LISA Pathfinder

Paul McNamara for the LPF Team

LISA Pathfinder Project Scientist

GWADW

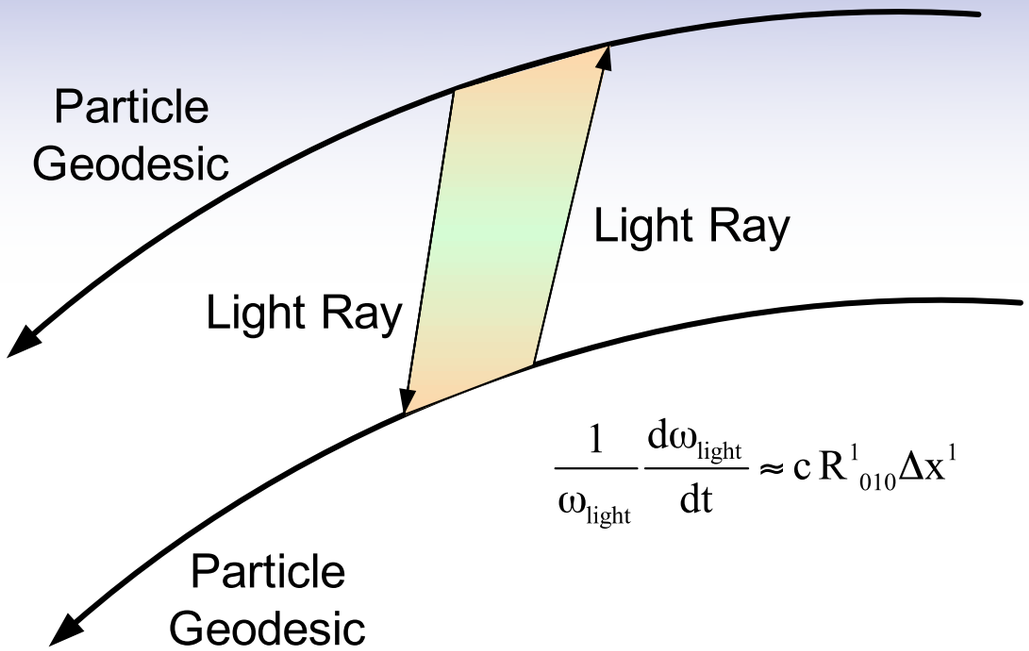
10th - 15th May 2009

G0900656-v1

Why LISA Pathfinder?

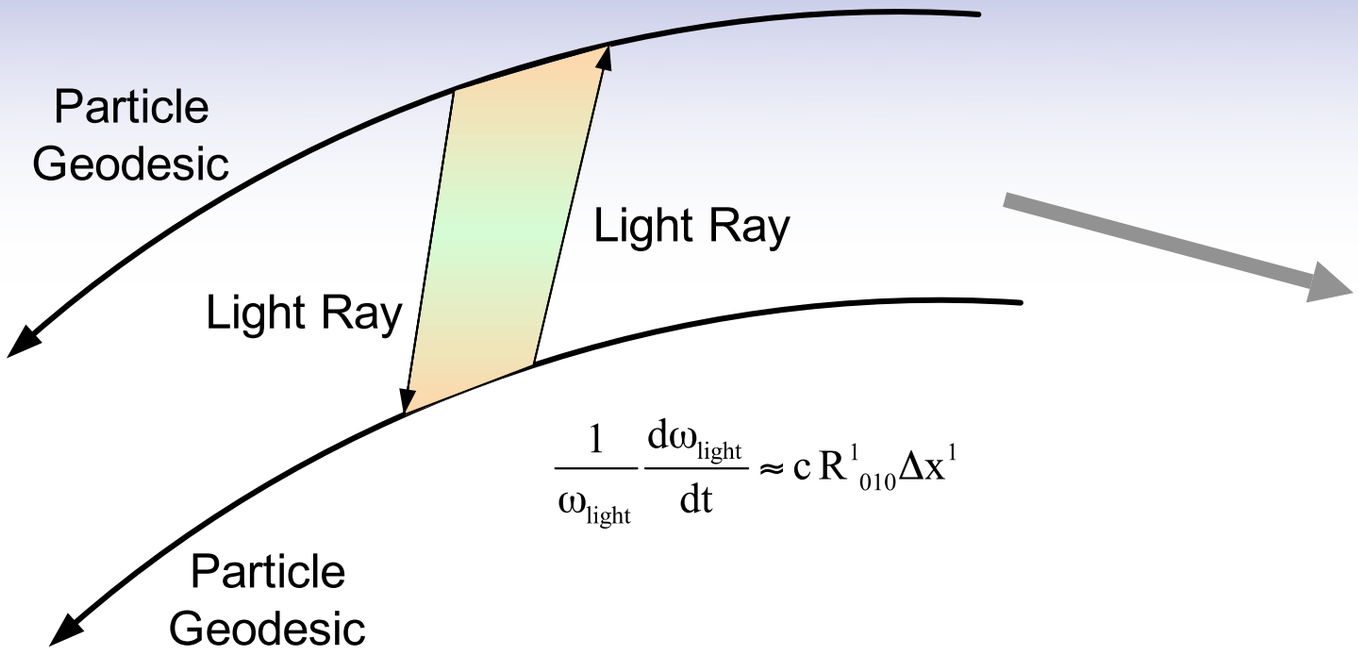
- The science case for LISA is extremely compelling and has continually been highly ranked by independent review boards
- However, both ESA and NASA believed that the risk was too high to fly LISA with an unproven measurement concept
- LISA Pathfinder was instigated by ESA to test the concept of low-frequency gravitational wave detection
- The LPF development has shown that the technologies required for LISA are difficult, but not impossible
  - LPF has already solved many of the challenges associated with low frequency gravitational wave detection

Mission Concept



$$\frac{1}{\omega_{light}}\frac{d\omega_{light}}{dt} \approx c\, R^{1}{}_{010}\Delta x^{1}$$

Mission Concept



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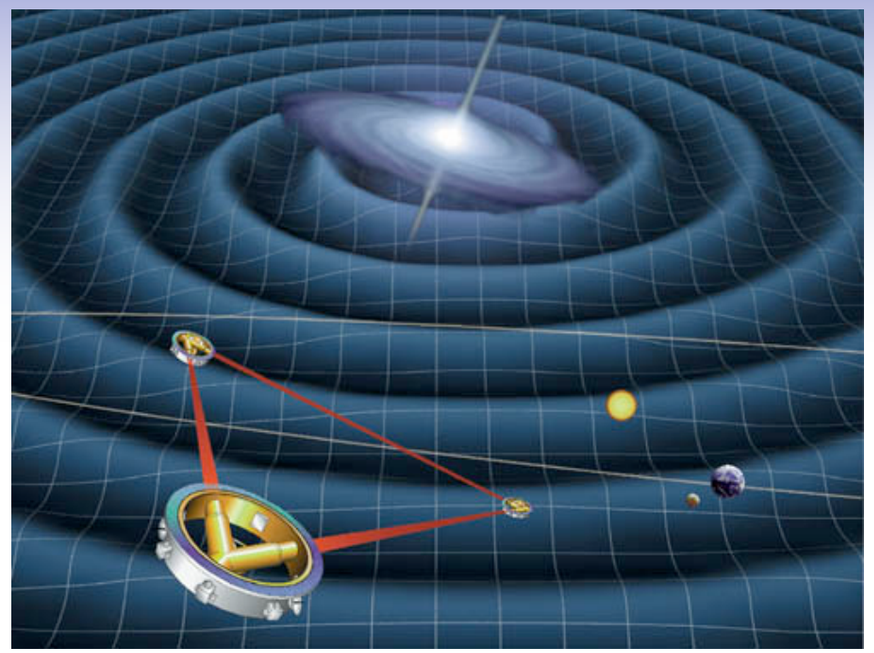

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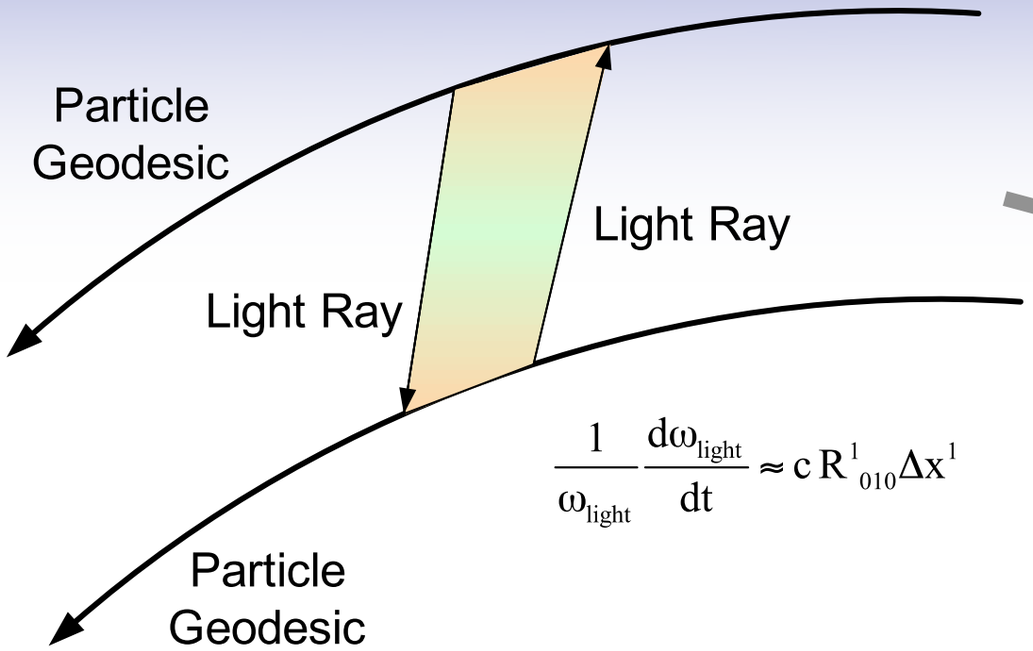

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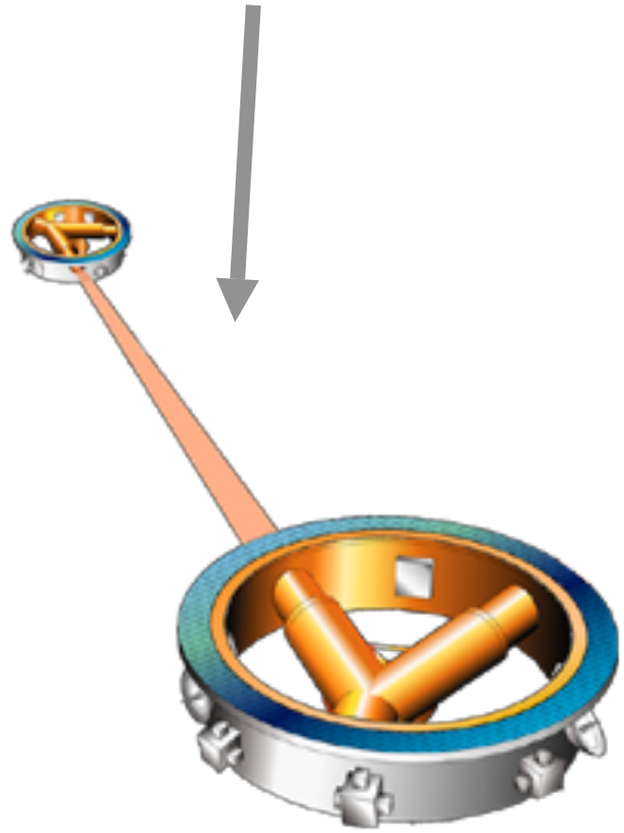

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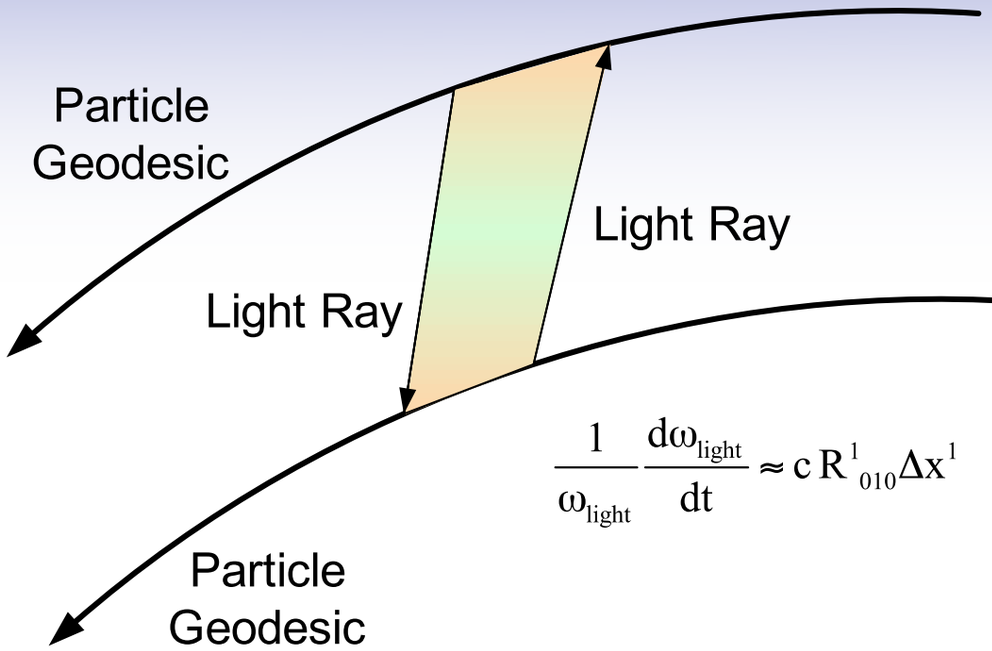

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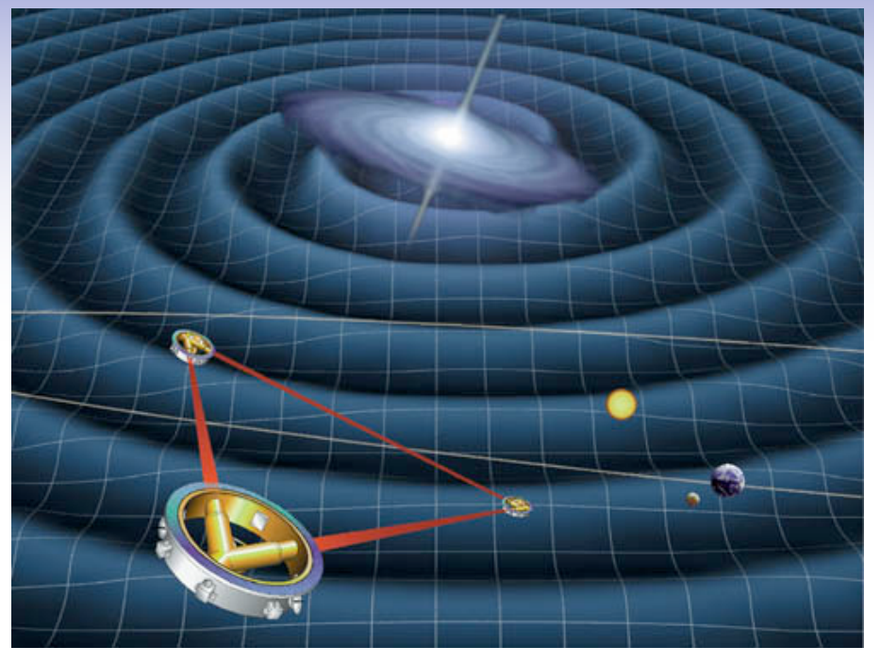

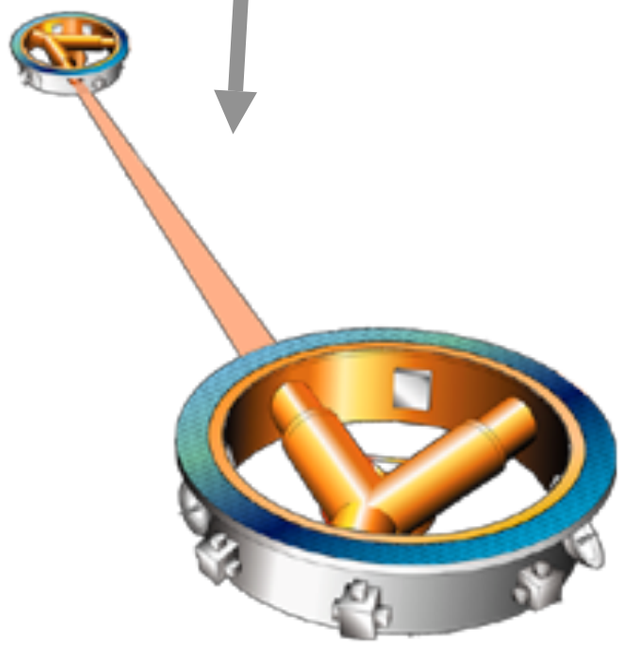

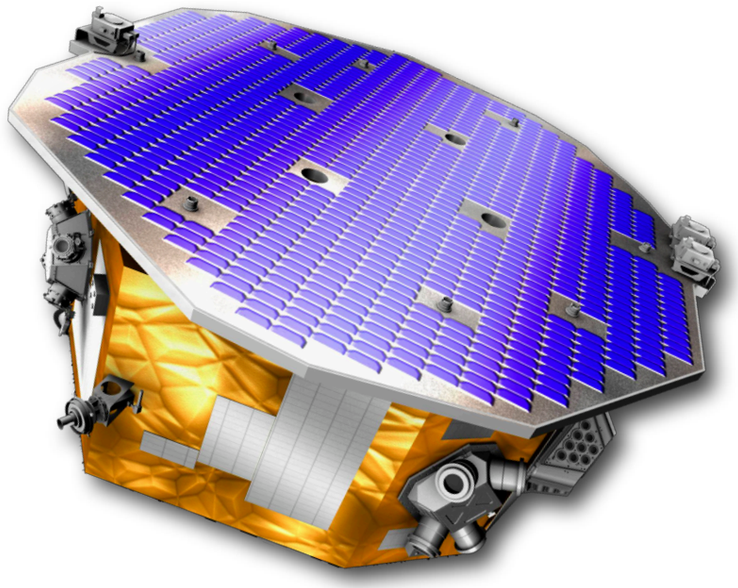

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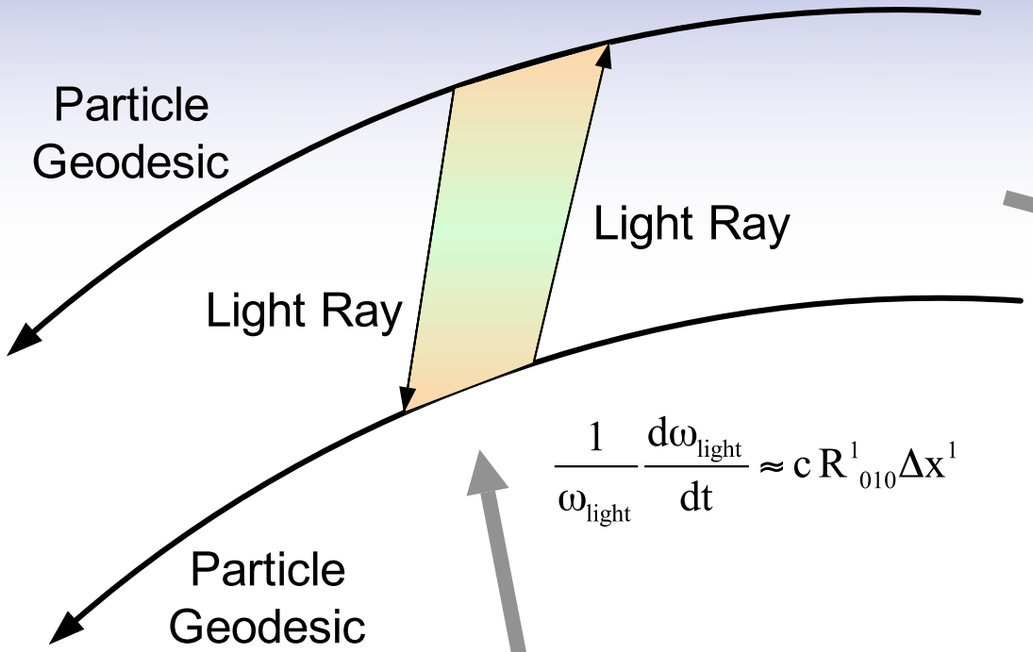

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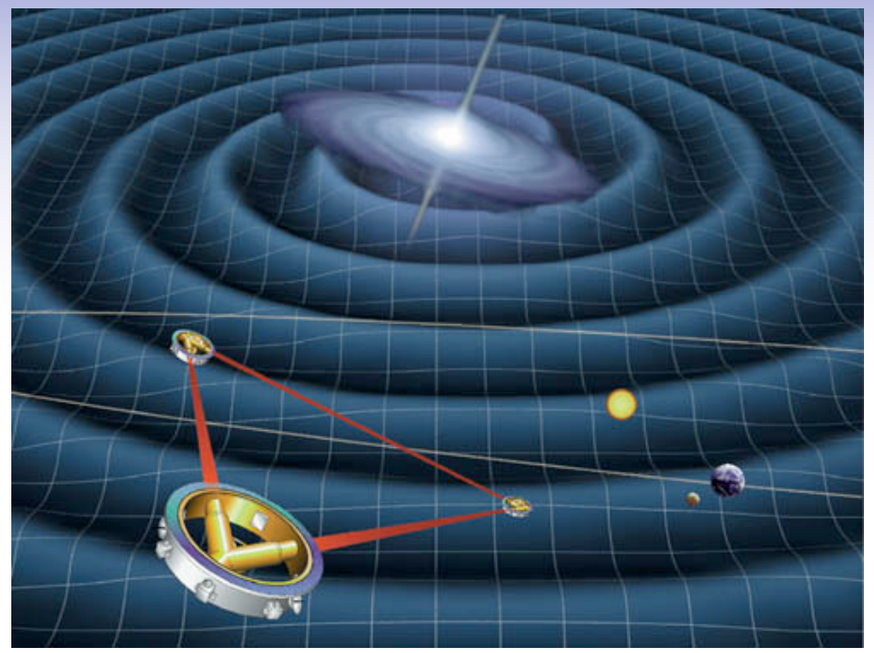

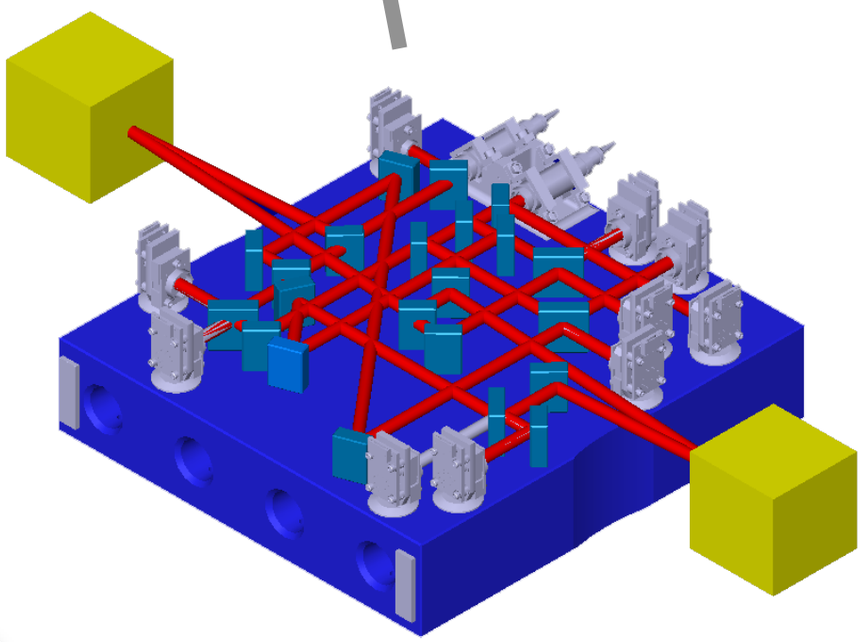

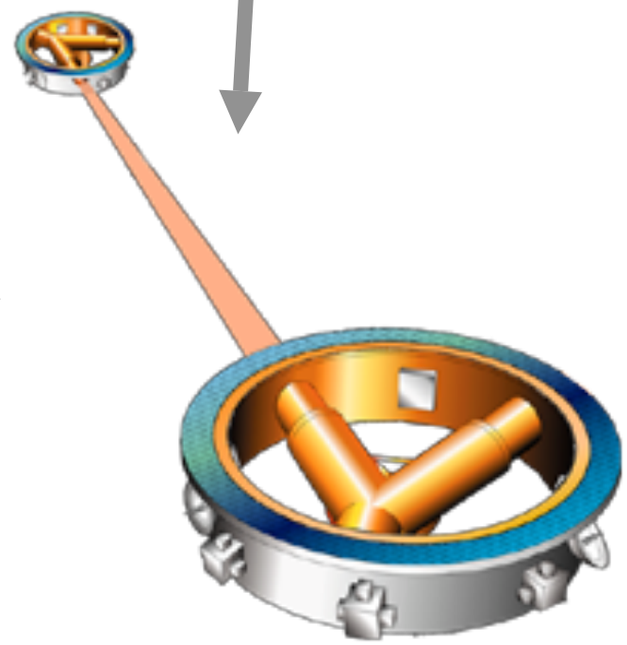

LPF Technology

- The LISA Pathfinder mission will test in flight:
  - Inertial sensors
  - Precision interferometry
  - Micro-Newton propulsion technology
    - Field Emission Electric Propulsion (FEEP)
    - Colloidal thrusters (provided by NASA - JPL)
  - *Drag Free and Attitude Control System (DFACS)*

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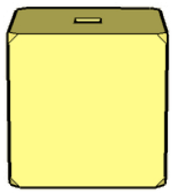
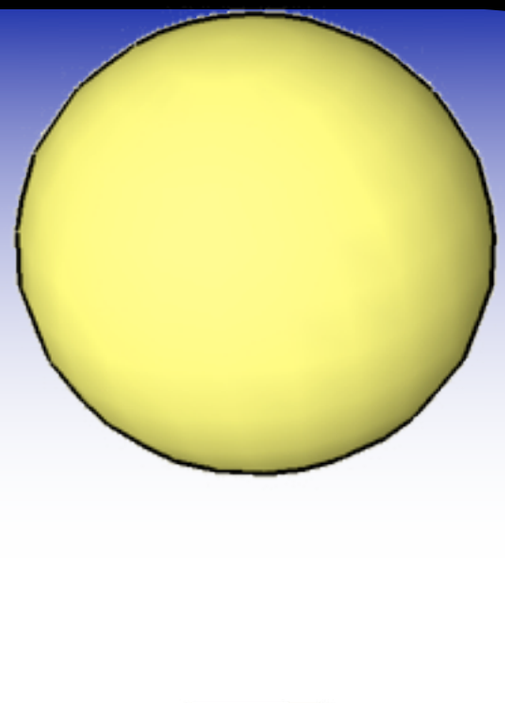
Concept of Drag-Free





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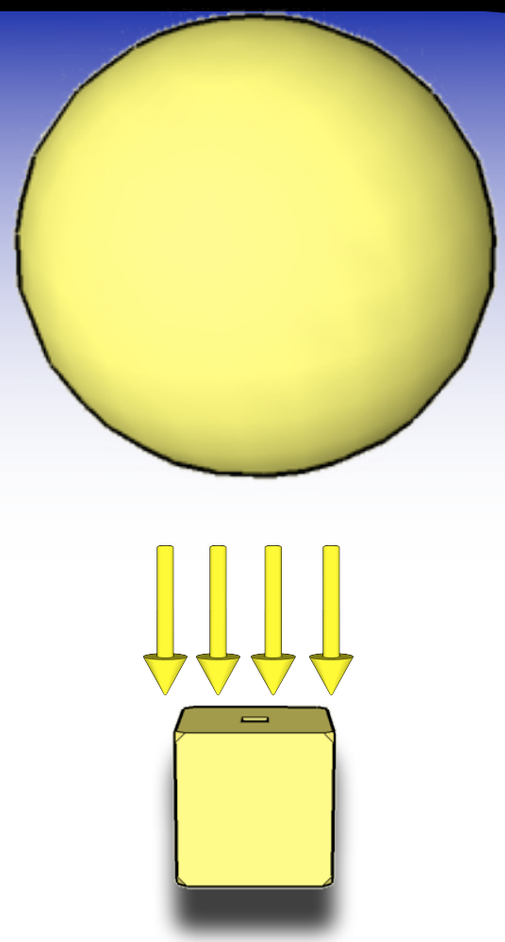

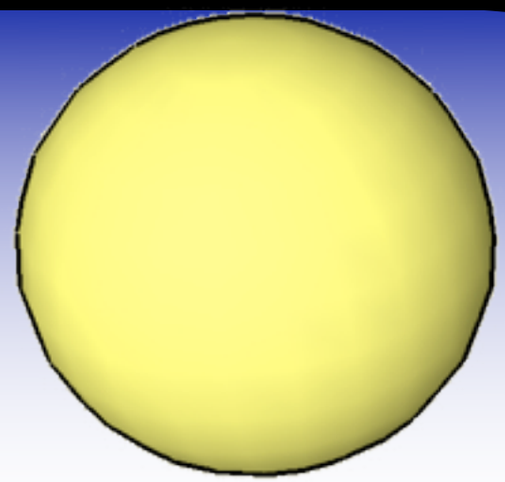

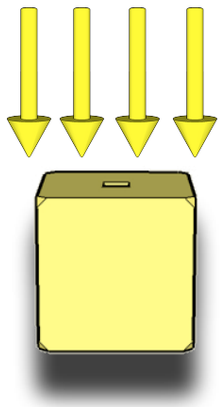

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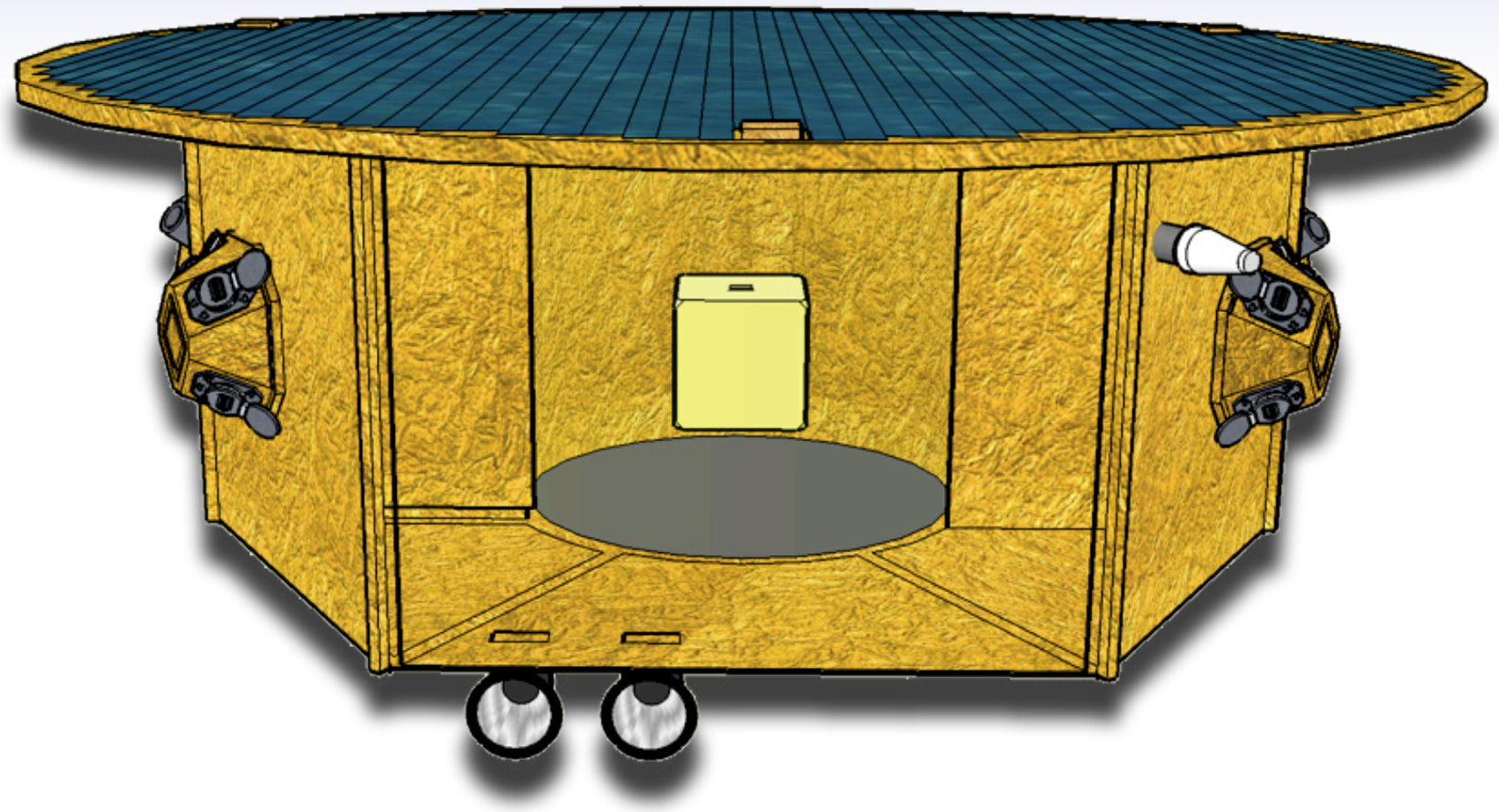

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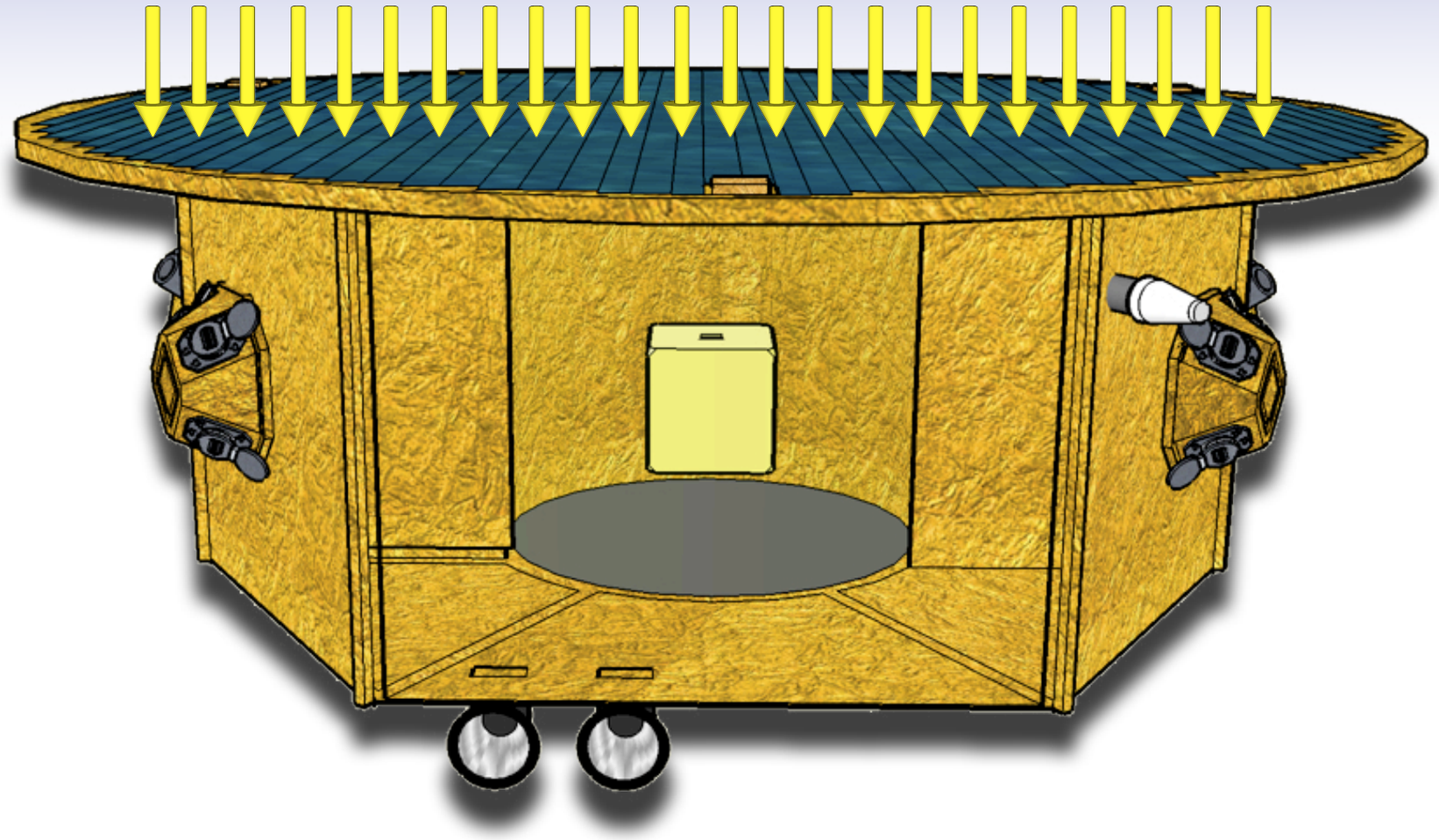

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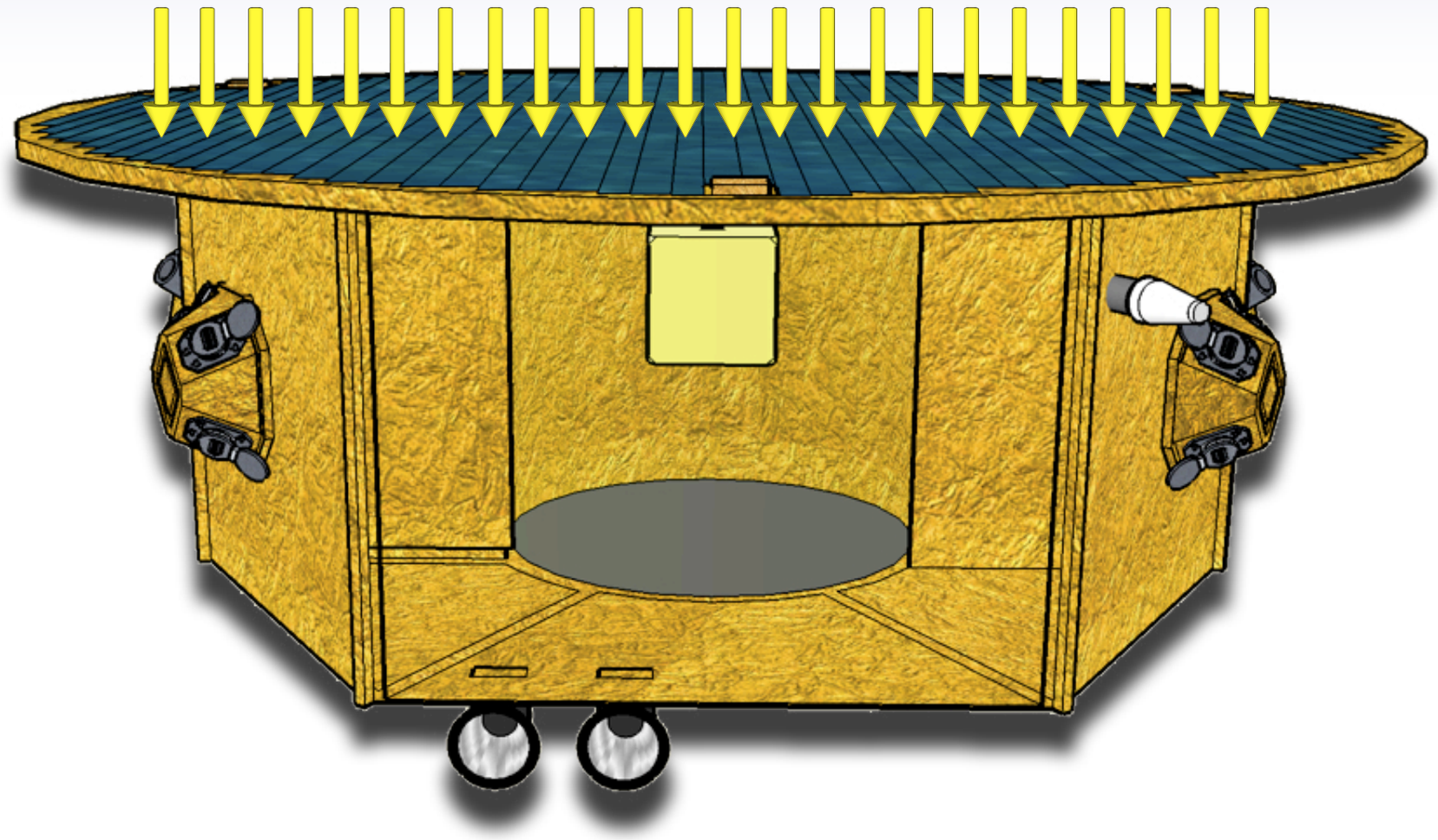

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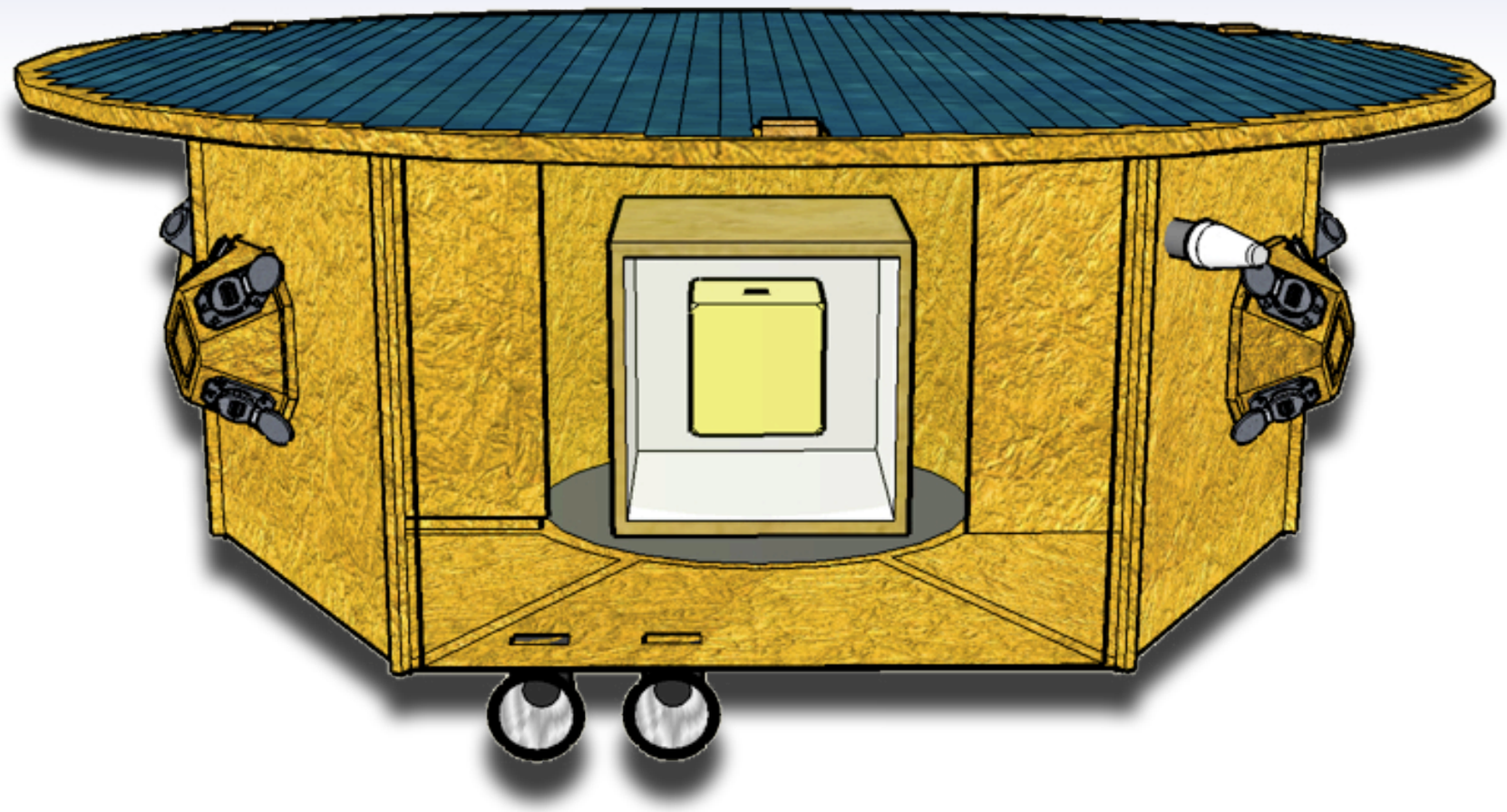

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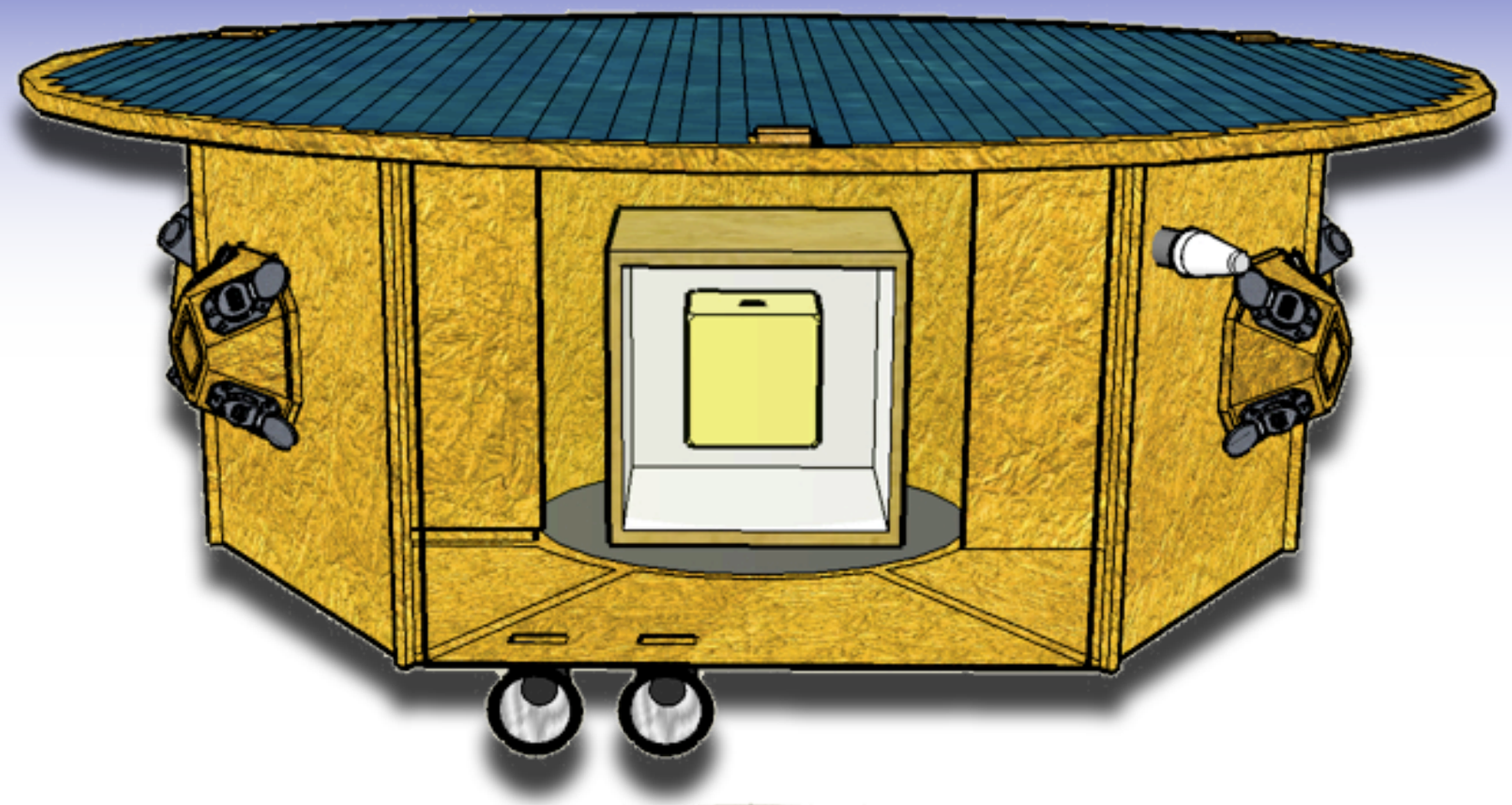

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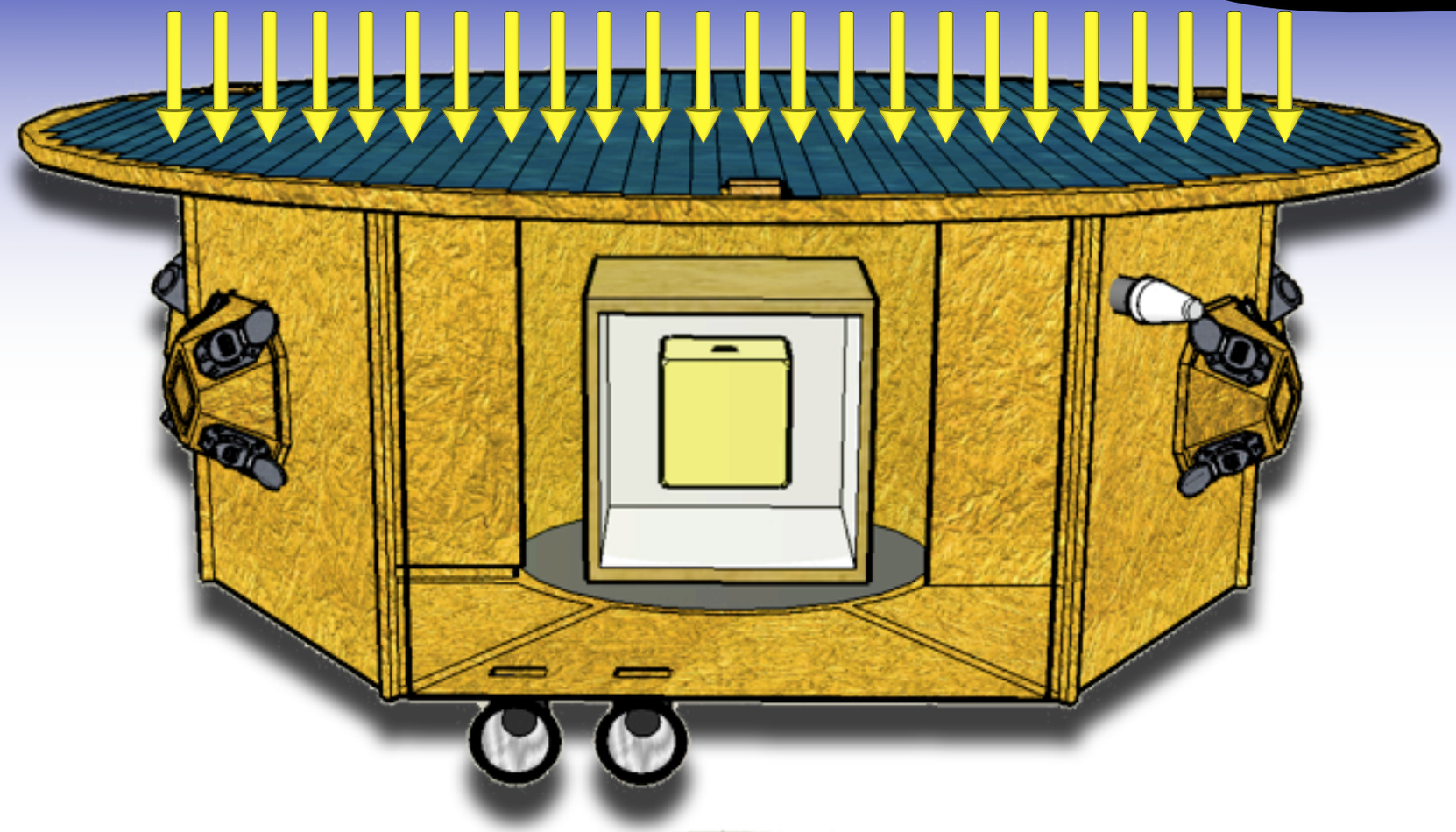

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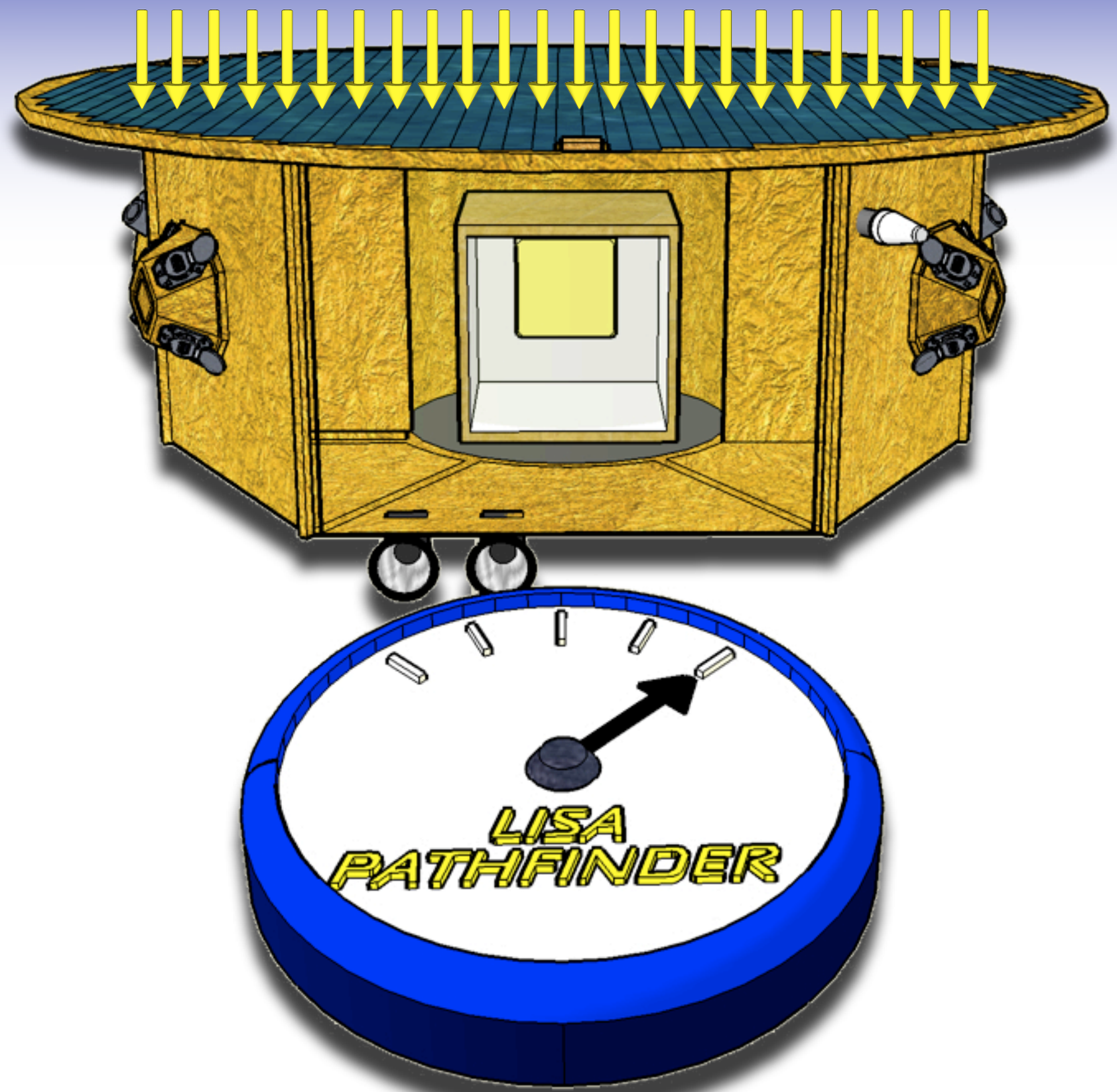

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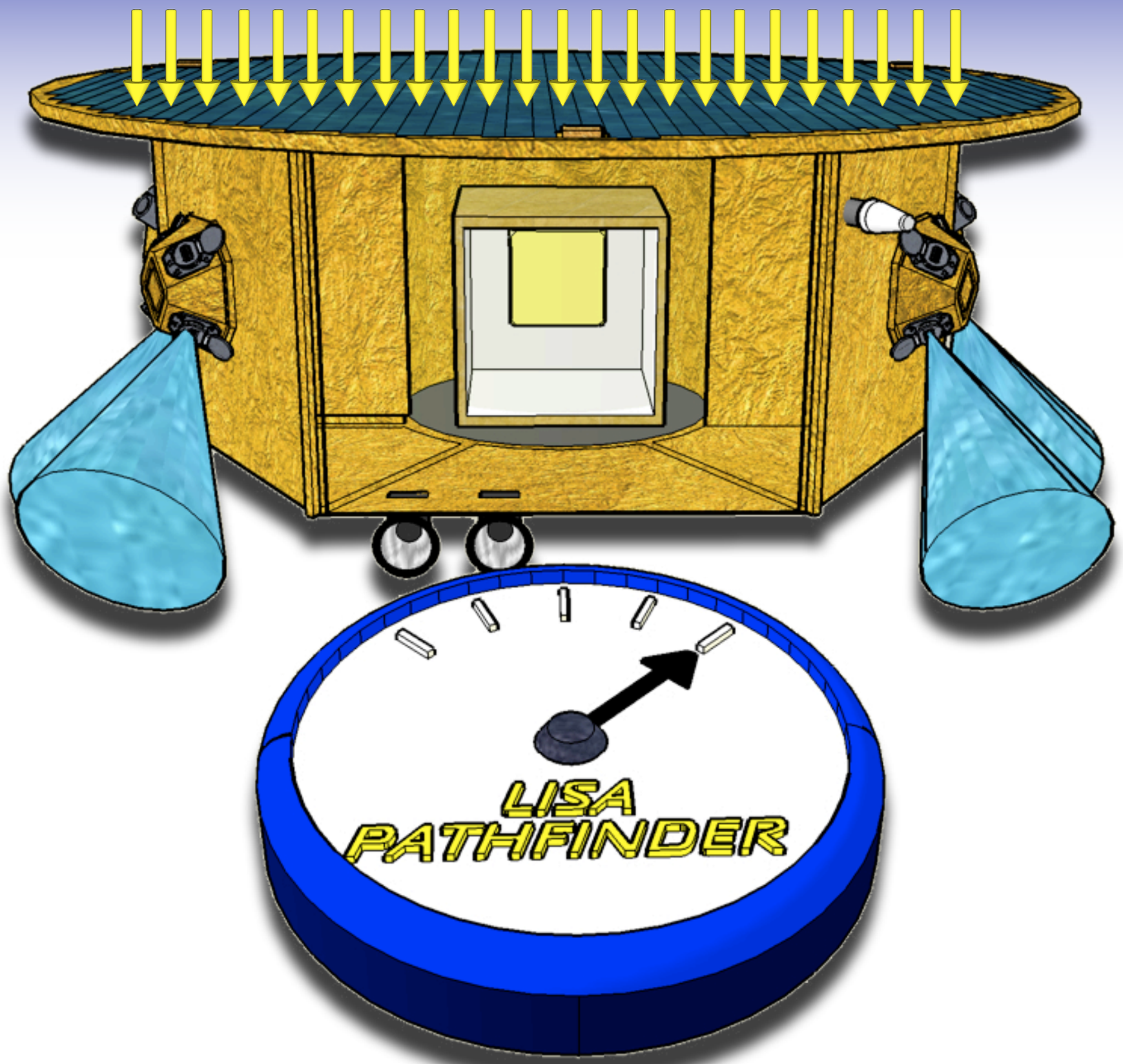

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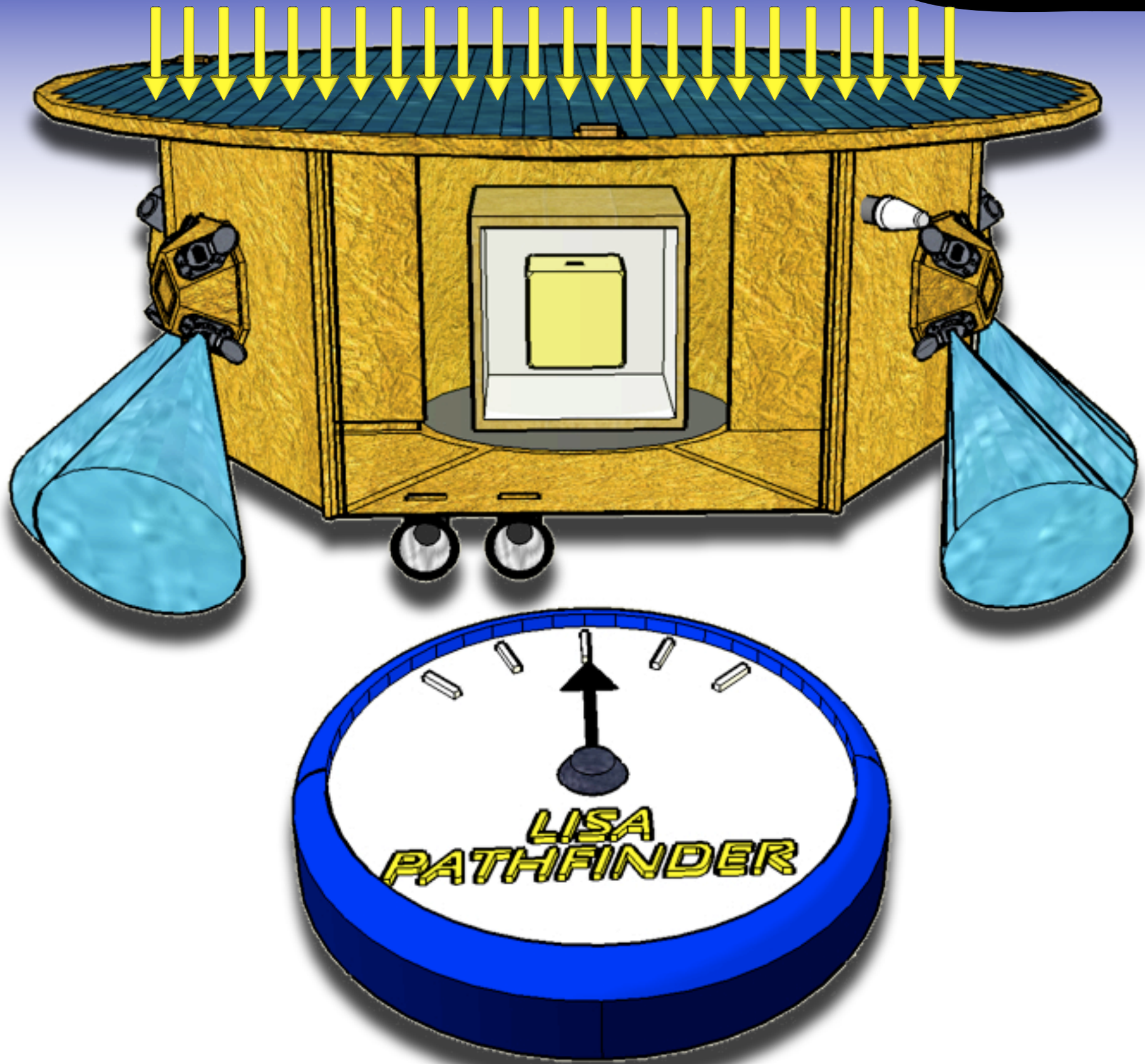


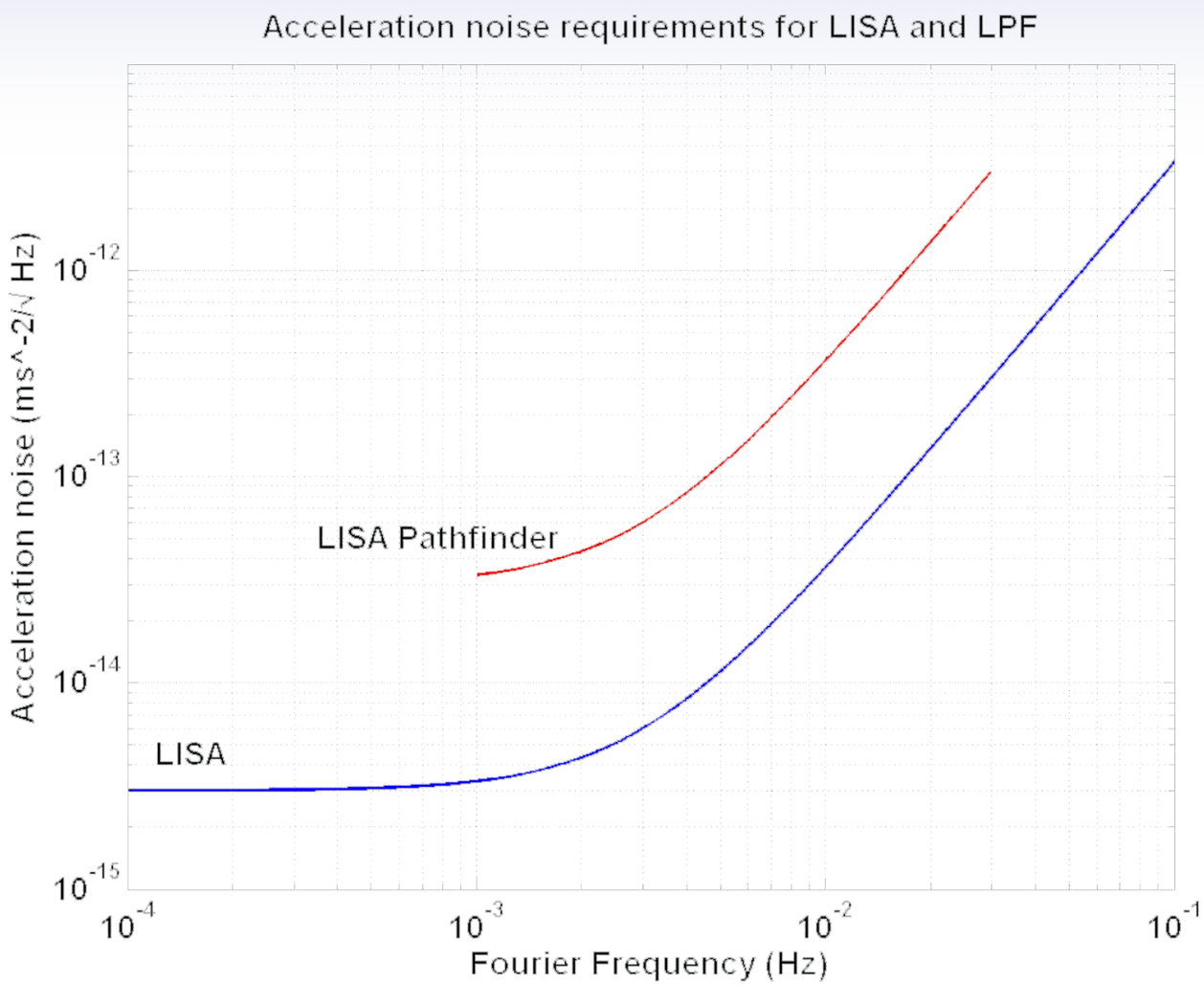
LISA Pathfinder

Mission Goal [1]

- The primary goal of LISA Pathfinder is to verify that a test mass can be put in pure gravitational free-fall with residual acceleration noise less than

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

over a frequency range of 1-30mHz

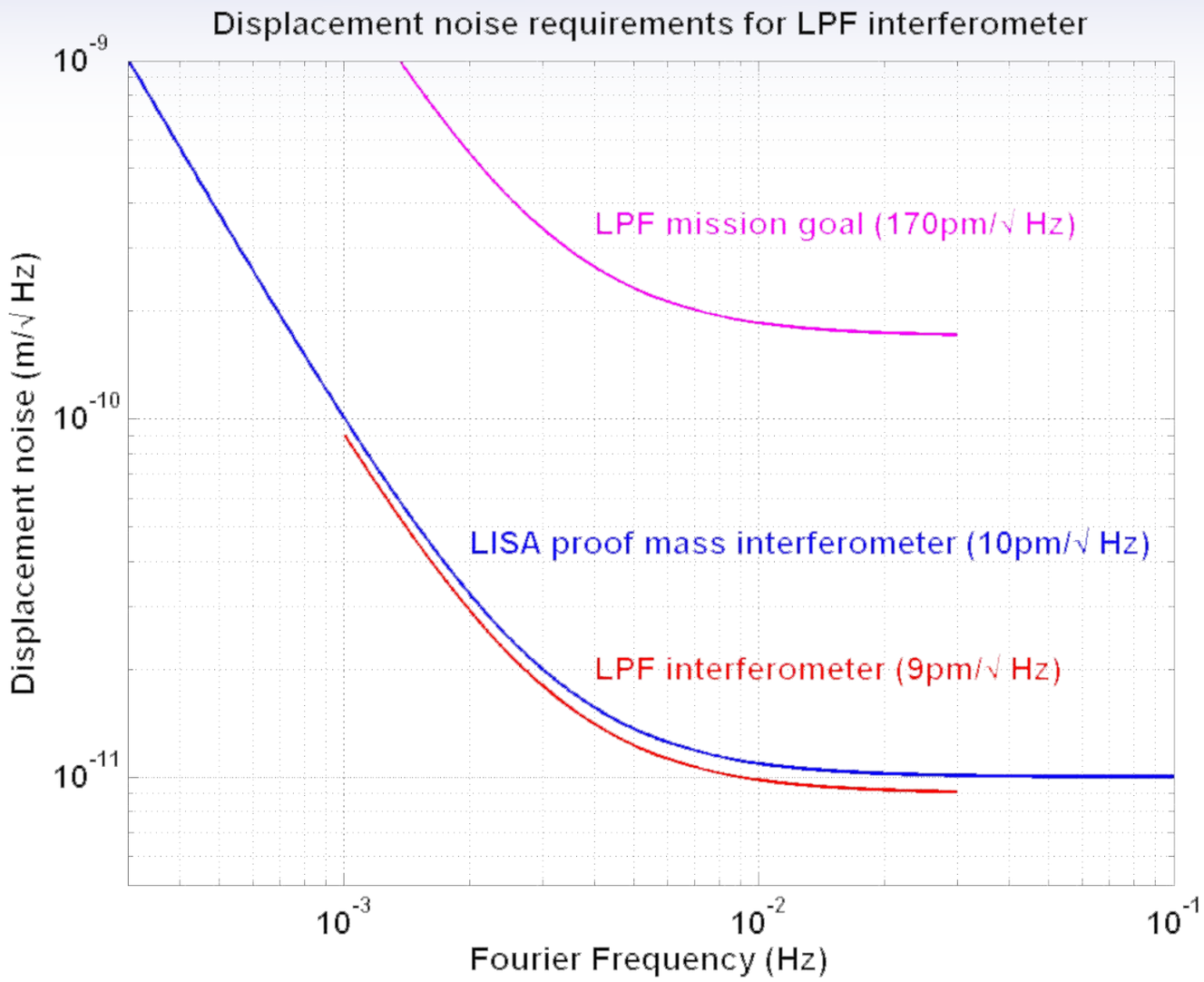


Mission Goal [2]

- A secondary goal, which has now become directly relevant to LISA, is to demonstrate laser metrology using free floating mirrors with a displacement sensitivity of

$$S_{\delta x}^{1/2} \leq 9\times10^{-12}\left[1+\left(\frac{3mHz}{f}\right)^{2}\right] m/\sqrt{Hz}$$

over a frequency range of 1-30mHz



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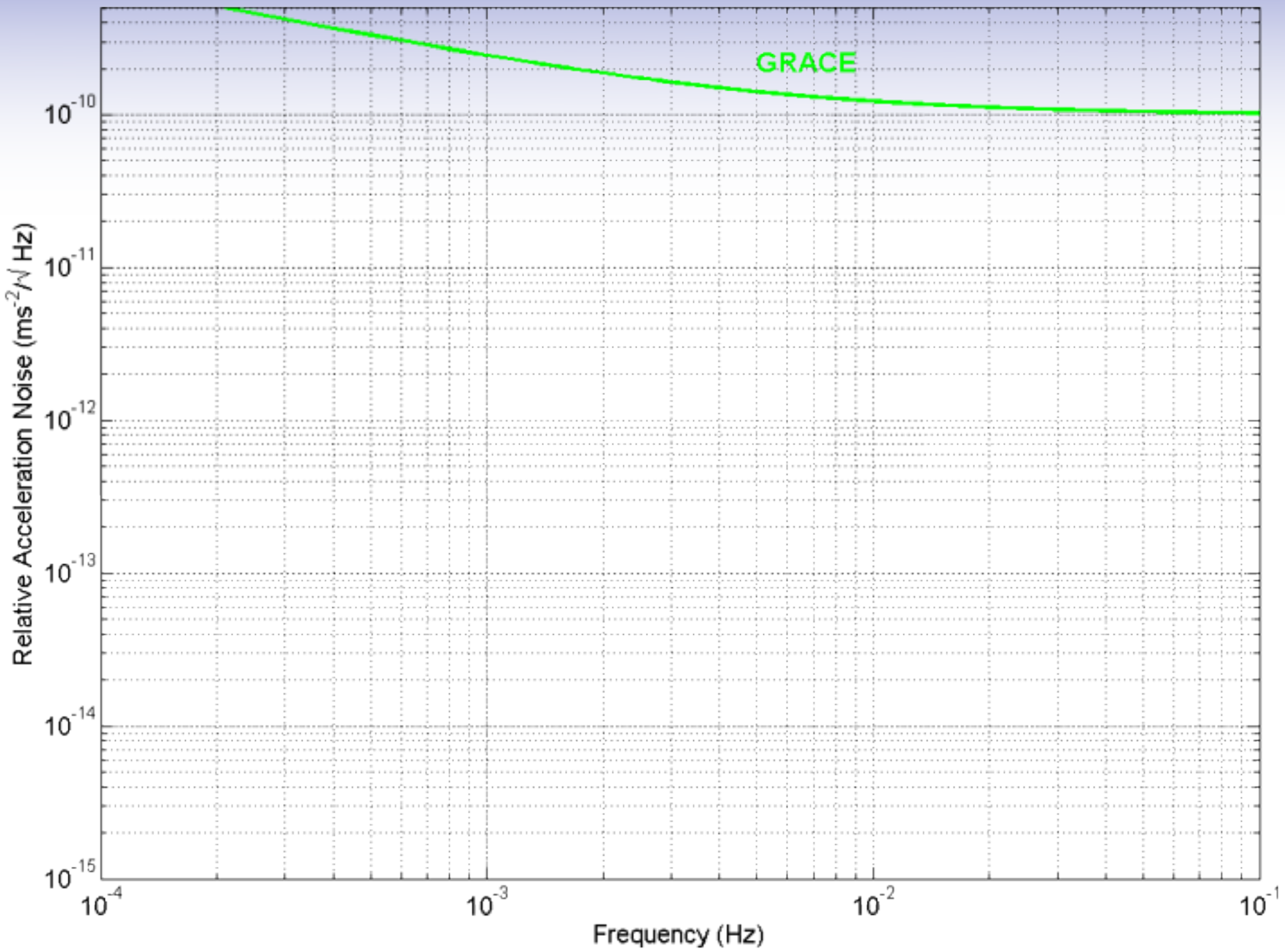
Performance of LPF



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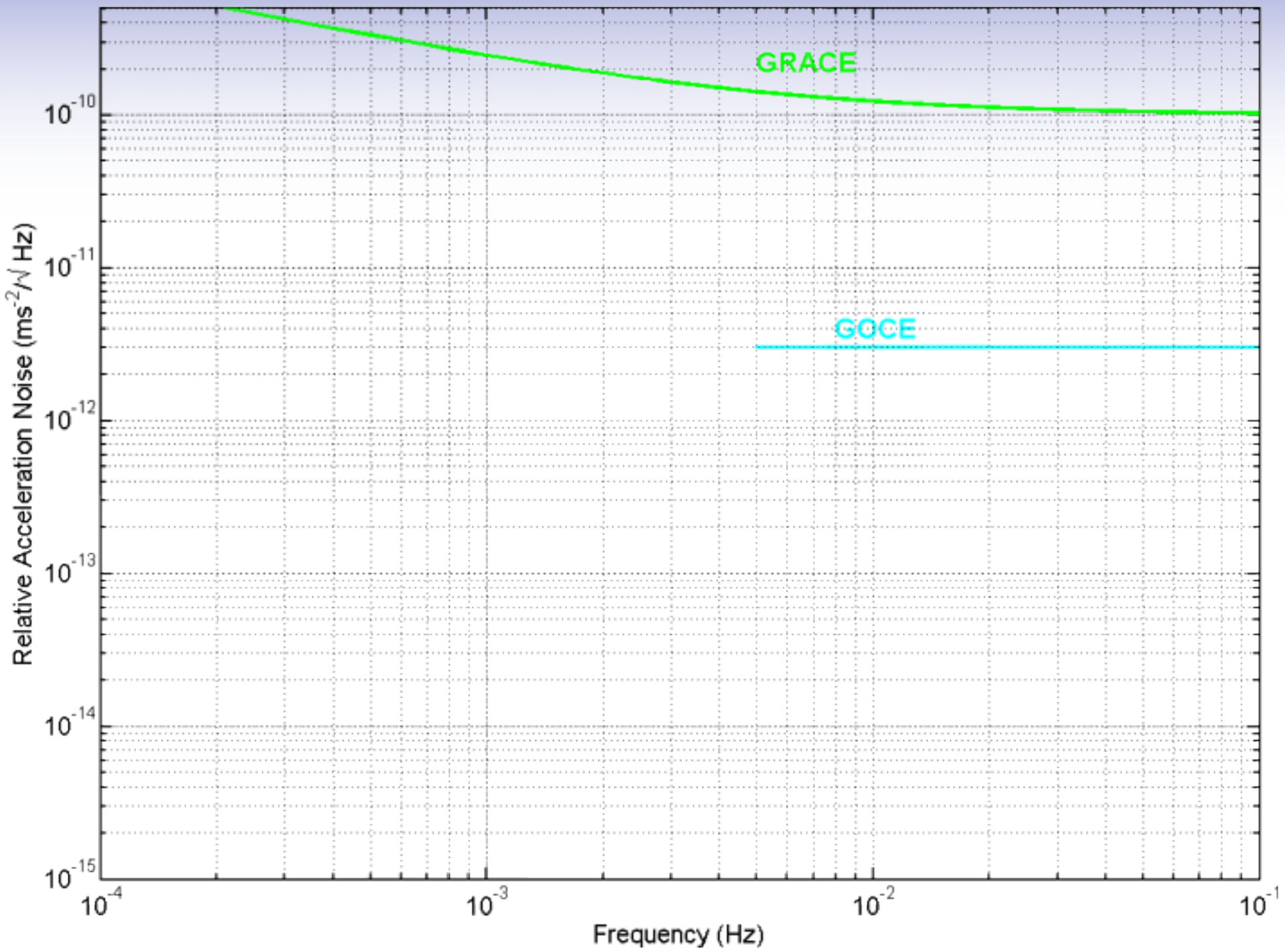

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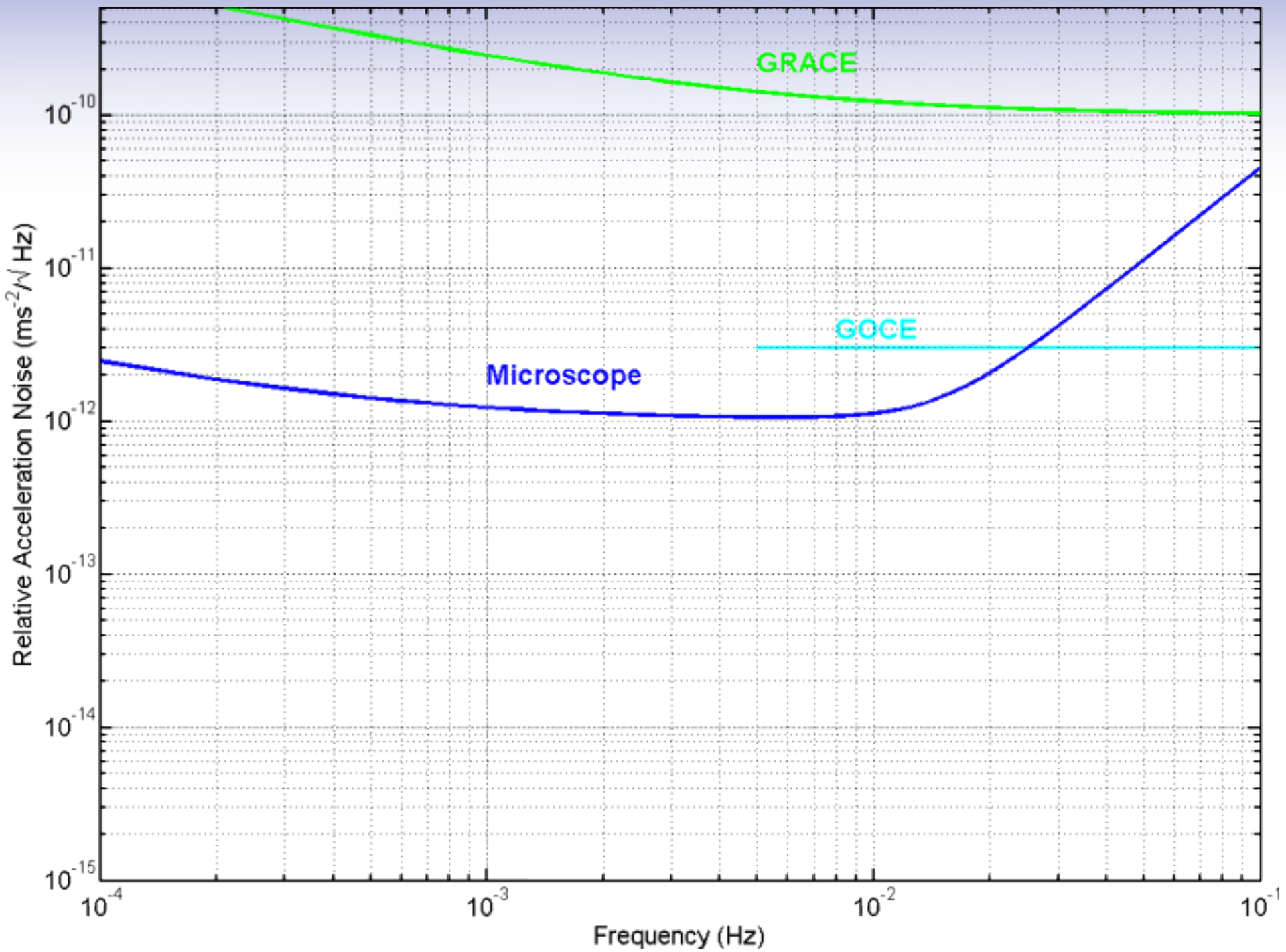

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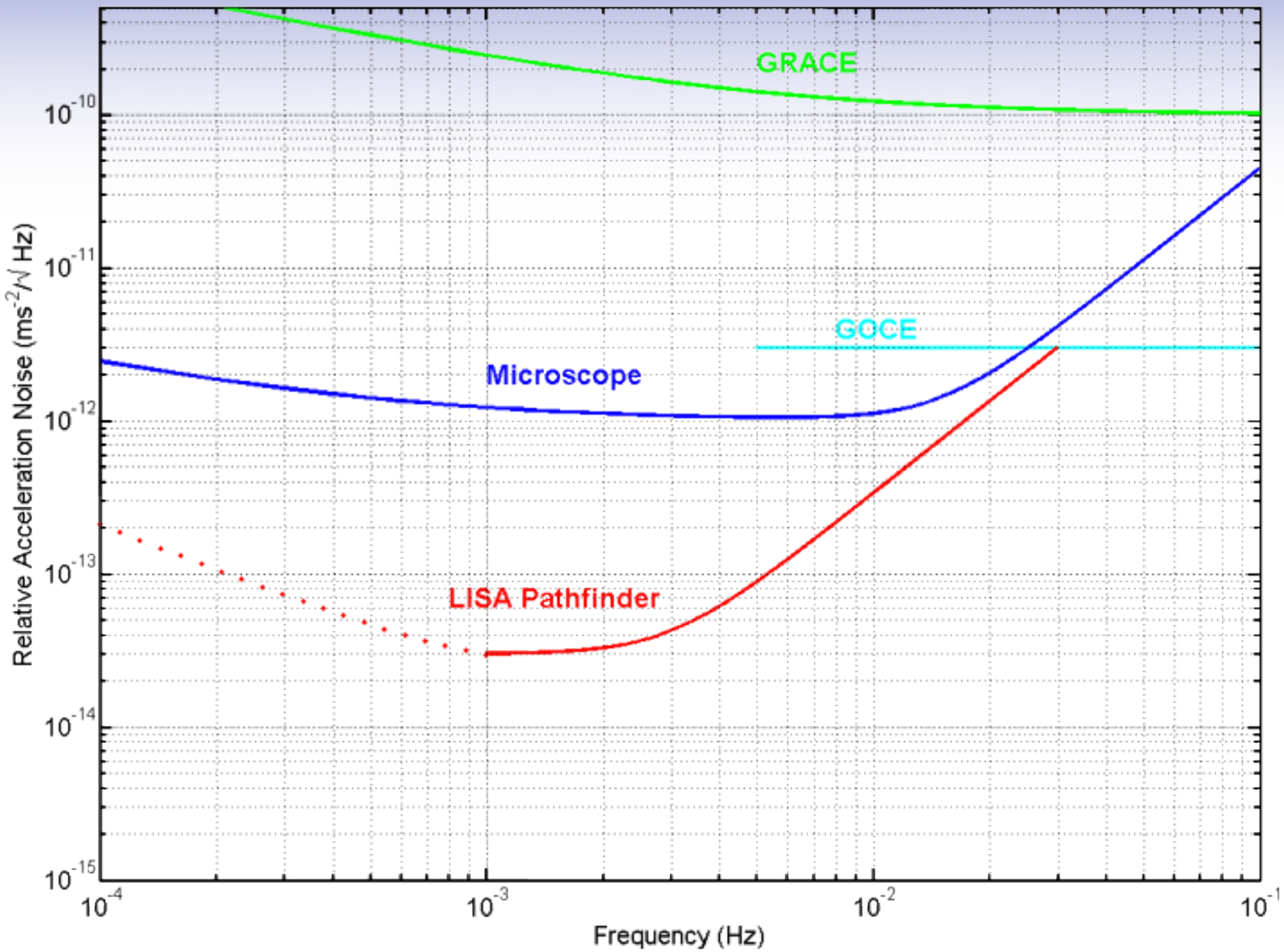

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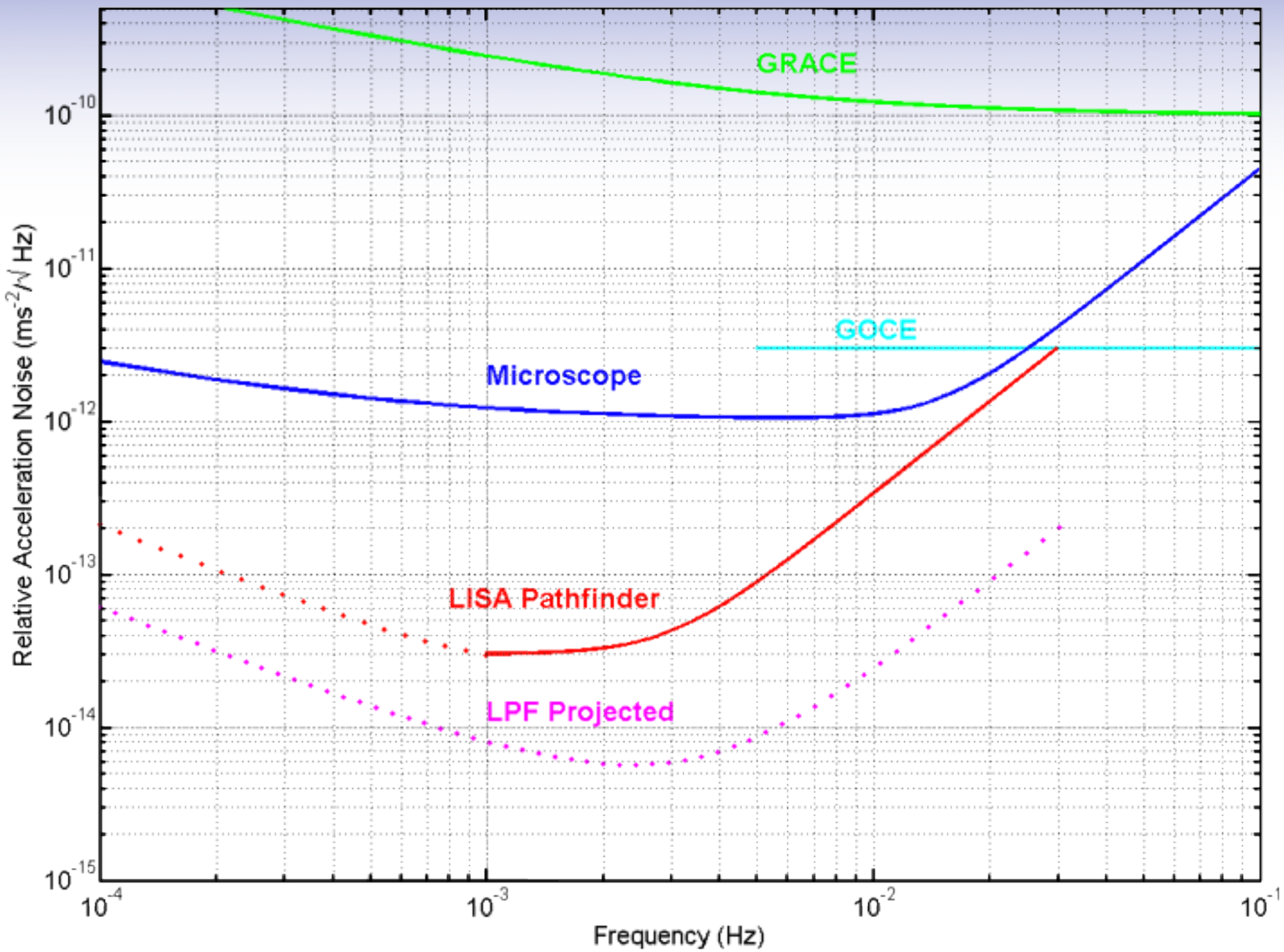

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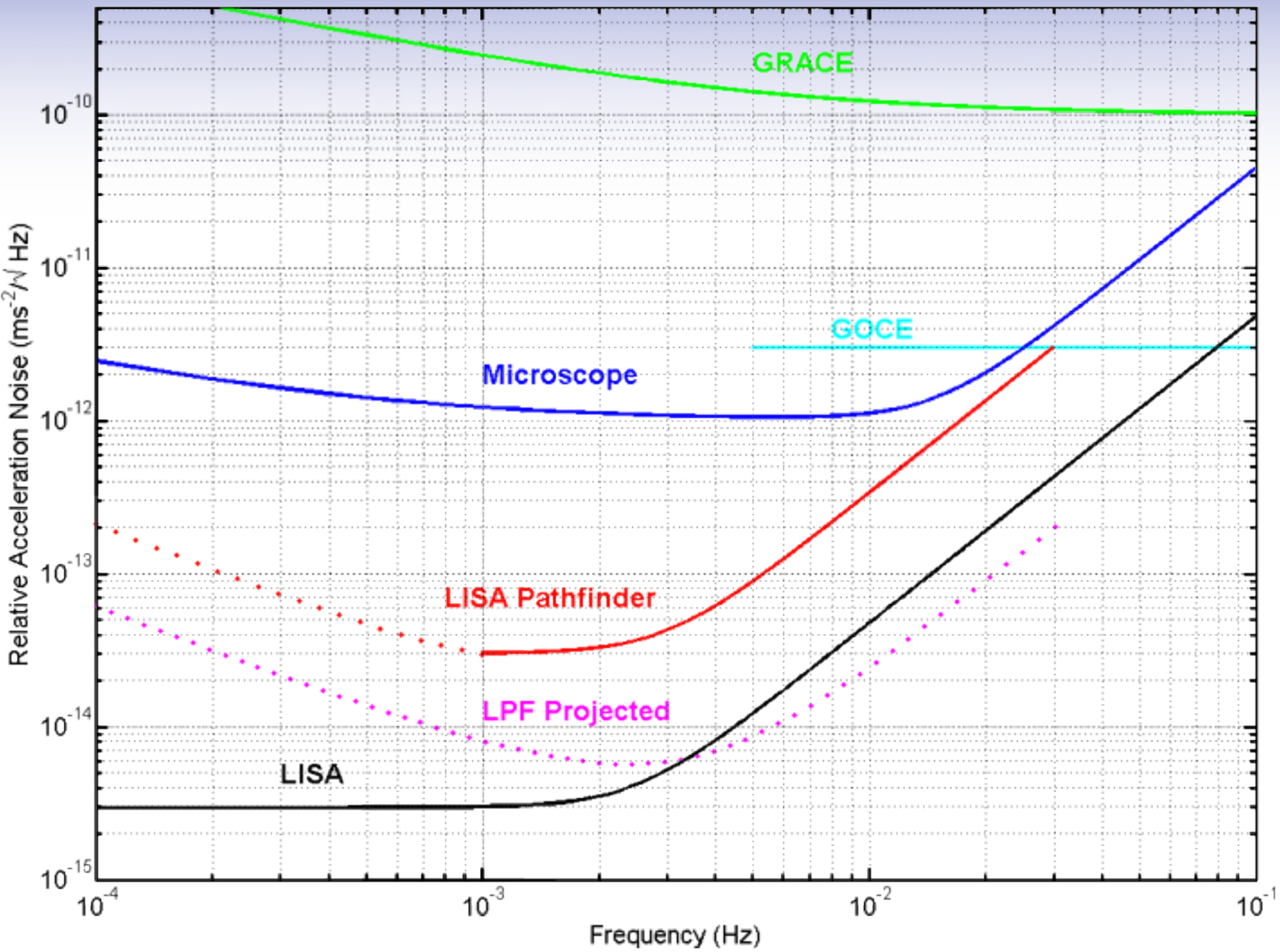
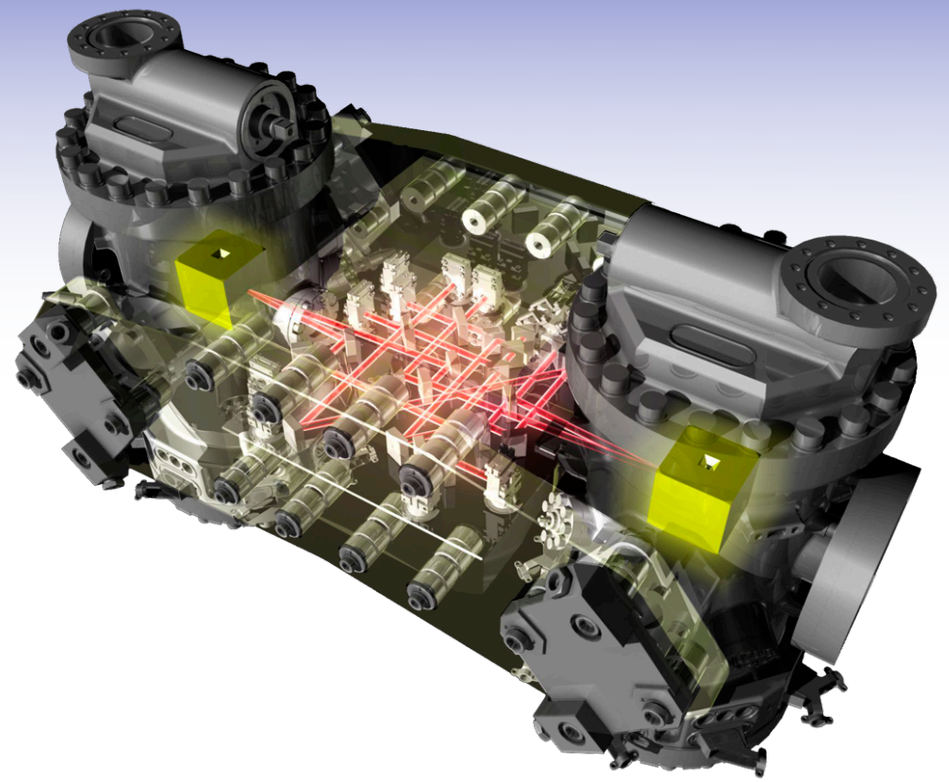
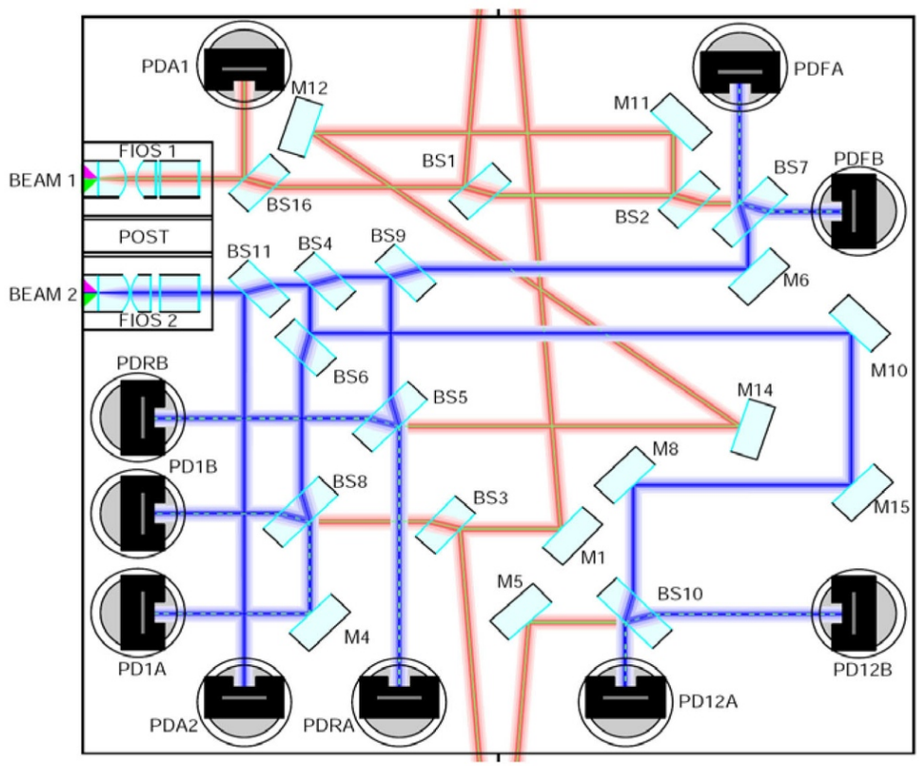


LTP Salient Features

- LISA Technology Package (LTP) is the instrument payload of LPF



- Two Au:Pt test masses housed in separate vacuum enclosures
- Relative position of test masses read-out by:
  - Heterodyne laser interferometry on sensitive axis
  - Capacitive sensing on all axes
- Four interferometers on ultra-low expansion optical bench
  - x1, x2-x1, Frequency noise, reference interferometer



LISA Technology Package

- Procurement and manufacture of the LTP funded by European member states and ESA

France:
Laser modulator
Germany:
PI, LTP Architect (Astrium), Laser
Italy:
PI, Inertial Sensor (ISS), Caging Mechanism
Netherlands:
ISS SCOE
Spain:
Data Diagnostics System, Data Management Unit
Switzerland:
ISS Front End Electronics
United Kingdom:
Optical Bench, Phase-meter, Charge Management

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Optical Metrology System

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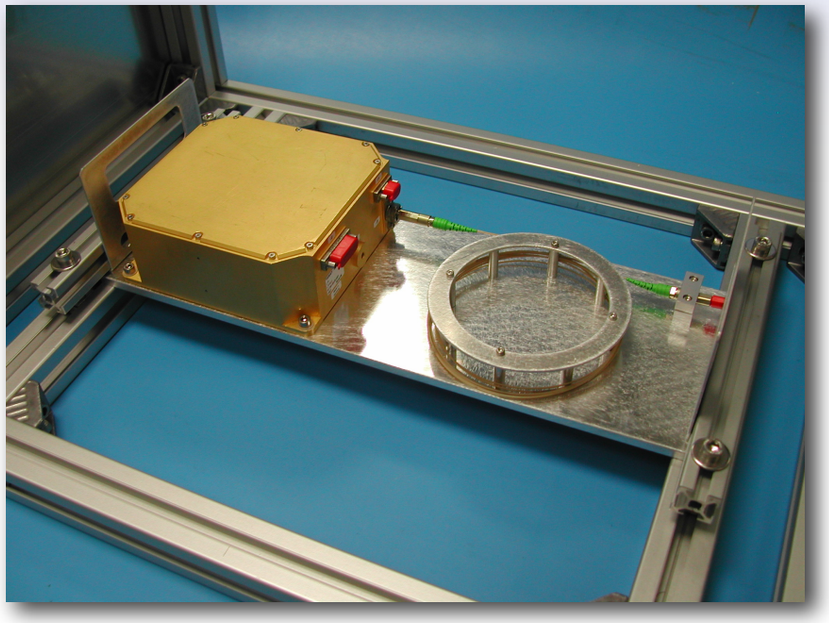
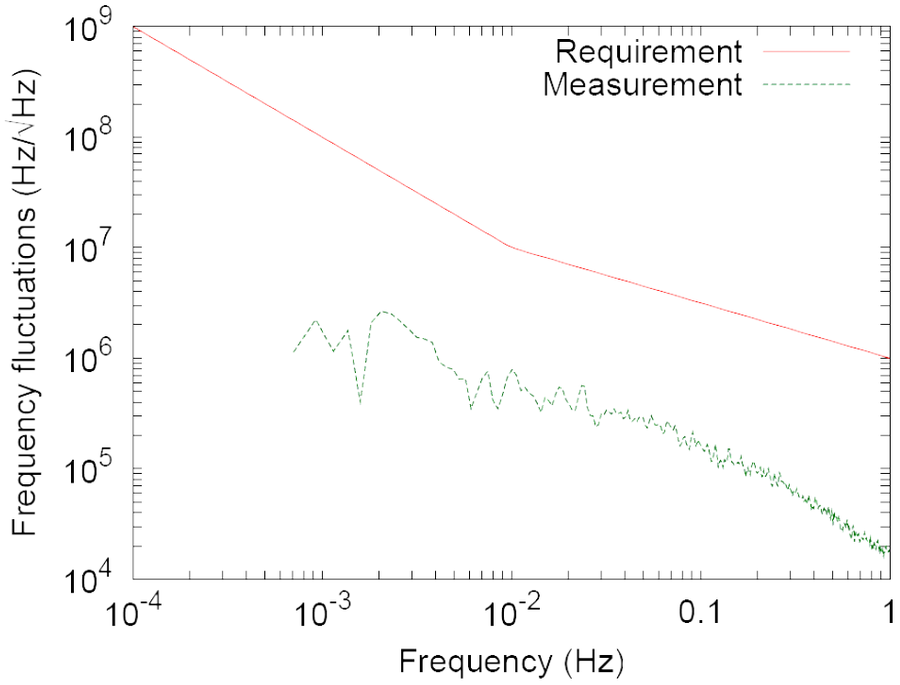
  - Reference Laser Unit





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  - Reference Laser Unit
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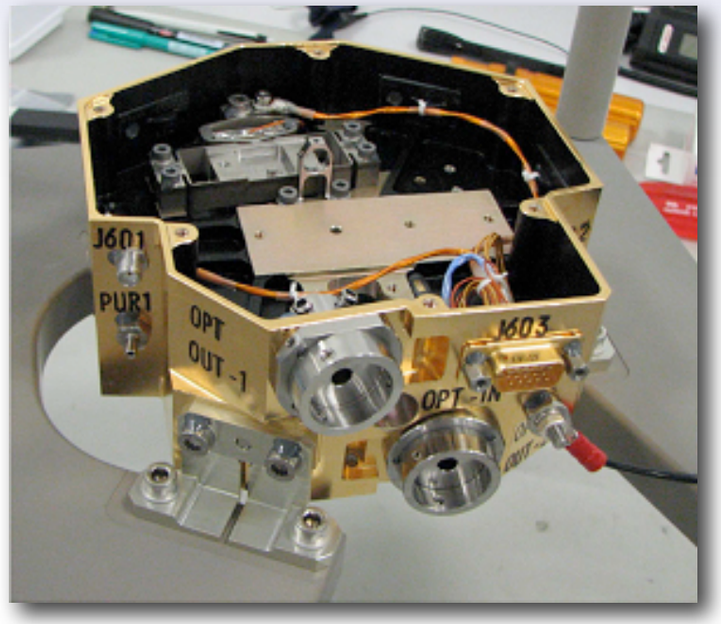

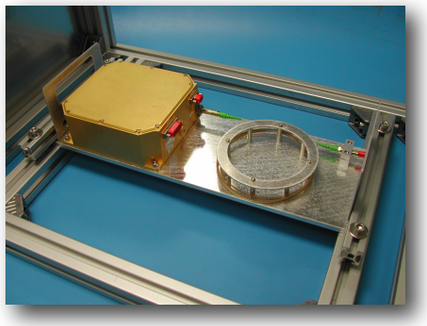

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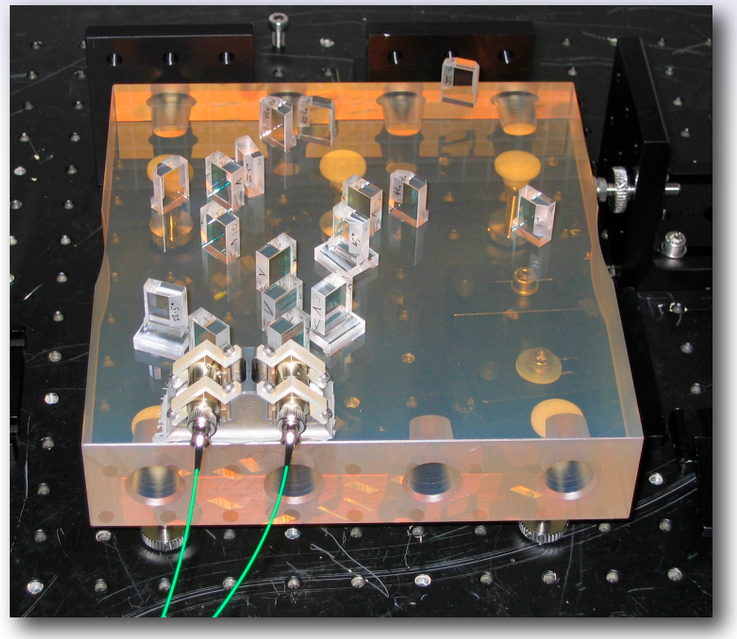

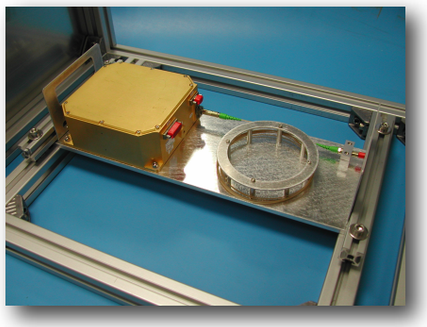

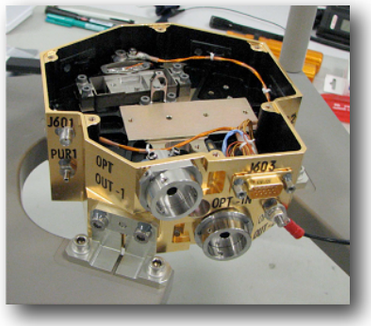

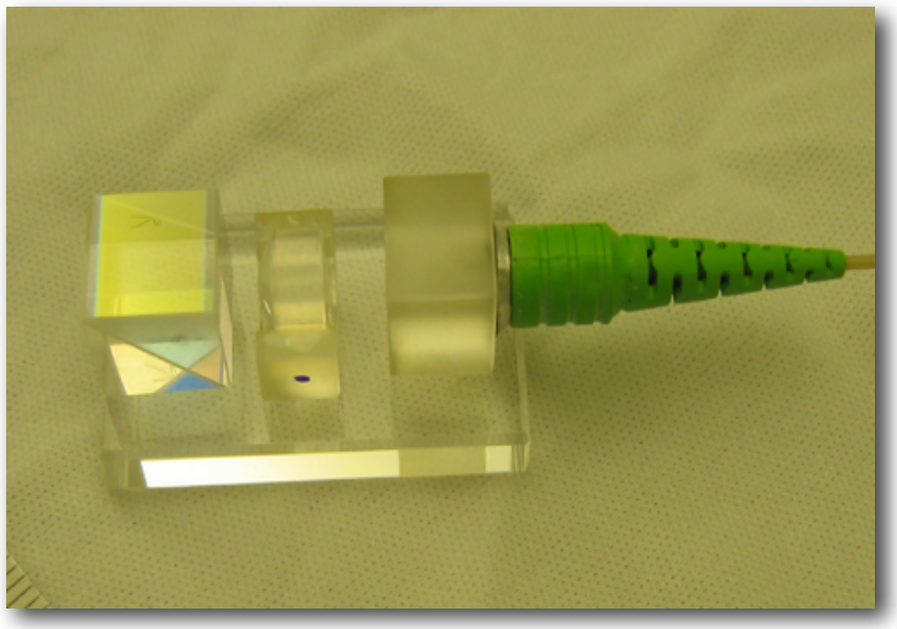

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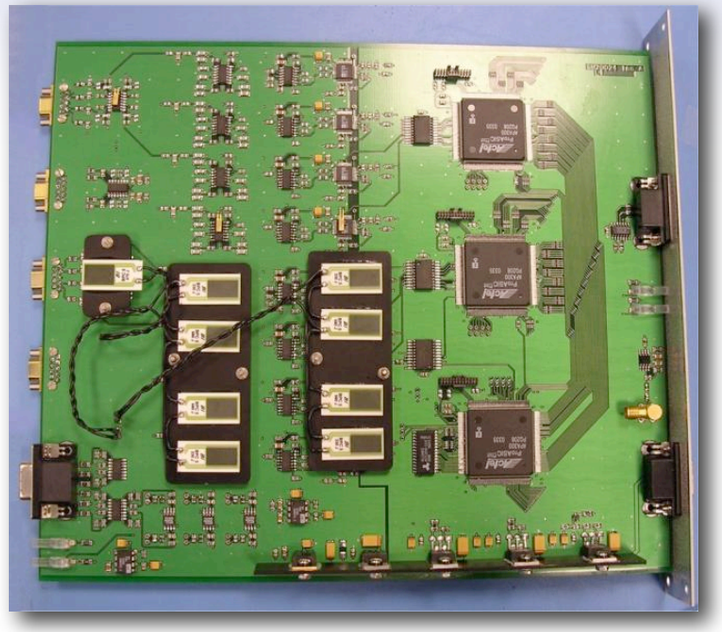

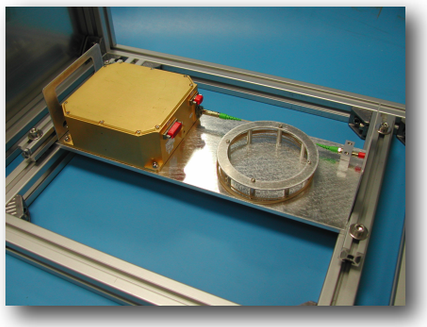

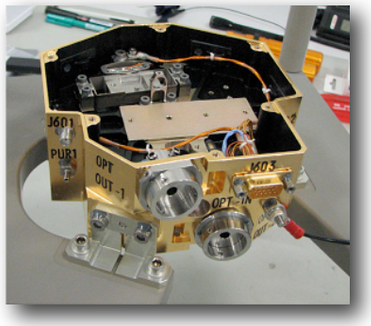

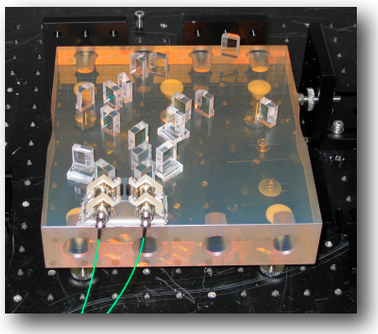

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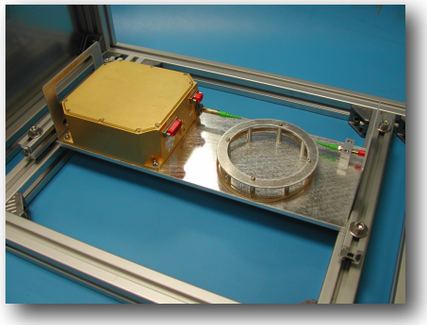
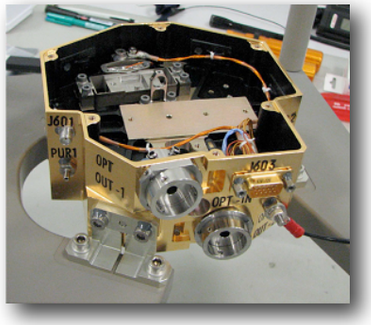
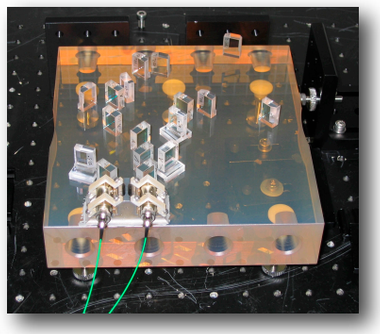
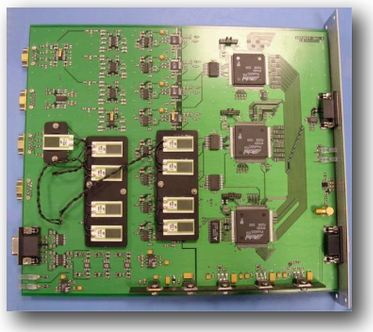
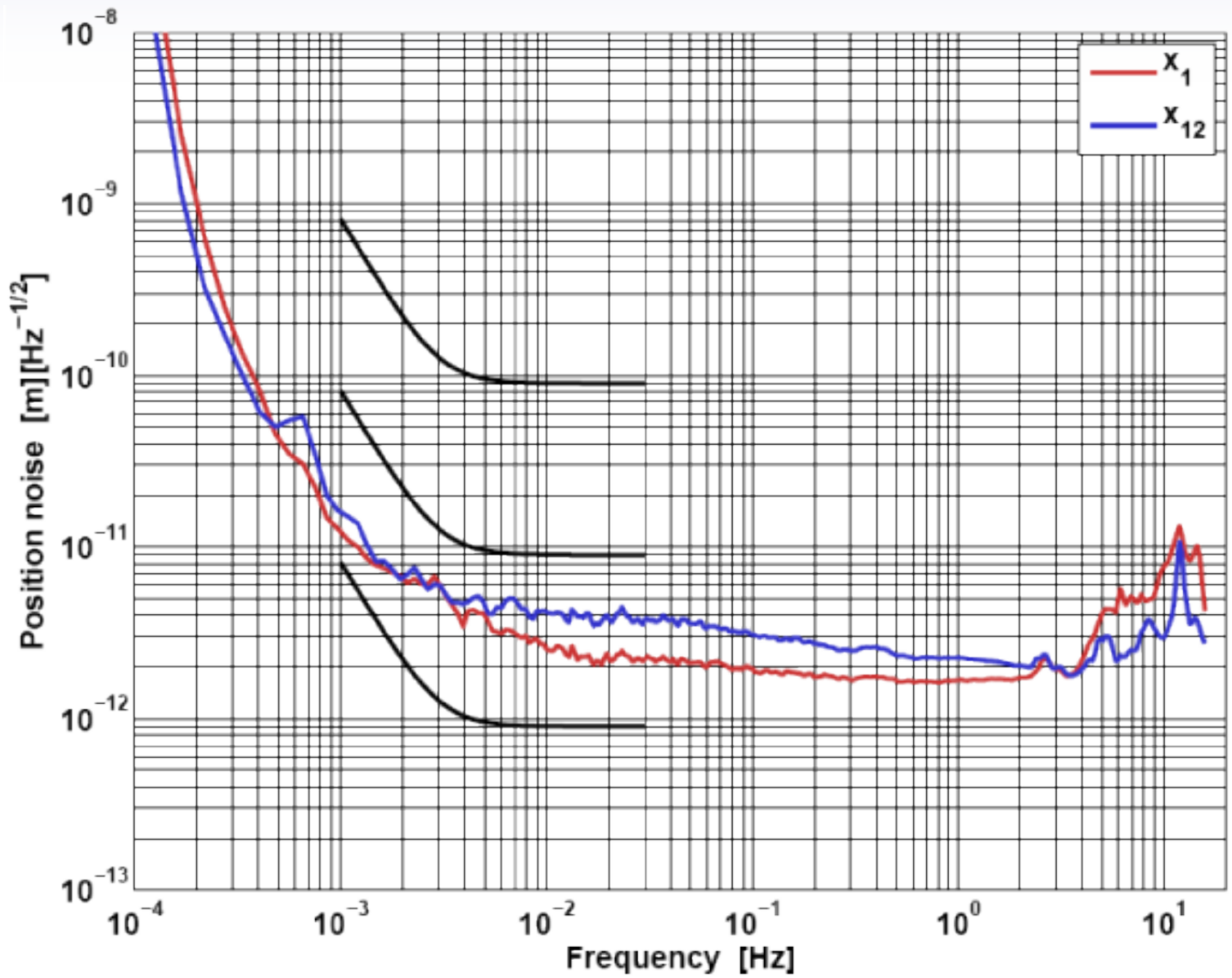






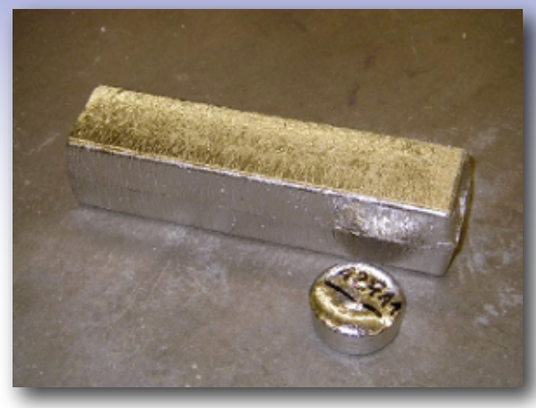


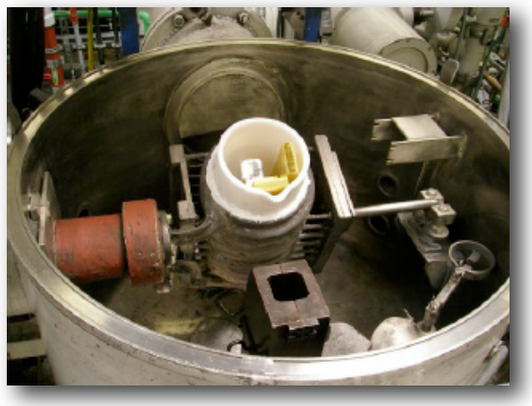


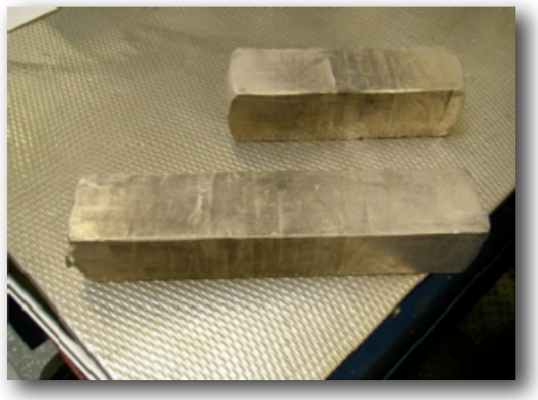
OMS closed loop tests (AEI, Hannover)

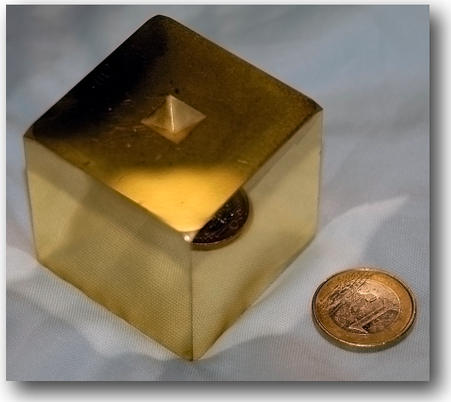
Inertial Sensor System

Proof mass





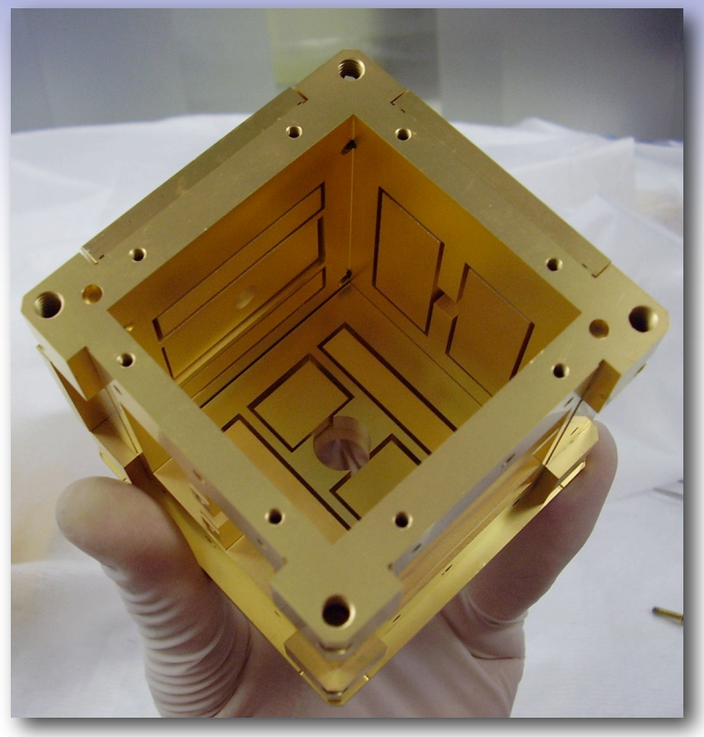




Build stages of the Au:Pt test mass

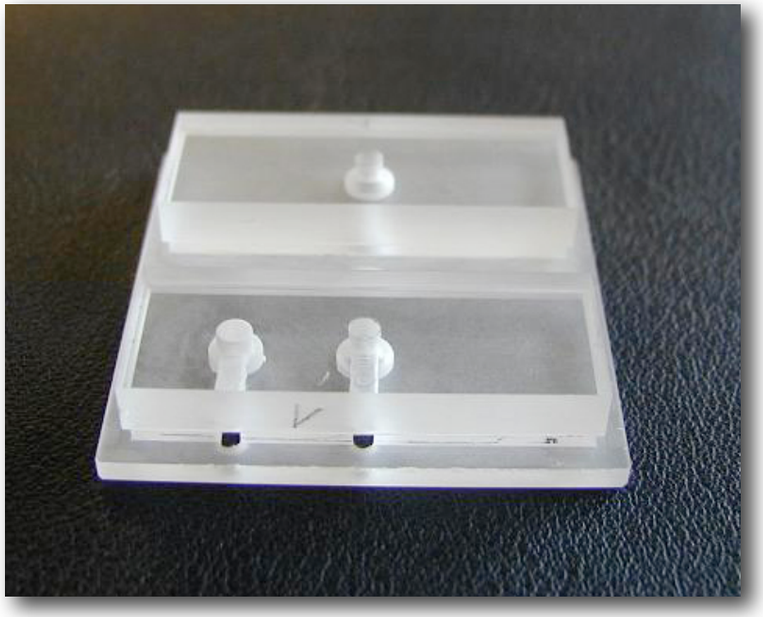
Inertial Sensor System

- Proof Mass
- **Electrode housing**

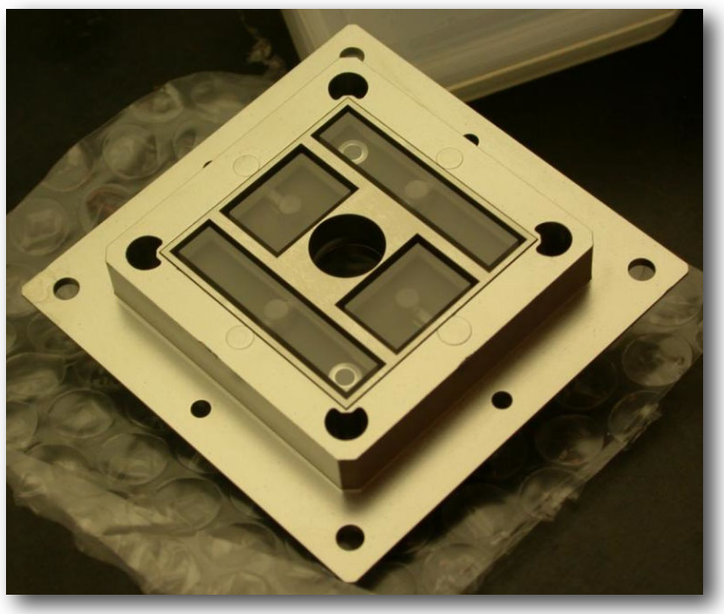


EM Molebdynum electrode Housing

EH Mandrel



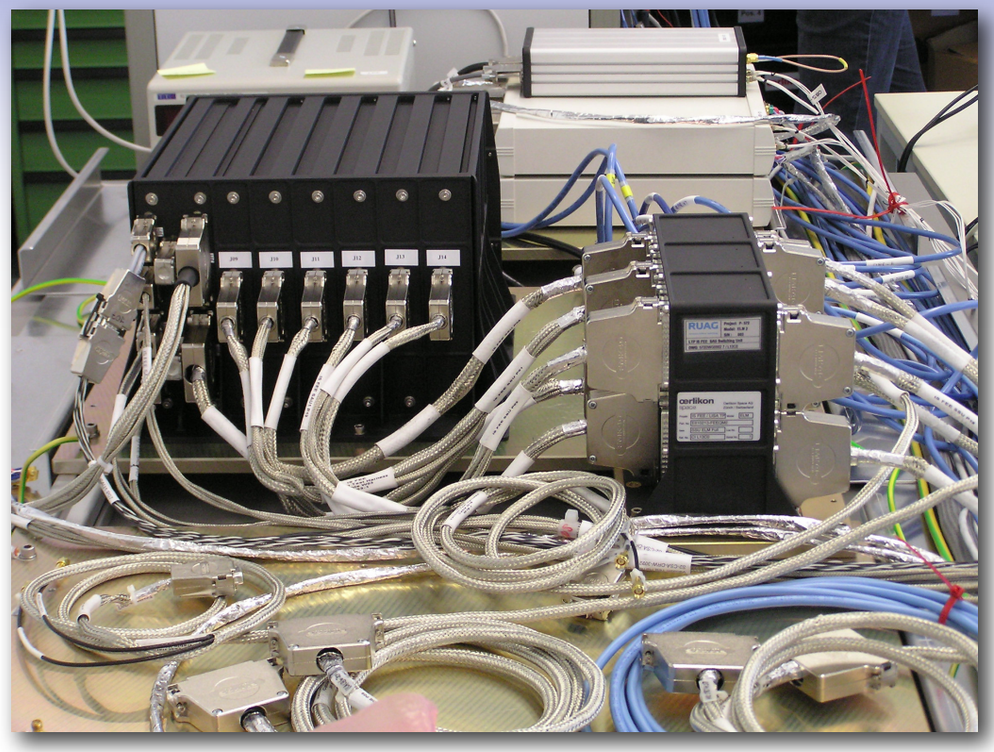
FM x-face Sapphire electrode



Uncoated z-face sapphire electrode in EH wall

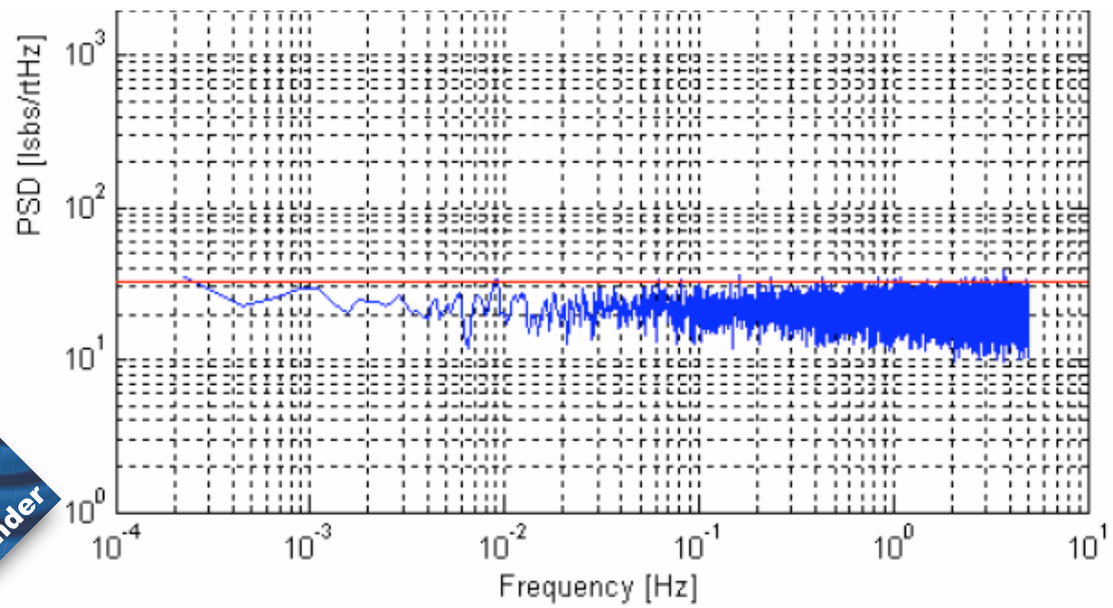
Inertial Sensor System

- Proof mass
- Electrode housing
- **Front end electronics**

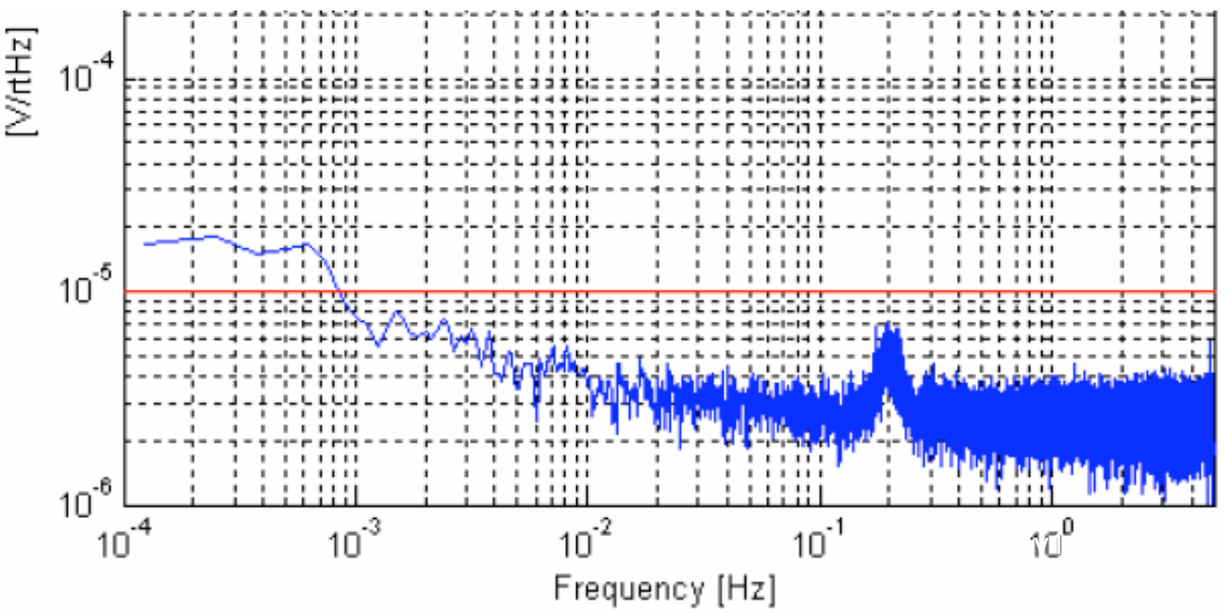


EM ISS FEE and switching unit

Sensing Noise



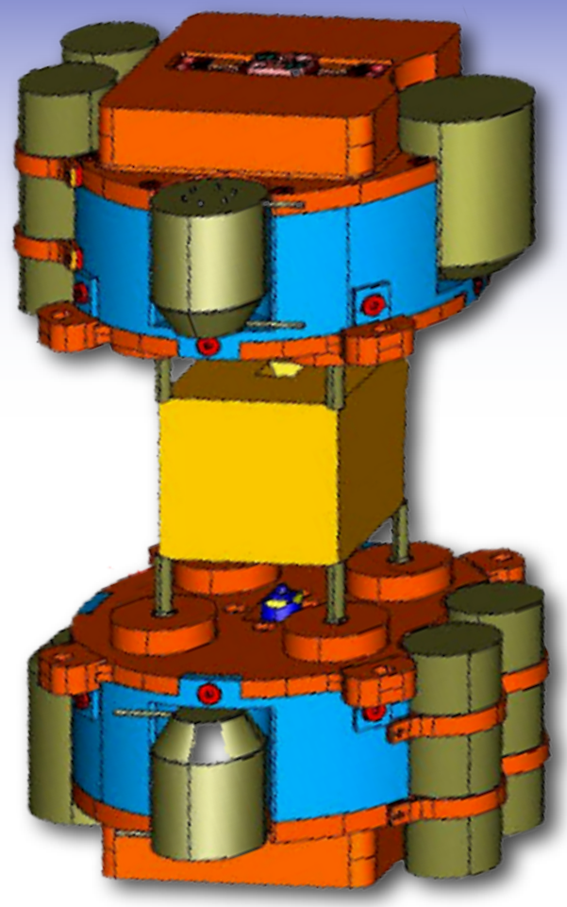
Actuation Noise

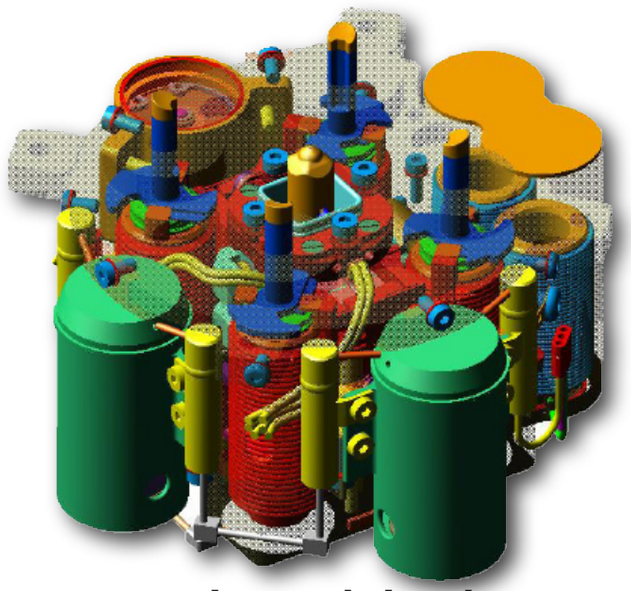


esa SCIENCE

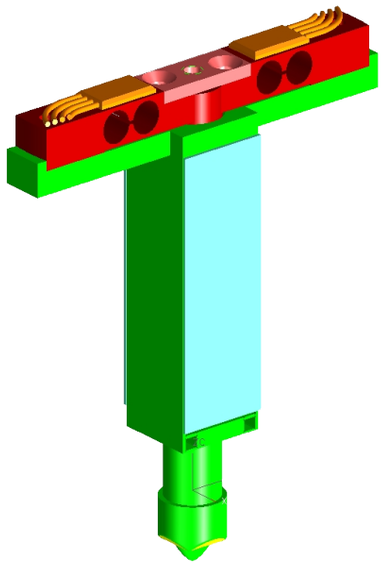
Inertial Sensor System

- Proof mass
- Electrode housing
- Front end electronics
- **Caging mechanism**

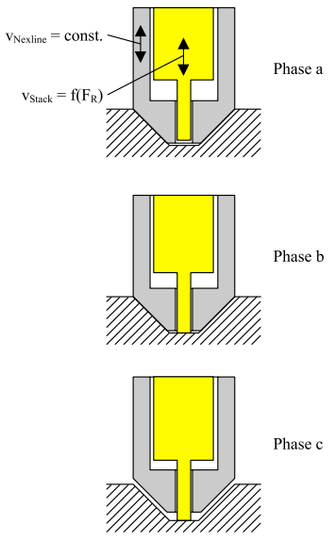




Launch Lock (3000N)



Positioning Actuator (100N)



Release Actuator (10N)

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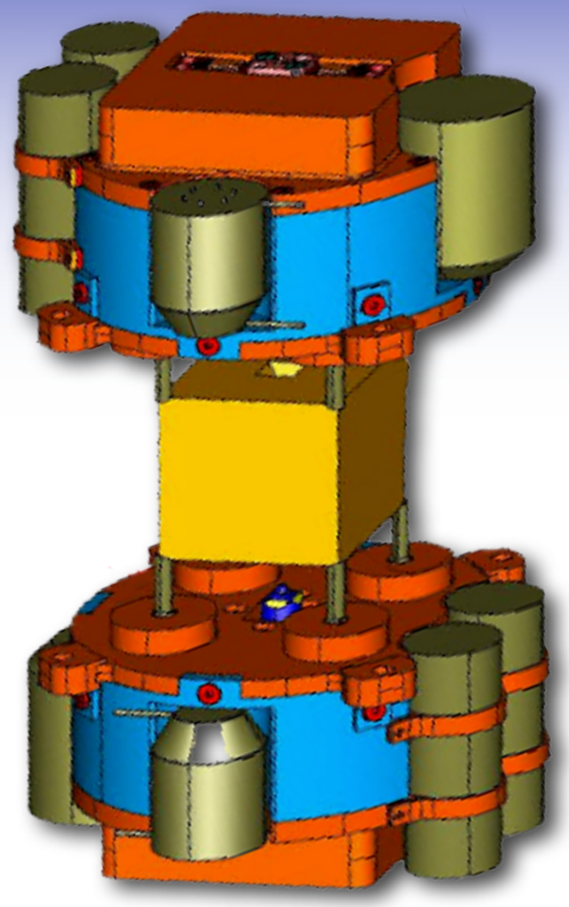
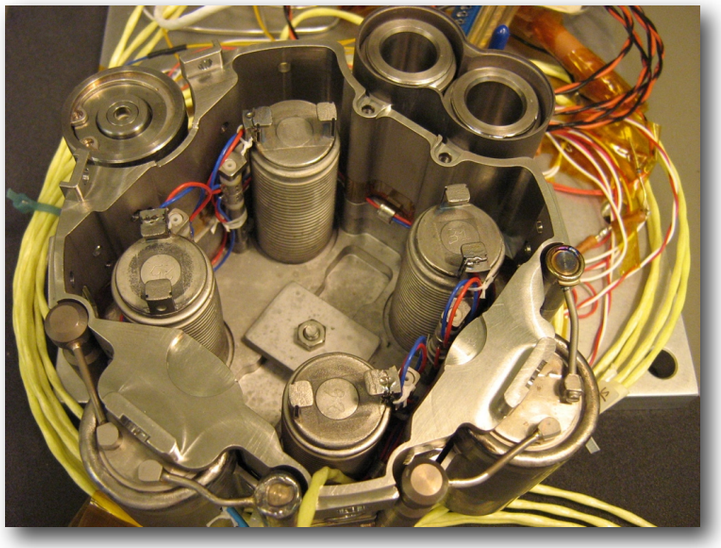
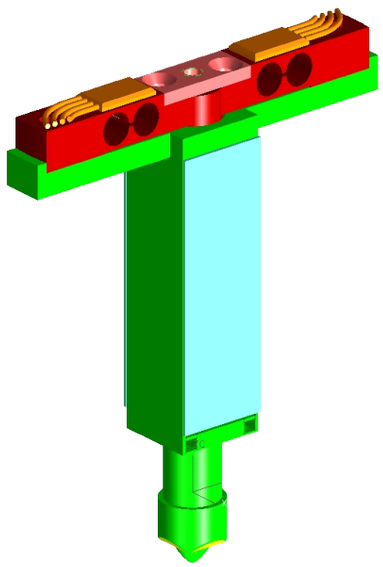
Inertial Sensor System

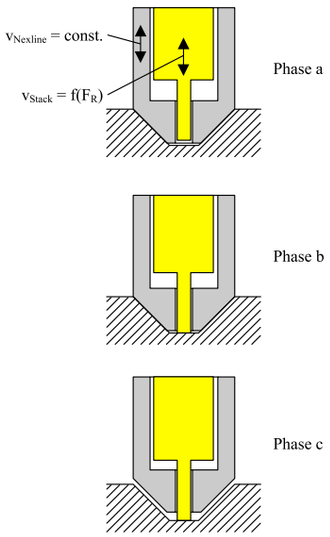
- Proof mass
- Electrode housing
- Front end electronics
- **Caging mechanism**







Positioning Actuator (100N)



Release Actuator (10N)

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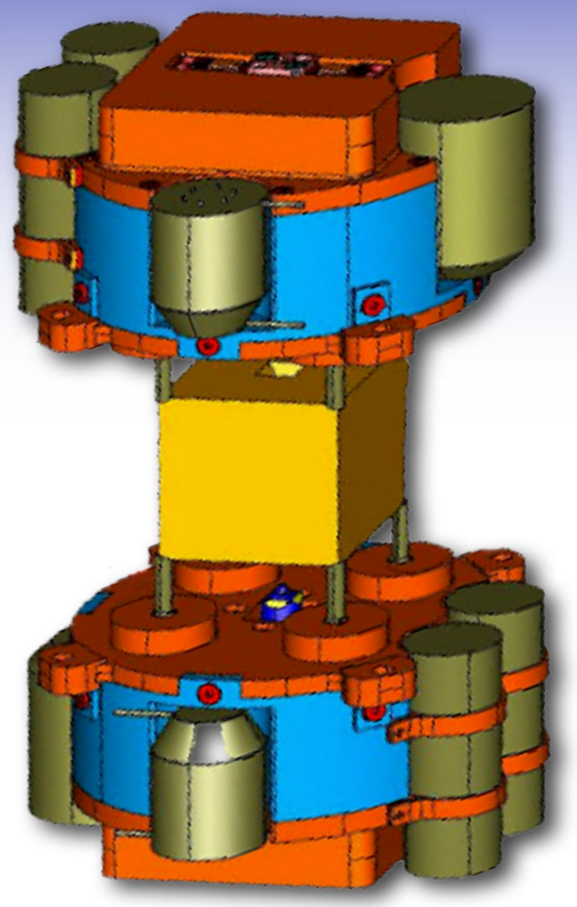
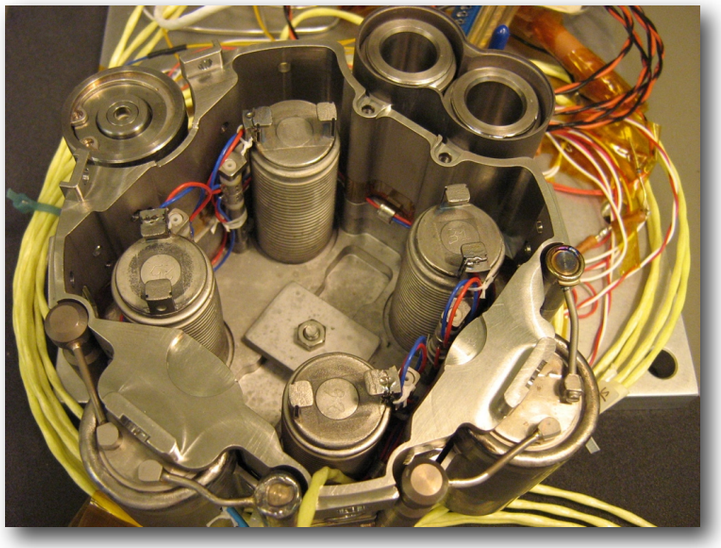
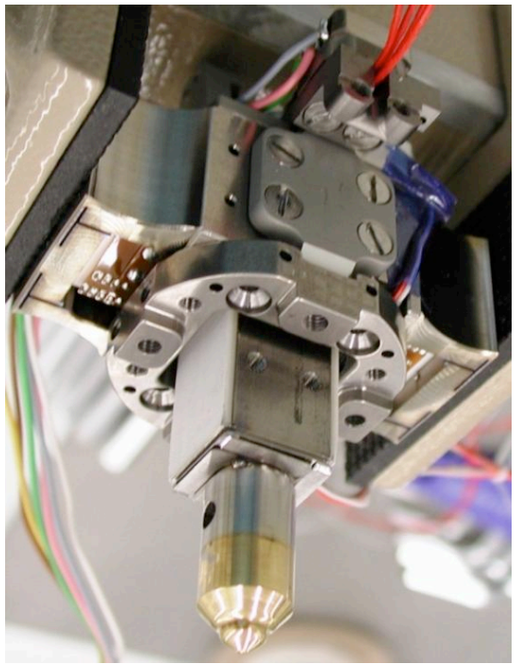
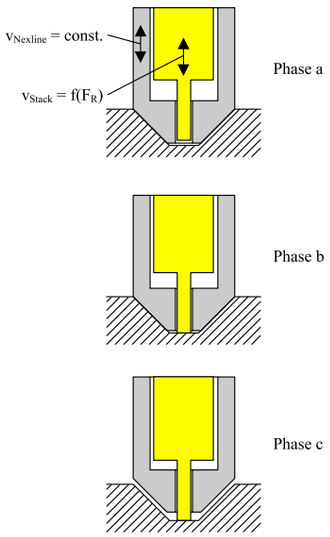
Inertial Sensor System

- Proof mass
- Electrode housing
- Front end electronics
- **Caging mechanism**









Release Actuator
(10N)

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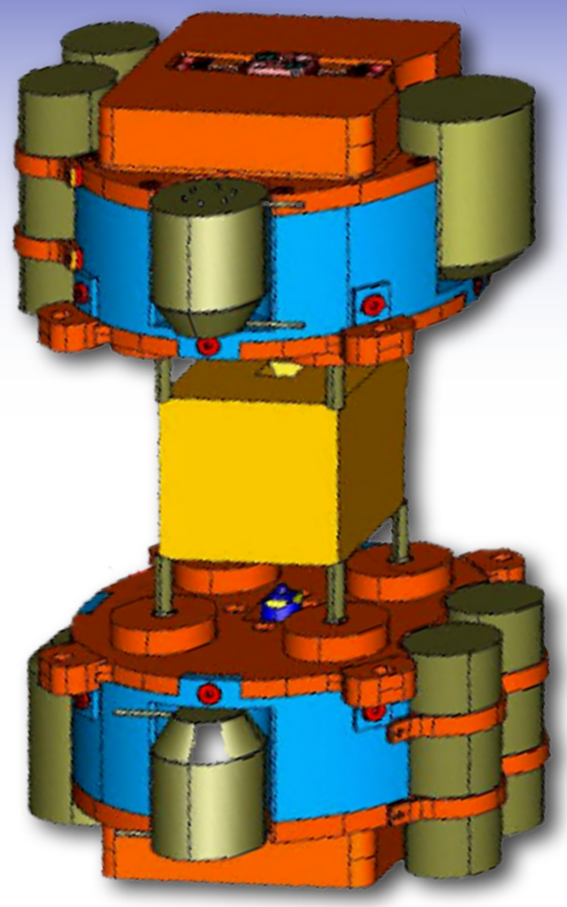
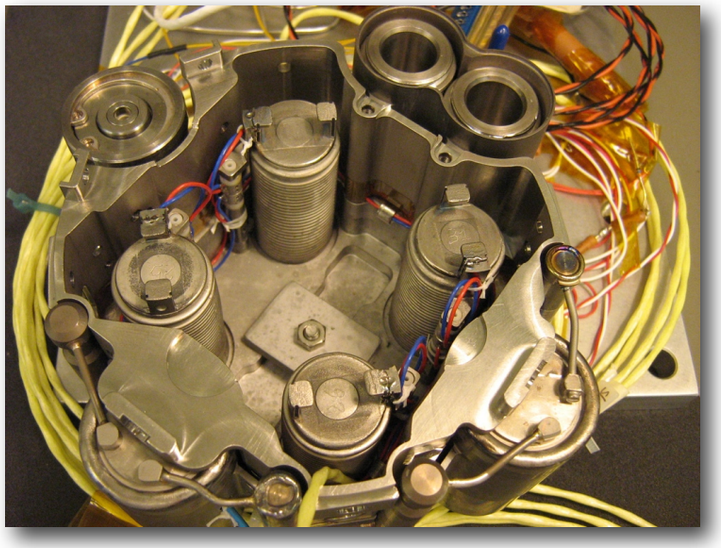
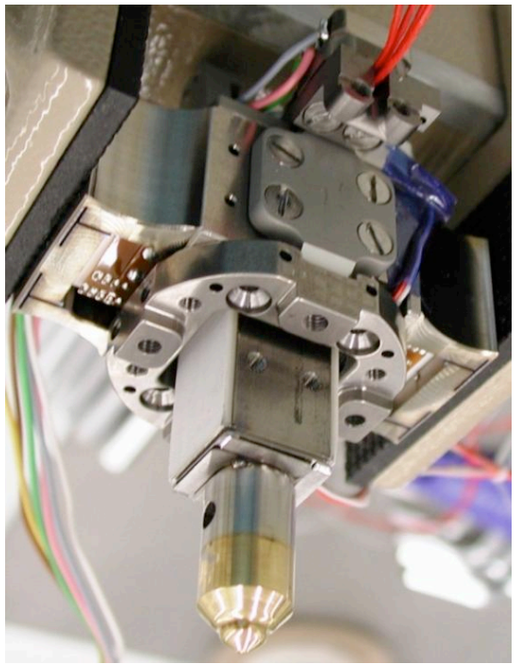
Inertial Sensor System

- Proof mass
- Electrode housing
- Front end electronics
- **Caging mechanism**

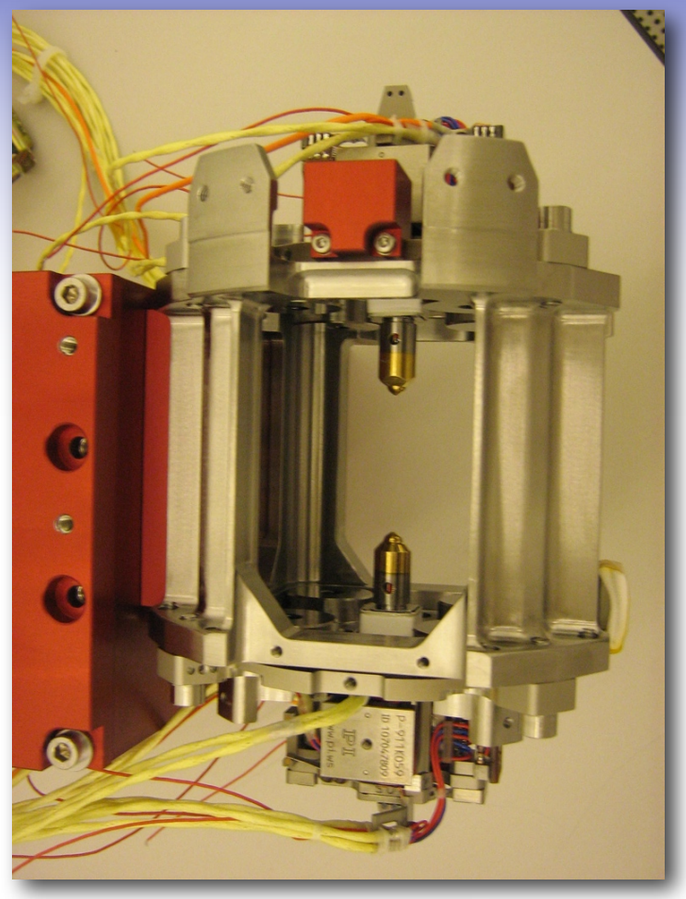


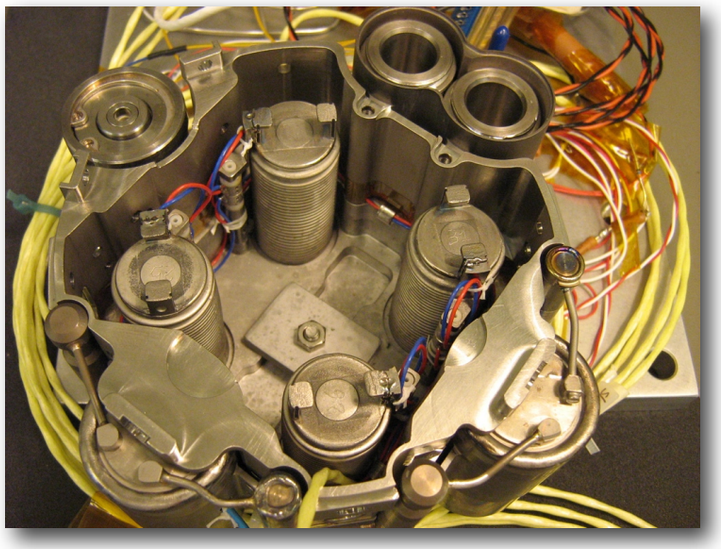


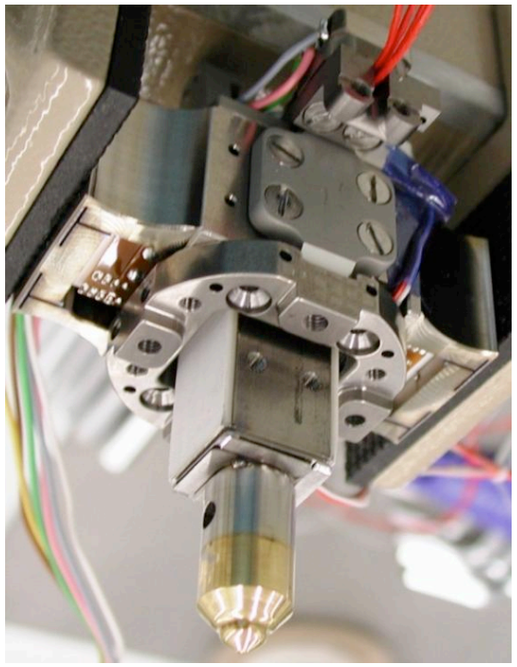


Inertial Sensor System

- Proof mass
- Electrode housing
- Front end electronics
- **Caging mechanism**

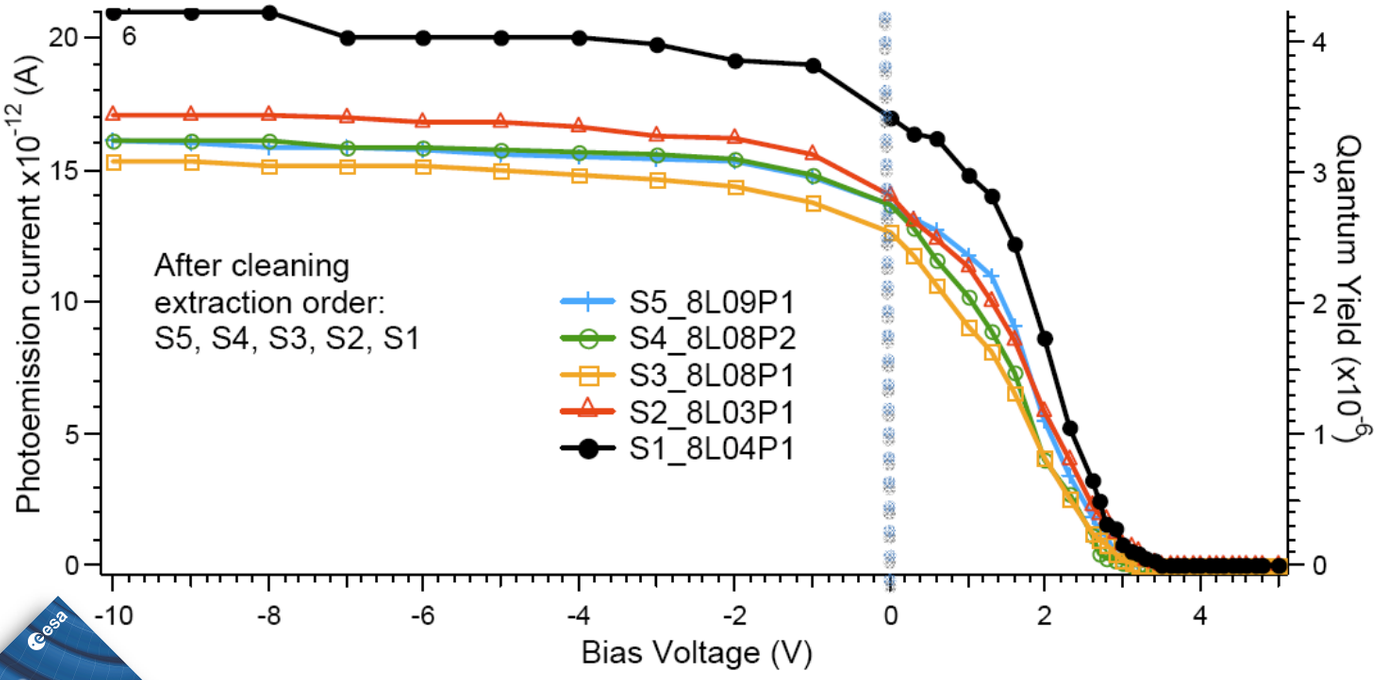


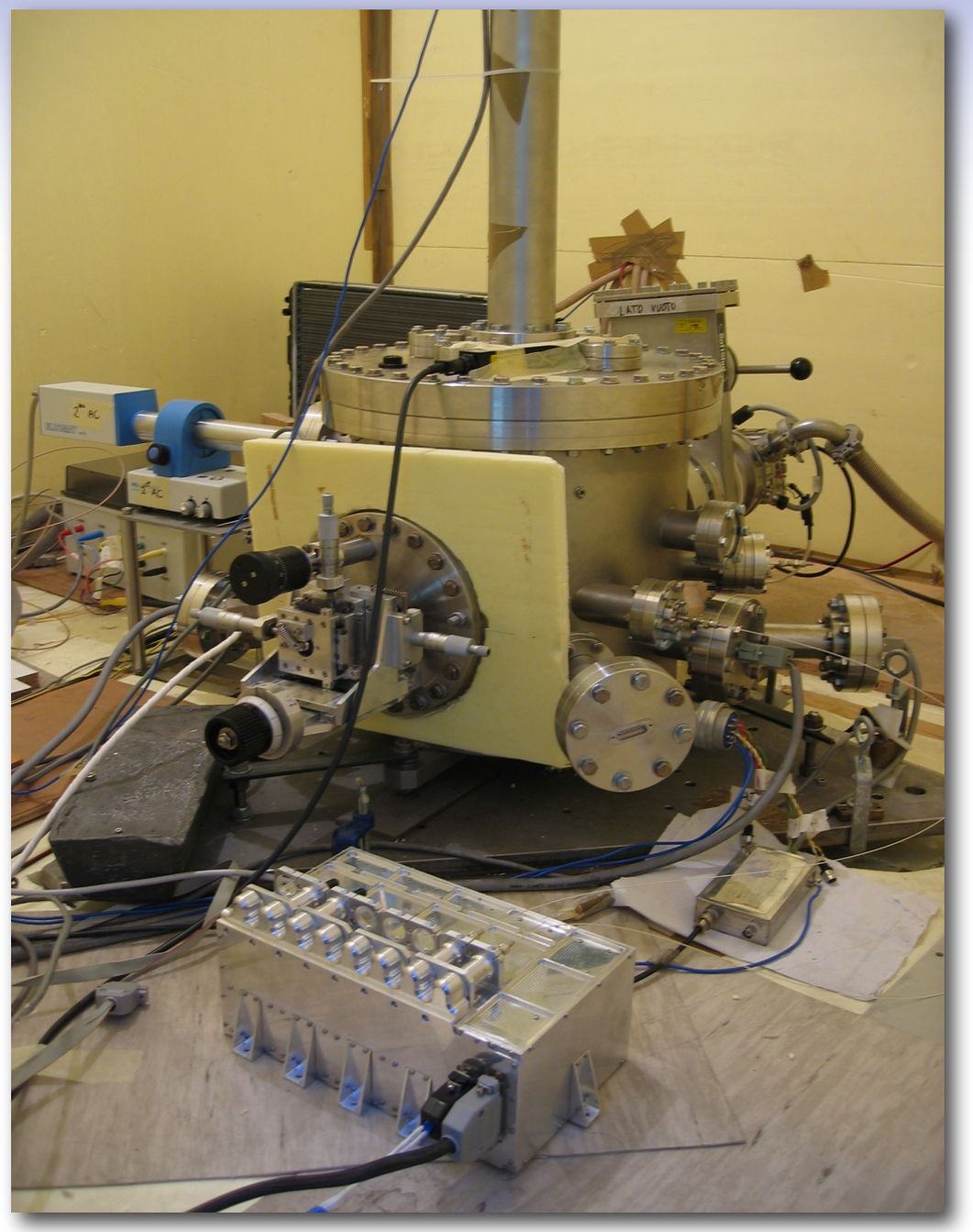




Inertial Sensor System

- Proof mass
- Electrode housing
- Front end electronics
- Caging mechanism
- **UV discharge system**



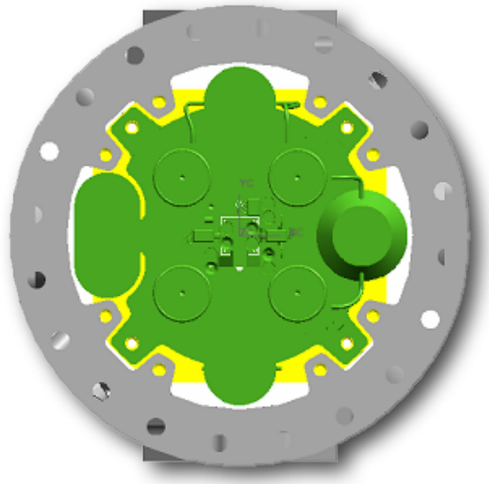


Charge Management system being tested on torsion pendulum facility

Inertial Sensor System

- Proof mass
- Electrode housing
- Front end electronics
- Caging mechanism
- UV discharge system
- **Vacuum System**

EM Titanium vacuum enclosure



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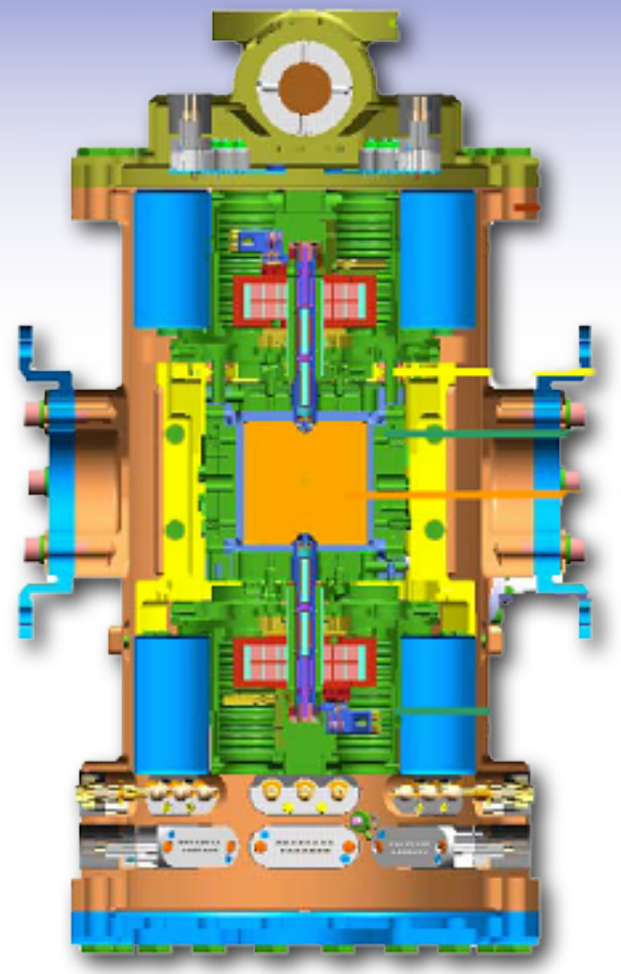
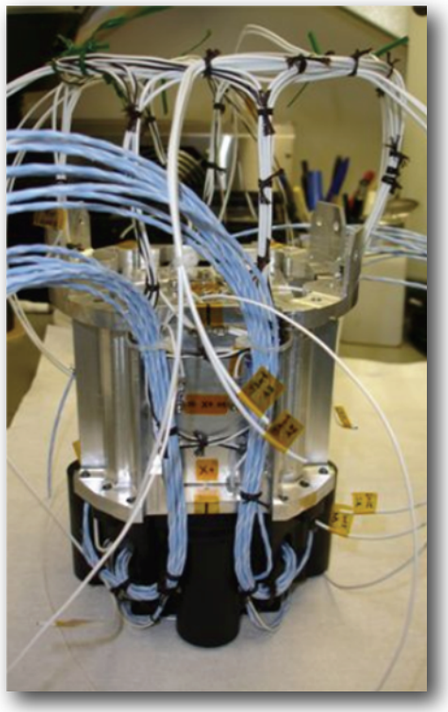
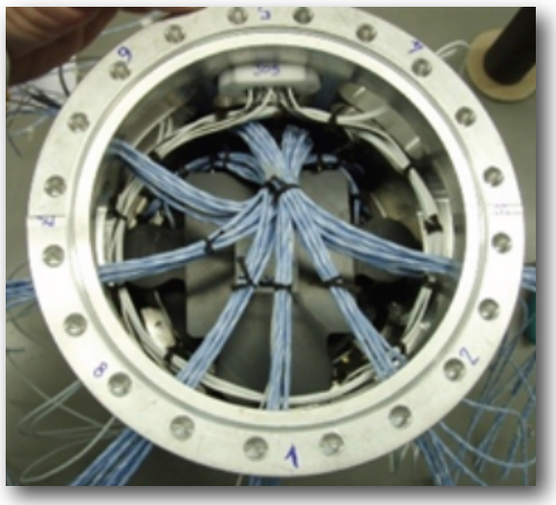
Inertial Sensor System

- Proof mass
- Electrode housing
- Front end electronics
- Caging mechanism
- UV discharge system
- **Vacuum System**





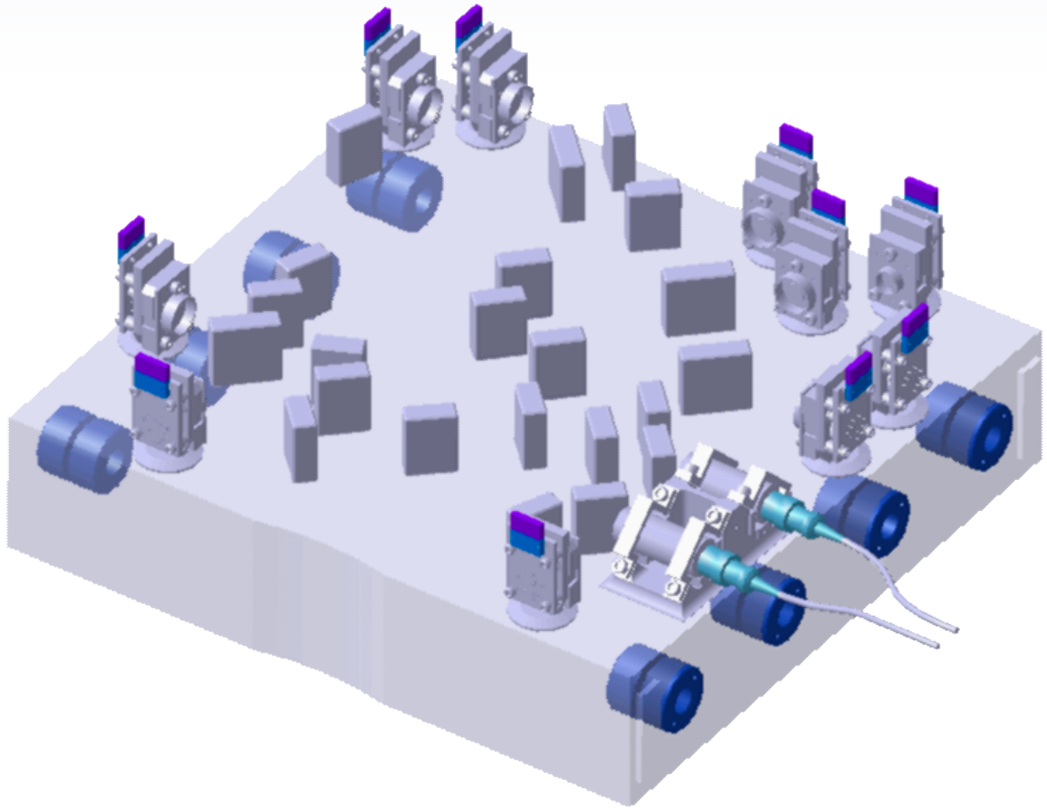


Data Diagnostic Unit

- The Data Diagnostic Unit is the LTP Payload computer
  - ERC32 space qualified processor running at 12MHz!!!
  - Main functions include:
    - TMTC of LTP units
    - Data handling of OMS and auxiliary data
    - Running OMS loops
      - Frequency noise, intensity noise, and optical path length difference
      - Loops running at 100Hz
    - Provide synchronisation clock to LTP units

Data Management Unit EQM (Payload Computer)

LTP Integration



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LTP Integration

LISA Pathfinder

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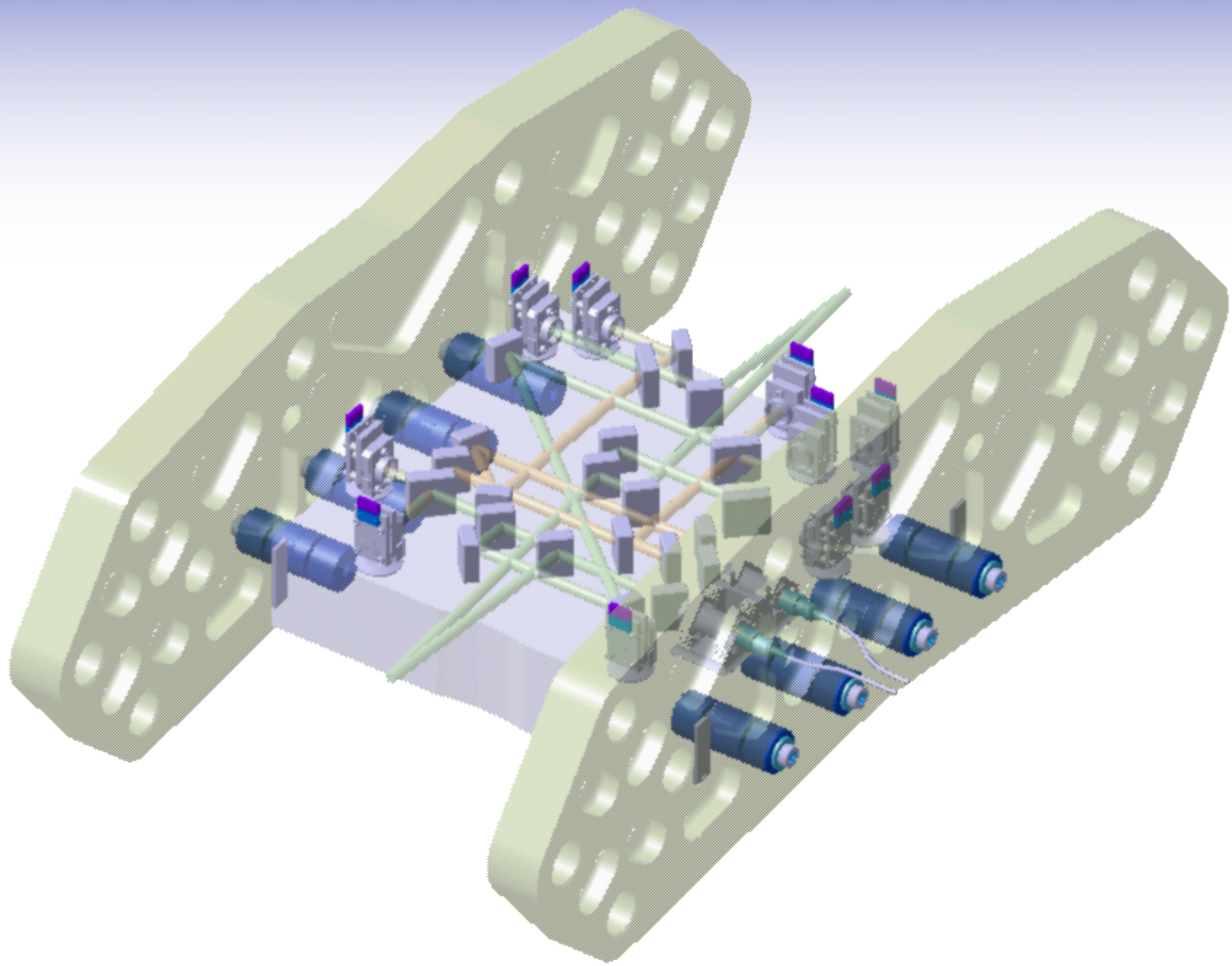

LISA Pathfinder

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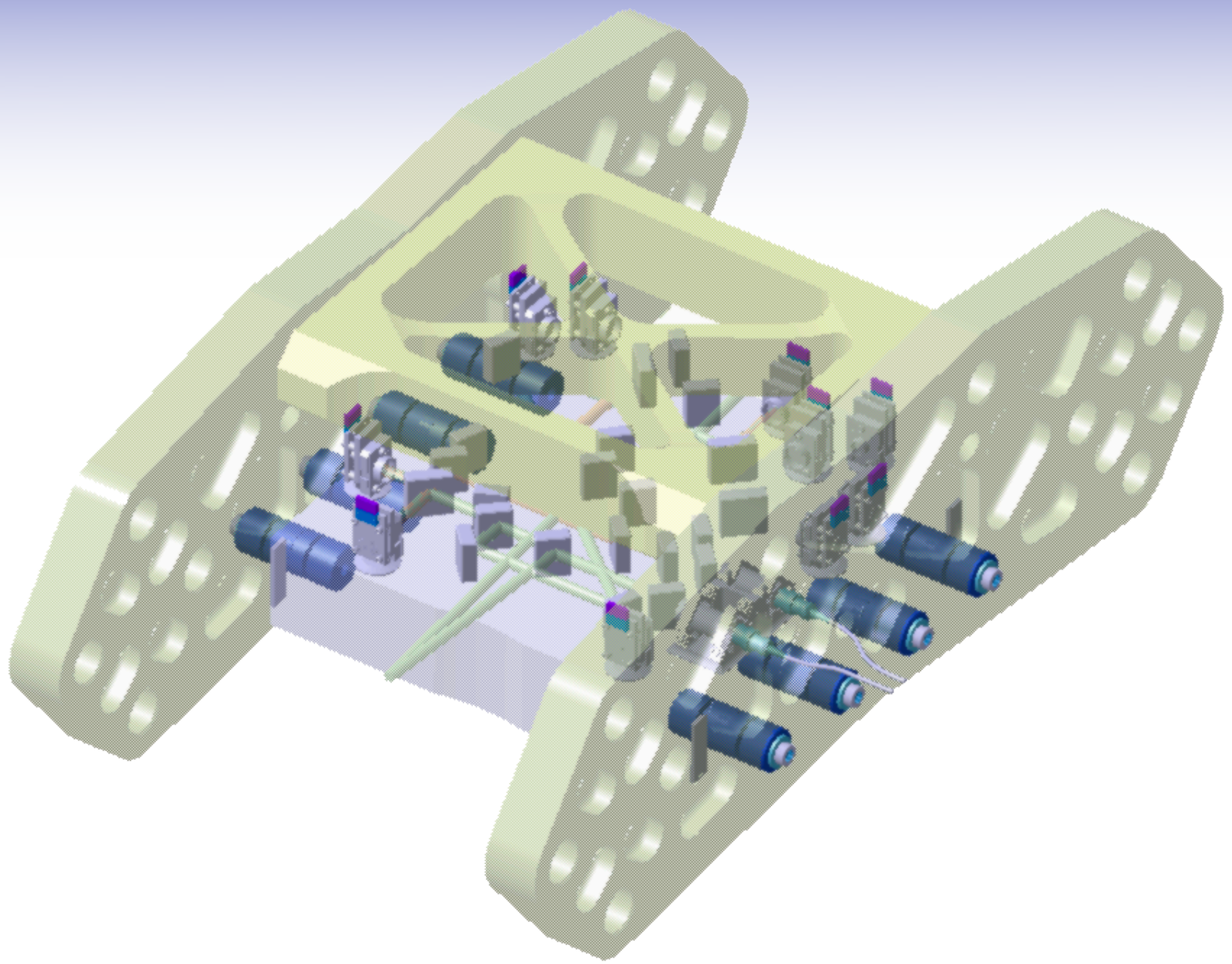
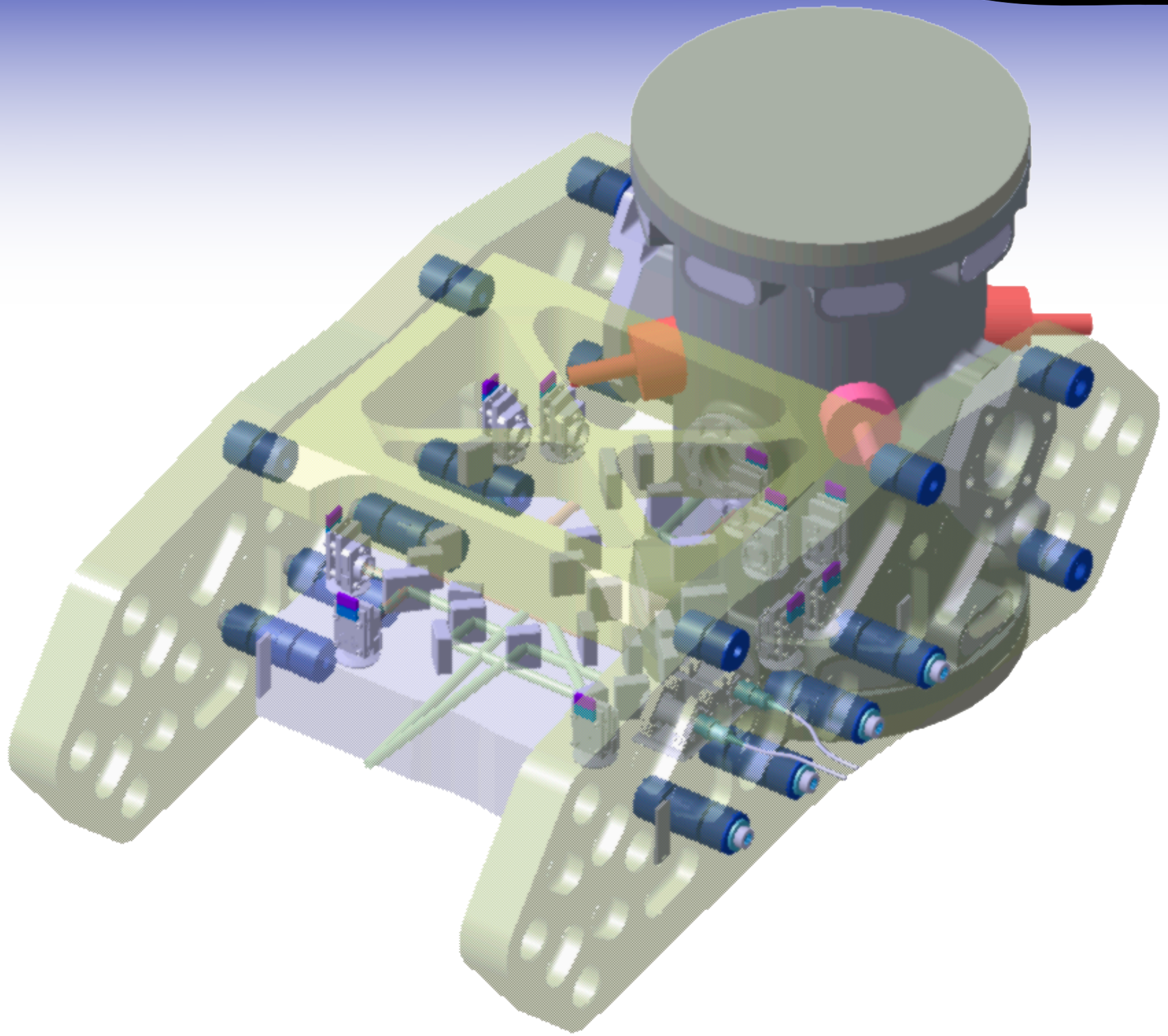


LISA Pathfinder

LISA Pathfinder

esa SCIENCE



LISA Pathfinder

LISA Pathfinder

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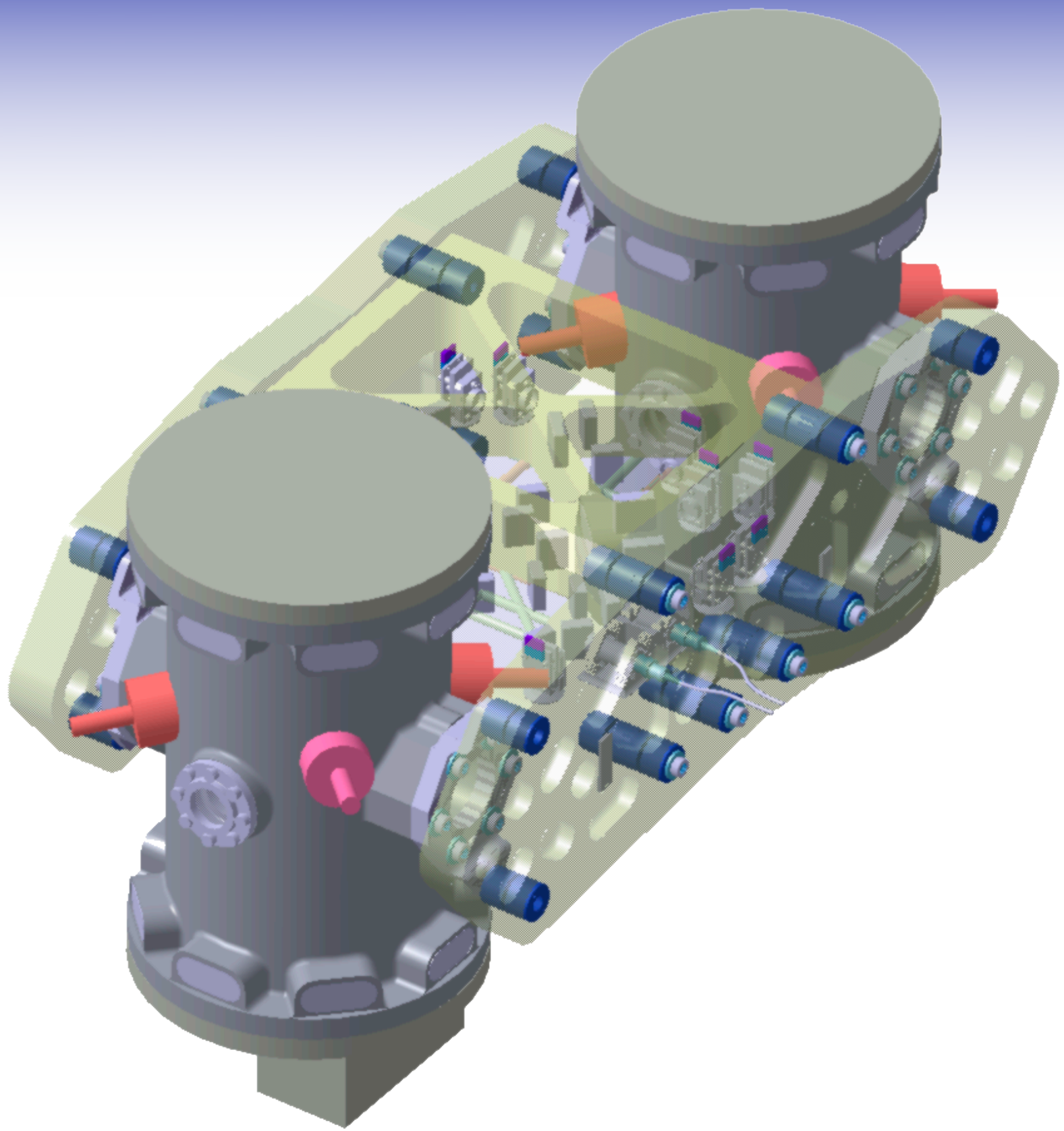

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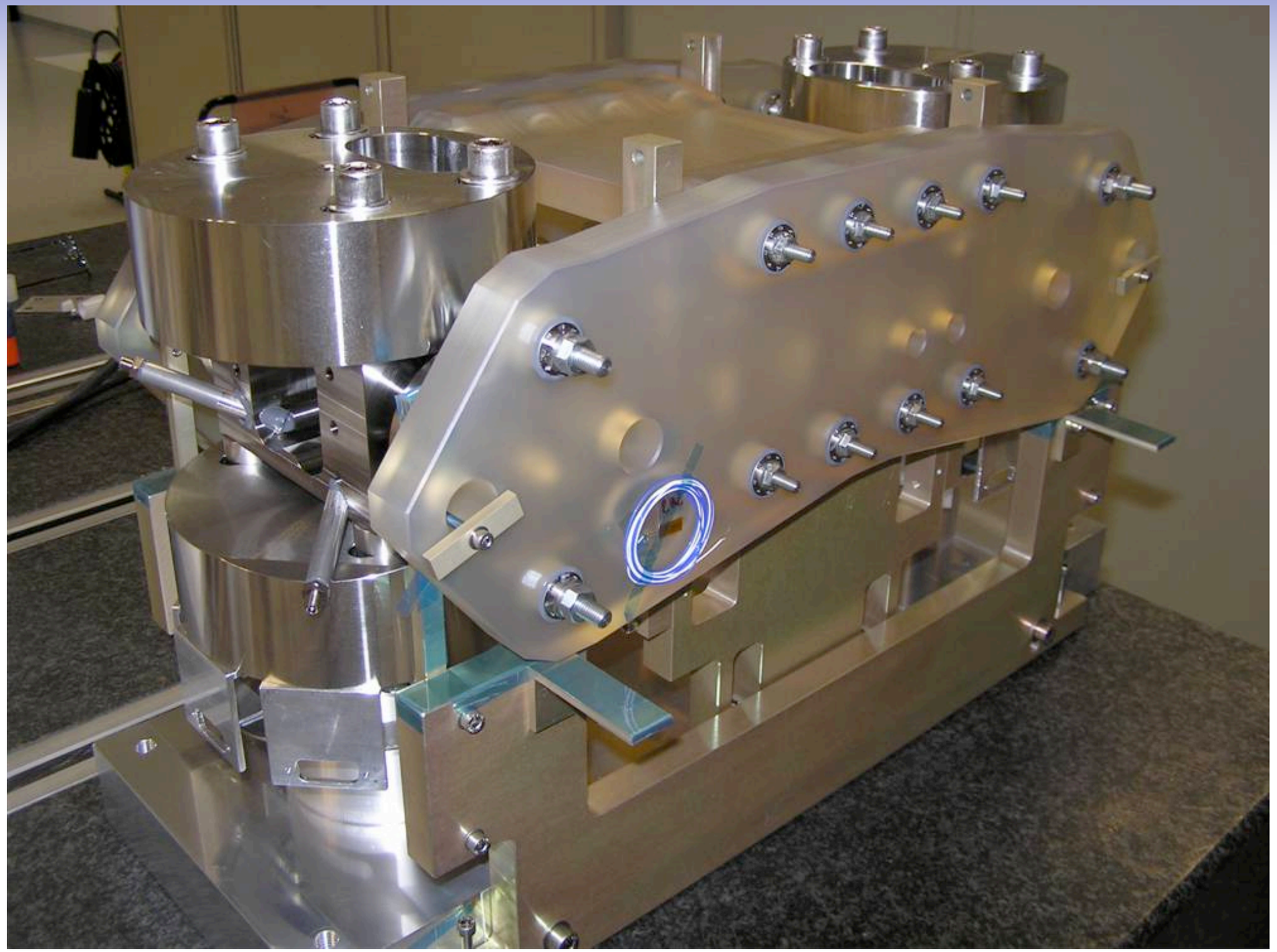

LISA Pathfinder

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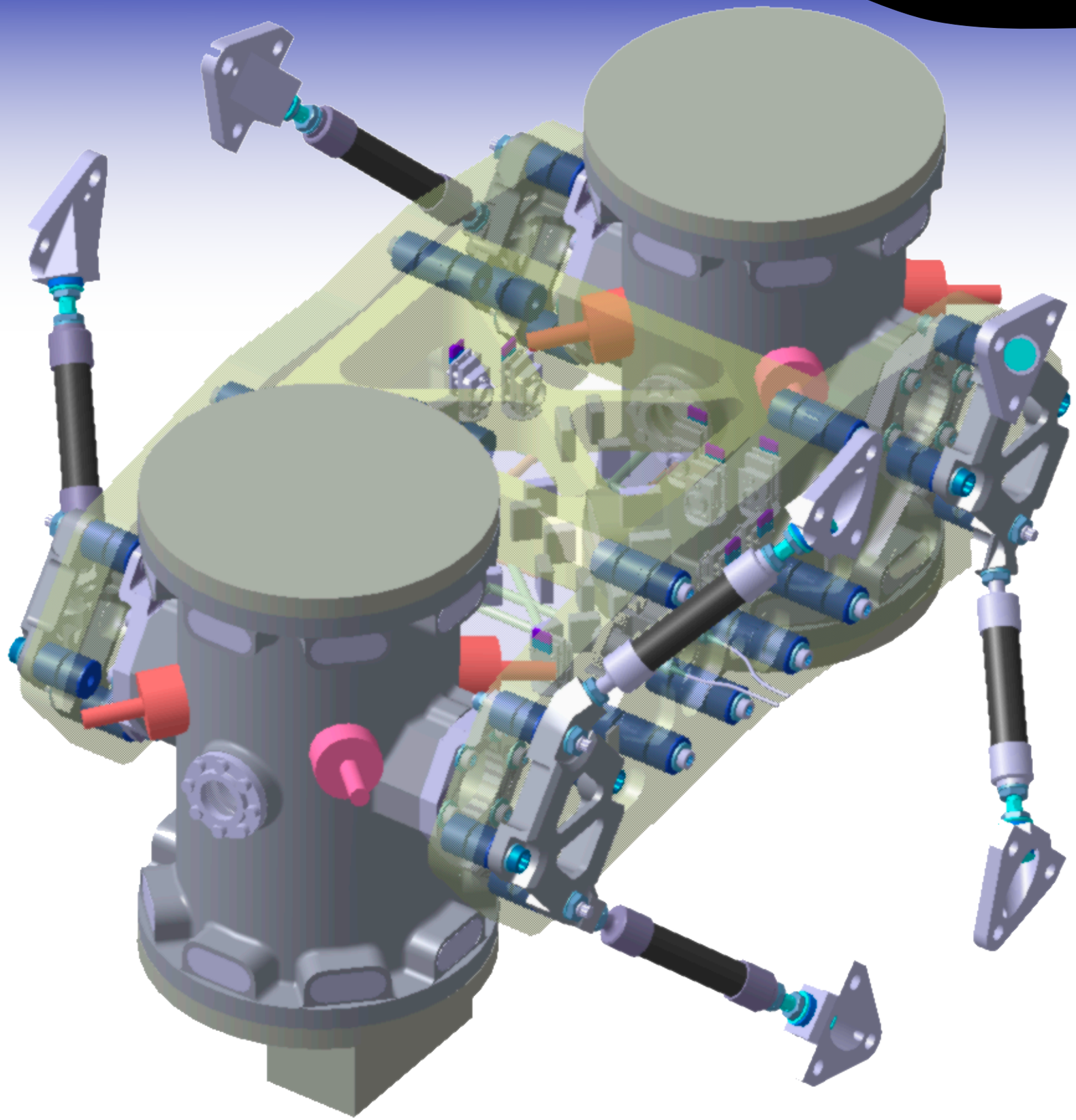
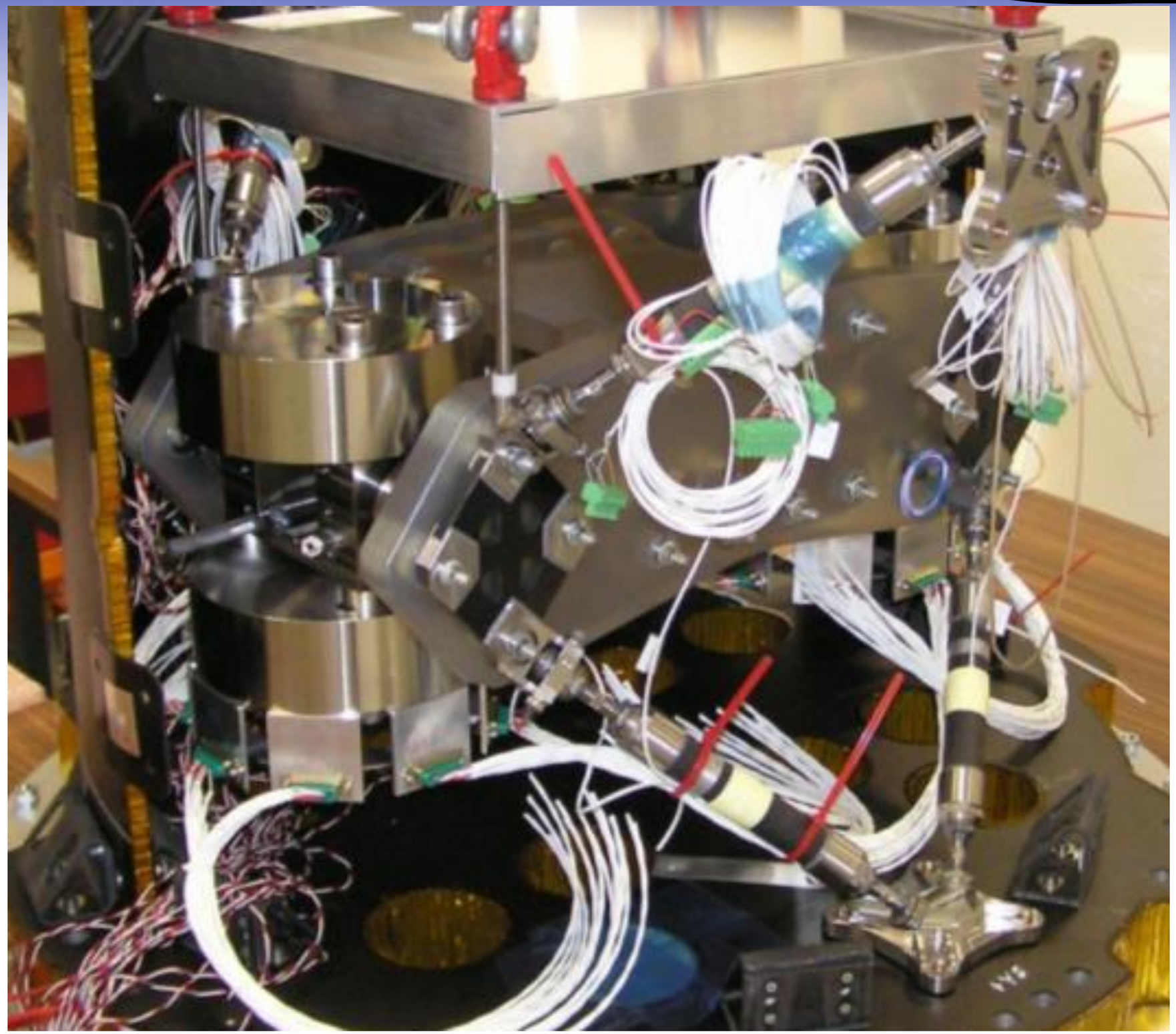


LISA Pathfinder

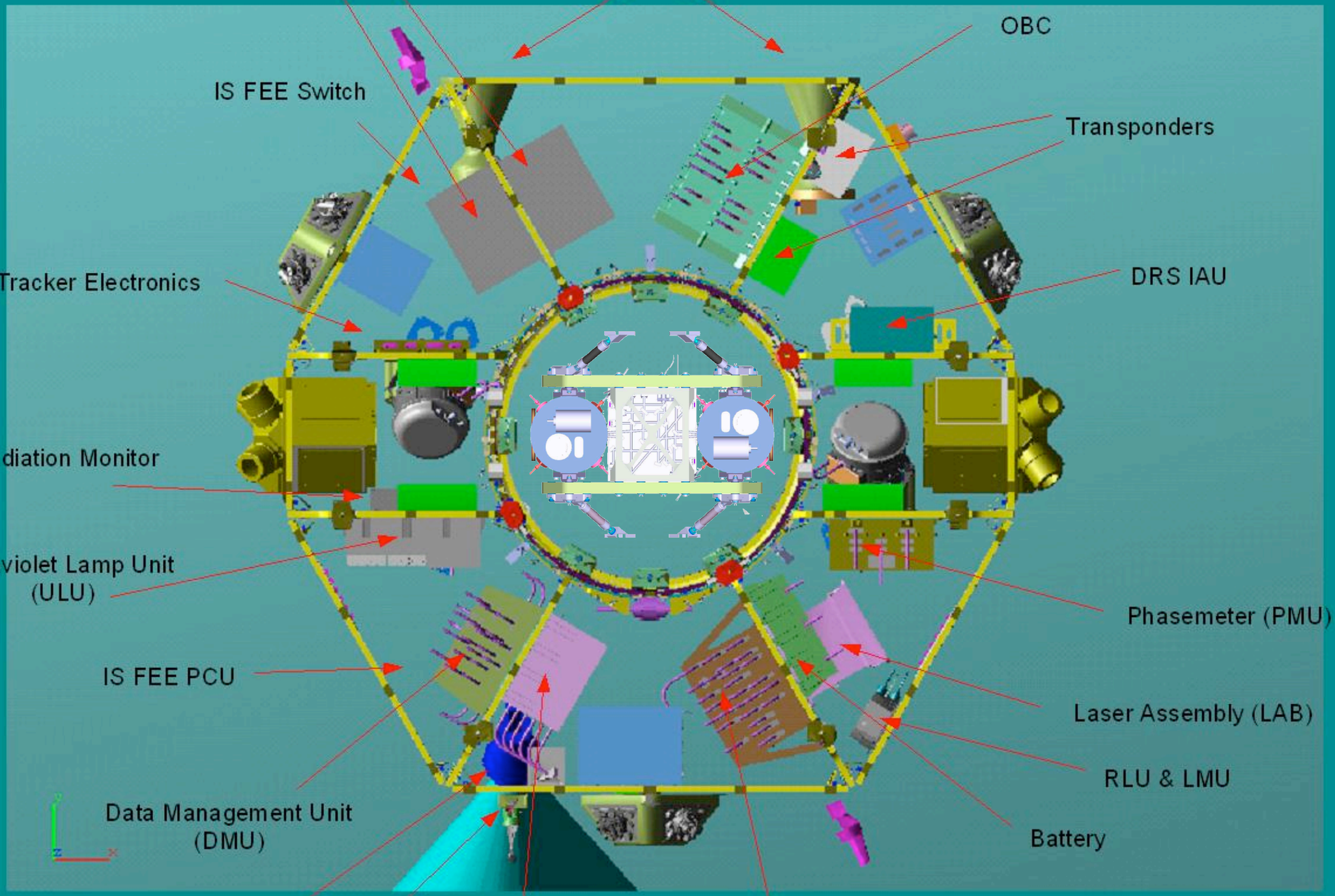
EADS ASTRIUM

esa SCIENCE



LISA Pathfinder

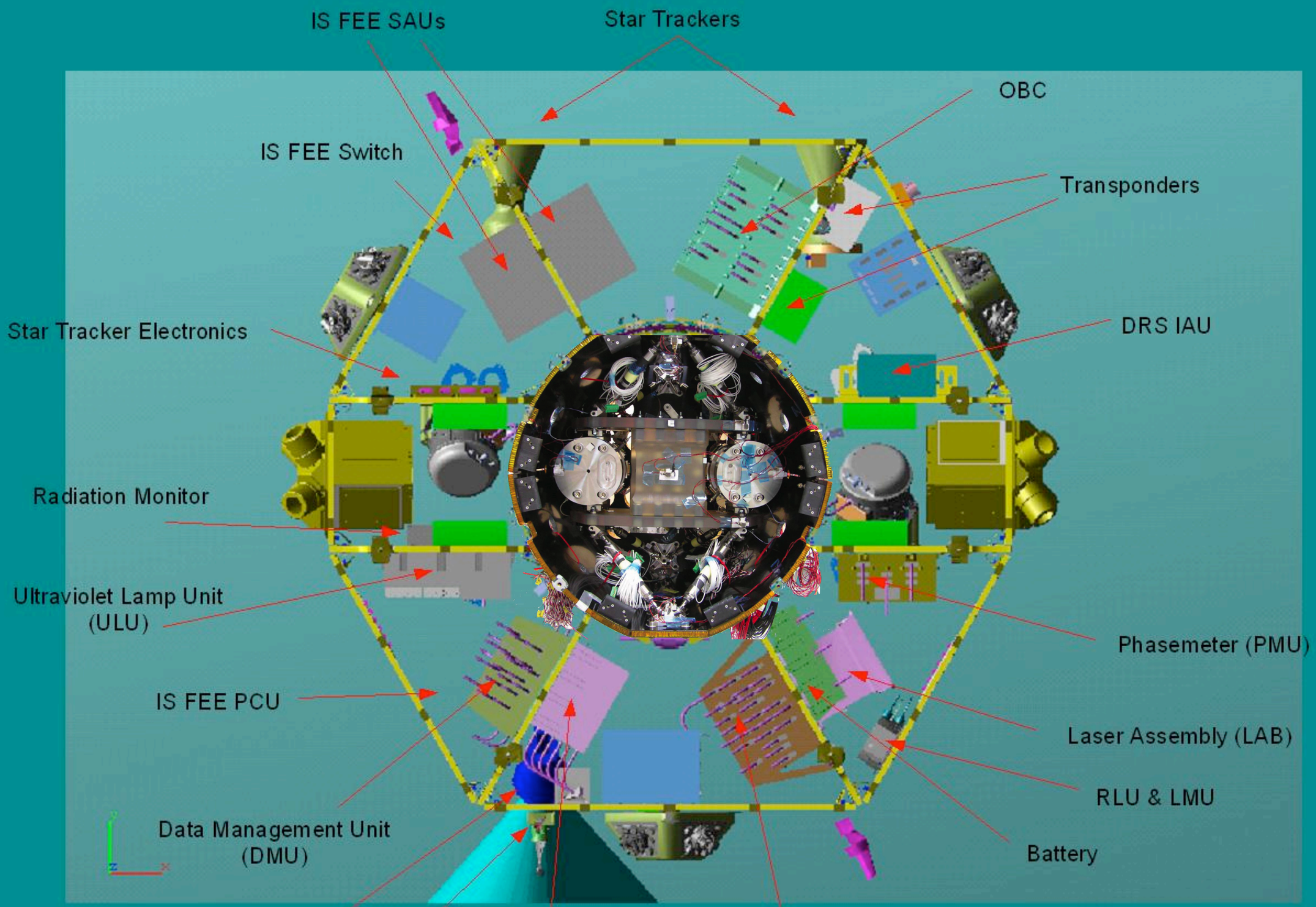
esa SCIENCE



EADS ASTRIUM

LISA Pathfinder

esa SCIENCE



EADS ASTRIUM

Micro-Newton Thrusters

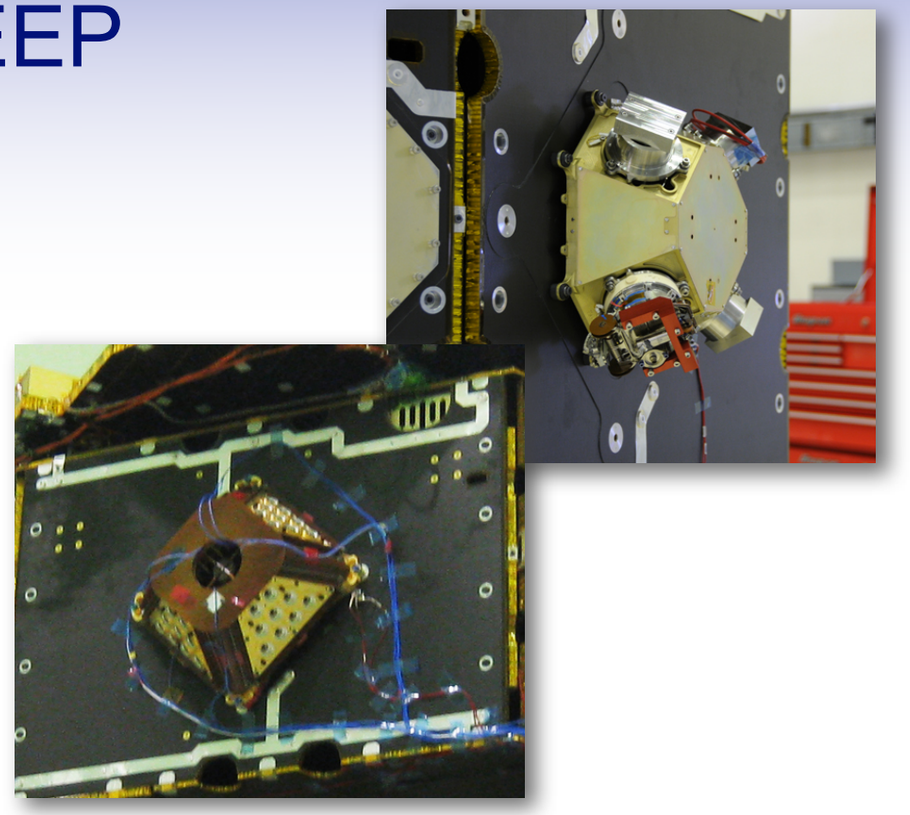
- LISA Pathfinder will carry two types of μ-Newton thrusters
  - Field Emission Electric Propulsion (FEEPs) [ESA]
  - Colloidal thrusters [NASA]
- Thruster requirements can be summarised as:

Key Requirement Specification	FEEP	Colloid
Thrust Range	0.3-150 μN	5-30 μN
Thrust Precision	<0.1 μN	<0.1 μN
Thrust Noise	<0.1 μN/√Hz	<0.1 μN/√Hz
Response Time	<340 ms	<100 sec
Specific Impulse	>4,000 sec	>150 sec
Cluster Power Consumption (4 thrusters @30μN)	55 W	25 W
Cluster Mass (4 thrusters, neutralizer and PCU)	13.7 kg	14.6 kg
Lifetime (Thruster-ON)	250 days	90 days
Total Impulse	2,000 Ns	300 Ns

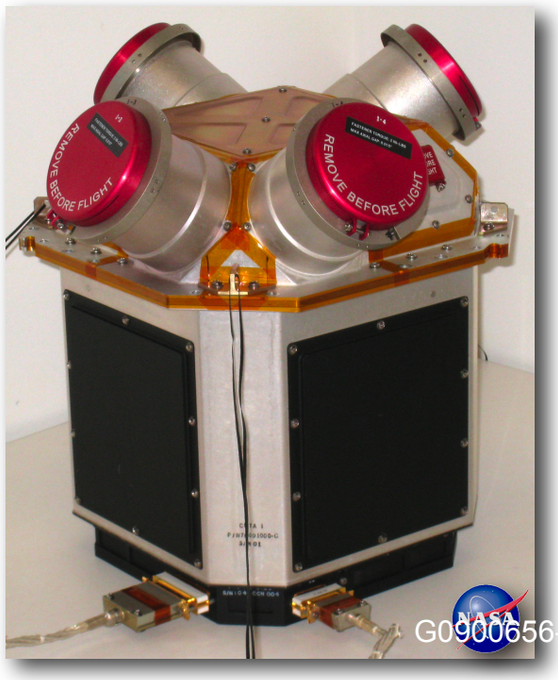
Note: LISA requires 40,000hours of operation and 4,000N specific impulse

Micro-Newton Thrusters [2]

- Europe are developing two types of FEEP
  - Slit FEEP with Caesium propellant
    - Now been chosen for flight
  - Needle FEEP with Indium propellant
    - Developed as back-up
- Cs FEEP has now demonstrated >3200hours (860Ns) of operation
  - Flight thrusters are now being built



- NASA Colloidal thruster flight units are complete and are waiting to be shipped to ESA



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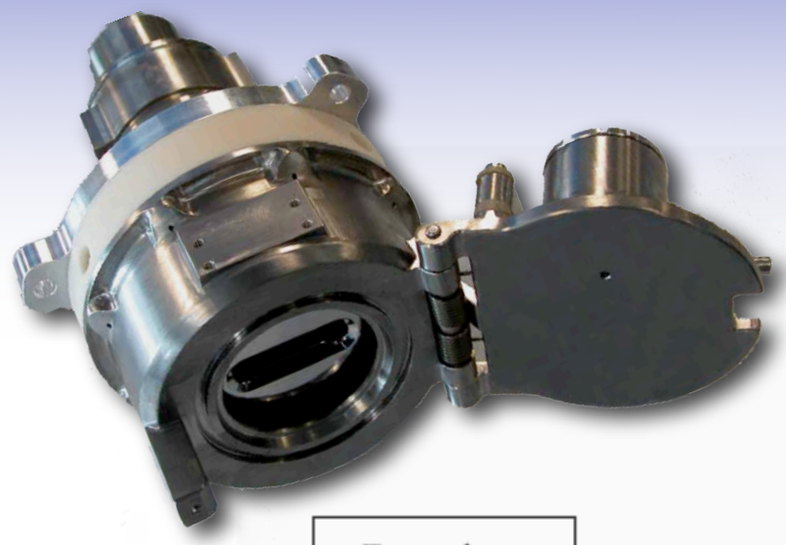
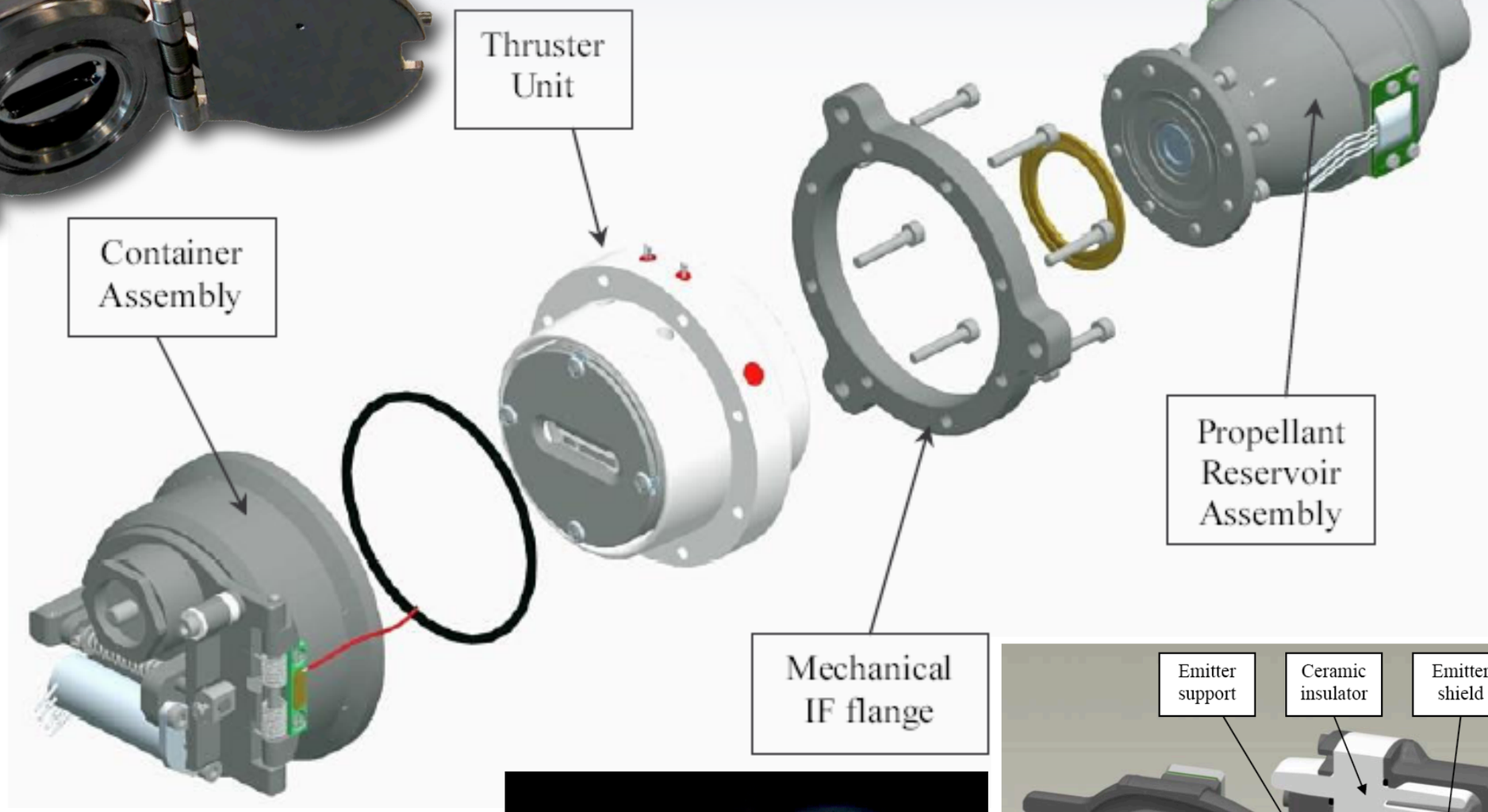
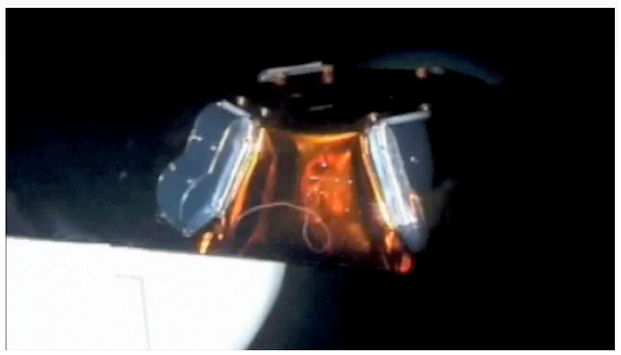
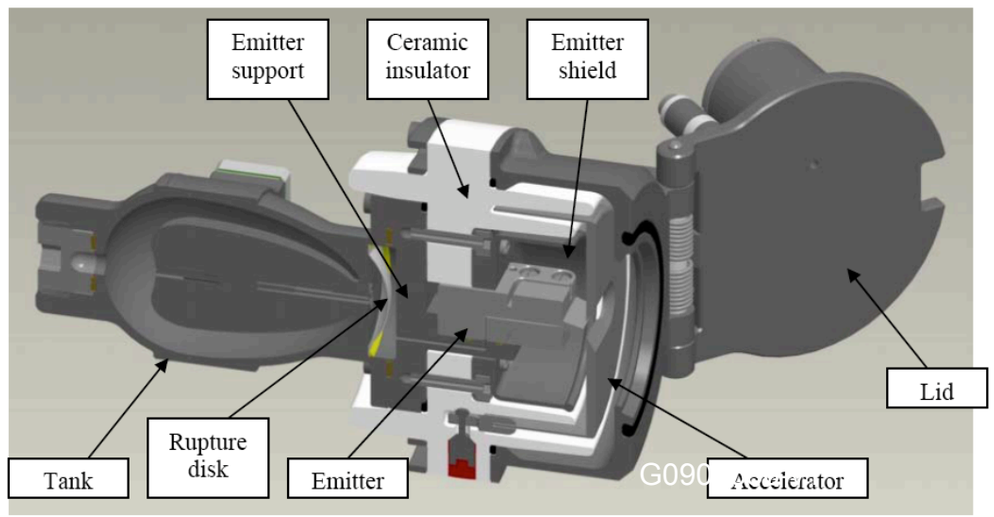
Micro-Newton Thrusters [3]



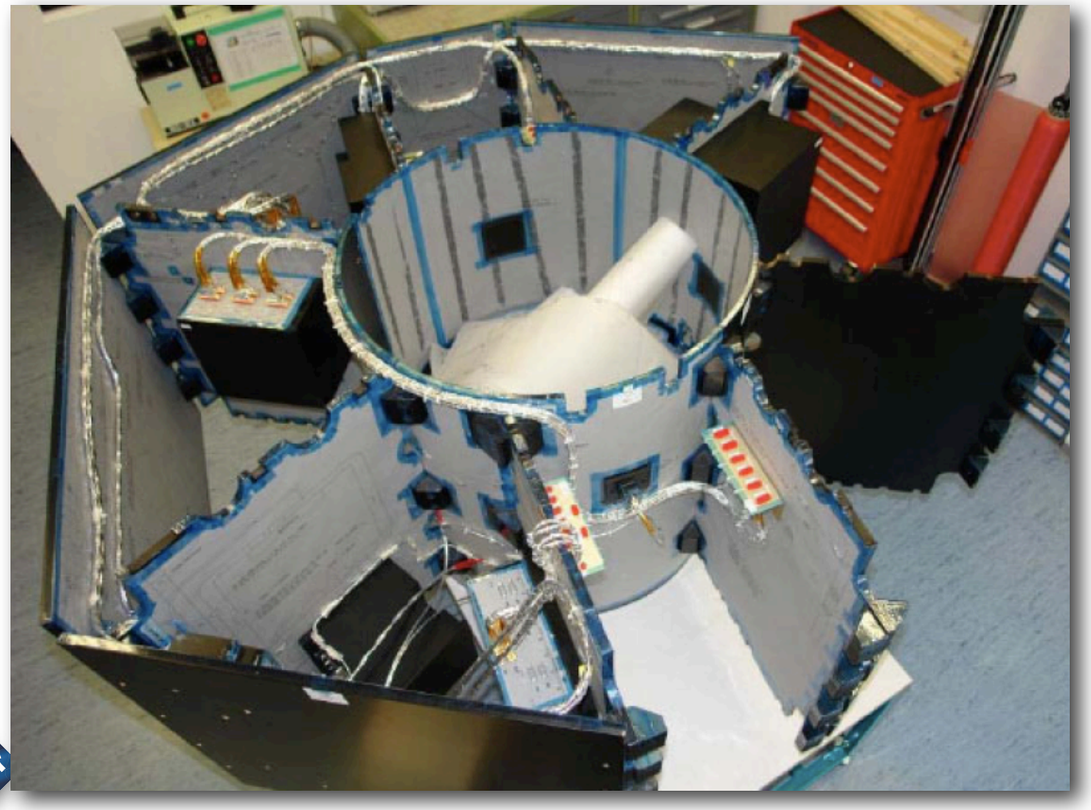




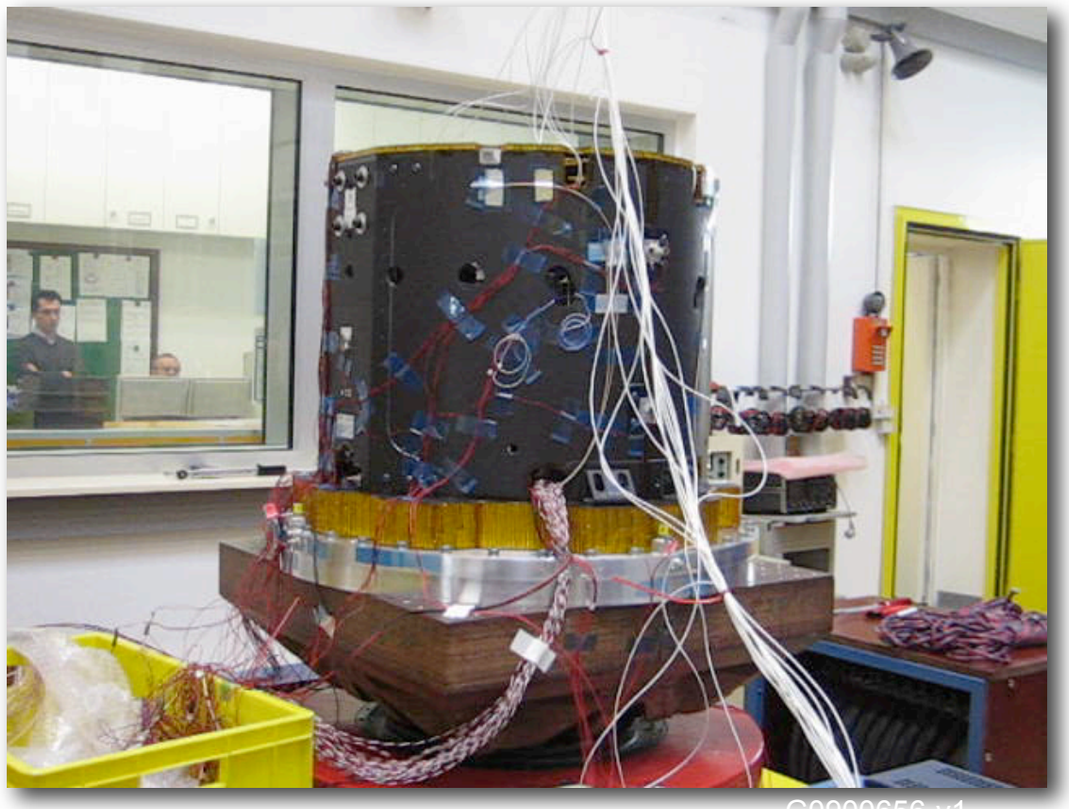


LTP Current Status

- LTP successfully passed its Critical Design Review in November 2007
- LTP Core Assembly (LCA) passed vibration qualification testing
  - LCA includes LTP, struts and mounting cylinder
- ALL LTP FM units are now under manufacture or testing
  - LTP harness will be installed on spacecraft this month!
- DFACS has passed CDR and is currently being tested with LTP real time test bed



FM electrical harness check



LCA STM vibration test

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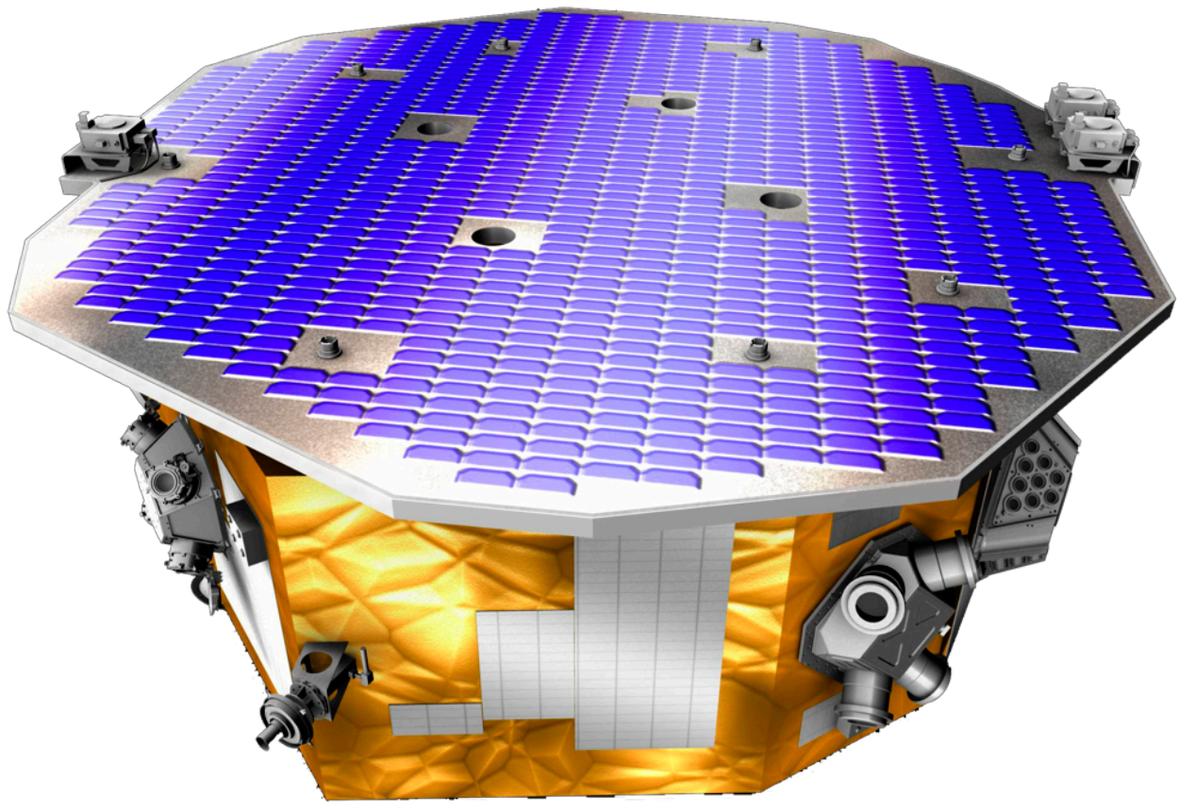
Spacecraft Flight Hardware

- Integration of electrical harness and e-boxes now starting at LPF Prime Contractor (Astrium UK)
- Both spacecraft and propulsion module have completed structural environmental tests
- Other hardware has been delivered, or is awaiting delivery review



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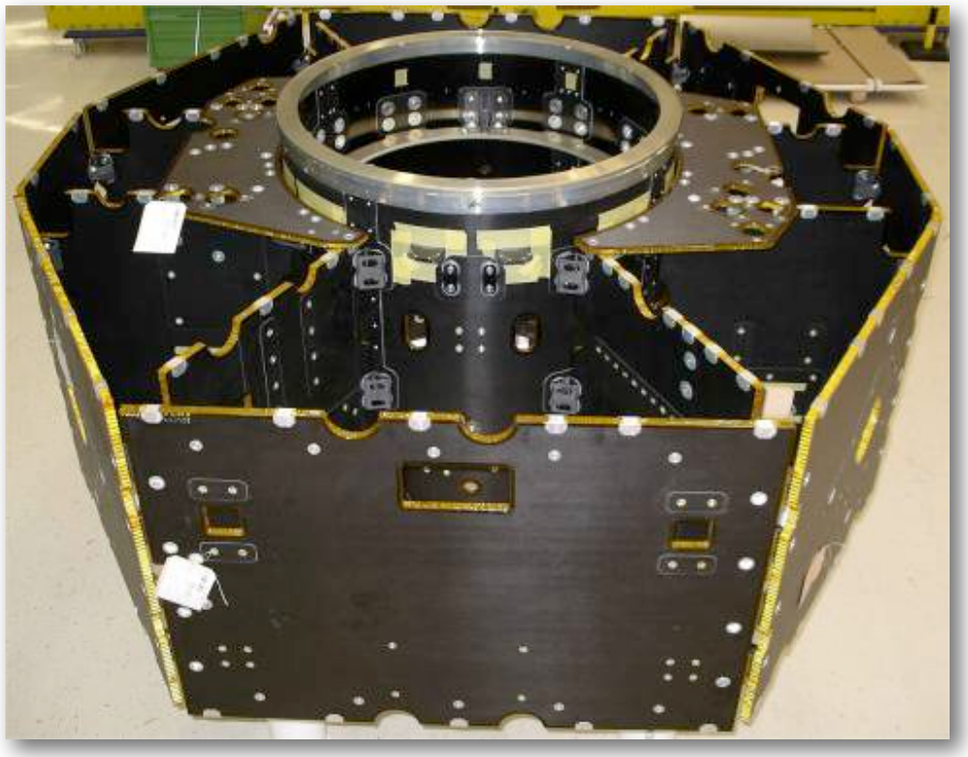

FM Spacecraft structure

Spacecraft Flight Hardware

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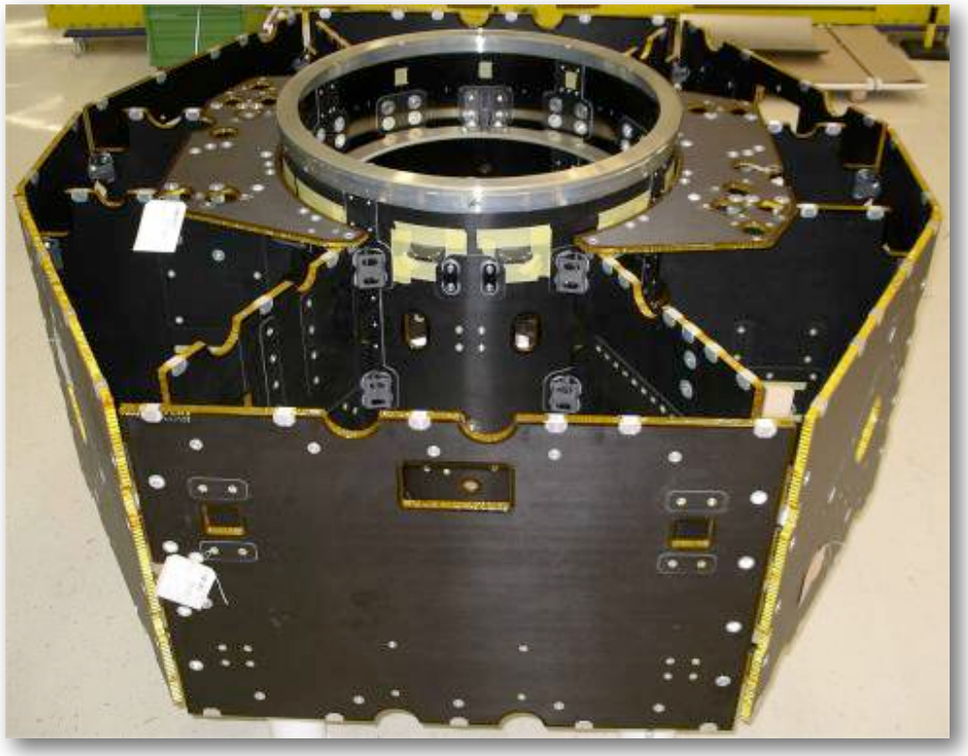


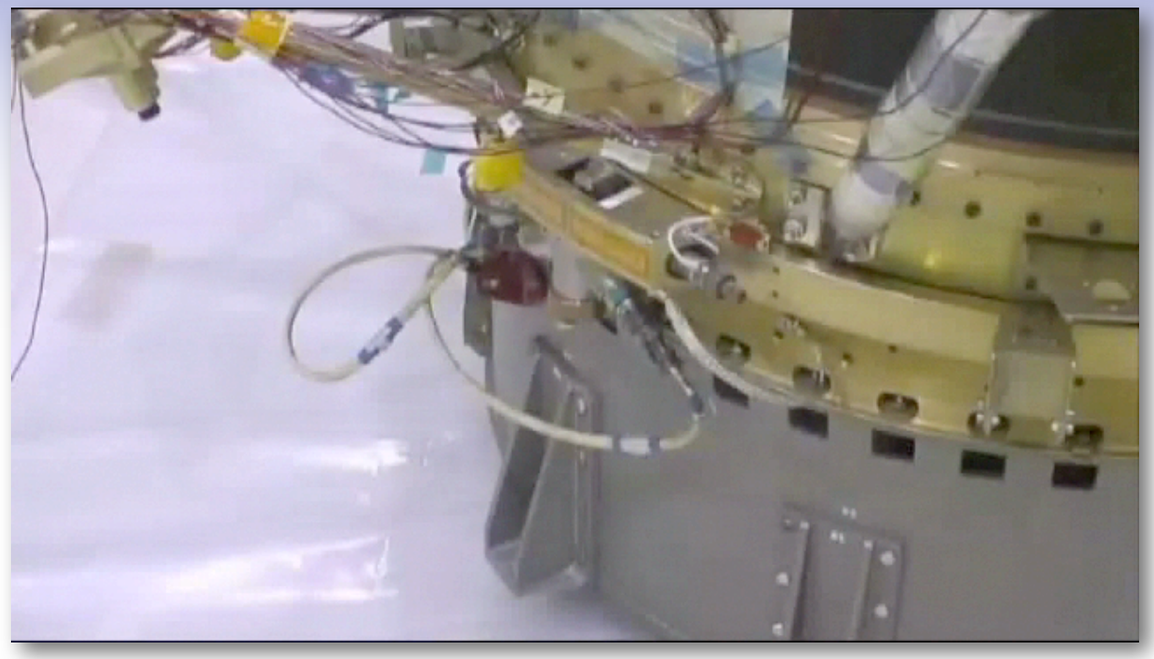
FM Spacecraft structure

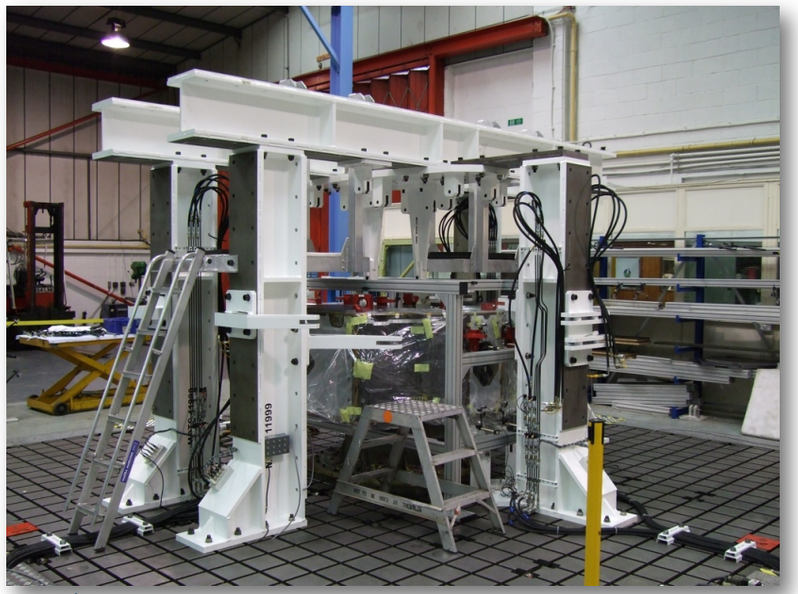
FM Propulsion Module structure

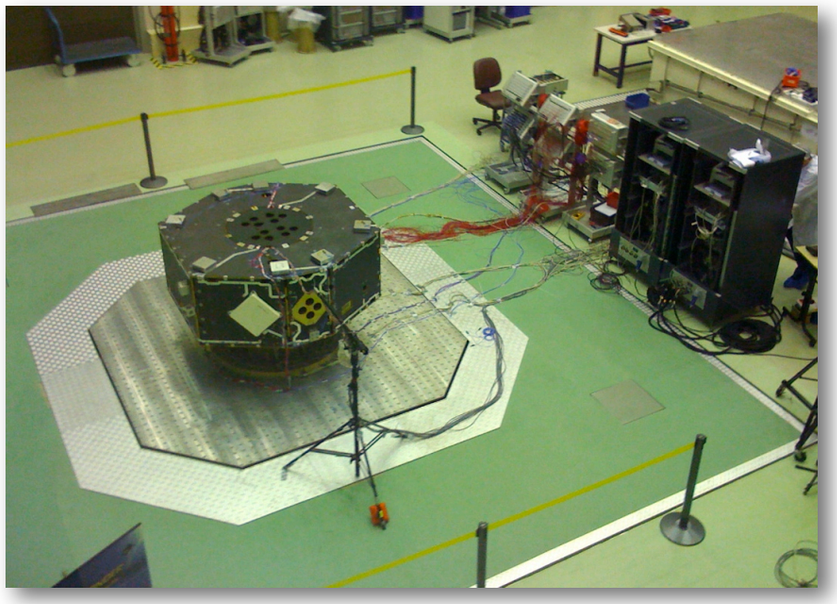
Structural testing

Structural Tests competed:

- Static load
- Acoustic
- Separation Shock
- Sine Dwell

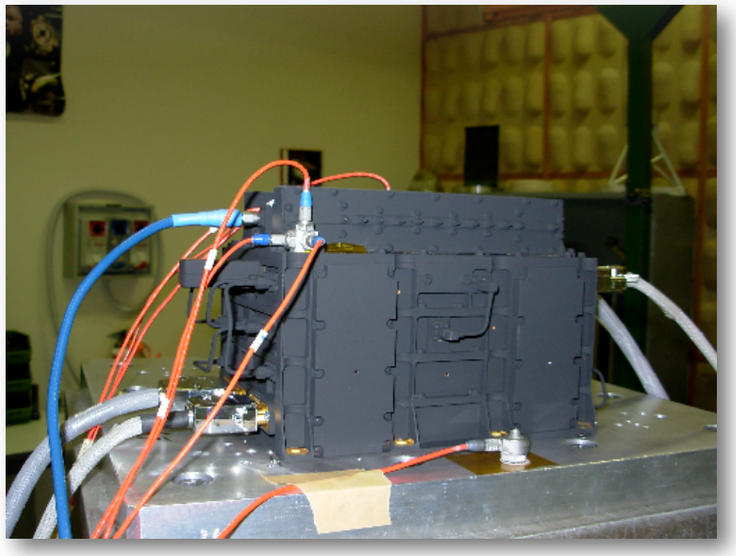




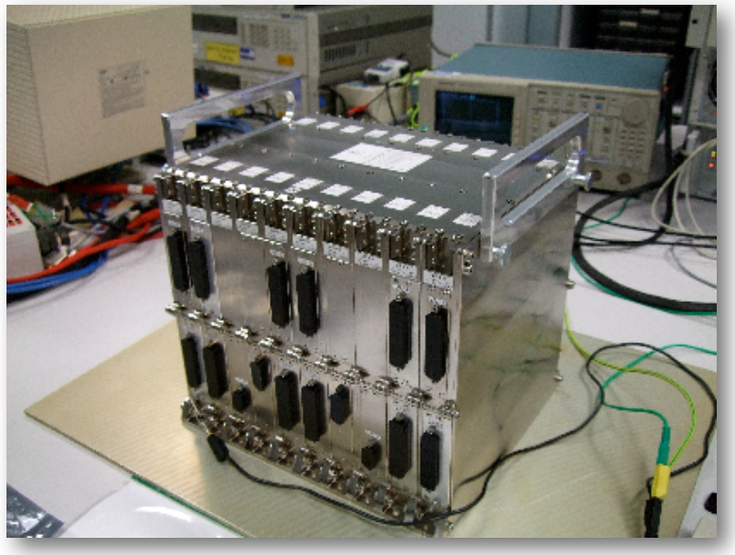


Spacecraft Electrical Systems

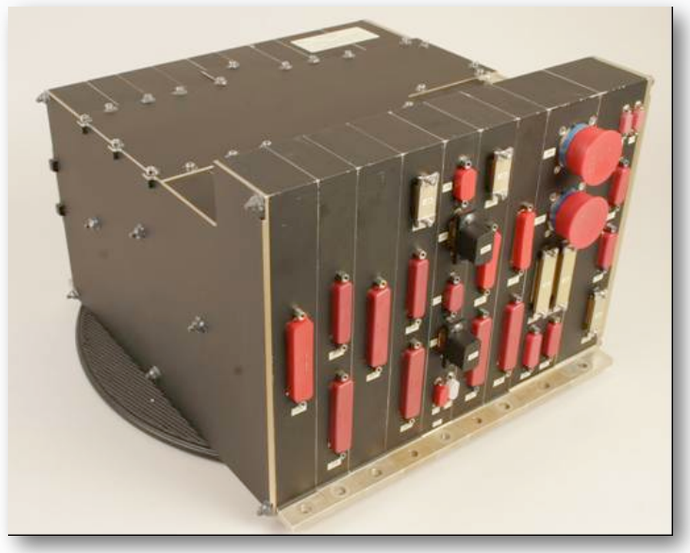
- E/QM hardware for OBC, PCDU, and Transponder ready for testbed operations



Transponder



On-board computer



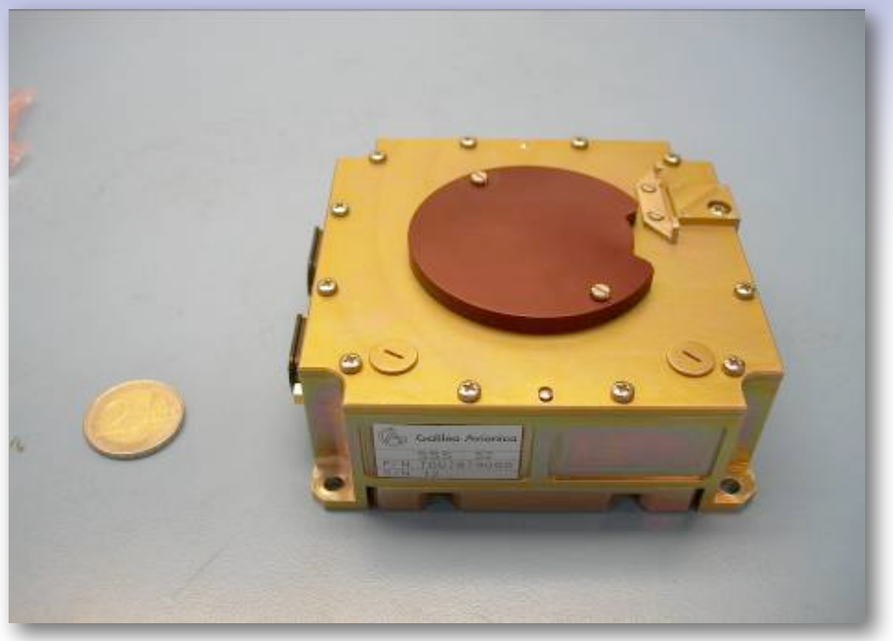
PCDU

Low Gain Antenna

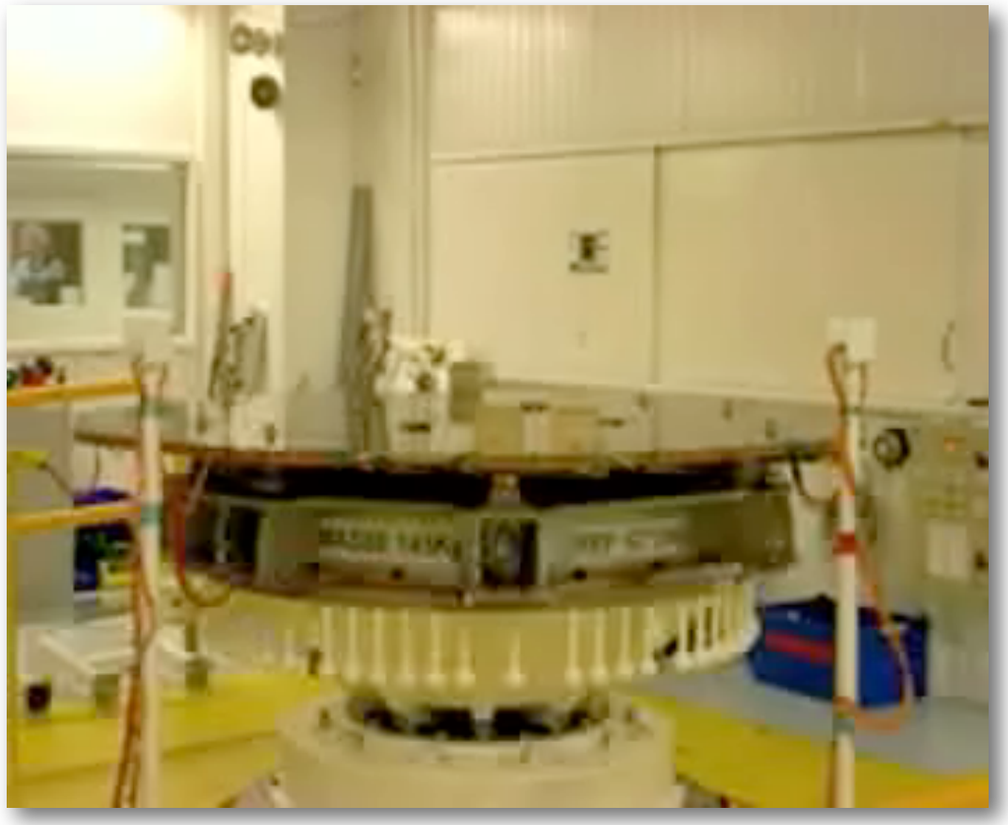
Medium Gain Antenna

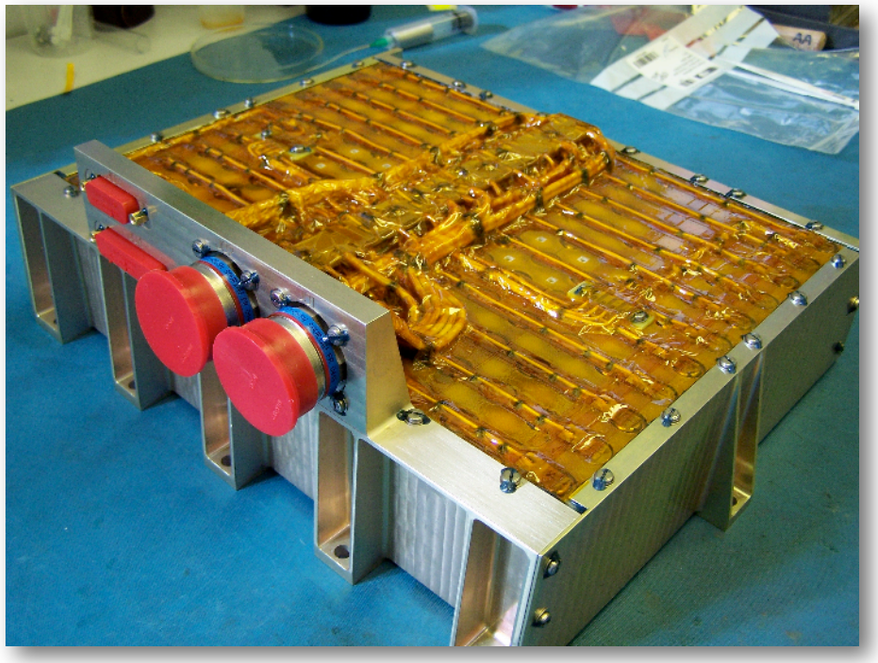
Spacecraft AOCS and Power

- FM sun sensors delivered
- FM battery delivered
- EM star-tracker ready
- FM Gyros ready for delivery
- FM Solar array in test



FM Digital Sun Sensor

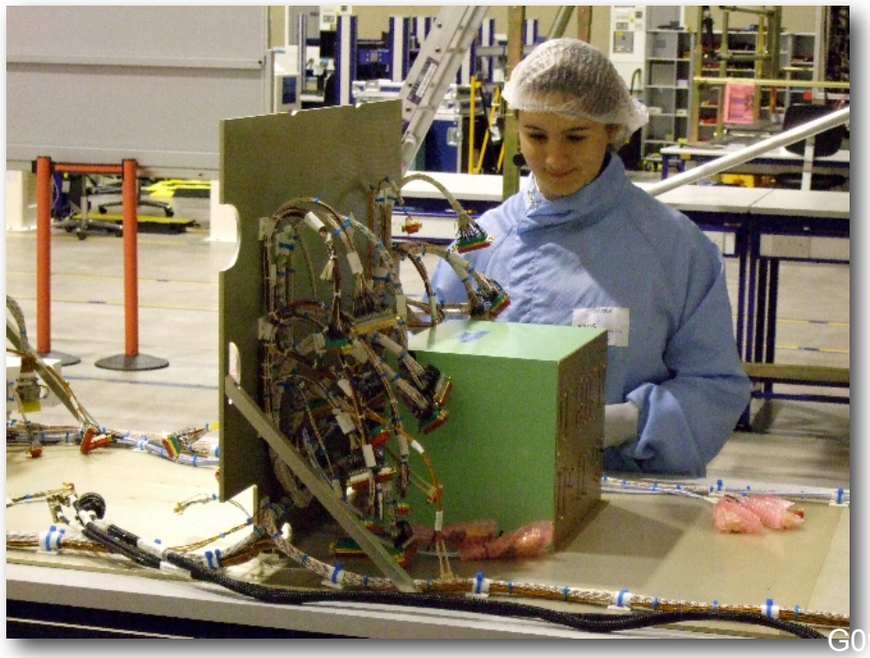




FM battery

Test Beds

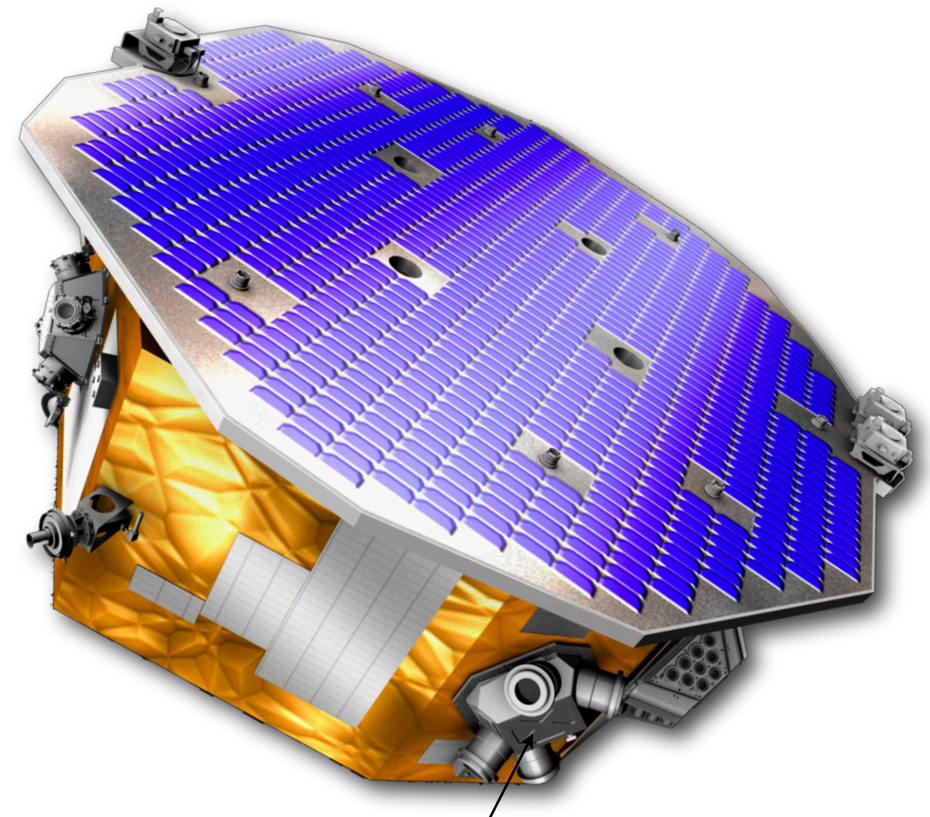
- Fundamental to the development of LISA Pathfinder (and all space missions) is the extensive use of a coherent set of simulators and test beds
  - An SVF and RTB to develop and test the DFACS design
    - In parallel a second SVF and RTB will be configured to develop and test the platform design and AOCS closed loops
  - The second test bed will be further developed to test the FM system including DFACS and AOCS using FM OBC, FM LTP units, DRS Simulator, PCDU and AOCS units.
    - Test will continue using EM units once S/C AIT starts



Spacecraft RTB at Astrium UK

Disturbance Reduction System

- DRS provided by NASA-JPL
- Originally consisted of LTP like payload (GRS), control law and micro-Newton thrusters
  - Mission was descoped and now consists of processor (control laws) and Colloidal micro-Newton Thrusters
  - DRS will use LTP as its inertial sensor
- *ALL* DRS flight hardware has been delivered to JPL
  - Pre-Ship Acceptance Review was held in JPL last year
- Flight Hardware to be delivered to ESA in June!



Colloidal micro-Newton thruster

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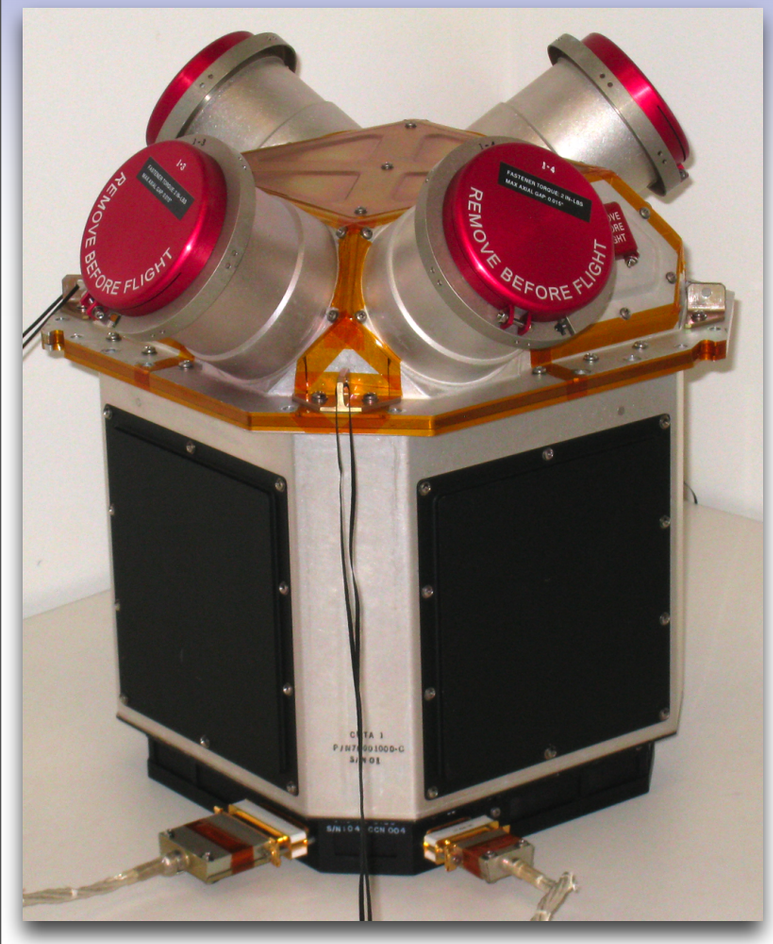
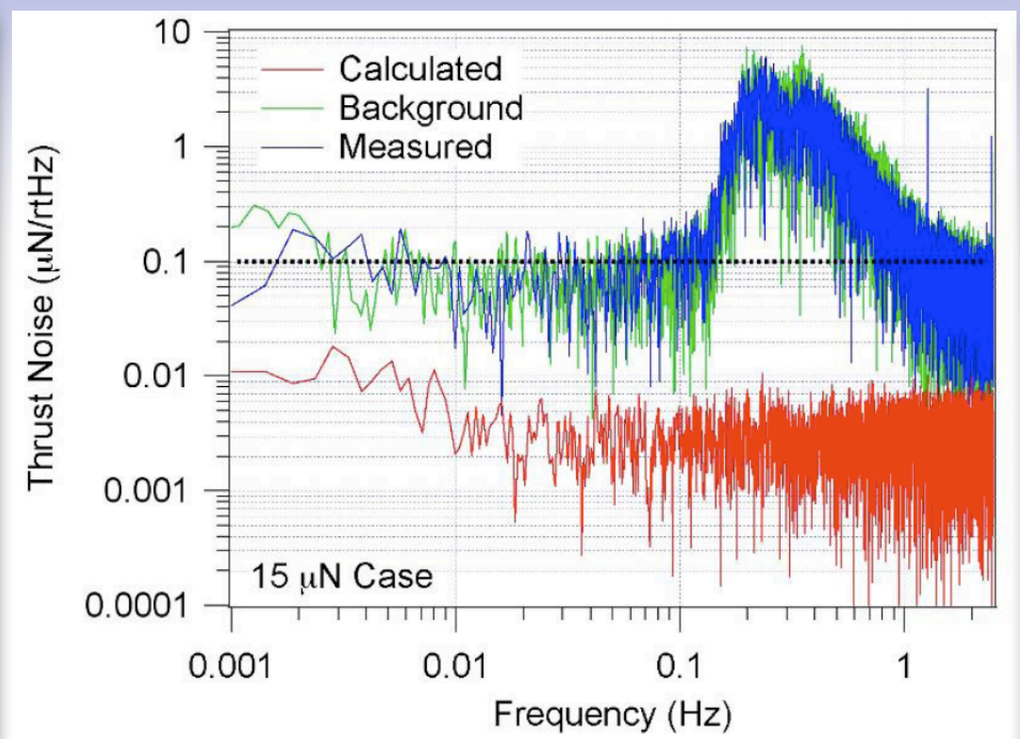
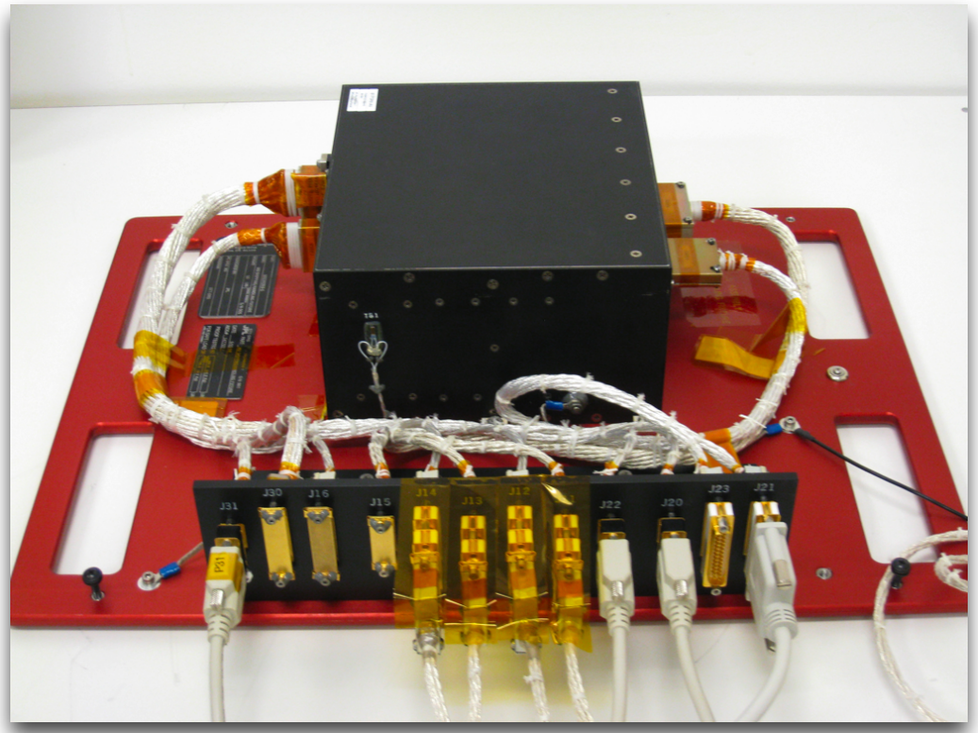
DRS Flight Hardware

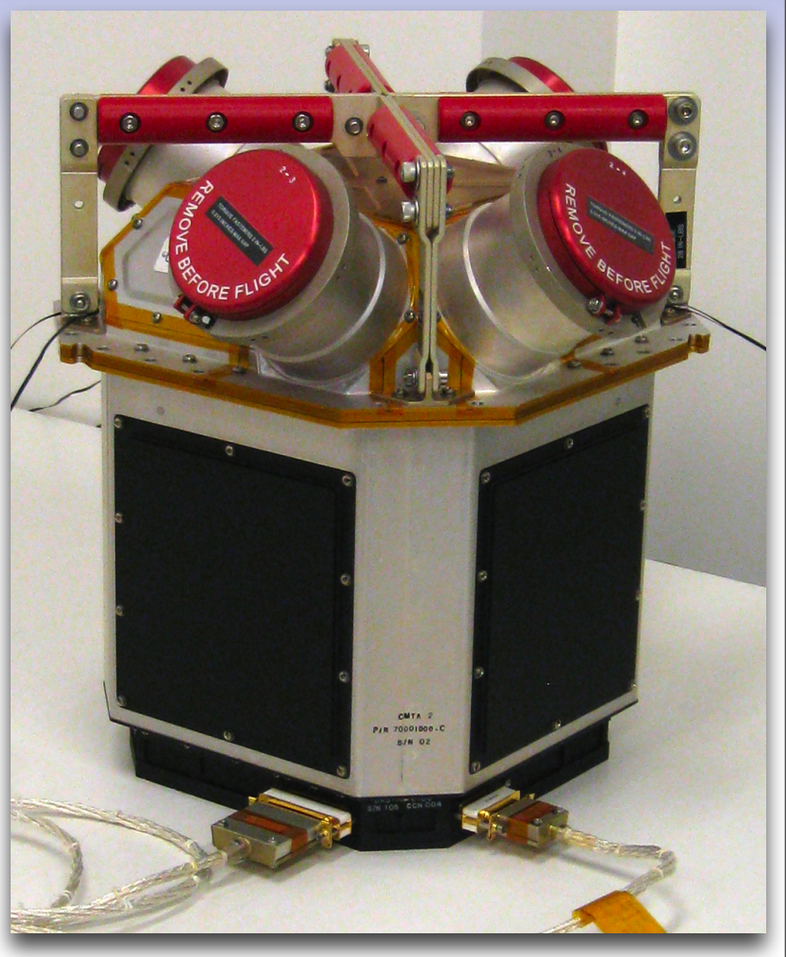


Thruster Cluster 1



Integrated Avionics Unit





Thruster Cluster 2

Launcher

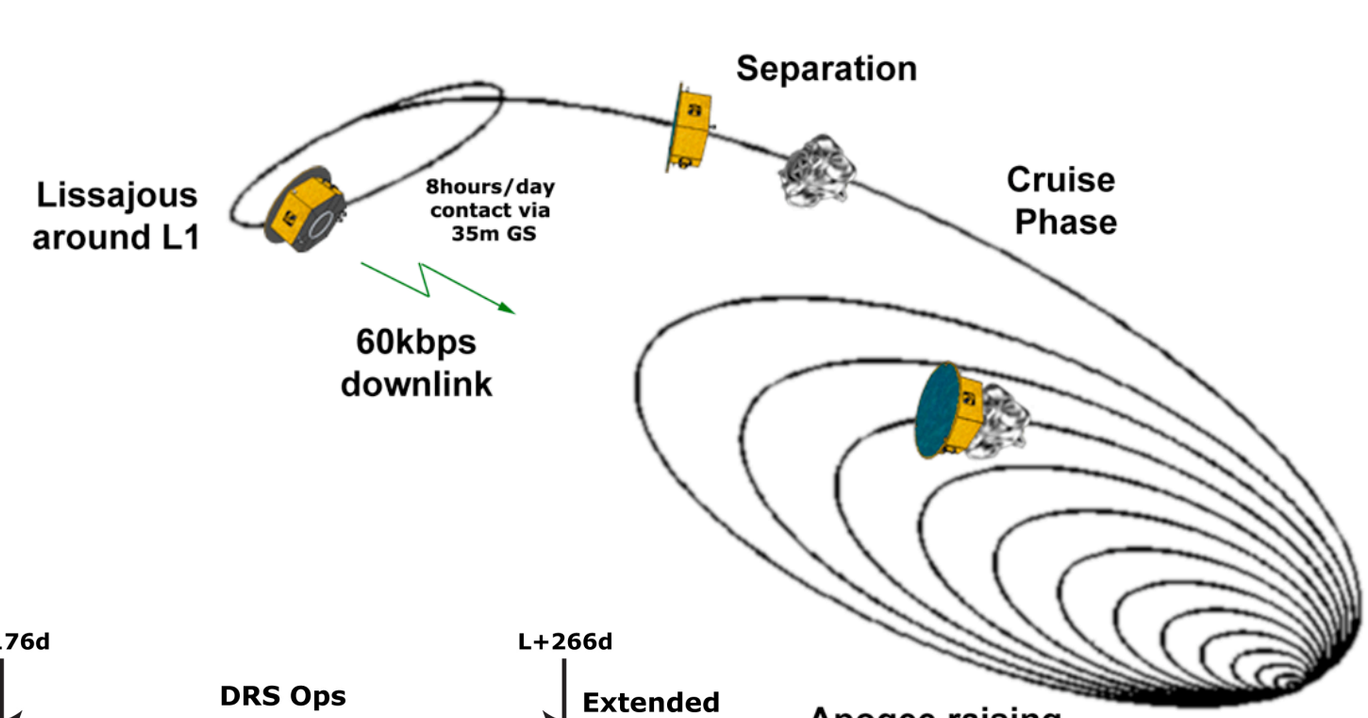
- Baseline launch vehicle is VEGA
  - ESA directive to target European launchers
  - Procured from Arianespace
  - New launcher
    - LPF scheduled to be on 3rd flight
  - Launch from Kourou, French Guiana
    - Latitude 5º
- Back-up options considered include
  - VEGA into Highly Elliptical Orbit
  - Rockot into Highly Elliptical Orbit

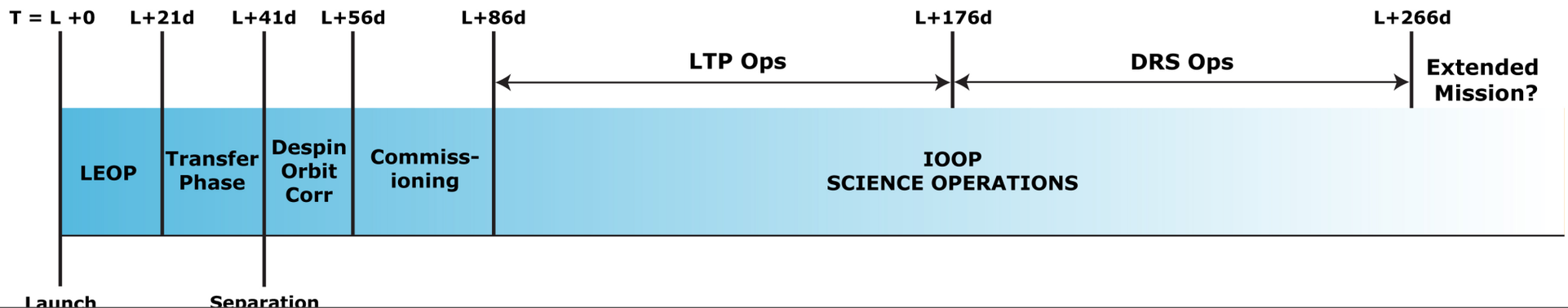
Artists impression of VEGA launcher

VEGA main engine test

Orbit

- LPF launched into 200x1600km orbit
- 9 apogee raising manoeuvers required to deliver LPF to L1
  - First time so many engines burns have been attempted by ESOC
- Prop module separates during transfer phase
- Final orbit is 500,000x 800,000km Lissajous orbit around L1





Operations

- Mission Operations controlled from ESOC, Germany
- 8 hours ground station contact per day
  - 35m ESA Cebreros station
  - Downlink rate of 60kbps
- Payload commanded via Payload Operation Requests stored in Mission Timeline
  - One POR lasts exactly 24 hours
  - Up to 6 PORs stored on-board at any time
- Real time commanding only during commissioning and contingency events

Conclusions

- LISA Technology Package and LPF System have passed CDR
  - Flight hardware delivery has started!!
- Spacecraft integration begins this week!

- Knowledge gained from LTP/LPF is directly applicable to LISA
- Additional lessons learned will also be transferred to LISA
  - I&T, ground segment, commissioning

- Launch of LPF scheduled for mid-2011
  - Initial results available ~3months thereafter

Thank you

- ESA ESTEC
- ESA ESAC
- ESA ESOC
- EADS Astrium UK
- EADS Astrium GmbH
- University of Trento
- Albert Einstein Institute
- University of Glasgow
- University of Birmingham
- Imperial College London
- ETH Zurich
- Institut d-Estudis Espacials de Catalunya
- Universidad Politecnica de Barcelona
- APC Paris
- Laben
- Carlo Gavazzi Space
- ALTA
- ARCS
- Contraves
- Kaiser Threde
- NTE
- SCISYS
- Spacebel
- SRON
- Technologica
- TESAT
- ZARM
- JPL
- NASA Goddard
- BUSEK

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