LISA Pathfinder and the LTP experiment

38th ESLAB Symposium

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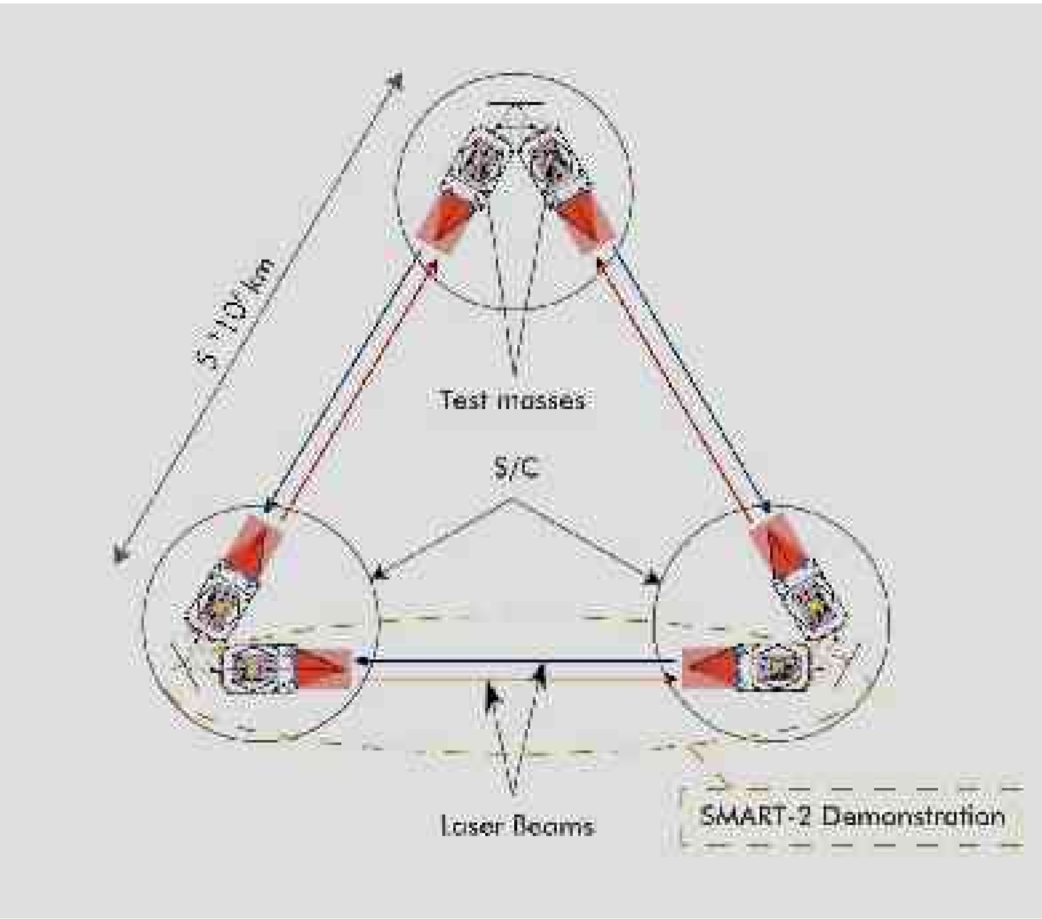
The Mission Statement

- Smart-2 is a technology demonstration mission for LISA -> LISA Pathfinder
- Two technology packages will be embarked:
  - The European LISA Test-flight Package (LTP)
  - The America Disturbance Reduction System (DRS)
- A Drag Free Attitude Control System (DFACS)
- In addition, a number of European microPropulsion technologies will be flight demonstrated for the first time:
  - Field Emission Electrical Propulsion (FEEP) thrusters
  - microNewton proportional Cold Gas thrusters and drive electronics

LPF: Mission Goal

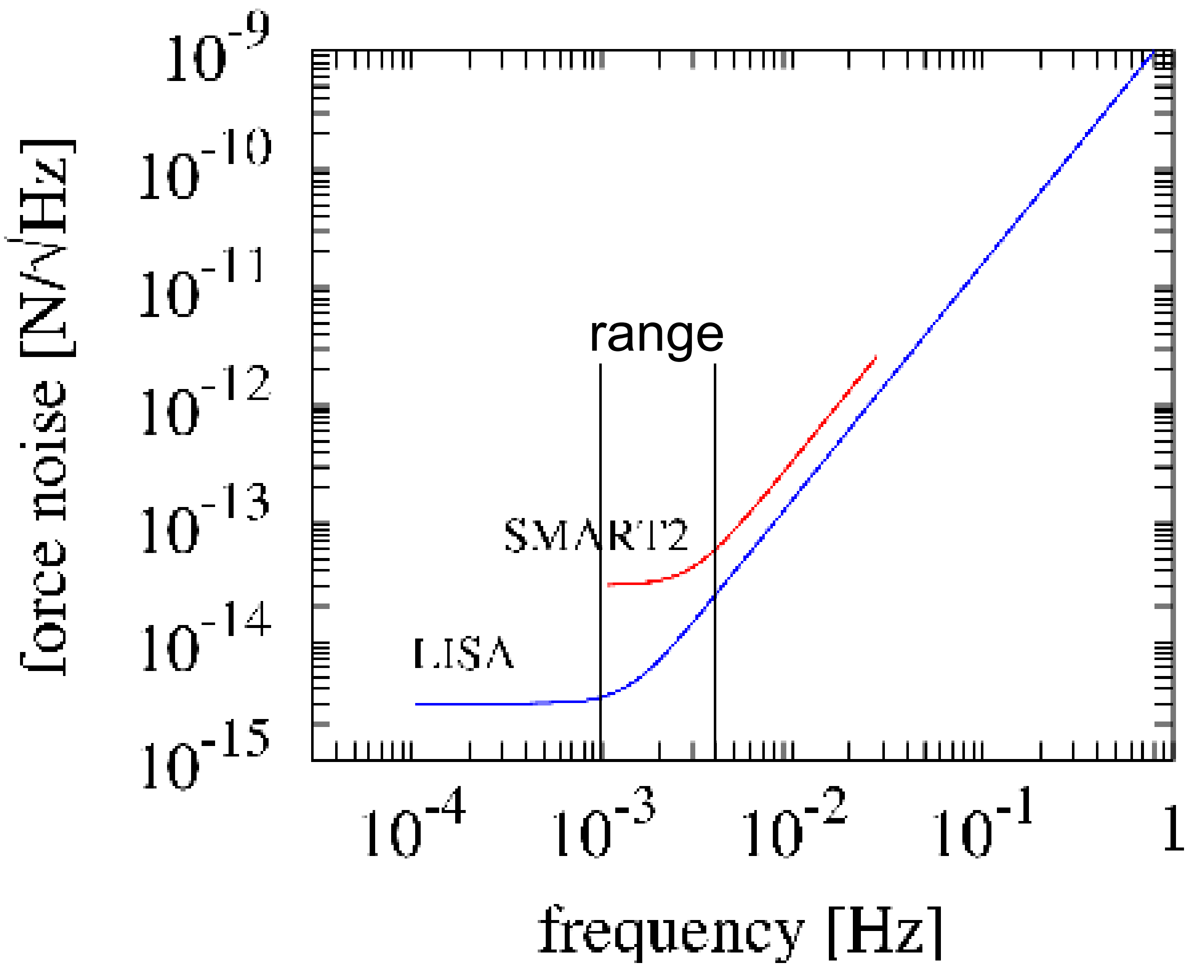


- **The technologies for LISA cannot be proven on the ground,** thus ESA has conceived SMART-2, the **LISA 'Pathfinder' Mission**
- **SMART-2** has one fundamental goal:
  - To be able to demonstrate the near-perfect free-fall of a Test Mass located inside the body of the spacecraft by limiting the spectral density of accelerations at the test mass to:

$$S_a^{1/2}(f) \le 3\times10^{-14}\left[1+\left(\frac{f}{3\ \text{mHz}}\right)^2\right]\frac{\text{m}}{\text{s}^2}\frac{1}{\sqrt{\text{Hz}}}$$

    between 1 and 30 mHz
- The basic idea is that of 'squeezing' one **LISA** interferometer arm from 5 *10⁶ km to a few centimetres (the so-called **LISA Test Package**) on-board a small spacecraft.
- A similar system ('**DRS**') is provided by NASA

LISA vs. LPF



force noise [N/√Hz]
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
range
SMART2
LISA
10^-4
10^-3
10^-2
10^-1
1
frequency [Hz]

The Mother of all Noises

$$a_{noise} = \underbrace{\frac{f_{T/M}}{m}}_{\text{Force on Test-Mass}} + \underbrace{\omega_p^2}_{\text{Parasitic stiffness}} \underbrace{\left(\underbrace{x_n}_{\text{Sensor noise}} + \frac{\overbrace{F_{S/C}}^{\text{Force on spacecraft}}}{\underbrace{M\omega_{fb}^2}_{\text{Drag-free gain}}} \right)}_{\text{Relative diplacement TM wrt S/C}}$$

LPF

Noise identification

- IS readout displacement noise
- Thermal effects
- Cross – Talk
- Electro-Magnetic disturbances generated within the spacecraft
- Magnetic disturbances due to interplanetary field fluctuation
- Random charging
- Laser readout noise and thermal distortion
- Laser radiation pressure fluctuation
- Fluctuation of local gravitational field due to distortion of the system components

Parasitic coupling

- DC-voltage
- AC-voltage
- Charge
- Magnetic stiffness
- Gravitational gradient
- Low frequency suspension

Disturbance Forces

- External Forces on the spacecraft include:
  - Thruster force, including noise
  - Difference in gravitational acceleration between test mass and spacecraft centre of mass
  - Solar radiation pressure
  - Interaction with planetary magnetic fields etc.
- Internal Forces acting on the proof mass and the spacecraft include
  - Thermal noise, radiation pressure
  - Pressure fluctuations, outgassing
  - Electrostatic, magnetic, gravitational fields
  - Force that arises from sensor noise feeding into thruster commands and hence resulting in random thrust noise

Operative Modes

- Off Mode
- Safe Mode
- Positioning Mode
- Accelerometer Mode

- M1
- M3
- M4

M1

- The spacecraft follows TM1 along the sensitive axis, by using the capacitive sensor measurement.
- TM2 is controlled along the sensitive axis by the electro-static suspension loop, by using the capacitive sensor measurement.
- Other DoF are controlled by a combination of thrusters and electrostatic-suspension, in and out of band.
- The main metrology signal is the relative position of TM1 vs. TM2 as measured by the interferometer.
- TM1 and TM2 shall be interchangeable. Some test runs are required by using the interferometer output instead of the capacitive readouts.

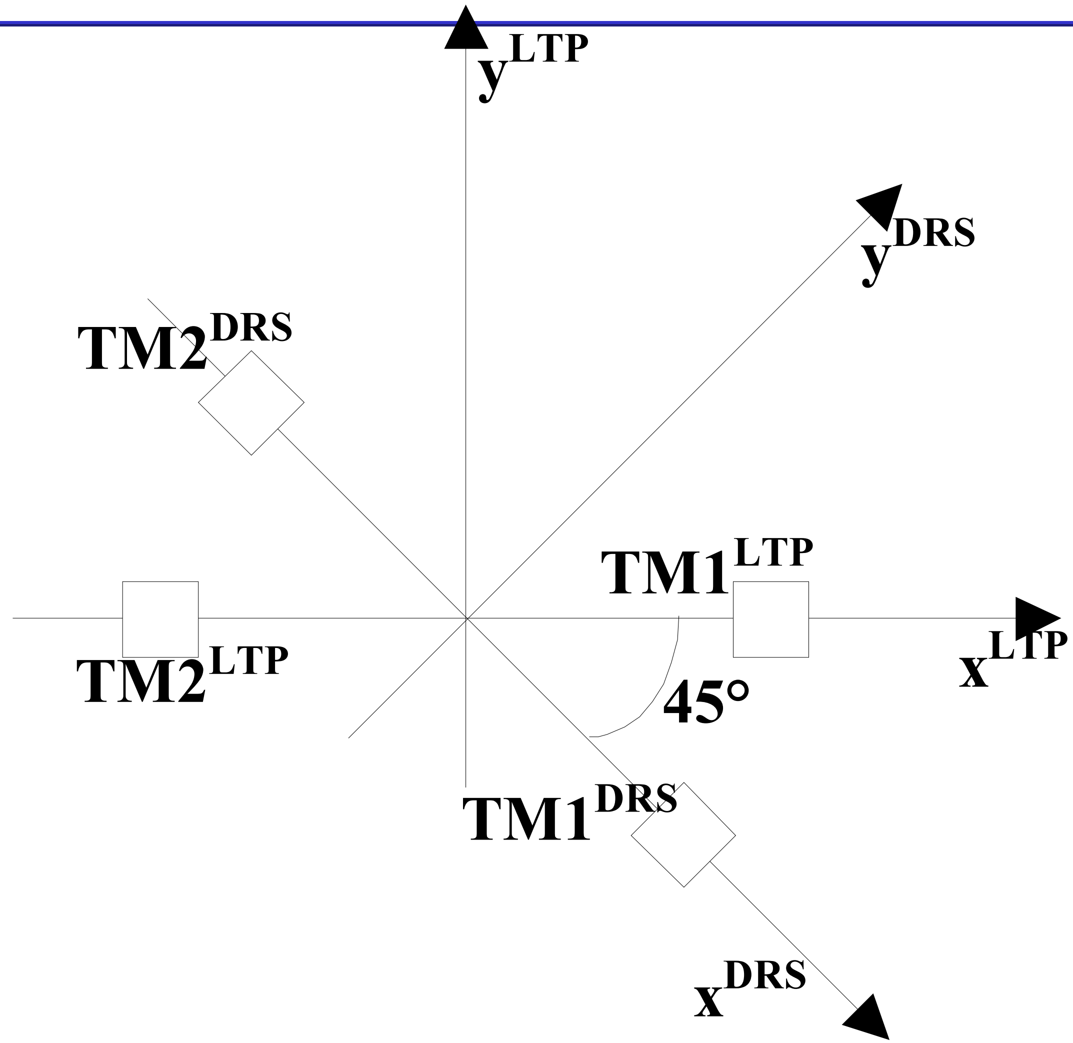
M3

- As M1 but TM2 is made to follows TM1 along the sensitive axis, by using the capacitive actuation.

$$\Delta x_{lsr} = \frac{\omega_{fb}^2}{\left(s^2+\omega_{fb}^2\right)\left(s^2+\omega_{lfs}^2\right)}\left[\overbrace{x_{n,laser}s^2\left(1+\frac{s^2}{\omega_{fb}^2}\right)}^{\text{Laser noise}}+\overbrace{\Delta x\left(\omega_{p,2}^2+\frac{s^2}{\omega_{fb}^2}\frac{\omega_{p,1}^2+\omega_{p,2}^2}{2}\right)}^{\text{Baseline distortion}}+\right.$$

$$\left.+\overbrace{\frac{f_{x,2}-f_{x,1}}{m}}^{\substack{\text{Difference}\\\text{of force}}}\left(1+\frac{s^2}{\omega_{fb}^2}\right)+\overbrace{\left(\omega_{p2}^2-\omega_{p1}^2\right)}^{\substack{\text{Difference of}\\\text{parasitic coupling}}}\overbrace{\left(x_{n,1}+\frac{F_{S/C}}{M\omega_{fb}^2}\right)}^{\substack{x_{S/C}=\text{Test-mass / Spacecraft}\\\text{relative dispacement}}}\right]$$

M4



M4

- Drag free along the x-axis of the LTP is controlled by the LTP x-axis capacitive sensor readout of the LTP TM1 (actuation normal to the DRS x-axis).
- Drag free along the x-axis of the DRS is controlled by the DRS x-axis capacitive sensor readout of the DRS TM1 (actuation normal to the LTP x-axis).
- Attitude along f (rotation around the common z-axis) is controlled within the MBW by the differential y-axis output of the IS1 and IS2 of LTP.
- TM1 and TM2 of the LTP are subject, along the y-axis, to a low frequency suspension loop driven by their common mode displacement.

Test Runs

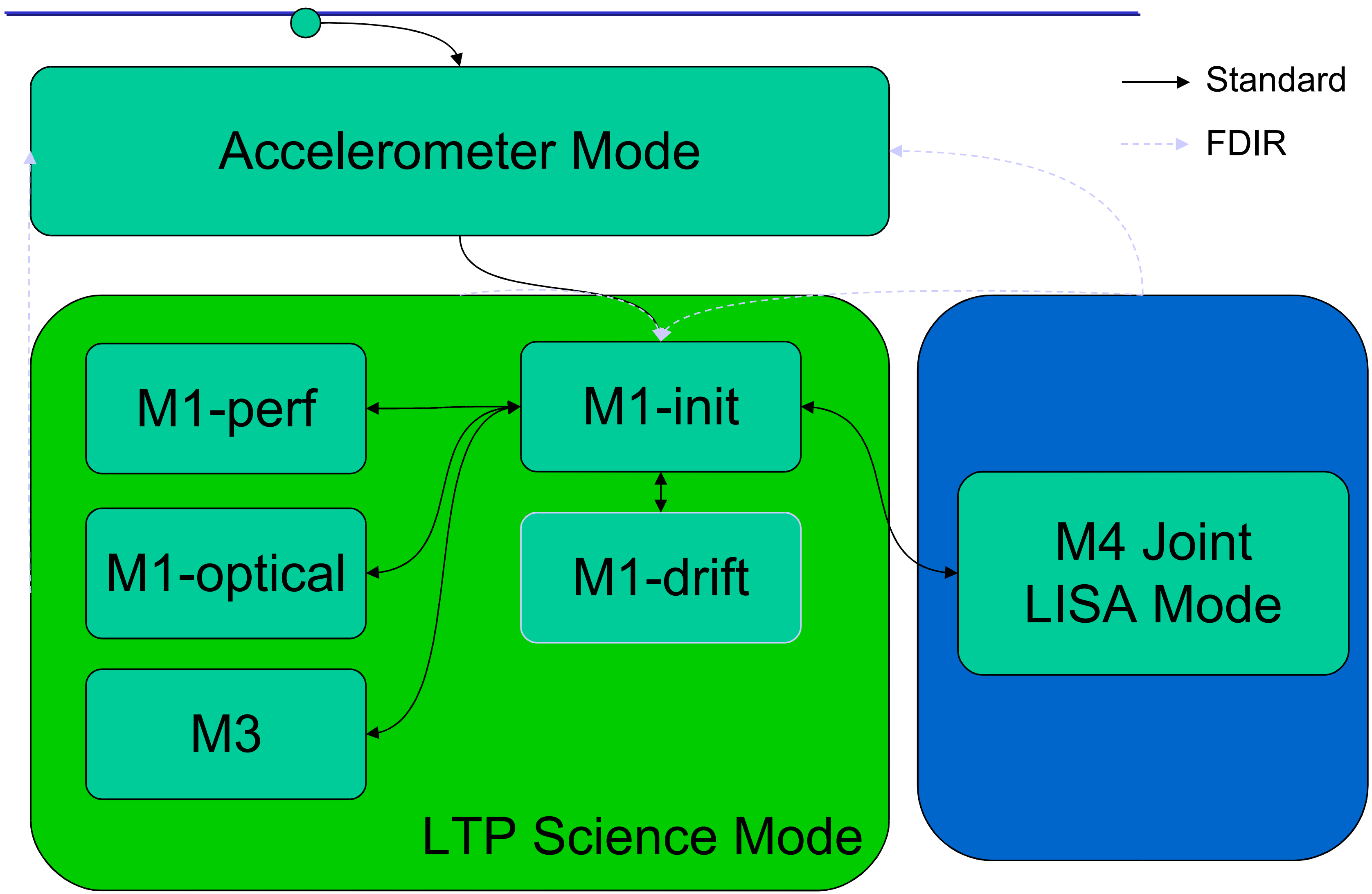
12 Main Runs. A Test Run is NOT a single demonstration sequence:

1. Measurement of total acceleration (M1)
2. Measurement of acceleration noise (M3)
3. Measurement of internal forces (M1 and M3)
4. Measurement of stiffness (M3)
5. Measurement of cross-talk (M3)
6. Test of continuous charge charge measurement (M3)
7. Test of continuous discharge (M3)
8. Drift mode
9. Acceleration noise at different working points (M3)
10. Noise measurement below the MBW (M1)
11. Sensitivity to magnetic field and thermal gradient (M3)
12. Joint operations with the DRS

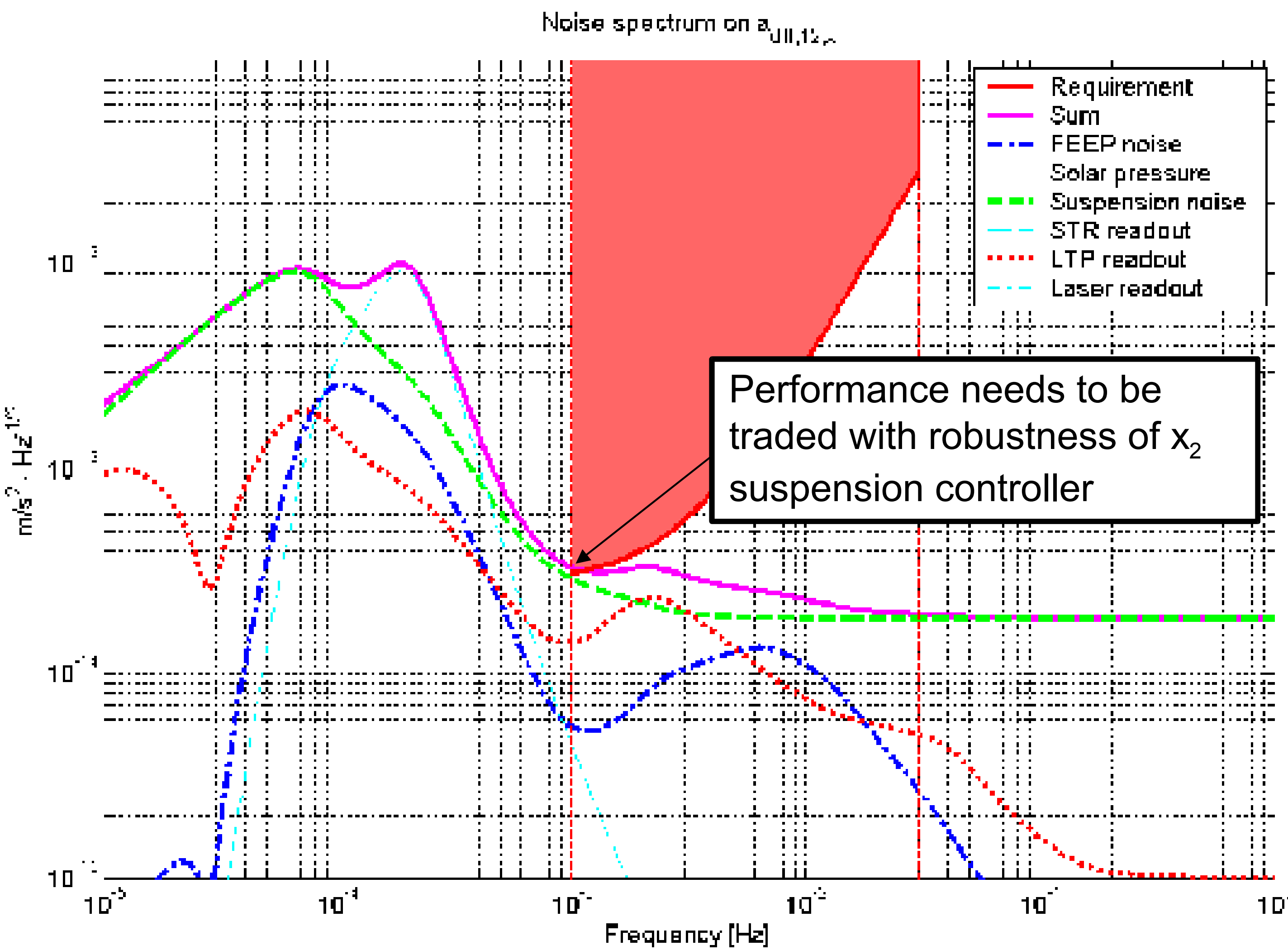
Joint Operations

- Simultaneous operation of LTP and DRS at full functionality for both packages.
- Use of the DRS test masses as a source of gravitational signal for the LTP.
- Use of the LTP test masses as a source of gravitational signal for the DRS.
- 2-axes 2-test-masses control with full functionality for both packages and one axis controlled by DRS **(mode M4)**.

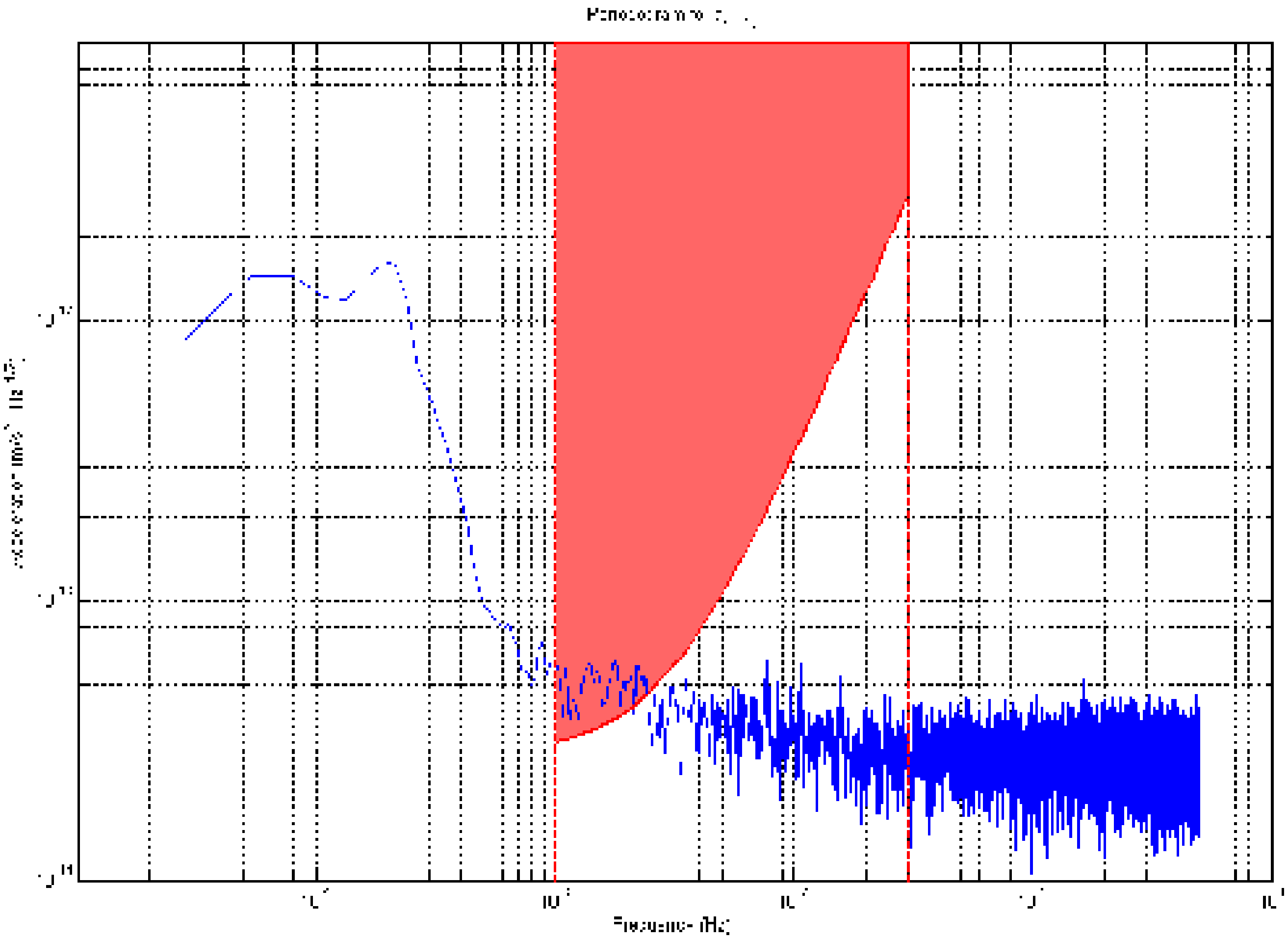
Mode Transition



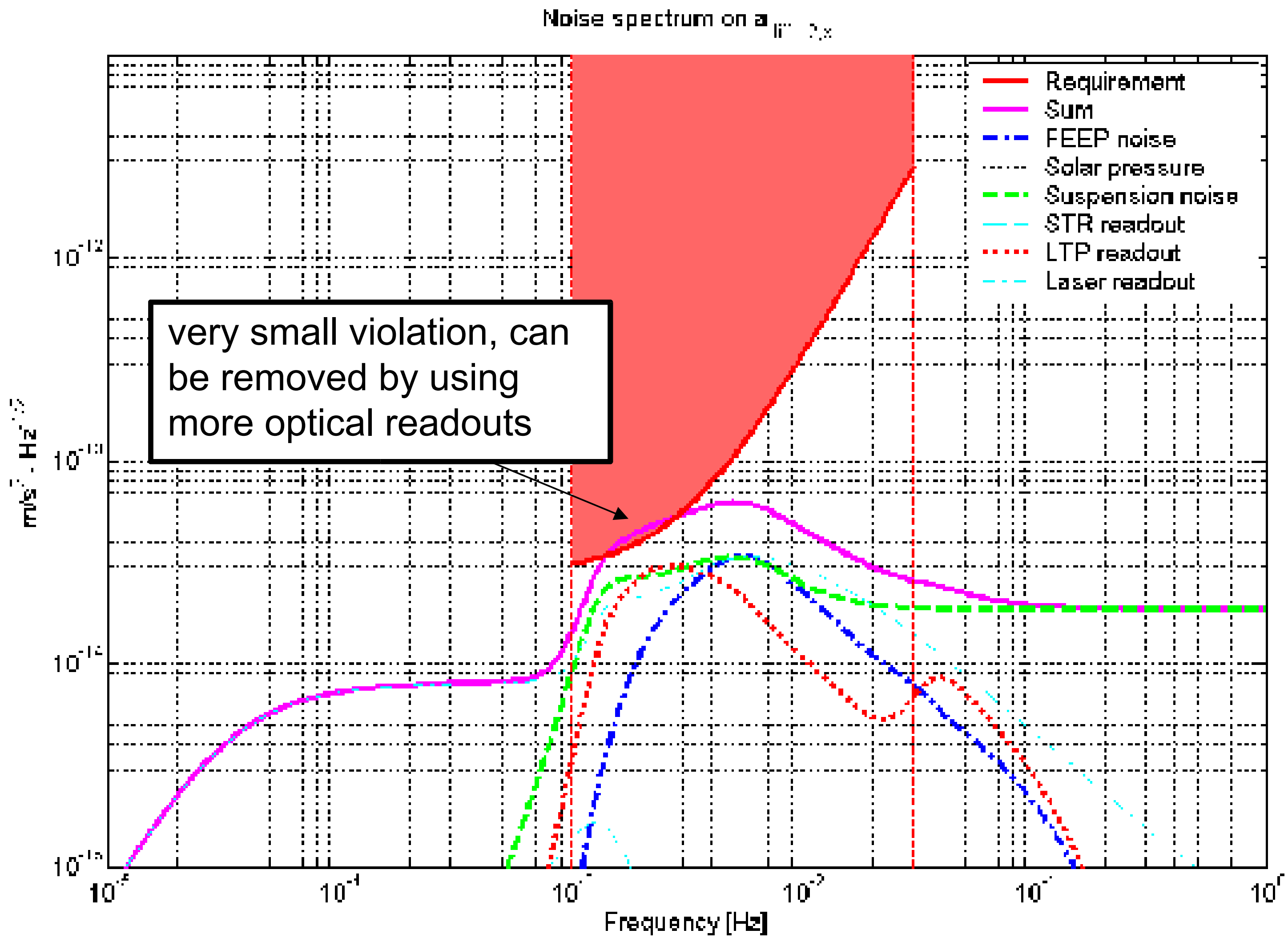
LPF M1 Differential Acceleration



LPF M1 Diff.Acc Time-Domain



LPF M3 Differential Acceleration



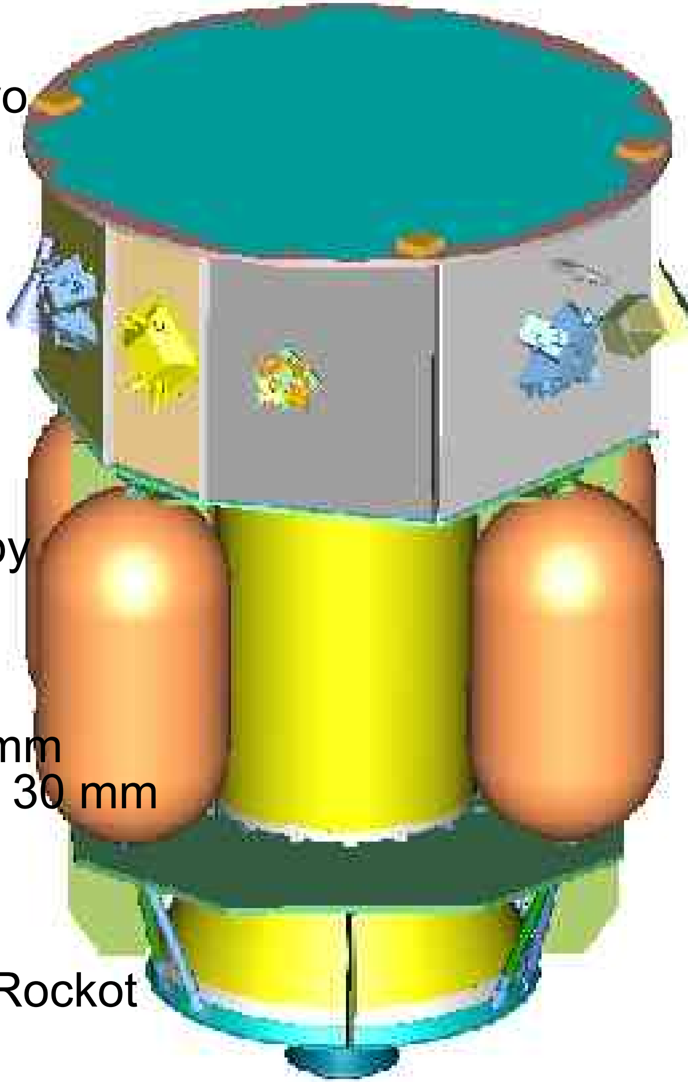
Spacecraft Configuration

Material from Prime Contractor

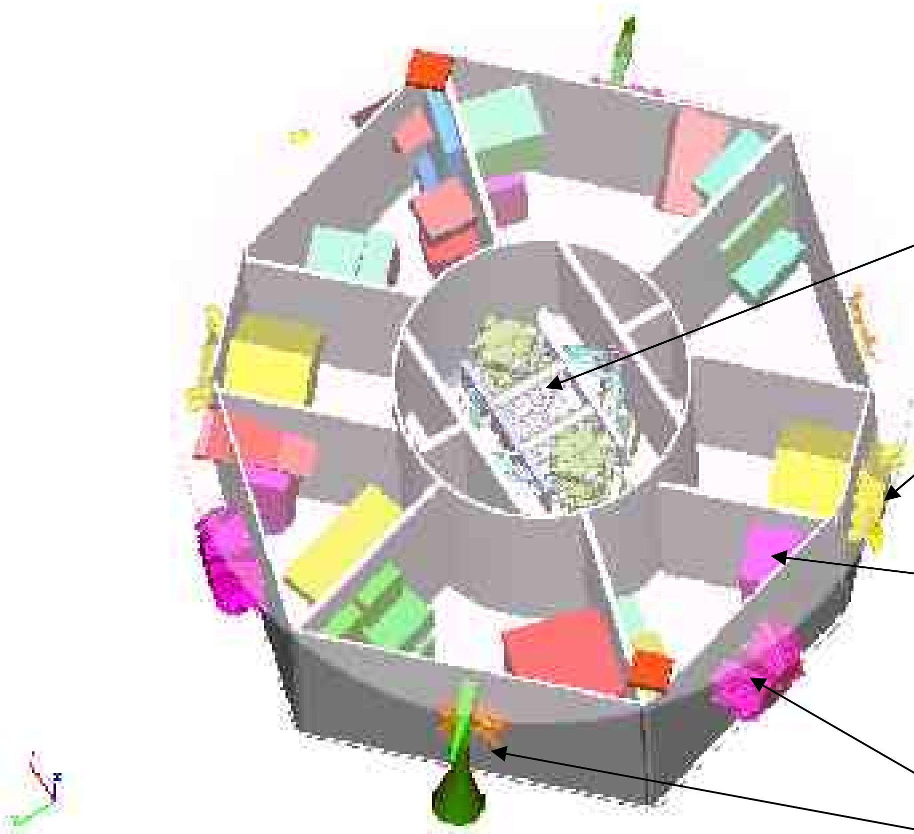
EADS Astrium Ltd. (UK)

System Overview

- LISA Pathfinder Launch Composite consists of two modules
  - Science Spacecraft
  - Propulsion Module
- Current Predicted Maximum Mass is 1881.3 kg.
- Maximum Launch Mass is 1910 kg (constrained by Rockot capability)
- Overall dimensions are 2836 mm high (plus 276 mm protrusion into LVA) and 2100 mm diameter (plus 30 mm antenna protrusion beyond this)
- Compliant with the envelopes of both Dnepr and Rockot



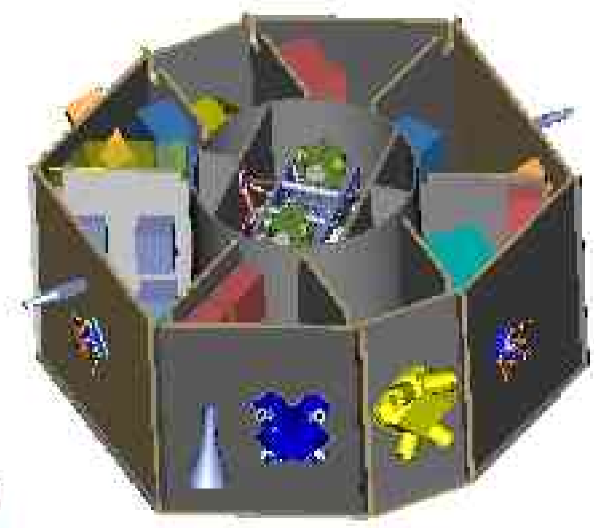
The Science Spacecraft

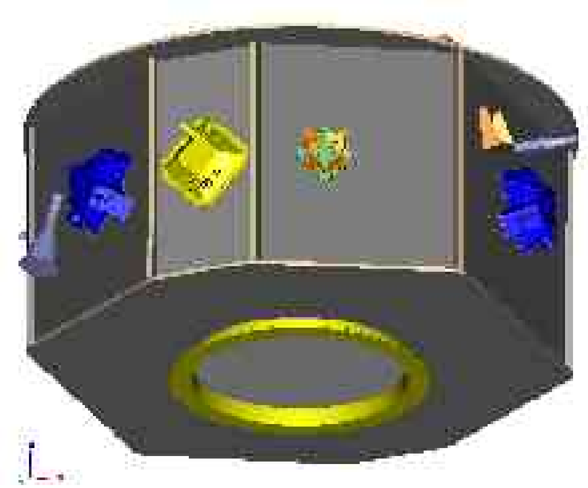


- The science spacecraft carries the the LTP and DRS, the micro-propulsion systems and the drag free control system. Total mass about 470kg
- The inertial sensor core assemblies are mounted in a dedicated compartment within the central cylinder.
- DRS Colloid thrusters are mounted on opposing outer panels.
- Payload electronics and spacecraft units are accommodated as far away as possible from the sensors to minimise gravitational, thermal and magnetic disturbance.
- The FEEP and cold-gas micro-propulsion assemblies are arranged to provide full control in all axes.

LPF Science Spacecraft

- Central Cylinder ϕ 788 mm x 900 mm long mounting:-
  - the LTP Optical Bench and the DRS Sensor Assembly
  - the Propulsion Module I/F
- Eight Shear Walls 864 high, 571 or 510 wide mounting:-
  - LTP Electrical Boxes, DRS Electronics Assembly
  - all subsystem elements not requiring external visibility
- Eight External Walls 864 high mounting:-
  - the thruster assemblies (2 Collodial, 3 Cold Gas & 3 FEEP)
  - the AOCS sensors (star trackers & eclipse detectors)
  - Low Gain and Medium Gain antennas
- Top Floor ϕ2100 mounting Solar Array and Sun Sensors
- Lower Closure Floors.
- Central Cylinder, all panels carbon fibre skins, aluminium honeycomb cores for low mass, high stiffness, low distortion
- Overall Dimensions 985 mm high, 2100 mm diameter (plus 30 mm antenna protrusion beyond this)
- Current Predicted Maximum Mass 472.1 kg.



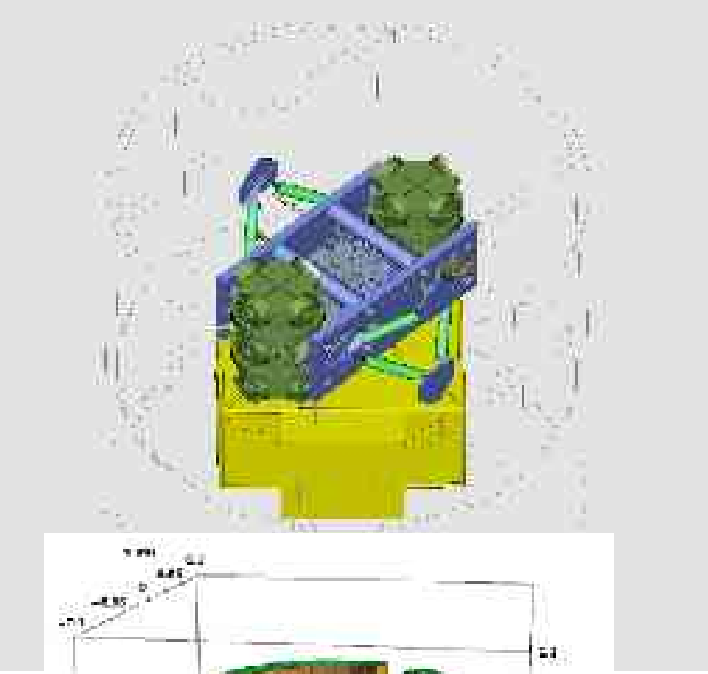


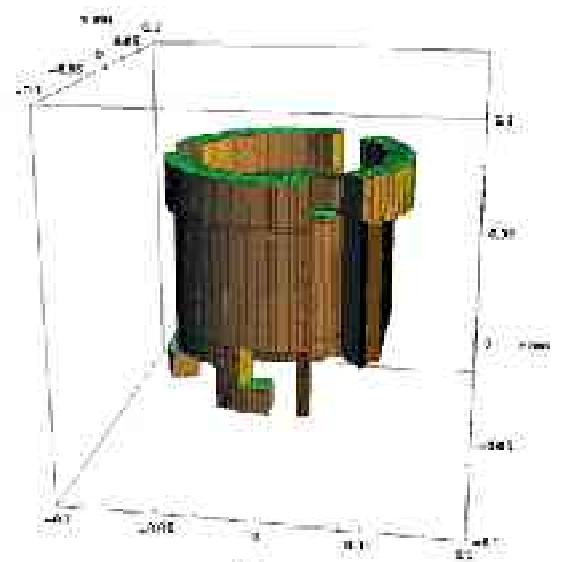
LPF Disturbance reduction

- Disturbances on the science spacecraft to be actively minimised by design:
  - No mechanisms on the science spacecraft
  - Known mass
  - No actively controlled thermal elements (does not preclude heaters, but does preclude thermostats)
  - Fixed sunshield, limited solar aspect angle
  - No liquids

Managing Self gravity

- DC force fields on spacecraft contribute to differential acceleration DC forces, stiffness and noise
- The main internal contributors to the DC force are self-gravity, magnetic and electrostatic fields.
  - Self gravity most difficult
- Dedicated central compartment isolates DRS & LTP inertial sensors - DRS is largest disturbance on LTP
- Compensation masses will be required inside LTP and DRS.
  - Masses designed by PI for LTP & DRS at same time
  - Must be defined early
- Gravitational modelling required
  - Detailed mass models of everything
- Fix configuration and masses early
  - Spacecraft provides final compensation
  - Mass critical, so adding extra mass not an option





•(image from Trento University:)

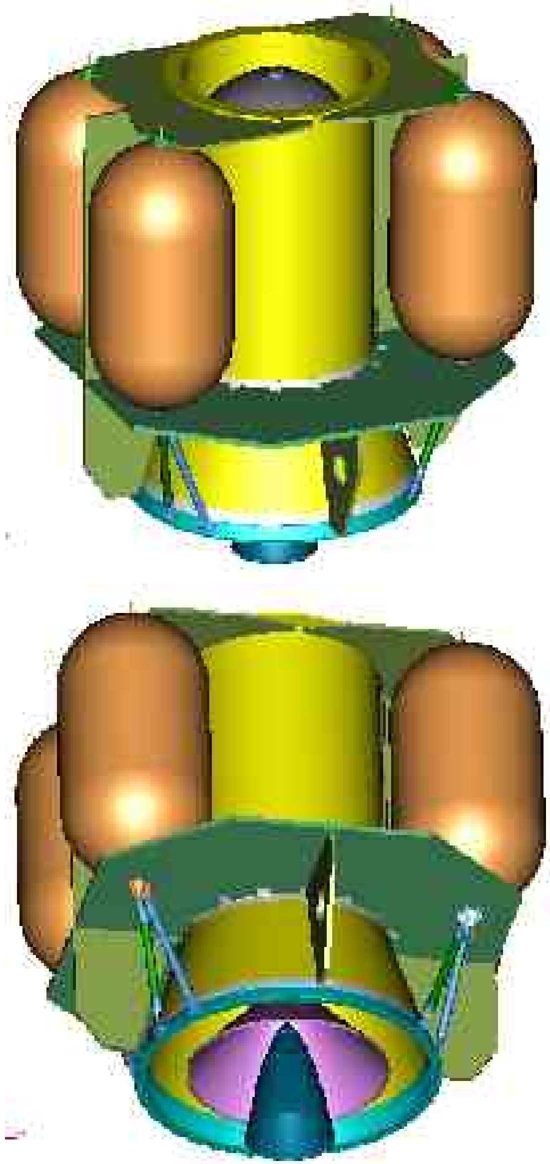
Gravity Budget

- Max differential acceleration between TMs specified in LTP Science Requirements (LTPA-UTN-ScRD-Iss002-Rev1)
- Three main contributors are – the inertial sensor (IS), the LTP and the spacecraft (including DRS). DRS and LTP largest external contributors to each other.
- Analysis performed using spreadsheet model & current spacecraft configuration shows uncompensated acceleration values about 3x10-8 m/s² - will require compensation
- Current requirements are:

	Differential Acceleration due to gravity(m/s^2) x 10^{-9}			
Axis	**Total**	**IS**	**LTP**	**Spacecraft**
∆Fx/M	1.1	0.35	0.40	0.35
∆Fy/M	1.7	0.55	0.60	0.55
∆Fz/M	3.2	1.10	1.10	1.0

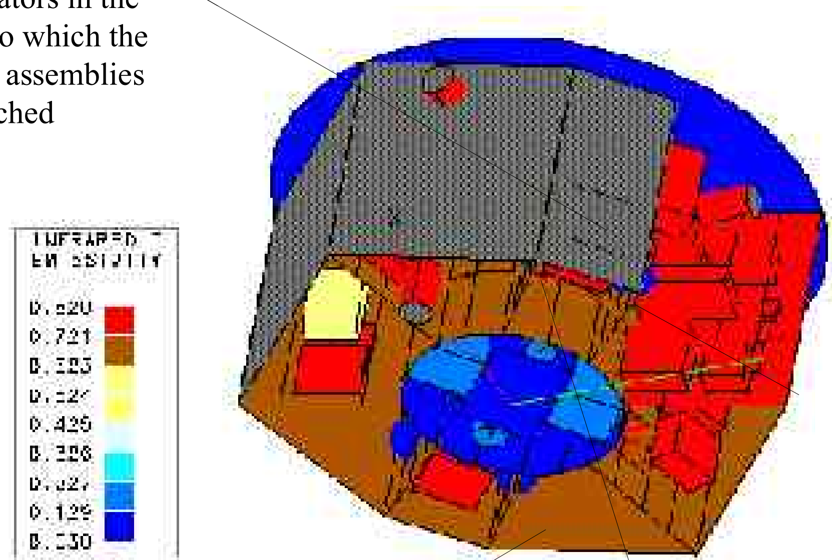
LPF Propulsion Module

- Single design compatible with launch on Rockot or Dnepr
- Propulsion module separates from the science spacecraft prior to drag free operations, to prevent disturbances which would be generated by the residual propellants acting on the inertial sensors.
- Electrical umbilical passes through to science spacecraft
- Configuration derived from Eurostar 3000
- Overall Dimensions are
  - 1851 mm high (plus 276 mm protrusion into LVA)
  - 2152 mm maximum diameter (across tank shells)
- Current Predicted Maximum Mass is 1409.2 kg, including 1207.7 kg of propellant.
  - Tank capacity 1218 kg
- Conventional bi-propellant configuration



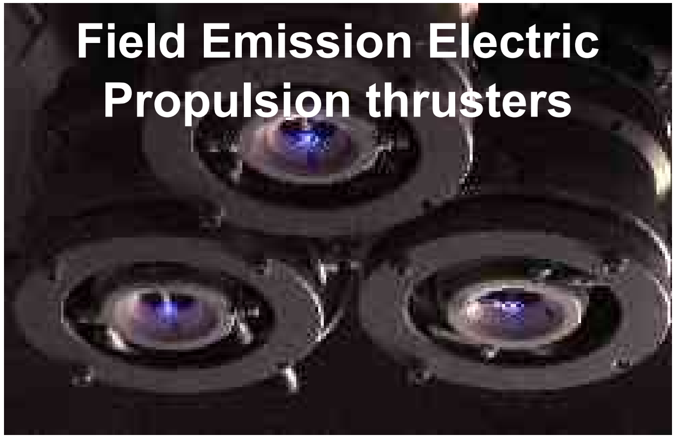
Thermal design

- Essentially passive design minimises thermal induced noise. Excess radiator area trimmed to suit.
- Constrained attitude, sunshield minimise solar fluctuations
- Sensor compartments increase isolation



Micro-Propulsion

- LISA PF must prove the use of proportional micro-thrusters for precision drag free control in space.
- A key element of the disturbance control system, they must meet stringent performance and stability requirements
  - very low thrust (0.1 to 75 μN in drag free modes)
  - very low noise (target <1μN/√Hz)
  - precisely controlled, low power
- LISA PF enables the calibration of the thruster performance using the LTP as an accelerometer
- FEEP and cold gas solutions under test by ESA



LPF Micro-propulsion (cont.'d)

- FEEP's use Indium or Caesium propellant
  - Issues with temperature (Indium) and reactivity (Caesium)
  - Must be liquid to operate (Indium must be heated)
- High voltage power supplies
- Noise performance may not be measurable
  - Nanobalance tests this year
- Lifetime is a potential problem:
  - Indium FEEP's failed life test on GOCE (although one thruster had accumulated over 3000 hours by then)
  - Caesium FEEP's have not been fired for more than 500 hours
- Cold gas Isp – 73 seconds with heated nozzle
  - Potentially 4.3 kg of propellant
  - Distributed tankage to minimise gravitation effects
- Cold gas thruster best considered as controlled leak
  - Able to operate up to 1mN for AOCS purposes

FEEP EM

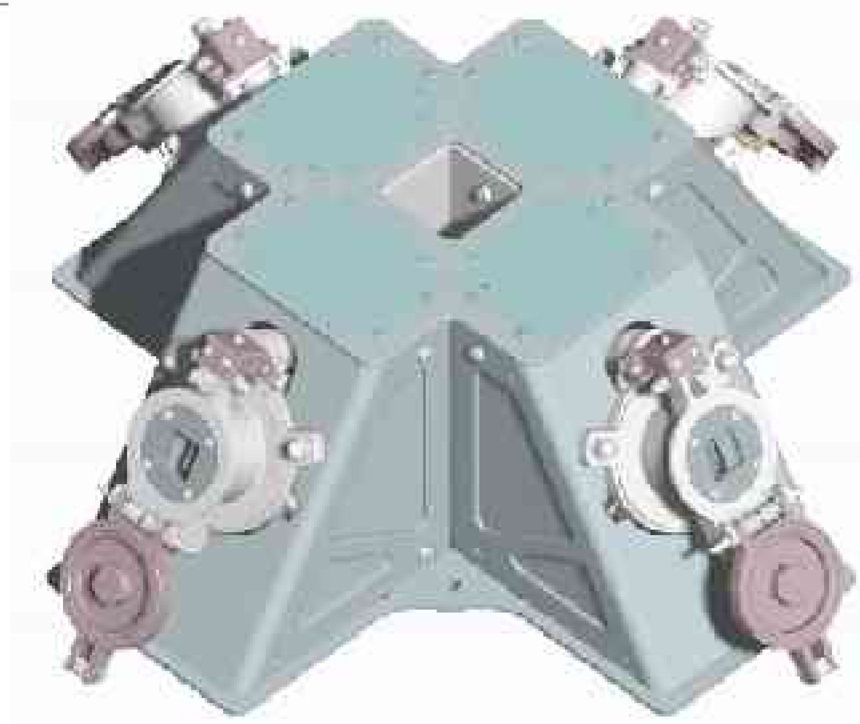
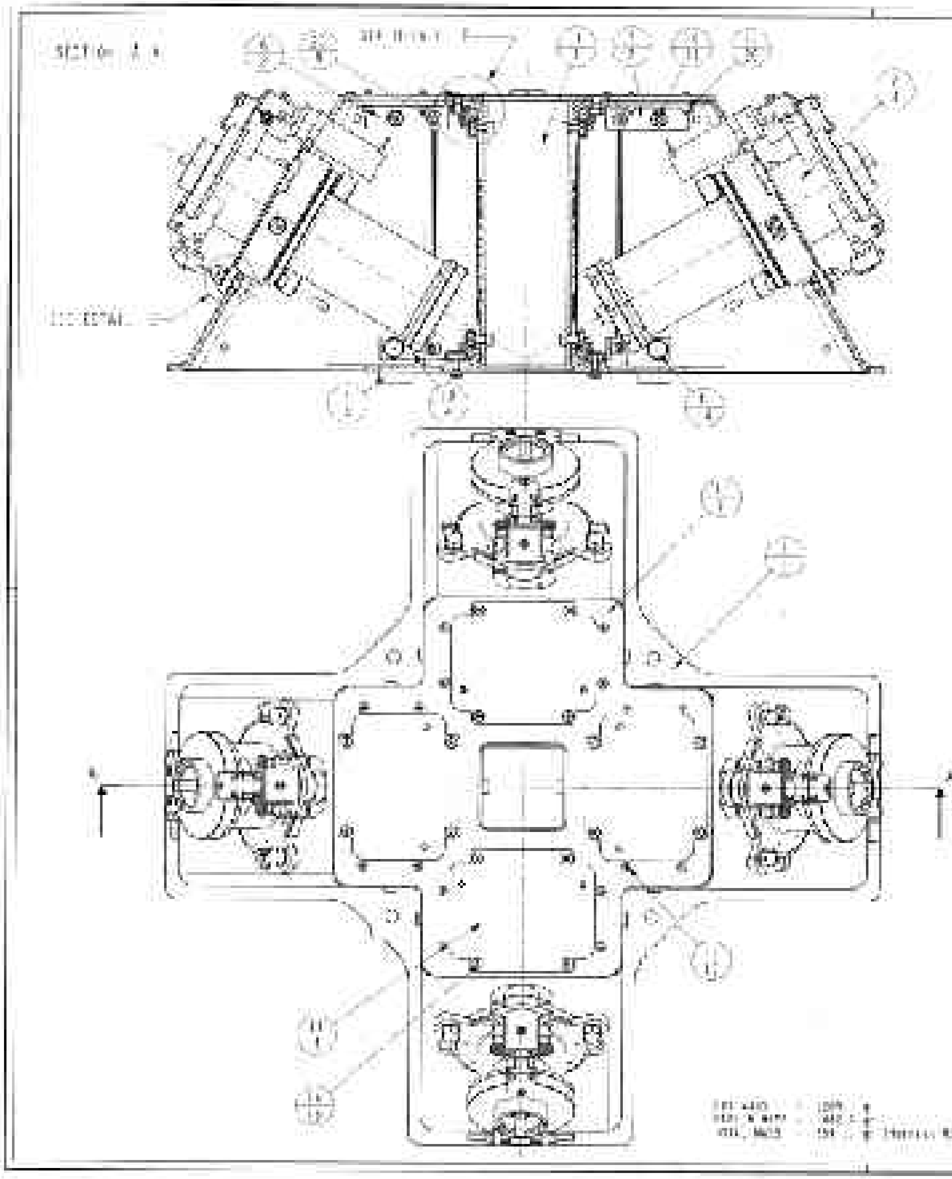


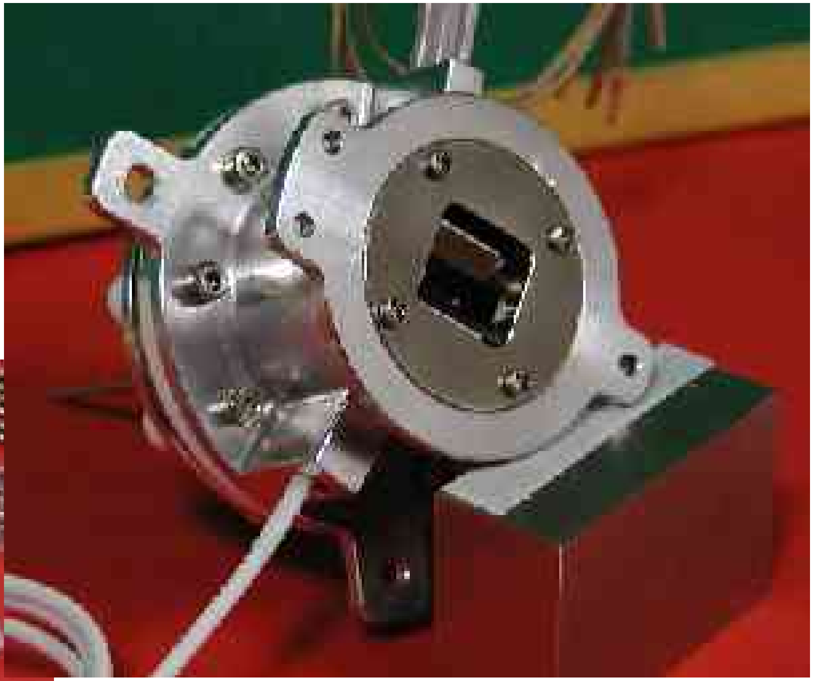
Figure 7.3: The FEEP Cluster

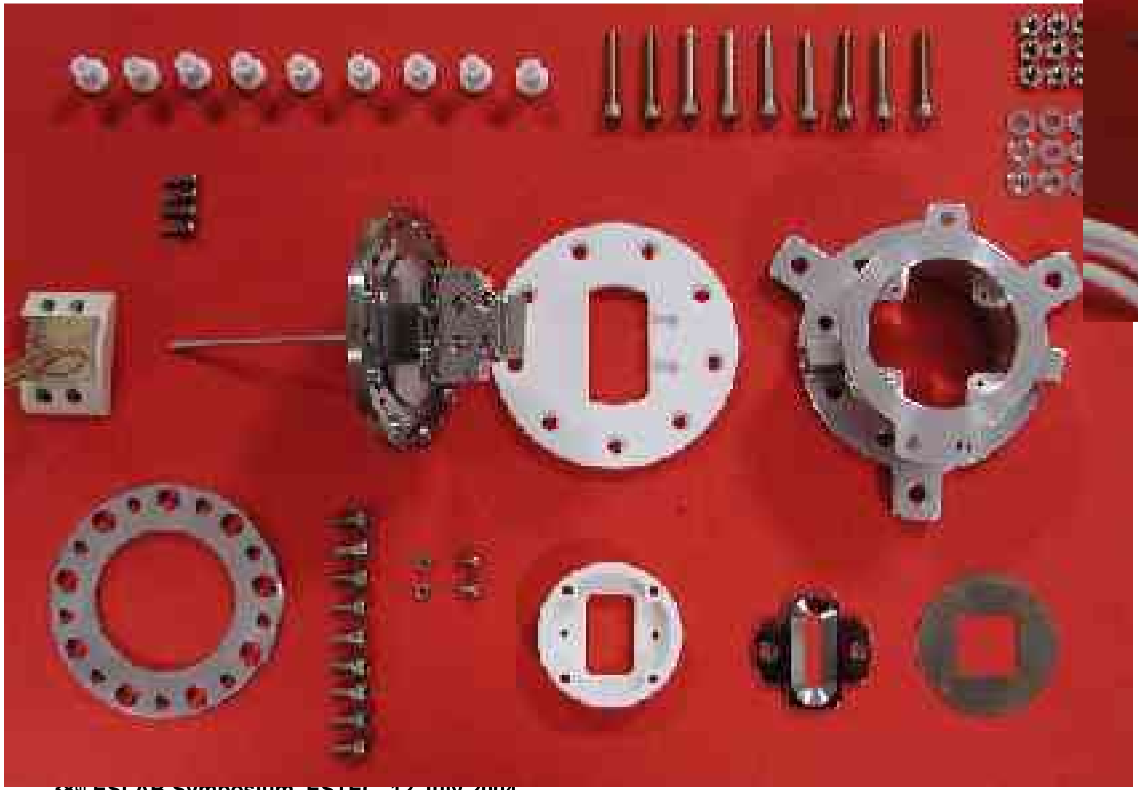


LPF

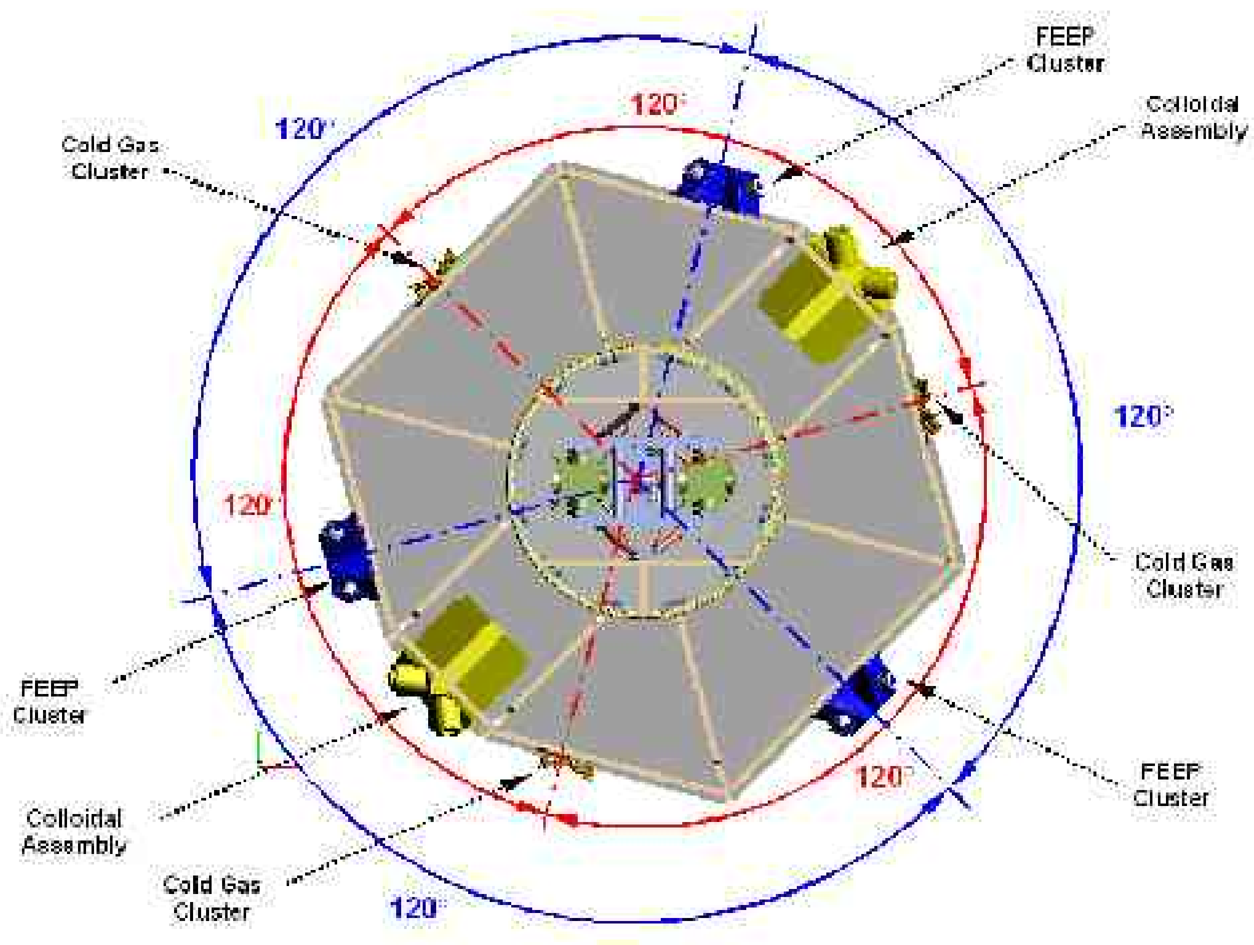
FEEP EM at ALTA

- FEEP's Thruster Unit parts and assembly at ALTA (I).





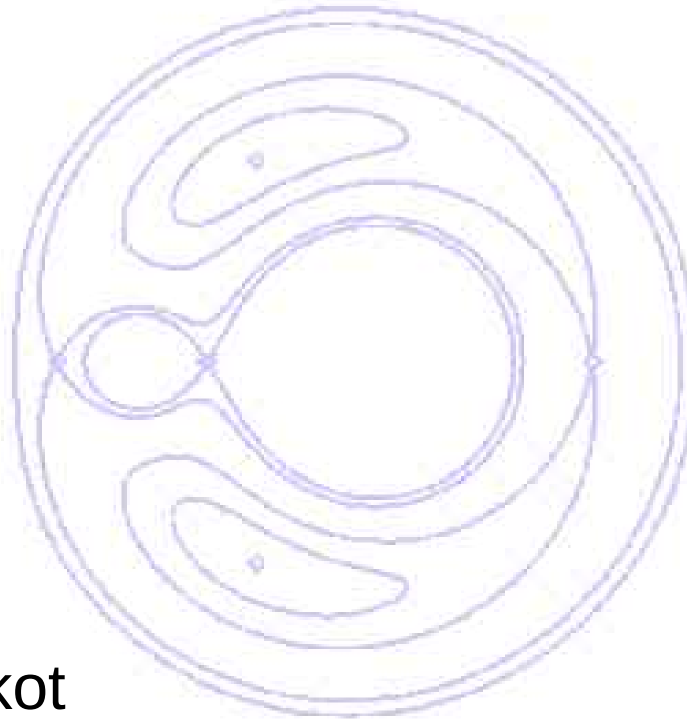
LPF Micropropulsion thruster configuration



LPF Thrust Measurement System

To obtain Direct Thrust Measurements (DTM), a nanobalance has been built by Alenia Spazio (I) with the support of Istituto Metrologico Gustavo Colonnetti (IMCG).

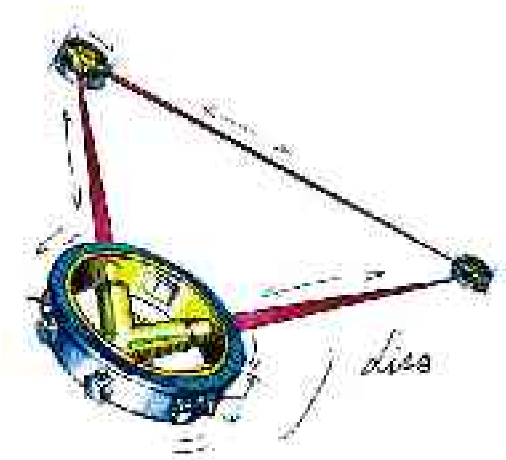
Mission Design



- mission requirements
- operational orbit
- transfer after launch by Rockot

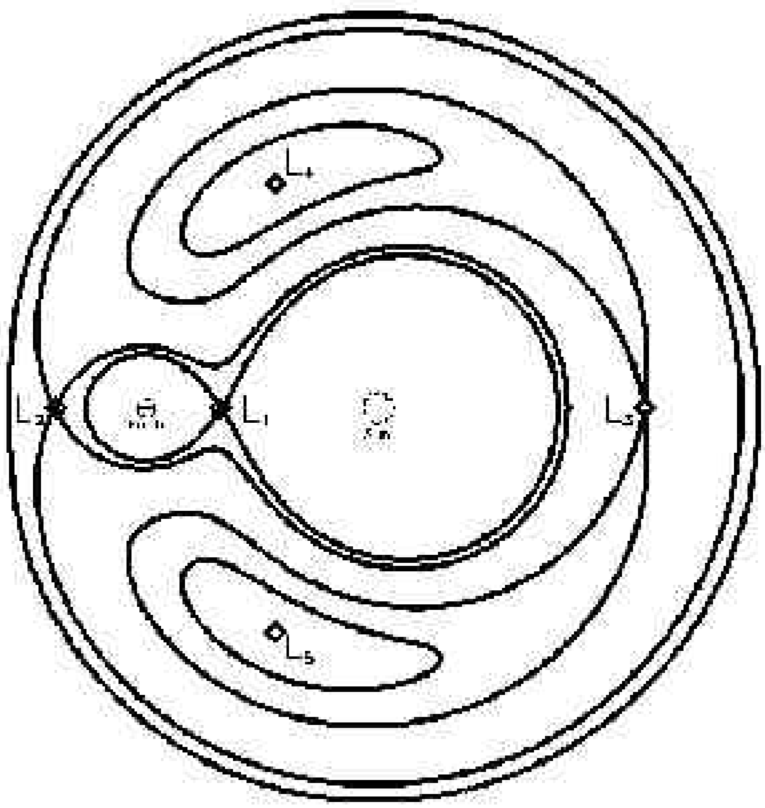
Mission Requirements

- differential acceleration of the two proof masses **$<2.5 \times 10^{-10}$ ms^{-2}**
- rotation rate **$<1.3 \times 10^{-5}$ rad s^{-1} = 64º day^{-1}**
- radiation-induced charge on the proof masses **$<2 \times 10^{7}$ e**
- thermal noise < **10^{-4} K Hz$^{-1/2}$** between 3 and 30 mHz
- magnetic field **< 10^{-5} T**
- all-year launch window
- minimum daily visibility from Villafranca station: 8 hours
- start of operations as soon as possible

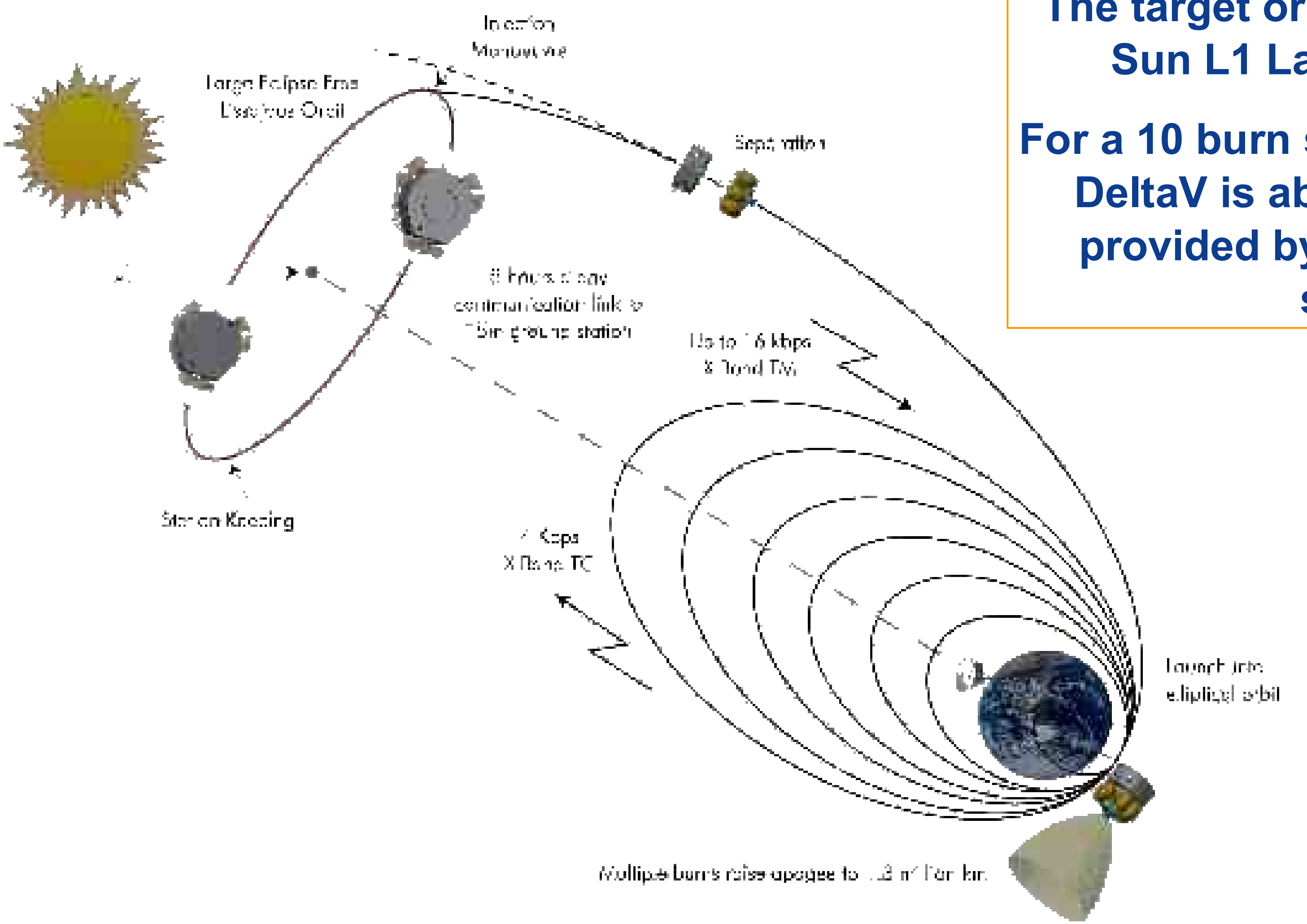


Libration Orbits

- libration orbits are possible at the Lagrange points $L_{1\text{-}5}$, where zero-velocity curves of the 3-body problem intersect
- L_1 is located 1.5 million km from Earth in the direction towards the Sun (figure not to scale)



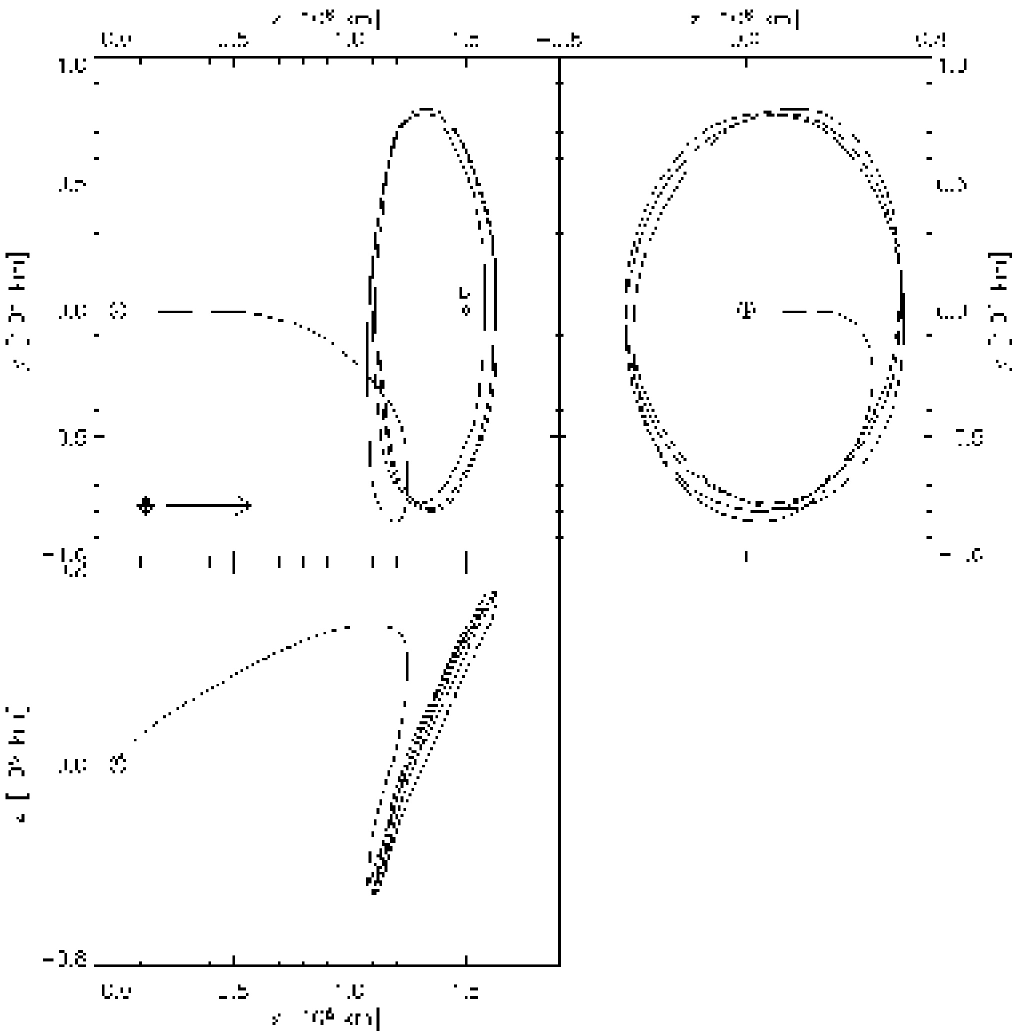
Mission Sequence



The target orbit is at the Earth-Sun L1 Lagrange point.

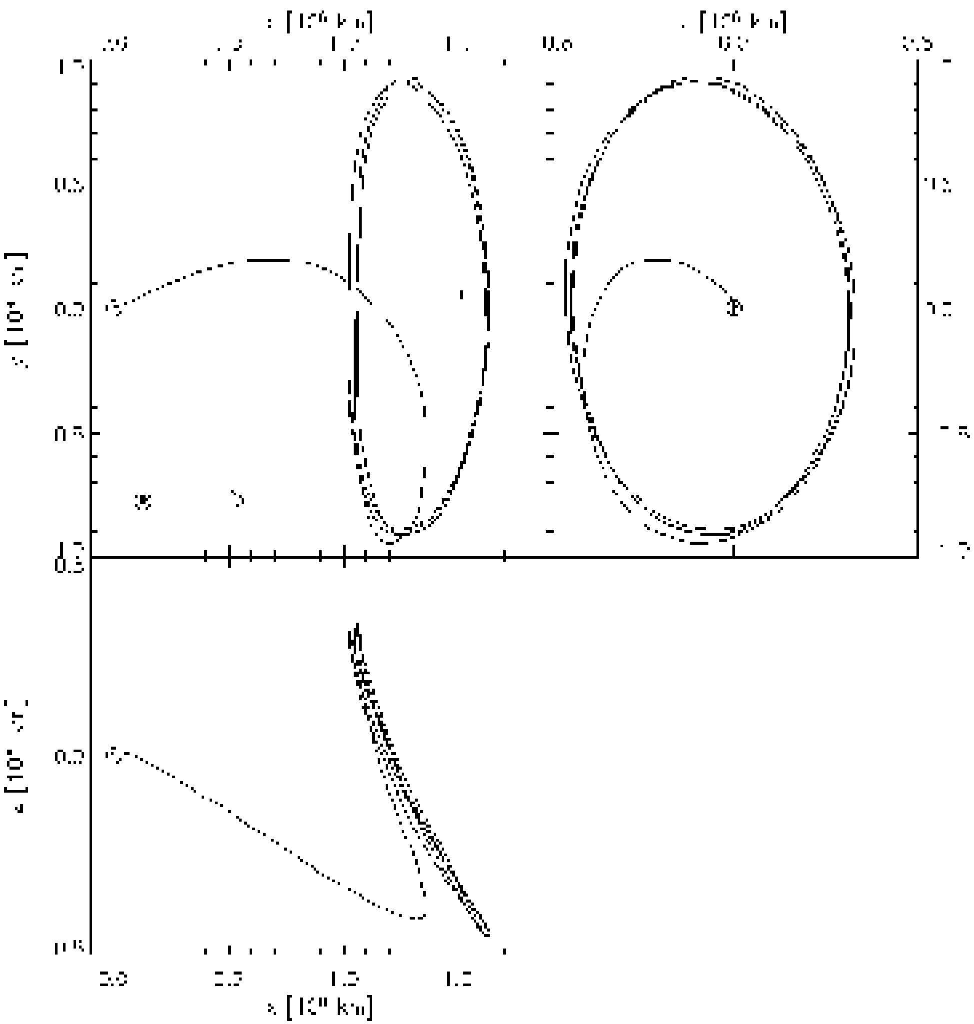
For a 10 burn sequence, the total DeltaV is about 3150 m/sec, provided by the propulsion stage

LPF operational orbit - type 1



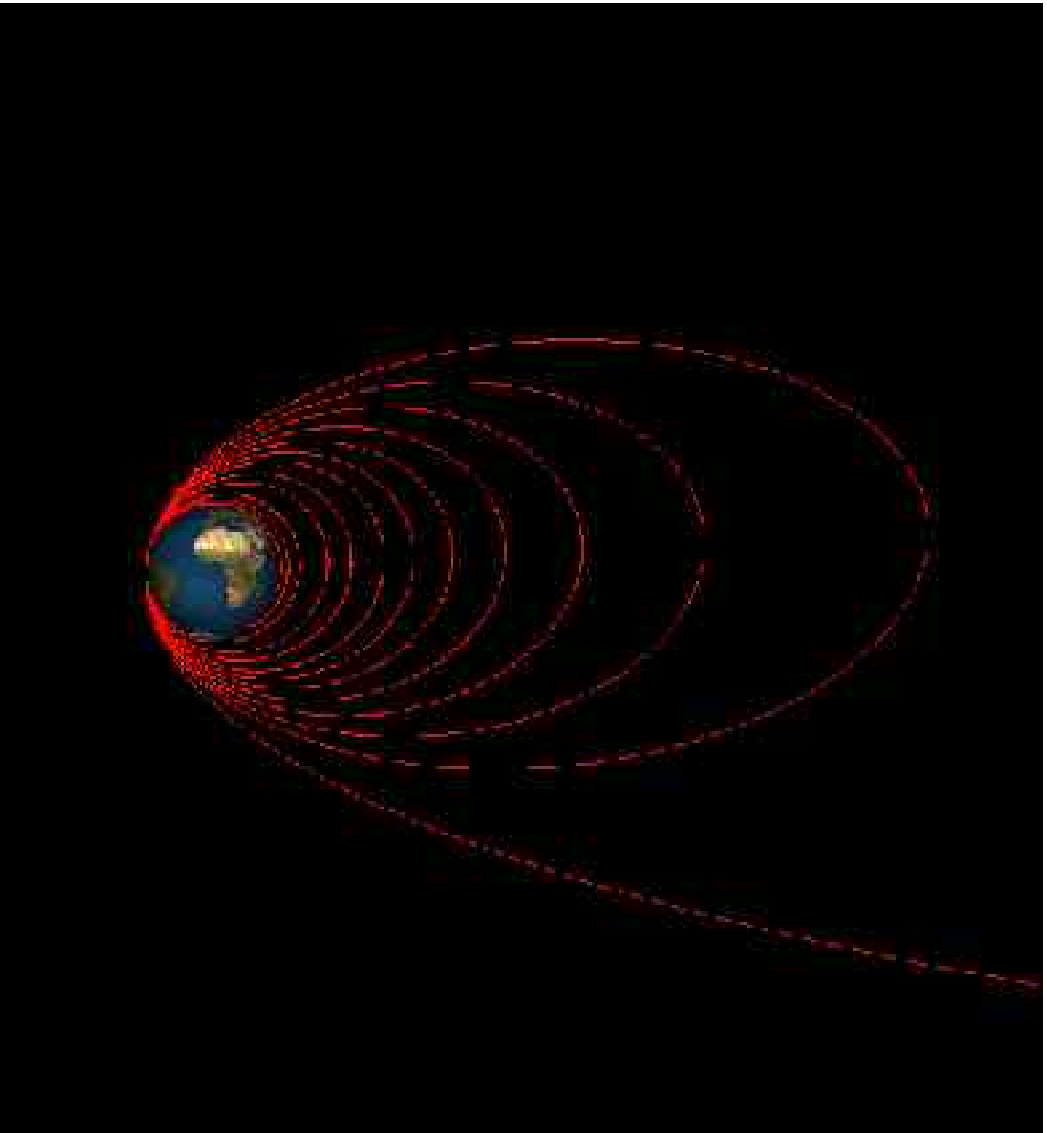
- in the synodic ecliptic frame, a libration orbit circles the Lagrange point
- type-1 orbits are tilted with the northern part away from the Earth, type-2 orbits are tilted towards it
- the average Earth-spacecraft distance is 1.5 million km
- the in-plane amplitude is 800,000 to 1,000,000 km
- the out-of-plane amplitude is 500,000 to 800,000 km
- The shape of the orbit determined the design of the on-board antenna

LPF operational orbit - type 2



- on a perfectly circular orbit, the Sun-Earth-spacecraft angle is constant and the spacecraft can theoretically use a fixed high-gain antenna
- however, circular orbits have large out-of-plane amplitudes and can be seen from a ground-station at northern mid-latitudes for only 2 hours during winter
- thus the transfer conditions and type (1 or 2) of the operational orbit are chosen to minimise the maximum negative declination and the variation of the Sun-Earth-spacecraft angle, for launches all year round

LPF Transfer Sequence - Rockot



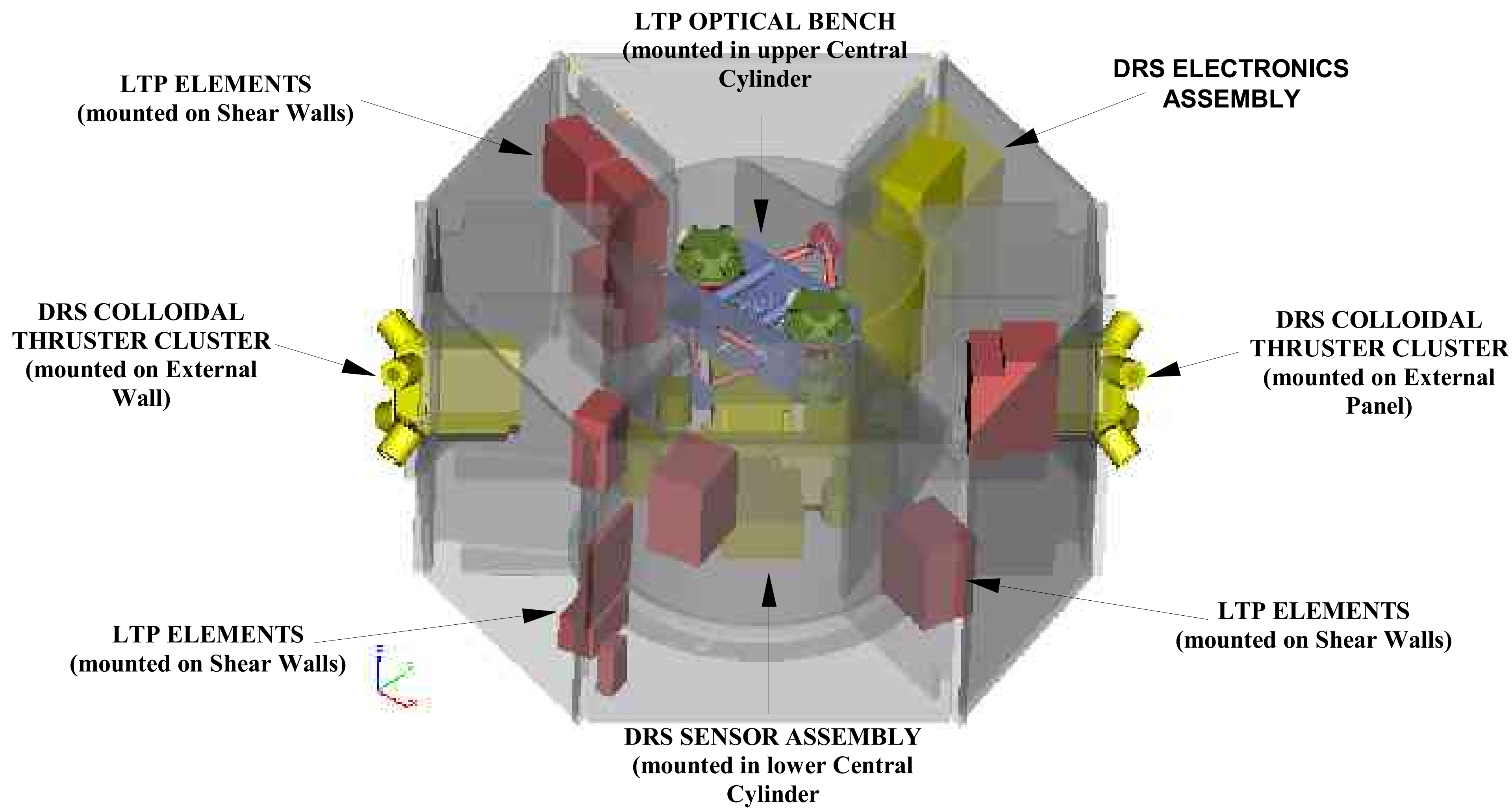
- initial parking orbit: 900x200km, 63º inclination
- a total Δv of more than 3 km s^{-1} is needed, which must be split in 11 individual manoeuvres in order to contain gravity loss
- between the manoeuvres there must be time for tracking, orbit determination, and commanding
- the total duration of the apogee-raise sequence is 9 days

LPF Mission Design Summary

- launch by Rockot in early 2008 into a slightly elliptic low Earth orbit with an inclination of 63°
- the orientation of the line of apsides of the parking orbit must be adjusted to target for an operational orbit that fulfils the station visibility constraints
- a sequence of 11 manoeuvres brings the spacecraft to a transfer towards L_1, the Sun-facing Lagrange point of the Sun-Earth system, 1.5 million km from Earth
- depending on the launch date, the operational orbit is a type-1 or type-2 Lissajous orbit in order to achieve a minimum of 8 hours of visibility from the ground-station in Villafranca

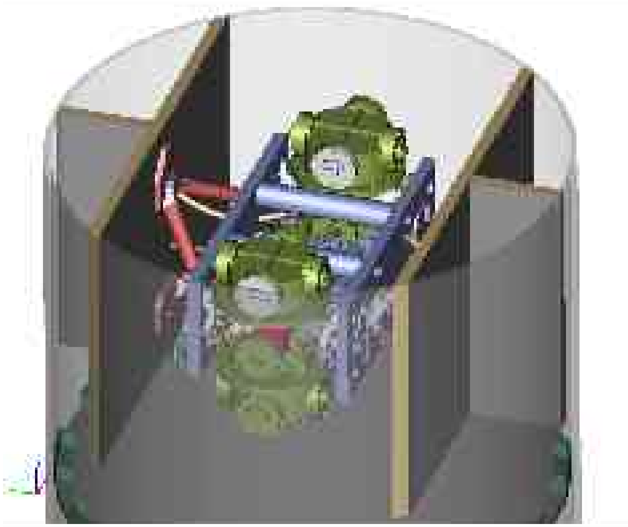
Payload Interfaces

LPF LTP & DRS Accommodation

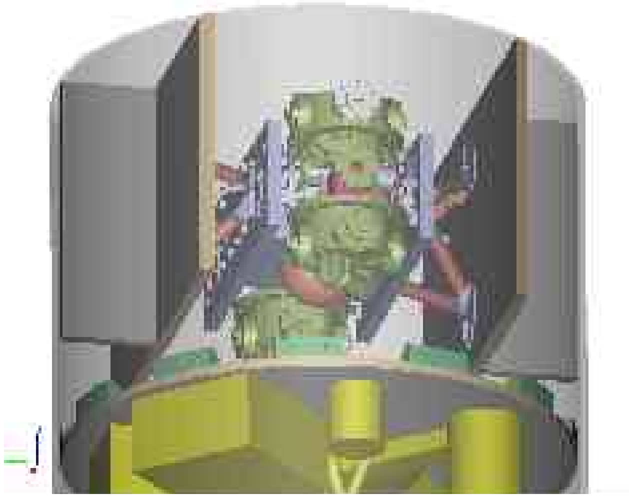


LPF — LTP Accommodation

- The LTP consists of the following assemblies
  - the Optical Bench
  - a Power Control Unit/Data Management Unit
  - two Front End Electronics SAU
  - a Charge Management System UV Lamp Assembly
  - a Charge Management Electronics Assembly
  - a Phase Meter
  - a Laser
  - a Modulation Bench
  - diagnostic probes (solar pressure sensors, magnetometer & particle detector)



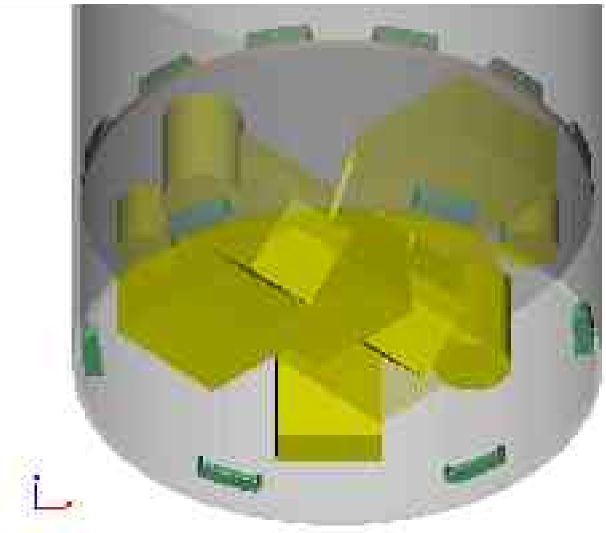
- LTP Optical Bench is mounted in the Central Cylinder between two Shear Panels
  - Mounted on 8 glass fibre struts (likely to change)
  - Symmetric mounting to minimise gravitational and thermal asymmetries



- The remaining LTP Elements are distributed around the Shear and External Walls to minimise the overall gravitation disturbance

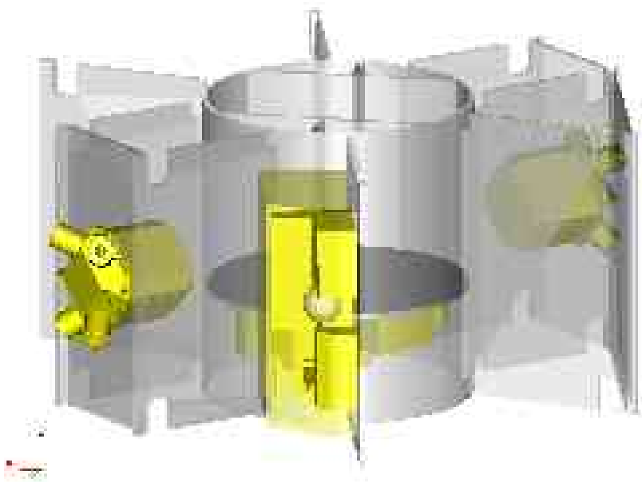
DRS Accommodation

- The DRS consists of four assemblies
  - one Sensor Assembly
  - one Electronics Assembly
  - two Colloidal Thruster Assemblies



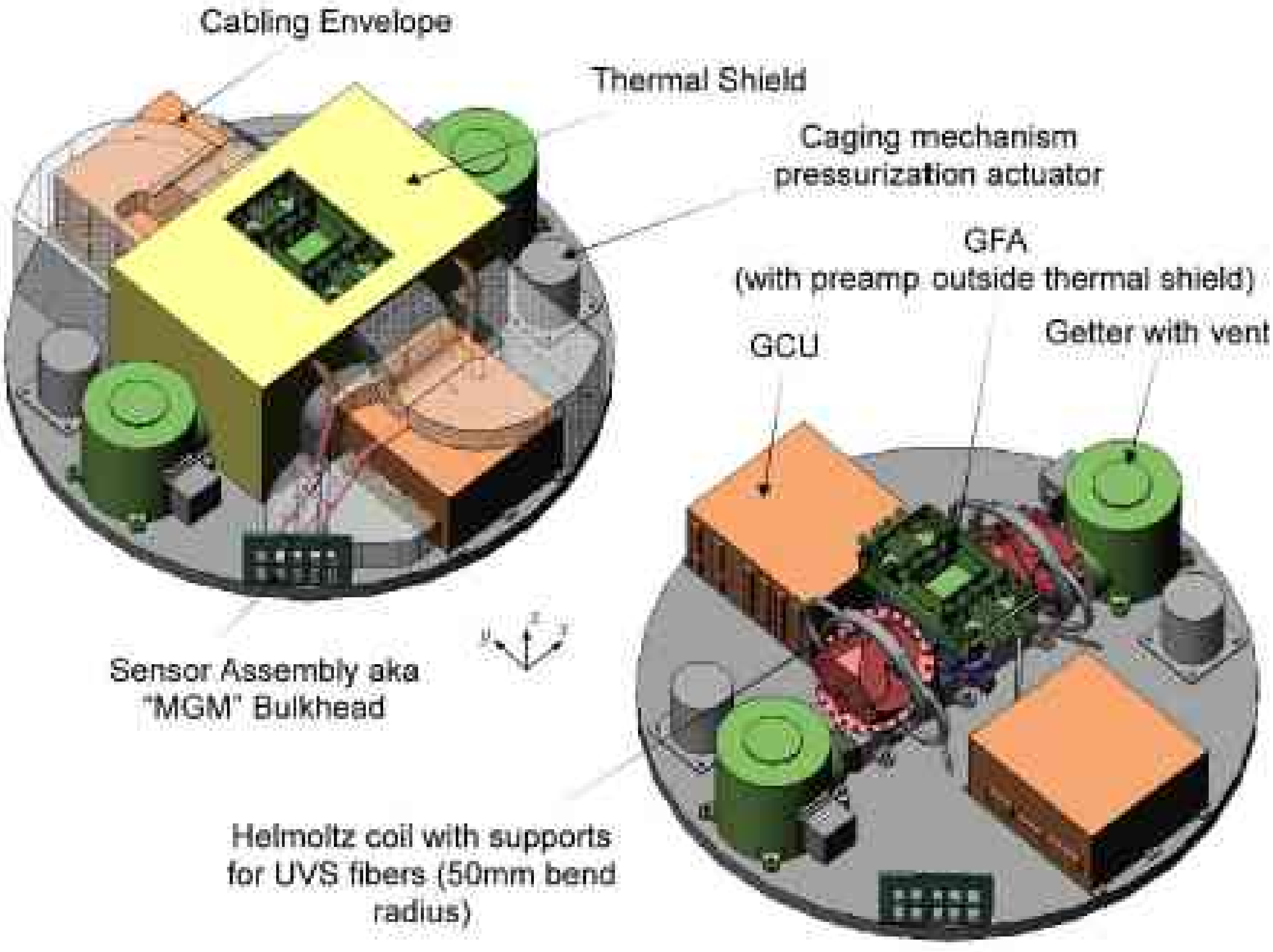
- The Sensor Assembly is mounted on the underside of a 40 mm thick panel in the lower third of the Central Cylinder

- The Electronics Assembly is mounted on a dedicated Shear Wall located orthogonally to the LTP sensitive axis



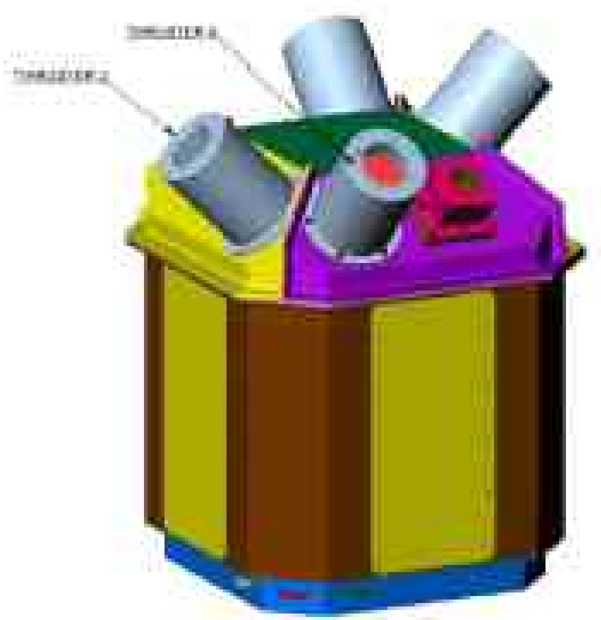
- The Colloidal Assemblies are mounted on opposing External Walls

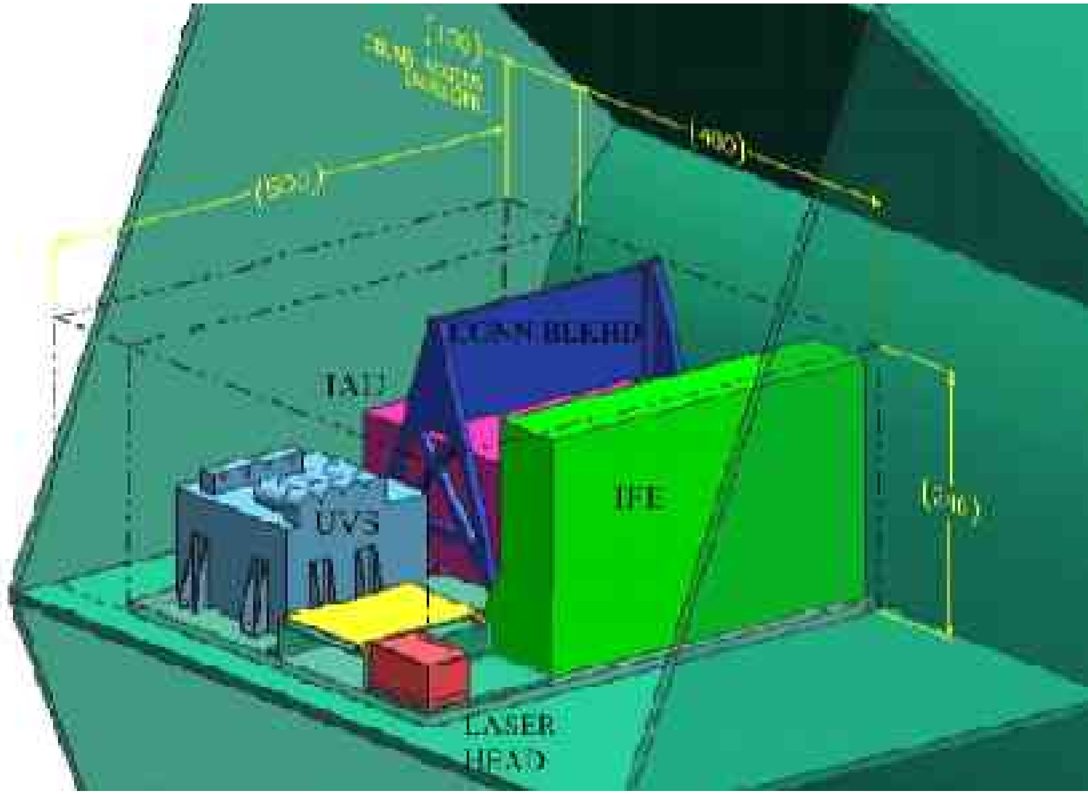
DRS Sensor Assembly



LPF DRS Thrusters & Electronics

Colloidal Thruster Assembly

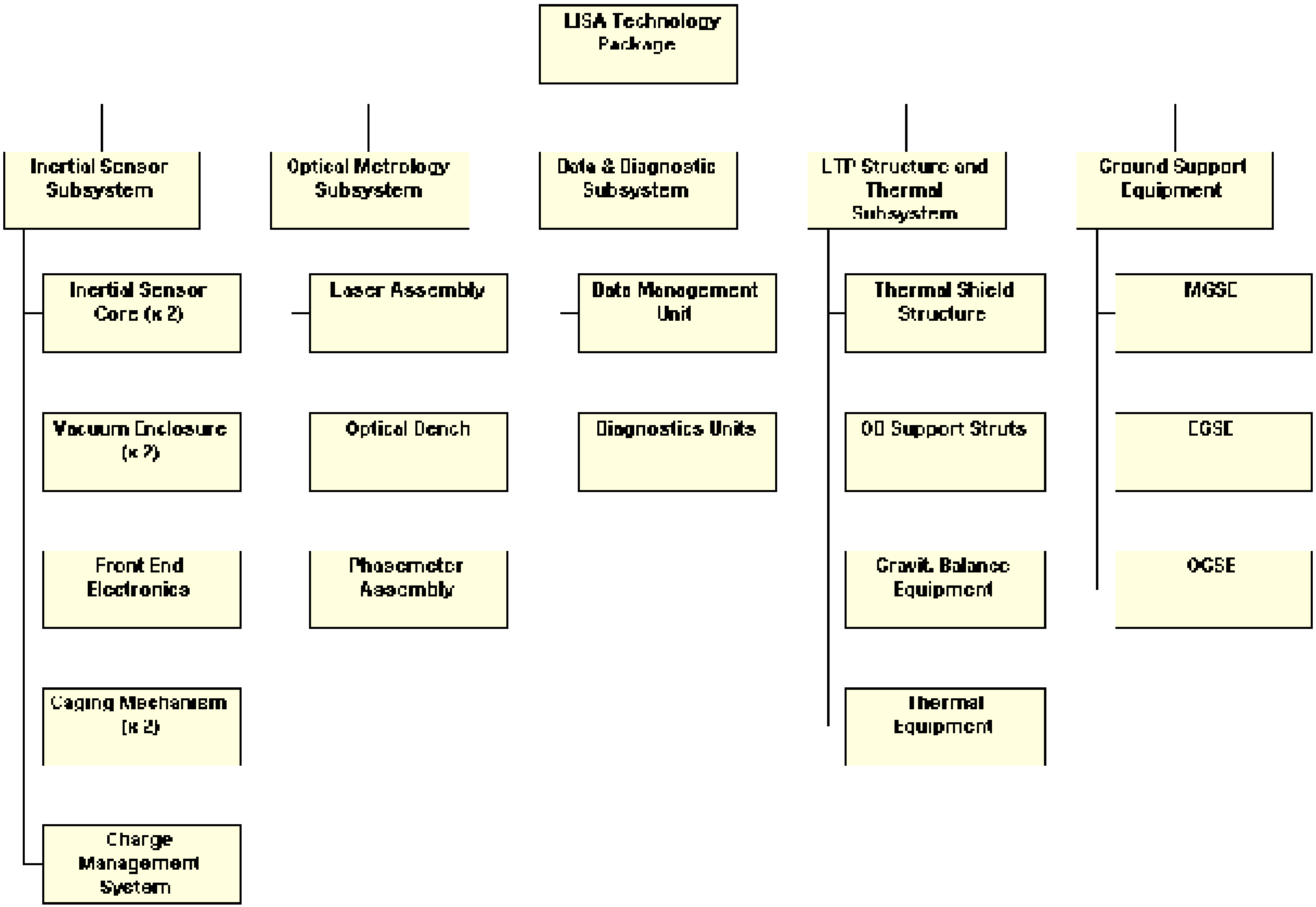




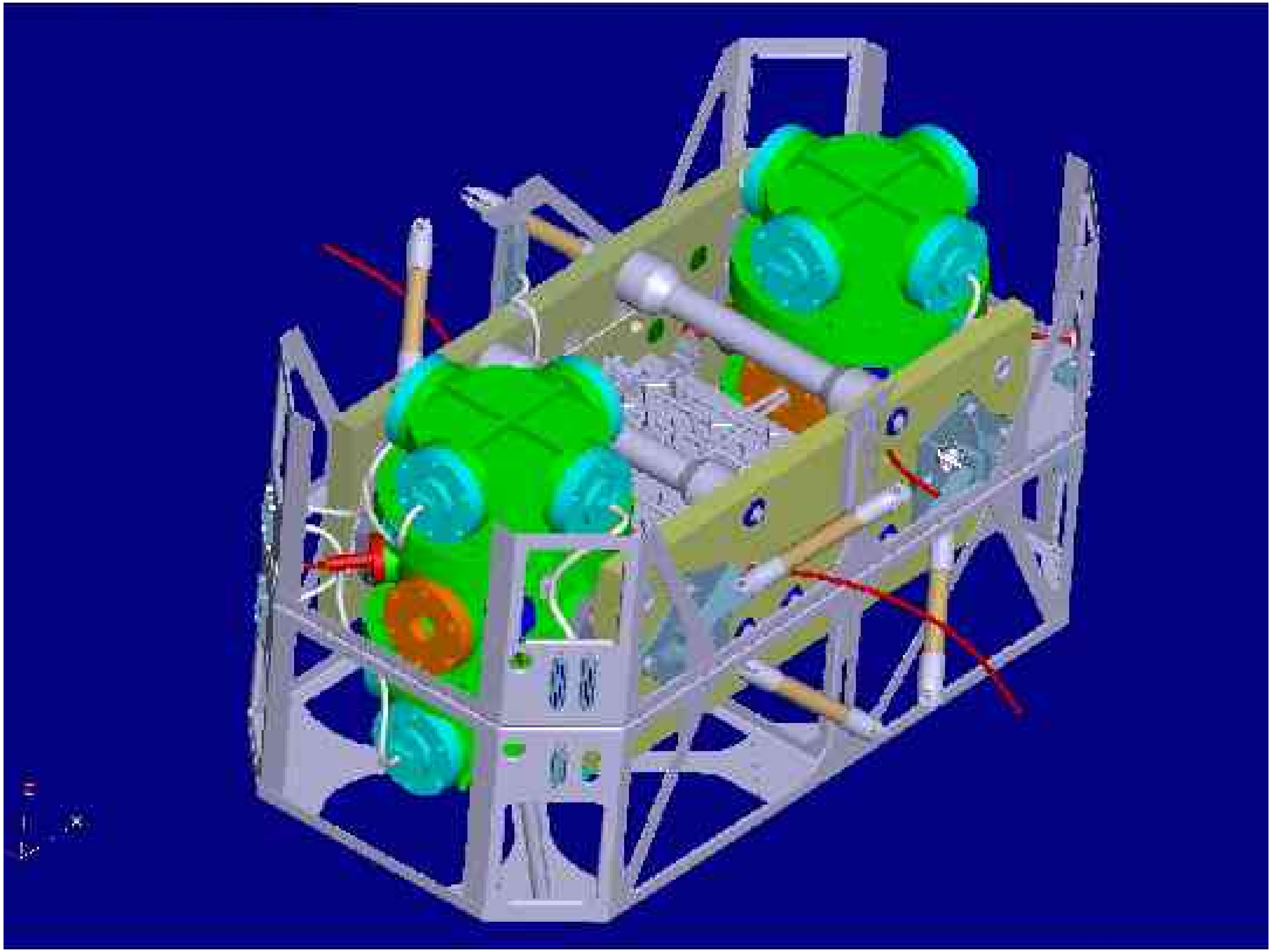
Electronics Assembly

The LISA Test-flight Package

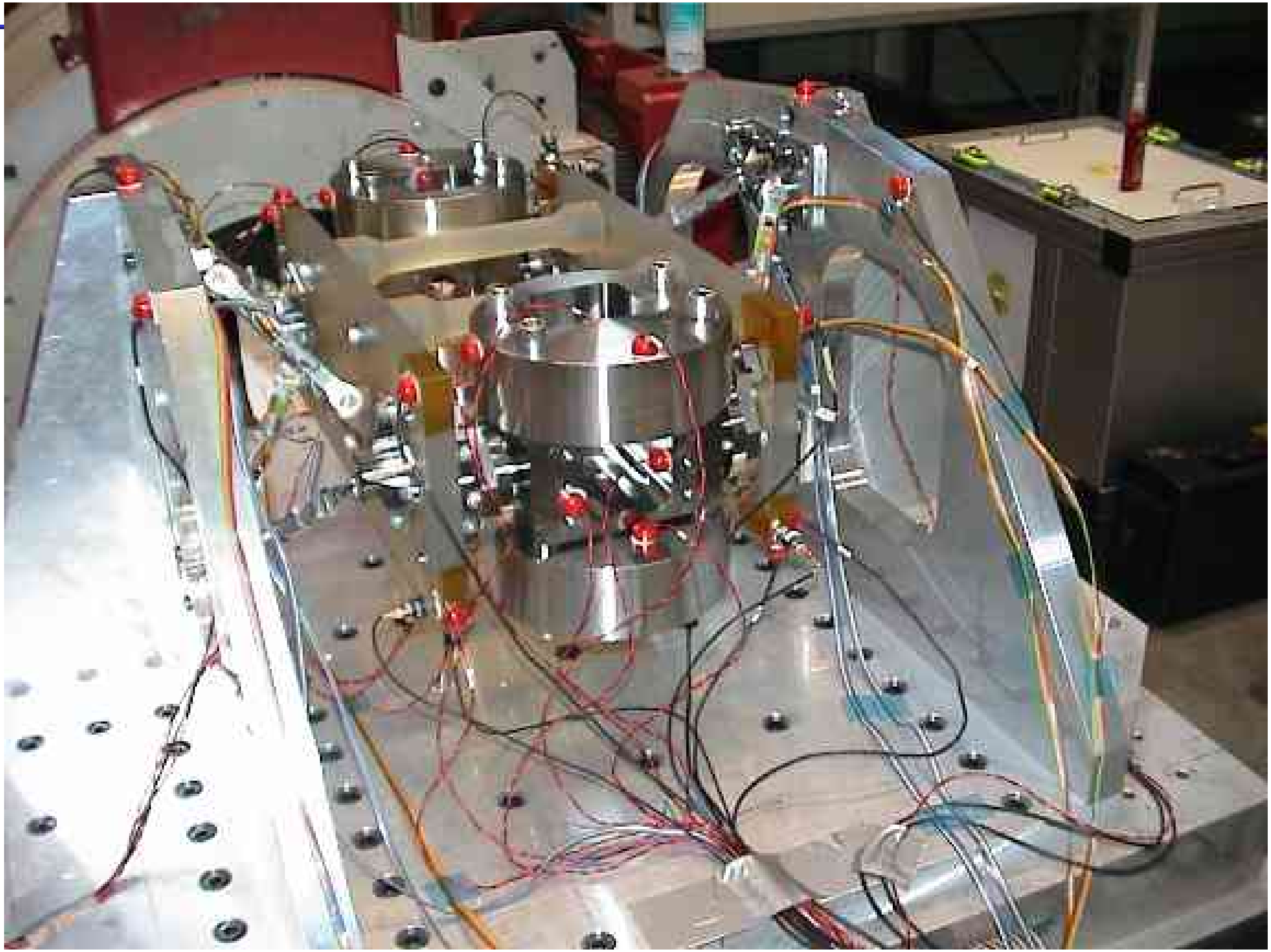
The LTP architecture

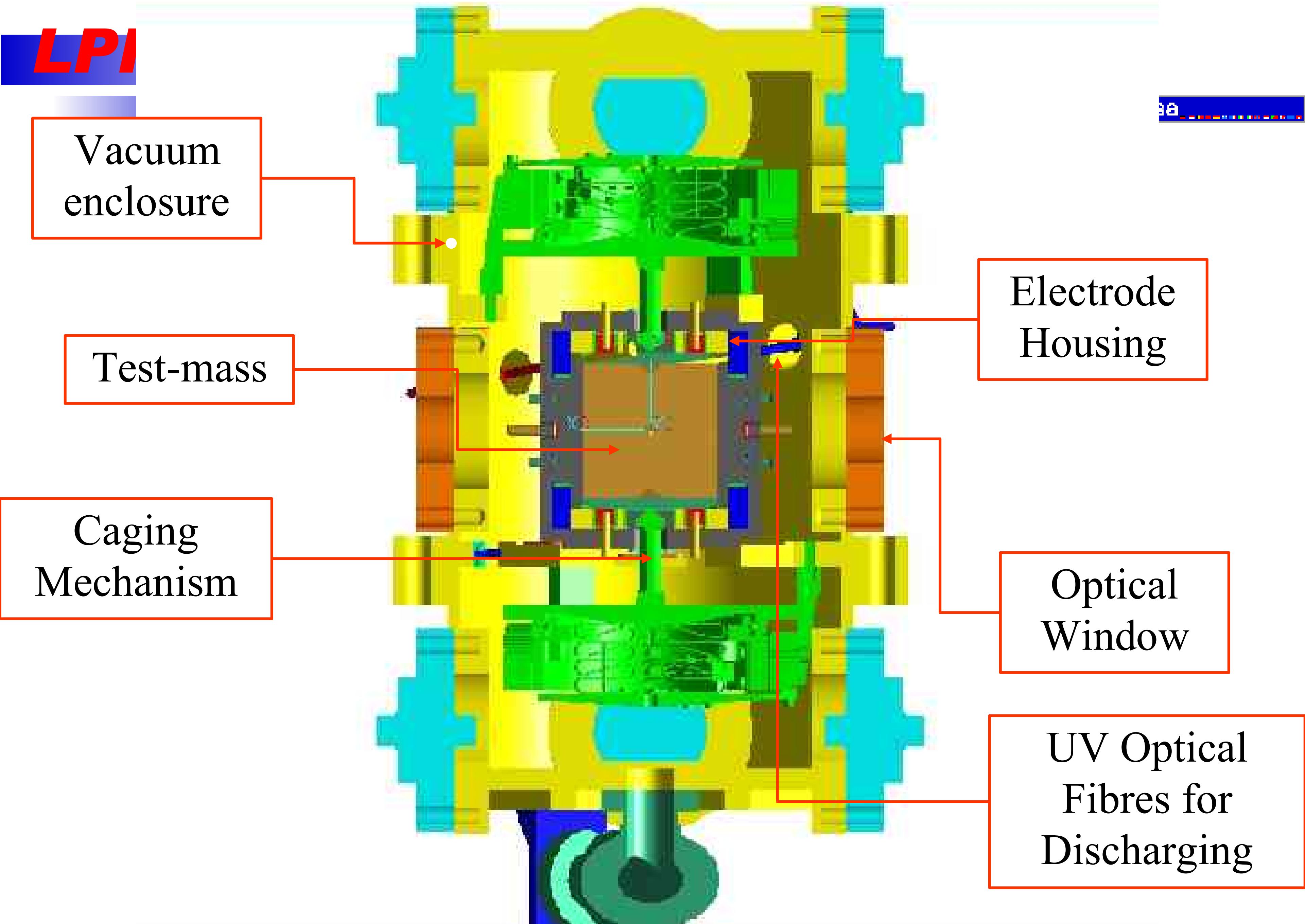


The LISA Test-flight Package



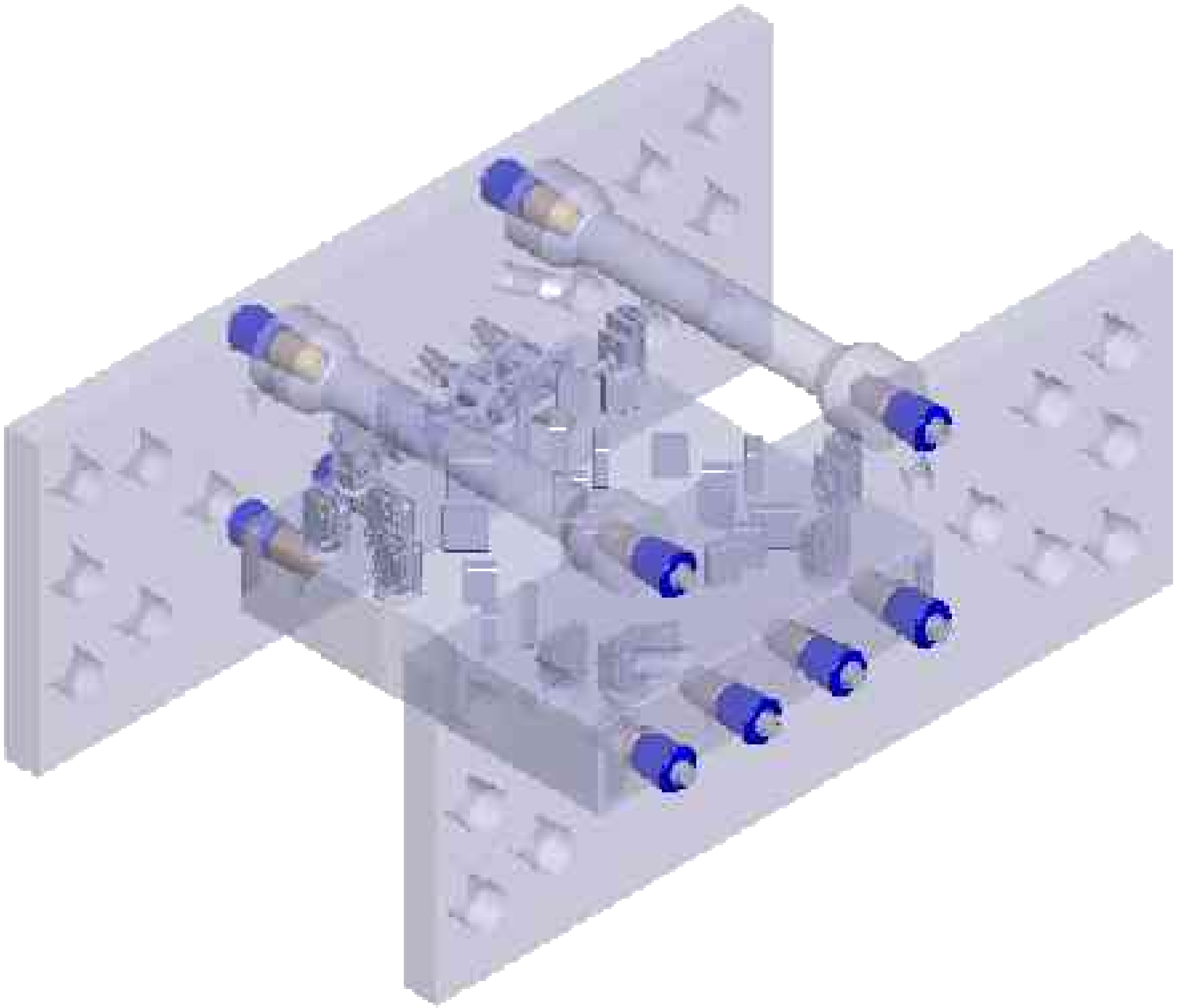
LPF The LTP EM




Vacuum enclosure
Test-mass
Caging Mechanism
Electrode Housing
Optical Window
UV Optical Fibres for Discharging

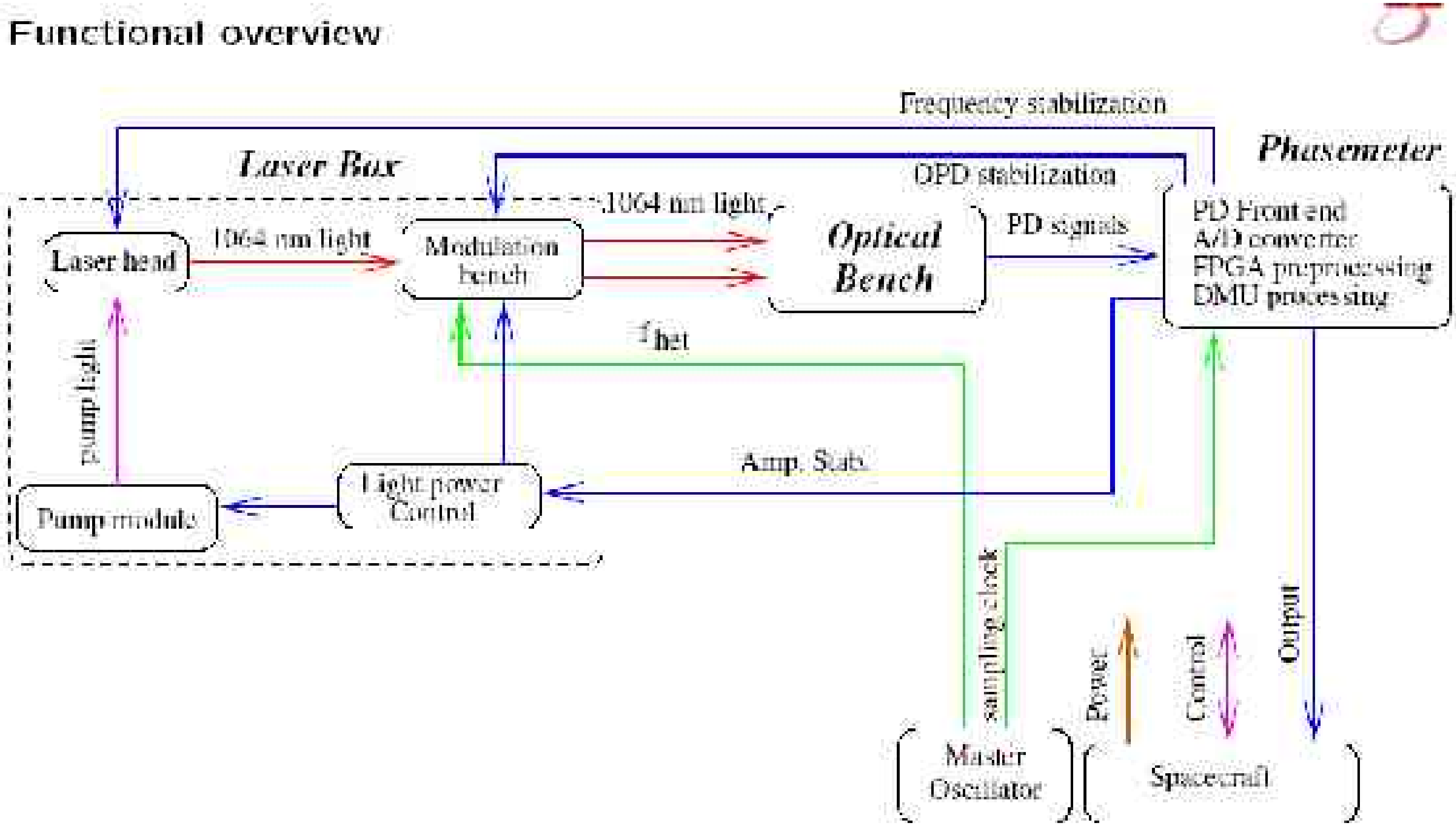
G.D.Racca

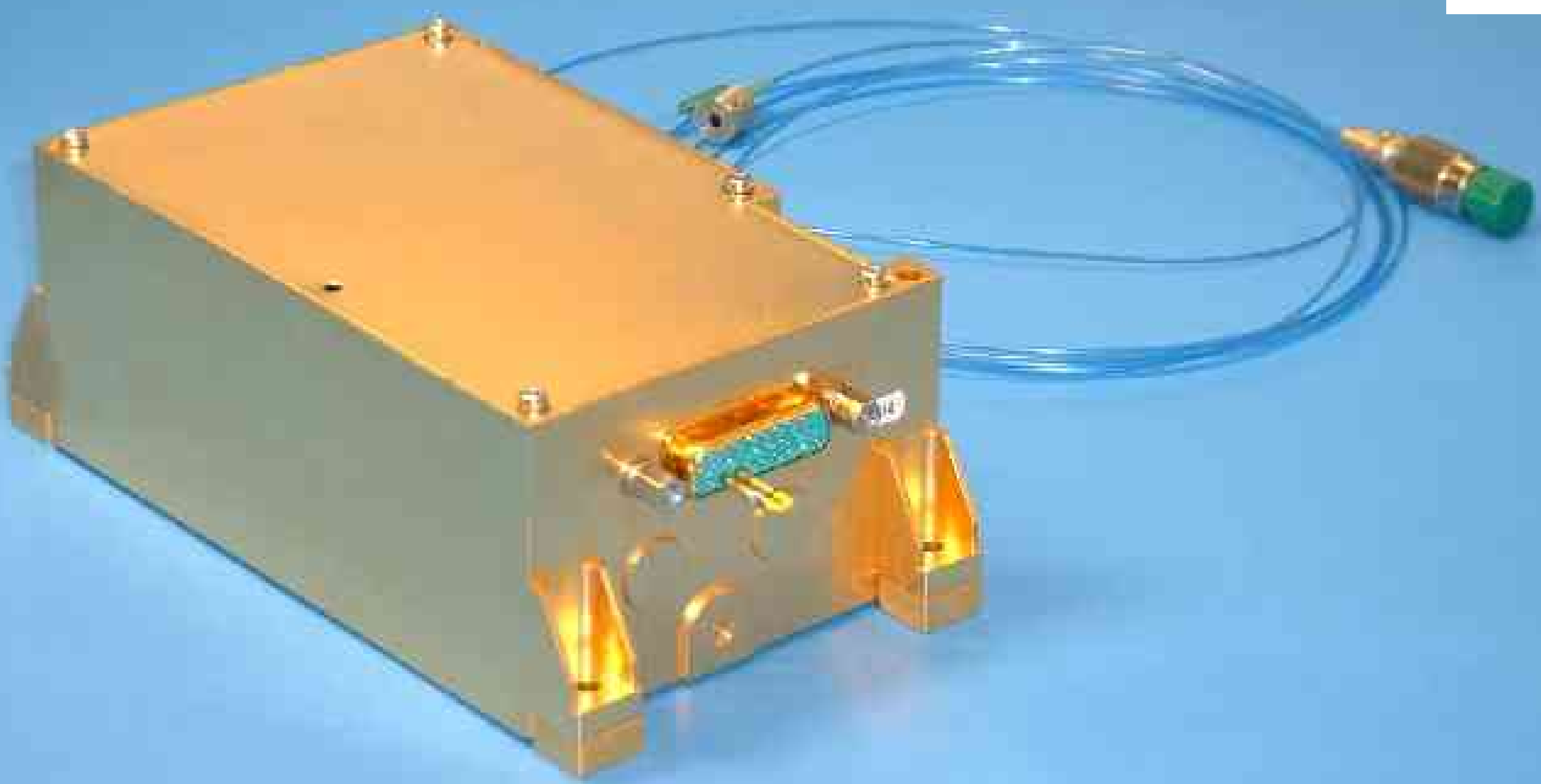
The LTP Optical Bench



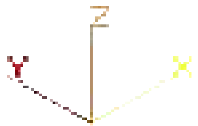
LPF The LTP Optical Bench EM

Laser Metrology





Laser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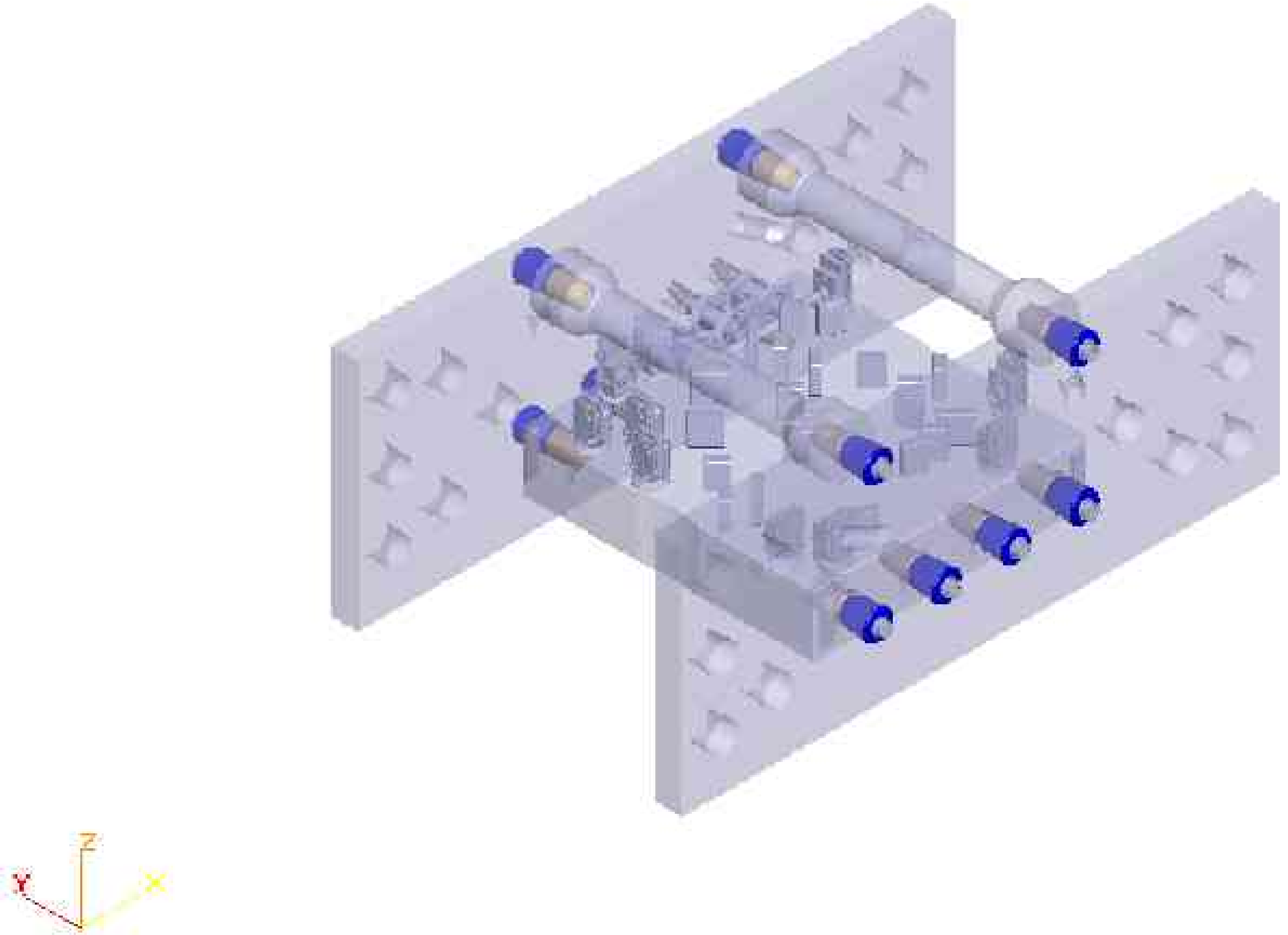
Y
X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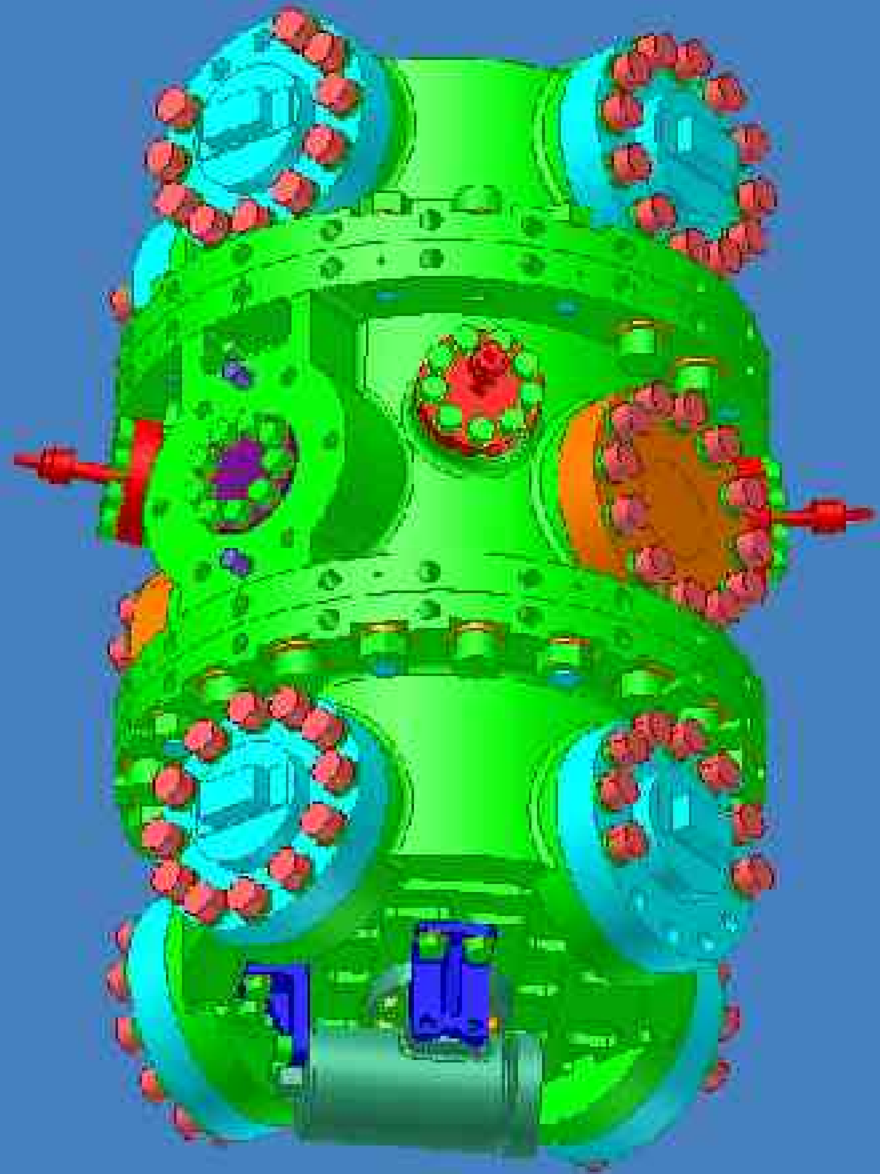

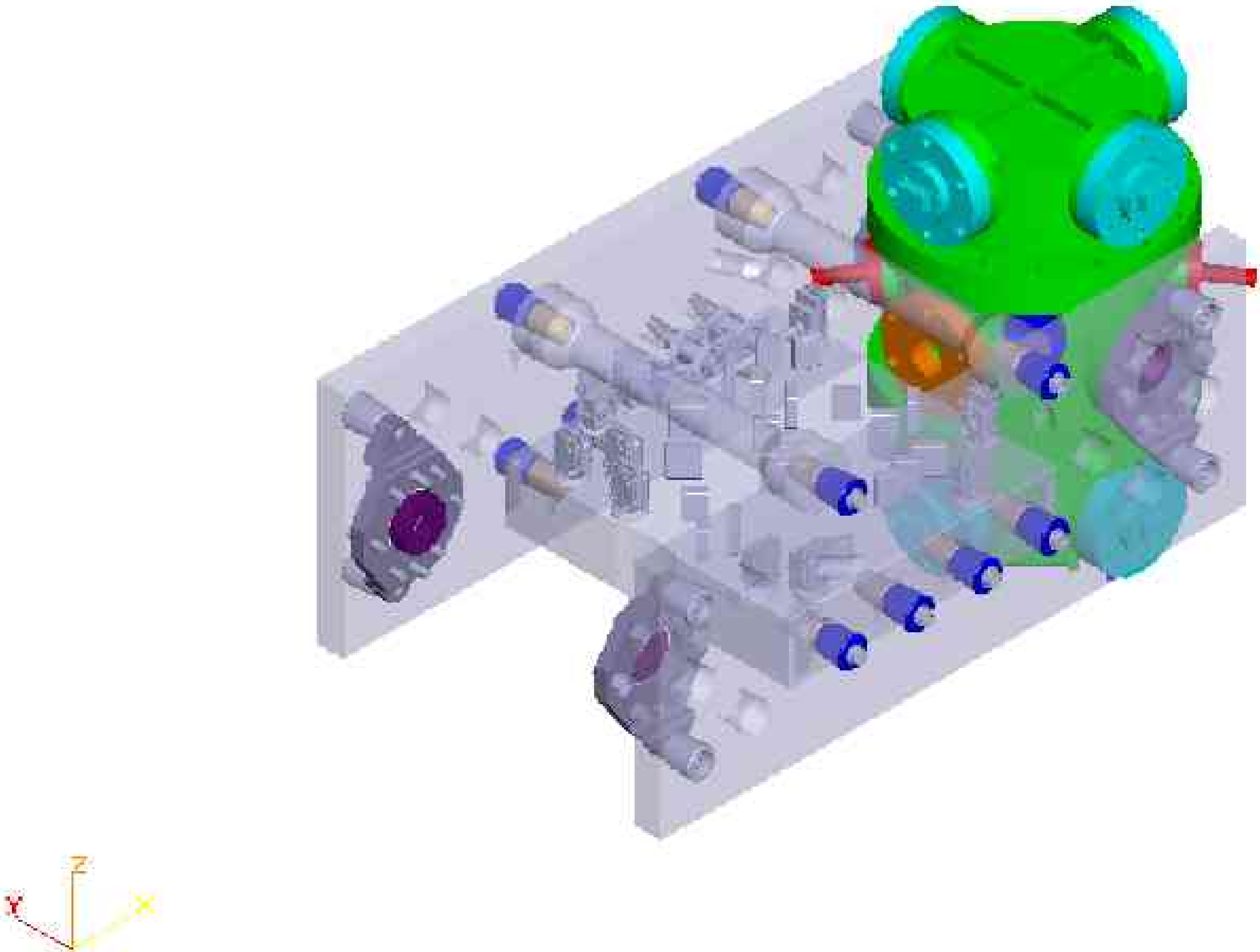
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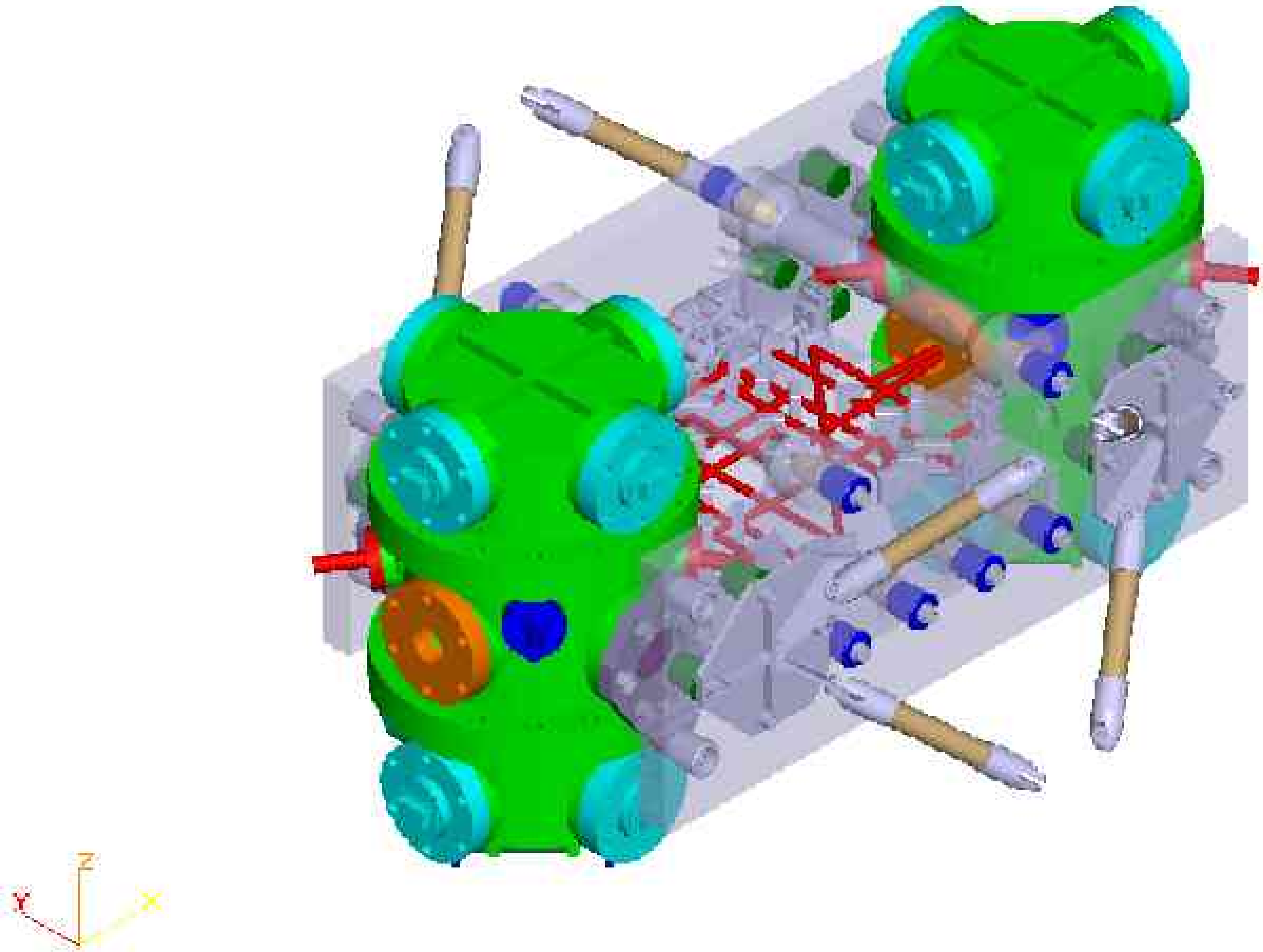
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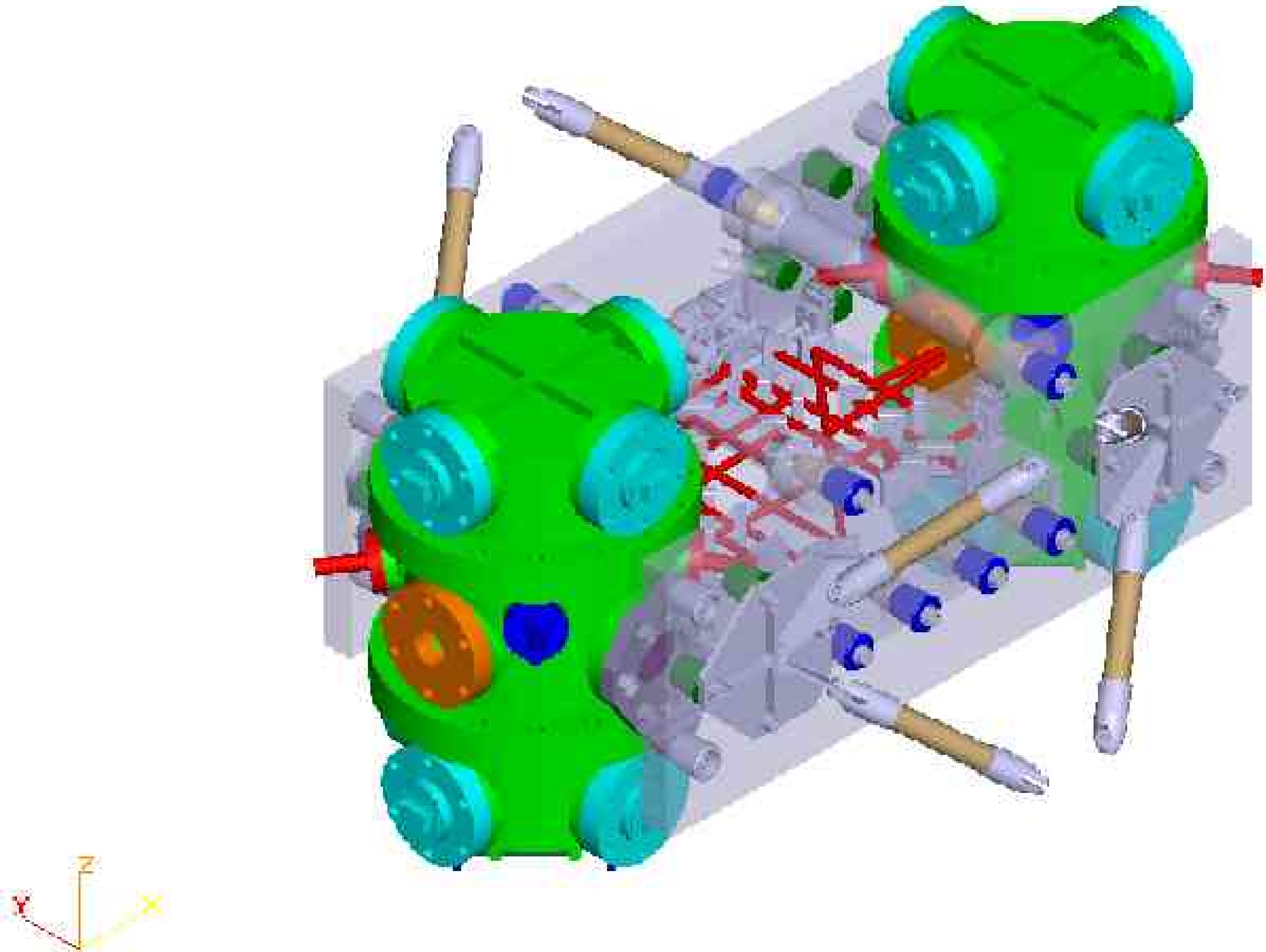
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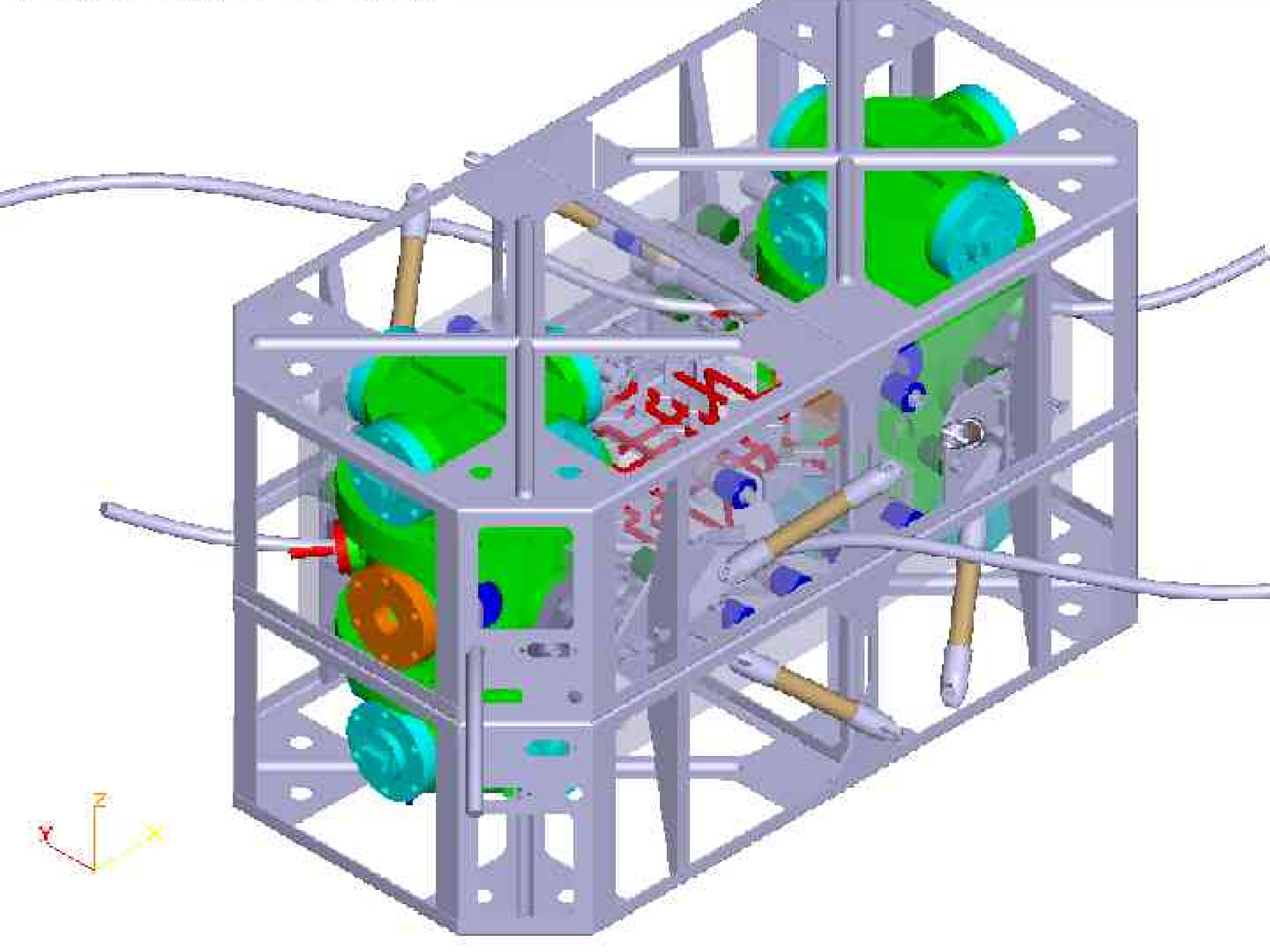

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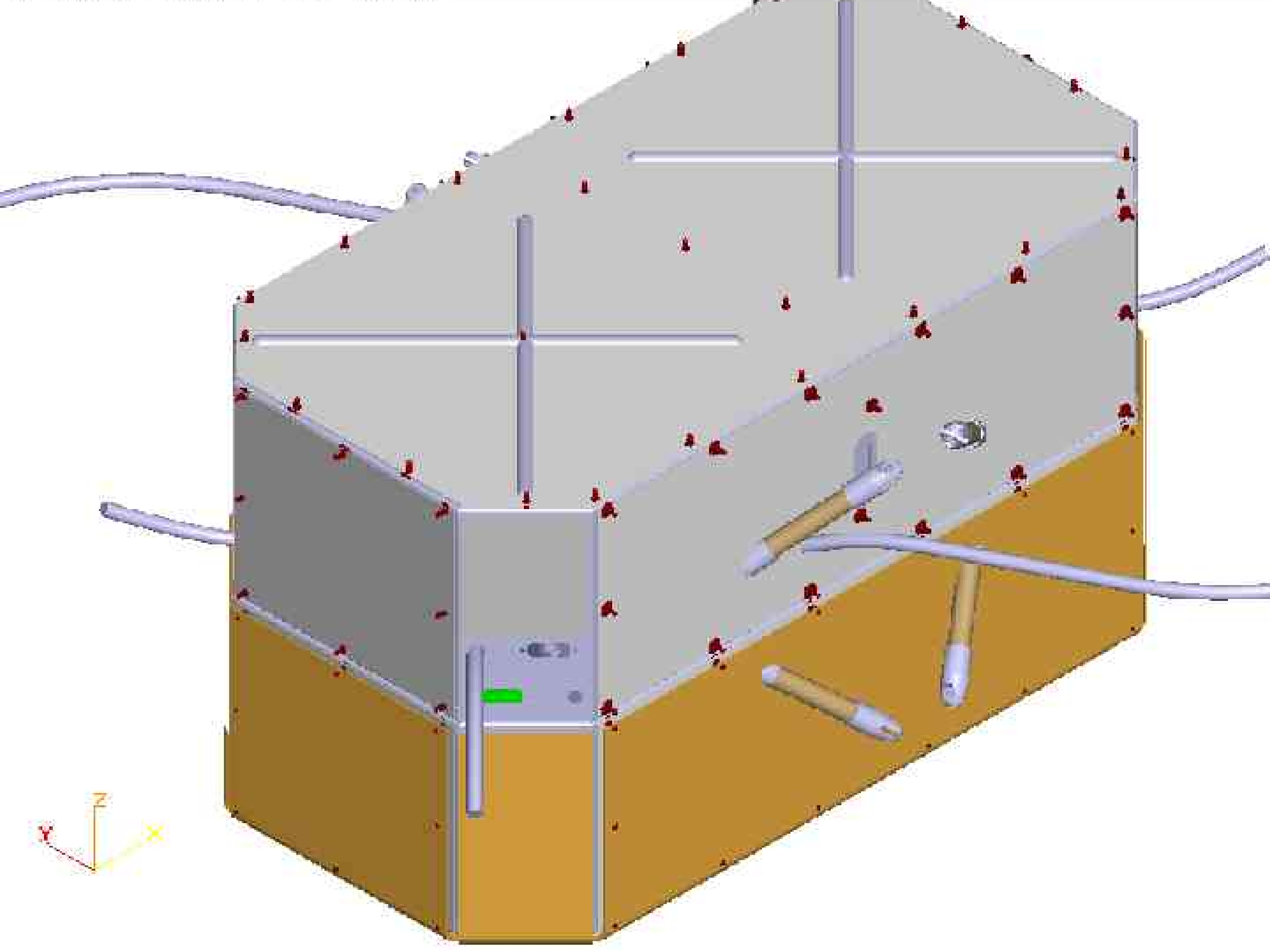
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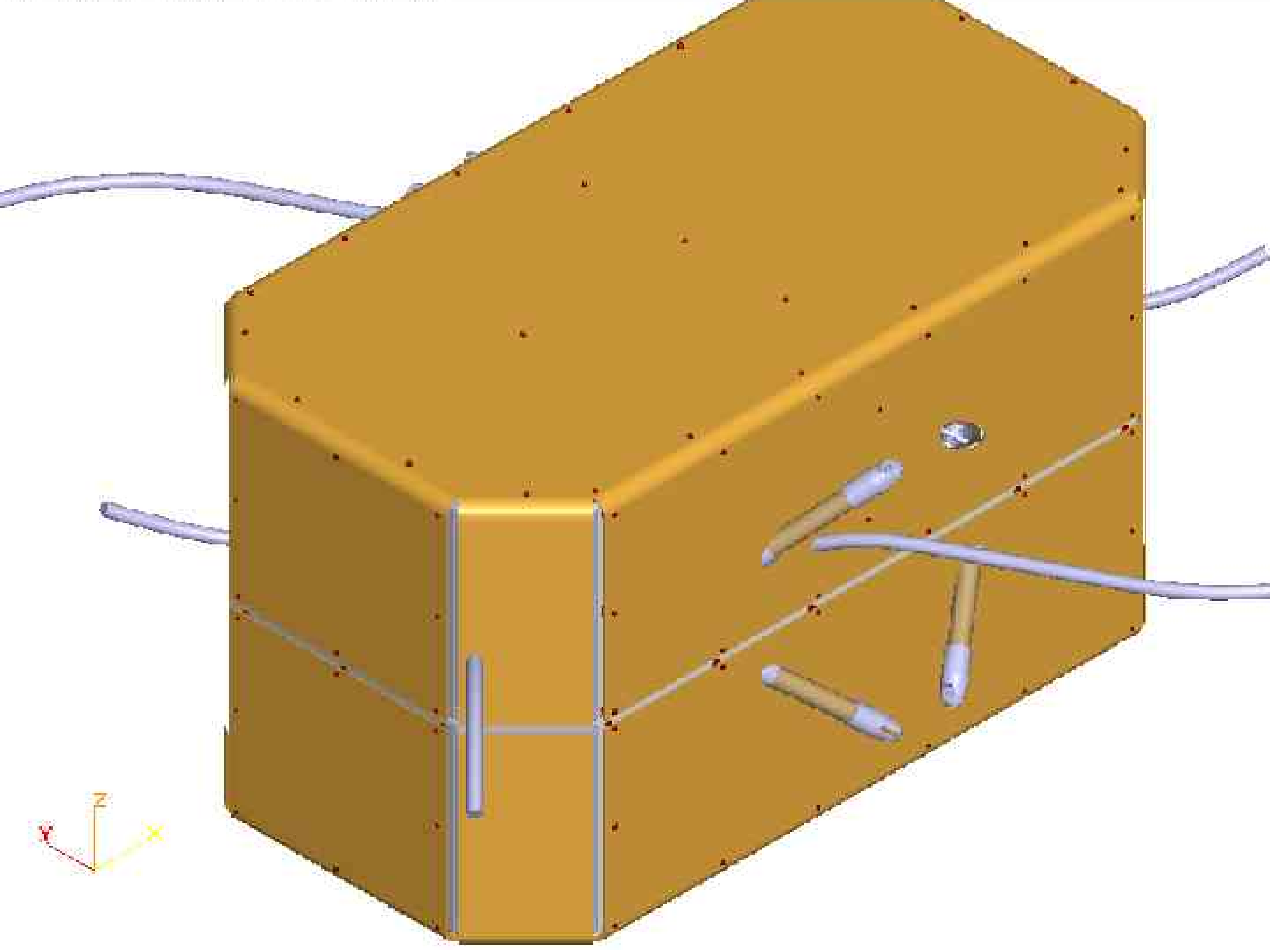


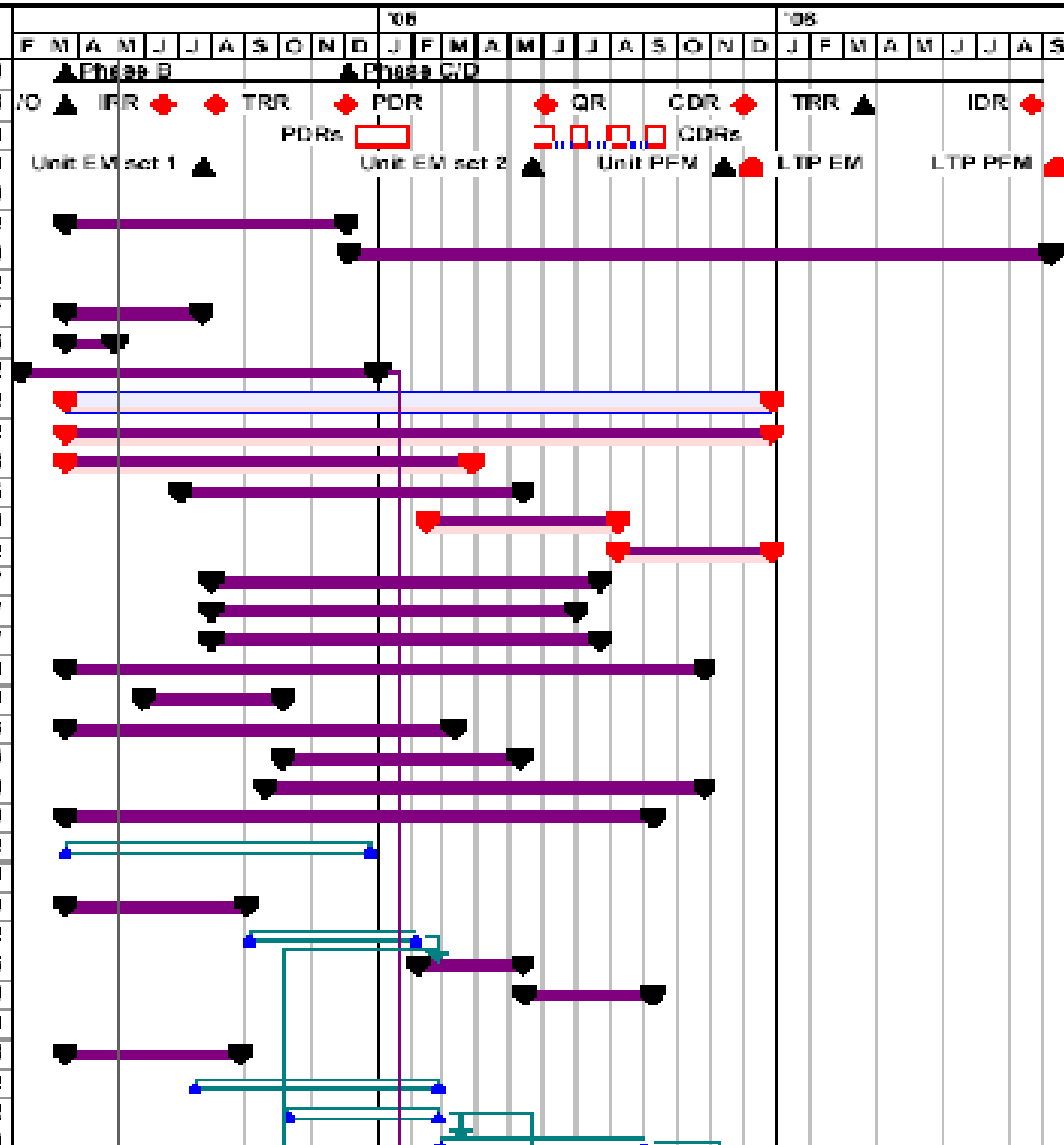
Z
Y
X

LPF

LTP schedule (1)

esa

ID	Task Name	Finish
1	PROJECT PHASES	01/09
4	LTP Reviews	22/08
13	Unit Reviews	20/09
16	Delivery Milestones	14/09
22	Project Office	08/09
23	Phase B	03/12
35	Phase C/D T B D	08/09
46	TRP/CTP Program (EM set 1)	31/12
47	Inertial Sensor Development	23/07
50	Optical Bench Development	05/05
55	IS/LTP Ground Test Program	31/12
59	S/S & Units Developments	27/12
60	Inertial Sensor Subsystem	27/12
61	Design and Analyses	28/03
70	LLI procurement	13/05
75	ISC MAIT	08/08
78	IS AIT	27/12
83	Caging Assembly	22/07
84	Caging Mechanism FM	01/07
91	Caging Control Unit	22/07
95	Charge Management Device	26/10
96	CMD Design	05/10
100	CMD EM Upgrade	11/03
104	ISUK FM MAIT	11/06
108	ULU/Harness FM MAIT	26/10
117	Front End Electronics	09/09
118	SAU & PCU FM LLI procurement	24/12
119	PCU FM	09/09
120	PCU Design update	03/09
125	PCU EM MAIT	04/02
126	PCU FM manufacturing	13/05
130	PCU FM acceptance tests	09/09
139	SAU EM/FM	02/09
140	SAU Archit. Design	27/08
145	Detailed Design	26/02
146	EM MAIT	25/02
147	FM MAIT	02/09

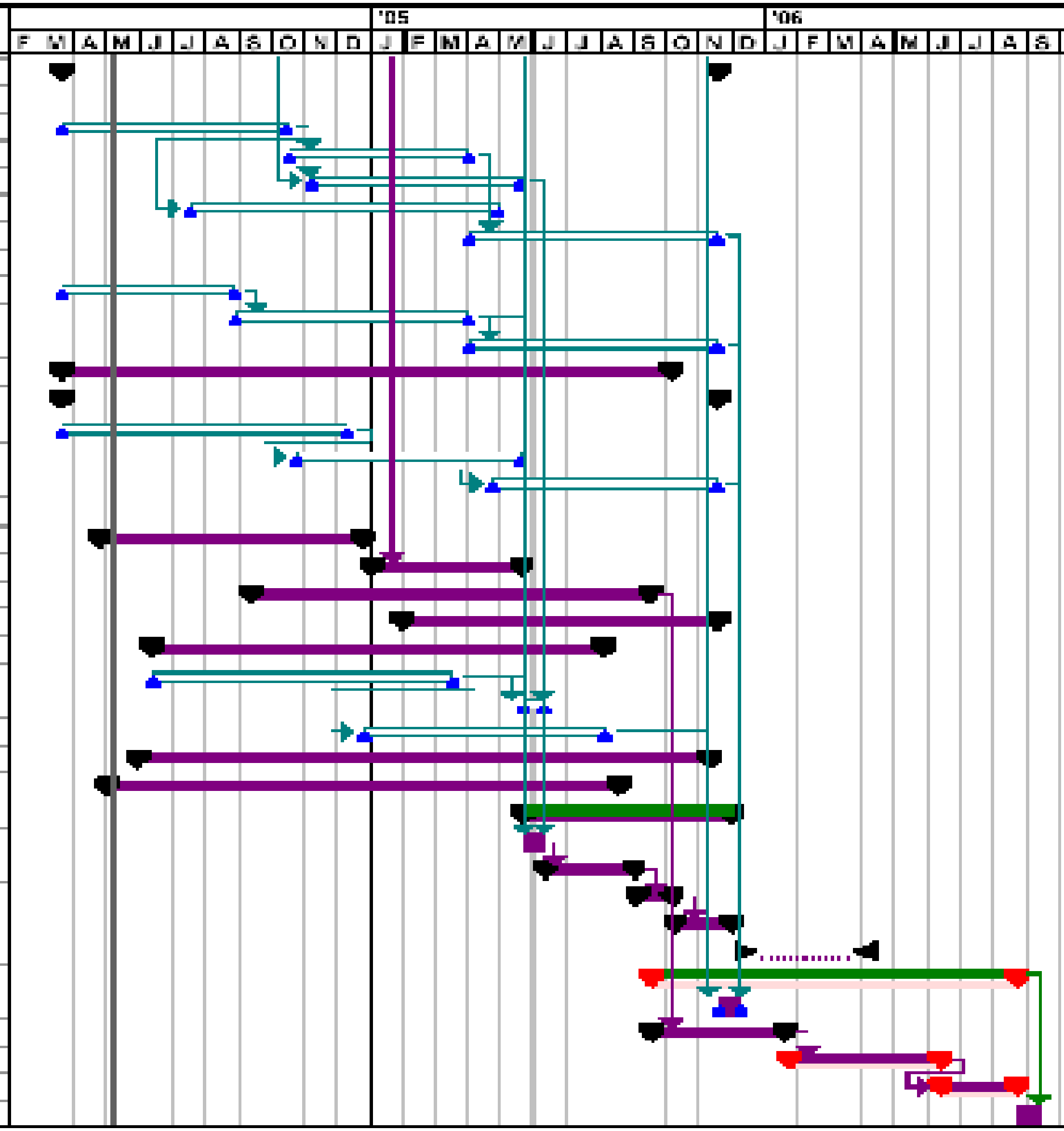


LPF

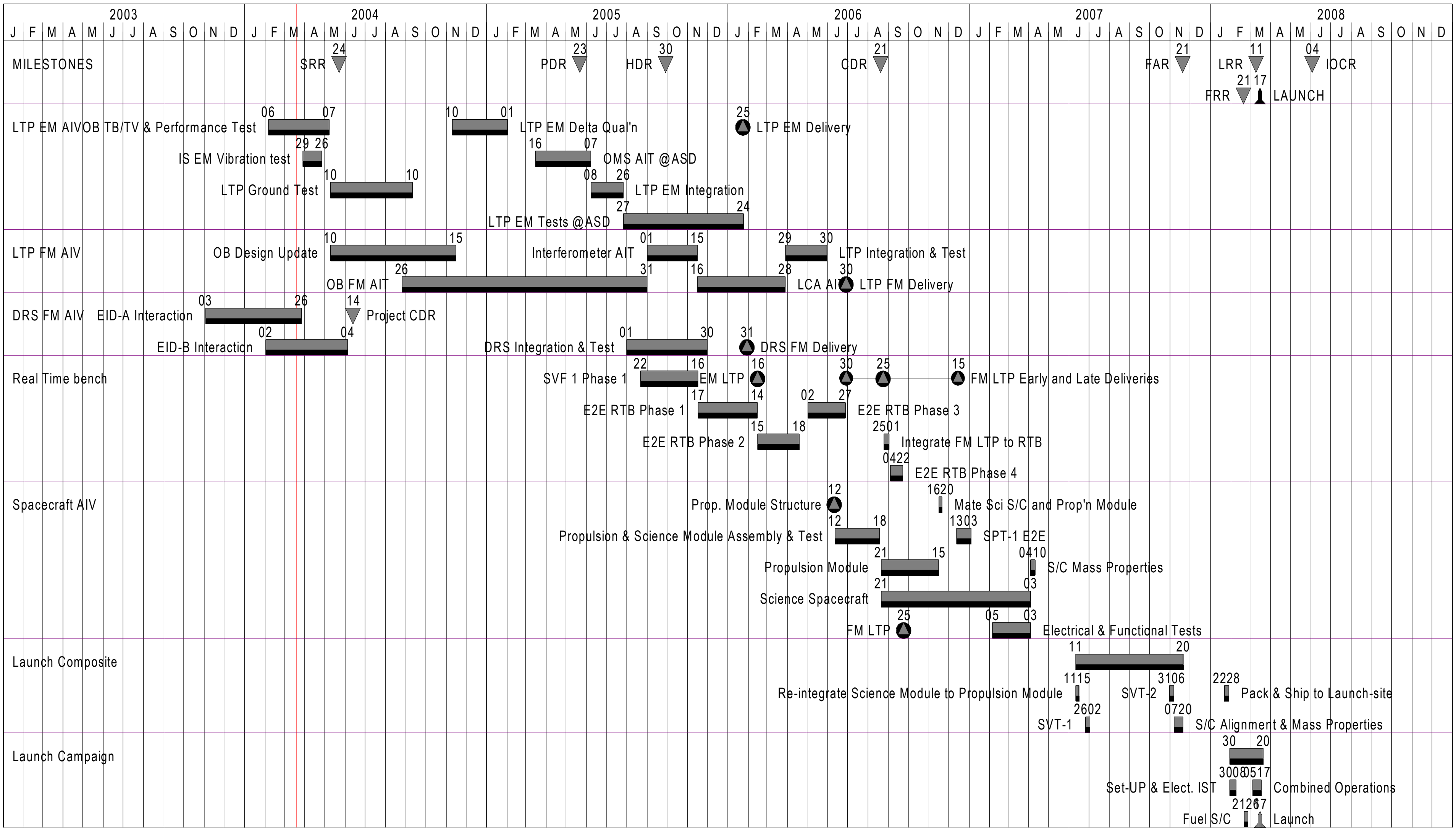
LTP schedule (2)

esa

ID	Task Name	Finish
148	Data & Diagnostic S/S	18/11
149	Data Management Unit	18/11
150	DMU Prel. Design	15/10
151	DMU Detailed Design	01/04
152	DMU EM MAIT	20/05
153	DMU S/W development	29/04
154	DMU FM MAIT	18/11
155	Diagnostic Transducers	18/11
156	Requirements / definition	27/08
157	Developm/EQM MAIT	01/04
158	DT FM MAIT	18/11
159	Structure & TC H/W	07/10
163	Laser Assembly	18/11
164	Design Definition	10/12
165	EQM MAIT	20/05
166	FM MAIT	18/11
167	Optical Bench	18/11
168	Design Upgrade	24/12
172	EM Upgrade / Delta Qual	20/05
176	OB FM MAIT	16/09
181	OB FS MAIT	18/11
186	Phasemeter Unit	05/08
187	PMU QM AIT	18/03
188	PMU/DMU Integrated Tests	10/06
189	PMU FM	05/08
190	Harness	11/11
195	GROUND SUPPORT EQU.	19/08
201	LTP EM AIT	02/12
202	Units Delivery CONTINGENCY	10/06
203	OMS AIT	02/09
209	LTP Integration	07/10
212	LTP Tests	02/12
216	System Level Tests @ ASD	14/04
220	LTP PFM AIT	22/08
221	Units Delivery CONTINGENCY	09/12
222	Interferometer AIT	20/01
228	LCA AIT	13/06
235	LTP Integration & Test	22/08
240	Instrument Contingency	14/09



LPF Mission schedule



LPF Key engineering milestones

- System specifications preparation => SRR (May 04)
- LTP & DRS EID-A/B finalisation => August 04
- Subsystem specifications => ITT (June 04-March 05)
- Engineering Analyses through to PDR (May 05)
- Hardware Design Review to start RTB test (Oct 05)
- End of RTB test and design phase => CDR (Aug 06)
- LPT integration in FM (Sep 06)
- Electrical and Functional tests (Jan-Mar 07)
- Environmental Tests (Jun-Nov 07)
- Launch Campaign (Feb-Mar 08)
- Launch (Mar 08)
- In Orbit Commissioning Review (May 08)