LISA Pathfinder:

First steps to observing gravitational waves from space

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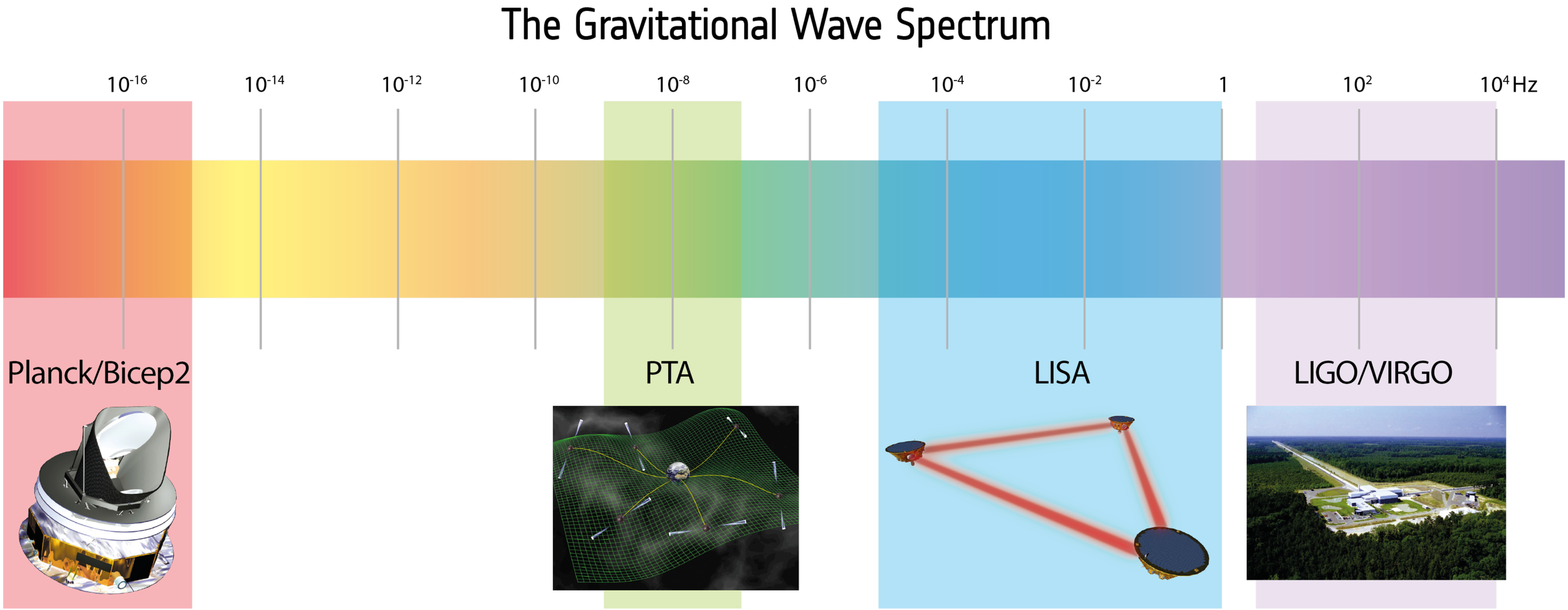
on behalf of the LISA Pathfinder team
GSFC, 27 January 2017

Introduction

- LISA Pathfinder (LPF) is the first step in the observation of gravitational waves from space
- LPF launched on a VEGA launcher from Kourou just over one year ago
- Since then, the performance of the instrument has exceeded even the scientists' most optimistic dreams!

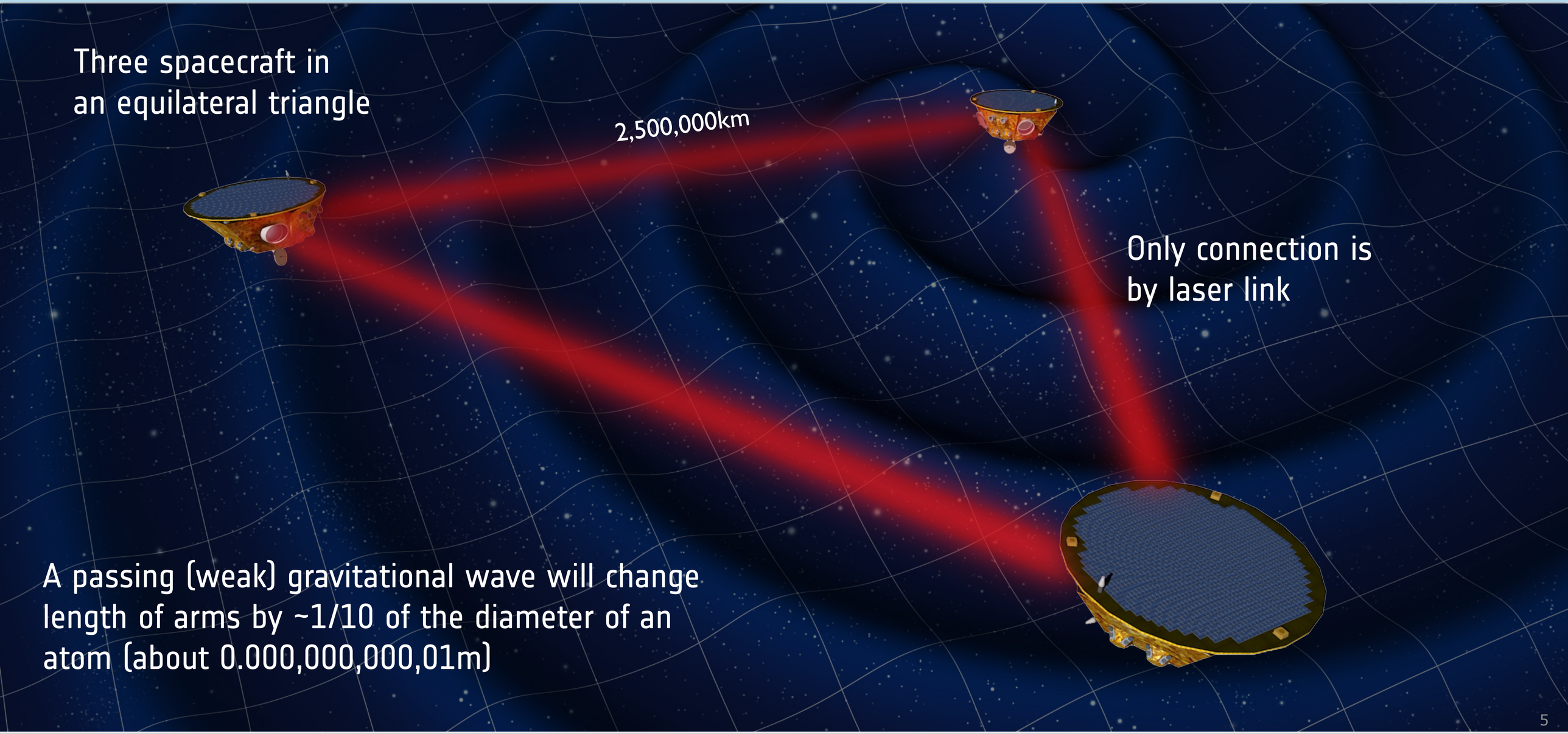
- LPF essentially shrinks one arm of LISA from ~million km down to ~40cm
  - Giving up the sensitivity to gravitational waves
  - Maintaining the instrument noise which could dominate the GW signal

The Gravitational Wave spectrum

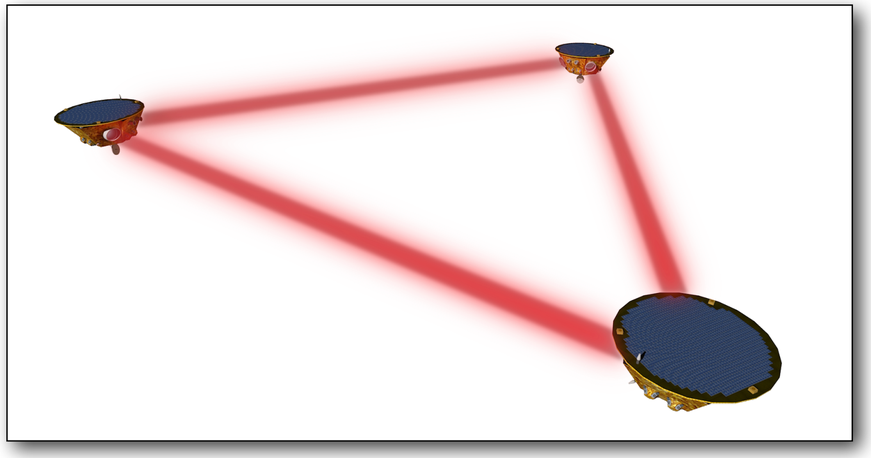


LISA - Laser Interferometer Space Antenna

So what is LISA?

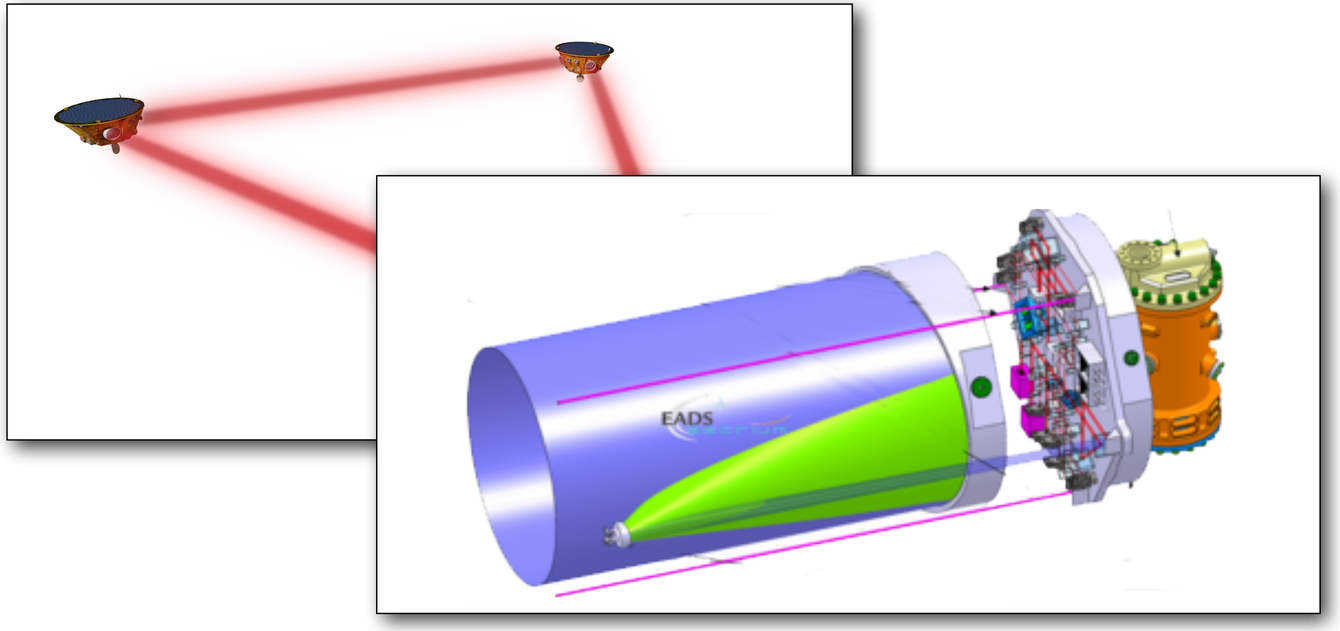


LISA to LISA Pathfinder



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

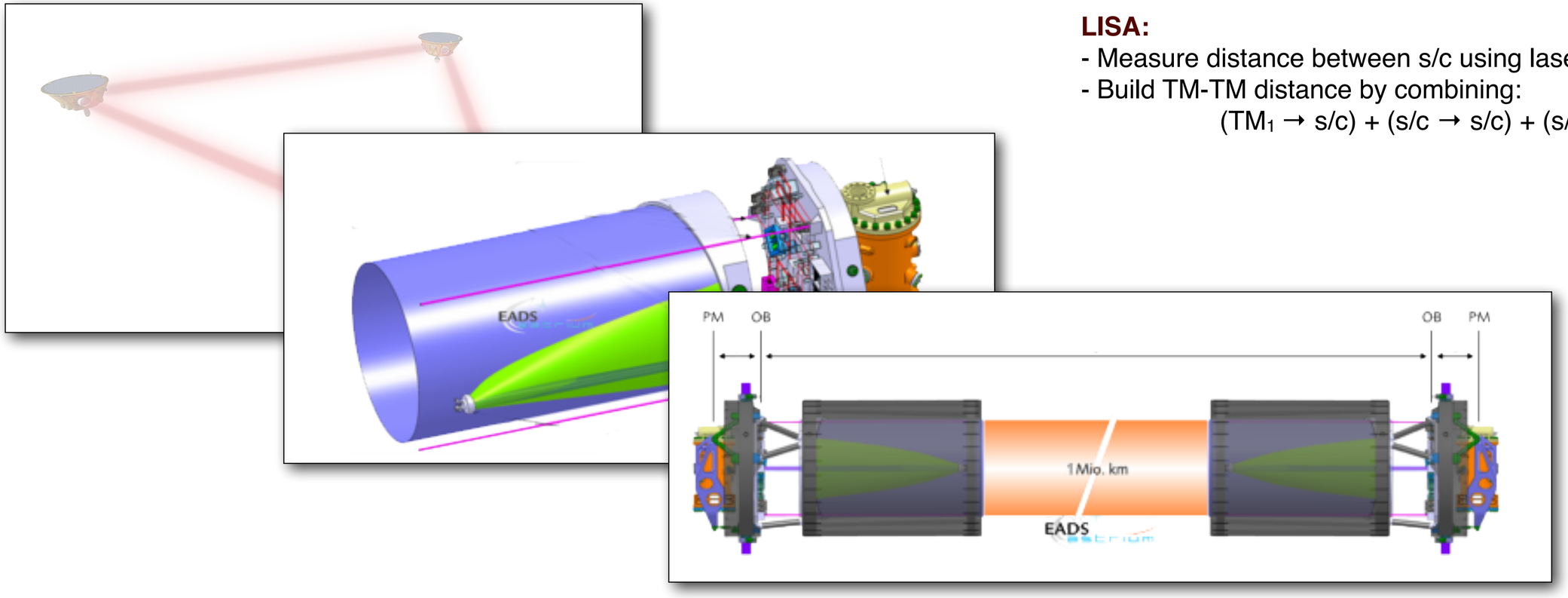
LISA to LISA Pathfinder



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

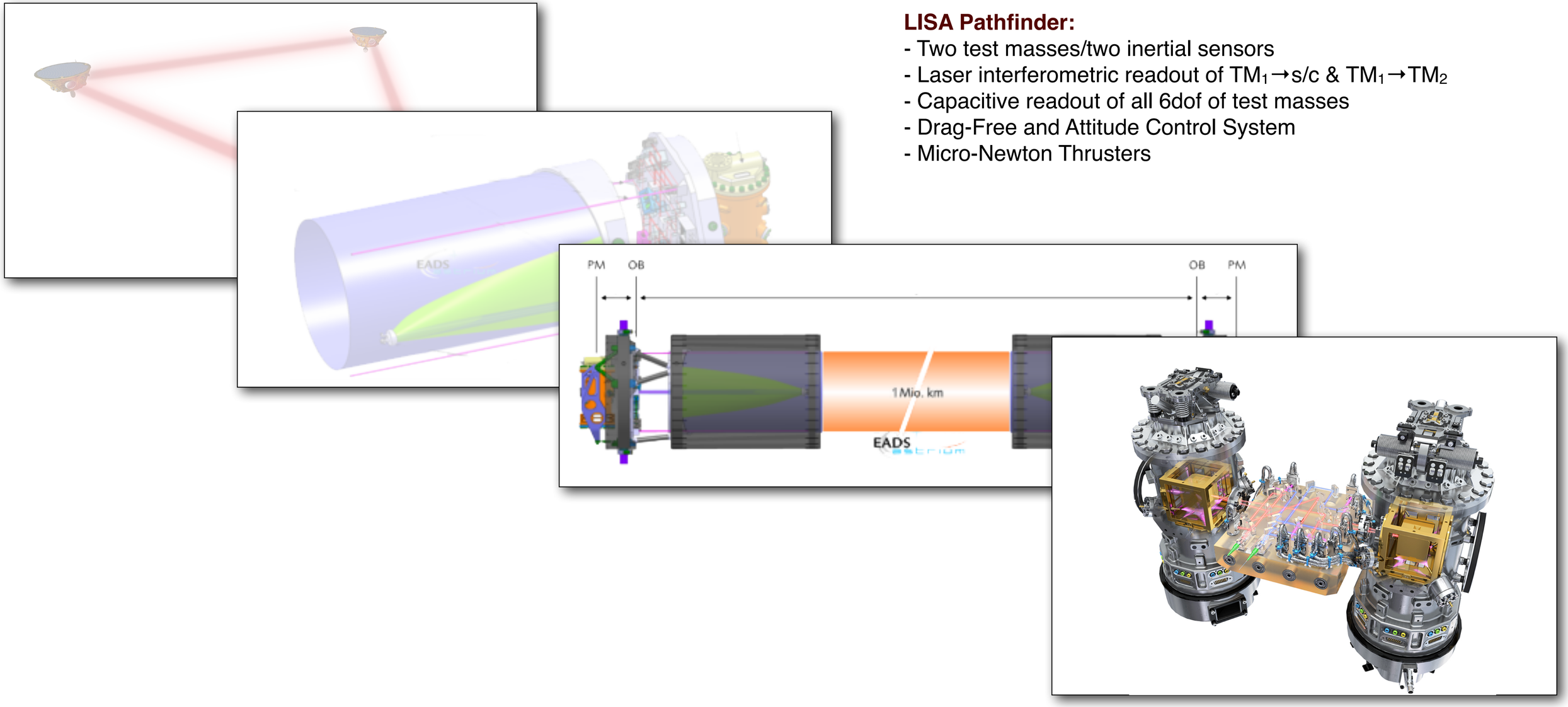


LISA:

- 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

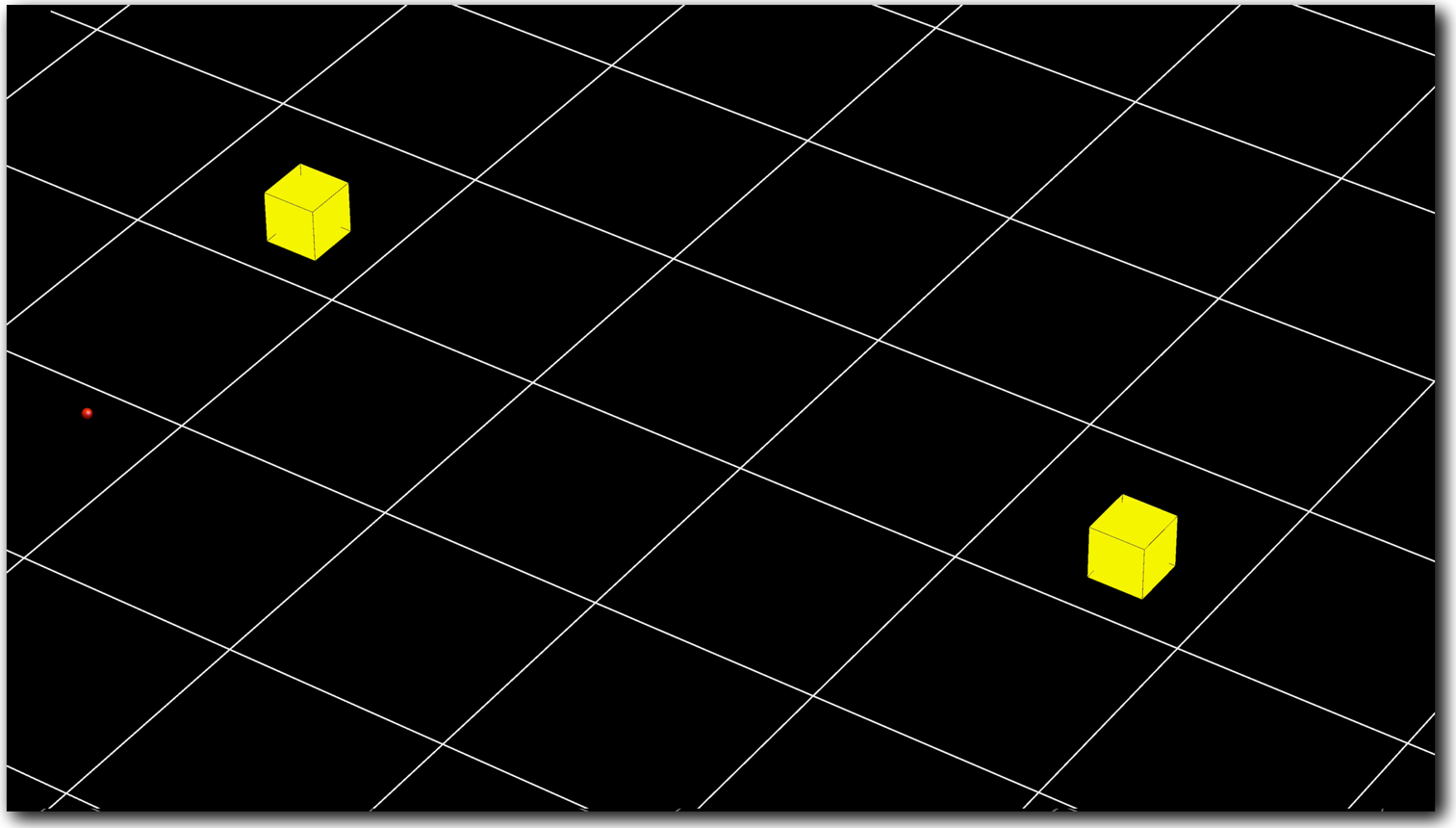


LISA Pathfinder:

- 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

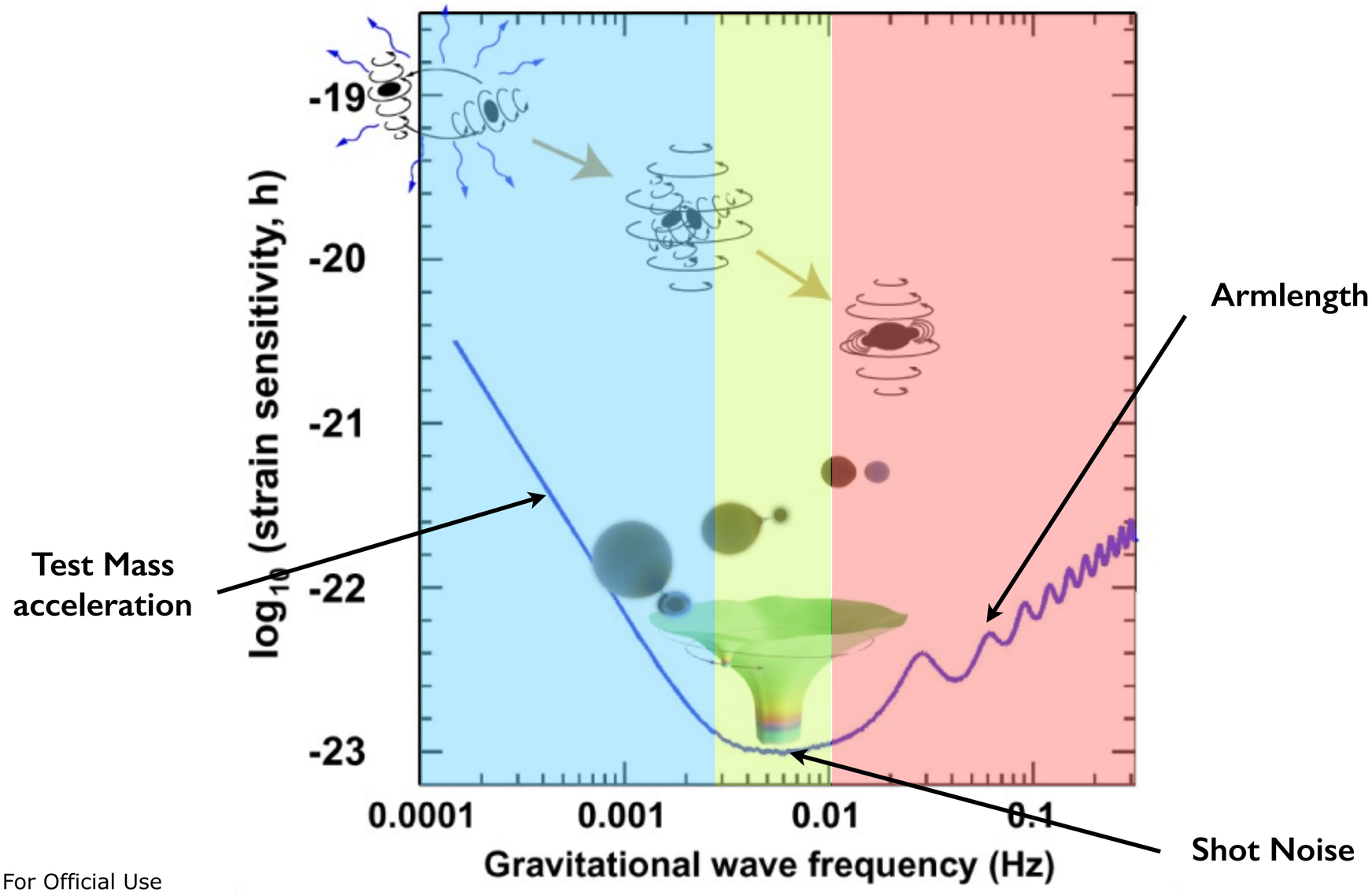
LISA Pathfinder

- The primary goal of LISA Pathfinder is to demonstrate that a body can be put in free fall such that any external forces are reduced to levels lower than those expected from the passage of a gravitational wave



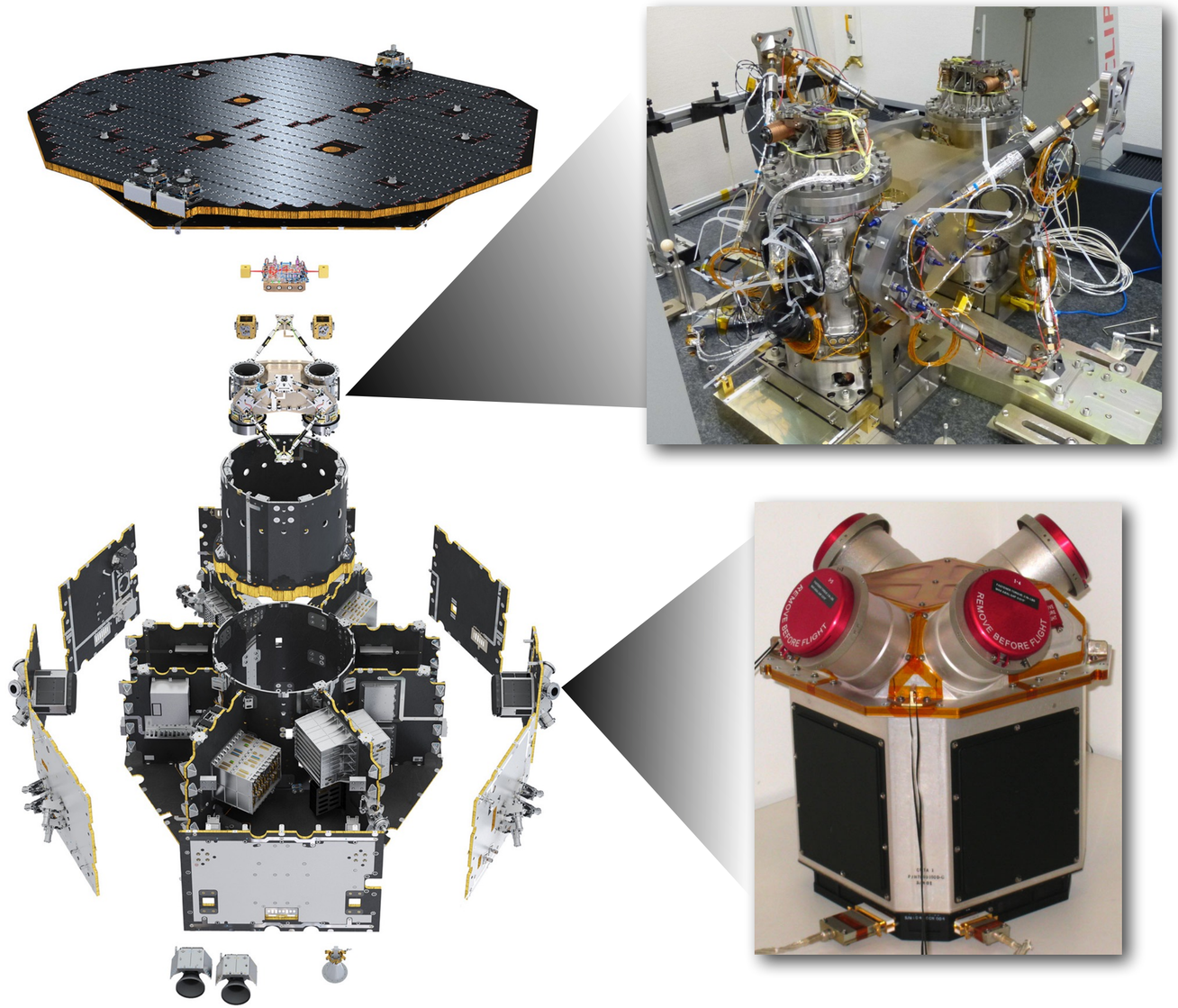
Credit: S.Vitale (Uni Trento)

LISA Sensitivity Curve



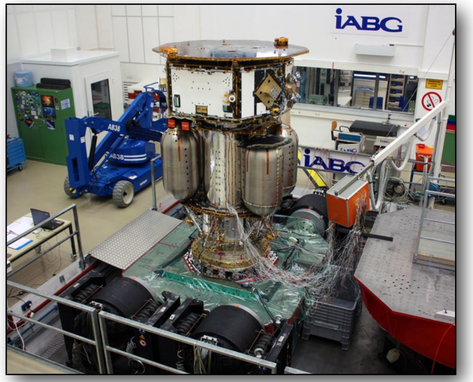
LISA Pathfinder

- 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

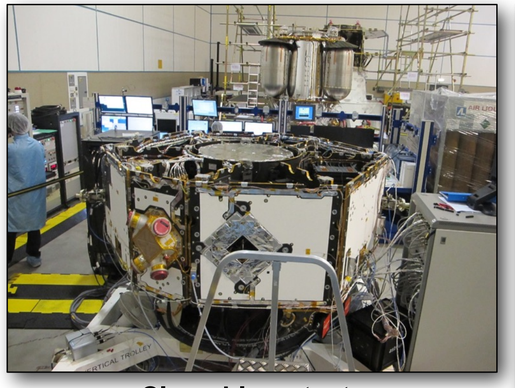


Development

- LPF is the first test of gravitational wave technology in space
  - Most technologies had no flight heritage
    - This led to a rather long development phase!

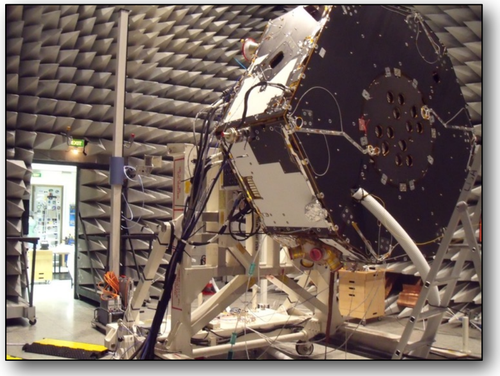


Vibration/shock tests


Closed-loop tests


Transfer Orbit Thermal Test

Launch Vehicle Fit Check


EMC

On-Station Thermal Test

Credit: Airbus Defence and Space and IABG

Preparing for launch…

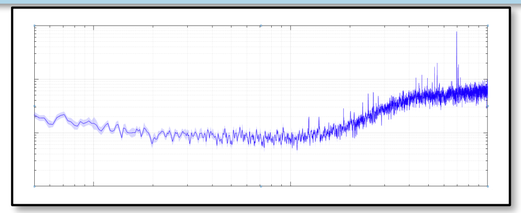
LISA Pathfinder Launch

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

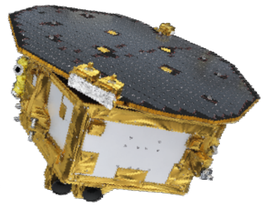
Telemetry (Analysis Objects)

STOC (Science Operations)

Simulator

Telemetry (Packets)

Telemetry (ascii)



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ADC72553	ADEF160U	DFA_SetCapaSignal_TM1_3	2016-04-23 07:33:41.403	2016-04-23 07:33:45.761	2016-04-27 06:04:44.000
ADC72554	ADEF160U	DFA_SetCapaSignal_TM1_4	2016-04-23 07:33:42.469	2016-04-23 07:33:46.714	2016-04-27 06:04:45.000
ADC00016	ADEF160U	DFA_IsParamUpdate	2016-04-23 07:33:42.469	2016-04-23 07:33:46.714	2016-04-27 06:04:46.000
ADC72581	ADEF170U	DFA_Set_CA_Fade_1	2016-04-23 07:33:43.395	2016-04-23 07:33:47.506	2016-04-27 06:04:56.000
ADC72582	ADEF170U	DFA_Set_CA_Fade_2	2016-04-23 07:33:44.181	2016-04-23 07:33:48.298	2016-04-27 06:04:57.000
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ADC72662	ADEF175U	DFA_Set_CA_Signal_2	2016-04-23 07:33:45.772	2016-04-23 07:33:50.105	2016-04-27 06:05:01.000
ADC00016	ADEF175U	DFA_IsParamUpdate	2016-04-23 07:33:45.772	2016-04-23 07:33:50.105	2016-04-27 06:05:02.000
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ADC00016	ADEF175U	DFA_IsParamUpdate	2016-04-23 07:33:54.249	2016-04-23 07:33:58.512	2016-04-27 07:05:02.000
CDC17001	SYEF901A	DHS_PerformConnectionTest	2016-04-27 07:22:20.146	2016-04-27 07:22:20.529	2016-04-27 07:22:20.529
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CDC94994	SYEF901A	DMP_ObcSwVersion	2016-04-27 07:23:42.997	2016-04-27 07:23:43.497	2016-04-27 07:23:43.497
CDC94988	SYEF901A	DMP_DHS_ResetReportIndex	2016-04-27 07:23:43.065	2016-04-27 07:23:43.639	2016-04-27 07:23:43.639
CDC82114	SYEF901A	DHS_ReportHkParameterReportList	2016-04-27 07:23:43.131	2016-04-27 07:23:43.835	2016-04-27 07:23:43.835
CDC82115	SYEF901A	DHS_ReportDiagnosticParameterReportList	2016-04-27 07:23:43.197	2016-04-27 07:23:43.980	2016-04-27 07:23:43.980
CDC94126	SYEF901A	DMP_ScvContextHealth	2016-04-27 07:23:43.362	2016-04-27 07:23:44.937	2016-04-27 07:23:44.937
CDC94129	SYEF901A	DMP_ScObsVector_1	2016-04-27 07:23:43.587	2016-04-27 07:23:45.698	2016-04-27 07:23:45.698
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CDC94127	SYEF901A	DMP_ScvConfigCommonAlloc	2016-04-27 07:23:43.915	2016-04-27 07:23:46.961	2016-04-27 07:23:46.961

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']

```
0x00: 7E AA 92 40 40 40 40 62 9E F4 64 86 AA 84 61 03
                                                5C C2 C2
                                                14 84 C2
                                                16 98 82
                                                14 88 CA
                                                D2 D8 D2
                                                00 00 F0
                                                03 46 02
                                                77 E0 75
                                                41 80 8F
                                                00 00 00
                                                00 00 00
                                                00 2B BE
```

```
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
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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]
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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

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```
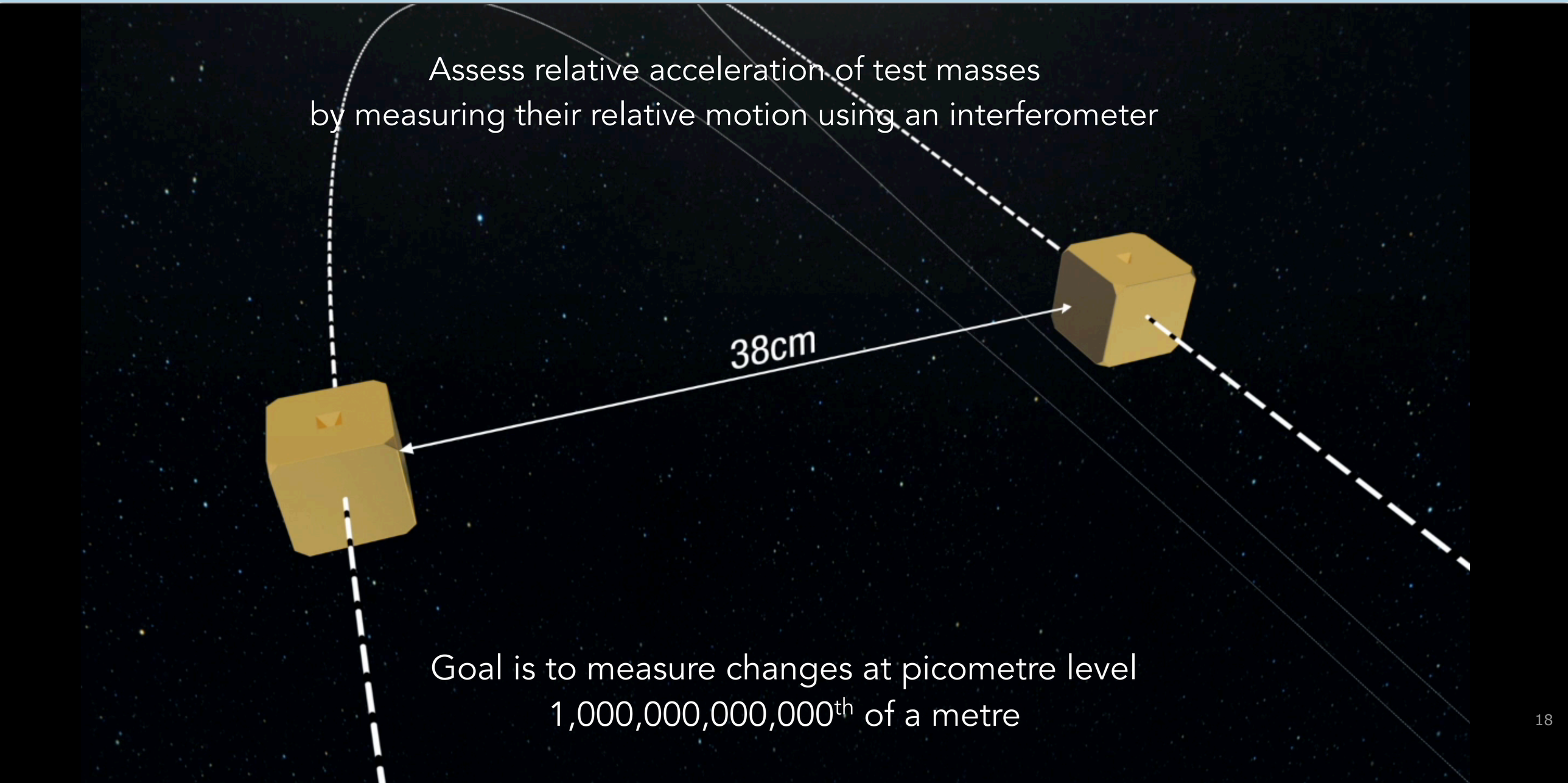
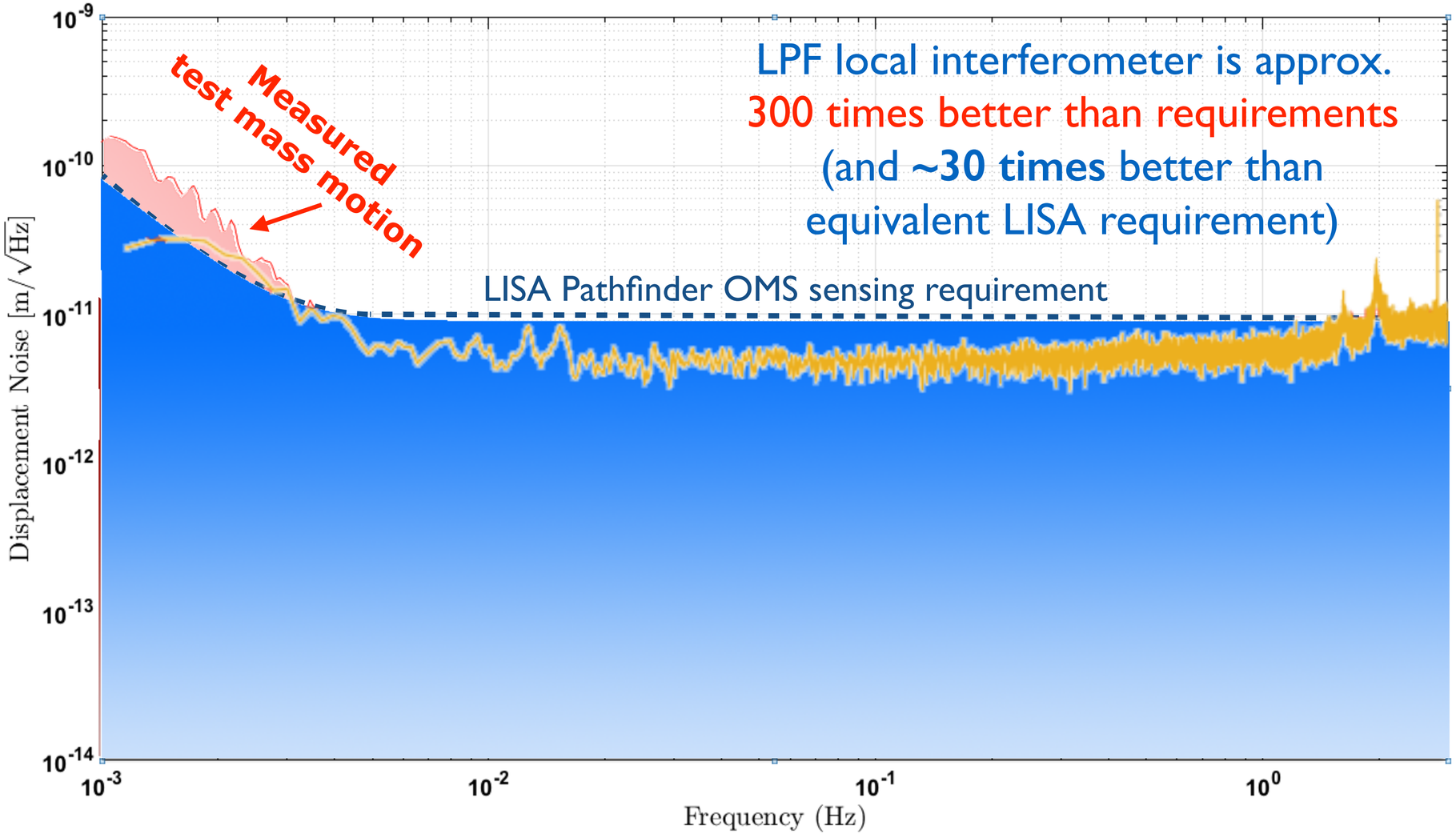

Laser Interferometry on LPF



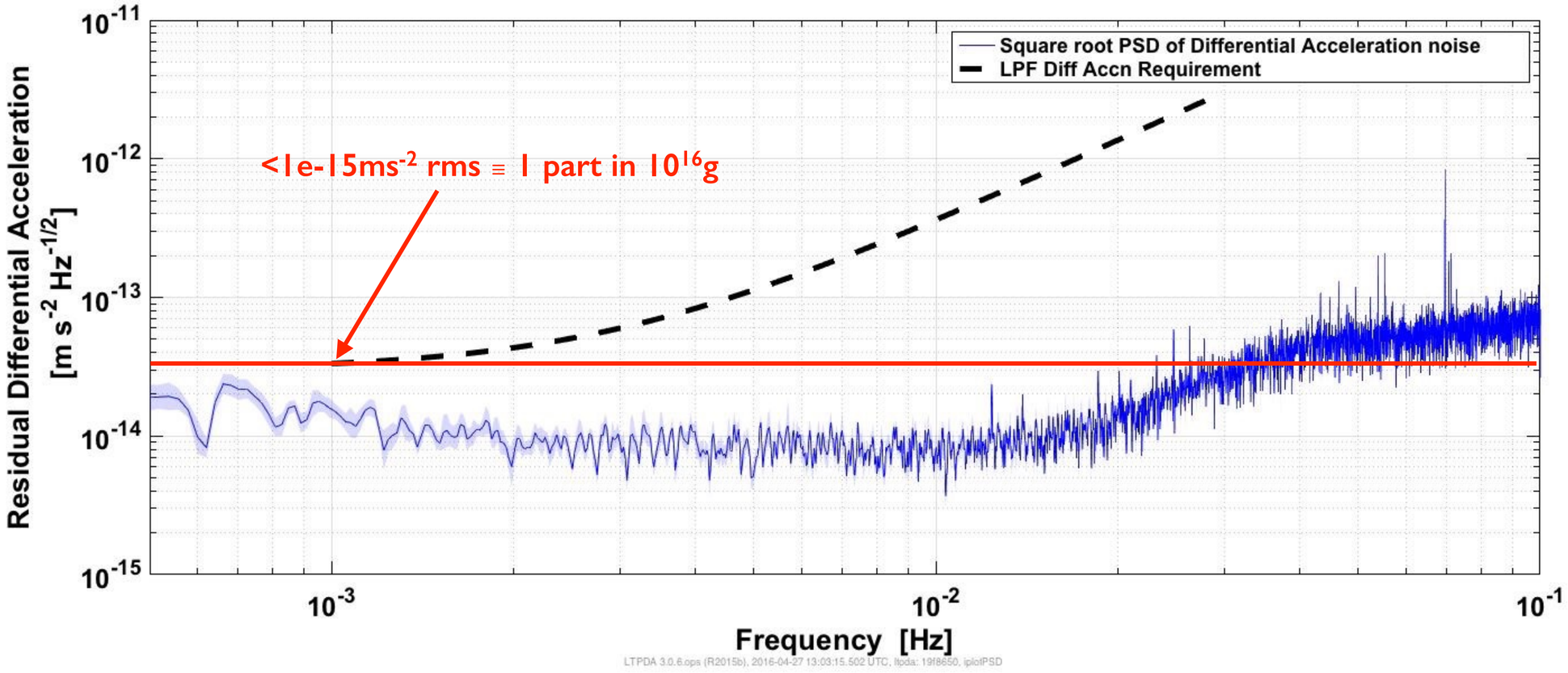
Performance: On-Orbit results



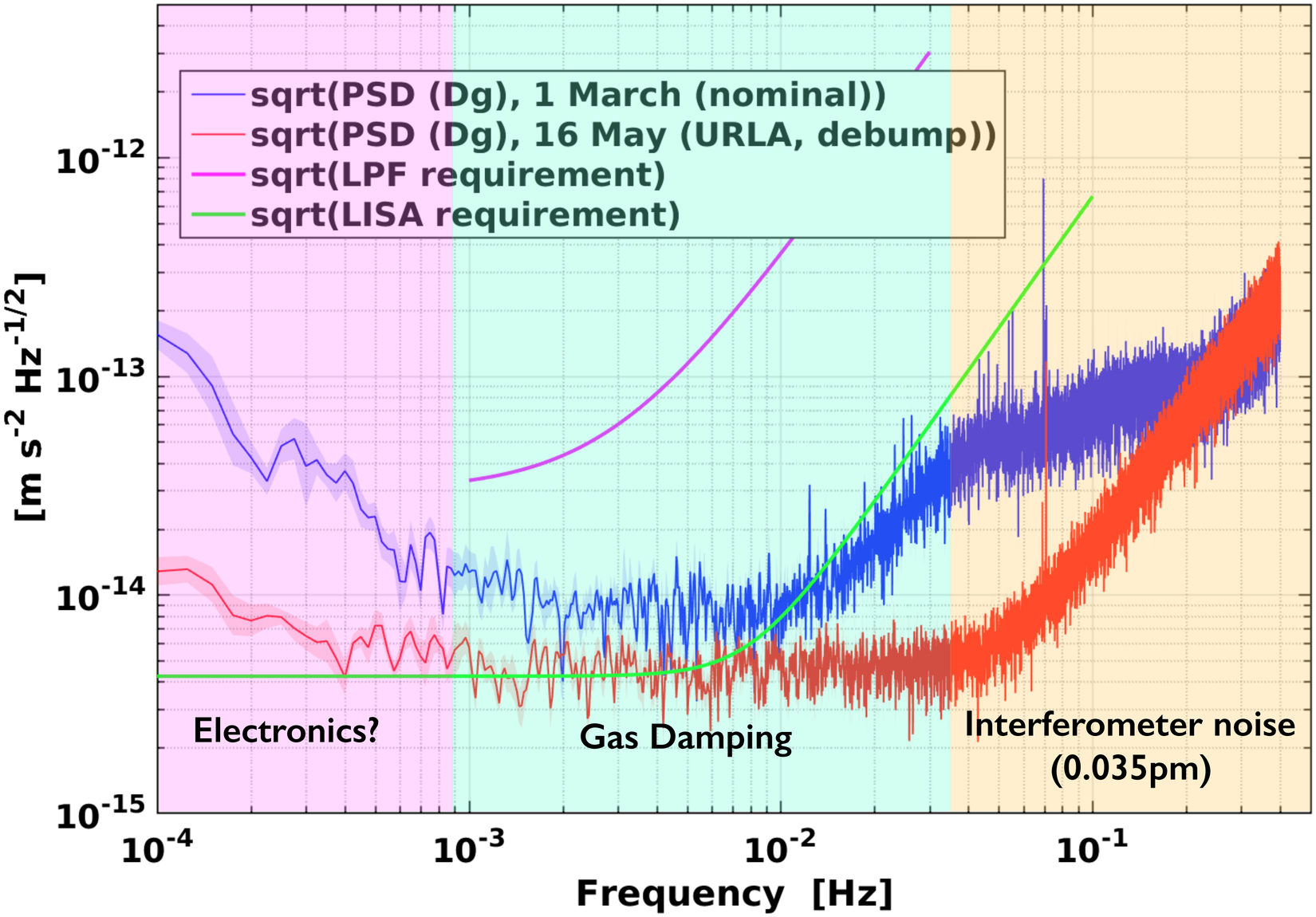
Differential Acceleration

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

  …and was met during commissioning!



The quietest place in the solar system?



Gravitational Balancing of s/c

- Spacecraft self-gravity must be balanced to $<1\times10^{-9}ms^{-2}$ at both test mass positions
  - Requires very accurate knowledge of all unit mass properties, location of units in s/c, a detailed model of the system, and finally balance masses to trim the field.
    - Units (e.g. electronic boxes) have CoM measured with error of <1mm
    - All hardware are located on the s/c with position accuracy of ~250µm

ASTRIUM — LISA Pathfinder — SC AIV Mass Tracking Log — S2.ASU.TN.2275 — 75.

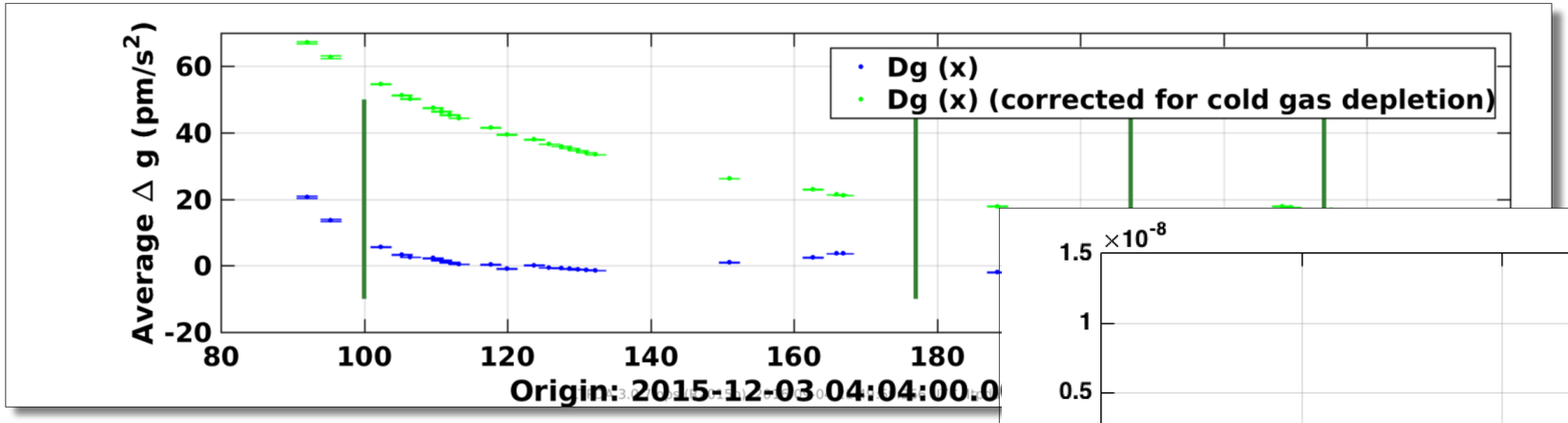
Line Item	Date	Time	Initials	ACS Reference	Description of Items Added/Removed (Use Multiple Lines, If Required)	Description of Location	Item Mass (g)	Item Mass (kg)	Add/ Subtract	Flight Hardware Y/N	Non-Flight Hardware Y/N	Comments
3044	24/10/14	15:00	TO	ACS 632	KAPTON, CHO-TALL, PTFE, CABLE TIES	MXMY EXT. PANEL	15.903g		+	✓		
3045	24/10/14	15:00	TO	ACS 632	CABLE TIES	PXMY EXT. PANEL	1.526g		+	✓		
3046	24/10/14	15:00	TO	ACS 632	PTFE, CABLE TIES	MY EXT. PANEL	19.336g		+	✓		
3047	24/10/14	15:00	TO	ACS 632	CABLE TIES	MXMY RAD. SHEAR WALL	3.141g		−	✓		
3048	24/10/14	15:00	TO	ACS 632	KAPTON CABLE TIES	PXMY PARALLEL SHEAR WALL	0.891g		−	✓		
3049	28/10/14	09:00	VL	ACS 631	Nut, washers & screw for DRS thruster	PX DRS1-3	1.600g		−		✓	Nut dropped during removal & lost.
3050	28/10/14	09:00	VL	ACS 631	Tyrap added to thruster cover (1-3 cover)	PX DRS 1-3 cover	0.486g		+		✓	Replacement to refit cover.
3051	28/10/14	15.50	LS	ACS 618	MLI grounds removed.	PY ext long	14.869g		−	✓		
3052	28/10/14	15.50	LS	ACS 618	MLI grounds removed.	PXMY ext medium	3.503g		−	✓		
3053	28/10/14	16:40	LS	ACS 548	Panel to panel grounds removed.	PY ext medium	1.561g		−	✓		
3054	28/10/14	16:40	LS	ACS 548	Panel to panel grounds locked.	All locations.	0.076g		+	✓		
3055	3/11/14	11.40	LS	ACS 606	1 off tybase bonded	MXPY Parallel S/W	0.769g		+	✓		
3056	3/11/14	11.40	LS	ACS 606	2 off tybases bonded.	MXPY Radial S/W	1.538g		+	✓		
3057	3/11/14	11.40	LS	ACS 606	1 off tybase bonded.	PY ext long	0.769g		+	✓		
3058	3/11/14	11.40	LS	ACS 606	1 off tybase bonded.	PX ext short	0.769g		+	✓		
3059	3/11/14	11.40	LS	ACS 606	1 off tybase bonded	PXMY Radial S/W	0.769g		+	✓		
3060	3/11/14	17.00	SD	ACS 620	PIPEWORK & PIPE ITEMS	MY CGS PANEL	96.953g		+	✓		
3061	3/11/14	17.00	SD	ACS 620	PIPE WORK & PIPE ITEMS	MXPY CGS PANEL	169.555g		+	✓		
3062	3/11/14	17.00	SD	ACS 620	PIPE WORK & PIPE ITEMS	PX PY CGS PANEL	79.996g		+	✓		
3063	3/11/14	17.00	SD	ACS 620	PIPE-ITEMS FOR RING MAIN	MXMY ~~CGS~~ EXT PANEL	11.697g		+	✓		
3064	3/11/14	17.00	SD	ACS 620	PIPE-ITEMS FOR RING MAIN	MX EXT PANEL	5.71g		+	✓		
3065	3/11/14	17.00	SD	ACS 620	PIPE-ITEMS FOR RING MAIN	PY EXT PANEL	12.095g		+	✓		
3066	4/11/14	11:45	LS	ACS 622	Eccobond (ground locking)	MXMY quadrant	0.074g		+	✓		
3067	4/11/14	11:45	LS	ACS 622	Epikote (ground locking)	MXMY quadrant	0.254g		+	✓		
3068	4/11/14	18:10	[illegible]	ACS 570	WIRE/CONNECTORS/CONTACTS/PTFE/TIE CAPS/KAPTON	PXPY COLD GAS PANELS	69.984g		−	✓		
3069	5/11/14	17.00	DI	ACS 609	CHO-FOIL + KAPTON	+Y-X RAD SHEARWALL SPU2	10.004		+	✓		
3070	5/11/14	17.00	DI	ACS 609	TYWRAPS + PTFE	-X-Y RAD SHEARWALL FEE PCU	4.008		+	✓		
3071	5/11/14	17:50	AT	ACS 579	X16 MPE Dust cap	-X-Y MPE	12.929		−		✓	

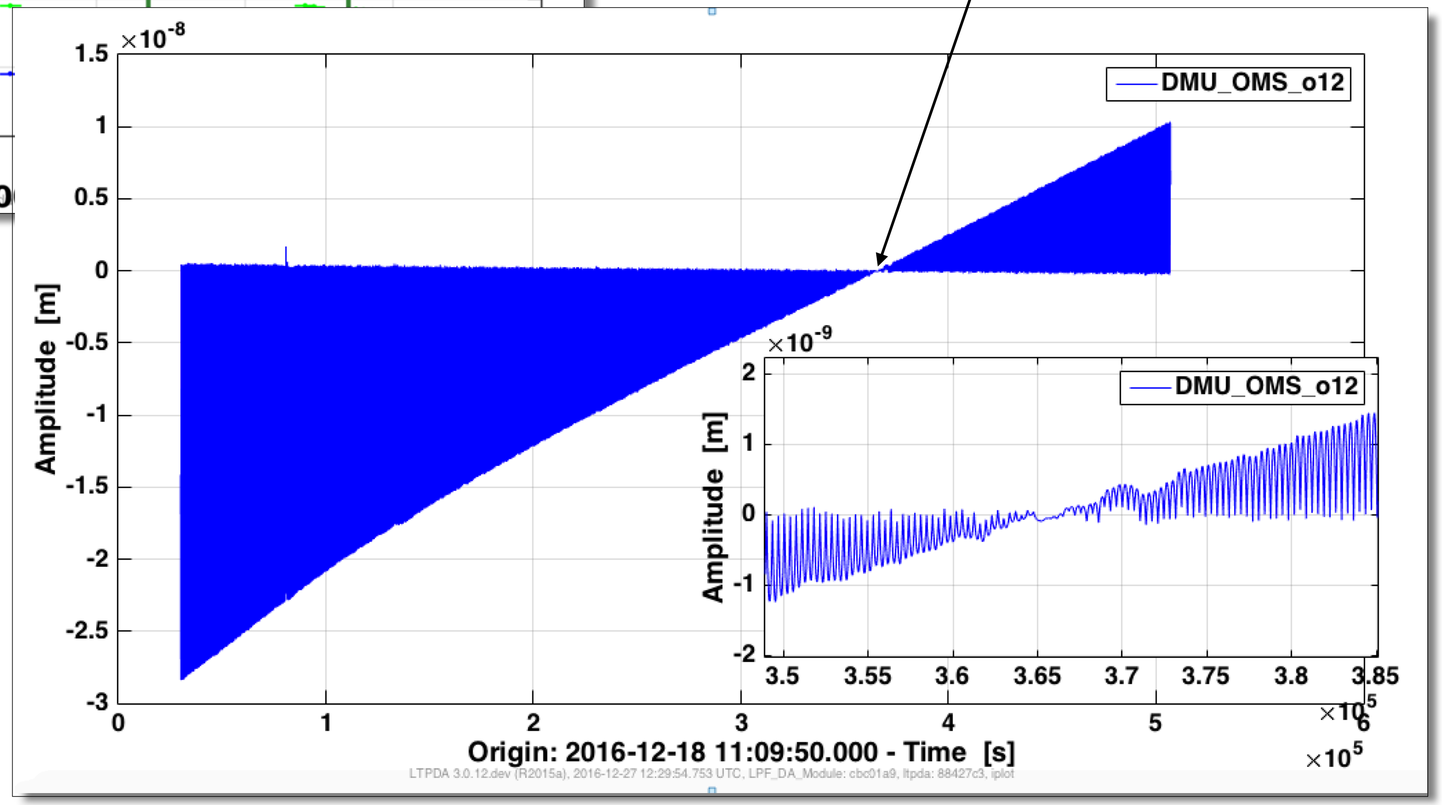
Total mass of cable ties and kapton tape

The mass of the cable tie which is cut off!

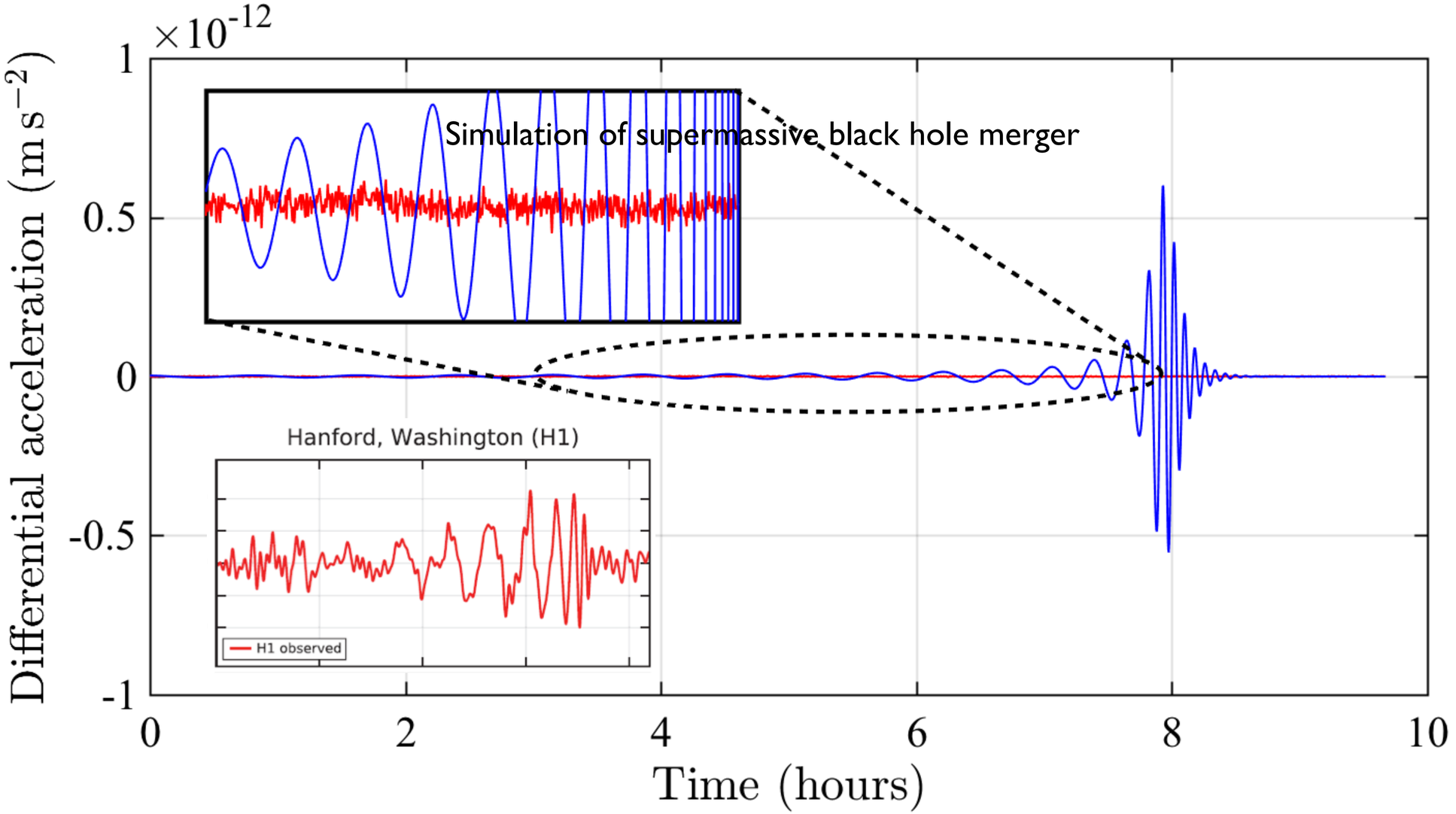
Did we meet the requirement?

- Yes….with quite some margin to spare!





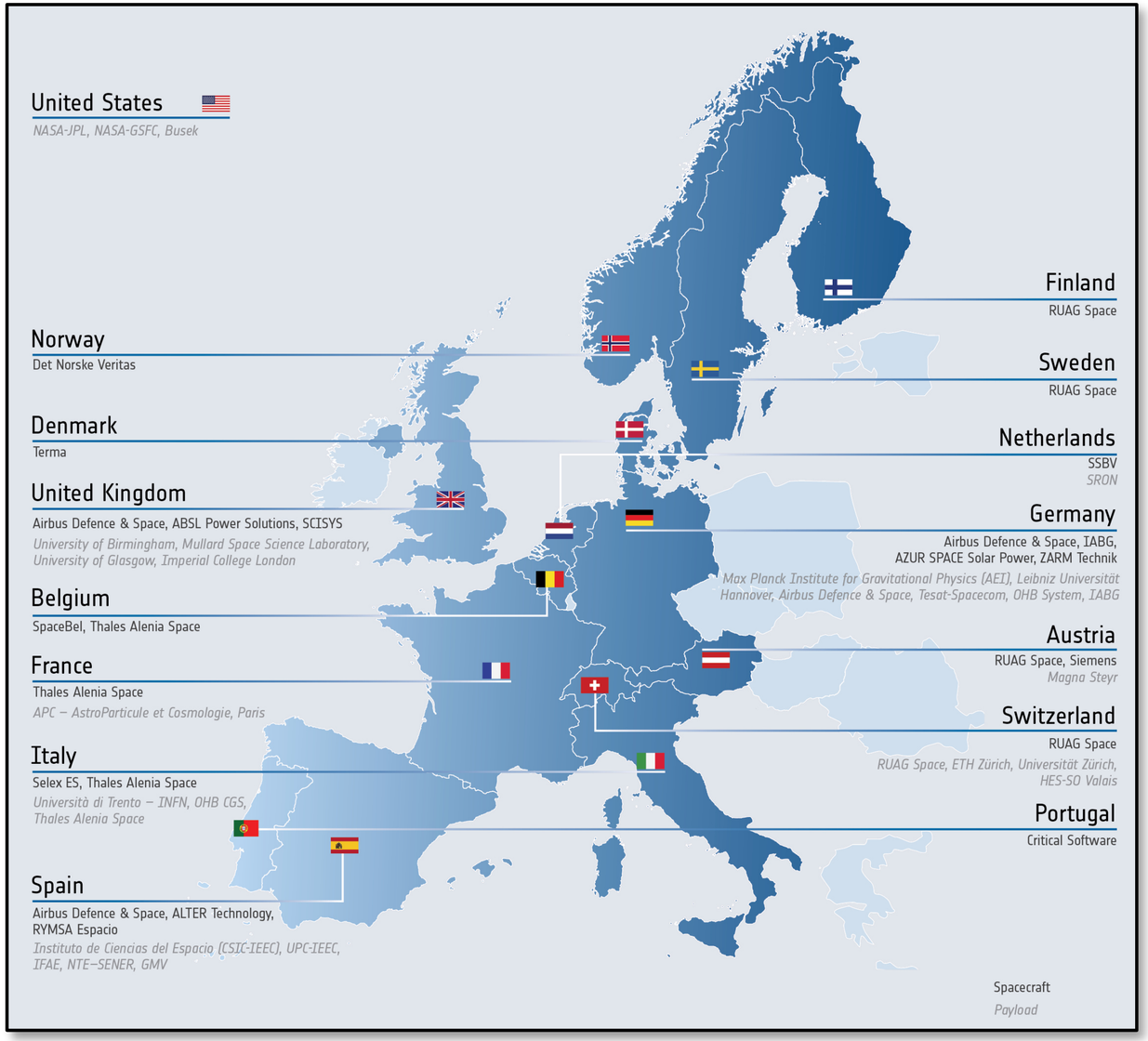
LPF performance and LISA?



LPF: An international success

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

- Next step…..**LISA**



Thank you

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University of Trento
Albert Einstein Institute
University of Glasgow
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Imperial College London
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