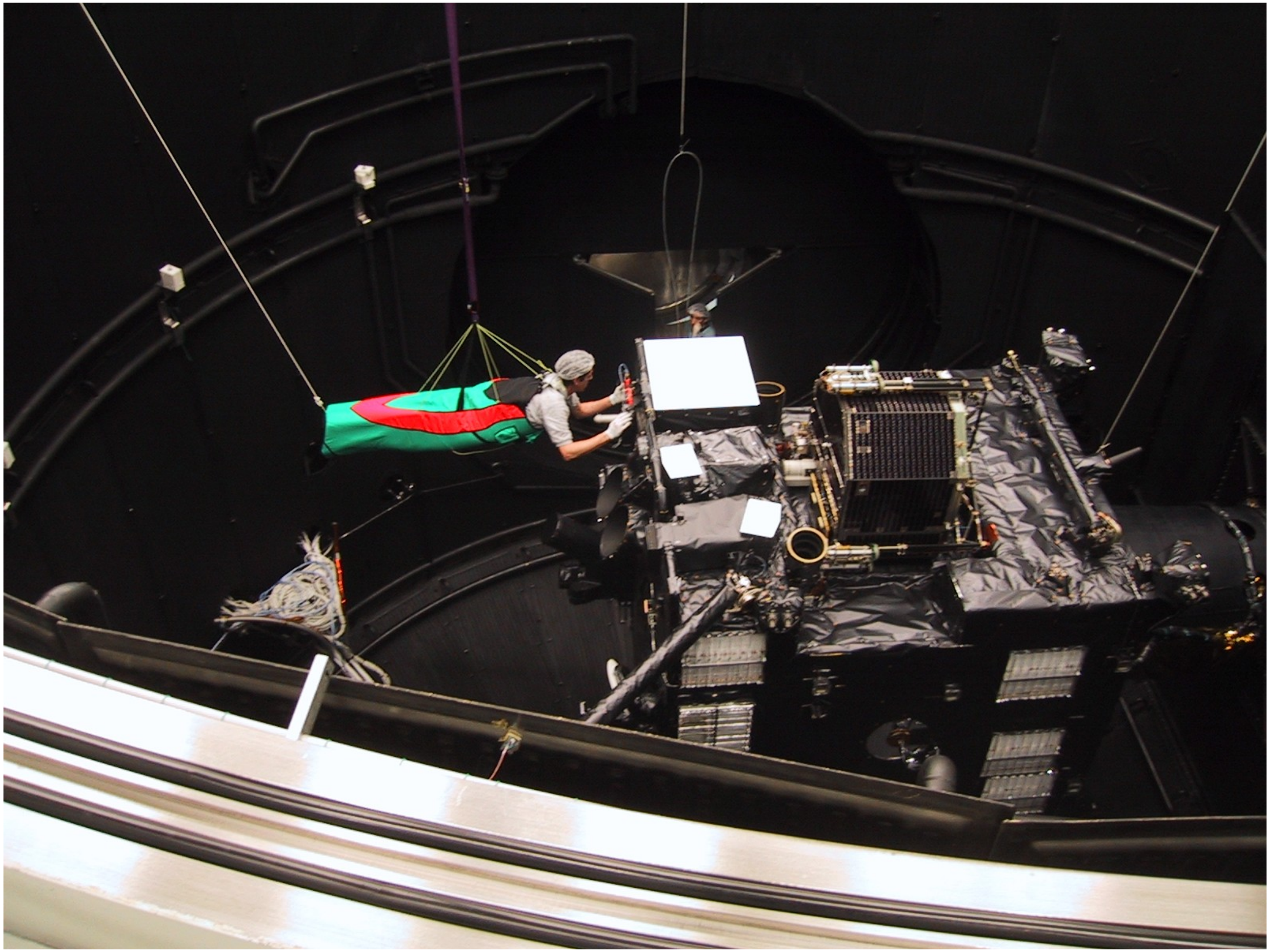
active protective systems :

- heaters (electrical or radoactive)
- coolers (Stirling)
- capillary heat pipes (zero-g)

Thermal-Vacuum / Thermal-Balance Test of ROSETTA Lander

at IABG, Munich

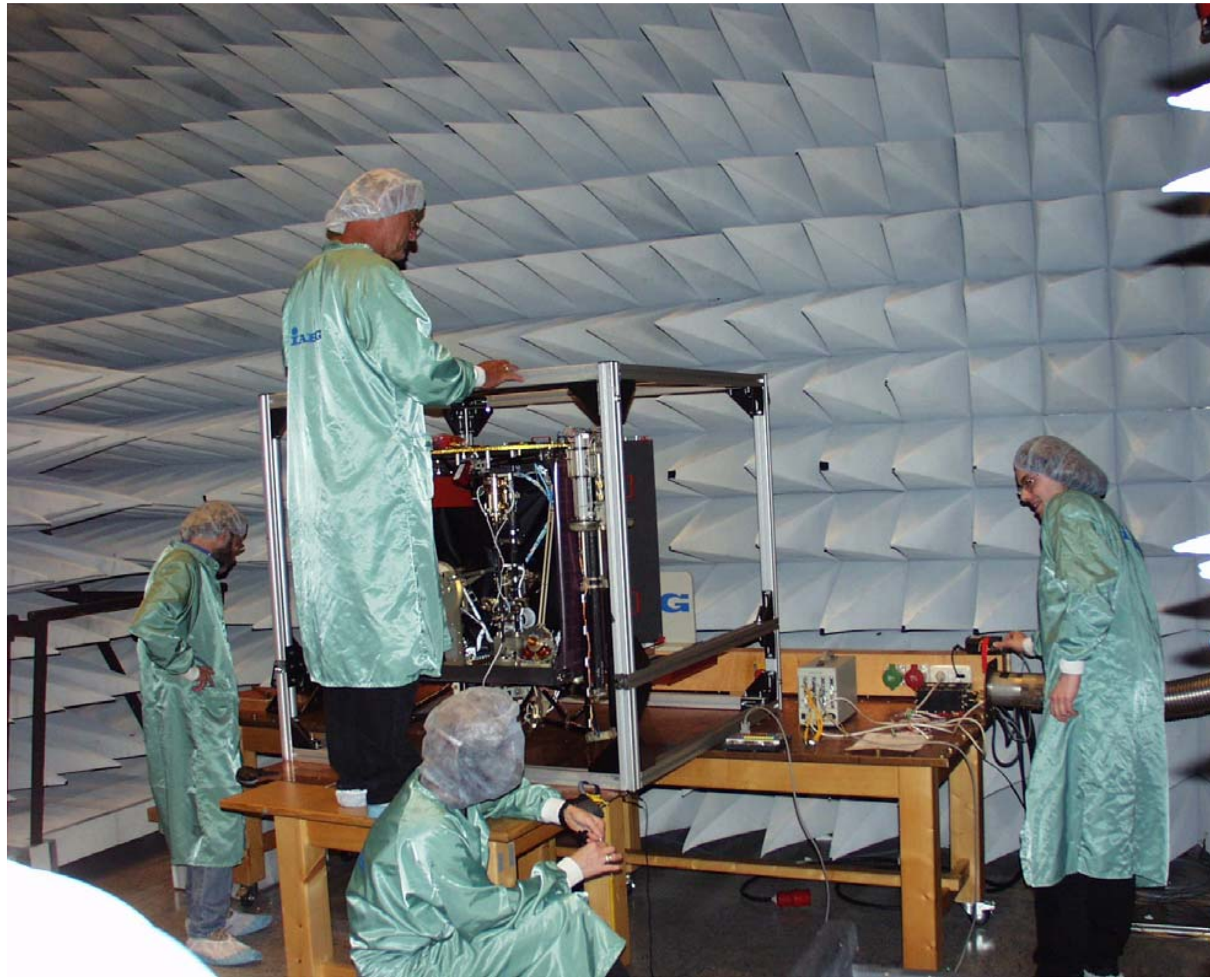
ROSETTA flight spacecraft inside Large Space Simulator test chamber at ESTEC, NL



EMC testing of ROSETTA Lander at IABG, Munich:

radiated & conducted emission,

radiated & conducted susceptibility



SUMMARY & General Recommendations :

- Keep track of requirement flowdown !
- Assemble (and maintain!) a good technical team !
- Start design with resource margins (25% min.) !
- Take design reviews serious – they help you !
- Nurse back-up solutions along with the main development !
- Keep documentation up-to-date !!! - you need it after launch!
- Test – test – test !!! (but don‘t overstress the Flight Unit !)
- Hold post-delivery “Lessons Learned“ review with your team !