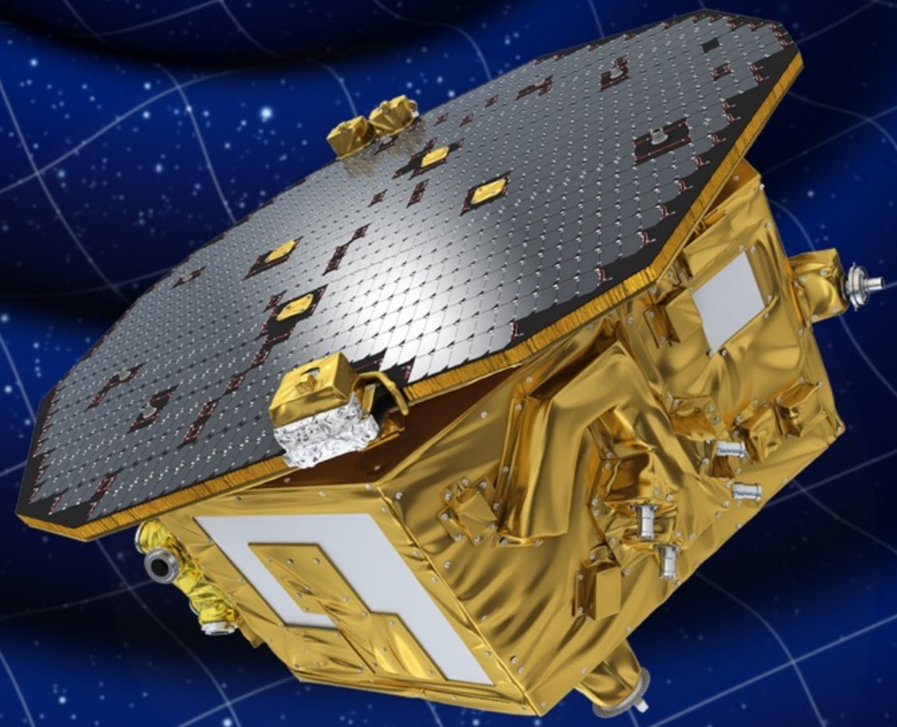
lisa pathfinder

FIRST STEPS TO OBSERVING
GRAVITATIONAL WAVES FROM SPACE

LISA Pathfinder



Paul McNamara on behalf of the LPF collaboration
LISA Pathfinder Project Scientist
European Space Agency

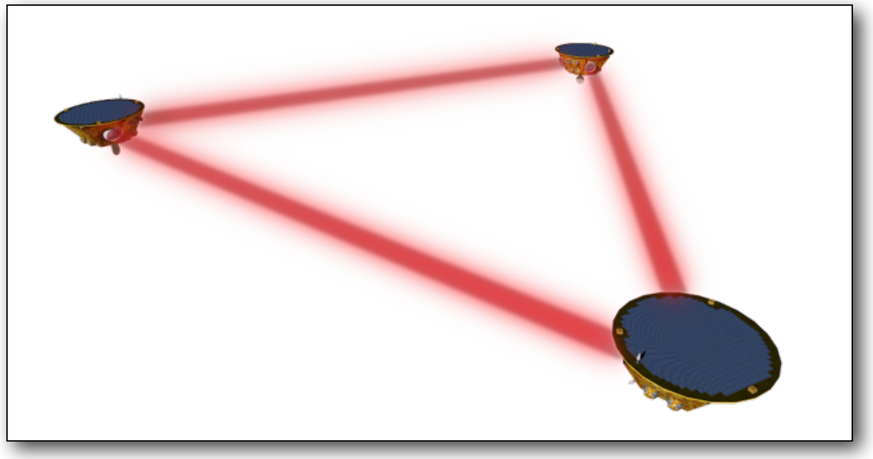
LISA Pathfinder

- LISA Pathfinder was selected by ESA to test the critical technologies for LISA which cannot be tested on the ground
  - Arm shrunk from million km to 10's cm
    - Gives up sensitivity to gravitational waves
    - Maintains (and worsens) instrument noise

- LISA Pathfinder was launched on 3 December 2015
  - Science Operations began in 1 March 2016
  - Science Operations ended on 30 June 2017
    - Last telecommand will be sent at 18:00UTC on 18 July

- Performance has far exceeded our most optimistic (pre-launch) expectations
  - We have demonstrated the full LISA performance over the LISA measurement bandwidth *goal*

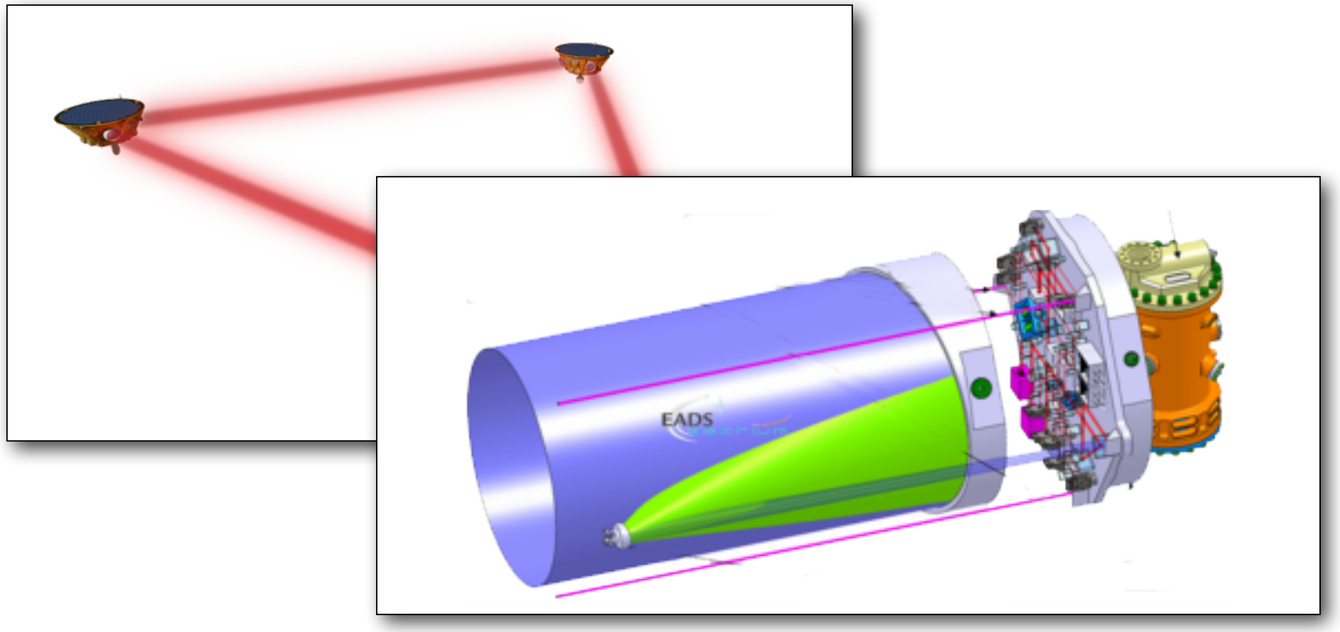
LISA to LISA Pathfinder



LISA:

- 3 spacecraft, separated by ~million km
- Role of each spacecraft is to protect the fiducial test masses from external forces

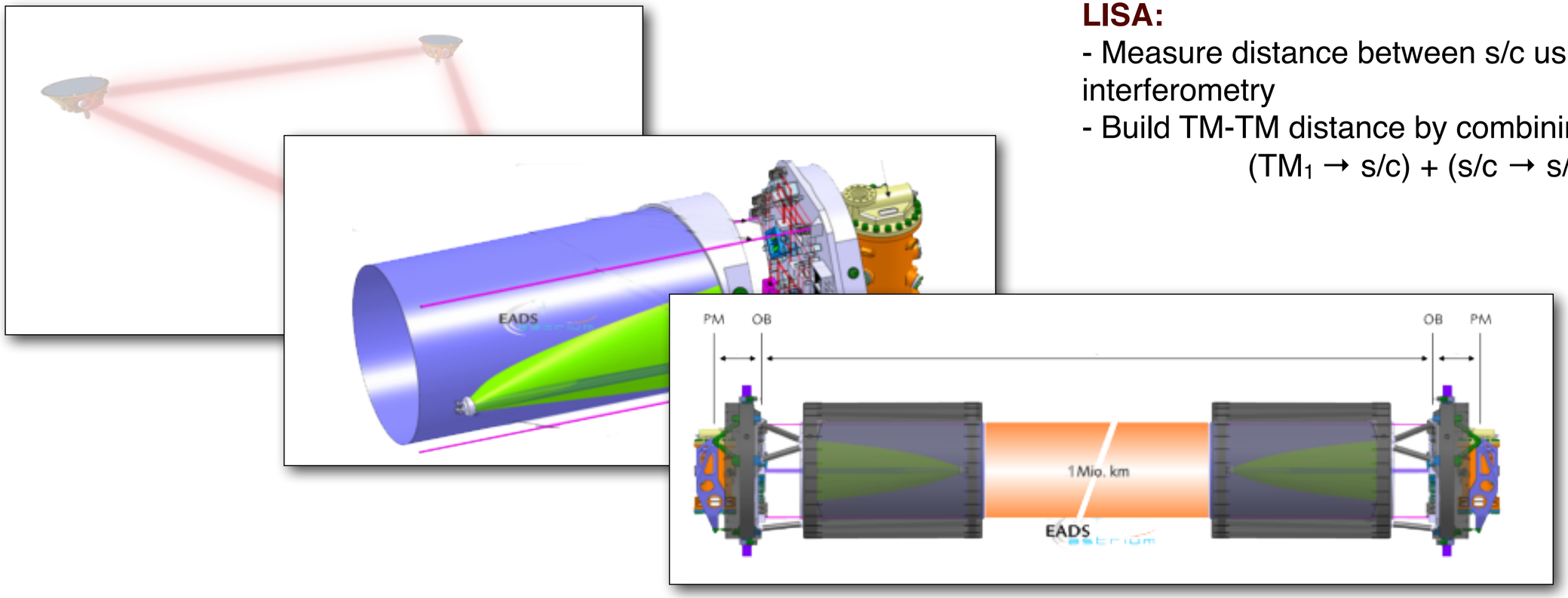
LISA to LISA Pathfinder



LISA:

- Locally measure distance from TM to s/c using:
  - Laser interferometry along sensitive axis (between s/c)
  - Capacitive sensing on orthogonal axes
- TM displacement measurements are used as input to DFACS which controls position and attitude of s/c with respect to the TM

LISA to LISA Pathfinder

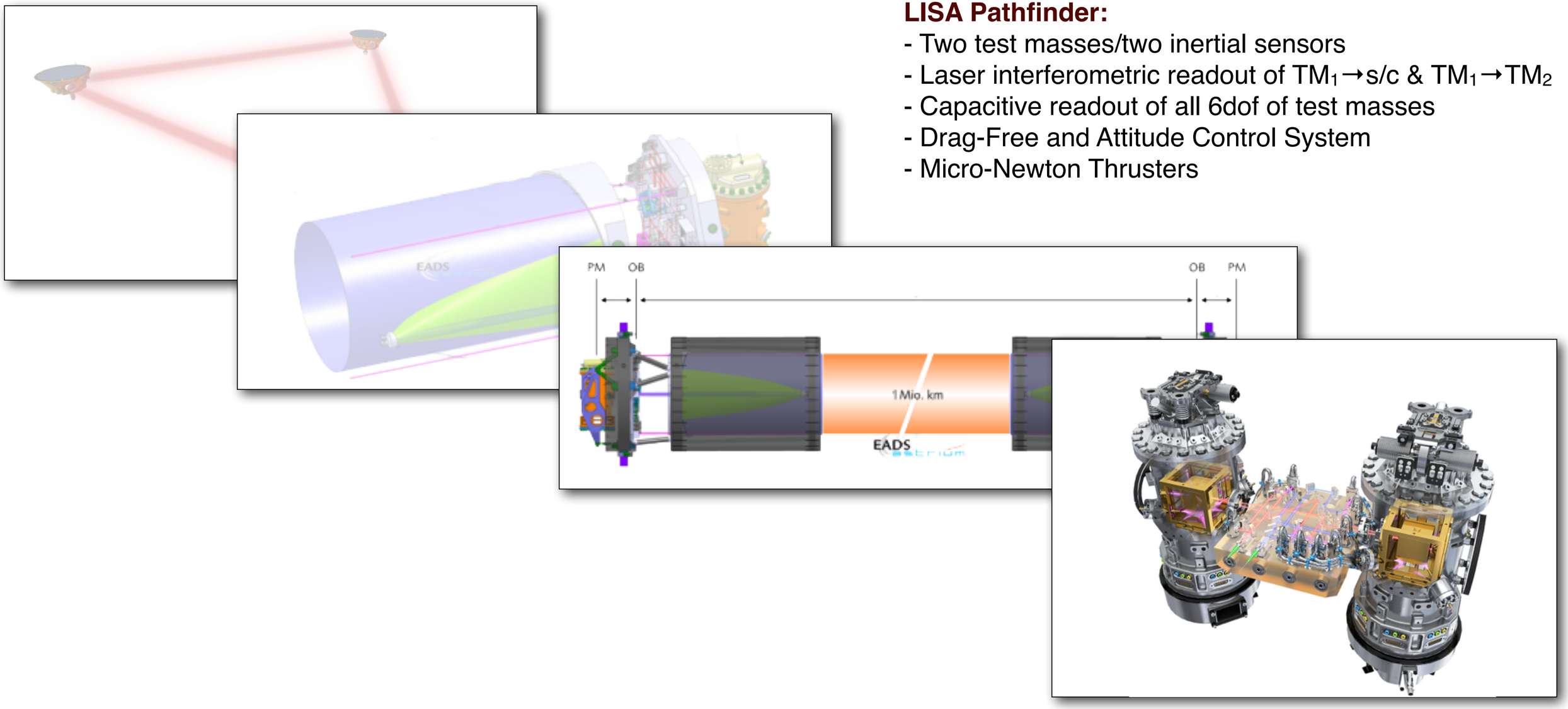


LISA:

- Measure distance between s/c using laser interferometry
- Build TM-TM distance by combining:

$$(TM_1 \rightarrow s/c) + (s/c \rightarrow s/c) + (s/c \rightarrow TM_2)$$

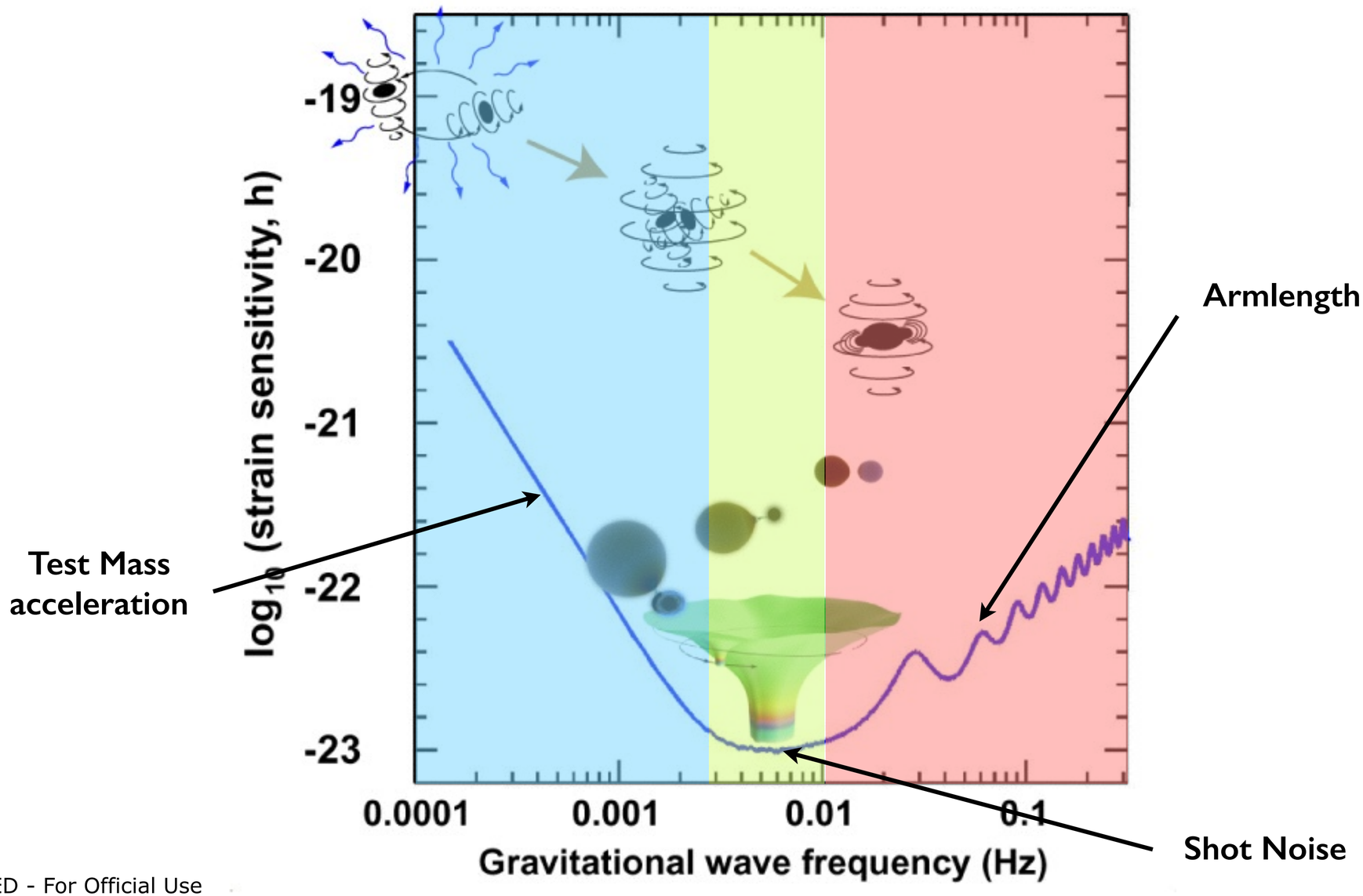
LISA to LISA Pathfinder



LISA Pathfinder:

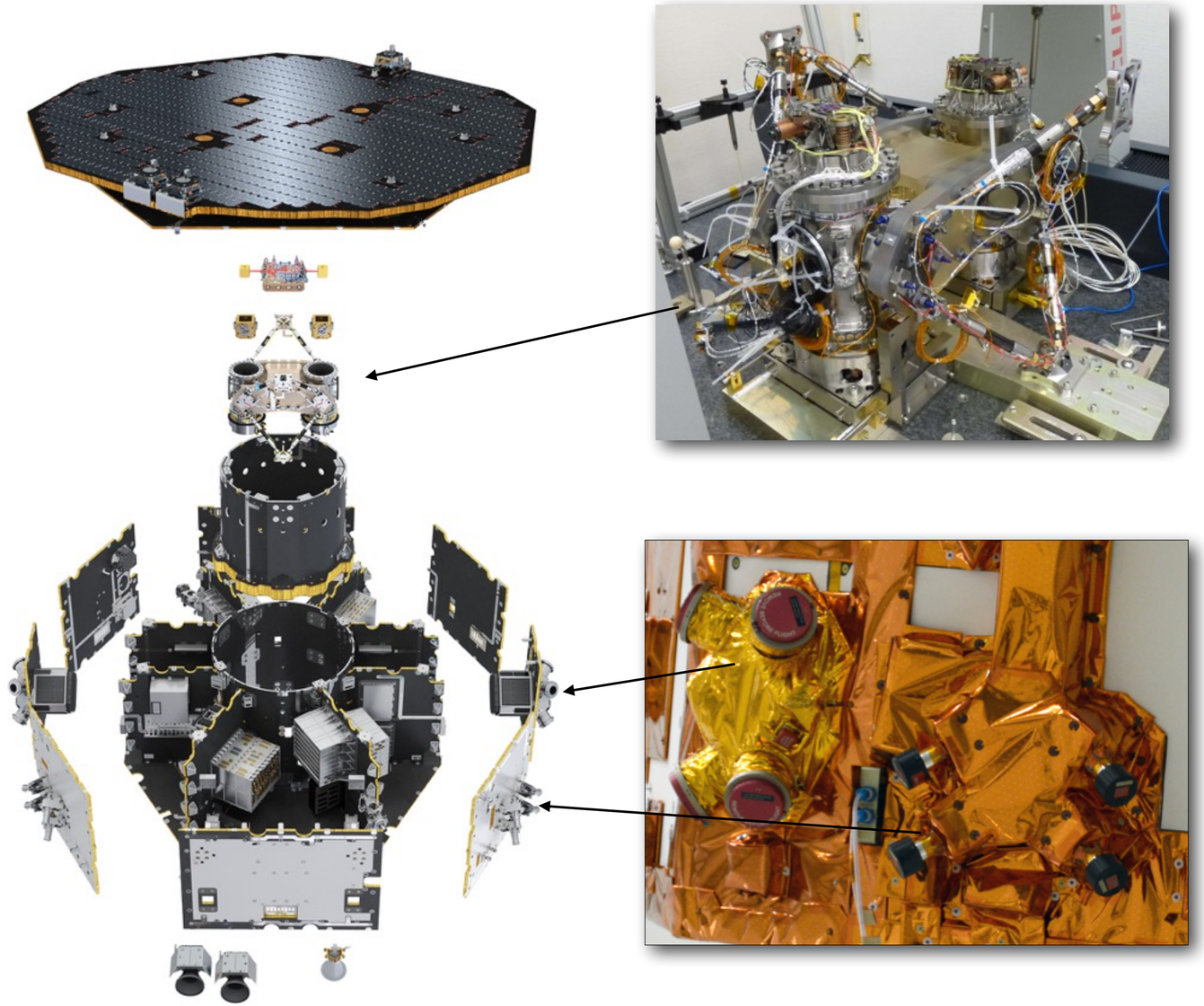
- Two test masses/two inertial sensors
- Laser interferometric readout of $TM_1 \rightarrow s/c$ & $TM_1 \rightarrow TM_2$
- Capacitive readout of all 6dof of test masses
- Drag-Free and Attitude Control System
- Micro-Newton Thrusters

LISA Sensitivity Curve



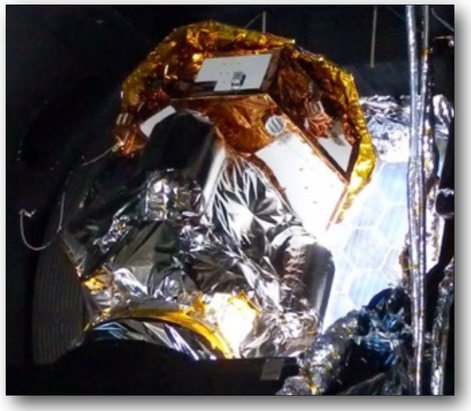
LISA Pathfinder

- LISA Pathfinder consists of:
  - **Spacecraft**
    - Provided by ESA
      - Industrial Prime Contractor: Airbus DS (UK)
    - s/c also includes the drag free control software and micro-Newton thrusters
  - **Payloads**
    - **The LISA Technology Package (LTP)**
      - Provided by European member states and ESA
      - Consists of inertial sensors, interferometric readout, payload computer and diagnostic subsystem
    - **The Disturbance Reduction System (DRS)**
      - Provided by NASA/JPL
      - Consists of processor running drag-free control software and micro-Newton thrusters



Constraints in going to space…

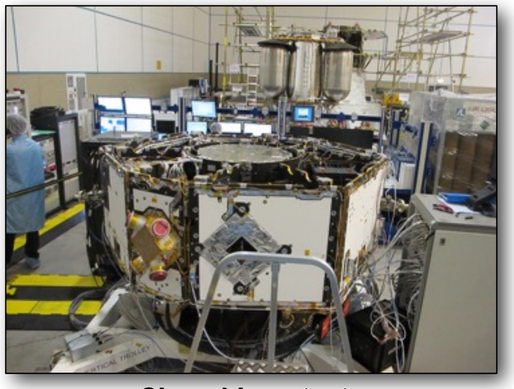
- Vibration
  - During launch we subject our very delicate s/c to ~141dB of white noise
    - This is similar to a jumbo jet taking off
- Thermal
  - Payload temperature range: 0C to +40C
  - Solar array temp range: -130C to +130C
- Radiation
  - Radiation-hard components are not state-of-the-art!
    - On-board computer clock speed = 22.5MHz
- Communications
  - Ground contact = 8 hours/day with 56kbps link
    - ~200MB of data per day maximum from s/c
    - Similar to 1990's dial-up modems



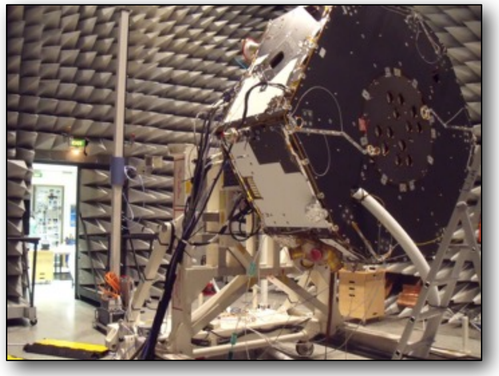
“Commissioning” of LPF

- The (LIGO-like) commissioning of a space mission happens before launch
  - On orbit commissioning of LPF was a functional check-out of equipment

Vibration/shock tests



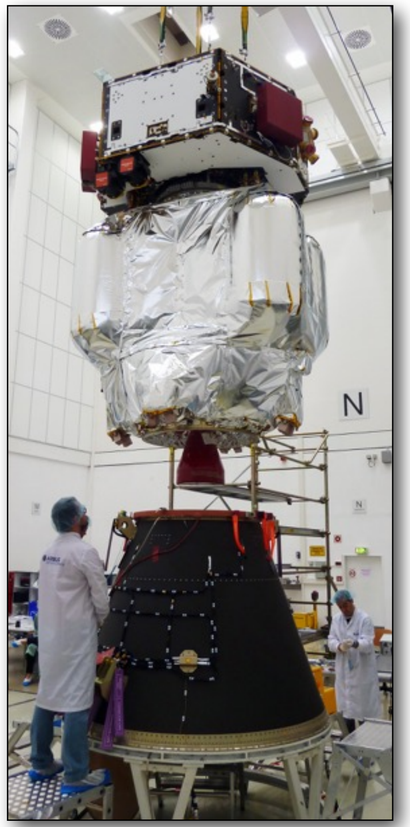
Closed-loop tests



EMC

On-Station Thermal Test

Transfer Orbit Thermal Test



Launch Vehicle Fit Check

Credit: Airbus Defence and Space and IABG

Preparing for launch…

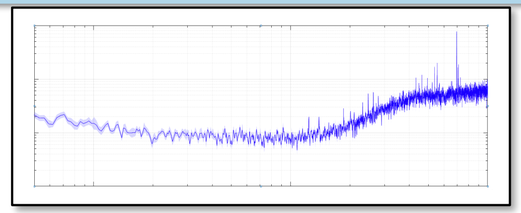
LISA Pathfinder Launch

LISA Pathfinder was launched on 3/12/2015 at 04:04UTC

En-route to L1

- Orbit raised via 6 apogee raising manoeuvres
- Transfer to Lagrange Point (L1) took ~50 days
- Separation of propulsion module on 2 February
- Final Orbit:
  - 500,000km x 800,000km around L1
  - Orbital Period of 6 months

A orbiting physics lab



Analysis Products

Experiment Planning

Investigation description

Data Analysis

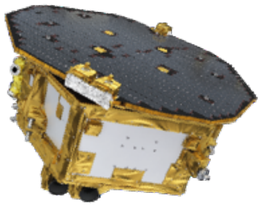
Telemetry (Analysis Objects)

STOC (Science Operations)

Simulator

Telemetry (ascii)

Telemetry (Packets)



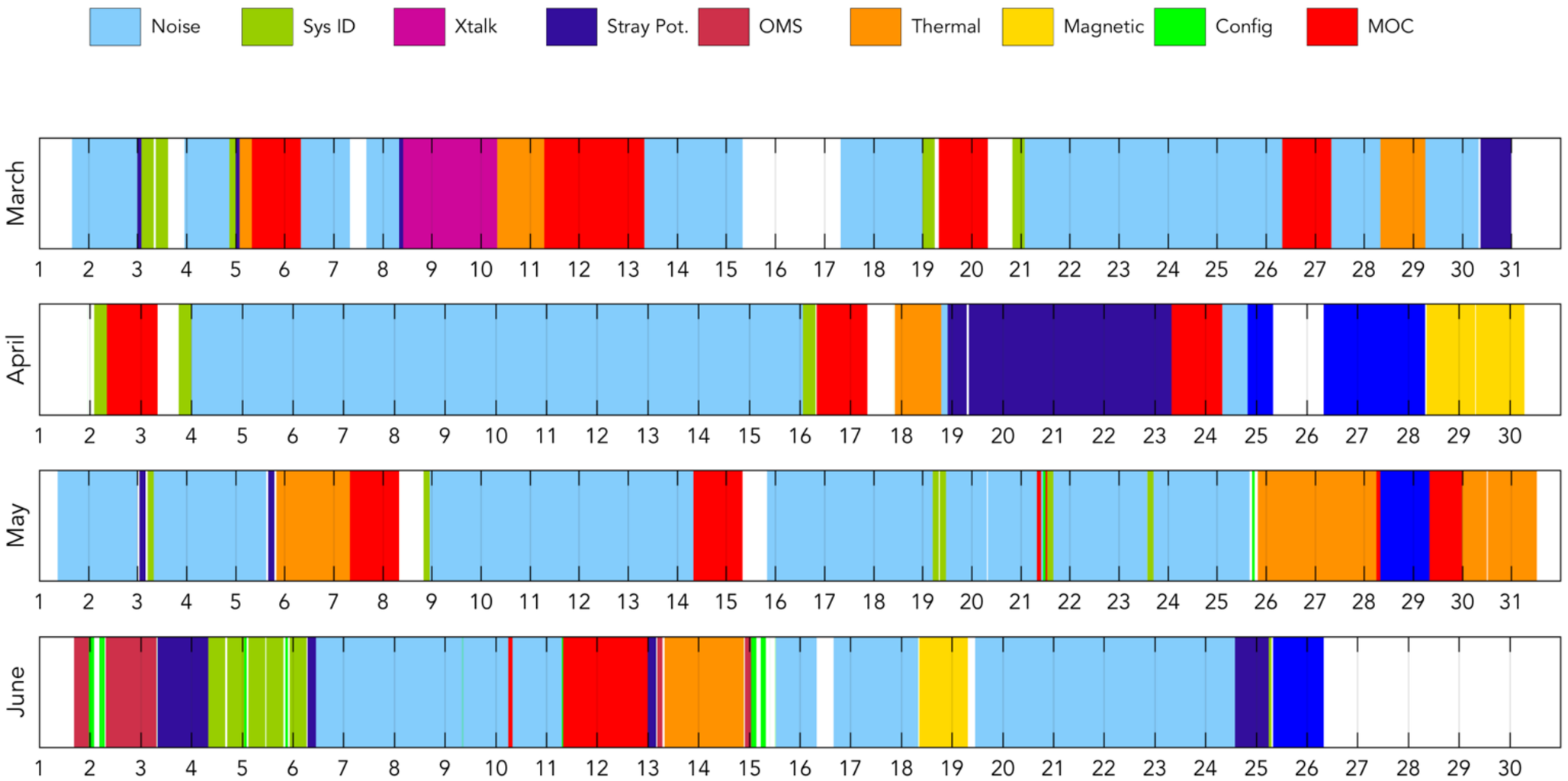
Location: unknown

08:00	–	11:00	New SysID - Drag-free injections- UURLA	inv01101:v003	[180']
11:00	–	16:00	New SysID - Suspension injections - UURLA	inv01102:v006	[300']
16:00	–	17:00	Change Max Authority to default (2200pN)	con_fee_maxf_dft:V001	[60']
17:00	–	20:00	New SysID - Drag Free injections	inv01101:V003	[180']
20:00	–	01:00	New SysID - Suspension Injections	inv01102:V006	[300']
01:00	–	02:00	Transition to CST1: SCI12 with matched stiffness	con_dfa_c1_s12MS:V004	[60']
02:00	–	02:30	Set matched force authority to 5nN on TM1x and TM2x	con_fee_maxf____:V024	[30']
02:30	–	05:30	New SysID - Drag Free injections	inv01101:V003	[180']
05:30	–	10:30	New SysID - Suspension Injections	inv01102:V006	[300']

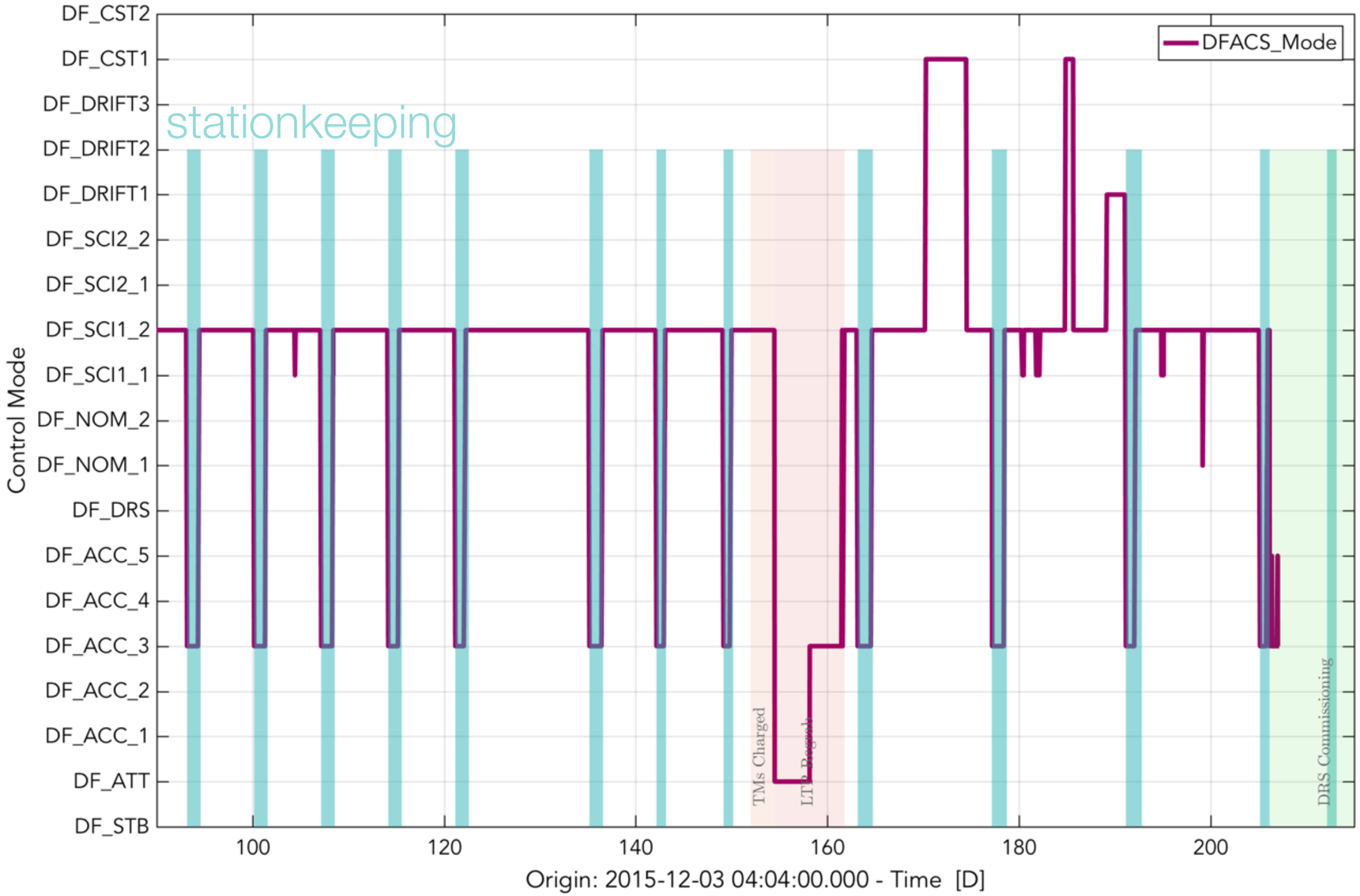
```
repoplist = plist(...
    'hostname', 'lpsdas03.esac.esa.int', ...
    'username', my_pass.username,...
    'password', my_pass.password,...
    'database', 'Models');
my_model = collection(repoplist.pset('UUID', '3f40d9dc-1a41-4df3-a49a-79a9d76abeeb'));

% Define the plist for the pipeStep 'BuildModel'
model_name = my_model.name;
pl = plist('based on', my_model, 'name', model_name);

% Build the model
outModel = pipe.runStep('BuildModel', pl);

%% #10 Evaluate the model

pl = plist('function name', model_name, 'input objects', delta_g_x_params);
delta_g_x = pipe.runStep('EvaluateFunctionHandle', pl);
delta_g_x = delta_g_x(1).unpack();

% LPF Product name
delta_g_x.setName(LPFProduct.Delta_g_x)
delta_g_x.setDescription(LPFProduct.Delta_g_x.description)

% split time-series
plsplit = plist('offsets',[13 -13]);
delta_g_x_split = split(delta_g_x,plsplit);
delta_g_x_noninertial_old_split=split(delta_g_x_noninertial_old,plsplit);
delta_g_x_corrected_old_split=split(delta_g_x_corrected_old,plsplit);

% Simplify y units
delta_g_x_split.simplifyYunits;
delta_g_x_noninertial_old_split.simplifyYunits;
delta_g_x_corrected_old_split.simplifyYunits;
```

```
# Exported Parameter(s) from GRAINS
# Parameter List:
ADT20027 [LPFFLIGHT],ADT20028 [LPFFLIGHT],ADT20029 [LPFFLIGHT],ADT20030 [LPFFLIGHT],ADT20031 [LPFFLIGHT],ADT20032 [LPFFLIGHT]
# Time Window Start (Time Date):
2016-02-15 07:50:00.000
# Time Window End (Time Date):
2016-02-15 08:40:00.000
# Number of samples (per parameter and total):
32932,32932,32932,32932,32932,32932,197592
# Number of parameters:
6
# Name,Unit,Description,Data,Type,Max,Min,Avg,StdDev
ADT20027,m,DFA_PreProcSen_IsTm2X,DOUBLE,0.001495,-0.000220,0.000074,0.000235
ADT20028,m,DFA_PreProcSen_IsTm2Y,DOUBLE,0.000090,-0.001427,-0.000148,0.000386
ADT20029,m,DFA_PreProcSen_IsTm2Z,DOUBLE,0.000156,-0.002045,-0.000268,0.000554
ADT20030,rad,DFA_PreProcSen_IsTm2The,DOUBLE,0.050149,-0.002056,0.005894,0.014172
ADT20031,rad,DFA_PreProcSen_IsTm2Eta,DOUBLE,0.062785,-0.019259,0.004498,0.014394
ADT20032,rad,DFA_PreProcSen_IsTm2Phi,DOUBLE,0.003265,-0.011945,-0.000568,0.002453
# DATE TIME,ADT20027 [LPFFLIGHT],ADT20028 [LPFFLIGHT],ADT20029 [LPFFLIGHT],ADT20030 [LPFFLIGHT],ADT20031 [LPFFLIGHT],ADT20032 [LPFFLIGHT]
2016-02-15 07:50:00.055,0.0000002886423532,0.0000020883333934,0.0000002126240847,0.0000597788274689,0.0001205437170791,0.0000155399880855

2016-02-15 07:50:00.155,0.0000003114992799,0.0000020853859780,0.0000002183940425,0.0000588061967621,0.0001221921795753,0.0000154500754396

2016-02-15 07:50:00.255,0.0000002960652209,0.0000020866839236,0.0000002165005898,0.0000599574523458,0.0001199095090284,0.0000155952905377

2016-02-15 07:50:00.355,0.0000003062980717,0.0000020849401465,0.0000002058469204,0.0000595608294568,0.0001208609669671,0.0000146788532040

2016-02-15 07:50:00.455,0.0000002966593030,0.0000020958925867,0.0000002125821951,0.0000580584044225,0.0001226996277295,0.0000155443773513

2016-02-15 07:50:00.555,0.0000002920754037,0.0000020836164240,0.0000002077753853,0.0000581938559341,0.0001206072720685,0.0000156443226110

2016-02-15 07:50:00.655,0.0000002909898301,0.0000020942378356,0.0000001980862259,0.0000581651233178,0.0001221293831571,0.0000163608694573

2016-02-15 07:50:00.755,0.0000002801012081,0.0000020993293711,0.0000001894069252,0.0000585640263125,0.0001206712354359,0.0000159963256665

2016-02-15 07:50:00.852,0.0000002915256912,0.0000020976463257,0.0000002000509882,0.0000585269332744,0.0001199734140114,0.0000161050494455

2016-02-15 07:50:00.855,0.0000002915256912,0.0000020976463257,0.0000002000509882,0.0000585269332744,0.0001199734140114,0.0000161050494455

2016-02-15 07:50:00.955,0.0000002932433912,0.0000020819245226,0.0000002029286985,0.0000580848569138,0.0001214317367407,0.0000159523098831
```

Nominal Phase



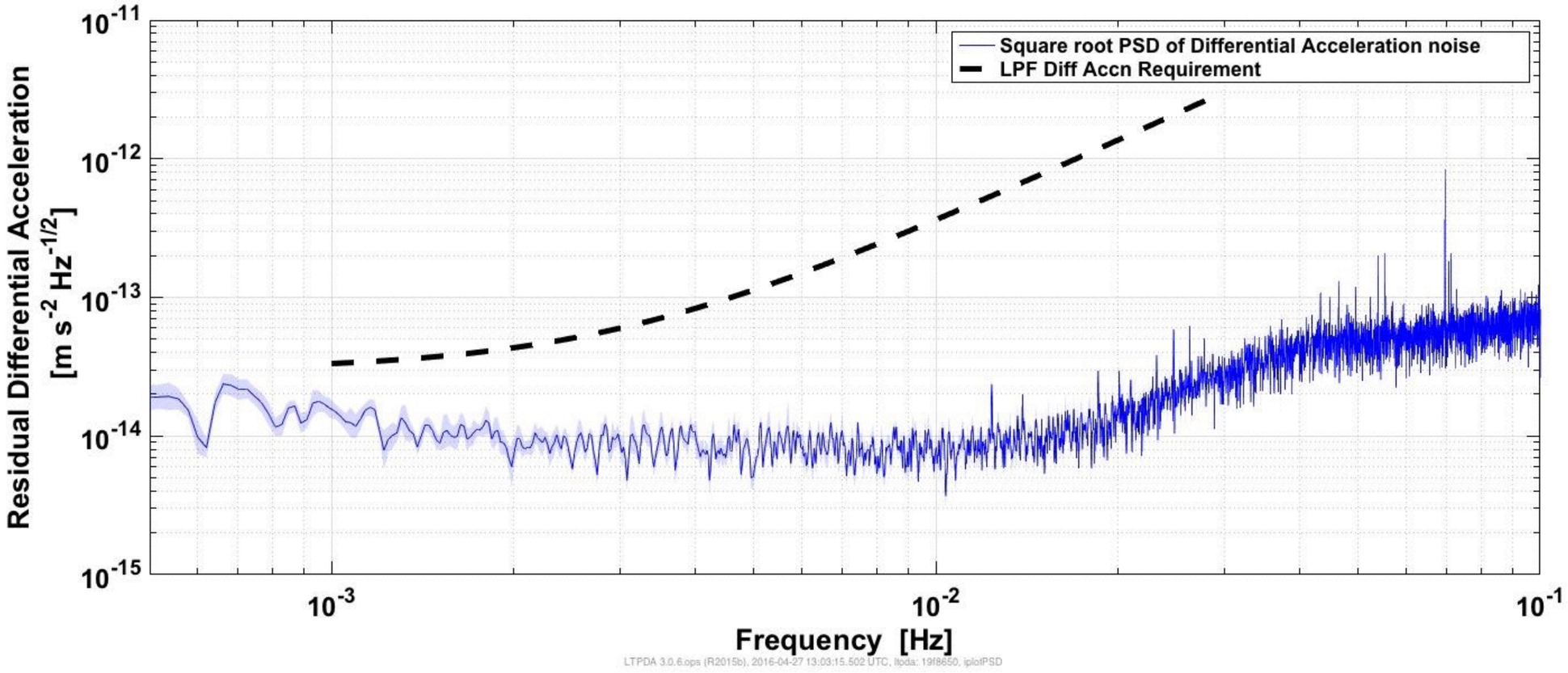
Duty Cycle during nominal science phase



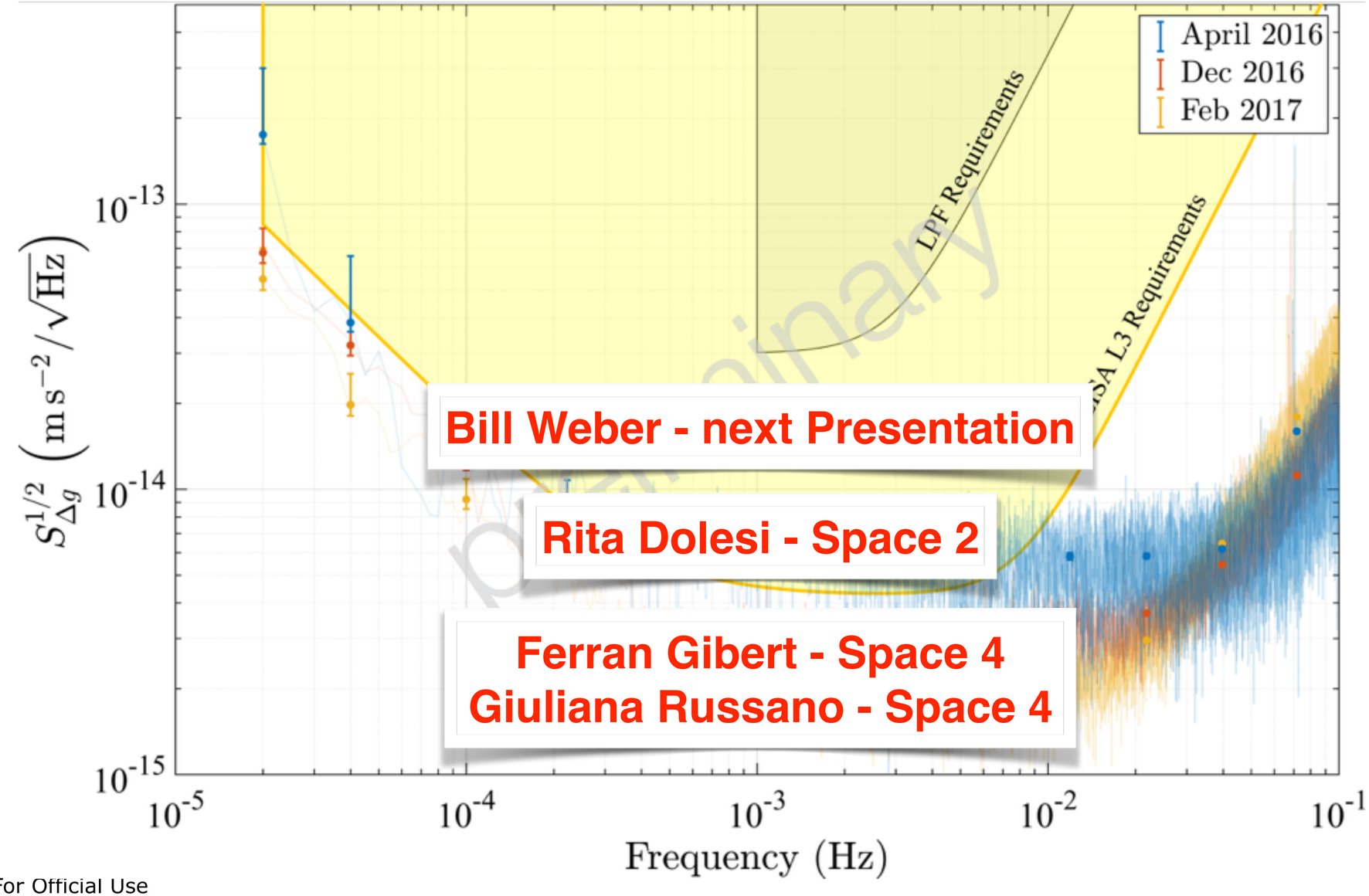
Differential Acceleration

- The differential acceleration between the test masses (known as “delta-g”) is the primary performance requirement of the mission…

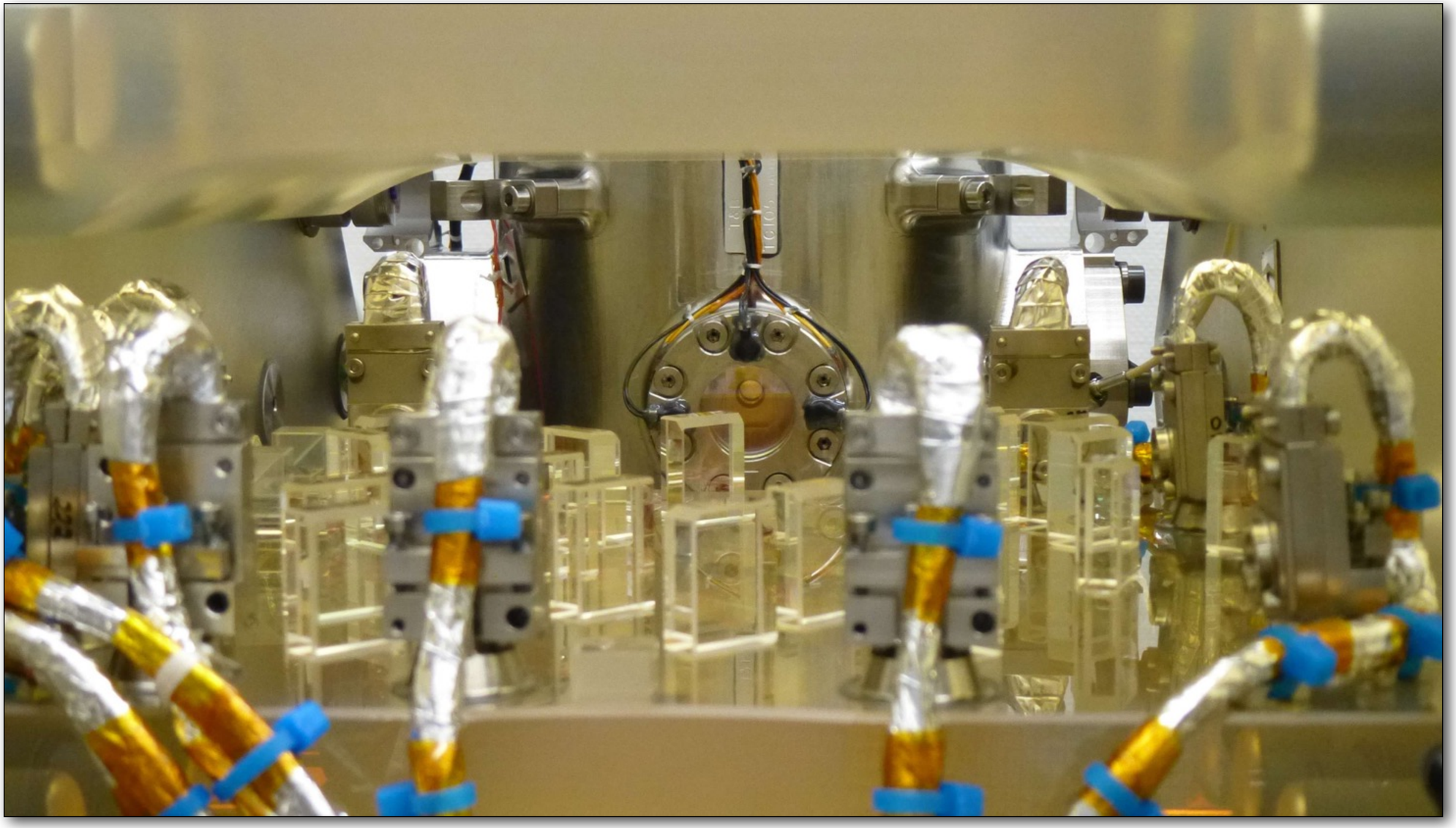
  …and was met during commissioning!



Latest performance...it keeps improving!

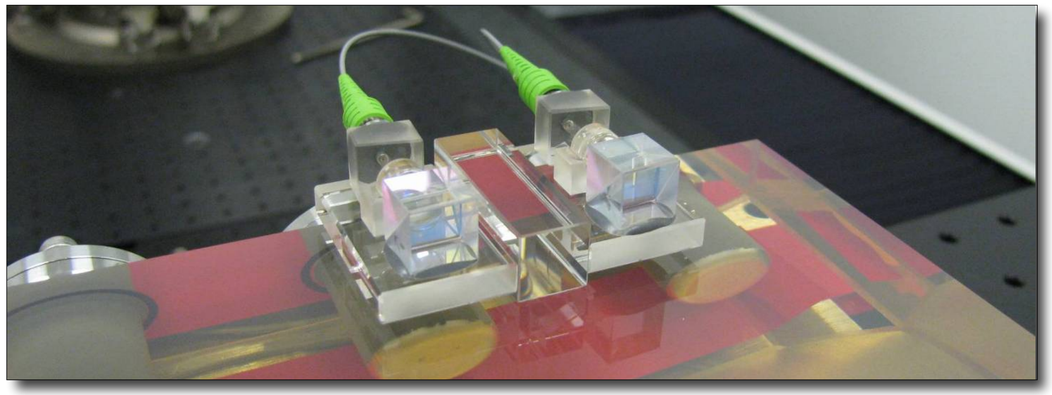


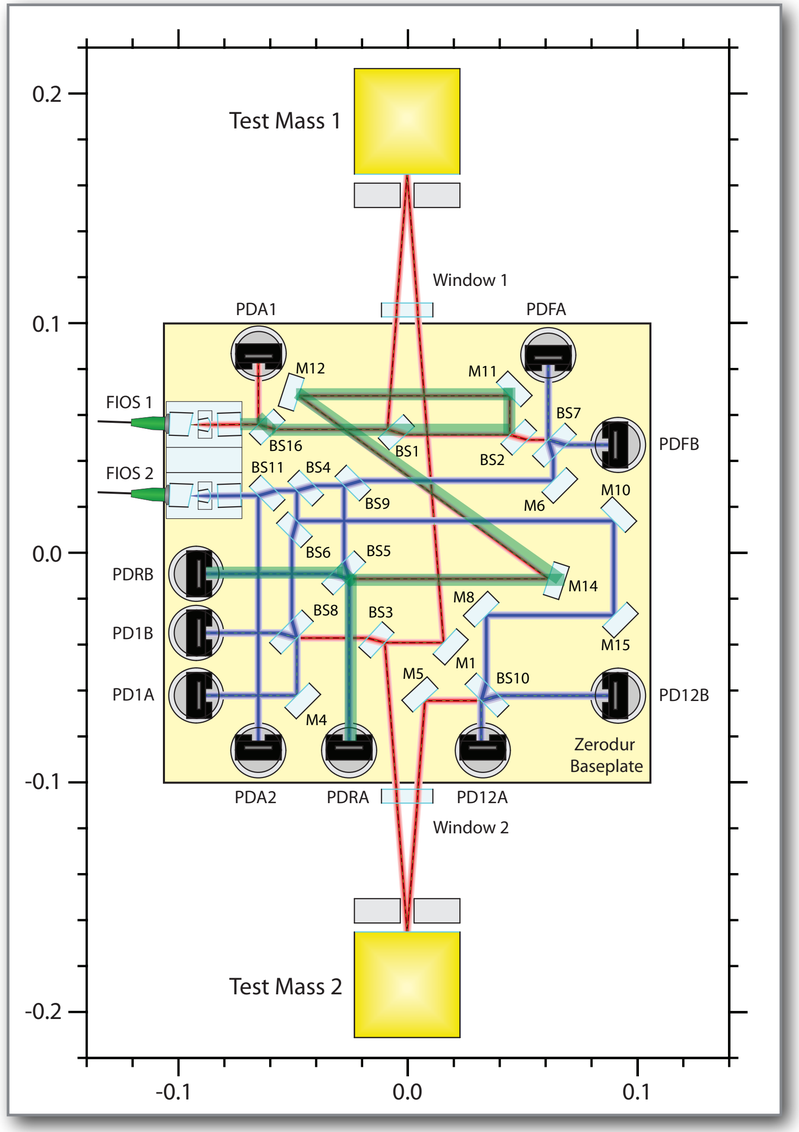
Optical Metrology System



Beam alignment (from ground to space)

- One major worry was OMS alignment change from ground to space
- Any distortion of the optical bench shows up as large misalignment due to lever arm of optical path on bench
- Optical bench alignment can be measured using the fixed interferometers
  - Reference ifo measurement beam is most sensitive to bench distortion





Alignment from ground to space

Measurement Beam

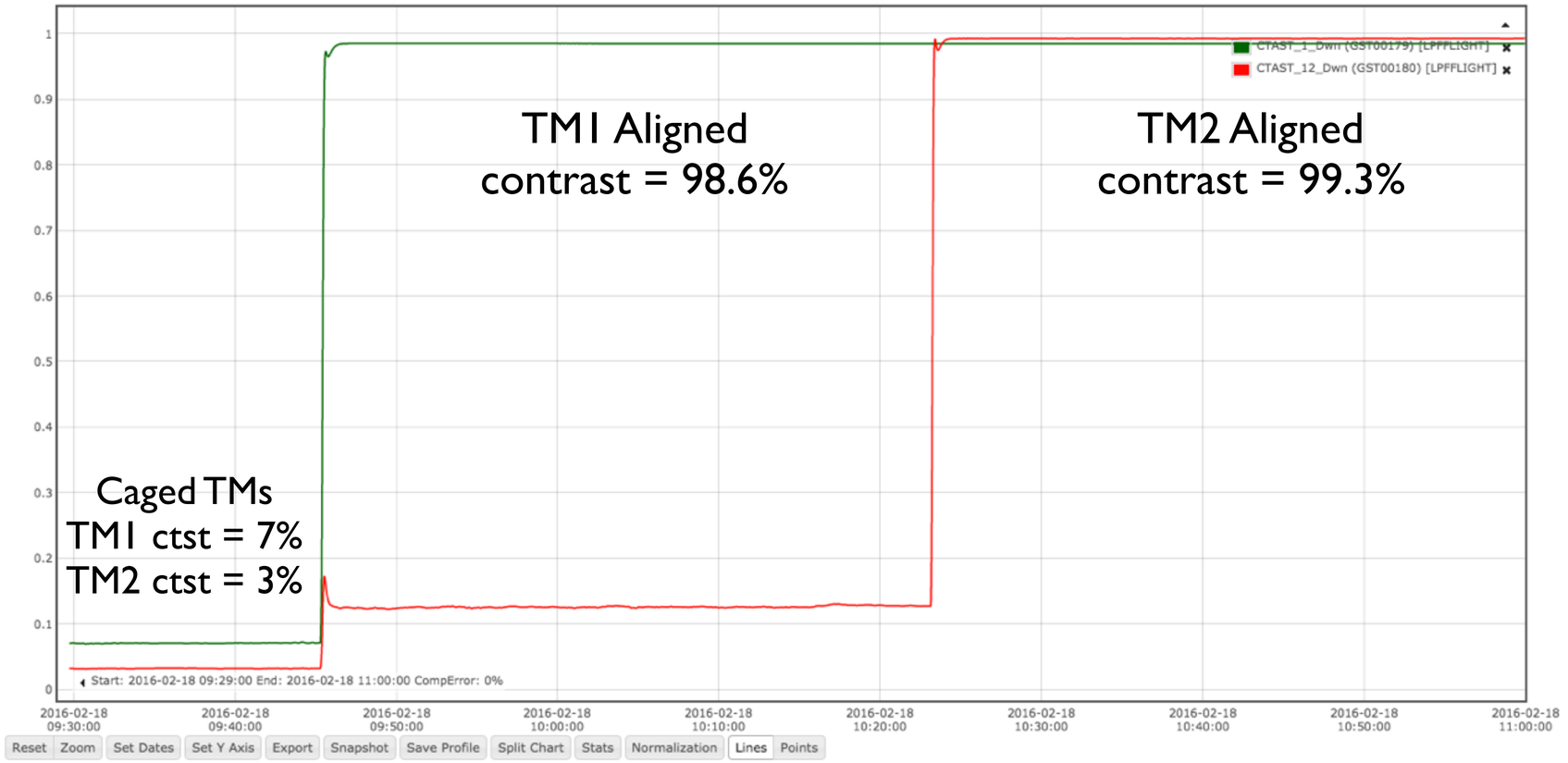
[um]			Flight	IABG	UGL	Flight - UGL	IABG - UGL	Flight - IABG
X1	A	x	34	35				-1
		y	-353	-343				-10
	B	x	13	13				0
		y	-350	-336				-14
X12	A	x	80	84				-4
		y	-389	-400				11
	B	x	-74	-76				2
		y	-390	-394				4
XF	A	x	21	21	21	0	0	0
		y	-40	-35	-32	-8	-3	-5
	B	x	13	9	6	7	3	4
		y	-25	-20	-15	-10	-5	-5
XR	A	x	7	9	6	1	3	-2
		y	-29	-15	-6	-23	-9	-14
	B	x	43	36	35	8	1	7
		y	70	79	83	-13	-4	-9

Reference Beam

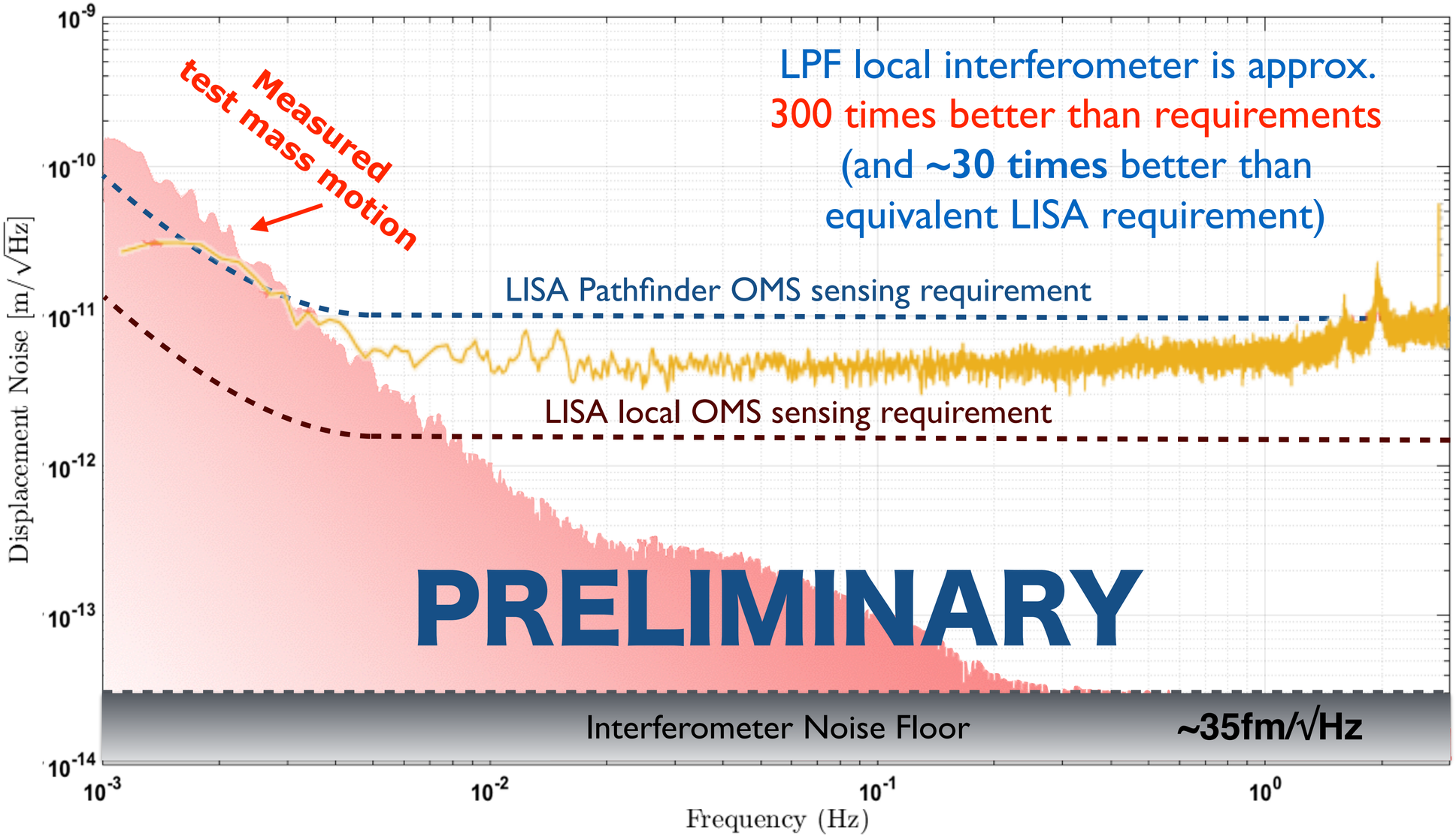
[um]			Flight	IABG	UGL	Flight - UGL	IABG - UGL	Flight - IABG
X1	A	x	12	18				-6
		y	-3	-7				4
	B	x	-5	-4				-1
		y	-9	-16				7
X12	A	x	18	13				5
		y	-23	-23				0
	B	x	8	11				-3
		y	16	16				0
XF	A	x	26	19	21	5	-2	7
		y	-35	-35	-29	-6	-6	0
	B	x	7	11	8	-1	3	-4
		y	-19	-20	-13	-6	-7	1
XR	A	x	-8	-11	-13	5	2	3
		y	-10	-12	-6	-4	-6	2
	B	x	60	59	58	2	1	1
		y	89	83	89	0	-6	6

Interferometer alignment

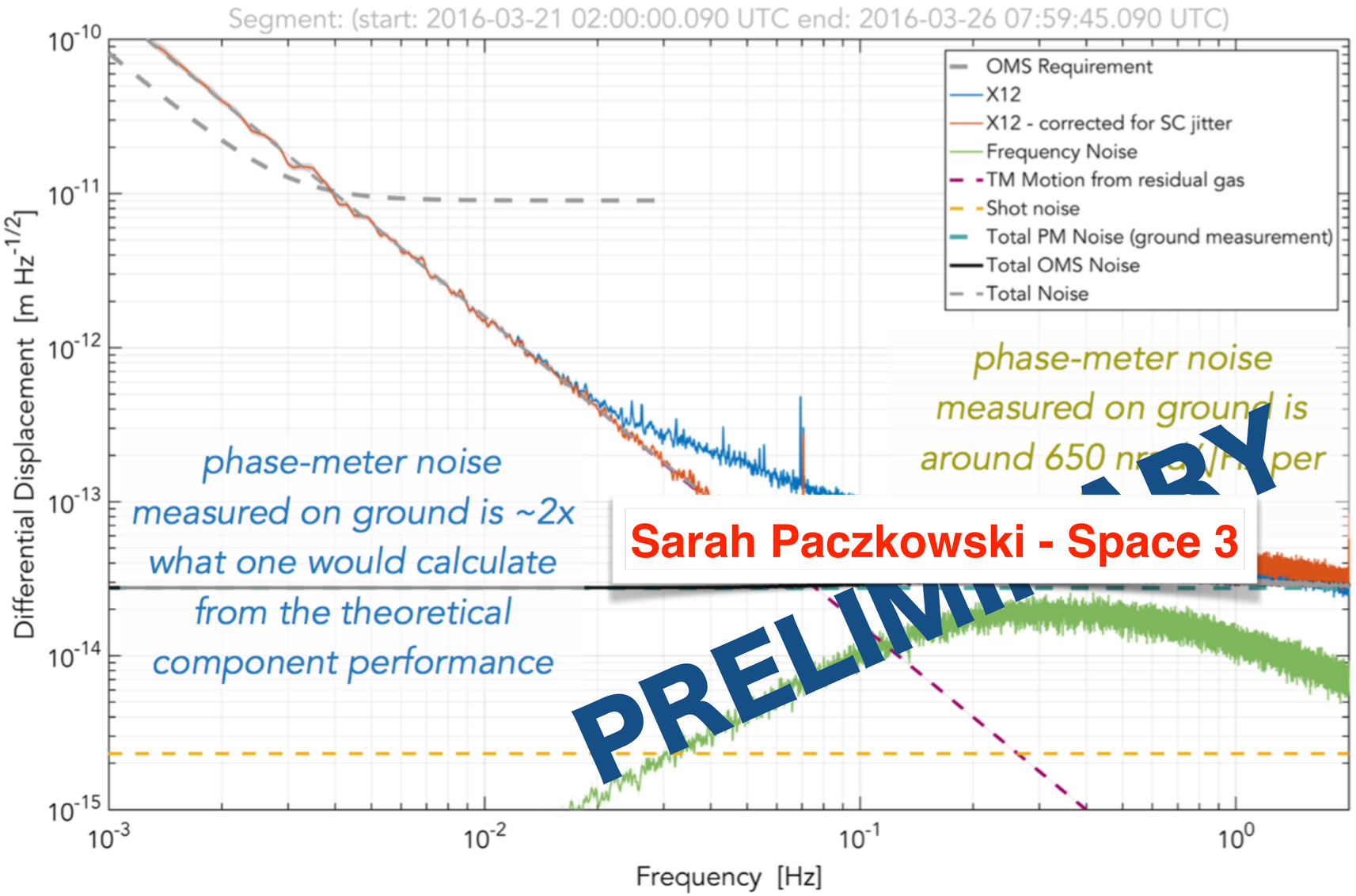
- Following TM release, we could align the free-floating test masses using the electrostatic actuation
  - Contrast increased from ~few % to close to 100%
    - Best ground measured alignment was ~92%



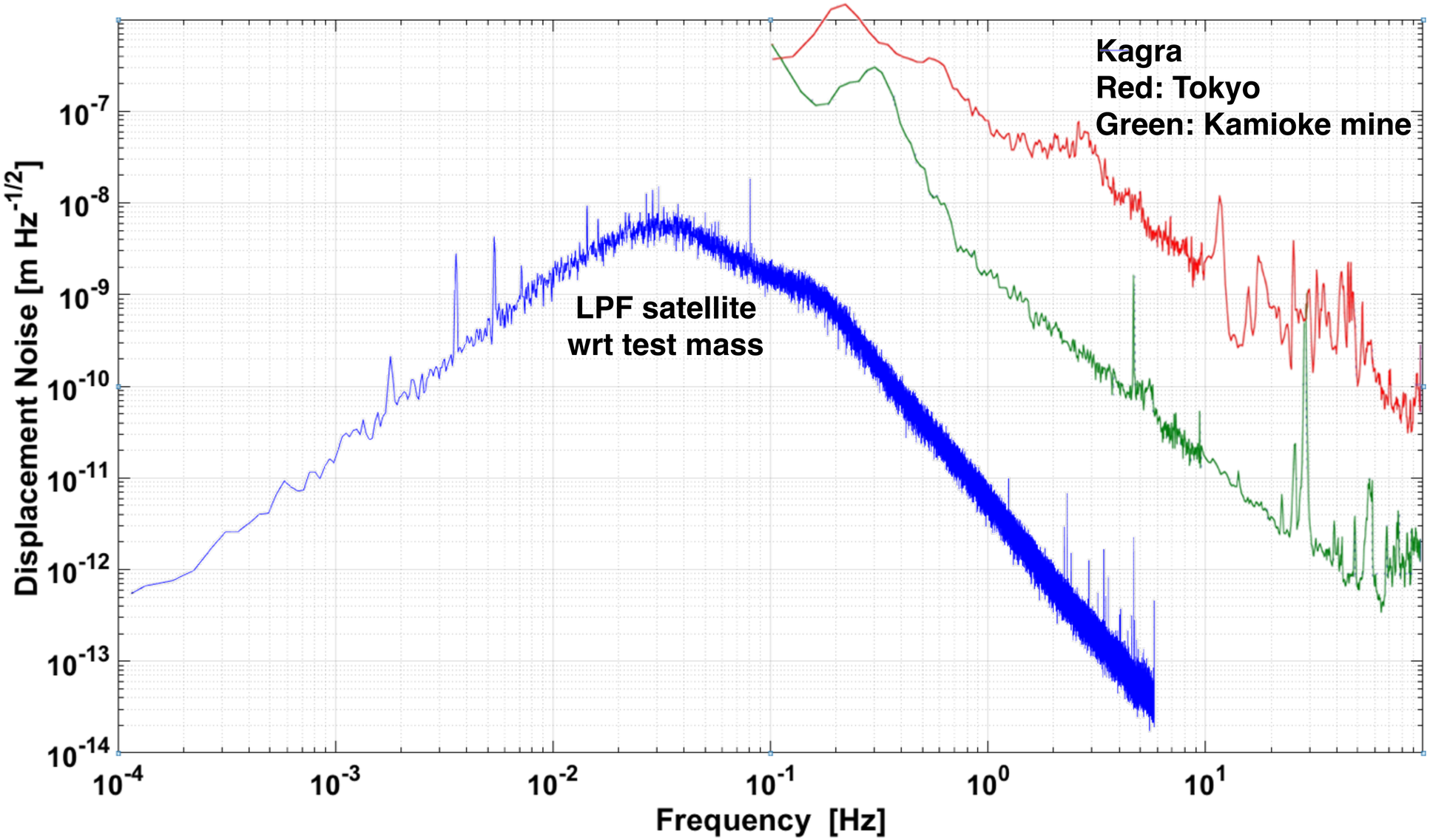
Performance: On-Orbit results



Noise Budget

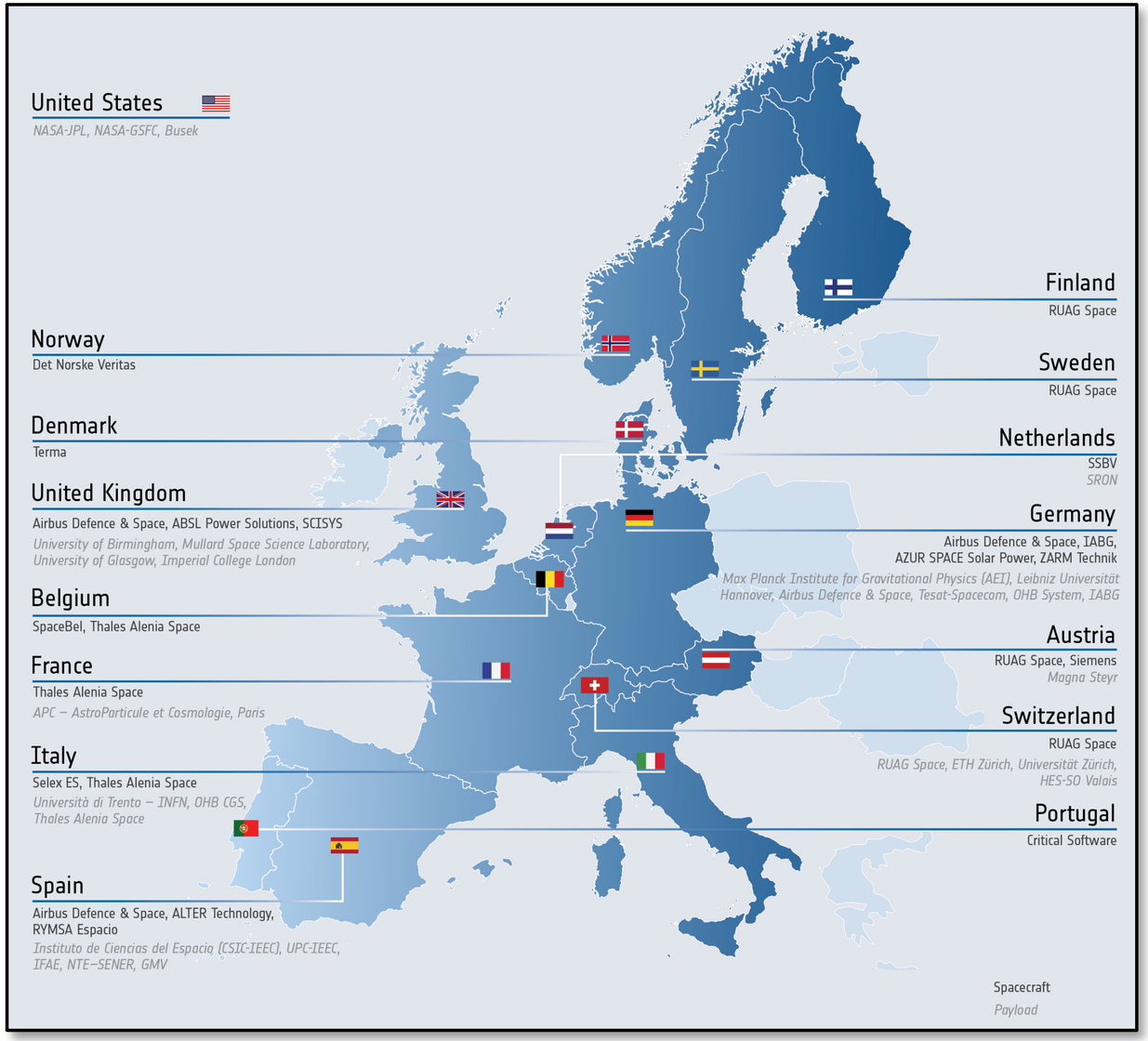


Why so good?....space is quiet!



LPF: An international success

- LISA Pathfinder is an international endeavour
  - More than 40 companies and institutes
  - From 14 European countries and the USA



Conclusions

- LISA Pathfinder is the first step in the observation of gravitational waves from space
- Successfully launched on 3 December 2015
- Mission operations lasted 16 months
  - End of Science Ops: 30 June 2017
- Final telecommand to be sent next week on 18 July
- All system performance requirements met *before* science operations began
- We have met the LISA performance requirements over the full LISA measurement bandwidth *goal*

Next step…..LISA!

Thank you