esa SCIENCE

LISA Pathfinder:

First Steps to Observing Gravitational Waves from Space

Paul McNamara

on behalf of the LPF Team

LISA Symposium XI

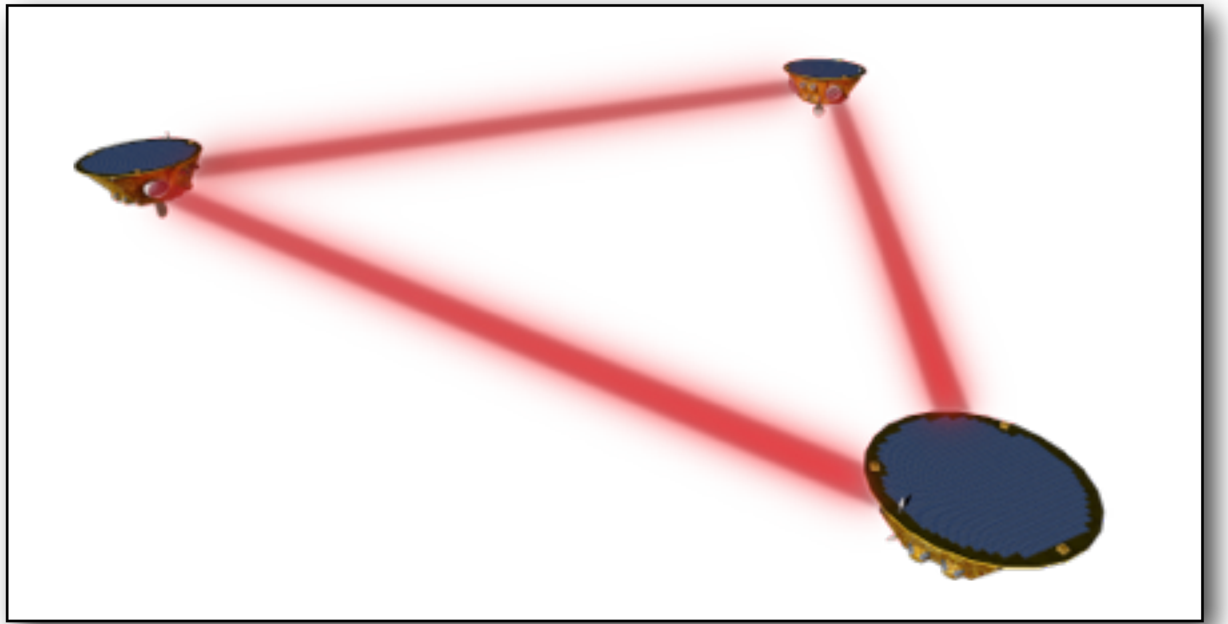
Zurich, 5-9 Sept 2016

lisa pathfinder

Introduction

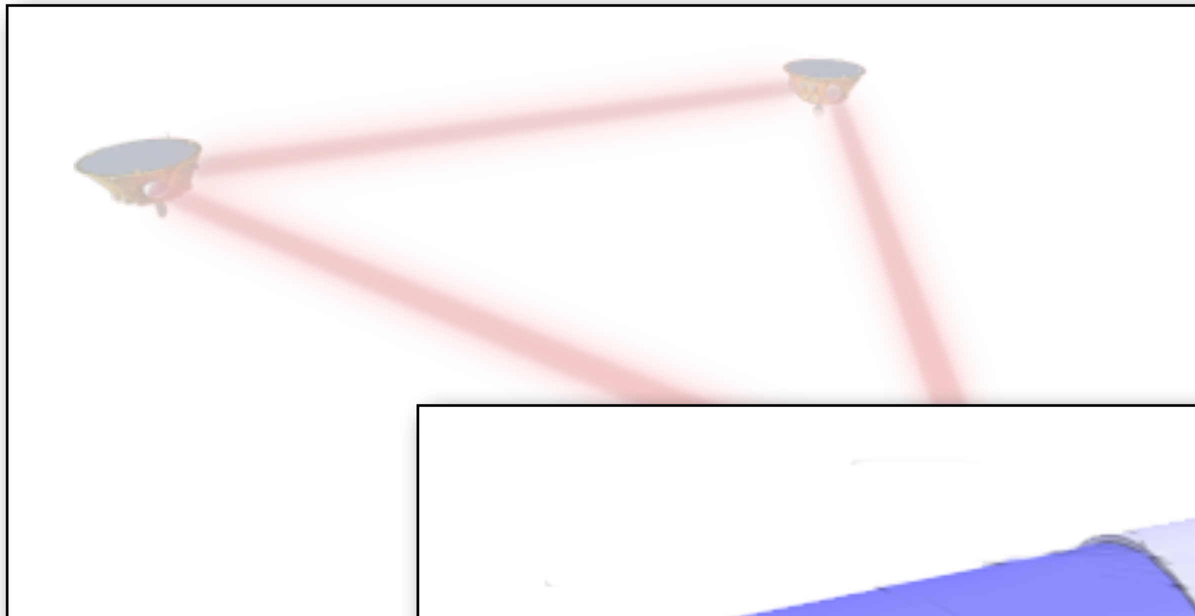
- LISA Pathfinder is the first step in the observation of gravitational waves from space
- LISA Pathfinder provides us with:
  - A better understanding of the physics of the forces acting on a free-falling test mass
  - Industrial experience in the development, manufacture, and testing of technologies required for GW detection
  - Data analysis algorithms and tools dedicated to the analysis of the system as a whole
  - Essential experience in the commissioning of a LISA-like mission
- 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

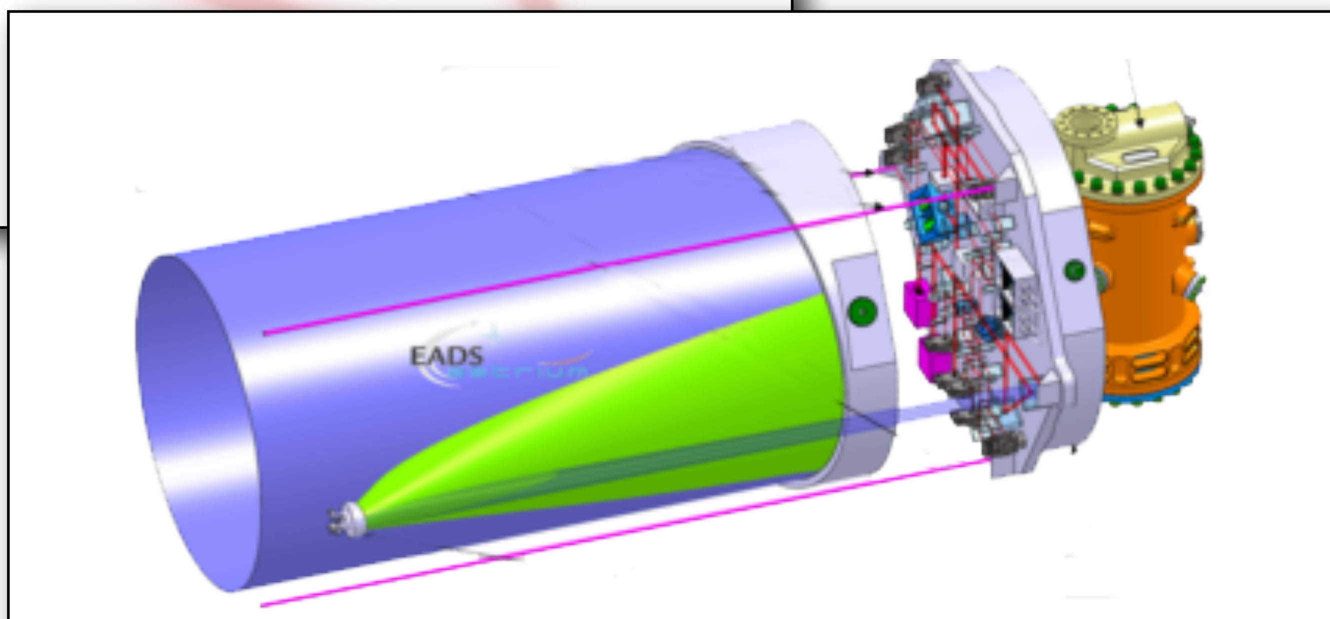
LISA to LISA Pathfinder



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

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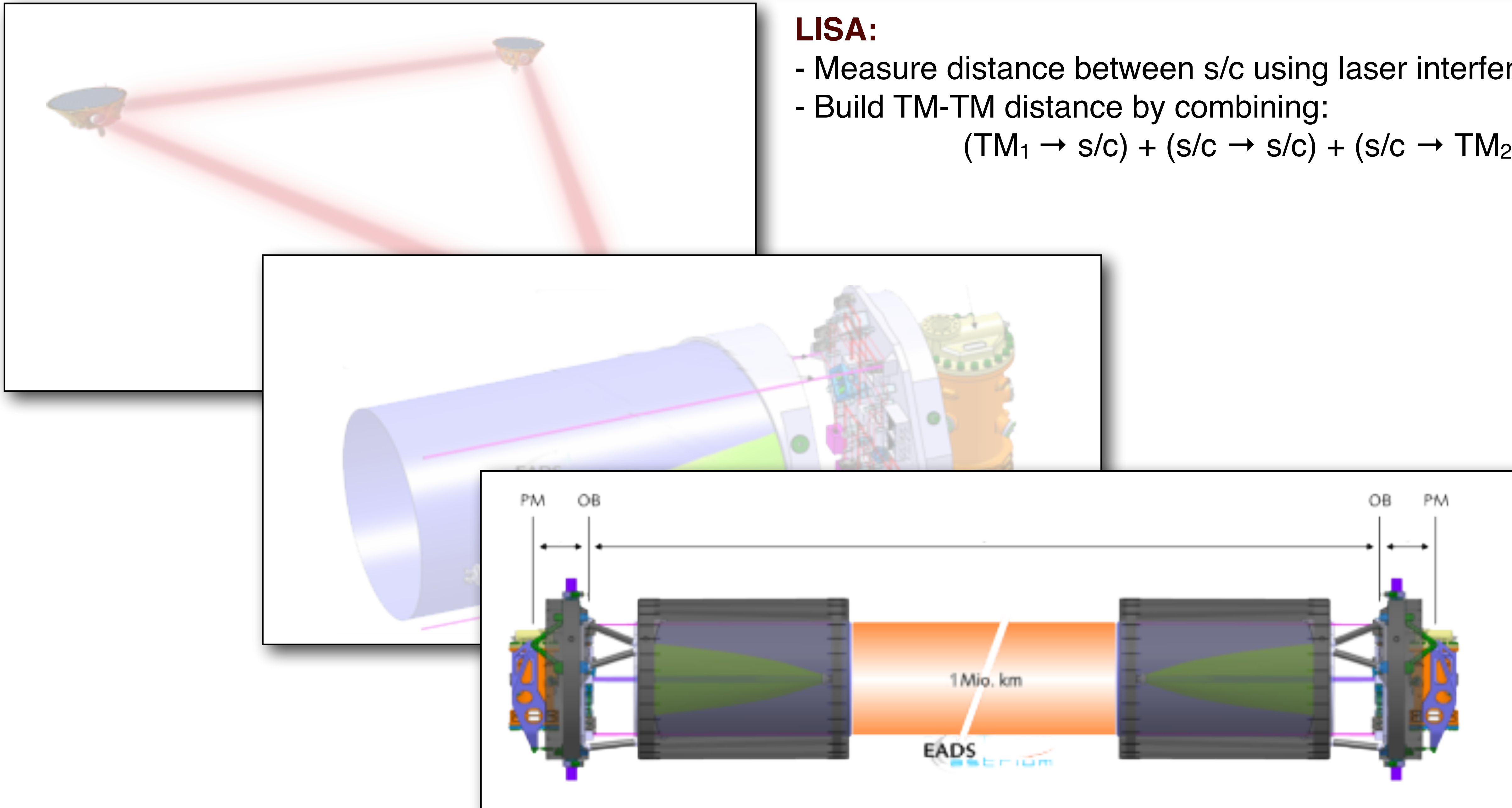
LISA to LISA Pathfinder

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

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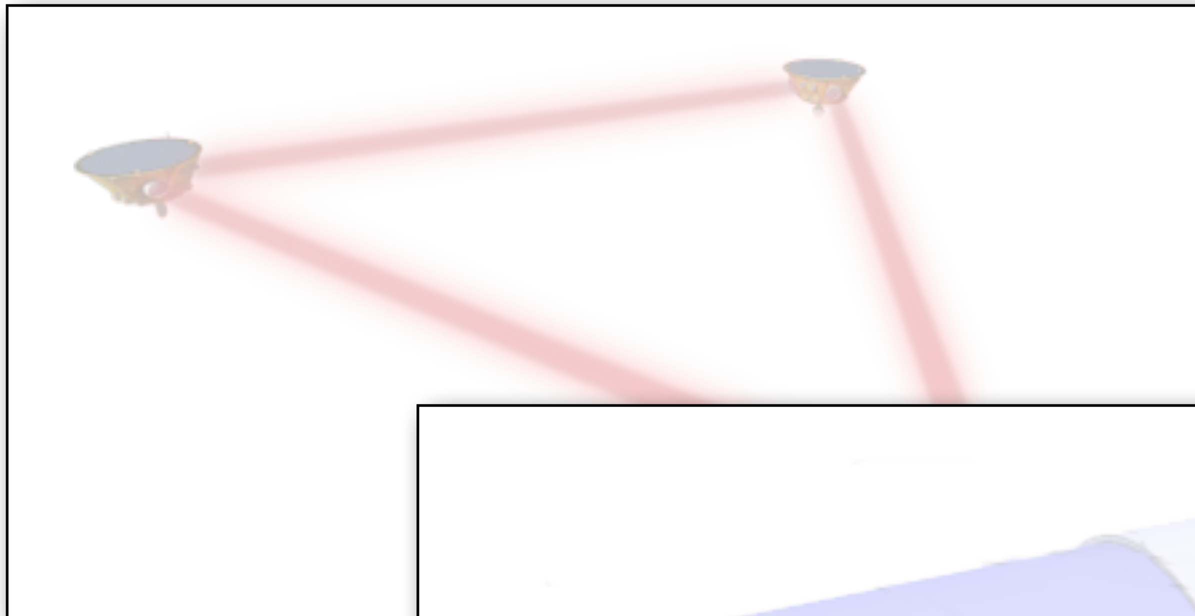
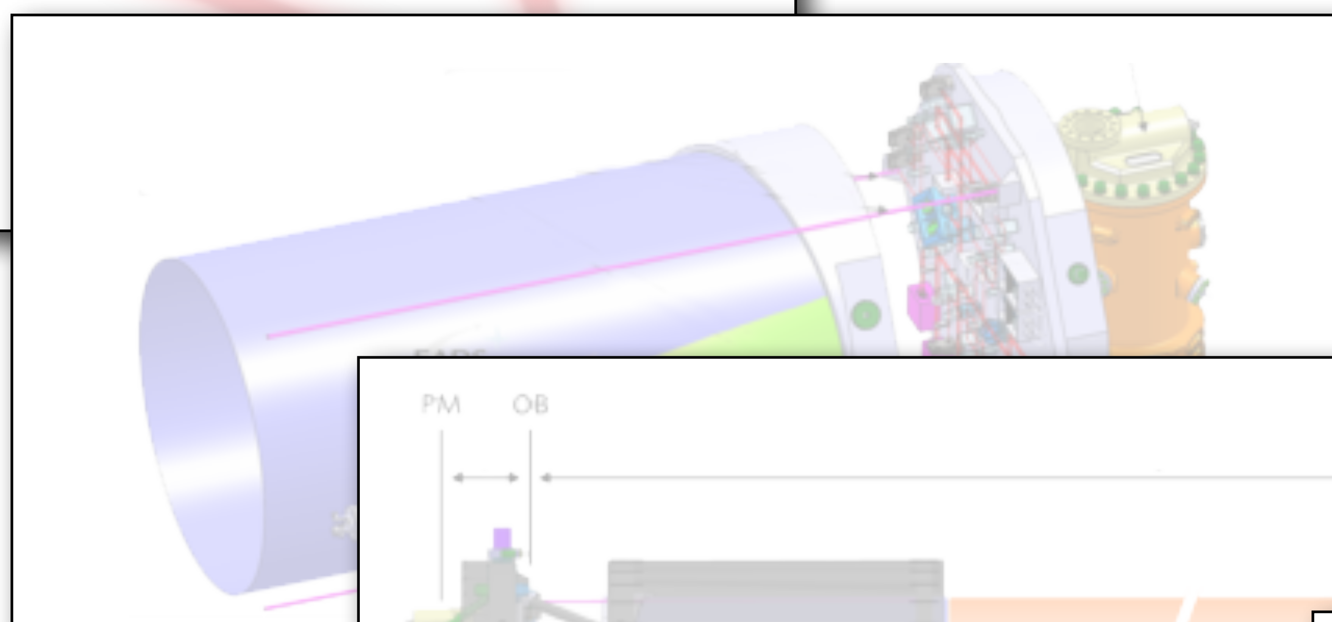
LISA Pathfinder:
- Two test masses/two inertial sensors
- Laser interferometric readout of $TM_1 \rightarrow s/c$ & $TM_1 \rightarrow TM_2$
- Capacitive readout of all 6dof of test masses
- Drag-Free and Attitude Control System
- Micro-Newton Thrusters





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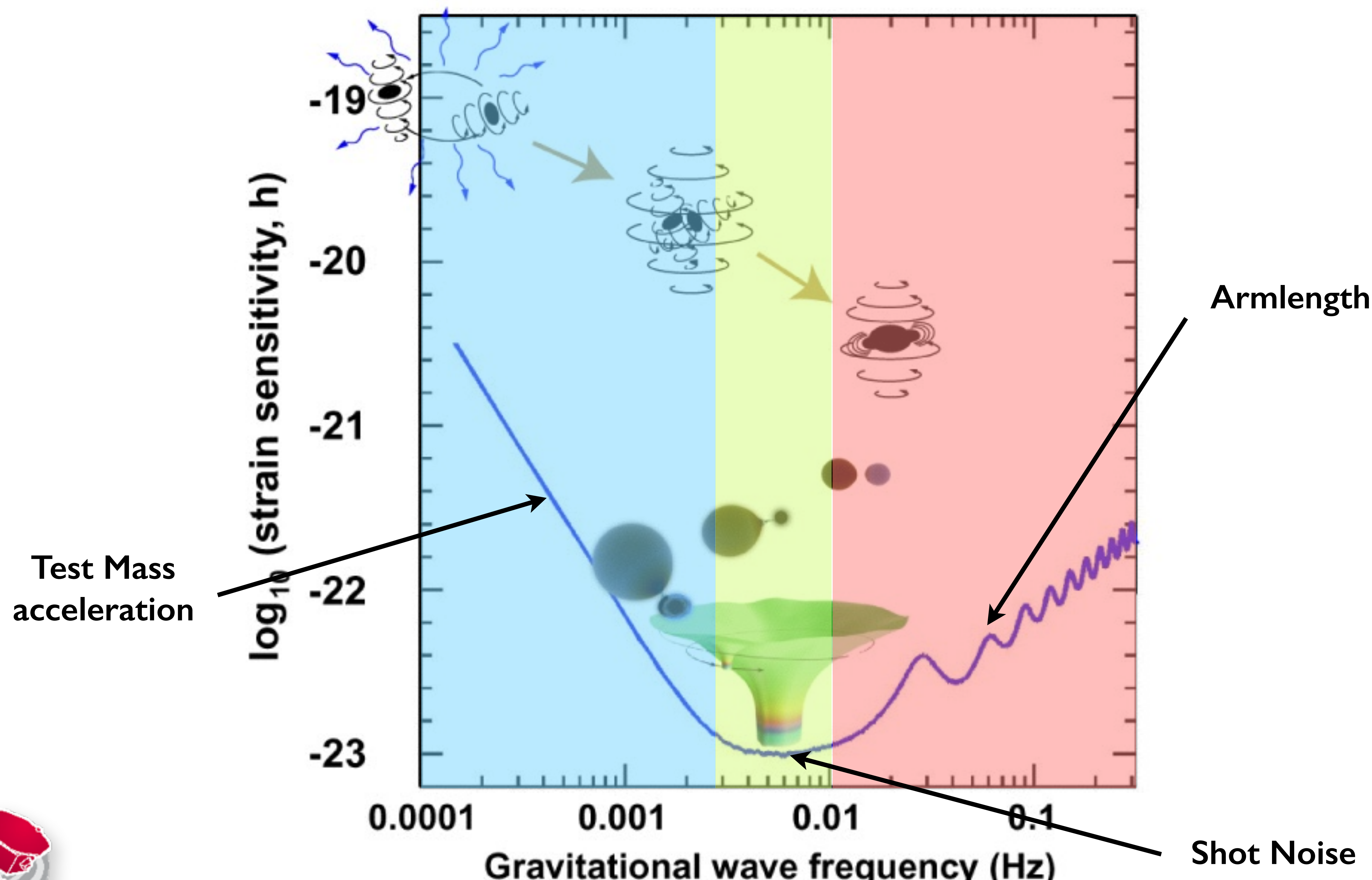
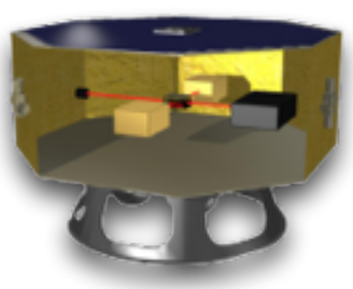
LISA Sensitivity Curve



A little bit of history...


ELITE
EUROPEAN LISA TECHNOLOGY
Demonstration Staellite
for the LISA Mission in
ESA's Space Science Programme

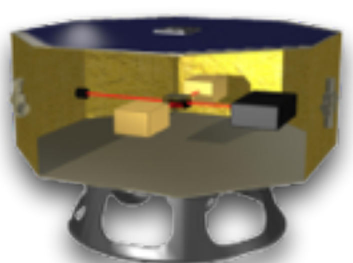
PROPOSAL
MAY 1998



1998

- First proposed as **ELITE** (European LIsa TEchnology) in 1998
  - Homodyne interferometer
  - Launch date 2002

A little bit of history...



1998

1st International LISA Symposium
Rutherford Appleton Laboratory
1996

A little bit of history...


ELITE

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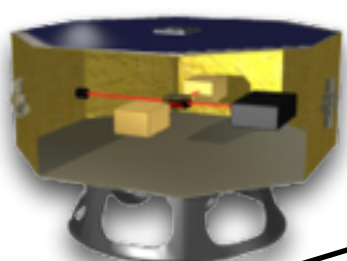
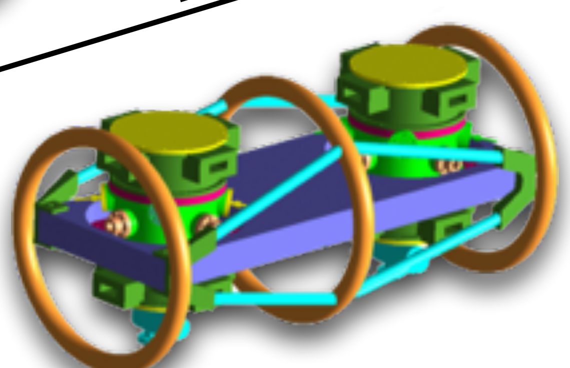
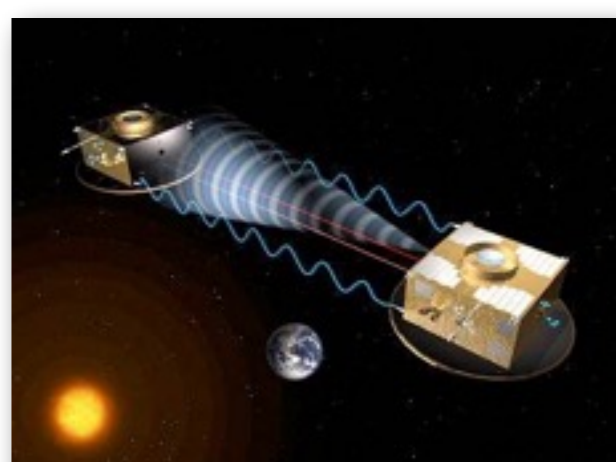


2002

1998





- ELITE proposal was refined and proposed to ESA in 2000 as **SMART-2**
  - Included LISA Pathfinder, ST-7 DRS, Darwin Pathfinder
  - Launch date 2006

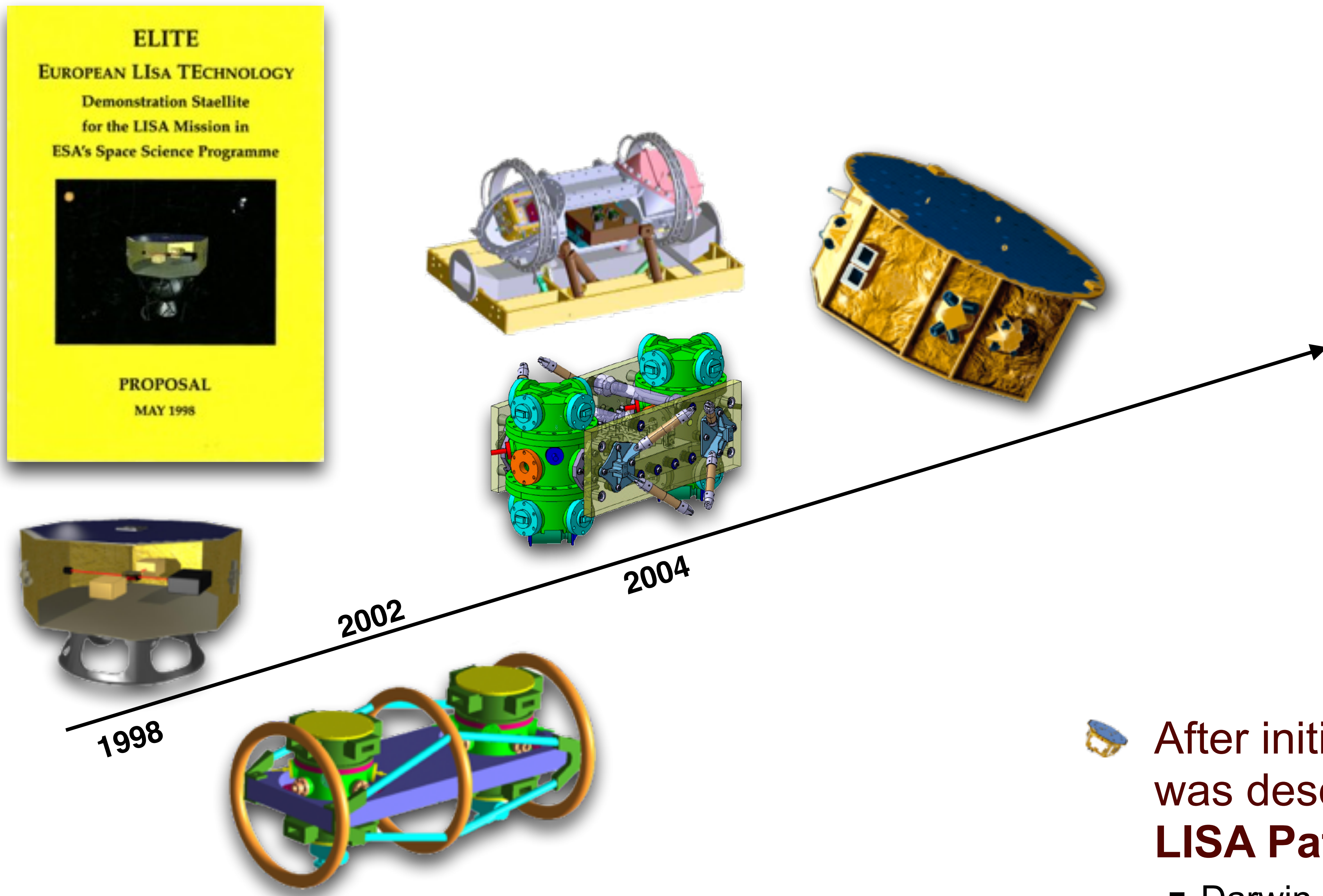
LISA Team on SMART-2 Proposal (2000)

The LISA Team

B. Allen	University of Wisconsin
J.W. Armstrong	Jet Propulsion Laboratory
P. L. Bender	University of Colorado
O. Blaes	University of California Santa Barbara
E.A. Boldt	Goddard Space Flight Center
A. Brillet	University Paris Sud
S. Buchmann	Stanford University
R.L. Byer	Stanford University
F. Cady	Montana State University
I. Ciufolini	University of Rome
A.M. Cruise	University of Birmingham
T. E. Chupp	University of Michigan
C. Cutler	Albert- Einstein-Institut
K. Danzmann	University of Hannover
D. B. DeBra	Stanford University
H. Dittus	ZARM - Bremen
F. Estabrook	Jet Propulsion Laboratory
T. Edwards	Rutherford Appleton Laboratory
F. Fidecaro	INFN- Sezione de Pisa
L.S. Finn	Pennsylvania State University
W.M. Folkner	Jet Propulsion Laboratory
J.H. Hall	University of Colorado
R.W. Hellings	Jet Propulsion Laboratory
D. Hills	University of Colorado
W. Hiscock	Montana State University
C. Hogan	University of Washington
J. Hough	Glasgow University
Y. Jafry	ESTEC
G.M. Keiser	Stanford University
P. McNamara	Glasgow University
R.D. Newmann	University of California Irvine
M. Peterseim	Max-Planck-Institut für Quantenoptik
E.S. Phinney	California Institute of Technology
T.A. Prince	California Institute of Technology
J.C. Ray	John Hopkins APl
D.O. Richstone	University of Michigan
D. Robertson	Glasgow University
M. Rodrigues	ONERA
R. Reinhard	ESA
A. Rüdiger	Max-Planck-Institut für Quantenoptik
M.C.W. Sandford	Rutherford Appleton Laboratory
G. Schäfer	University of Jena
R. Schilling	Max-Planck-Institut für Quantenoptik
B. Schutz	Albert-Einstein-Institute
M. Shao	University of Illinois
S. Shapiro	Jet Propulsion Laboratory
D. Shoemaker	Massachusetts Institute of Technology
C. Speake	University of Birmingham
R.T. Stebbins	University of Colorado
T. Summer	Imperial College
B. Teegarden	Goddard Space Flight Center
K. Thorne	California Institute of Technology
M. Tinto	Jet Propulsion Laboratory
P. Touboul	ONERA
E.L. Turner	Princeton University
J.-Y. Vinet	University Paris Sud
S. Vitale	University of Trento
H. Ward	Glasgow University
R. Weiss	Massachusetts Institute of Technology
W. Winkler	Max-Planck-Institut für Quantenoptik

RED: LISA Pathfinder team, GREEN: ST7 team

A little bit of history…



- After initial study, SMART-2 was descoped and renamed **LISA Pathfinder**
  - Darwin Pathfinder cancelled
  - Single s/c, with two payloads: LTP and DRS

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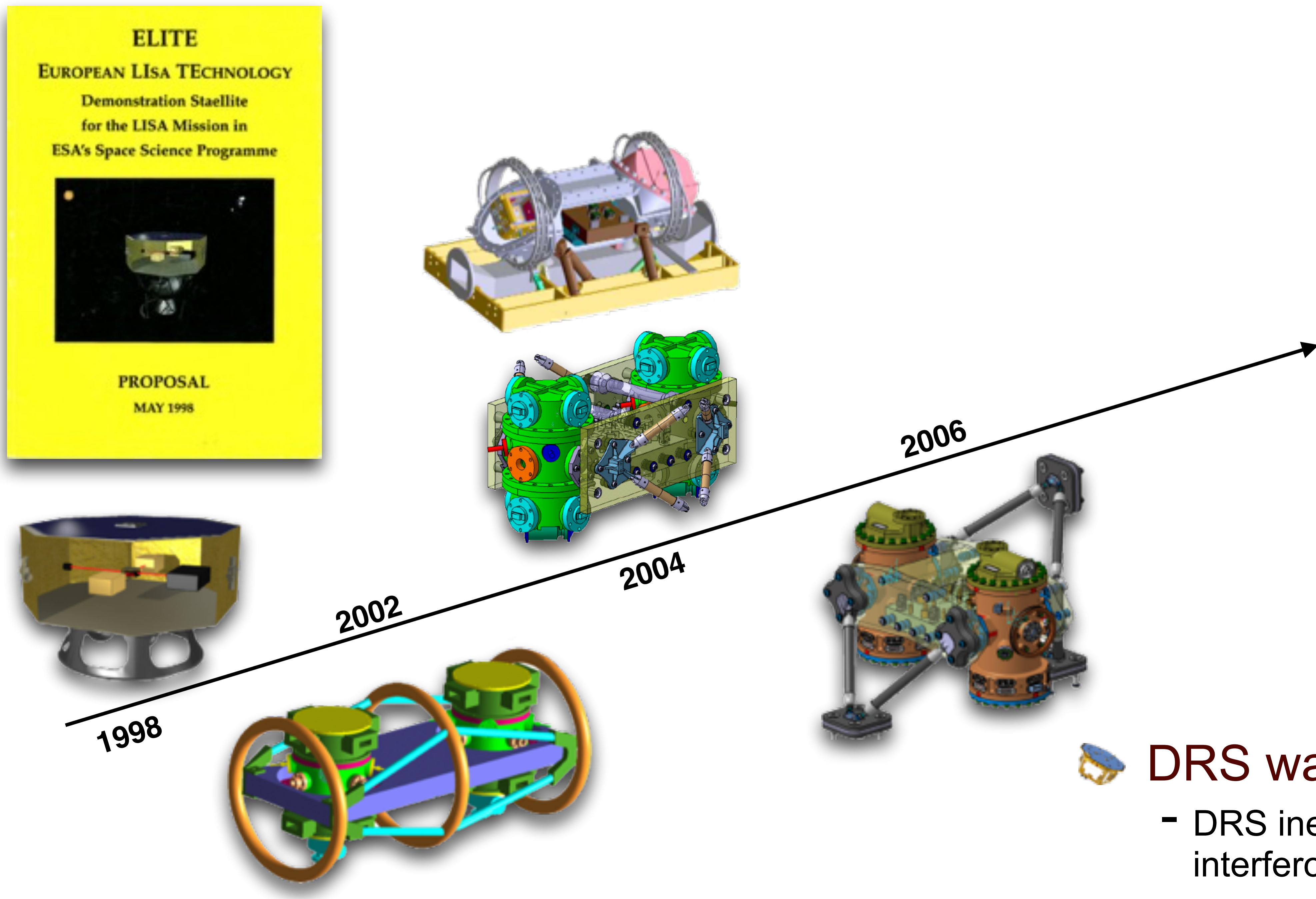
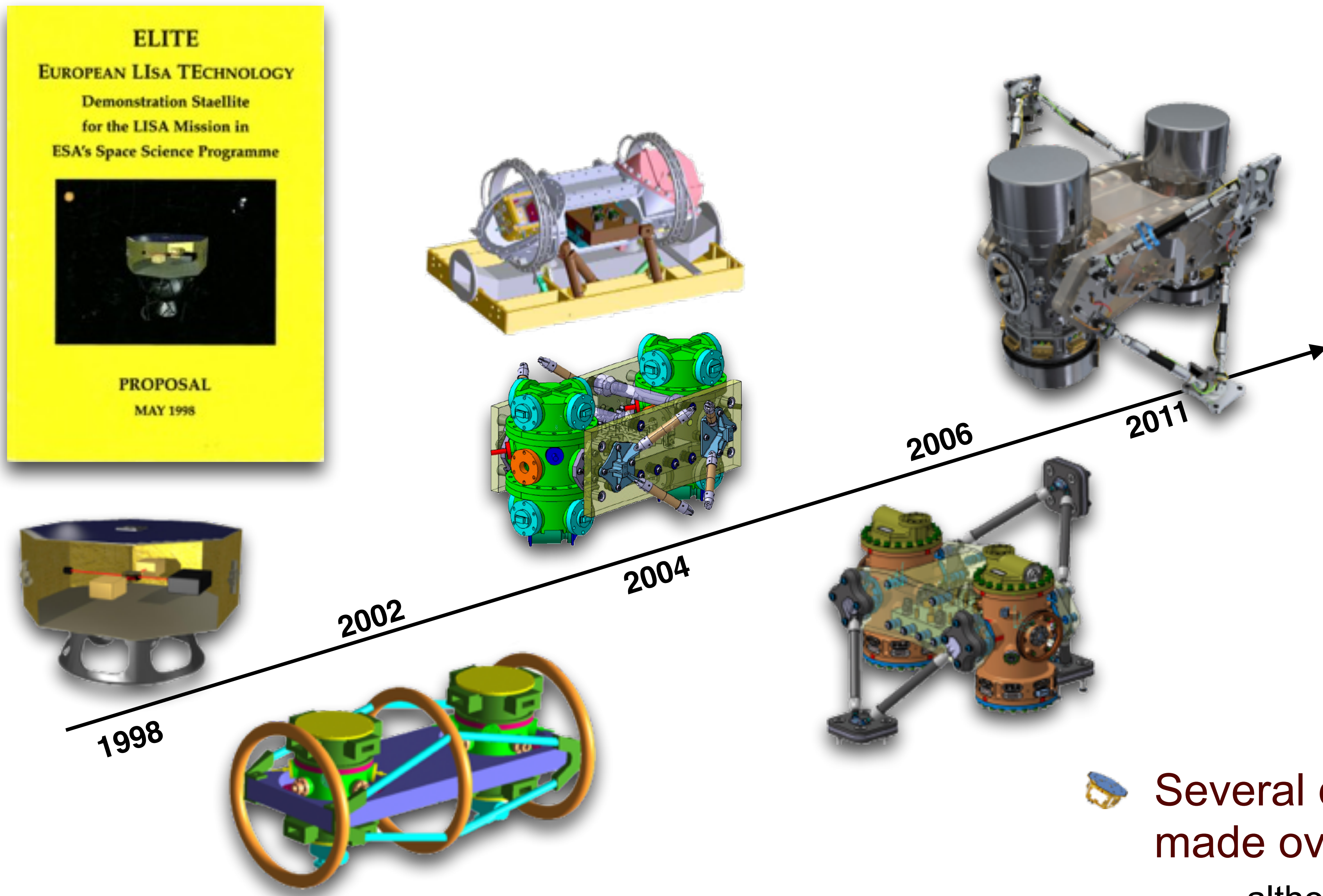
A little bit of history…



- DRS was descoped in 2005
  - DRS inertial sensor and interferometer cancelled
  - DRS now uses the LTP inertial sensor

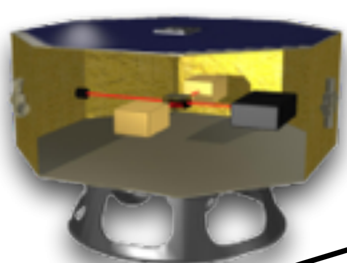
A little bit of history…

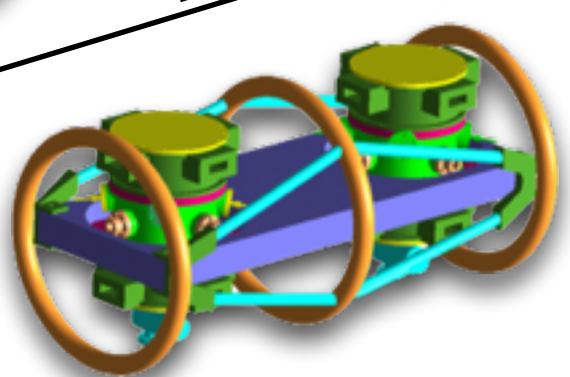


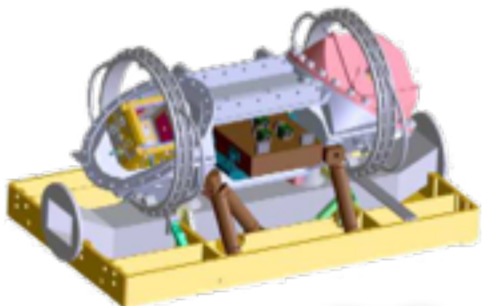
- Several design changes were made over the years….

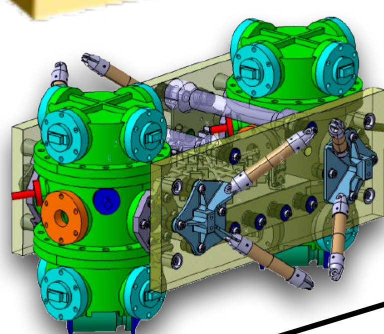
  ….although the underlying concept has been stable since the beginning

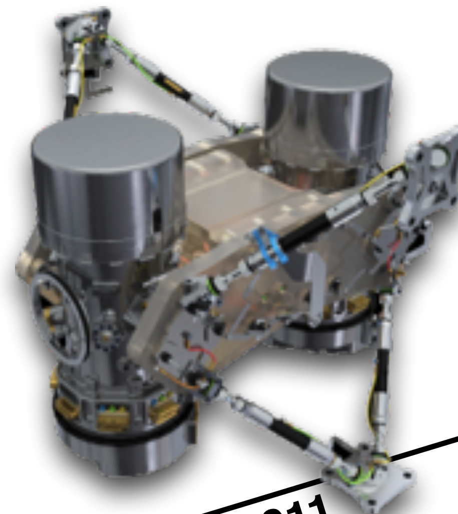
A little bit of history…











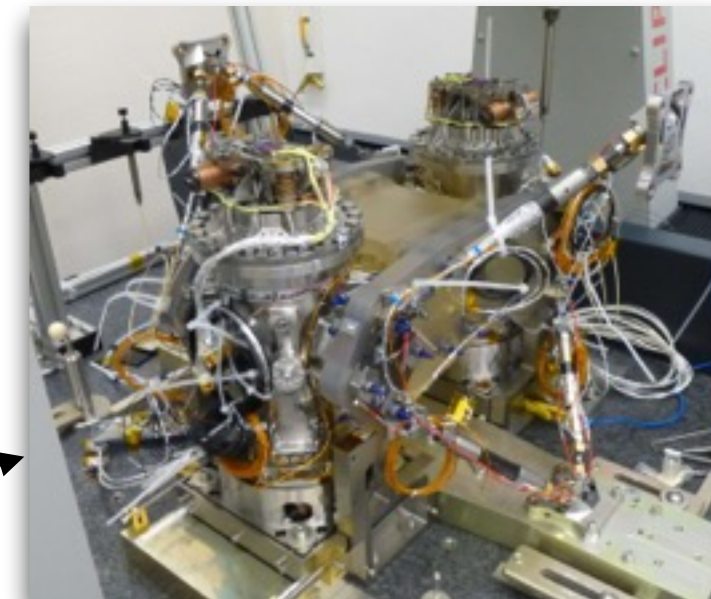
1998

2002

2004

2006

2011



2015

- The LISA Technology Package (LTP) was delivered in May 2015

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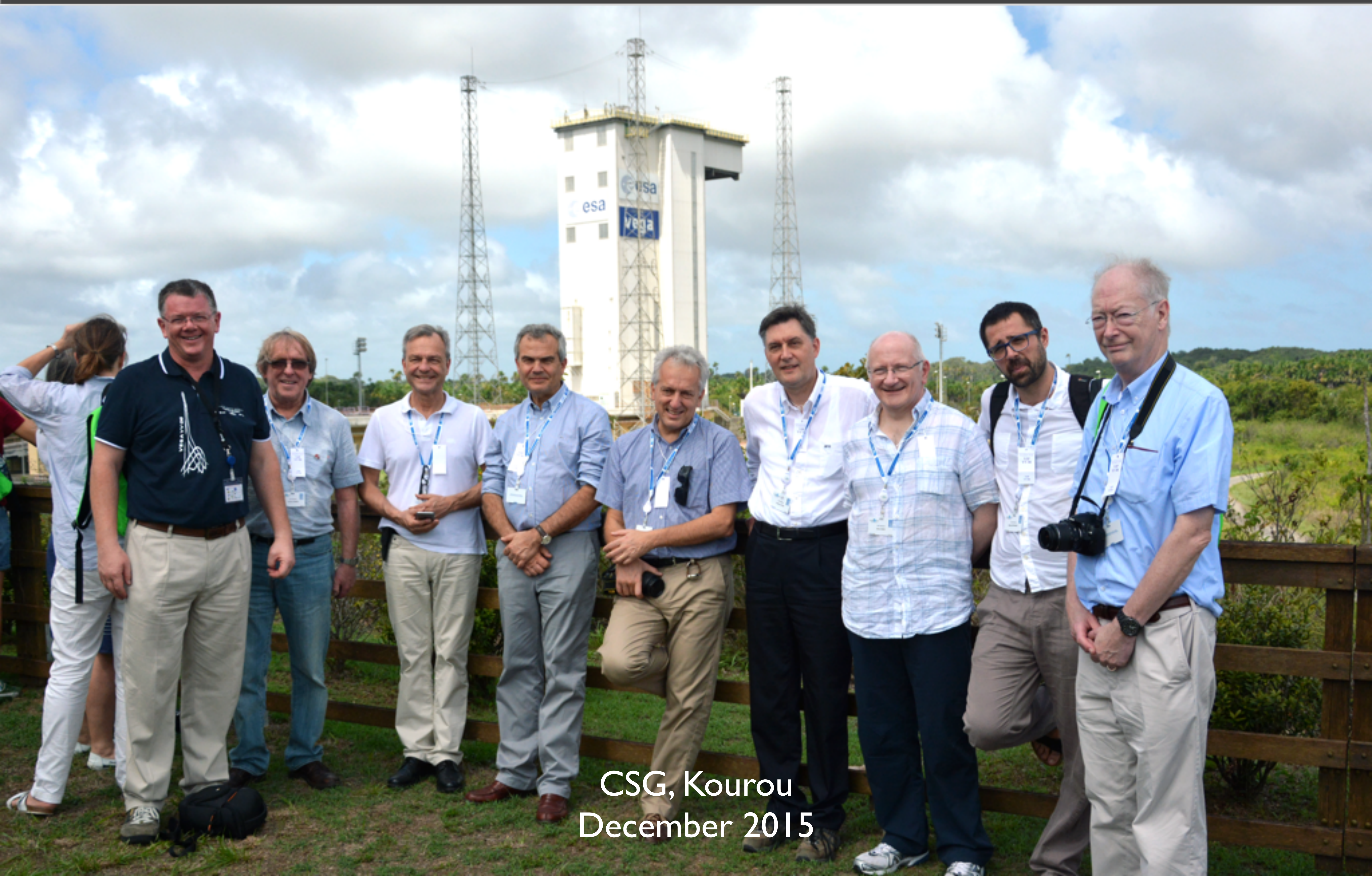
At the launch site...



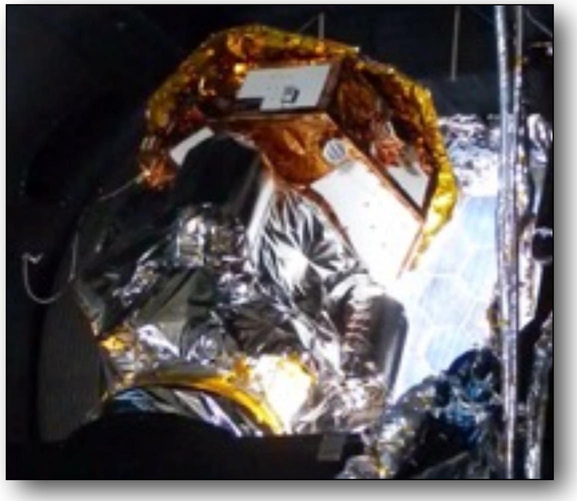
Uniqueness of space missions

- Unlike ground based detectors, space missions have a wealth of unique constraints which must be overcome, e.g.
  - Launch…intense vibration and acoustic noise
  - Eclipses…large thermal swings during low earth orbits
  - Radiation…especially when passing through the belts
  - Mass…we need to get it there
  - Power…we only use *green* energy!
  - Communications…LPF is in orbit around L1 (1.5million km from Earth)
- In addition, ‘commissioning’ must be done *before* launch
  - After launch, we don’t have many knobs to turn!

LPF on shaker table to simulate launch conditions
z-axis swept sine

Some numbers...

- Vibration
  - During launch we subject our very delicate s/c to ~141dB broad band acoustic noise (peak at ~100Hz)
- 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
- Mass
  - Not only total mass, but where it is located…



Christian Trenkel
Engineering LISA Pathfinder

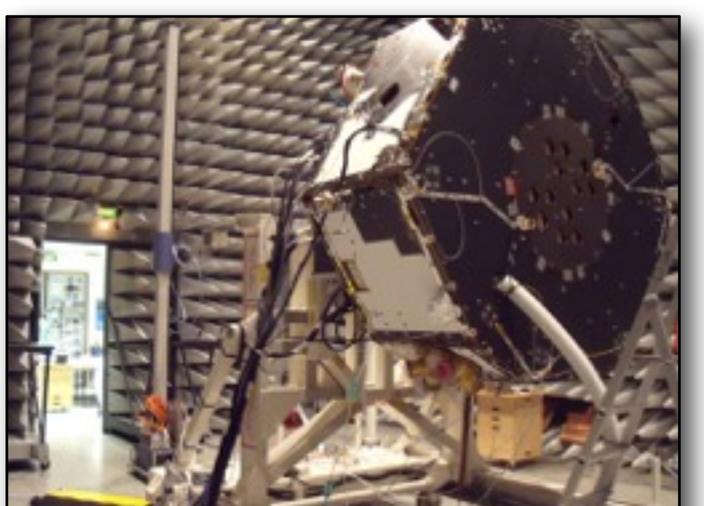
Ground Testing

- We only have one shot on orbit…

…therefore, we spend years testing on the ground

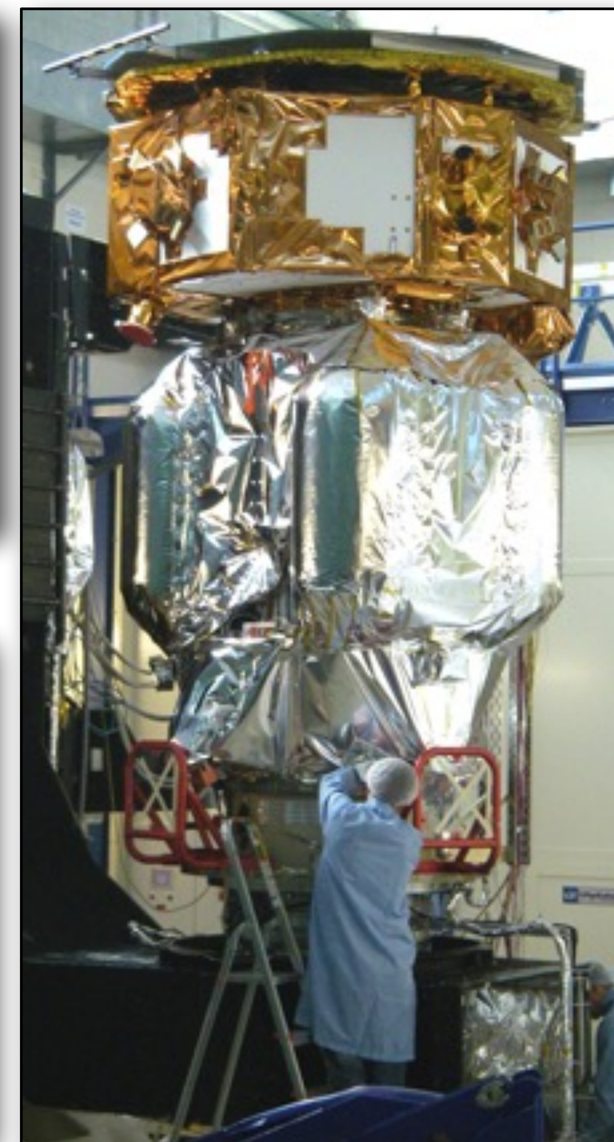
Vibration/shock tests

Closed-loop tests



EMC

On-Station Thermal Test



Transfer Orbit Thermal Test

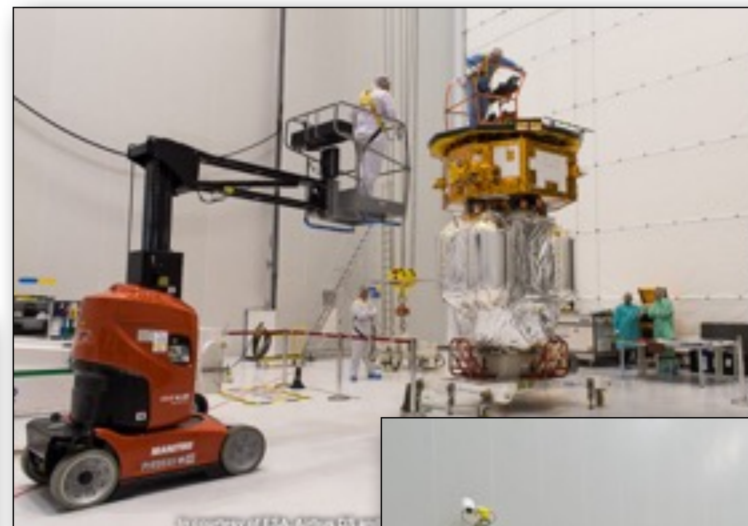
Launch Vehicle Fit Check

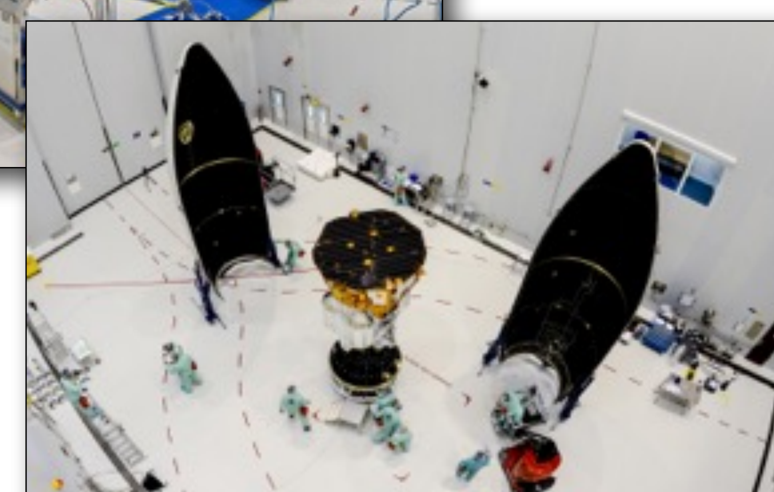
Credit: Airbus Defence and Space and IABG

And then it gets serious.... ...the launch campaign

- LPF was transported to the launch site on 8th October 2015
- The launch campaign was short, but intense…







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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

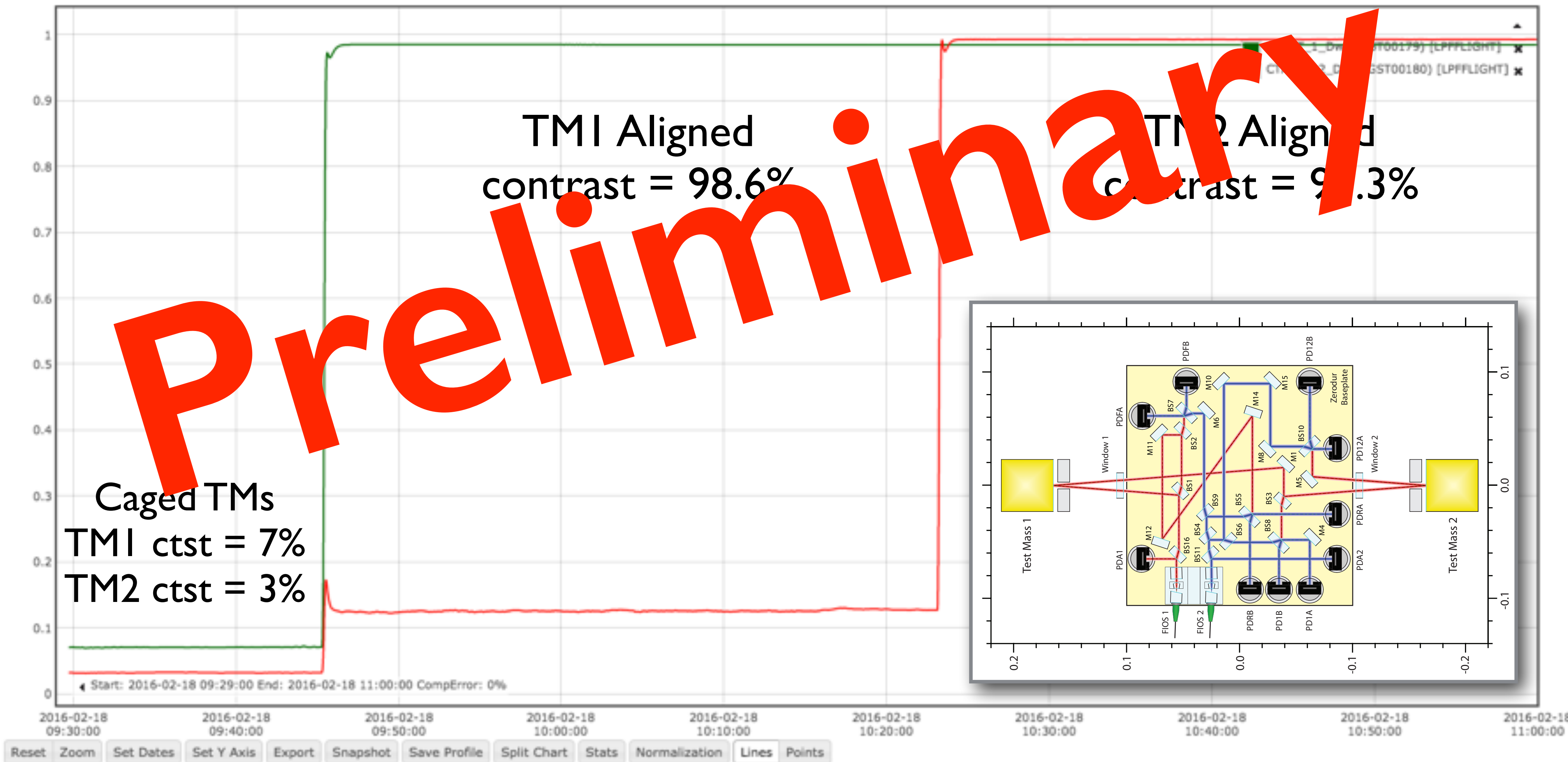
Operations Timeline

Date	Milestone
3 December ‘15	Launch of LISA Pathfinder
11 January	Switch-on of the LISA Technology Package
2 February	Release of test mass launch locks and opening of venting valve
15 & 16 February	Test mass release → free floating test masses
18 February	Alignment of the laser interferometer
22 February	First entry to Science Mode
1 March	Start of Science Operations
25 June	End of LTP Science Ops & start of DRS Ops
27 June	DRS Commissioning, Phase 2
15 December	End DRS Operations, start extended mission
31 May 2017	End of mission

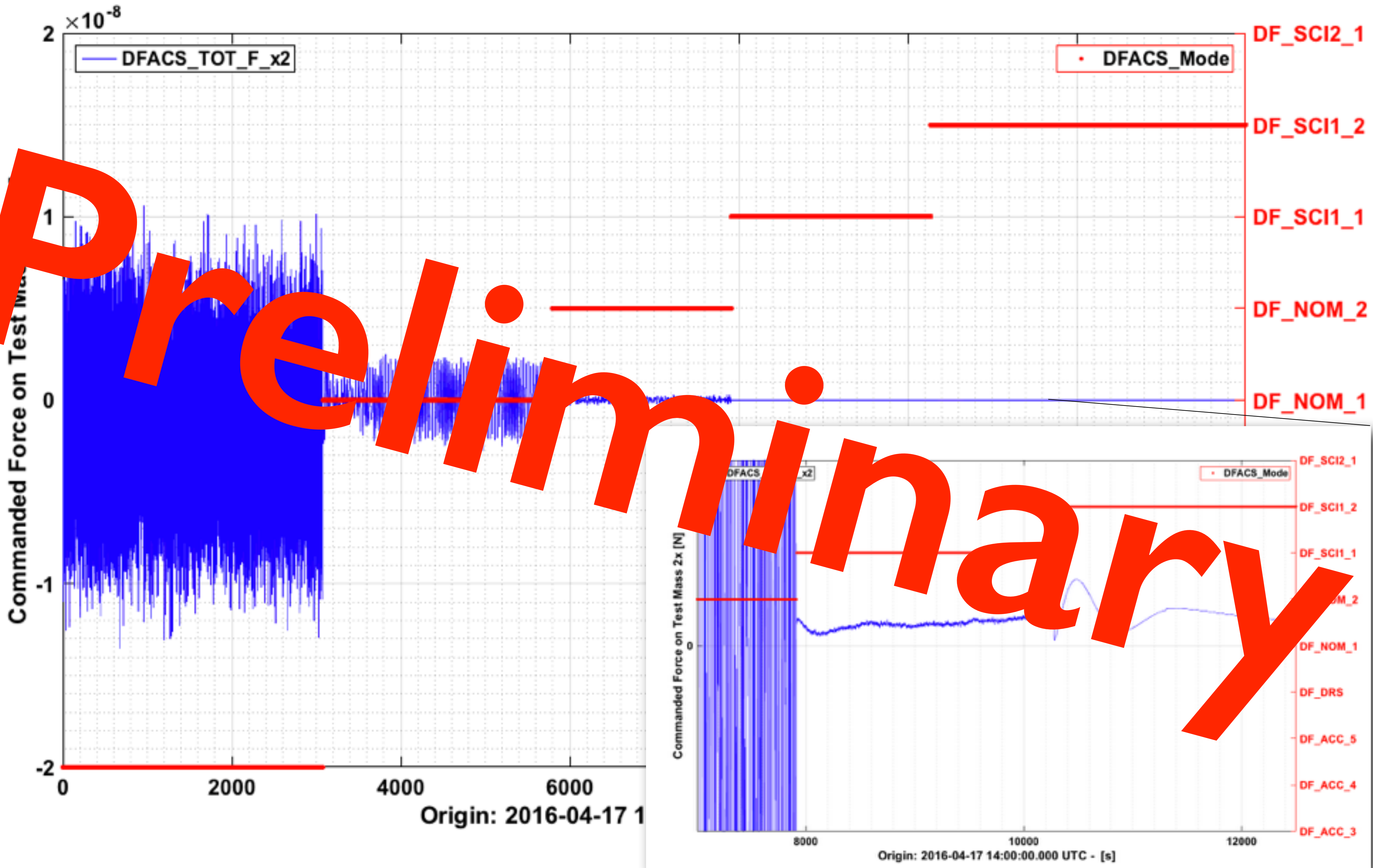
Highlights of commissioning [1]

Interferometer alignment

- Test masses are controlled to align the interferometer (using differential wavefront sensing)
- Alignment is outstanding!

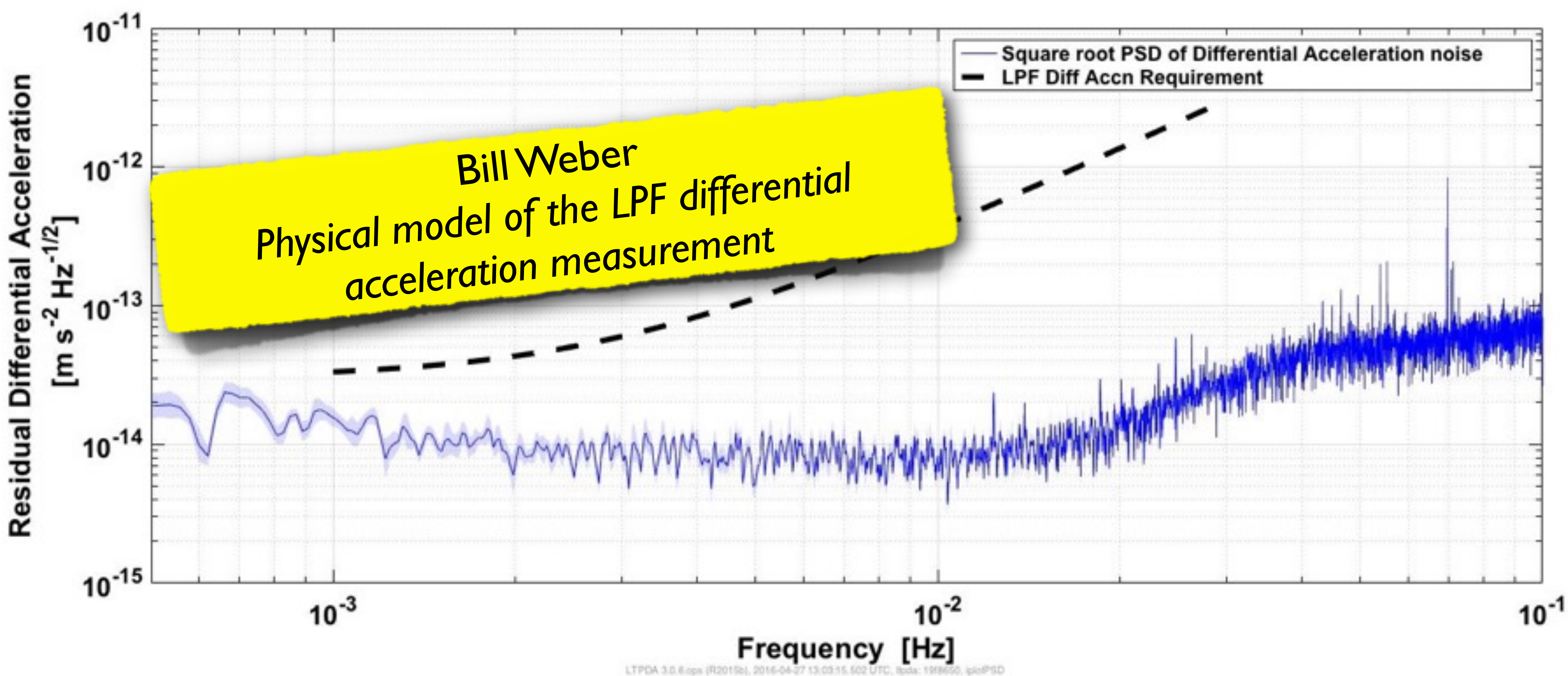


Transition from Acc3 to Science Mode: Commanded Force on TM2x

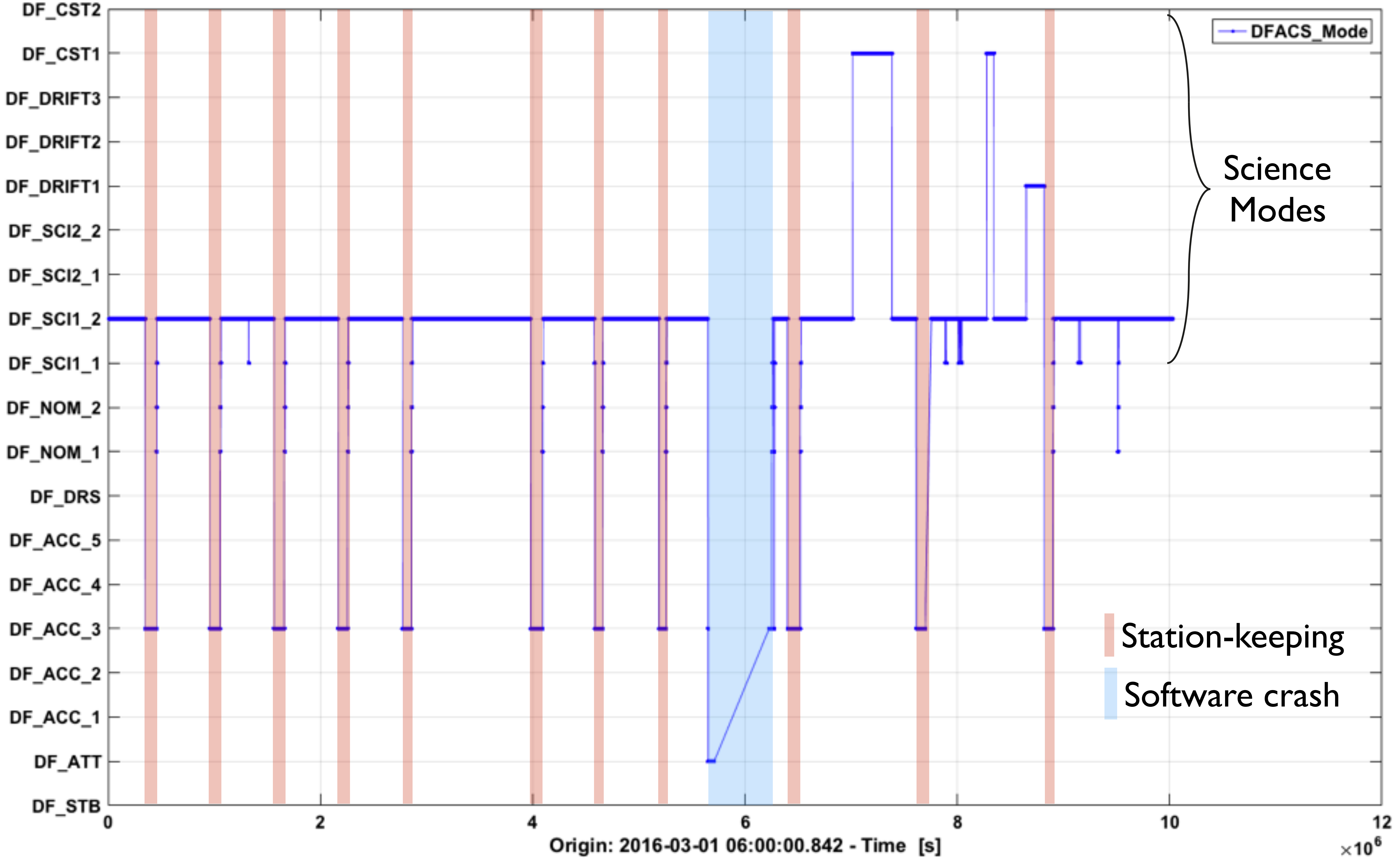


Highlights of commissioning [2]

- The first measurement of the differential acceleration, before we even started science operations, already met the performance requirements!
  - LPF worked "straight-out-of-the-box"



Operational Duty Cycle



Day-to-day operations

DOY154: 02/06/16, (08:00 – 08:00)

Location: unknown

	08:00	–	07:30	DWS Noise Floor	inv06602:V001	[1410']

DOY155: 03/06/16, (08:00 – 08:00)

Location: unknown

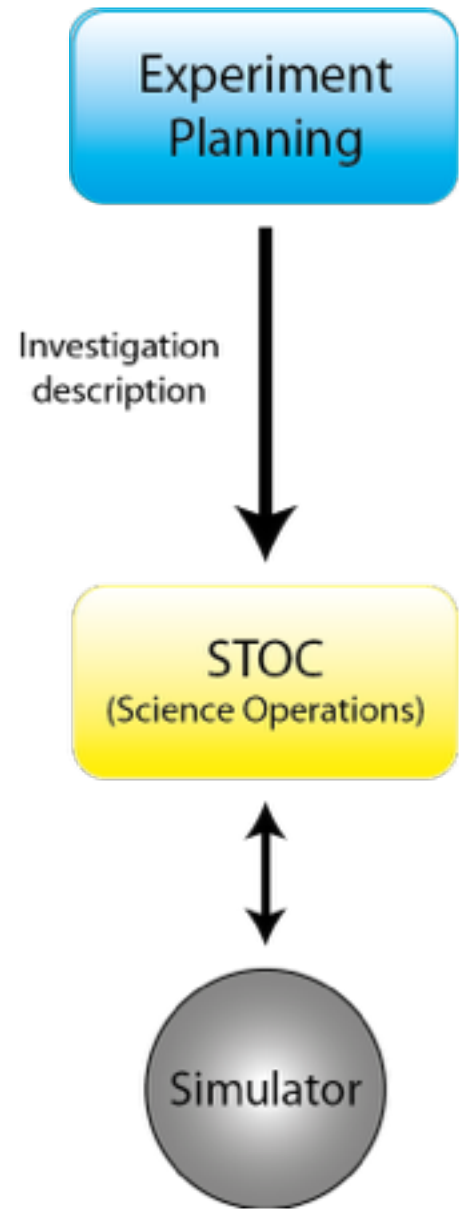
	08:00	–	08:10	Set max force authority to UURLA	con_fee_maxf___:V022	[10']
	08:10	–	08:12	Unload SDM19	con_SDM19_unload:V001	[2']
	08:12	–	08:14	Load SDM20	con_SDM20_load__:V001	[2']
	08:14	–	19:14	(Short) Charge Burst - TM1	inv04210:V007	[660']
	19:14	–	06:14	(Short) Charge Burst - TM2	inv04220:V007	[660']
>	06:14	–	08:10	Discharge TMs	inv04330:V001	[116']

DOY156: 04/06/16, (08:00 – 08:00)

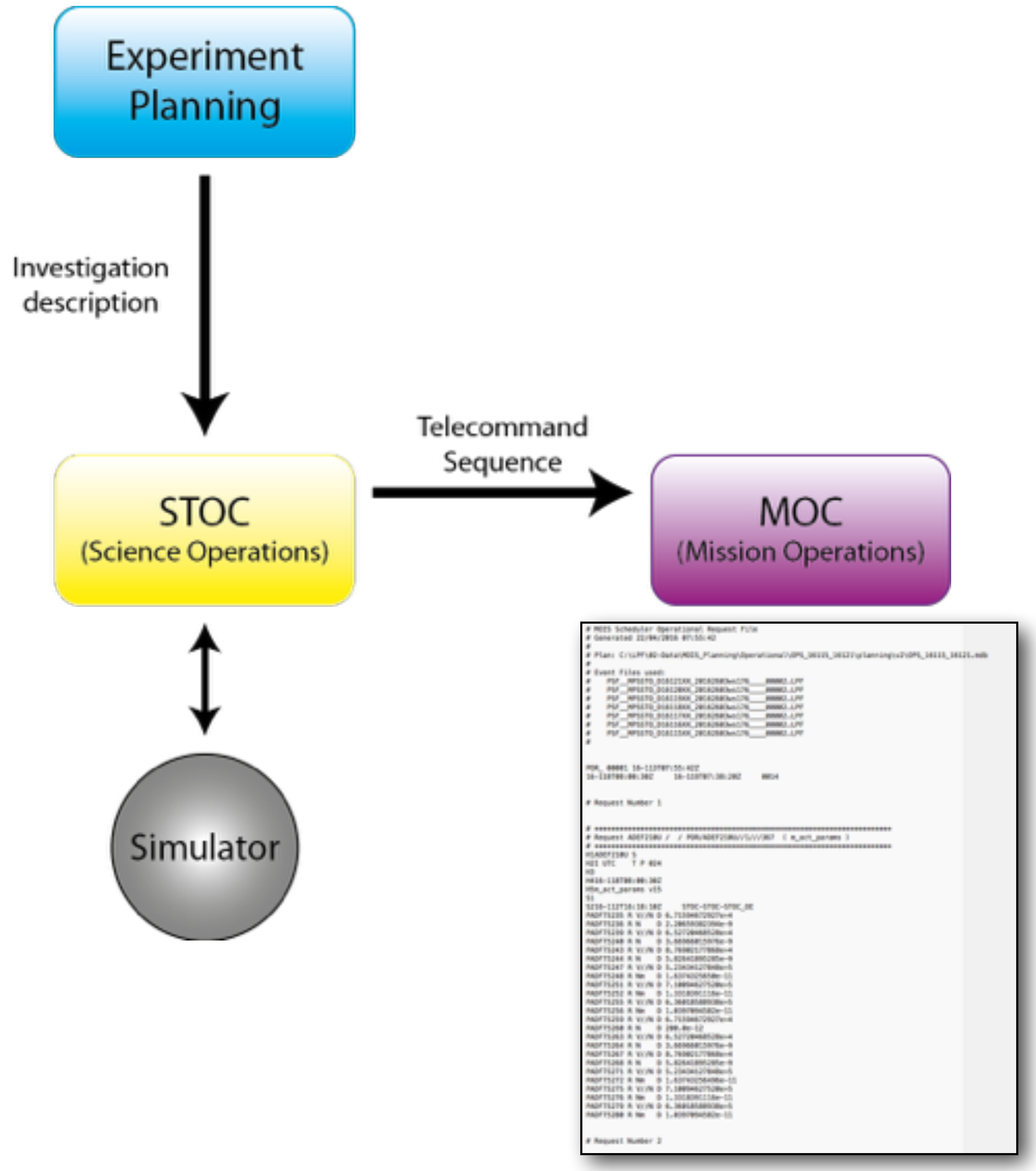
Location: unknown

	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']

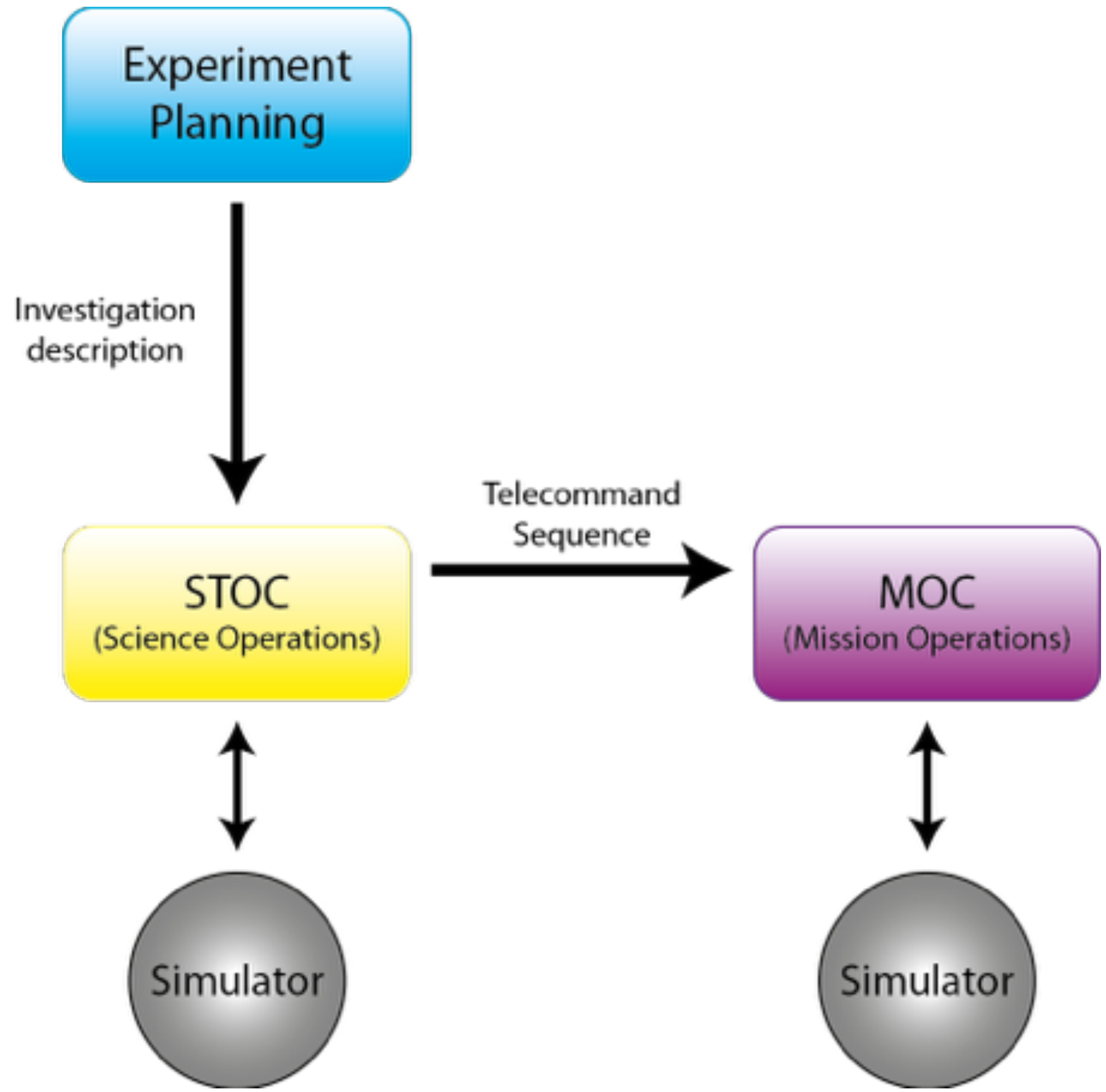
Day-to-day operations



Day-to-day operations



Day-to-day operations



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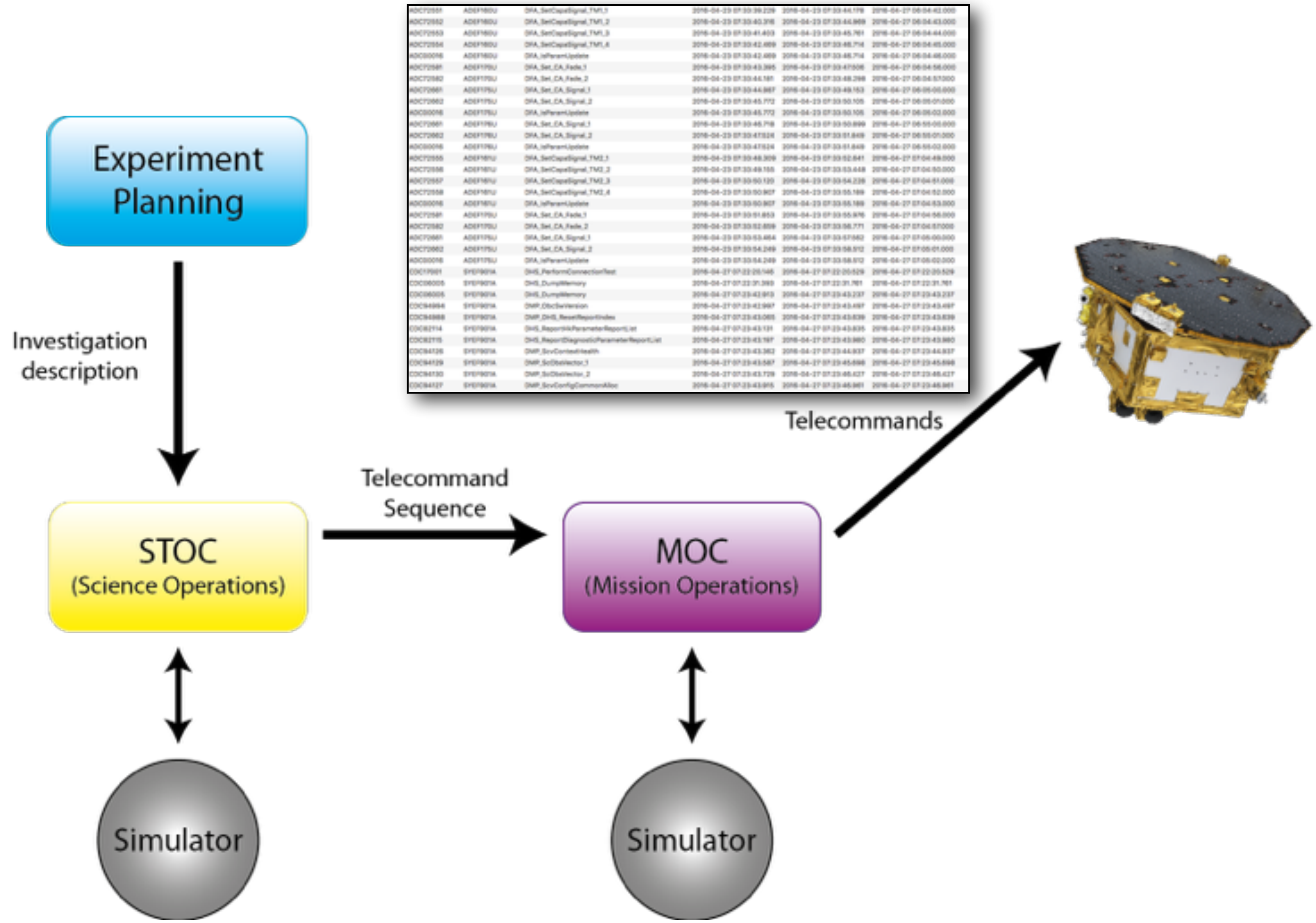
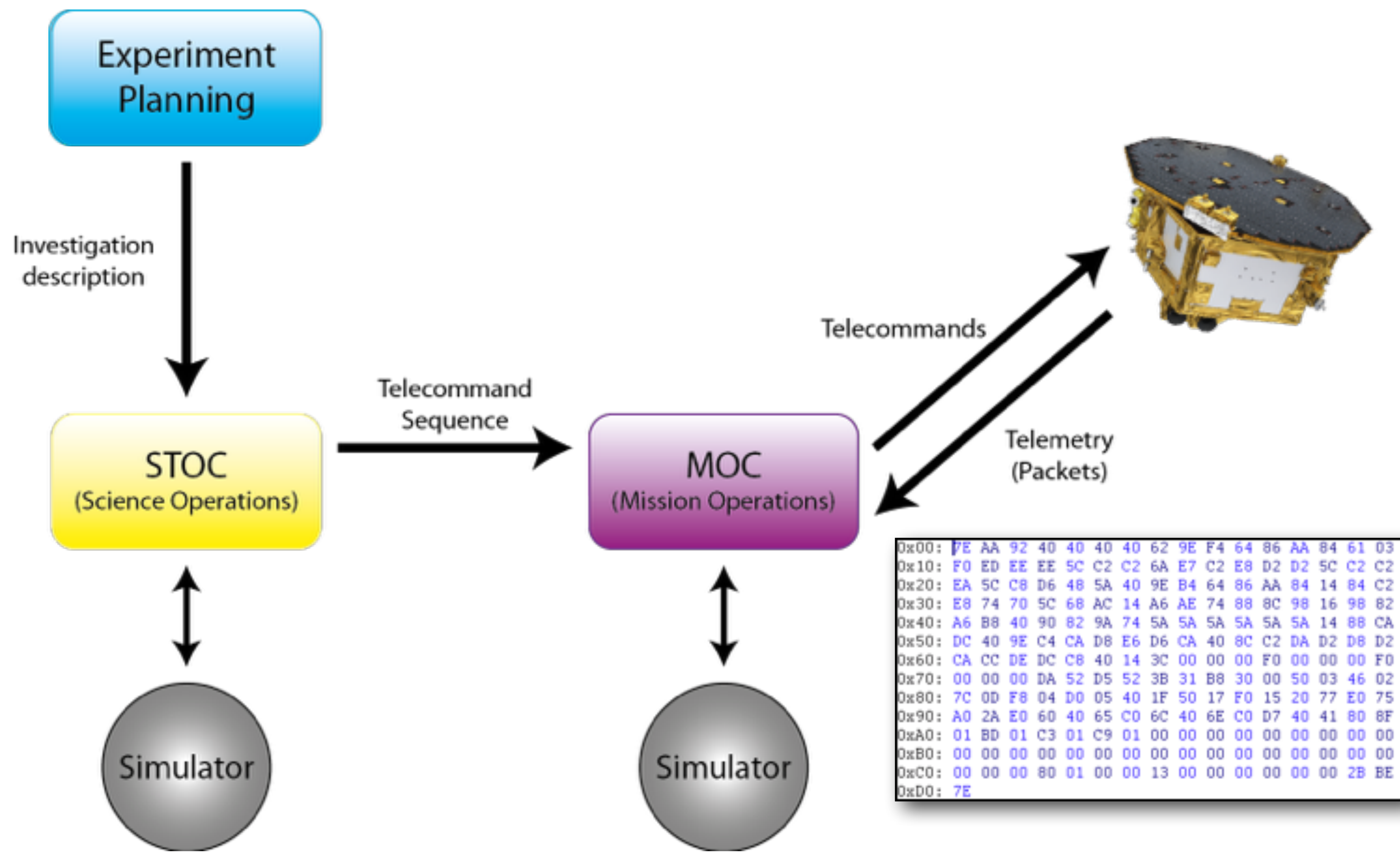
Day-to-day operations



Day-to-day operations



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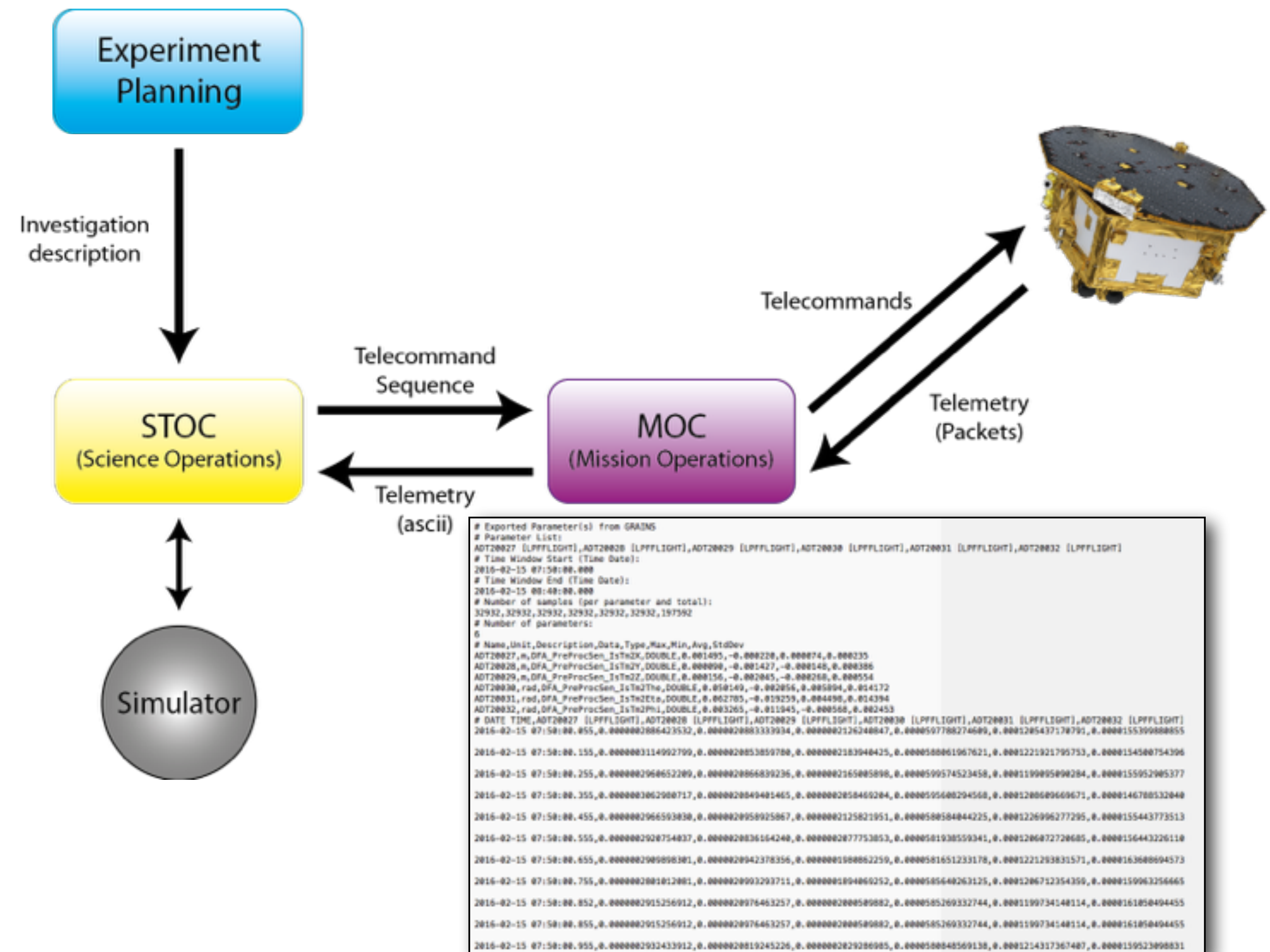
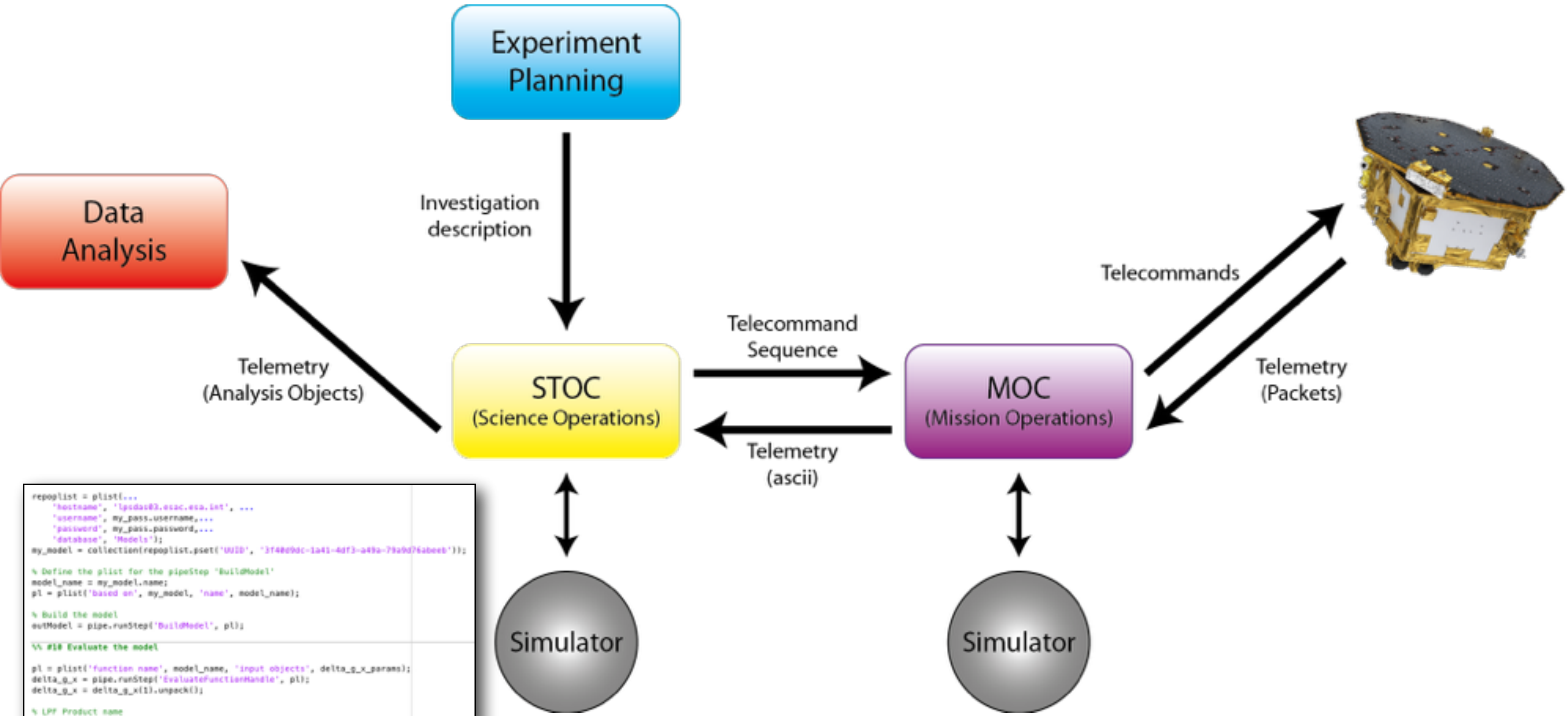
Day-to-day operations

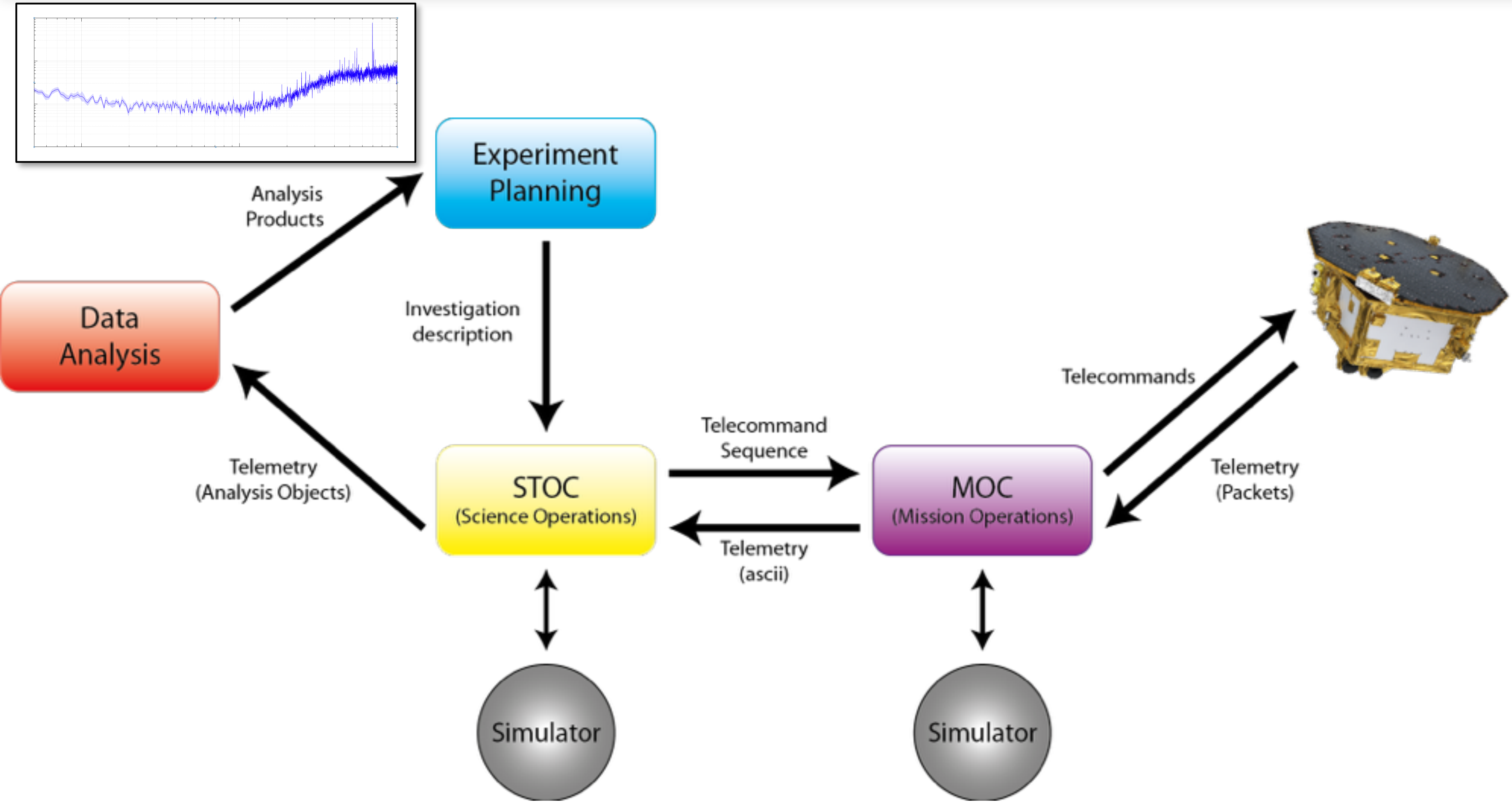


Day-to-day operations




```
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;
```

Day-to-day operations



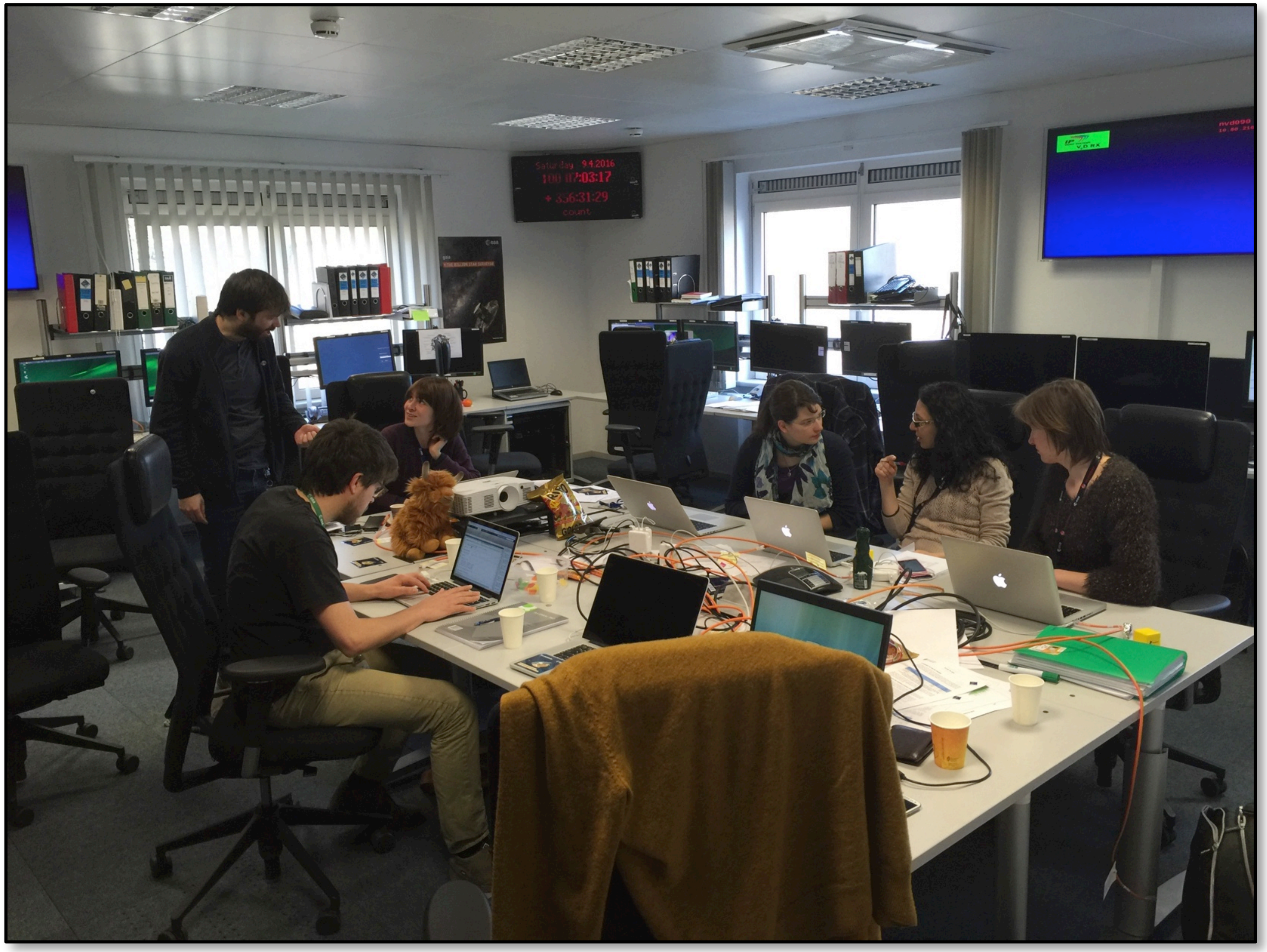
LTP Science Operations

- Some figures:
  - 92 days of science operations
  - Equal to **2214 hours** of data taking, of which:
    - **1491 hours** of noise measurement (taking data with no injections)
    - **723 hours** of 'active" investigations
      - From a total of 136 investigations
  - **~20GB** of data
  - ~24 days of MOC activities (e.g. station keeping)
  - 193 simulation equivalent days for scientific validation
    - 138 of which were unique investigations
  - Minimum of two data analysis teams at ESOC each day during science operations
    - In addition we had:
      - Other scientists (PS, PI, DA managers)
      - MOC team (several engineers and Spacon)
      - STOC team (Operations manager, engineers (x2), scientist)

The LTP team at ESOC

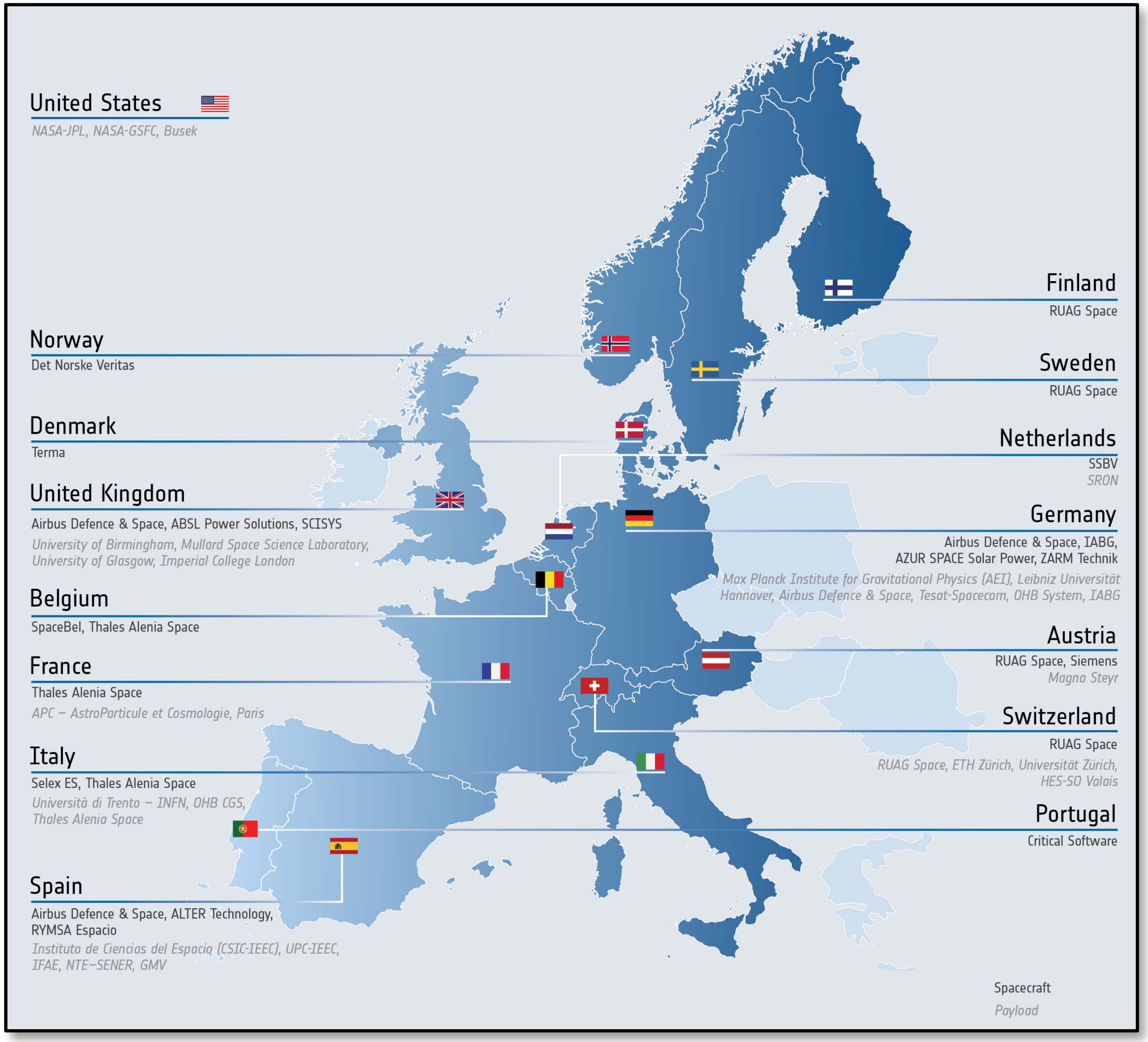
LTP Commissioning Team

The LTP team at ESOC



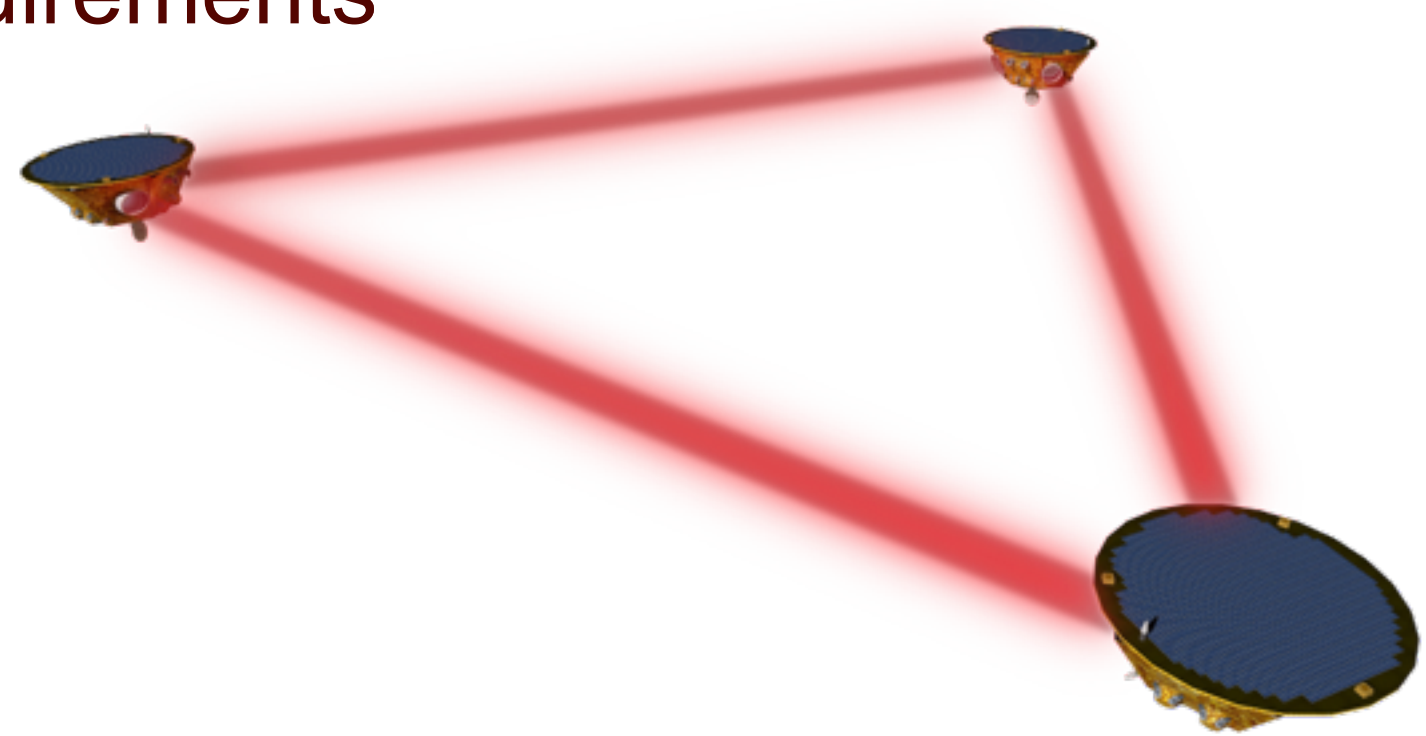
LPF: An international success

- 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
- All system performance requirements met *before* science operations began
- We are now approaching, or are have already met, the LISA performance requirements
- Next step…..LISA!



Thank you

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Airbus Defence and Space D
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

IFR Stuttgart
Thales Alenia Italy
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