LISA Pathfinder

a status report

M Hewitson, AEI Hannover
for the LPF Team

eLISA Cosmology Workshop, CERN, April 14th 2015

Observing GWs from space

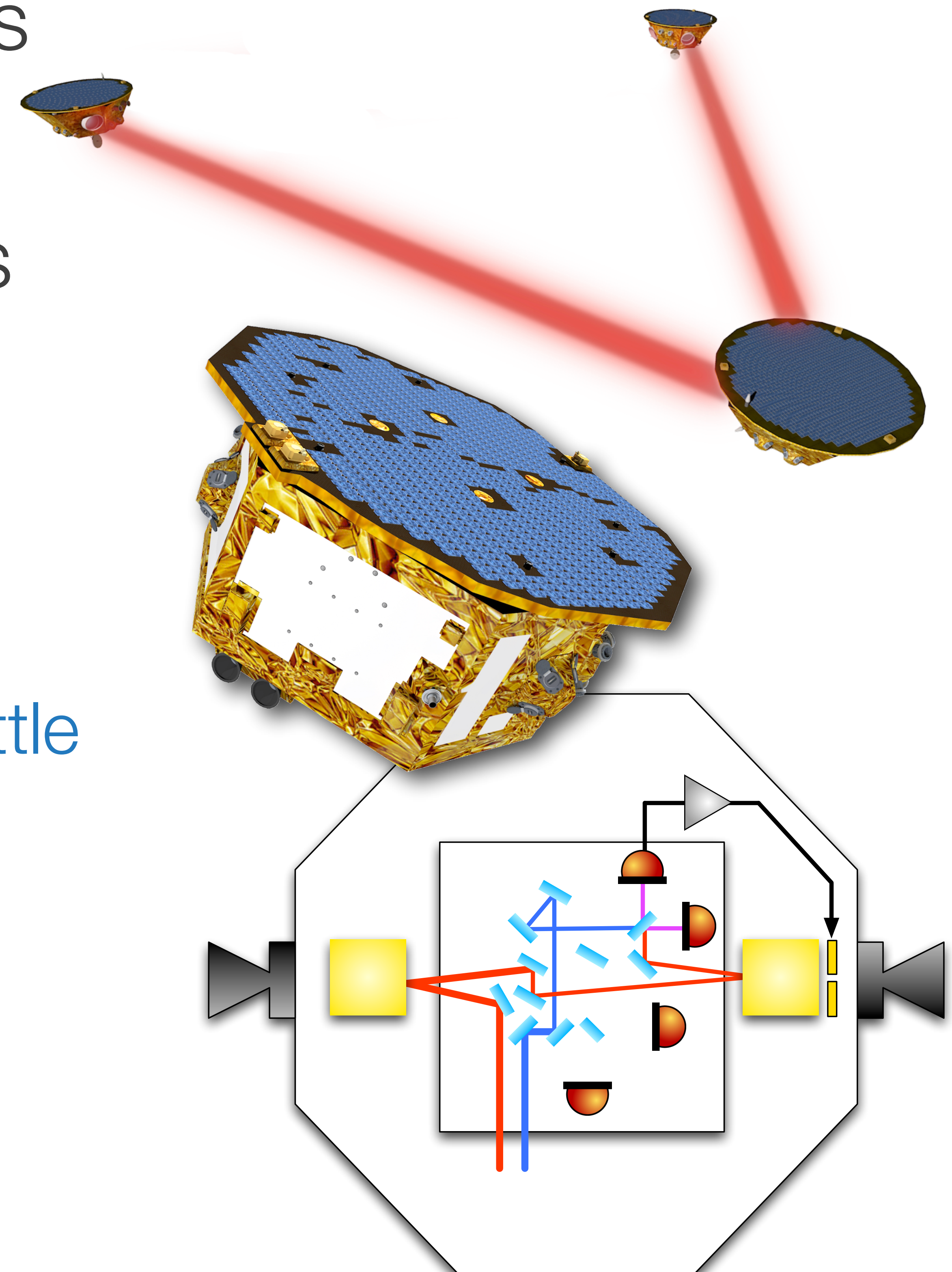
- Push down to much lower frequencies: mHz
  - expect rich science from, e.g., super-massive BH binaries out to high redshift, EMRIs
- Fractional length stability of ground-based instruments is difficult to achieve at these frequencies
  - temperature and structural fluctuations
- Increase arm-length to improve strain sensitivity
  - go to space

LISA Pathfinder

lisa pathfinder

- Devised to test key technologies for LISA-like space-based gravitational wave observatories

- The idea was to shrink a LISA arm into a single space-craft
    - tests length stability but has very little sensitivity to strains in space-time
    - allows us to test most of the technology needed for a LISA-like mission



What do we test?

- Technology demonstrator for a GW Observatory in space (LISA-like design):
  - micro-Newton propulsion
  - Gravitational Reference Sensor
  - Interferometric techniques
  - Drag-free control
- LPF will be placed in orbit around L1
- Requirements relaxed compared to a typical space-borne GW observatory to make testing feasible:
  - 1 order of magnitude in differential acceleration
  - 1 order of magnitude higher frequency
- Two science payloads:
  - LISA Technology Package (LTP)
  - ST7 (NASA provided payload)

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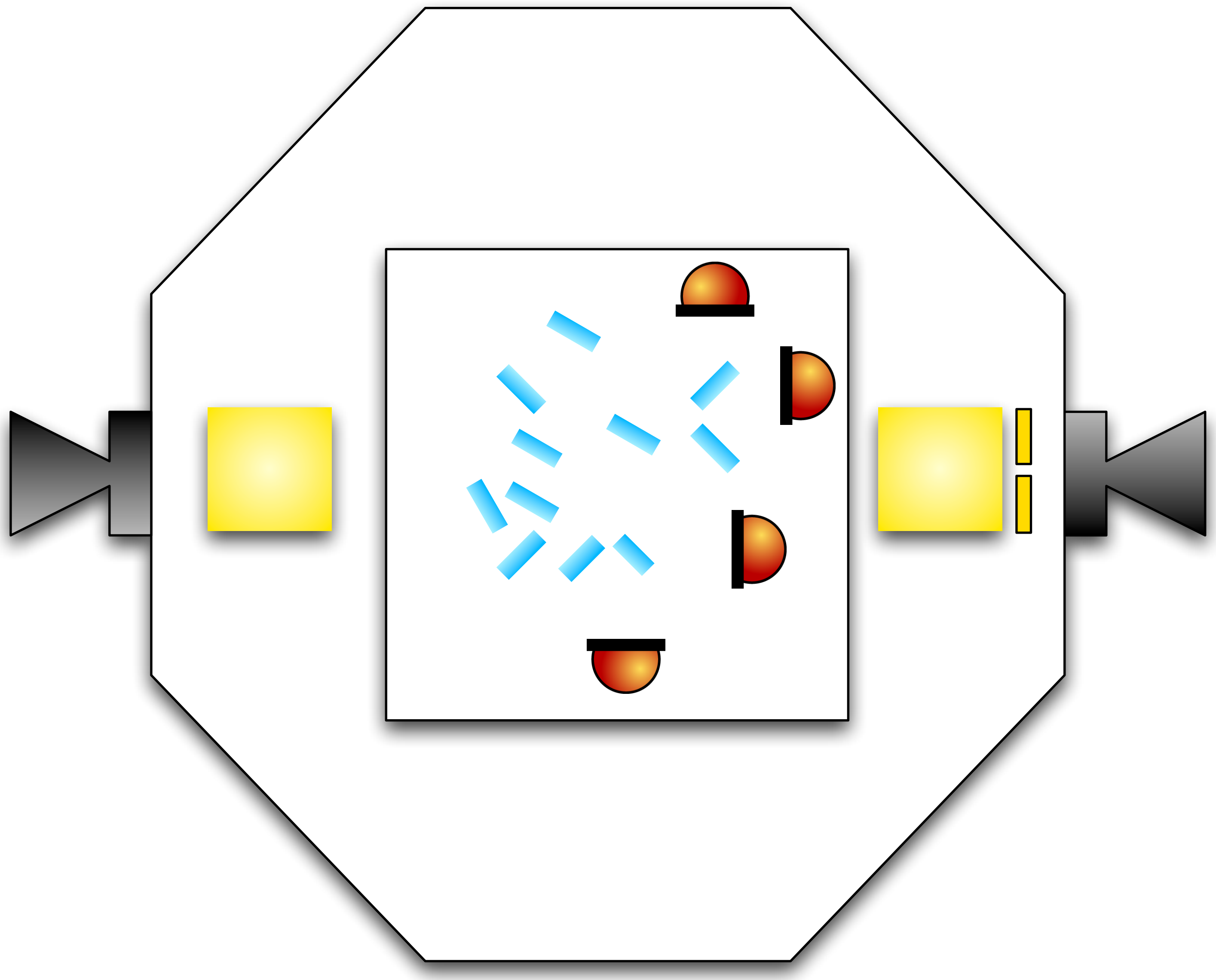
measurement of
residual differential acceleration of
$30\ \mathrm{fm\ s^{-2}}/\sqrt{\mathrm{Hz}}$ at 1 mHz
between two free-falling test-masses
(pm accuracy position measurement)

Measurement concept



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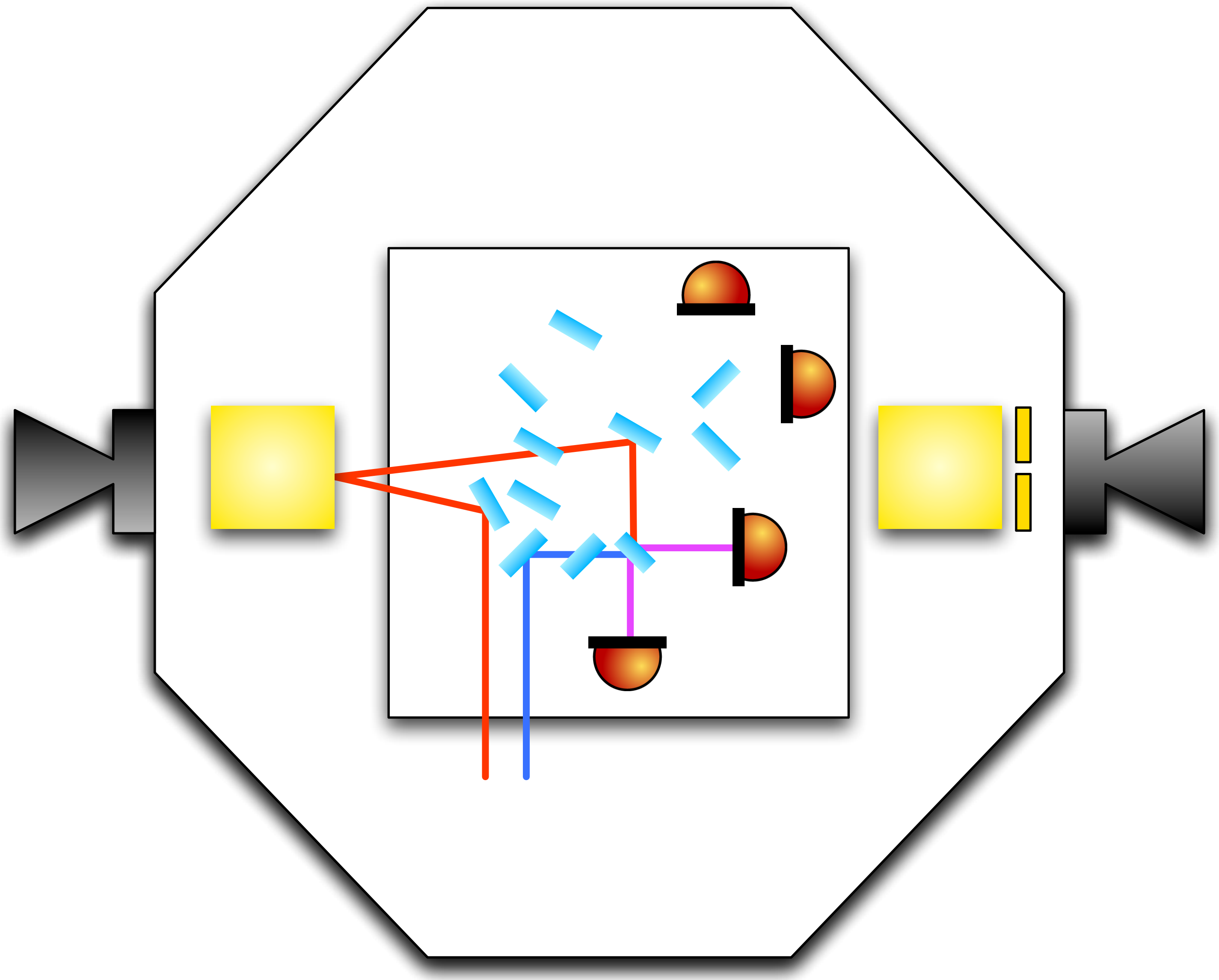

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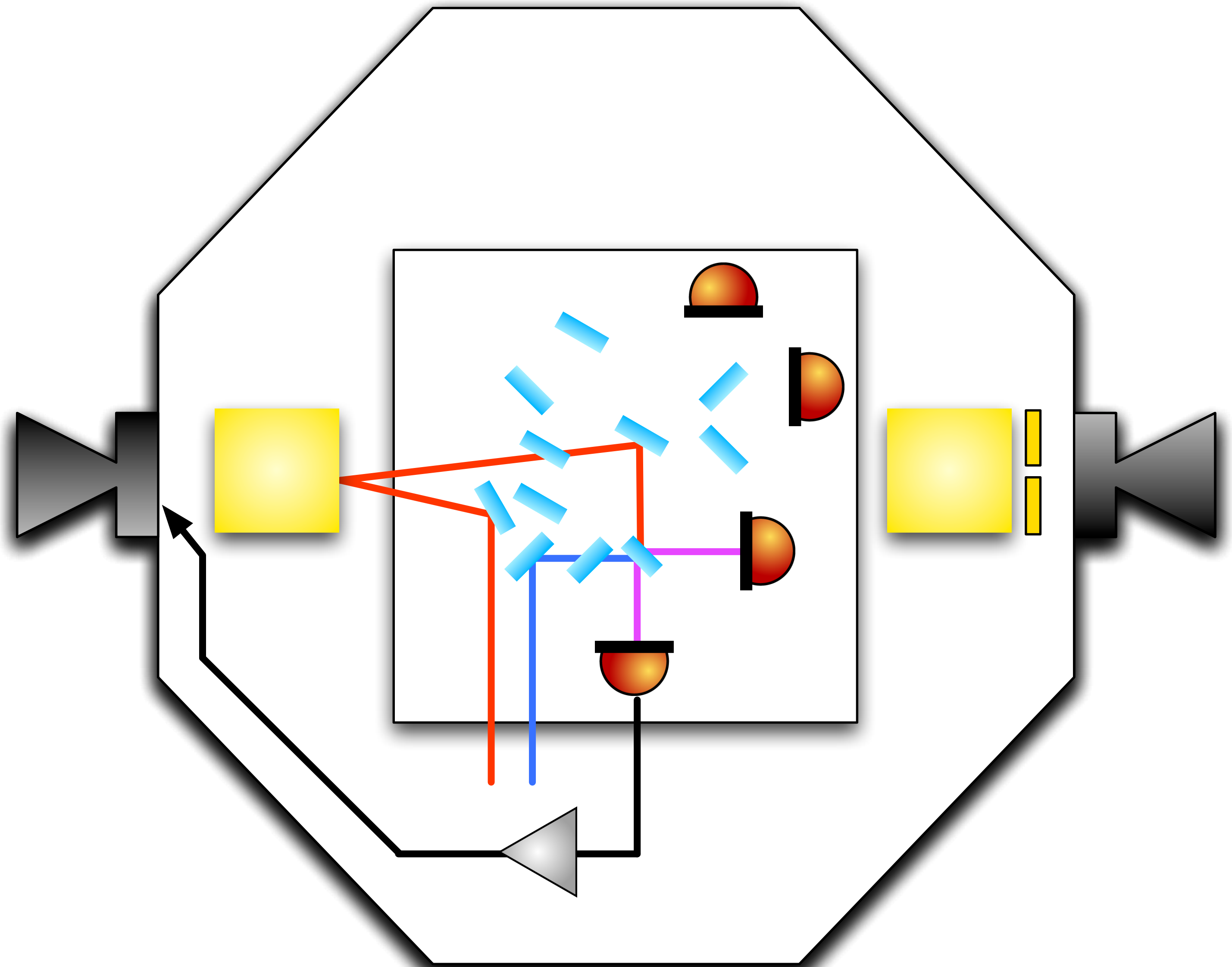

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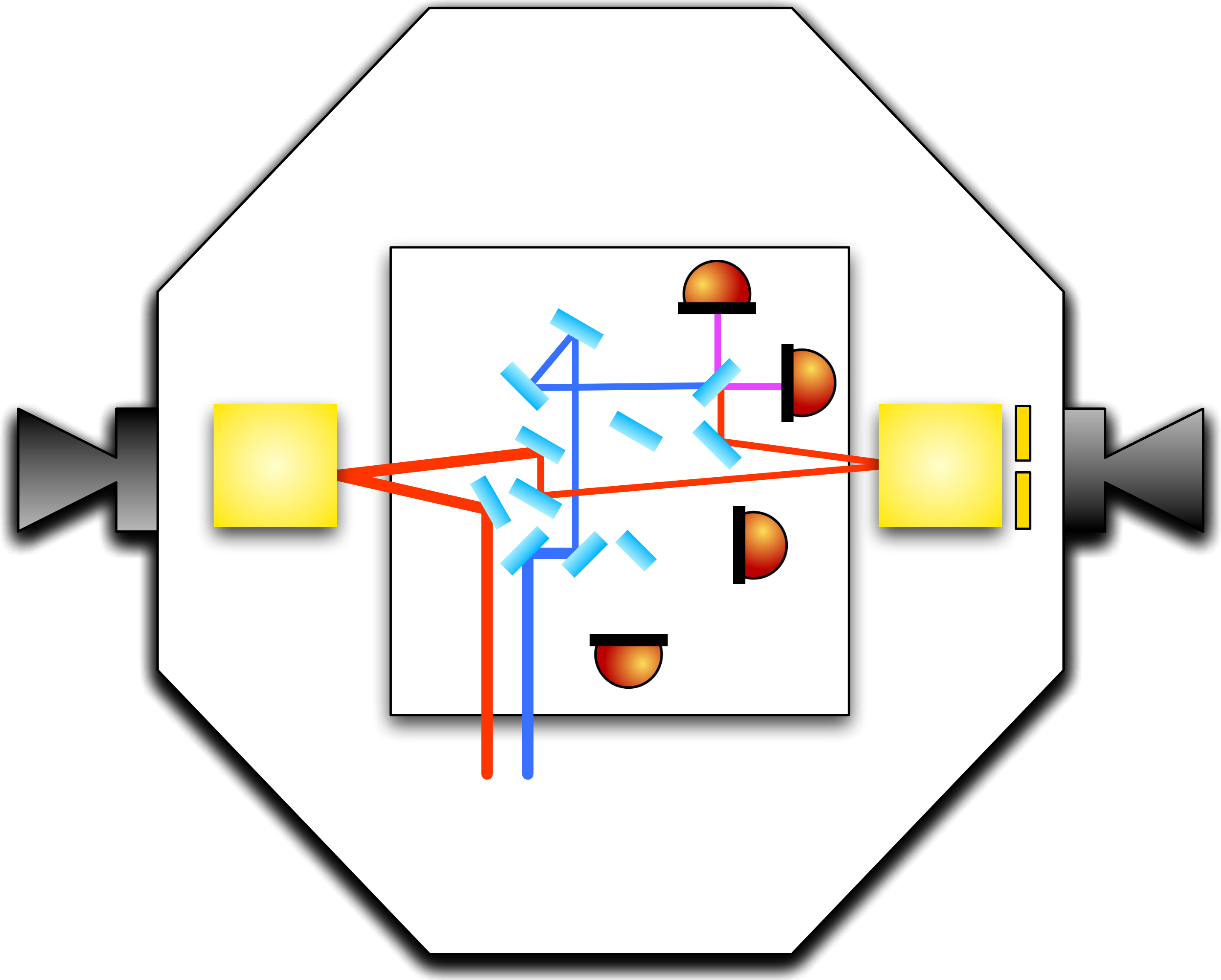

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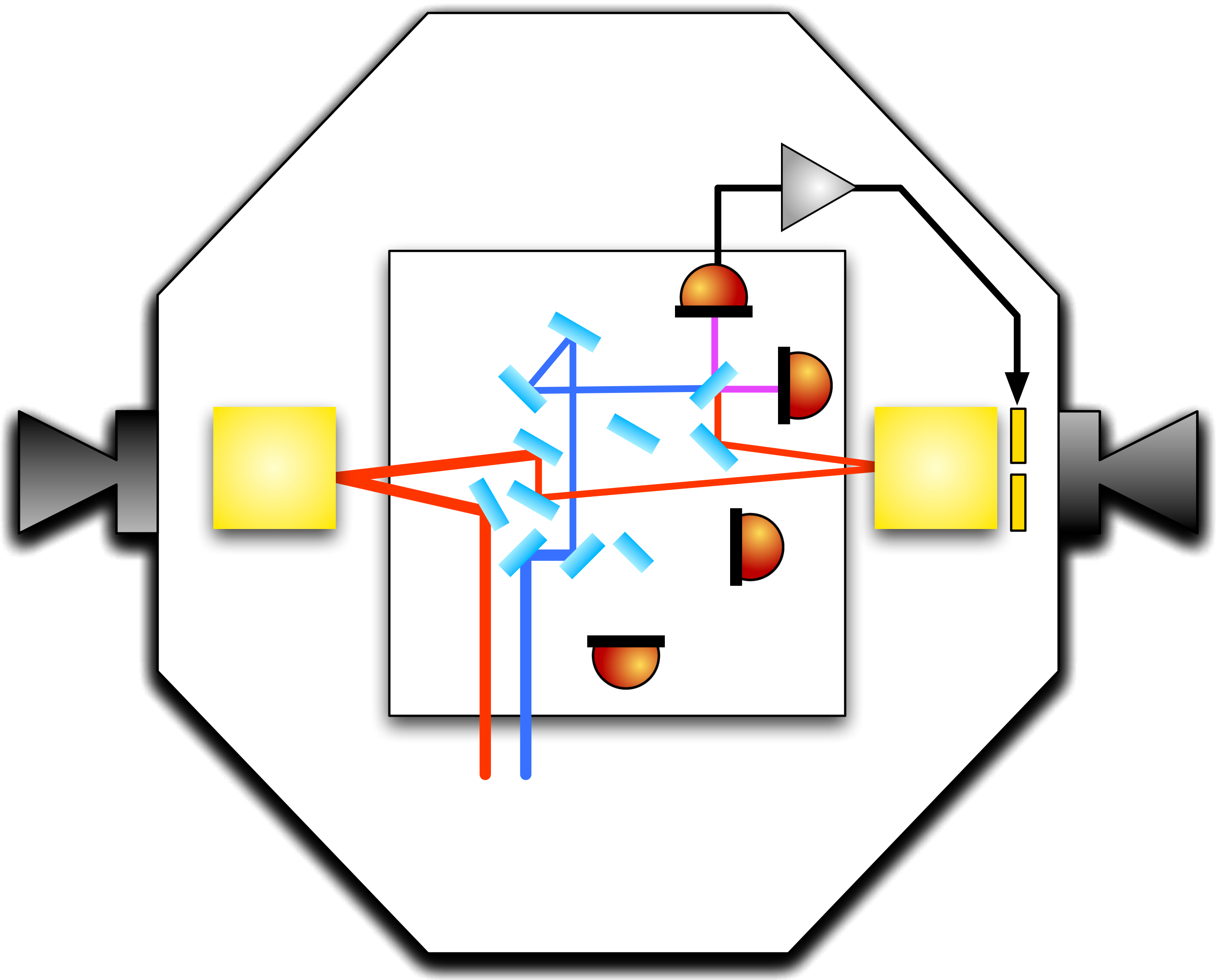
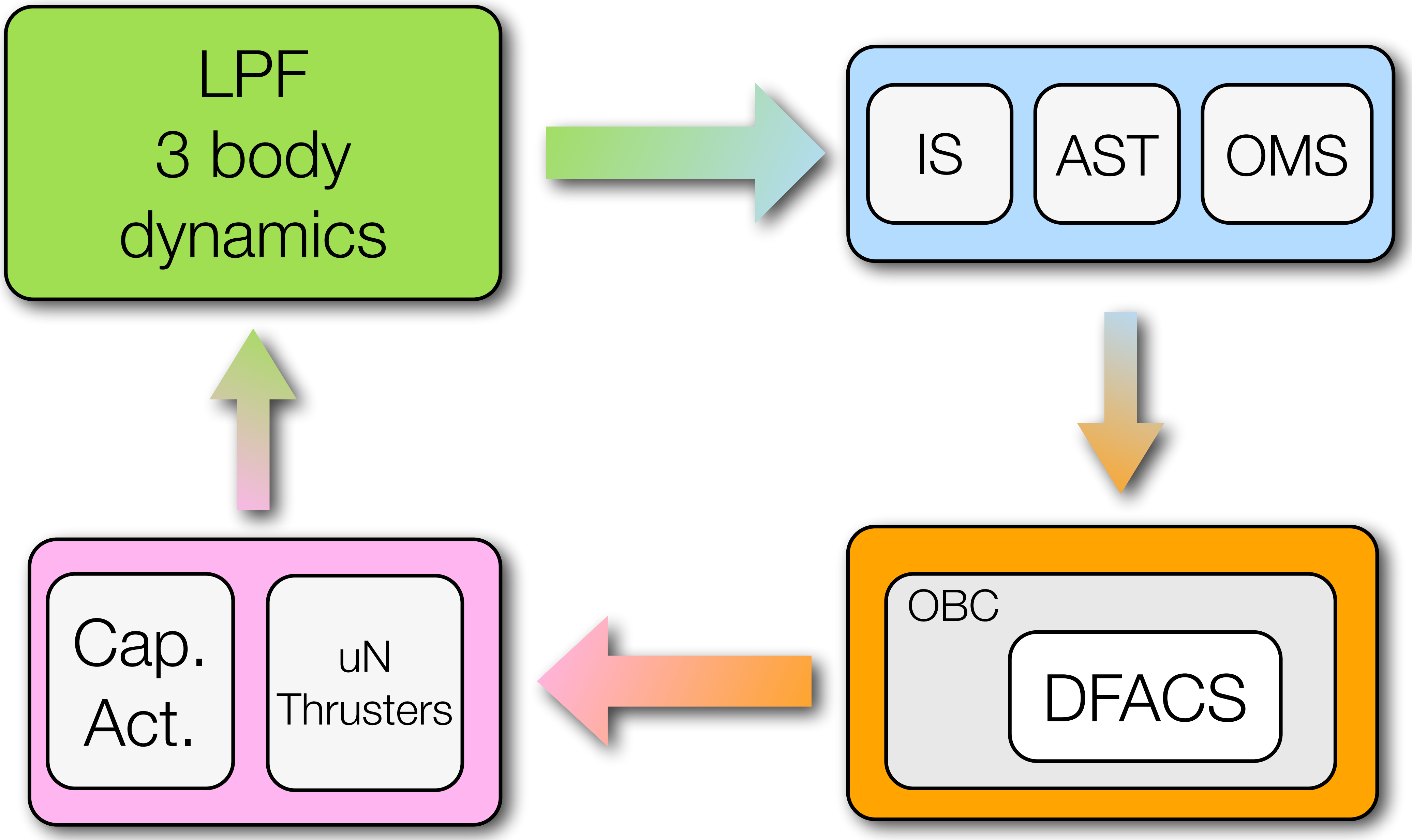
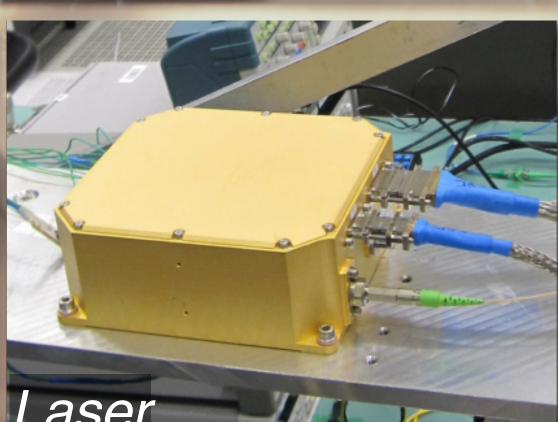


System level

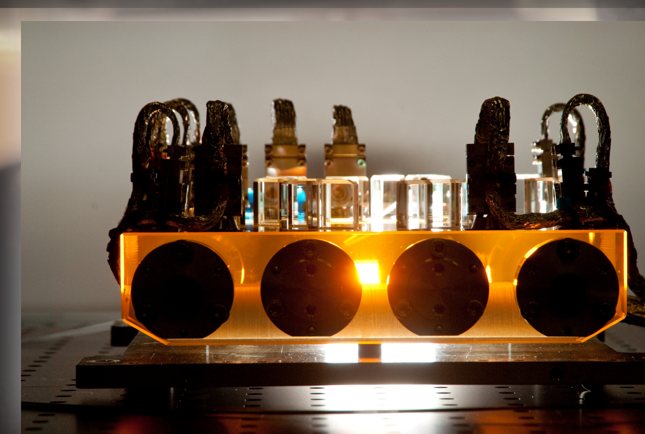


Optical Metrology System

- 2W laser
- Multi-channel Phasemeter
- 4 interferometers bonded on a Zerodur baseplate
  - 2 measure relative TM/SC positions
  - 1 measures frequency noise of laser
  - 1 measures optical path length fluctuations
- Data Management Unit


Laser


Phase-meter

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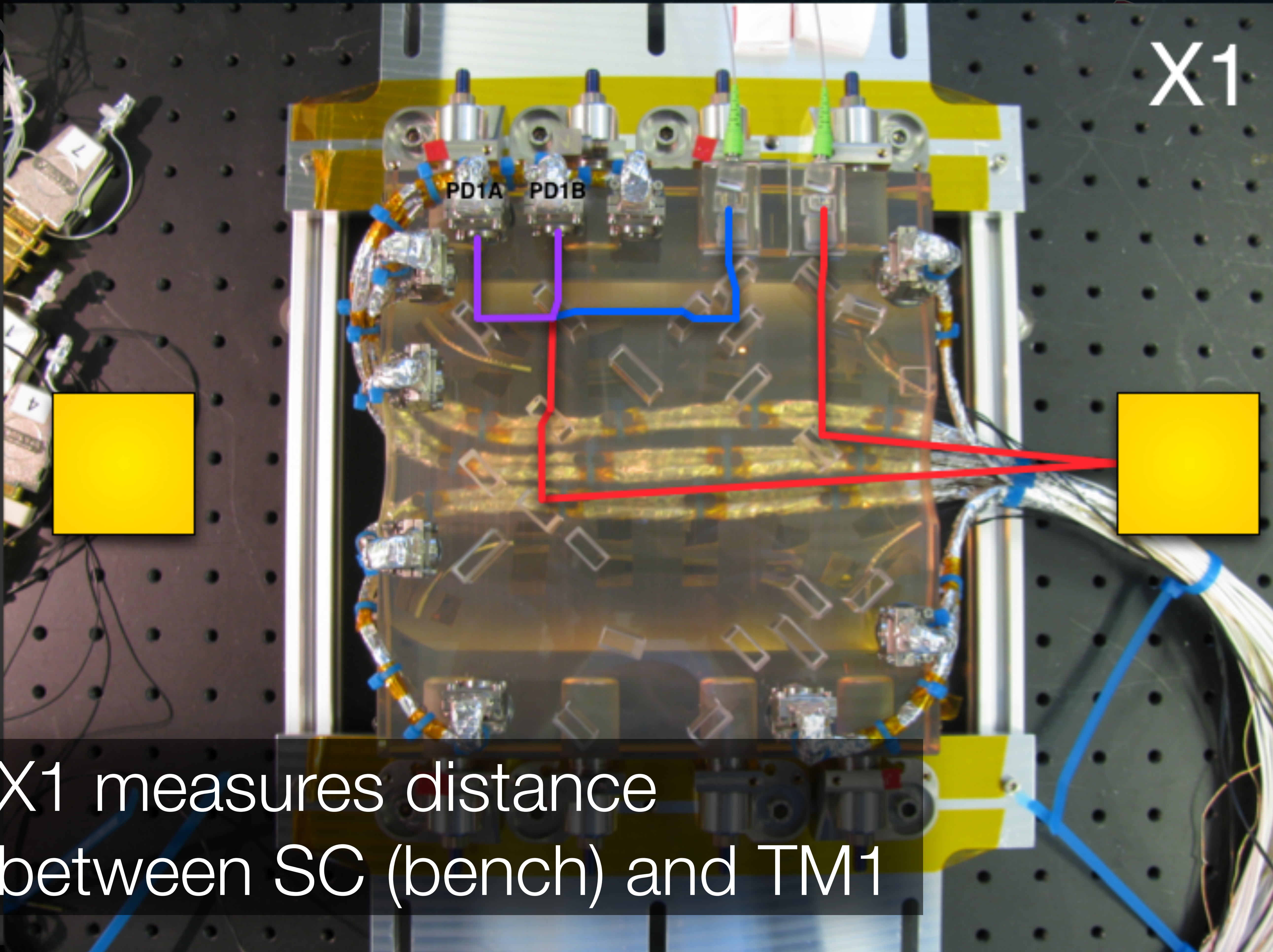
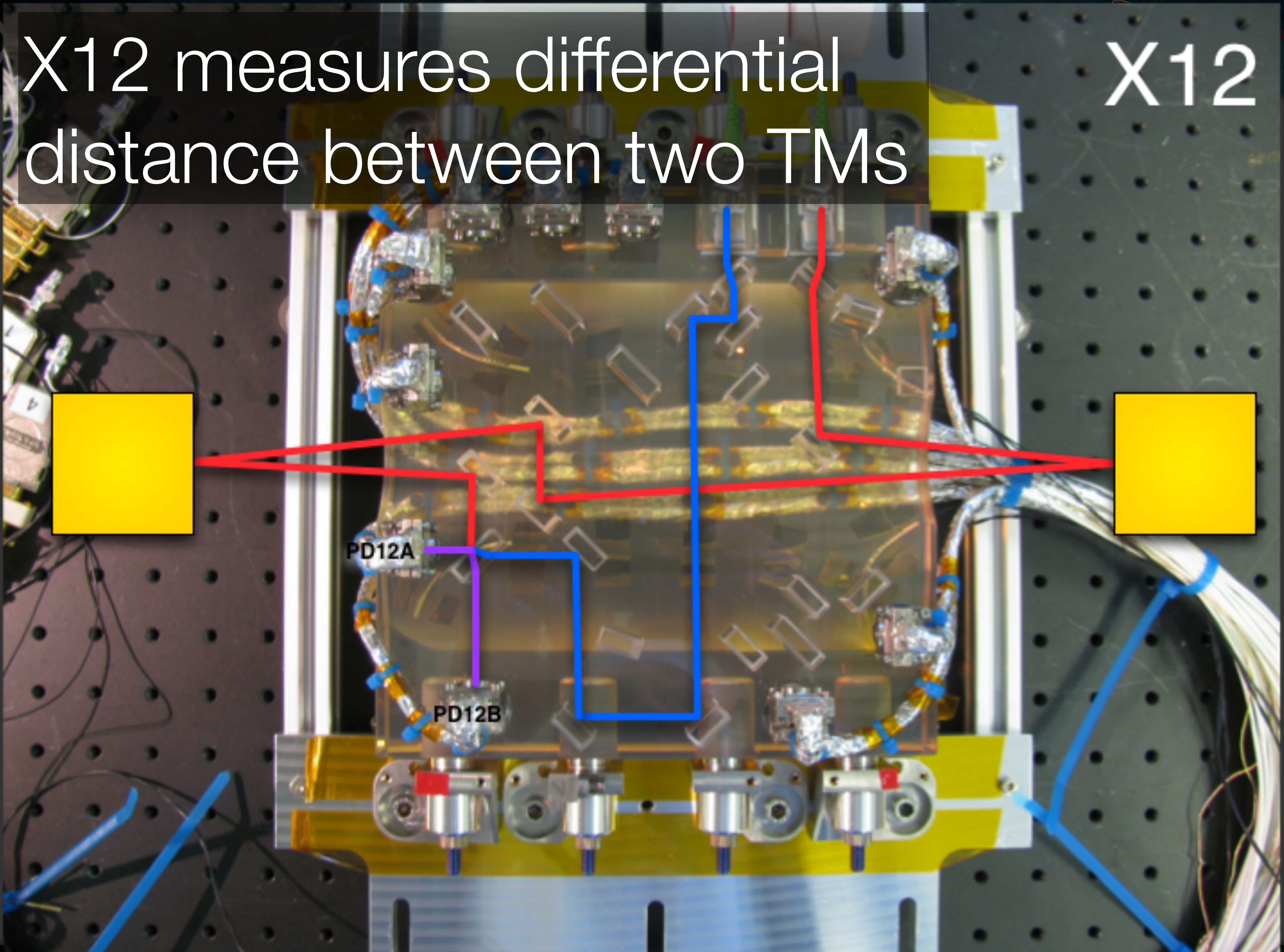
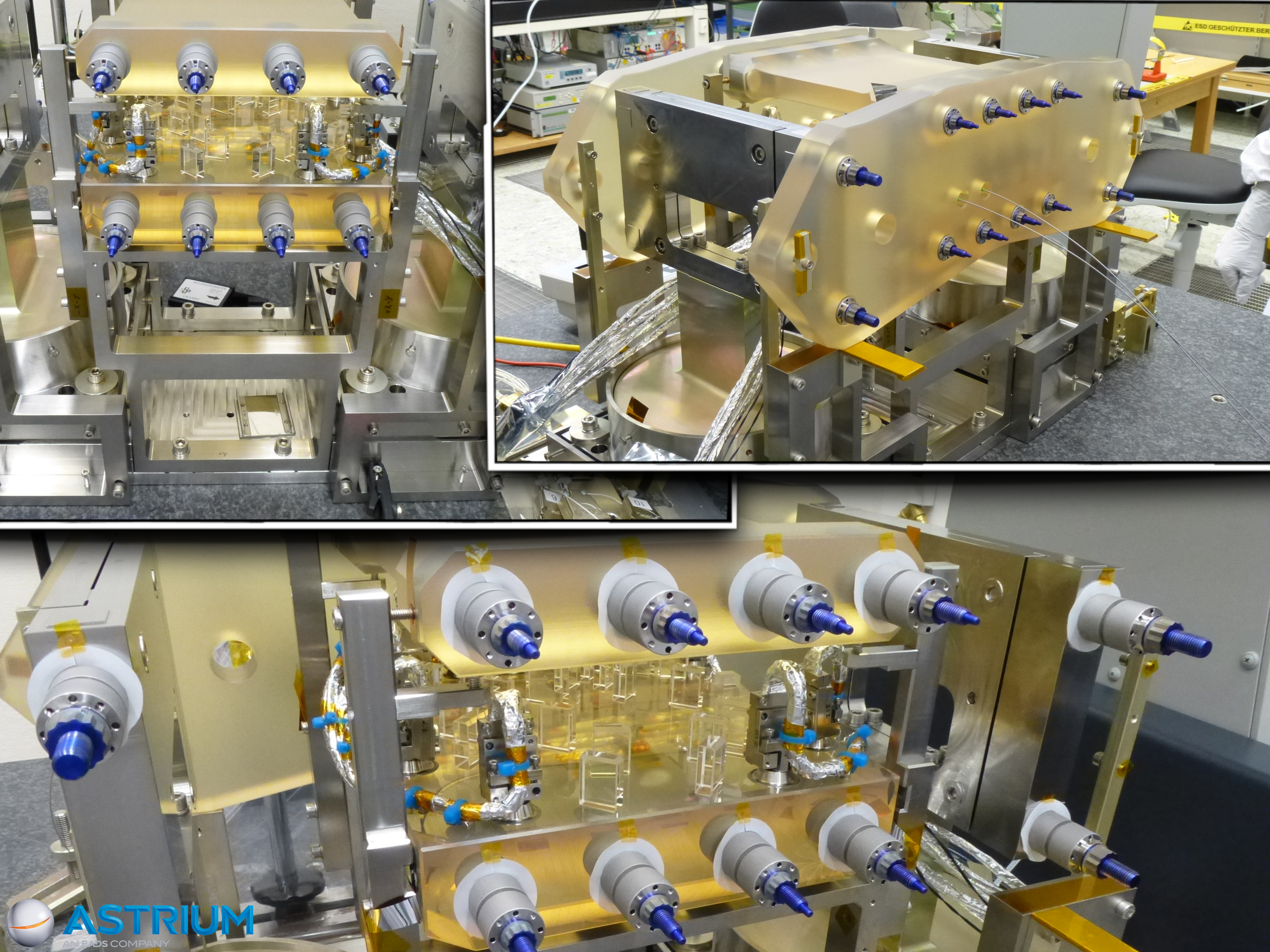


X1 measures distance between SC (bench) and TM1

X12 measures differential distance between two TMs




ASTRIUM
AN EADS COMPANY

Inertial Sensor Subsystem

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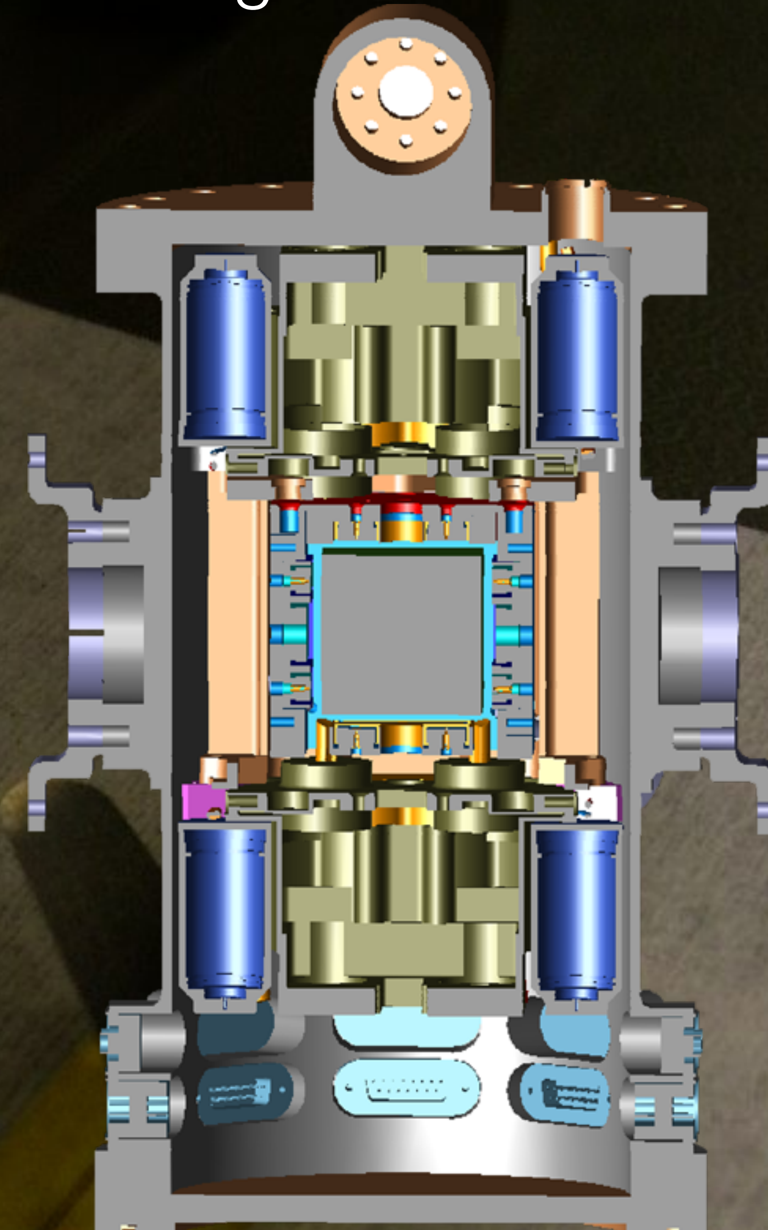
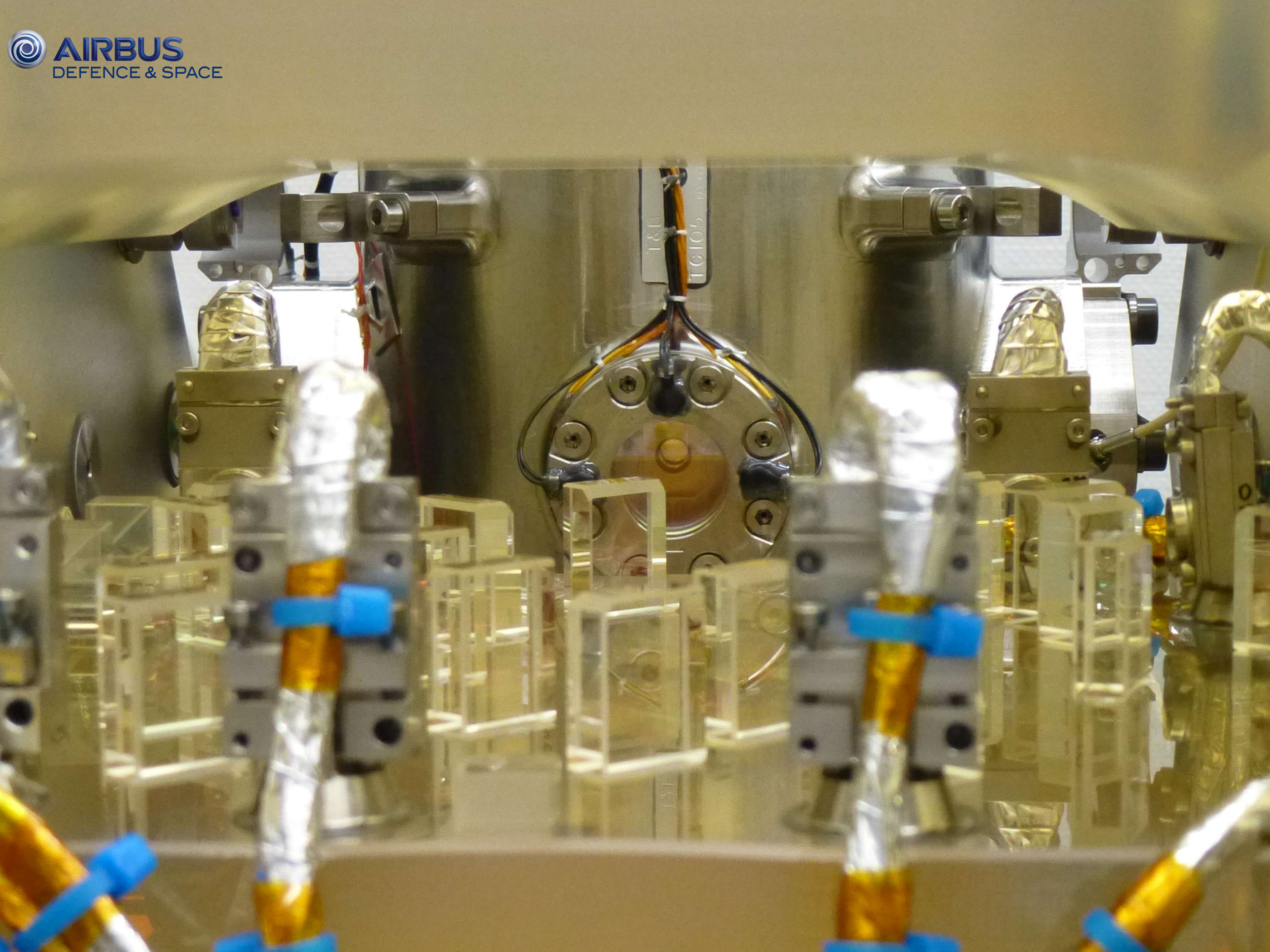
- Test masses are surrounded by electrodes which provide 6 degree-of-freedom sensing (and also actuation)
  - forms a differential capacitance meter
- Can sense absolute position of TM within 200um of the housing centre with an accuracy of nanometers
- System includes the grabbing and release mechanism
- Has two modes of operation:
  - High Resolution mode
    - low sensing noise 1.8 nm/Hz$^{1/2}$
    - Sensing range +/- 200 μm
    - Actuation authority 5 nN
  - Wide Range mode
    - Relatively high sensing noise
    - Sensing range 4 mm (all motions)
    - Actuation authority 8 μN

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DEFENCE & SPACE

LTP Integration

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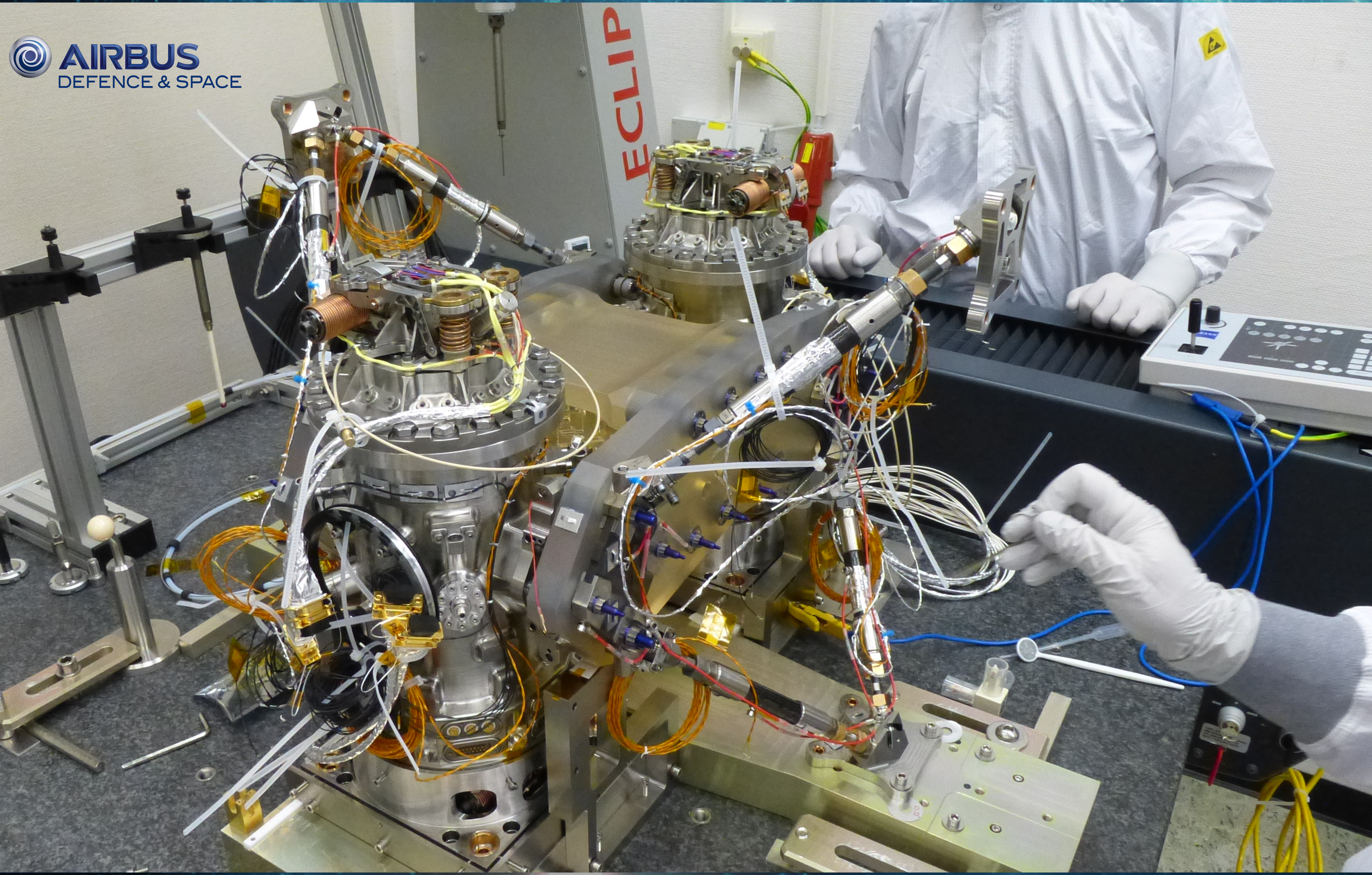

Integration of LCA

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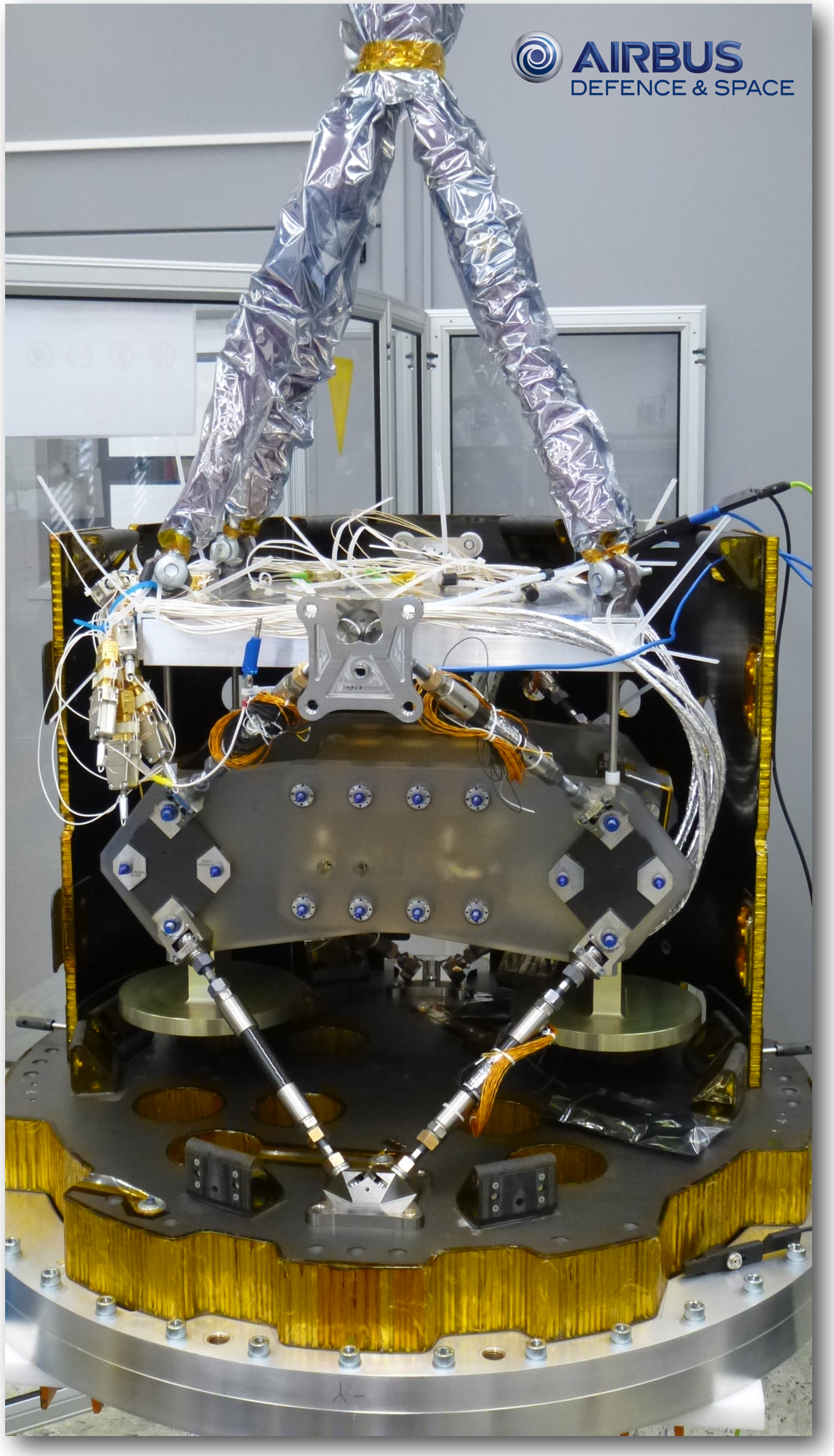
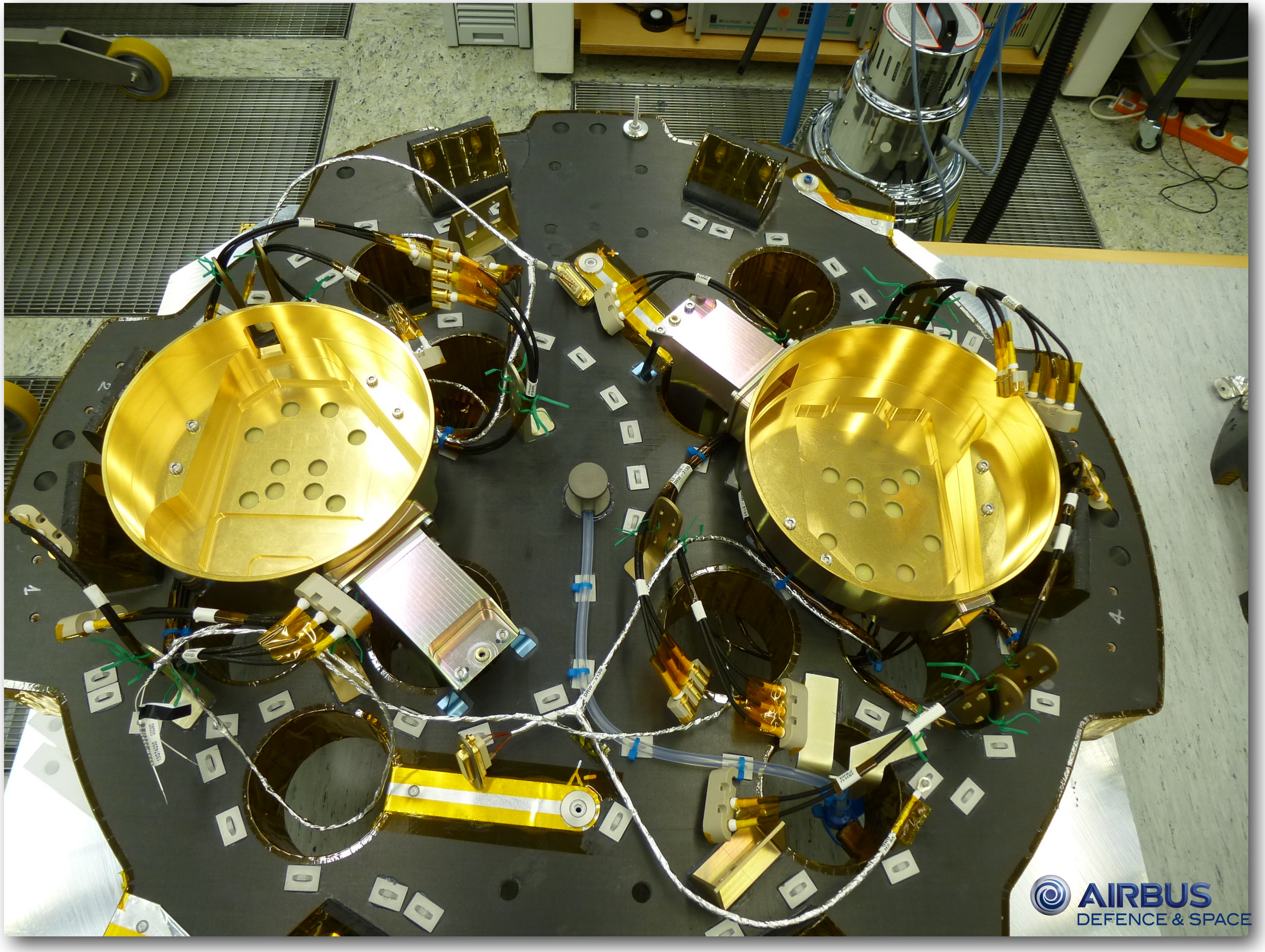
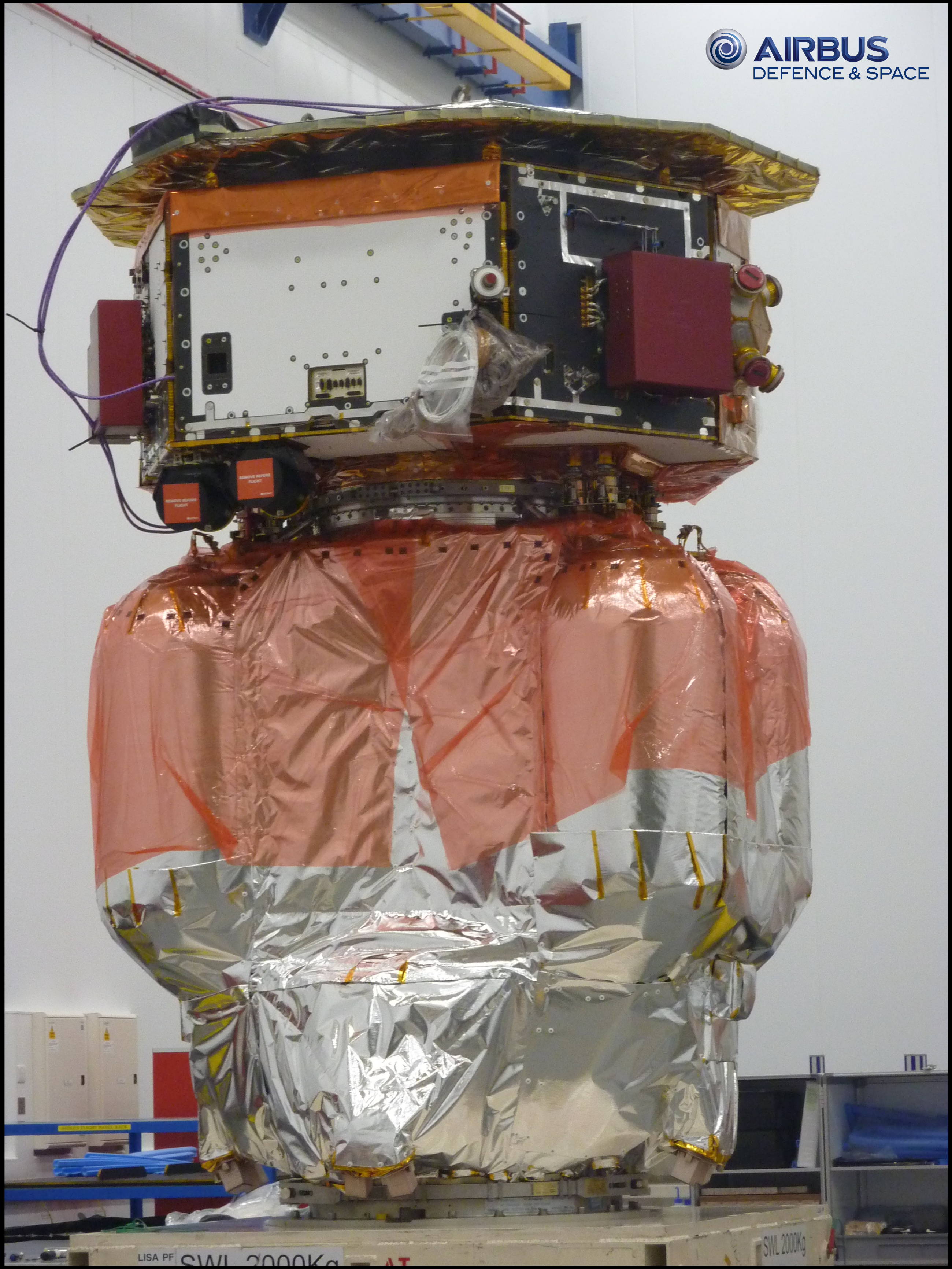




Spacecraft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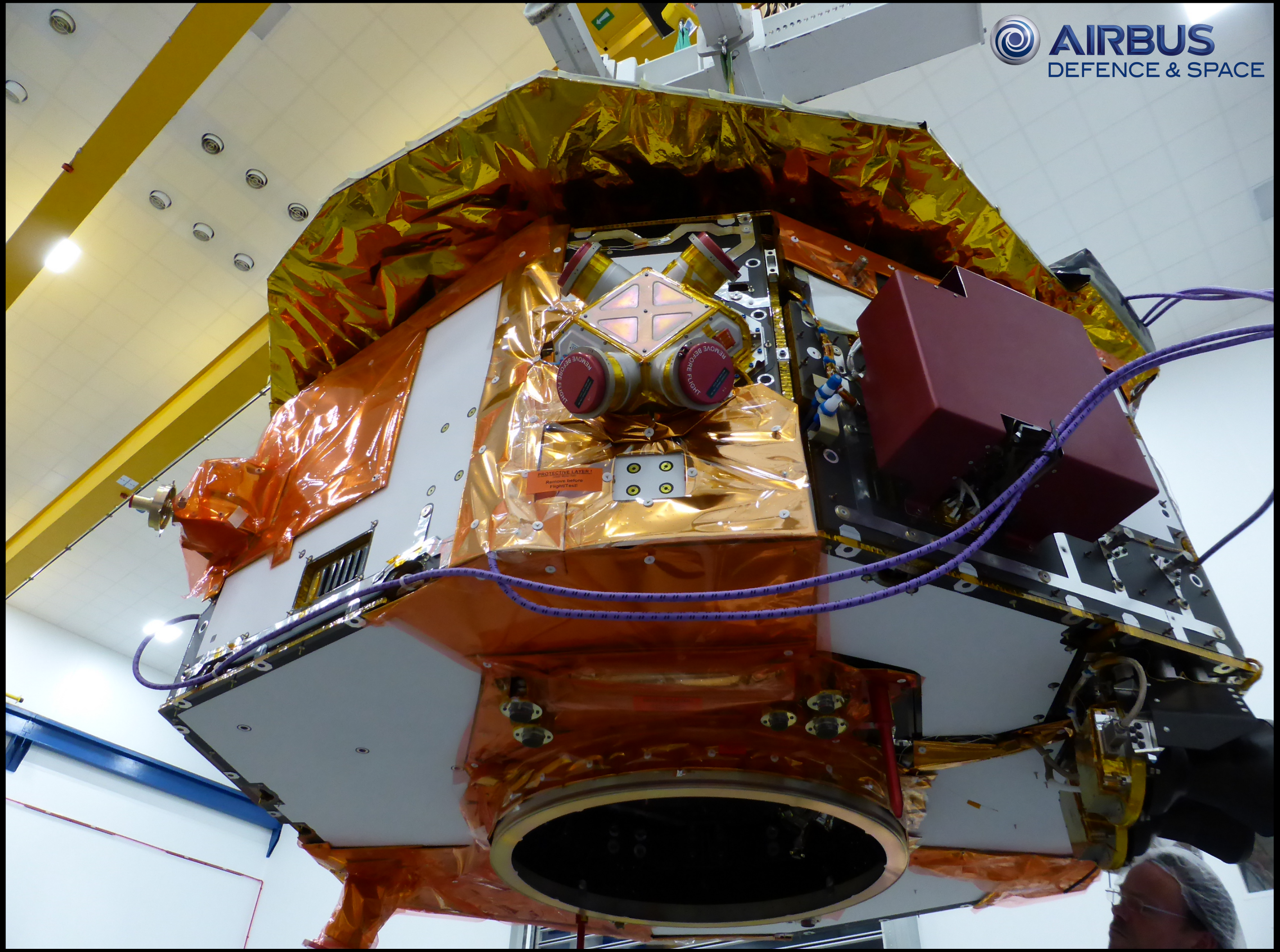
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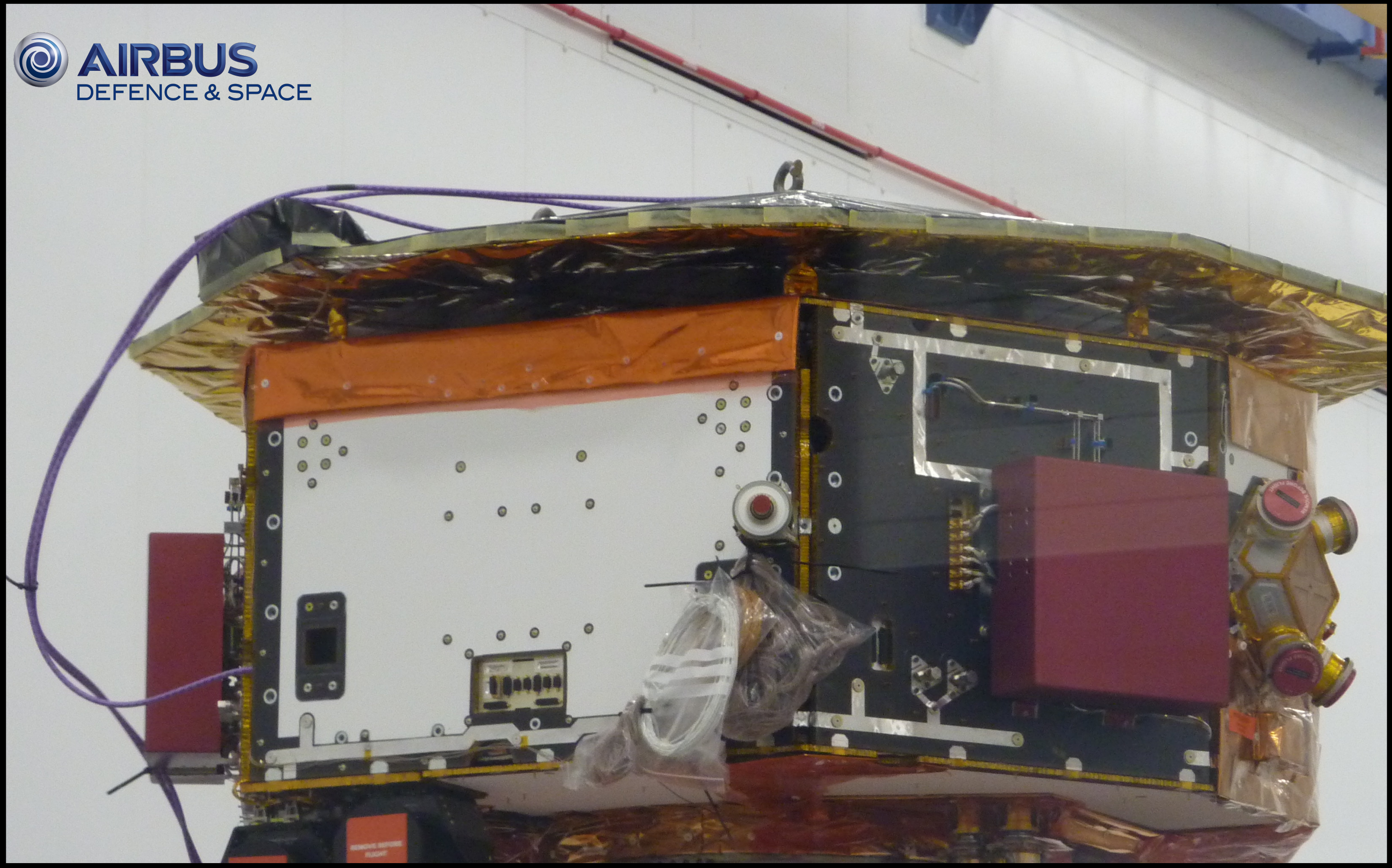
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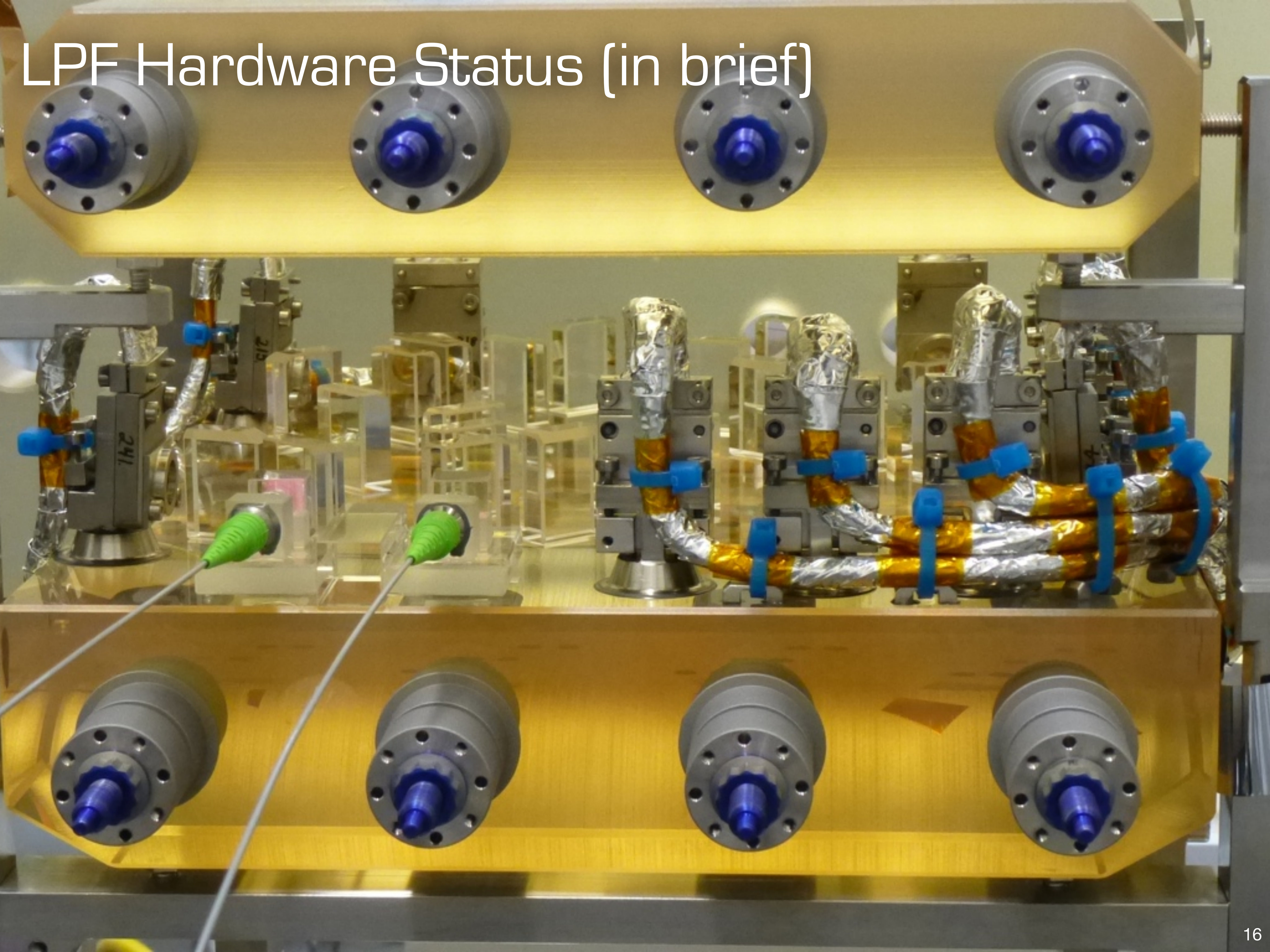
LPF Hardware Status (in brief)



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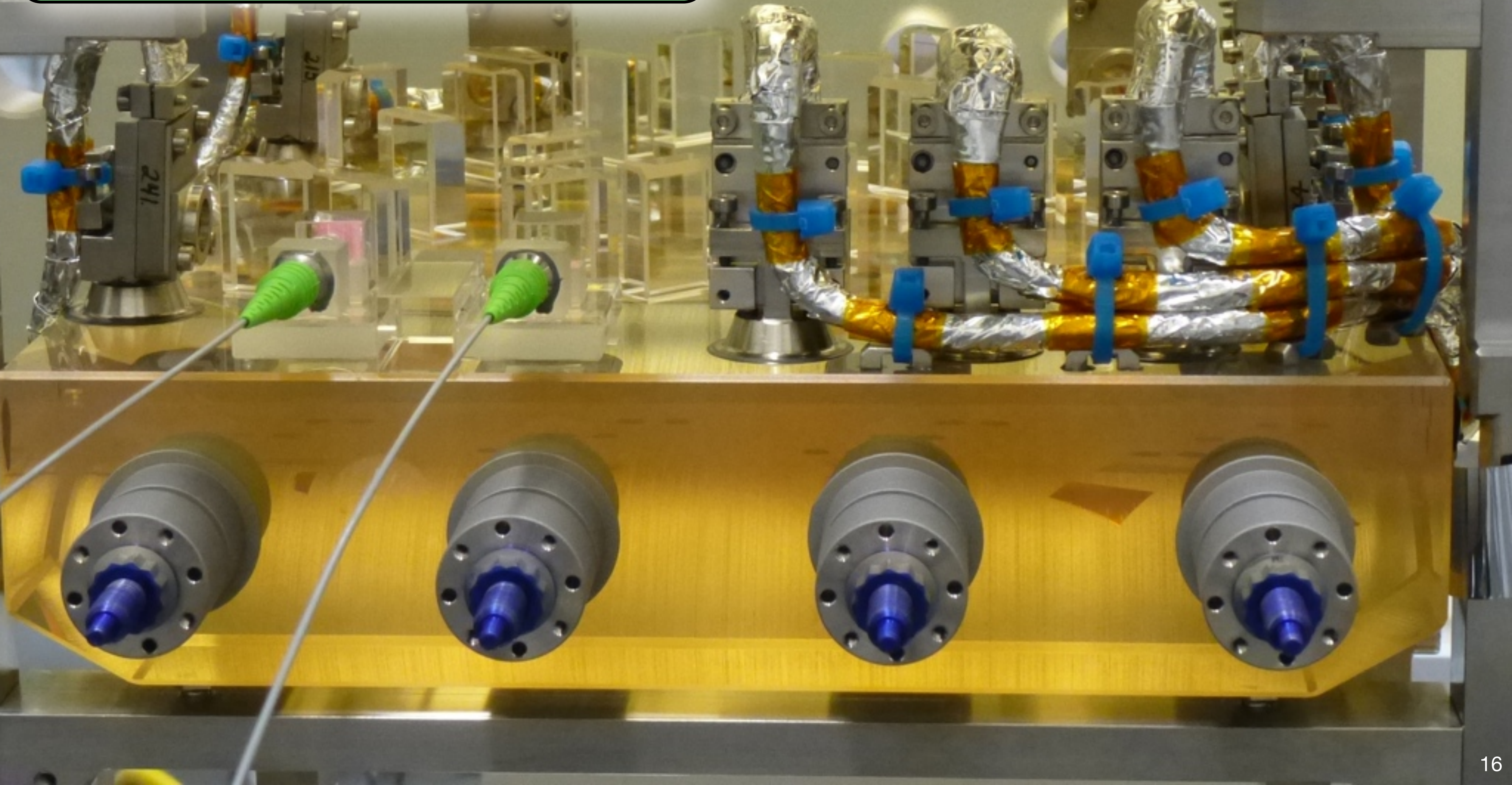

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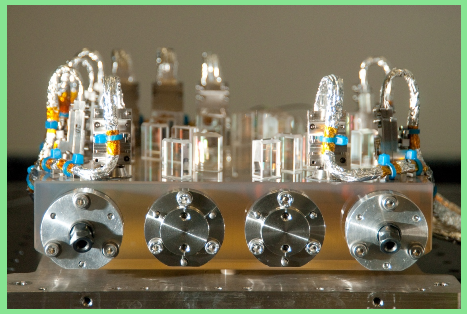

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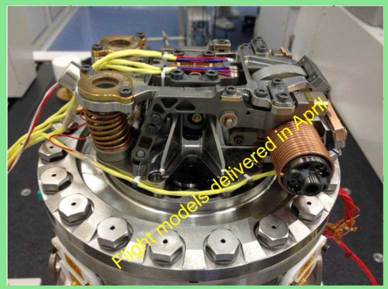
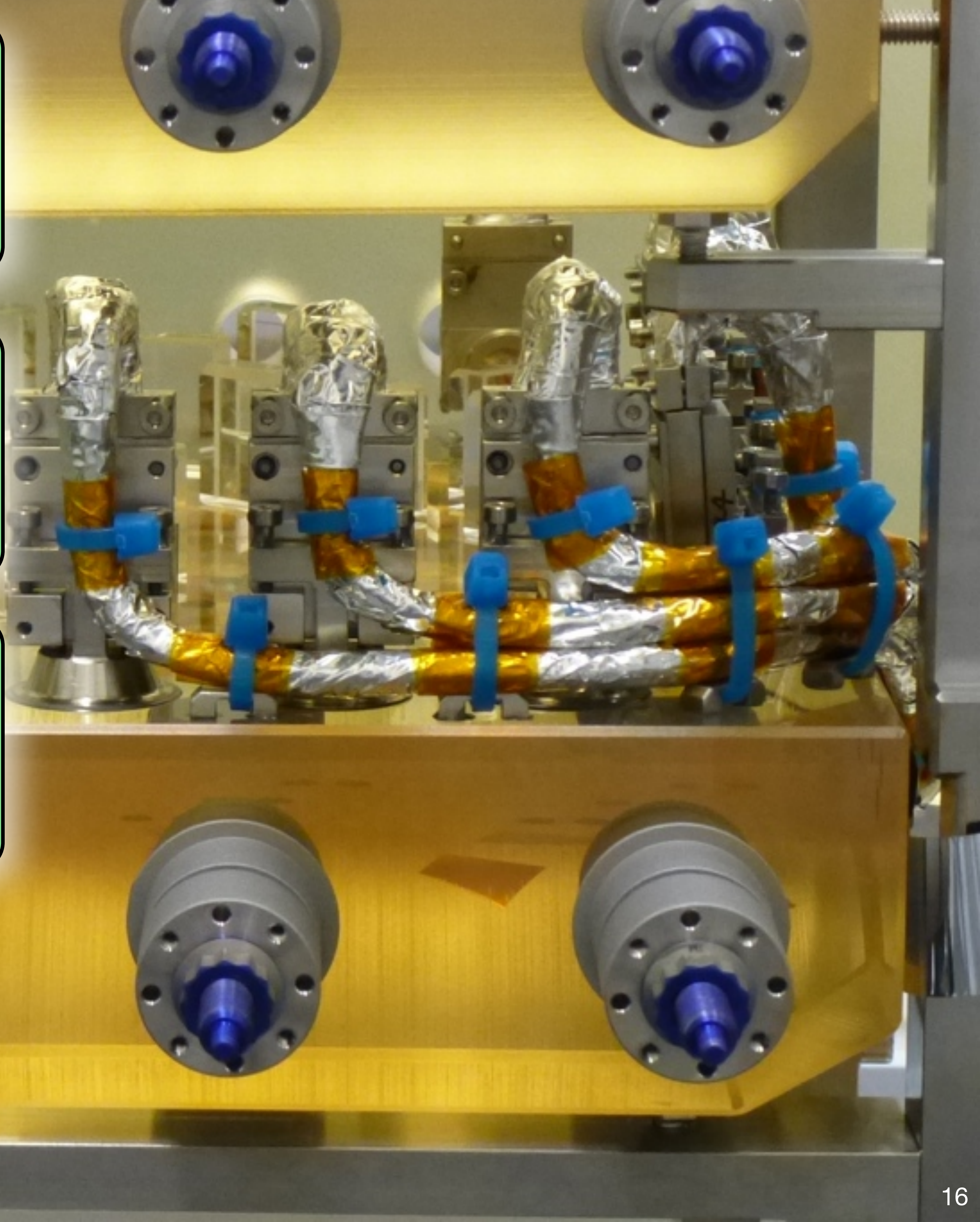


Caging mechanism delivered



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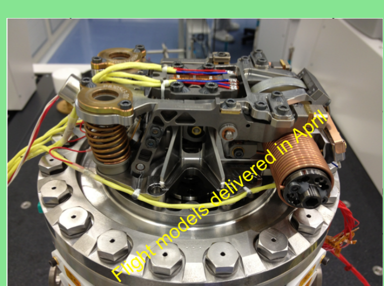

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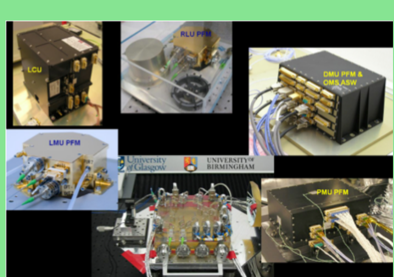
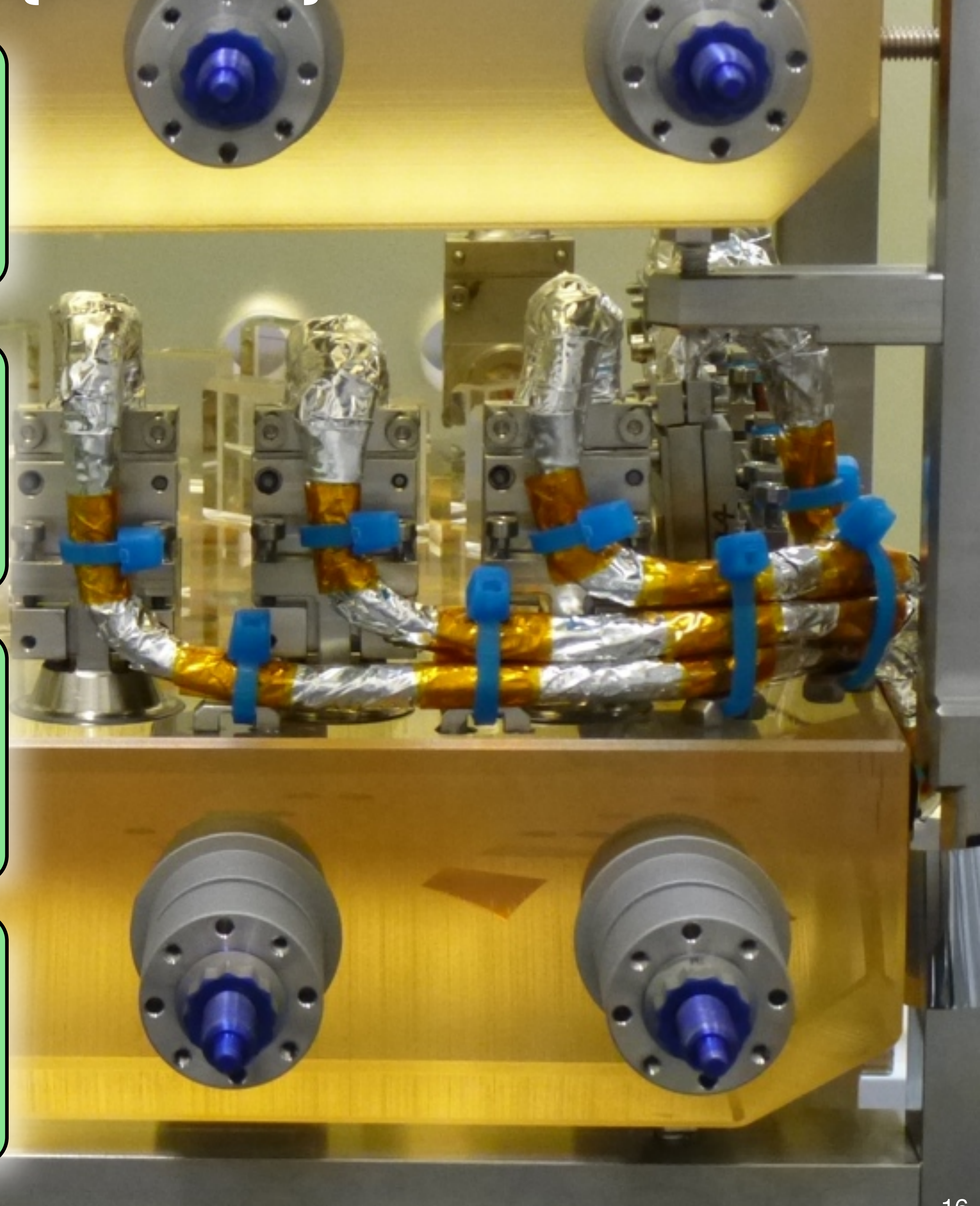


Laser and electronics on SC



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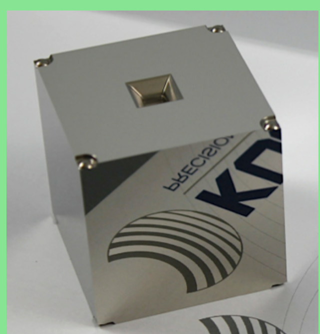

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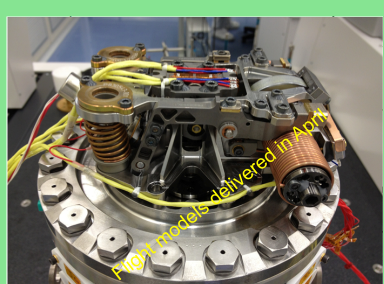

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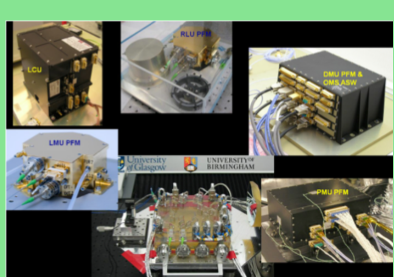

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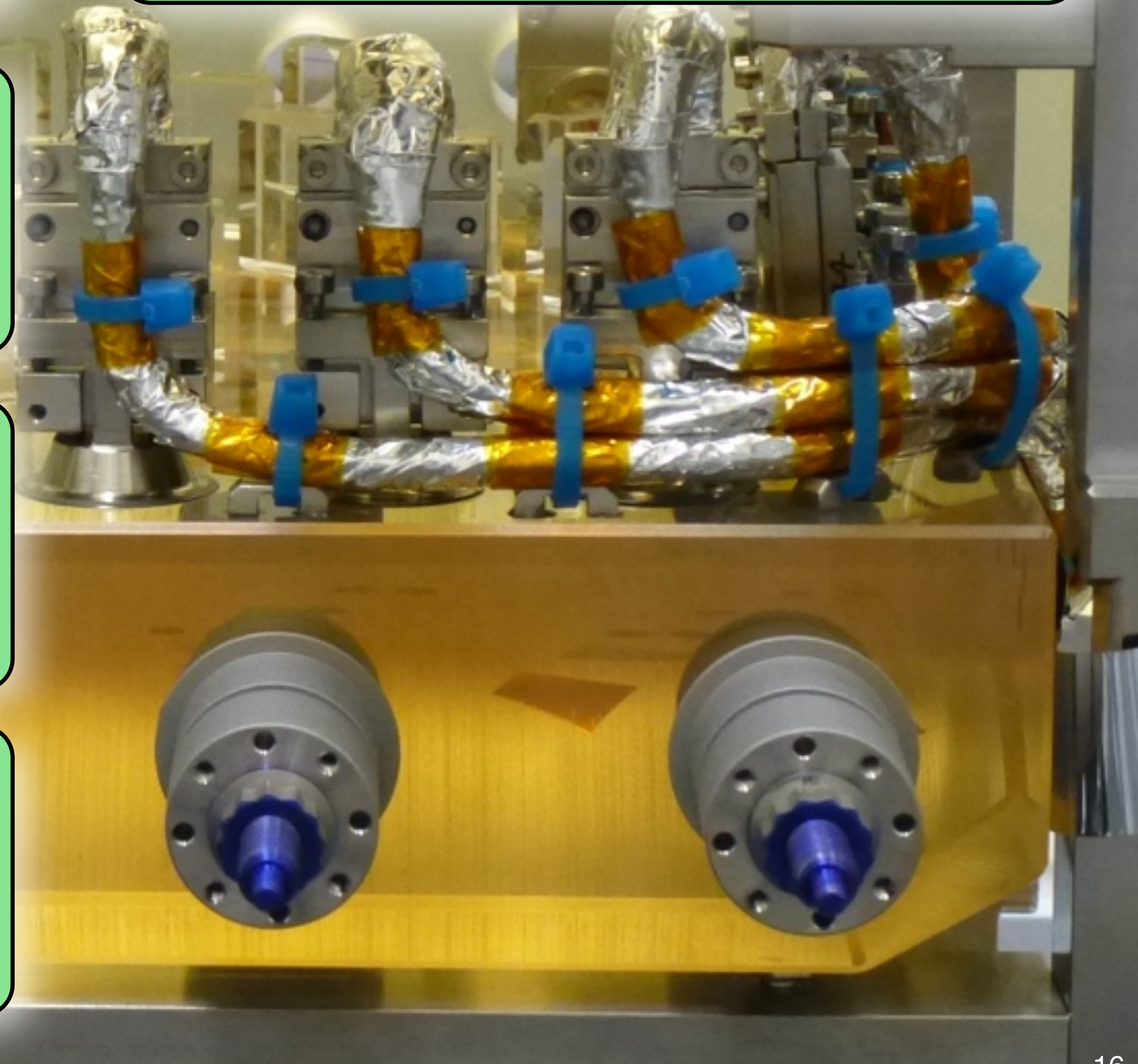

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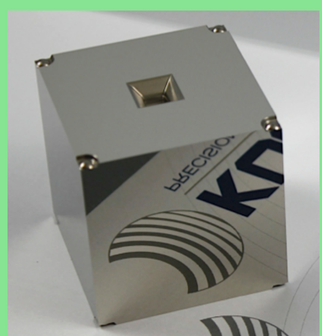

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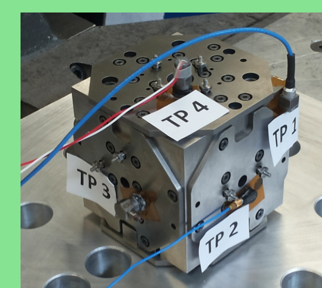

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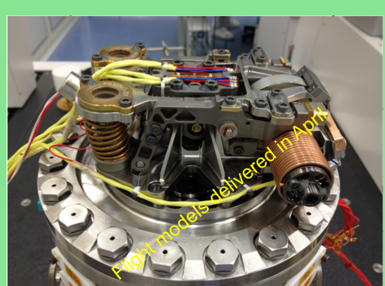

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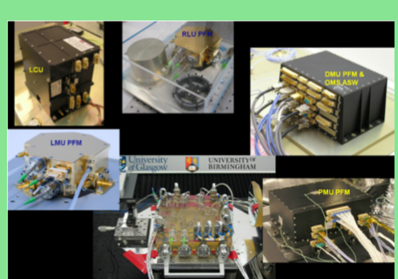

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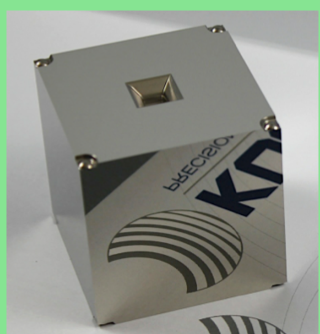

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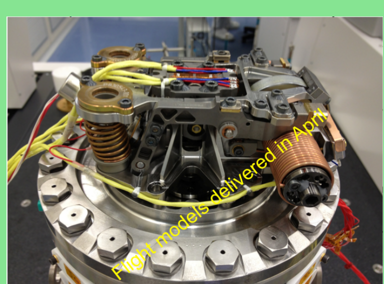

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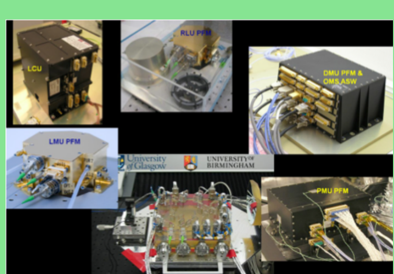

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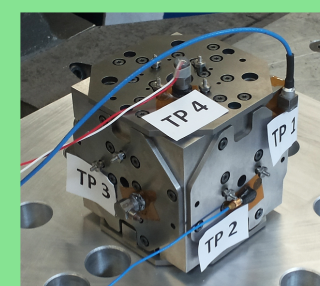

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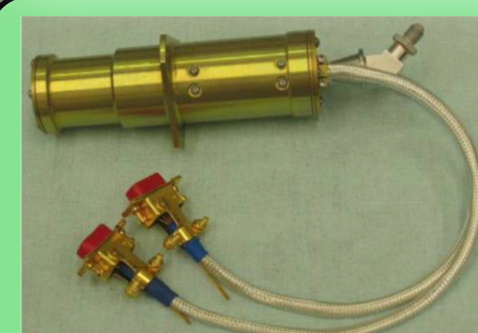

Cold Gas thrusters: off the shelf, flying on Gaia.

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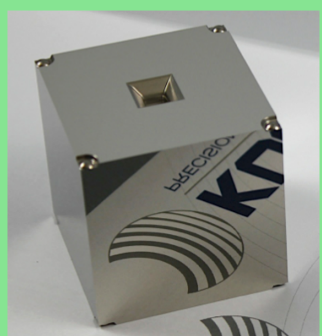

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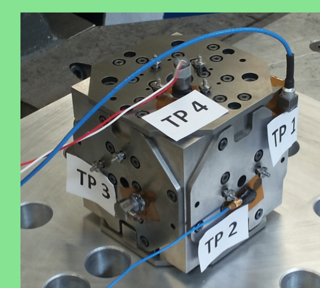

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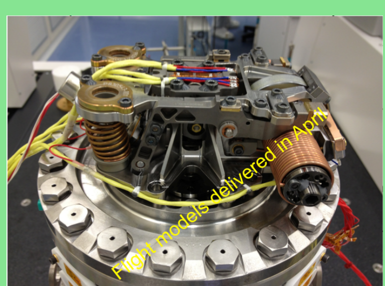

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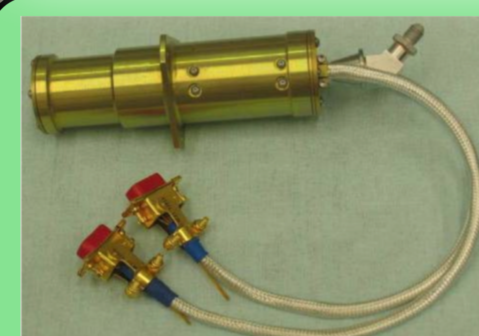

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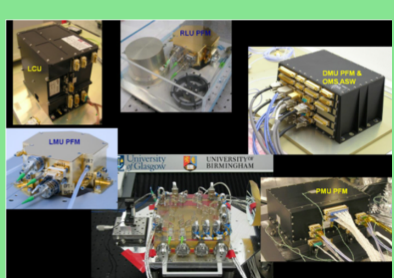
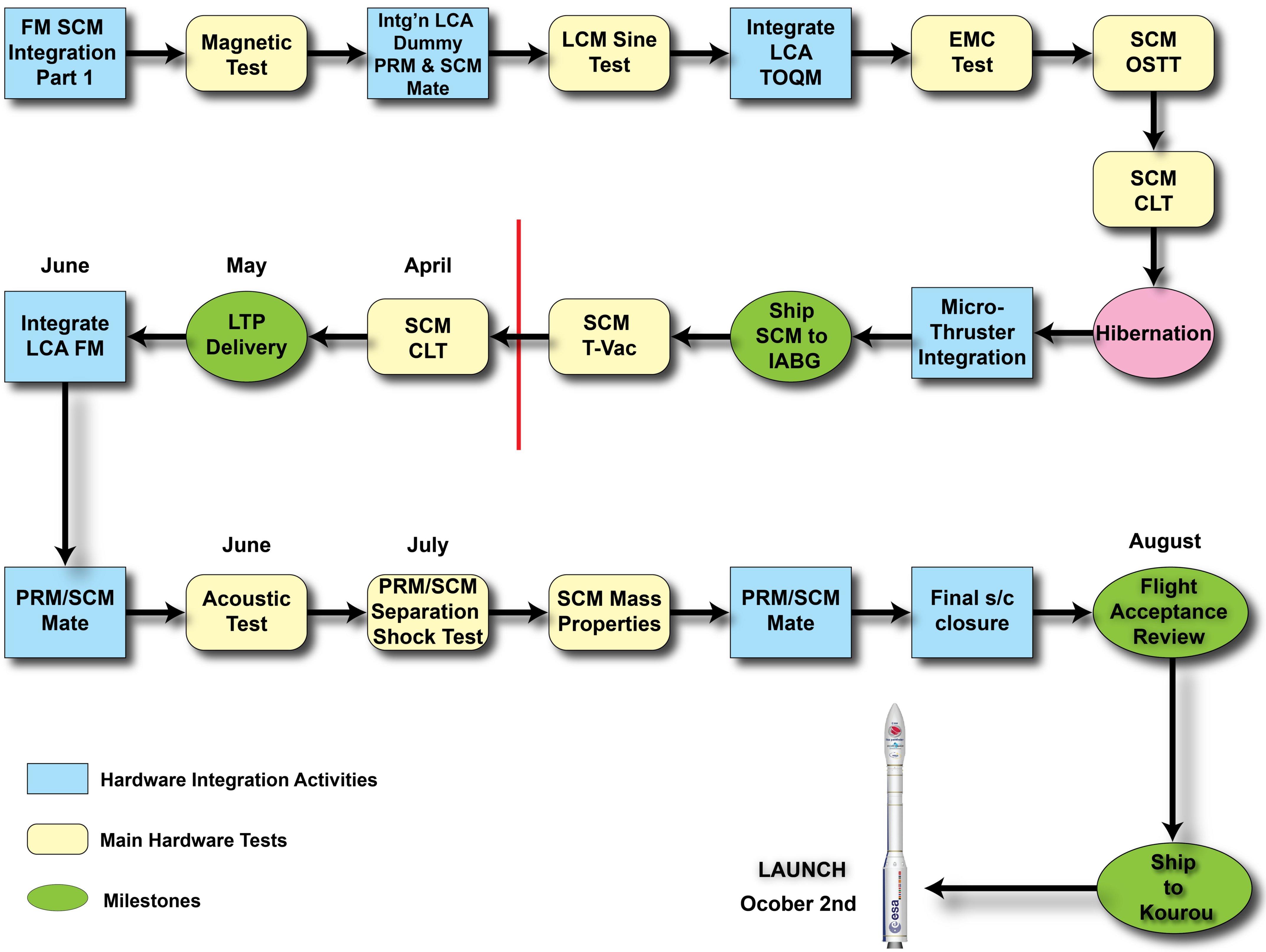


Laser and electronics on SC

Well on-track for Oct 2015 launch

Path to launch



Operations

Launch | IOCR

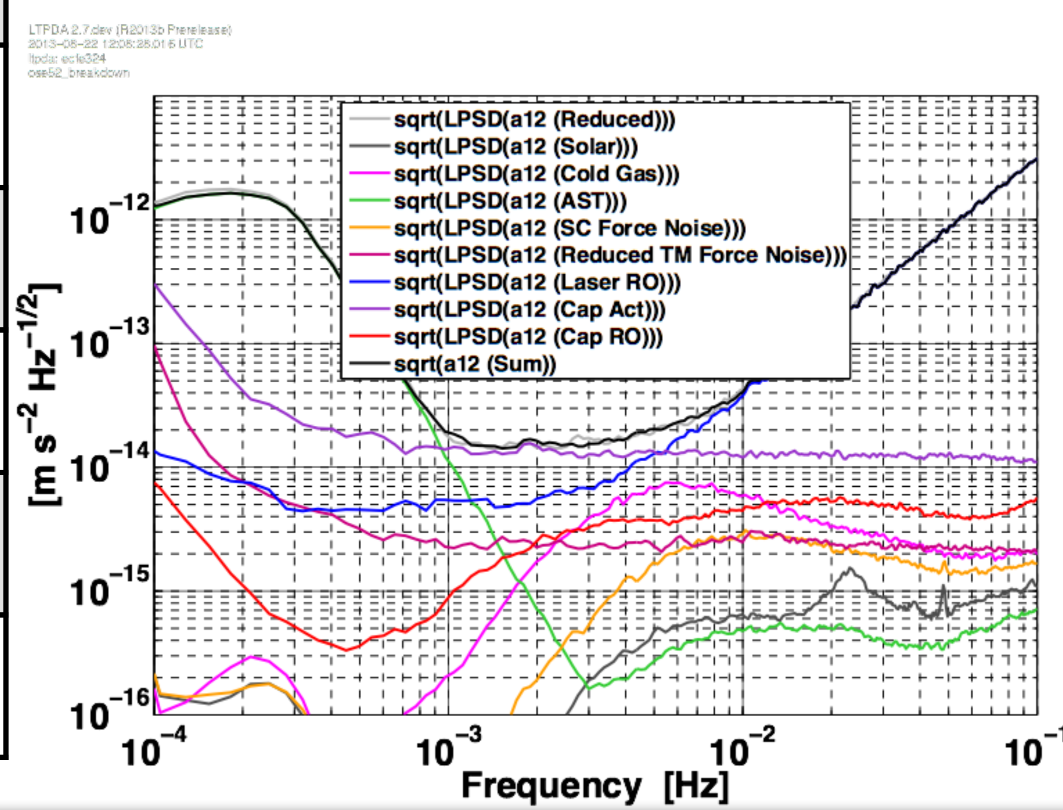
Launch, LEOP, Transfer, Separation, De-spin	Commissioning	LTP Science Ops	DRS Commissioning	DRS Operations
60 days	14 days	3 months	10 days	3 months

<table>
<tr><th></th><th>Day 1</th><th>Day 2</th><th>Day 3</th><th>Day 4</th></tr>
<tr><td>H1</td><td rowspan="3">Noise Run</td><td>Discharge</td><td rowspan="5">Noise Run</td><td>Discharge</td></tr>
<tr><td>H2</td><td rowspan="3">Working Point</td><td rowspan="4">Stray Potentials</td></tr>
<tr><td>H3</td></tr>
<tr><td>H4</td><td rowspan="2">Sys ID</td></tr>
<tr><td>H5</td><td></td></tr>
</table>

What’s on the menu?

Measurement of Parasitic Voltages
Measurement of differential acceleration noise on LISA Pathfinder
Measurement of cross-talks in the system
Measurement of LTP dynamical coefficients by system identification
Analysis of Data from the Radiation Monitor on LISA Pathfinder
Thermal experiments on board the LTP
Magnetic experiments on board the LTP
OPD noise investigations for LTP
Laser frequency noise characterisation for LTP
Laser Amplitude Noise Characterisation for LTP
The Drift Mode for LISA Pathfinder

Modulate TM2 z electrodes with compensation voltage -100mV
Modulate TM2 y electrodes with compensation voltage -100mV
Modulate TM2 x electrodes with compensation voltage -100mV
…



Starting science operations

- The first two weeks are all about gathering information and gaining experience
- This is our first interaction with the system
- Focus on:
  - noise runs
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	Hour																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Noise run in Sci 1.2																							
2	CE1		CE2		Noise run in Sci 1.2																			
3	CE1		CE2		Sys ID (low amp)								Noise run in Sci 1.2											
4	CE1		CE2		Working point scan (x,y,z), both TMs																			
5	CE1		CE2		Cross-talk investigations, low amplitude																			
6	CE1		CE2		Noise run in Sci 1.2																			
7	Station Keeping												Transition Acc3 -> Sci 1.2								FD1		FD2	

Estimating Residual Differential Acceleration

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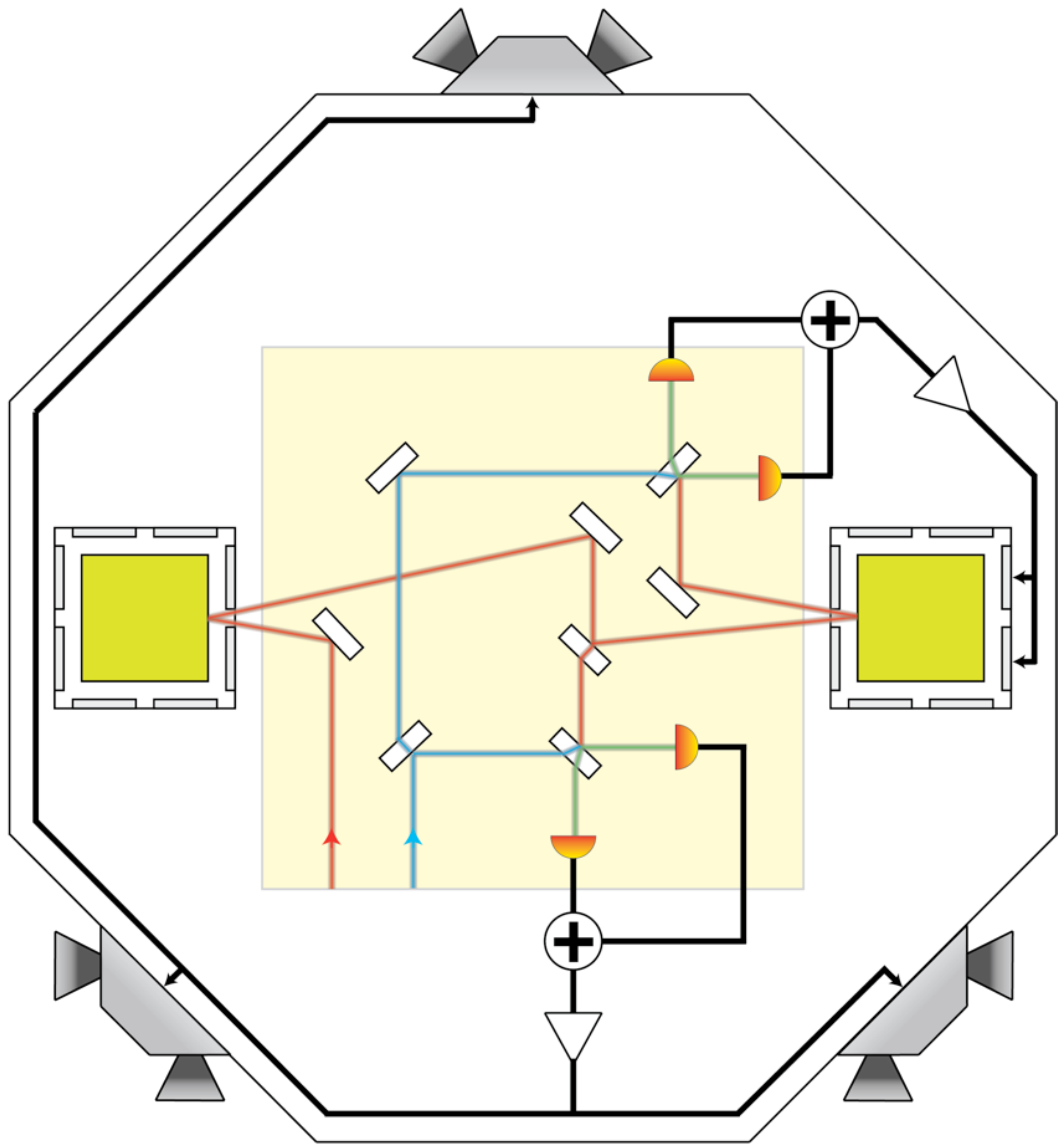
$$g_{\mathrm{res}} = \ddot{x_{12}}$$

- Try to account for the contributions of g_res that we know
  - applied control forces
  - couplings due to force gradients

$$\begin{aligned} g_{\mathrm{res}} = & \ddot{x_{12}} \\ & -g_{\mathrm{control}} \\ & -\omega_{\Delta}^{2} x_{1} - \omega_{2}^{2} x_{12} \end{aligned}$$

System Identification

Goal is to measure the key parameters needed for estimating the residual differential acceleration



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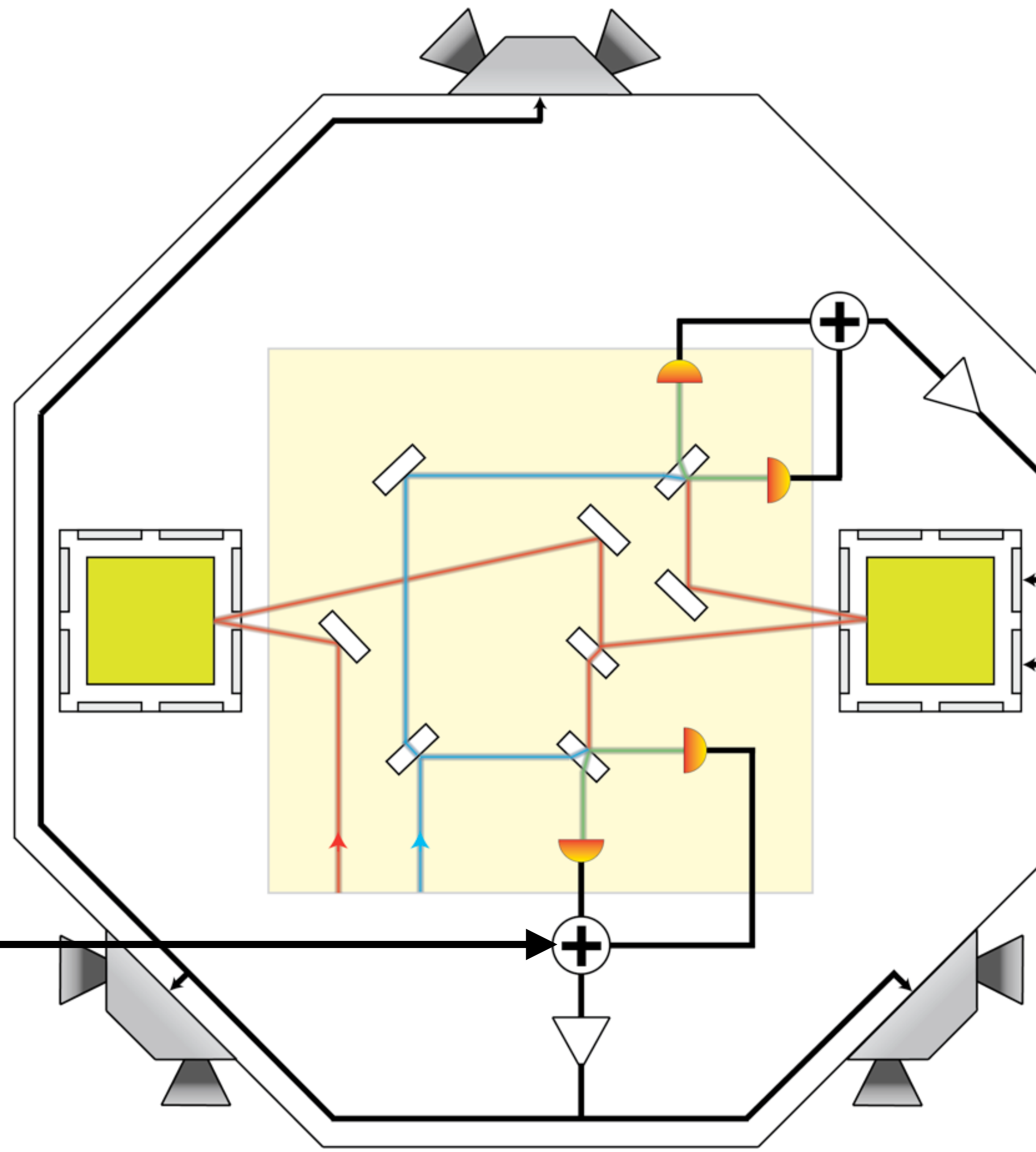

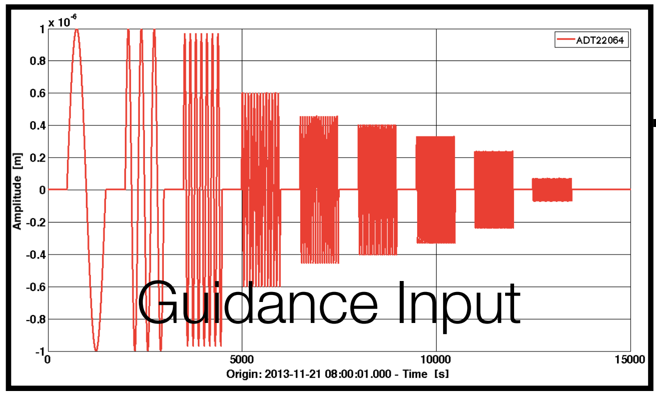

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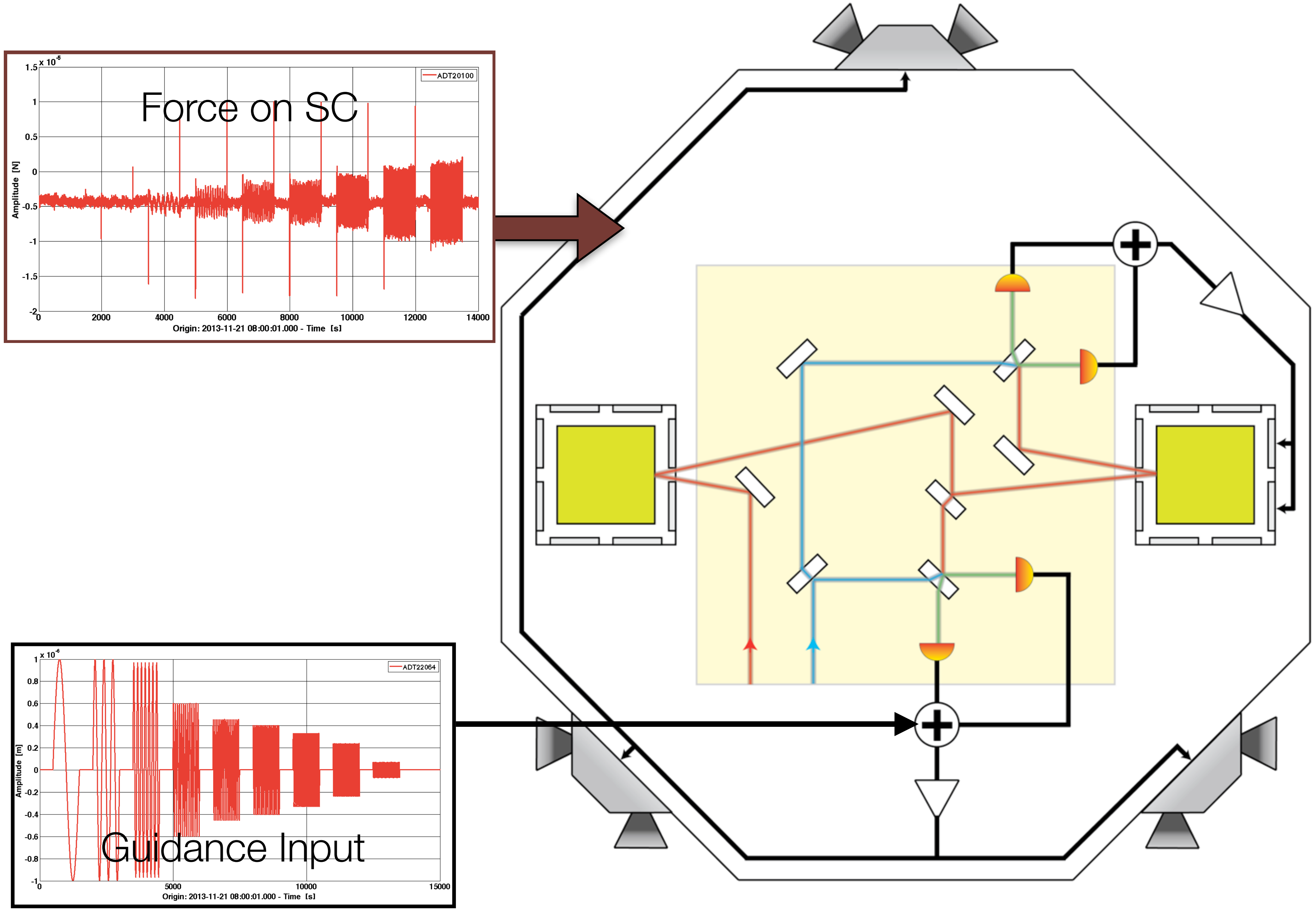

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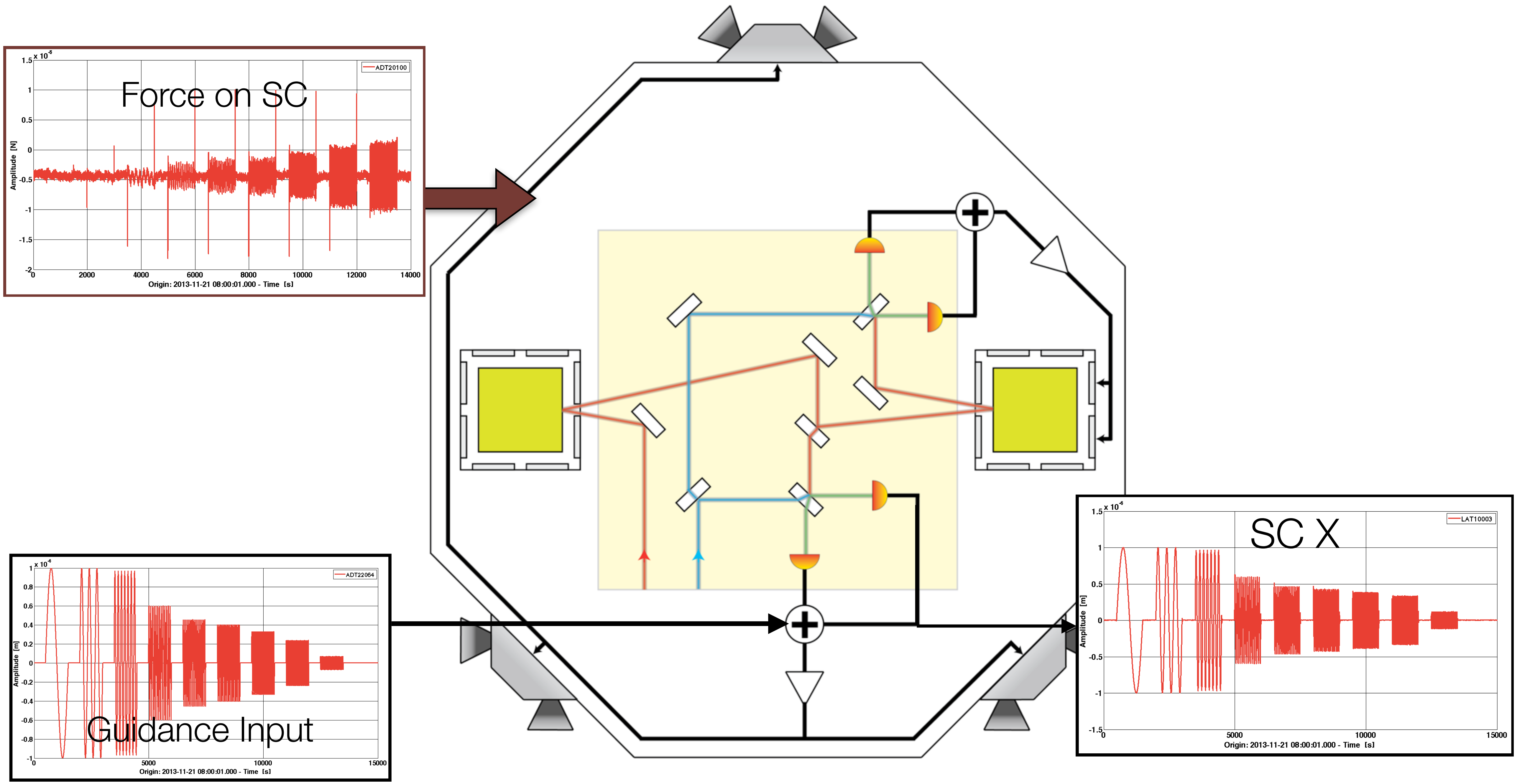
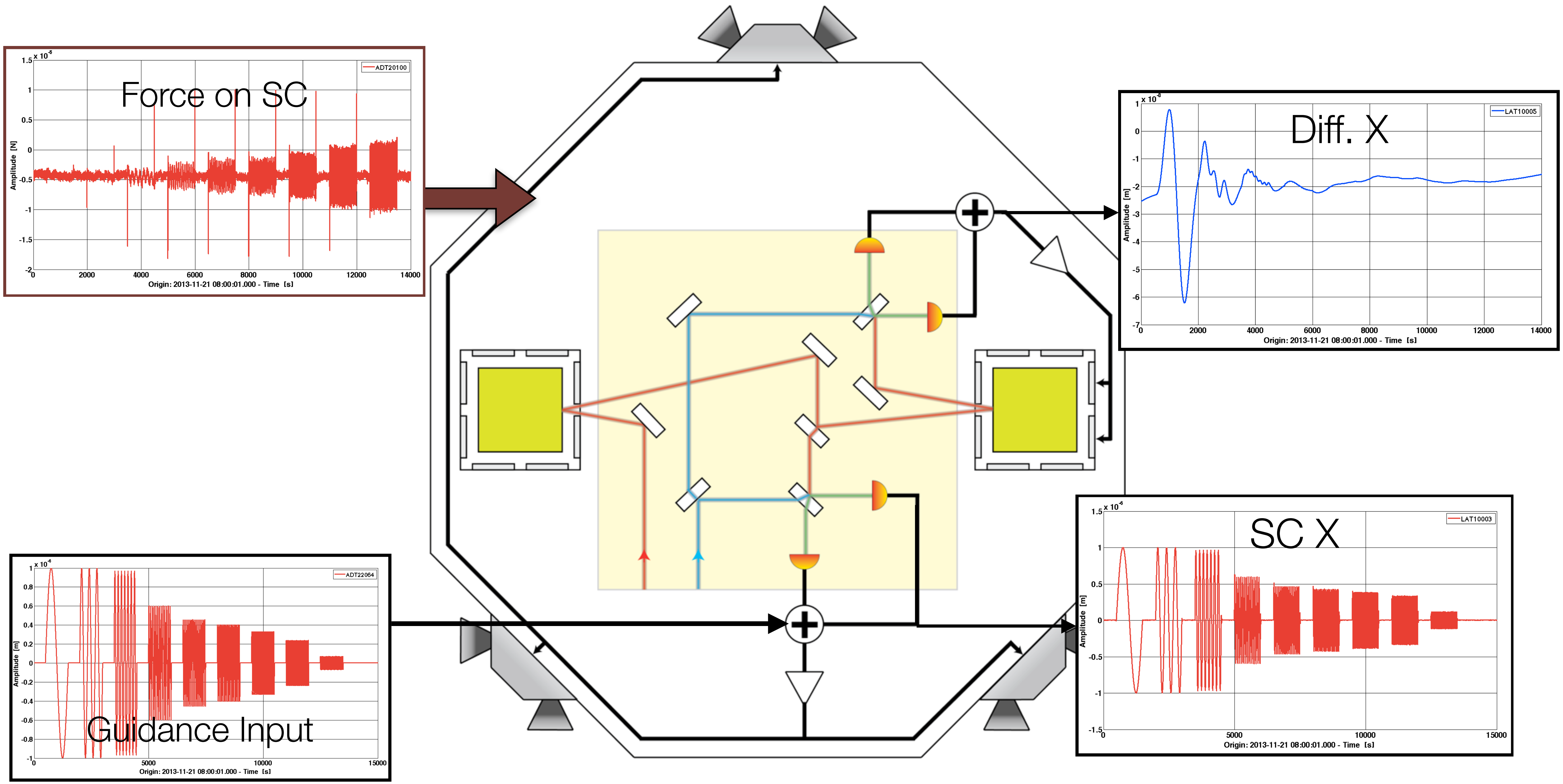
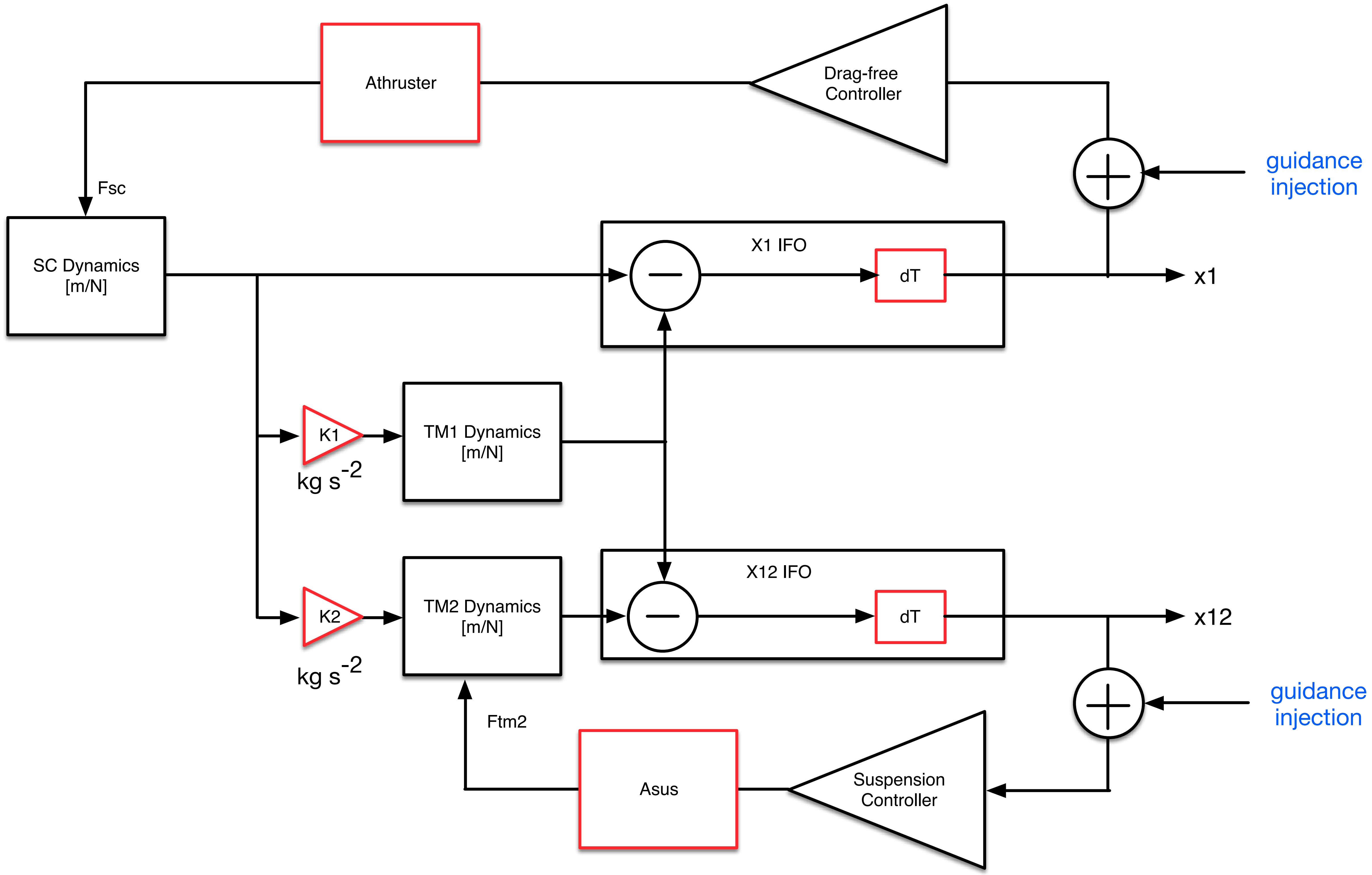


System Identification

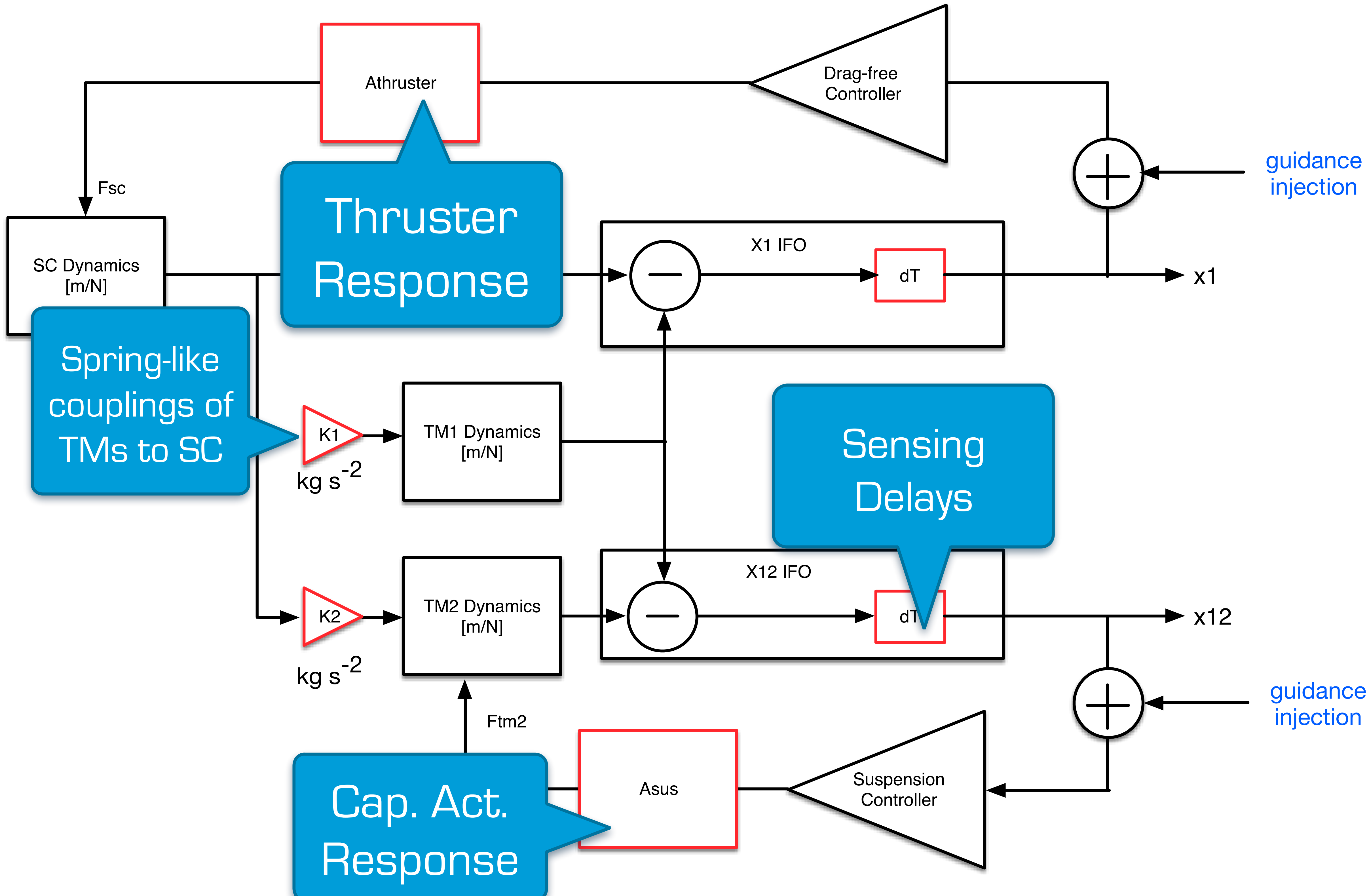
Goal is to measure the key parameters needed for estimating the residual differential acceleration



Parameter estimation

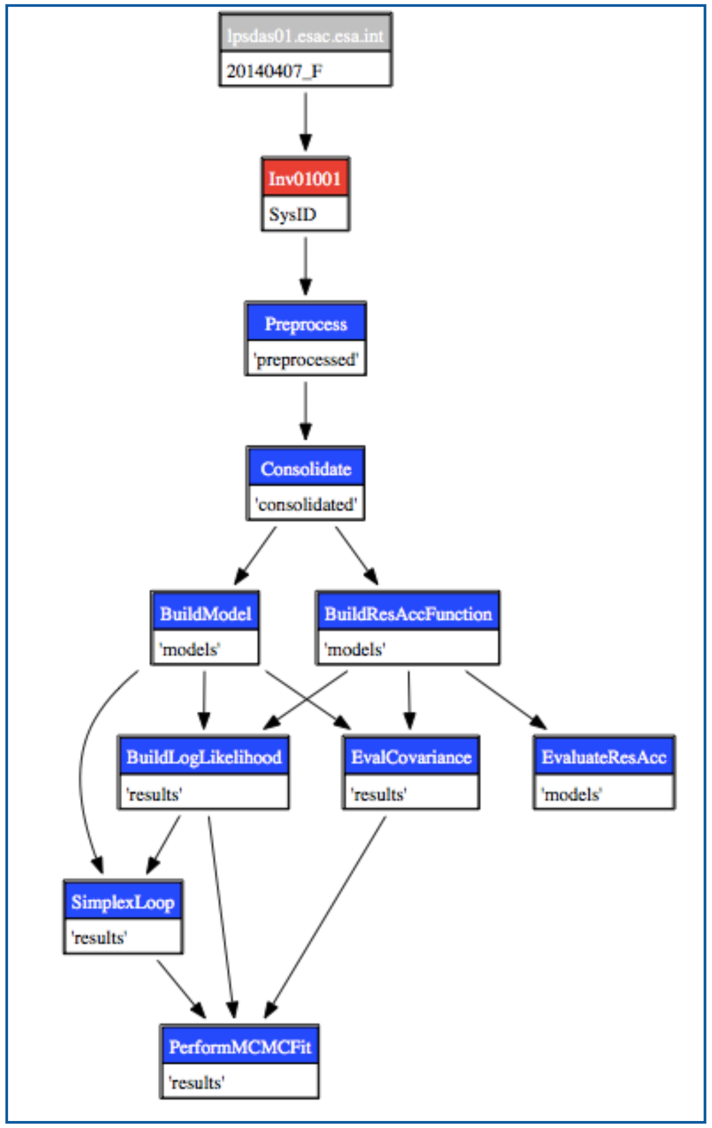


Parameter estimation



Analysis

- Follows the same form as for estimating residual differential acceleration
- But now the coefficients in the model are fit so that the linear combination of terms fit the observation
- When a good fit is found, the residuals contain no trace of the injected signals

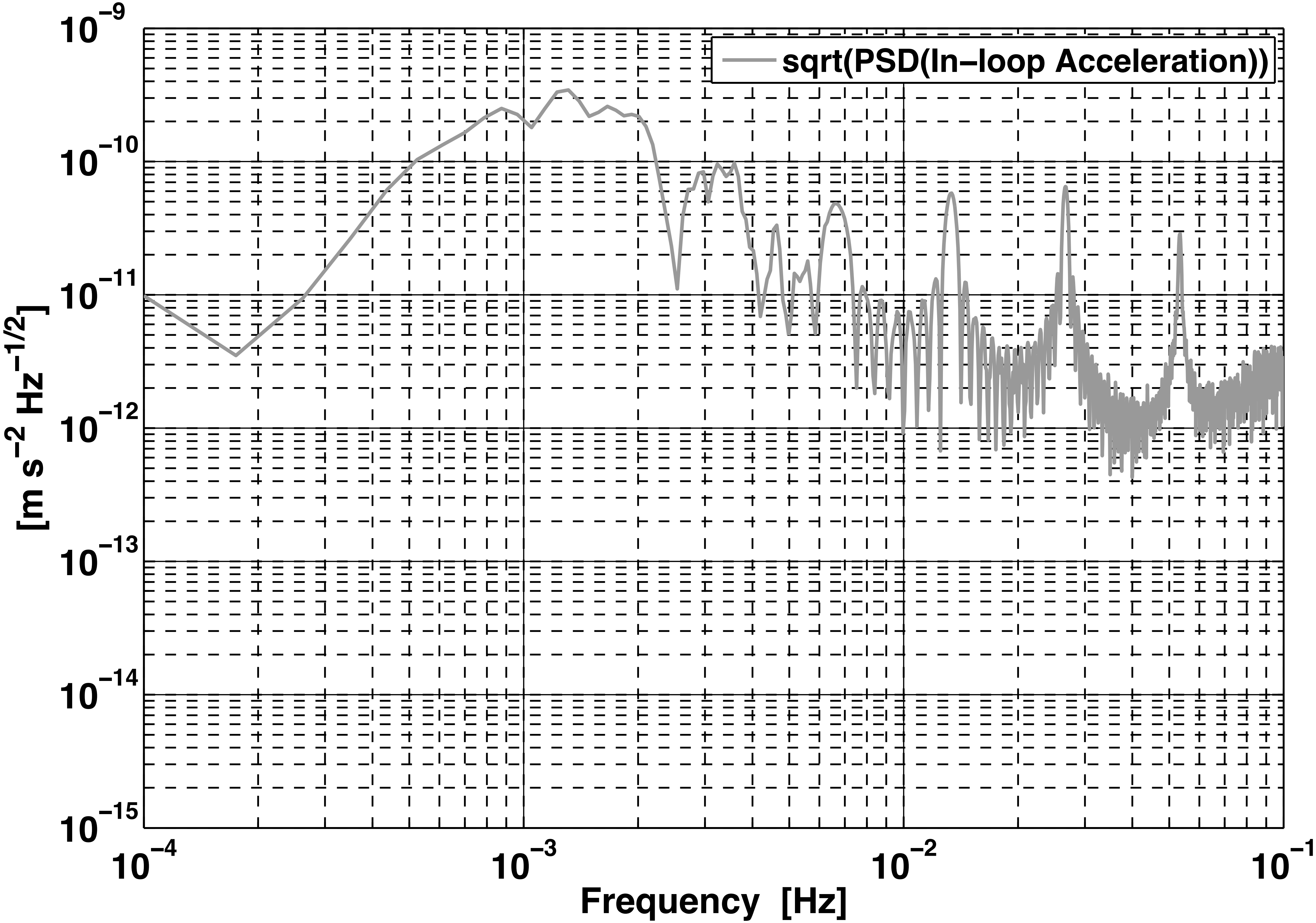


Fit $\text{observation} = \ddot{x}_{12}[k]$ to

$$\begin{aligned}\text{model} \quad = \quad & -A_{\text{sus}} F(g_{\text{control}}[k], \Delta T) \\ & -(\omega_2^2 - \omega_1^2) x_1[k] \\ & -\omega_2^2 x_{12}[k]\end{aligned}$$

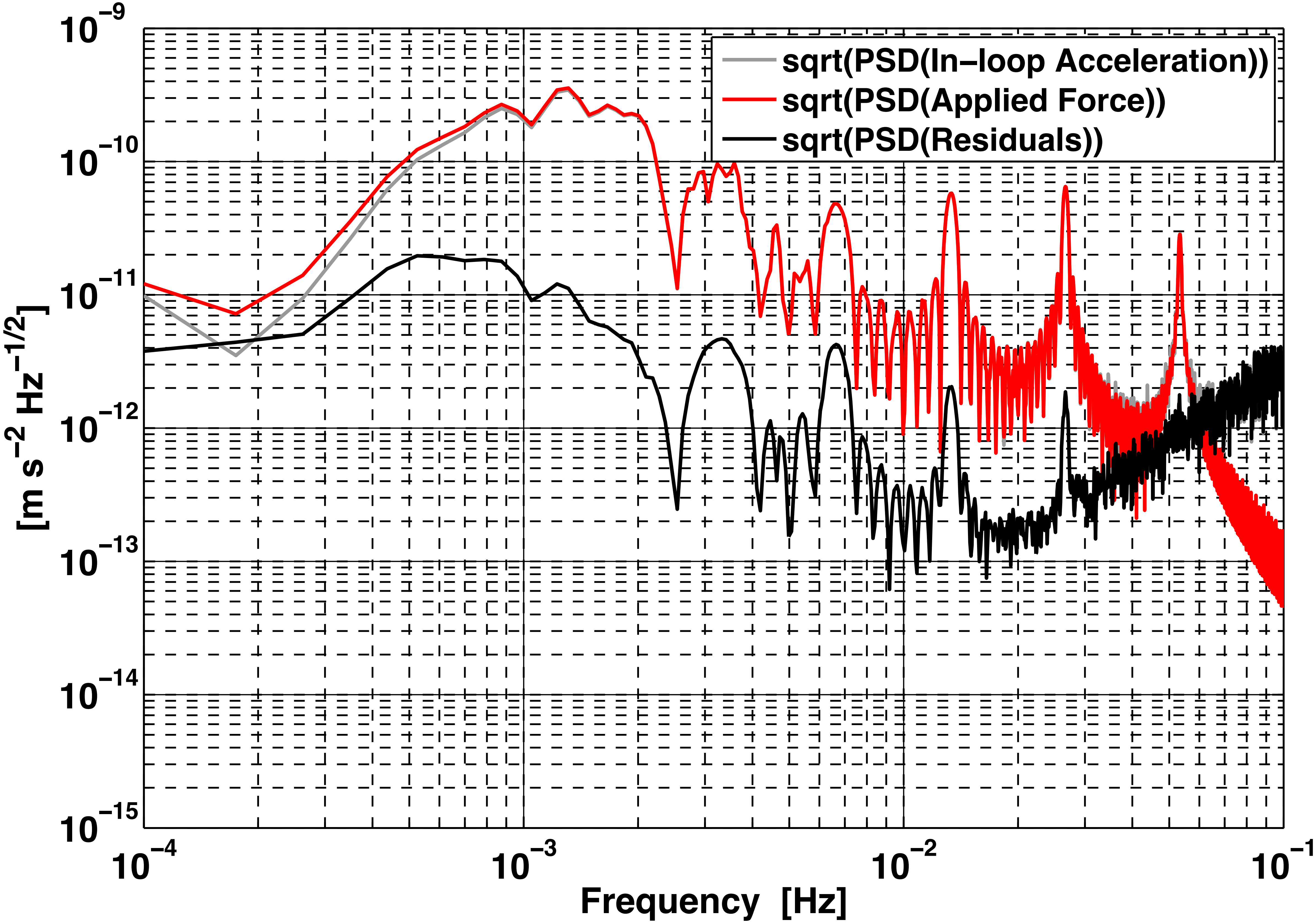
Residuals

Residuals



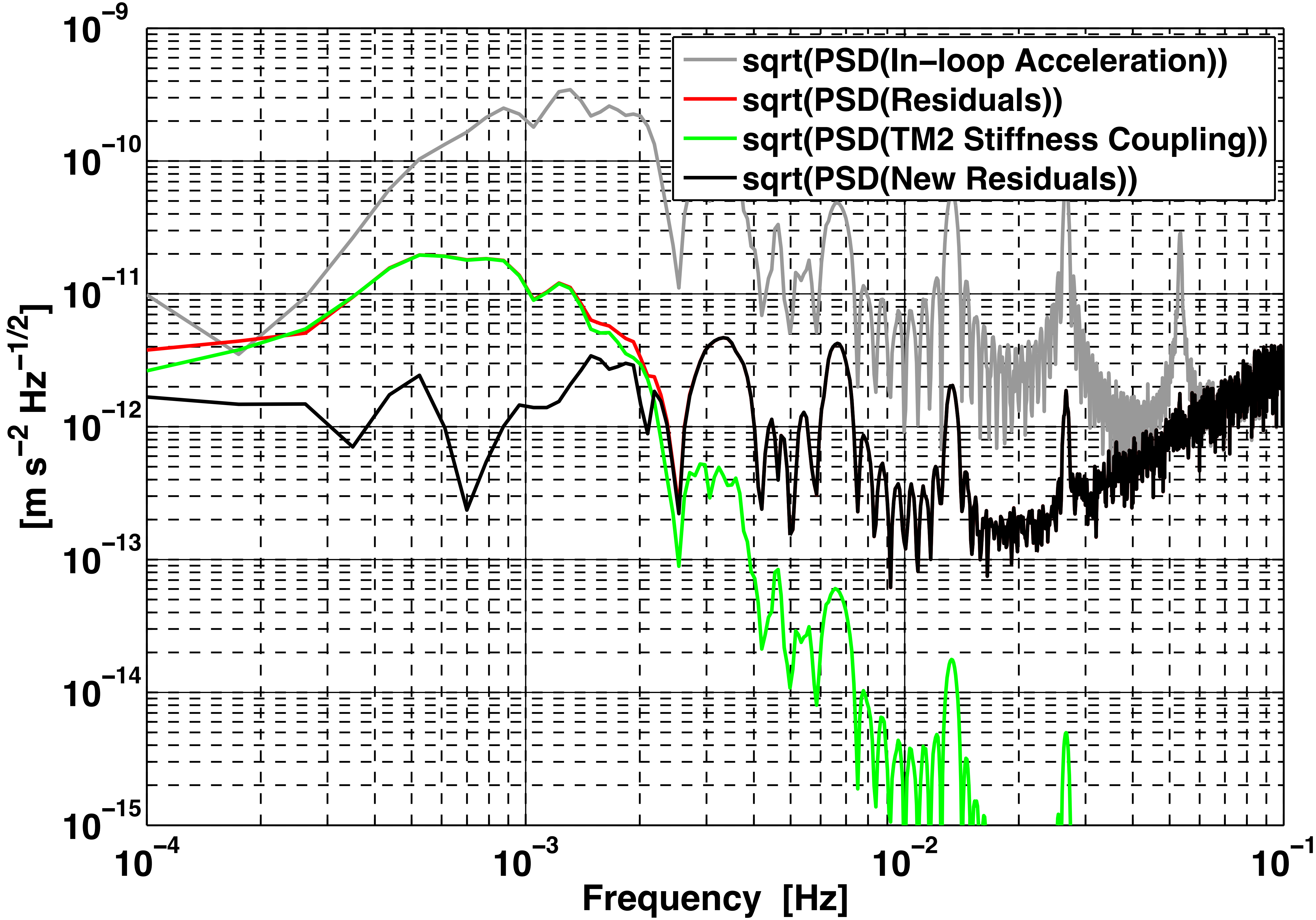
sqrt(PSD(In−loop Acceleration))
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$[\mathrm{m\ s^{-2}\ Hz^{-1/2}}]$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency [Hz]

Residuals



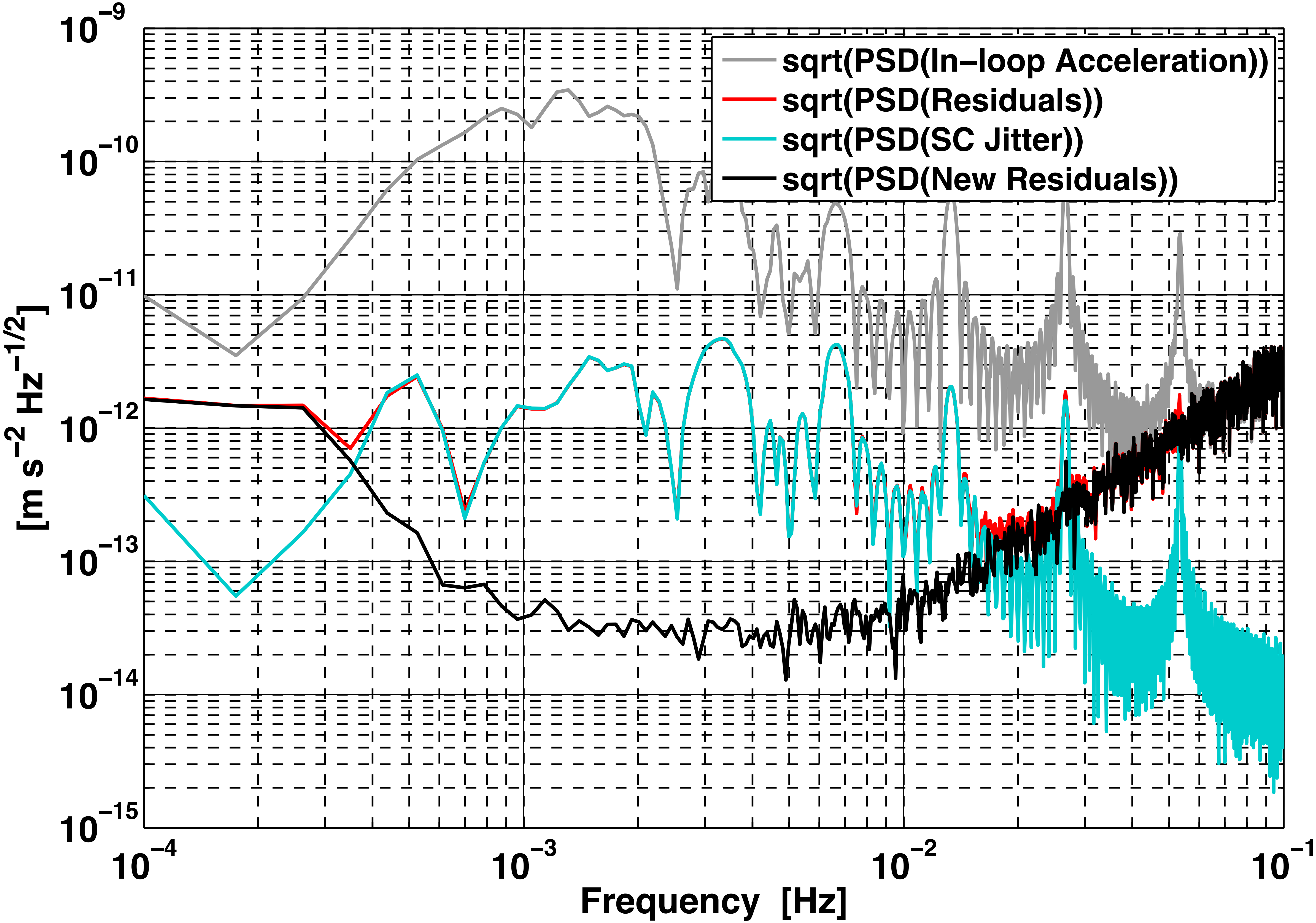
sqrt(PSD(In−loop Acceleration))
sqrt(PSD(Applied Force))
sqrt(PSD(Residuals))
[m s^{-2} Hz$^{-1/2}$]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency [Hz]

Residuals



sqrt(PSD(In−loop Acceleration))
sqrt(PSD(Residuals))
sqrt(PSD(TM2 Stiffness Coupling))
sqrt(PSD(New Residuals))
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$[m\ s^{-2}\ Hz^{-1/2}]$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency [Hz]

Residuals

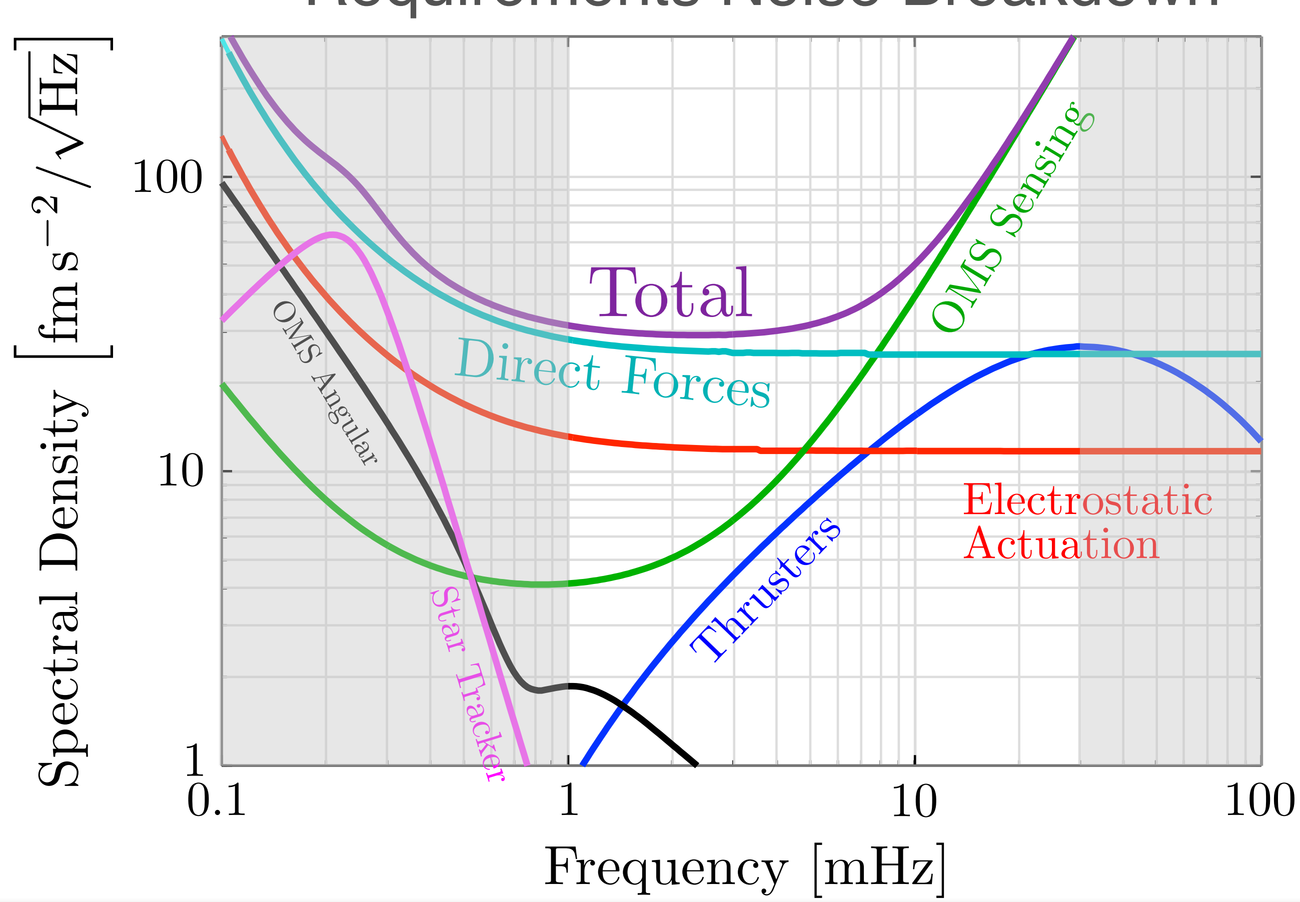


sqrt(PSD(In−loop Acceleration))
sqrt(PSD(Residuals))
sqrt(PSD(SC Jitter))
sqrt(PSD(New Residuals))
$[m\ s^{-2}\ Hz^{-1/2}]$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency [Hz]

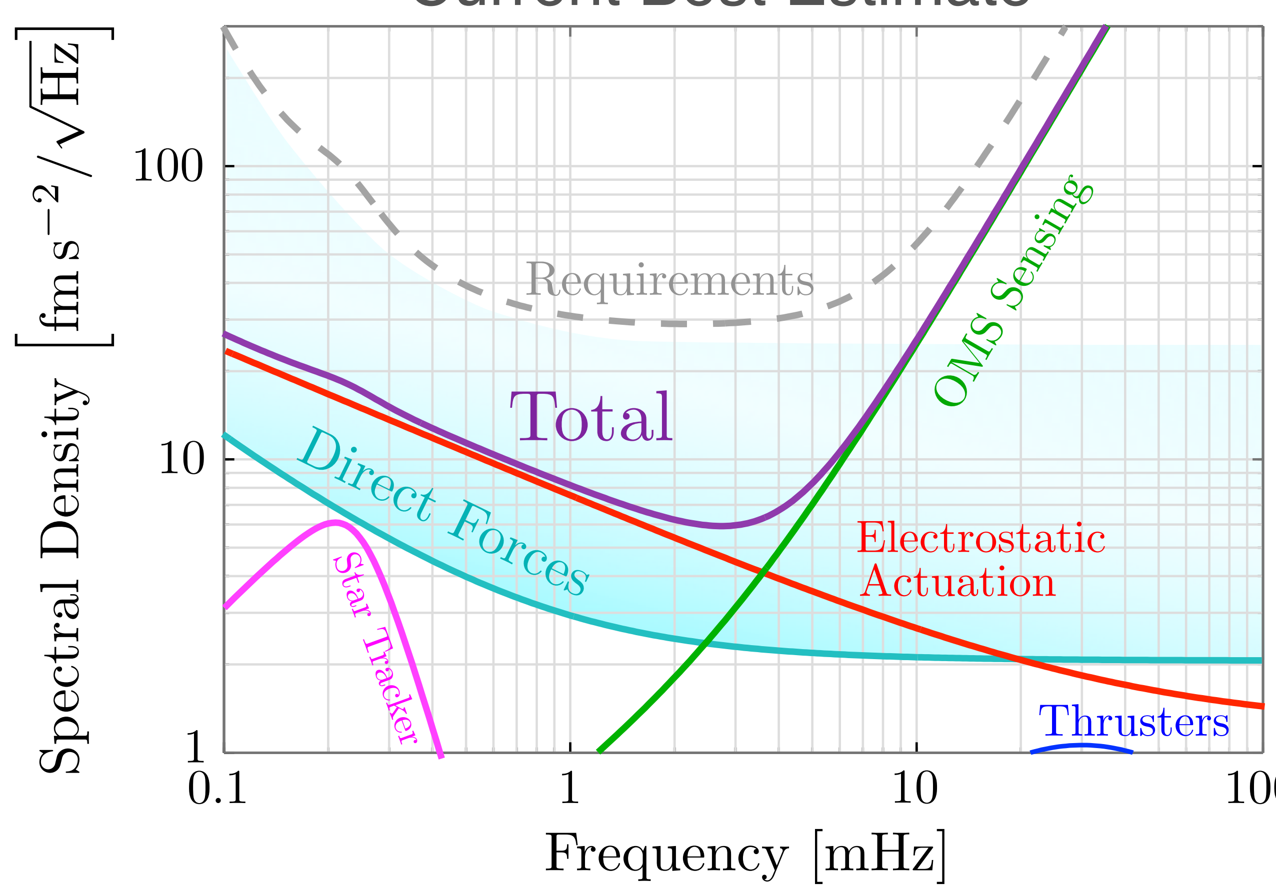
Noise Budget

- How does our observed residual differential acceleration differ from what we expect?
- Why does it differ?
  - this drives the next activities to be performed

Requirements Noise Breakdown



Current Best Estimate



Preparing for operations

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- Mock Data Challenges
  - kick-off development of tools
  - learn about system modelling

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  - more operational like simulations of segments of the science operations timeline

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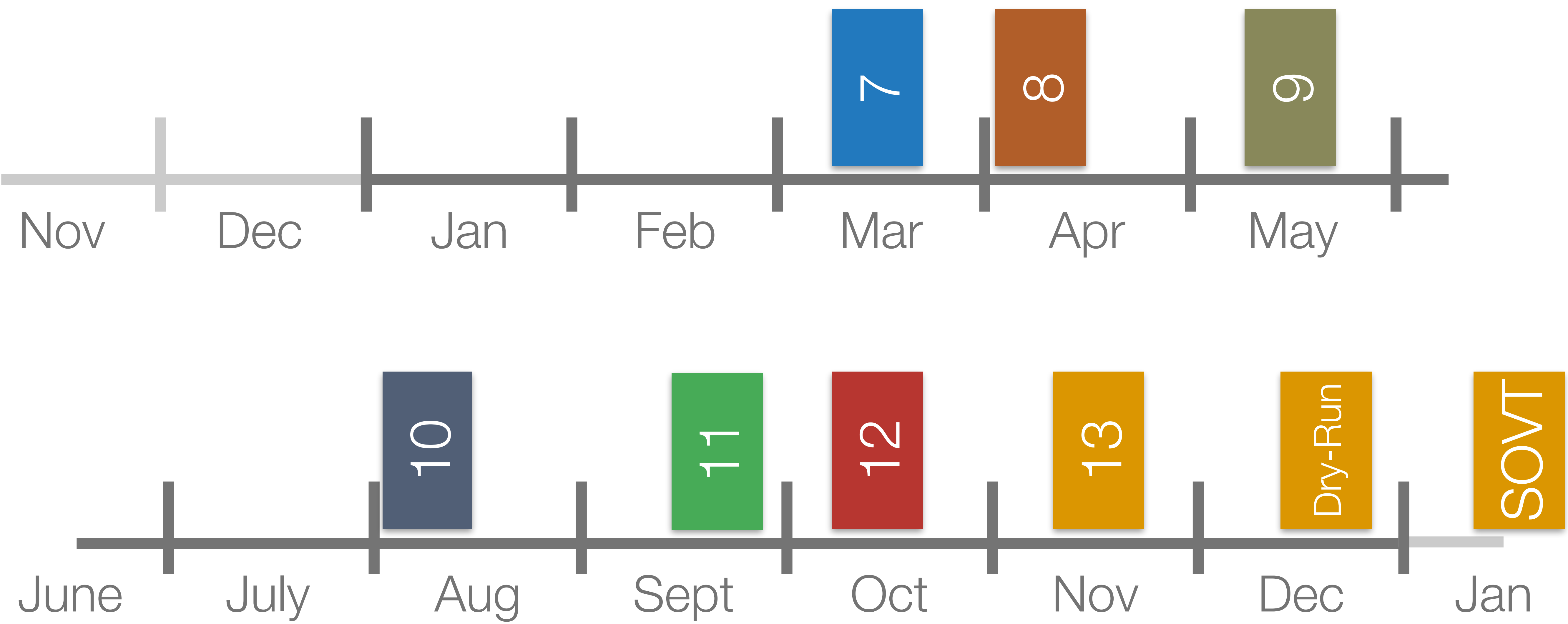
- Mock Data Challenges
  - kick-off development of tools
  - learn about system modelling
- STOC Simulations
  - more operational like simulations of segments of the science operations timeline
- SOVT (System Operations Validation Test)
  - formal ESA test campaign to validate the ground segment
  - Many pre-SOVT runs to prepare for this

Preparing for the SOVT

- We ran 14 pre-SOVT tests
- The first 6 of these were for developing the ground segment, commanding and analysis
- The last 8 have targeted the testing of specific investigations with the aim of covering as much of the mission time-line as we can

Run Calendar



SOVT Environment

- Time-line was executed on the Real-time Test Bed (RTB)
  - includes hardware IS FEE, OBC, DMU
  - SCOEs for dynamics (RTS), OMS, thrusters, etc

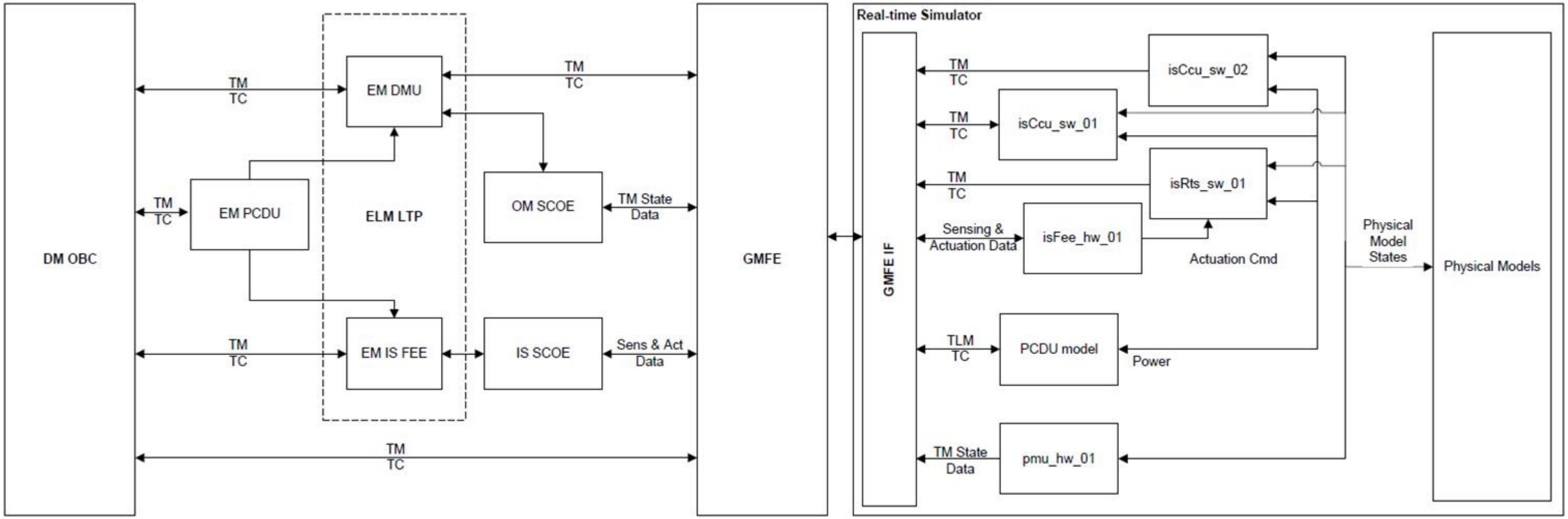


Figure 3-2: Set-up in LTP & AOC RTB configuration

Run Constraints

<table>
<tr><th></th><th>Day 1</th><th>Day 2</th><th>Day 3</th><th>Day 4</th><th>Day 5</th></tr>
<tr><td>0</td><td></td><td rowspan="17">LTP Ops</td><td rowspan="24">LTP Ops</td><td rowspan="15">LTP Ops</td><td rowspan="19">DRS Ops</td></tr>
<tr><td>1</td><td></td></tr>
<tr><td>2</td><td></td></tr>
<tr><td>3</td><td></td></tr>
<tr><td>4</td><td></td></tr>
<tr><td>5</td><td></td></tr>
<tr><td>6</td><td></td></tr>
<tr><td>7</td><td rowspan="3">RTB Powerup & Handover to MOC</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td>10</td><td rowspan="14">LTP Ops</td></tr>
<tr><td>11</td></tr>
<tr><td>12</td></tr>
<tr><td>13</td></tr>
<tr><td>14</td></tr>
<tr><td>15</td><td rowspan="3">Handback to MOC
SCOE Reset
Handover to DRS</td></tr>
<tr><td>16</td></tr>
<tr><td>17</td><td>MOC Maintenance</td></tr>
<tr><td>18</td><td rowspan="6">LTP Ops</td><td rowspan="6">DRS Ops</td></tr>
<tr><td>19</td><td rowspan="2">Handback to Airbus</td></tr>
<tr><td>20</td></tr>
<tr><td>21</td><td></td></tr>
<tr><td>22</td><td></td></tr>
<tr><td>23</td><td></td></tr>
</table>

Day 1

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DOY019: 19/01/15, (08:00 – 08:00)

	07:30	–	09:00	RTB Power up	ASU	[90']
	09:00	–	09:00	Handover to MOC (ACC3)	ASU -> MOC	[0']
	09:00	–	09:14	Load SDM19 (OMS @ 10Hz)	con_00017_load__:V1	[14']
	10:30	–	15:30	Transition from ACC3 to SCI1_2	con_dfa_a3_s12__:V1	[300']
	15:30	–	15:31	Enable Sigma-Delta Loop	con_dfa_sdl_on__:V1	[1']
	15:31	–	16:31	Charge measurement, TM1, inject on theta, 3V at 3mHz with +-+-	inv04014:V001	[60']
	16:31	–	17:31	Charge measurement, TM2, inject on theta, 3V at 3mHz with +-+-	inv04024:V001	[60']
	17:31	–	22:45	Acceleration Noise Measurement	inv00001	[314']
	22:45	–	01:45	Drag-free Injections	inv01101:V001	[180']
	01:45	–	04:45	Suspension Injections	inv01102:V001	[180']
	04:45	–	05:00	Match Stiffness	con_dfa_c1_s12MS:V1	[15']
	05:00	–	06:00	Acceleration Noise Measurement	inv00001	[60']
>	06:00	–	09:00	Suspension Injections	inv01102:V001	[180']

- charge measurement
  - assess initial charge (modelled)
  - tests modulated dc voltages on IS FEE (both)
- system identification
  - allows us to measure representative system delays
  - IS FEE (actuator) gains

Configuration blocks

Investigations

Day 2

DOY020: 20/01/15, (08:00 – 08:00)

	09:00	–	12:20	Swap TMs	con_acc3sci12itm:V1	[200']
	12:20	–	16:00	Acceleration Noise Measurement	inv00001	[220']
	16:00	–	16:50	Go back to Acc 3	con_dfxx_acc3__:V1	[50']
	16:50	–	16:55	Unload SDM19	unknown	[5']
	16:55	–	17:00	Load SDM17 (OMS @ 1Hz)	unknown	[5']
	17:00	–	17:00	Handback to MOC		[0']
	17:00	–	17:00	Transition to Acc3		[0']
	17:00	–	18:00	SCOE Reset		[60']
	18:00	–	18:00	Handback to STOC		[0']
	18:00	–	18:05	Unload SDM17	unknown	[5']
	18:05	–	18:19	Load SDM19	unknown	[14']
	18:19	–	21:34	Acceleration Noise Measurement in Acc3	inv00001	[195']
	21:34	–	03:34	Transition back to Sci 1.2	con_acc3_sci12__:V1	[360']
	03:34	–	03:35	Enable Sigma-Delta Loop	con_dfa_sdl_on__:V1	[1']
	03:35	–	07:35	phi1 guidance injections	inv01168:V002	[240']
>	07:35	–	11:35	phi2 guidance injections	inv01174:V002	[240']

- Swap TMs
  - x-axis actuation on 1st test mass
  - noise of TM1 IS FEE
- Acc 3 noise run
  - wide range noise of IS FEEs
- phi guidance injections
  - delays and gains on other degrees of freedom
  - IS FEE cross-talk

Teams

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- We had two teams of 4 taking shifts
- Additional personnel in STOC
  - Operations Scientist
  - Project Scientist
  - LTPDA Manager
  - LTPDA Developer
  - Additional local DA support
- External support
  - supporting teams at main LPF institutions

SOVT photos

Life in the PISA room

Conclusions of SOVT

- Ground segment aspects worked well
  - operational environment was suitable
  - interactions worked well (various daily telecons)
  - data flow performed as expected
  - analysis tools works as expected
- Science results
  - difficult to extract much ‘science’ from the tests on the hardware
    - glitches, test environment instabilities leading to restarts
  - validation of a (compressed) section of mission timeline

Leading up to launch

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- Further operations simulations
  - full-scale STOC Simulation (~10 days)
  - MOC simulations (2 or 3 on the science ops)
  - Training: tools, operations
- Data Analysis
  - Preparation of:
    - investigations
    - pipelines
    - analysis procedures
- Observation of tests
  - Space-craft closed-loop tests
  - Short functional tests of sub-systems (in particular OMS)
  - System Validation Tests (run by MOC)

Summary

- We have about 172 days to go to launch
- Commissioning starts around beginning of December (~60 days after launch)
- LTP Operations should start in mid-December (~2 weeks after commissioning)
- LTP Operations will end around end of March (after about 90 days of science operations)

Thank you