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)

**ROSETTA** (ESA planetary cornerstone mission)
instrument selection: 1995 → launch: Mar 2004

**WHY?**
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

<table>
<thead>
<tr>
<th></th>
<th>SOHO</th>
<th>ROSETTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument</td>
<td>scientific instruments accumulated</td>
<td>scientific instruments accumulated</td>
</tr>
<tr>
<td>mass</td>
<td>= 610 kg</td>
<td>= 186 kg</td>
</tr>
<tr>
<td>mass at launch</td>
<td>= 1850 kg</td>
<td>= 2900 kg</td>
</tr>
<tr>
<td>launcher mass</td>
<td>= 237 500 kg</td>
<td>= 760 000 kg</td>
</tr>
<tr>
<td>launch cost ATLAS II AS</td>
<td>= 72 000 000 €</td>
<td>= 100 000 000 €</td>
</tr>
<tr>
<td>specific launch cost for instrument</td>
<td>118 000 €/kg</td>
<td>537 634 €/kg</td>
</tr>
</tbody>
</table>

[for comparison: price of gold (Au): 17 500 €/kg]
A closer look at:

- total launch support mass / scientific payload mass ratio:

  **SOHO**: \[(237,500 + 1,850 - 610) \text{ kg} / 610 \text{ kg} = 391\]

  **ROSETTA**: \[(760,000 + 2,900 - 186) \text{ kg} / 186 \text{ kg} = 4101\]

  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, occurring 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

Tuesday May 18, 2004

00:00 Welcome and Introduction – K. U. Keller
00:10 Goal of the Meeting – D. Noffs
00:20 DAWN Project Status – C. Rummell
08:30 Overview FC – Science Objectives and Requirements – R. U. Keil
09:50 FC Team Organizations and Top Level Workpackages – H. Sehrs
10:00 Instrument Concept and Implementation – H. Hartwig
10:15 Coffee Break

Camera Read

10:30 Optical Design – H. Meischke-K T
10:45 Lens System, Fitter, Riffle, and Related Analysis – H. Meischke-K T
11:00 CCD and Front End Electronics – S. Meischke
11:20 Front End Mechanism and Pail Safe Mechanism – H. Hartwig
11:30 Filter Wheel Mechanism – H. Hartwig
11:45 Discussion

12:00 Lunch Break

Electronics Box

13:10 Electrical Interfaces Block Diagram & Grounding Concept – I. Hooge
13:15 Data Processing Unit and Mass Density – K. Michalik/IDA
13:30 Power Converter Unit – P. Boeg
13:45 Mechanism Controller Unit – W. Kreher
14:00 Housekeeping Data Acquisition – I. Hooge

14:15 FC Radio Concepts – H. Sehrs

14:30 Probes Breakdown – H. Sehrs
14:45 Mass Breakdown – H. Hartwig
14:50 MICD & Accommodation – H. Hartwig
15:00 Coffee Break

15:00 Instrument Modelling

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

Software

16:00 Low Level Software – K. Michalik/IDA
16:20 Operating Software – K. Michalik/IDA
16:30 EGS – Configuration and Software – K. Michalik/IDA
16:45 EM demonstration run in room 51-49

Wednesday May 19, 2004

09:00 Model Philosophy and Schedule – H. Sehrs
09:20 Qualification Approach and Environmental Test Matrix – H. Sehrs
09:30 QA Approach and Design – M. Richards
09:45 Operations Plans – P. Gnesin
10:00 Calibration Plans – K. Schneider
10:15 Coffee Break

10:30 FC Data Processing Approach – R. Isajev
10:50 Risk Mitigation Plan – H. Sehrs
11:00 Review of FC RFAs – H. Sehrs
11:30 Discussion

12:00 Lunch Break

12:30 Board Summary, Action Items, and Wrap-up

Board Members:

Dave Norris (Chairman)
Fred Vaccaro
John Scalco
P. Boeg
K. Michalik

Attendance List:

UCLA:
Chao Russell
Steve Jay

JPL:
Scott Clark
Betha Price
Shelana Allen
Paul House
Steve Potocki
Jerry DeWitt
Chad Mavis
Example:

**Structural Mathematical Model**

**Finite Element Analysis**

**Framing Camera on the DAWN Mission**

**Finite Element Analysis** : Modelling

- Model analyzed with:
  - MSC NASTRAN
- Pre-/post-processing with:
  - MSC PATRAN
- Element type used:
  - TET10(3D)
- Element size:
  - 4 mm 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

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

- thermal mathematical model

Finite Difference Analysis

(ESATAN/ESARAD)

Framing Camera on the DAWN mission

Steady State Analysis - Operations (continued)

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

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3 History Record
4 Connector Matching Cycle Record
5 Operating Time / Cycle Record
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8.3 Program Lists / Source Code
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10.1 Placement Plan
10.2 PCB Routing
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11.1 Connector Pin Allocations
11.2 Connector Layout Drawings
11.3 Connector Data Sheets
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12.3 Program Lists / Source Code
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13.1 Mechanics Interface Drawings
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15 Declared Materials List
16 Declared Process List
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Table 1: Sample table (caption above table, use "insert caption - label table")
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

<table>
<thead>
<tr>
<th>Test item</th>
<th>QM</th>
<th>STM</th>
<th>EEM</th>
<th>FM</th>
<th>FS</th>
<th>responsible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Properties</td>
<td>M / X</td>
<td>X</td>
<td>M / X</td>
<td>M / X</td>
<td>M / X</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>(COG, Mass, Dimensions)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td>Q</td>
<td>Q</td>
<td>---</td>
<td>A</td>
<td>A</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Shock</td>
<td>Q</td>
<td>(Q)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Acoustic Noise</td>
<td>(X)</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Thermal Balance</td>
<td>M / X</td>
<td>X</td>
<td>X</td>
<td>---</td>
<td>---</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Thermal Vacuum</td>
<td>Q</td>
<td>---</td>
<td>---</td>
<td>A</td>
<td>A</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Mechanical Functional</td>
<td>M / X</td>
<td>M / X</td>
<td>M / X</td>
<td>M / X</td>
<td>M / X</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Electrical Functional</td>
<td>M / X</td>
<td>---</td>
<td>M / X</td>
<td>M / X</td>
<td>M / X</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Optical Functional</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Electrical Test</td>
<td>M / X</td>
<td>---</td>
<td>M / X</td>
<td>M / X</td>
<td>M / X</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>(Grounding, Bonding, isolation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMC (Conducted and Radiated</td>
<td>(M) / X</td>
<td>---</td>
<td>X</td>
<td>X conduc</td>
<td>X conduc</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Interference)</td>
<td></td>
<td></td>
<td></td>
<td>only</td>
<td>only</td>
<td></td>
</tr>
<tr>
<td>DC Magnetic Properties</td>
<td>(M) / X</td>
<td>---</td>
<td>---</td>
<td>X</td>
<td>X</td>
<td>All / MPAE</td>
</tr>
<tr>
<td>Alignment</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>M / X</td>
<td>---</td>
<td>(M) / X</td>
<td>M / X</td>
<td>M / X</td>
<td>All / MPAE</td>
</tr>
</tbody>
</table>

**Models:**

- **QM:** Qualification Model
- **STM:** Structural Thermal Model
- **EEM:** Electrical Engineering Model
- **FM:** Flight Model
- **FS:** Flight Spare Model

**Module Tests:** To be performed at the responsible institute or manufacturer prior to E-Box integration:

- **M:** Required, no specific test level
- **( ):** Desirable

**Instrument Tests:** (Modules integrated in E-Box), to be done at MPAE or test house, 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)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>In-plane (X and Y)</th>
<th>Frequency</th>
<th>Out-of-plane (Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Hz to 20 Hz</td>
<td>9.3 mm(0-p)</td>
<td>5 Hz to 18 Hz</td>
<td>11.5 mm(0-p)</td>
</tr>
<tr>
<td>20 Hz to 70 Hz</td>
<td>15 g const.</td>
<td>18 Hz to 50 Hz</td>
<td>30 g const.</td>
</tr>
<tr>
<td>70 Hz to 100 Hz</td>
<td>8 g const.</td>
<td>50 Hz to 70 Hz</td>
<td>20 g const.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70 Hz to 100 Hz</td>
<td>15 g const.</td>
</tr>
<tr>
<td>Sweep rate</td>
<td>2 oct/min</td>
<td></td>
<td>2 oct/min</td>
</tr>
</tbody>
</table>

### SIR-2 Random qualification levels (TBC by ISRO)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>In-plane p.s.d. (X and Y axis)</th>
<th>Out-of-plane p.s.d. (Z axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Hz to 100 Hz</td>
<td>+ 3 dB/octave</td>
<td>+ 3 dB/octave</td>
</tr>
<tr>
<td>100 Hz to 700 Hz</td>
<td>0.1 g²/Hz</td>
<td>0.3 g²/Hz</td>
</tr>
<tr>
<td>700 Hz to 2000 Hz</td>
<td>- 3 dB/octave</td>
<td>- 6 dB/octave</td>
</tr>
<tr>
<td>RMS level</td>
<td>11.8 g</td>
<td>18.2 g</td>
</tr>
</tbody>
</table>
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 radioactive)
- 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 over-stress the Flight Unit!)
- Hold post-delivery “Lessons Learned“ review with your team!