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lisa pathfinder

LISA Pathfinder

Experiment details & results

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for the LPF Team
ASTROD 2nd International Workshop, Taiwan
May 2017

Contents

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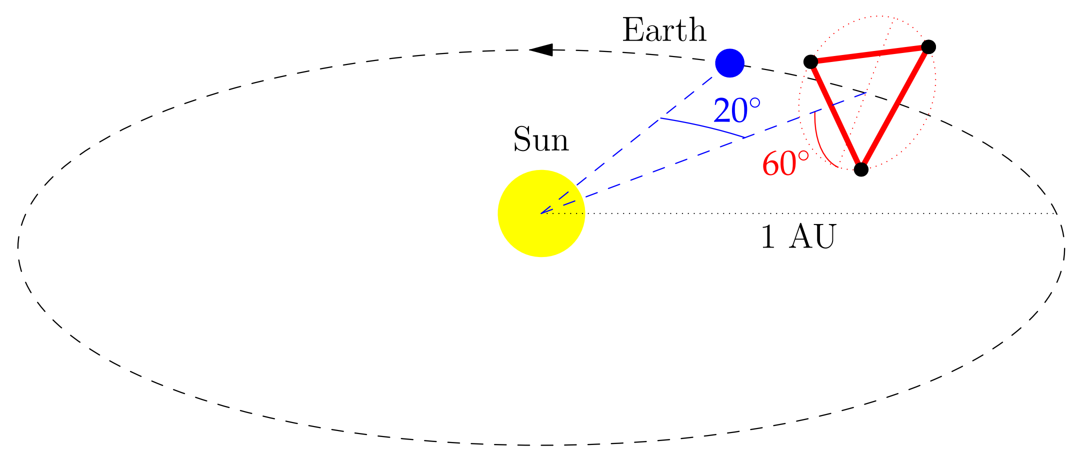
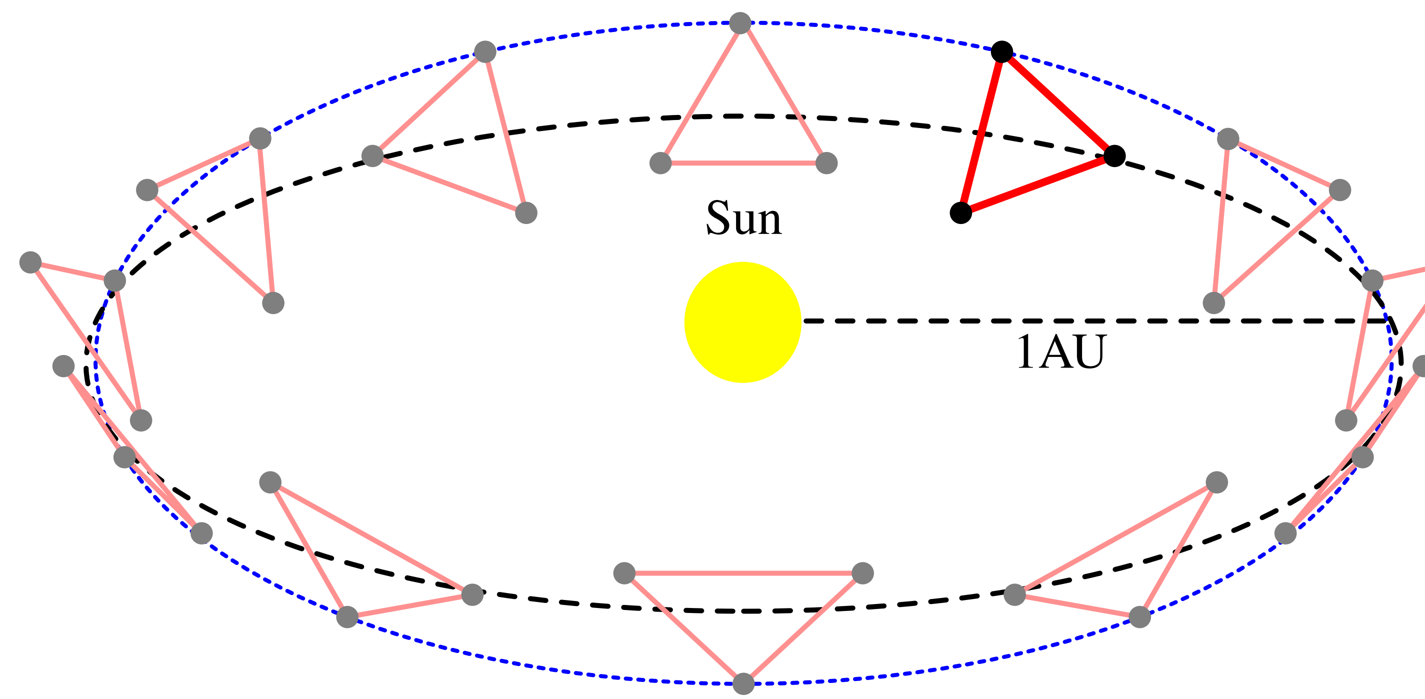
- Mission aims
- Experiment plan
- Example experiments
- Conclusions

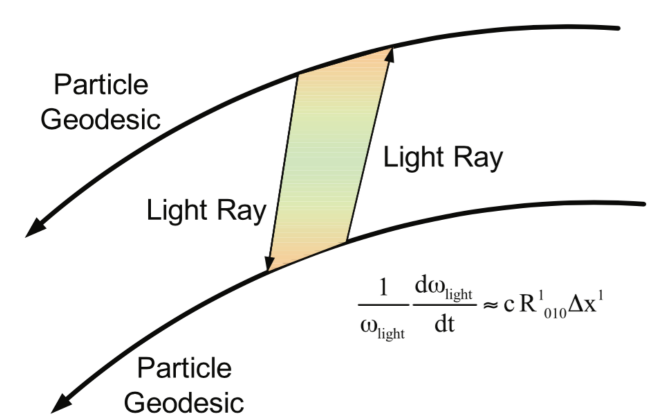
Introduction

The LISA Measurement Concept

- Probe the change in proper time between free-falling test masses caused by GWs
- Free-falling test masses are housed in drag-free spacecraft separated by a few million km
- Proper time is inferred by the time of flight of photons exchanged between the satellites
- We have multiple transponder links from which we can form a Michelson-like signals







LISA Performance

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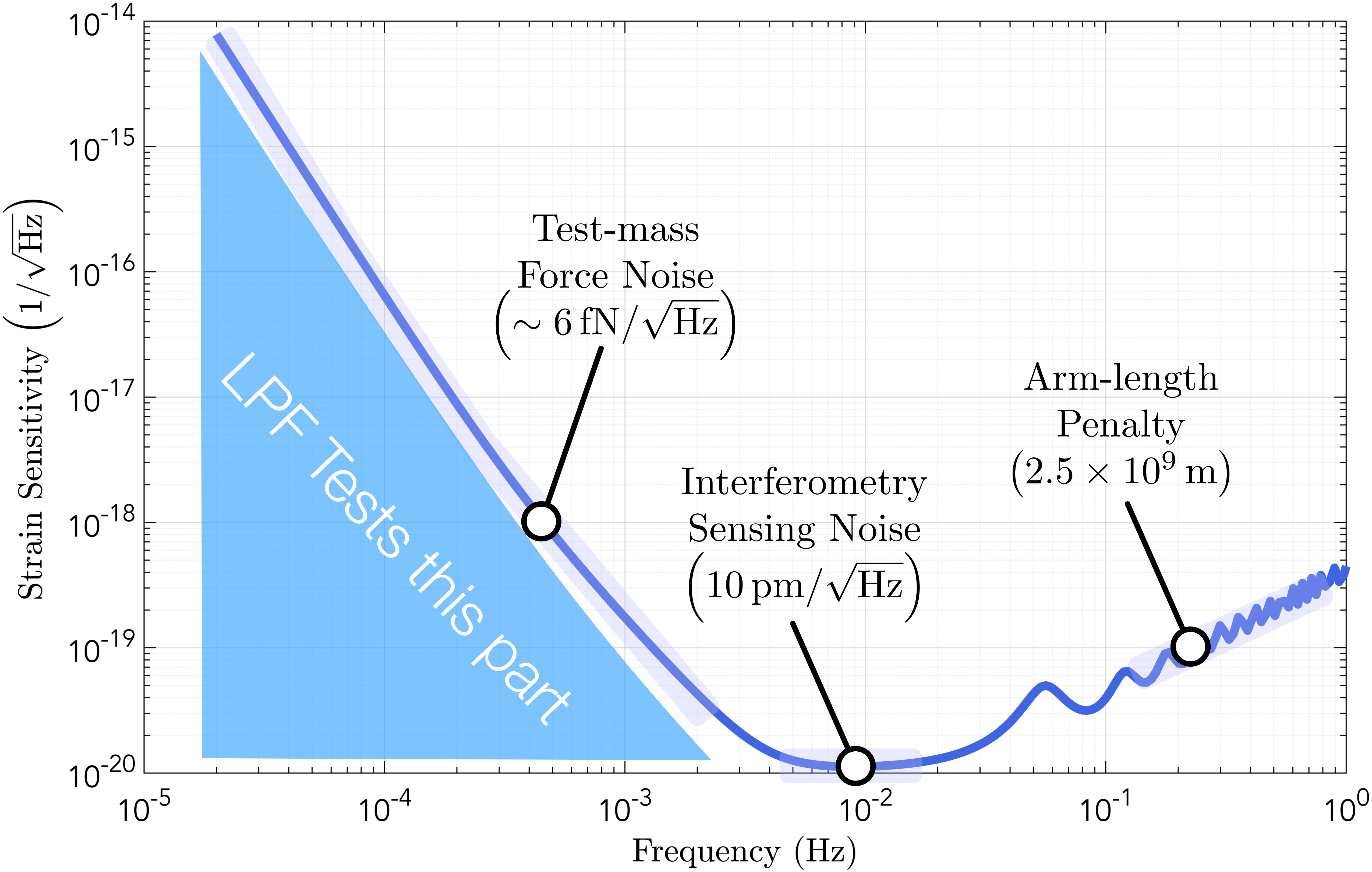

LISA Pathfinder

- Aims to test a lot of the LISA performance budget
  - all relevant local test mass disturbance forces
  - local interferometry
- And much of the critical technology
  - drag-free control
  - test mass charge control
  - gravitational balancing
  - SC environment control (thermal, magnetic)
- Additional payload from NASA (ST7) to demonstrate
  - alternative drag-free control
  - alternative micro-Newton thrusters

Control concept on LPF

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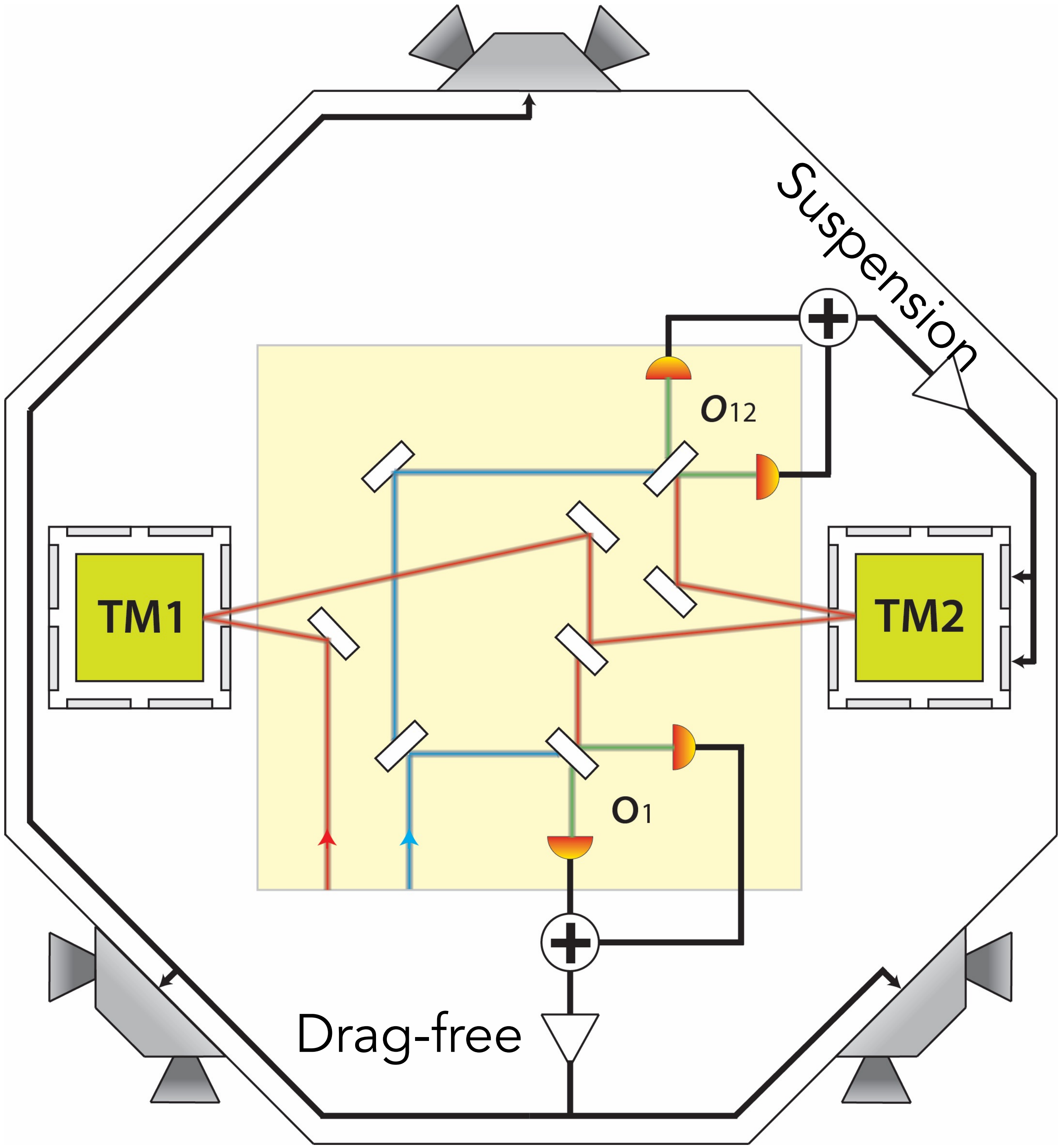
- Shrink a LISA arm from 2.5 Gm to 38 cm
- Free-falling test mass
- Drag-free satellite
- Suspended witness mass

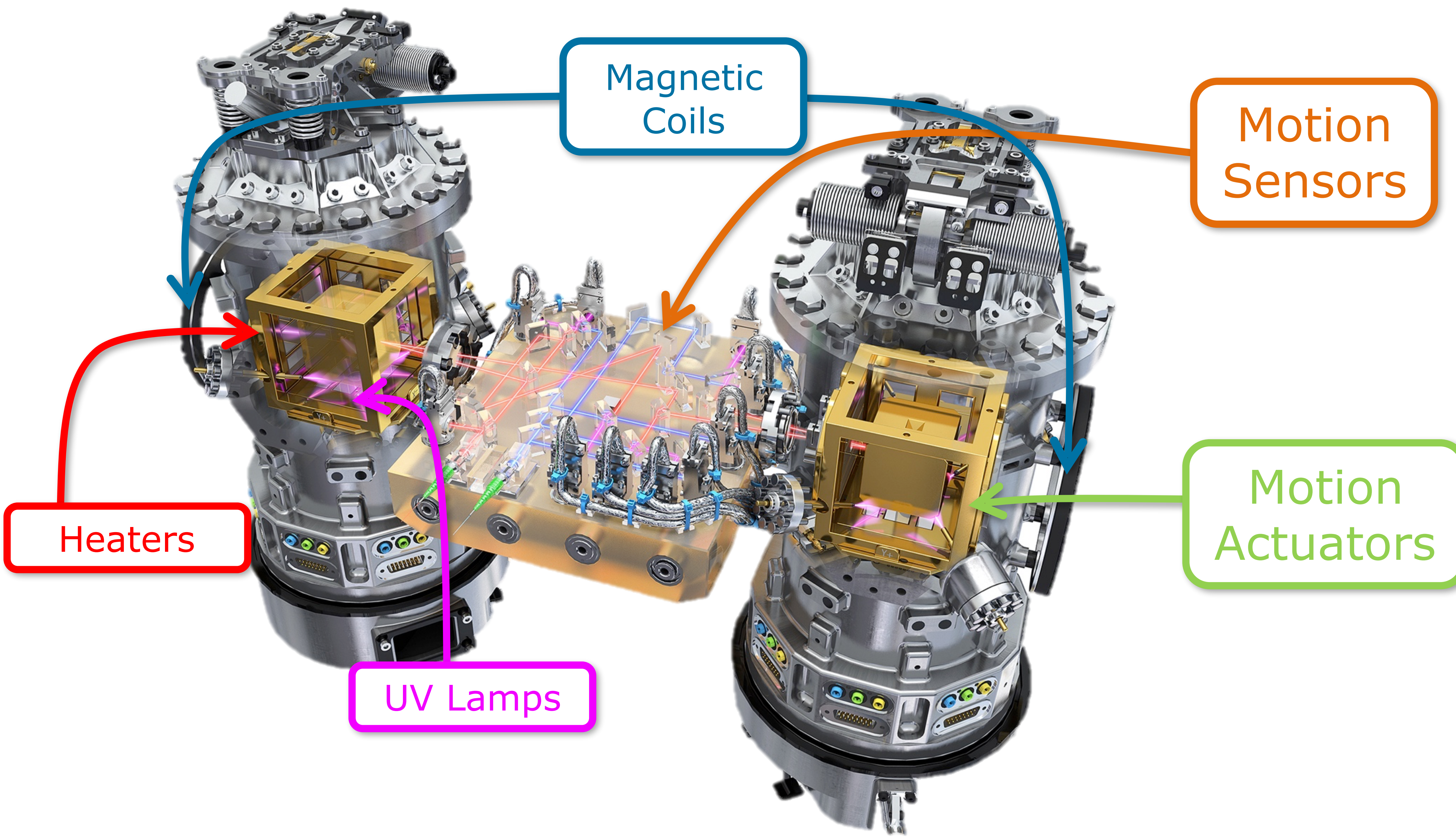


Metrology

Assess relative acceleration of test masses
by measuring their relative motion using an interferometer

Goal is to measure changes with a precision of
a few pm/√Hz at millihertz frequencies

Physics Lab in Space



Timeline

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- All hardware delivered and integrated mid-2015
- Launch campaign from September to December
- Launch on December 3rd 2015
- Science operations since March 1st 2016


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PYRO CAPS
NR2
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finder
space


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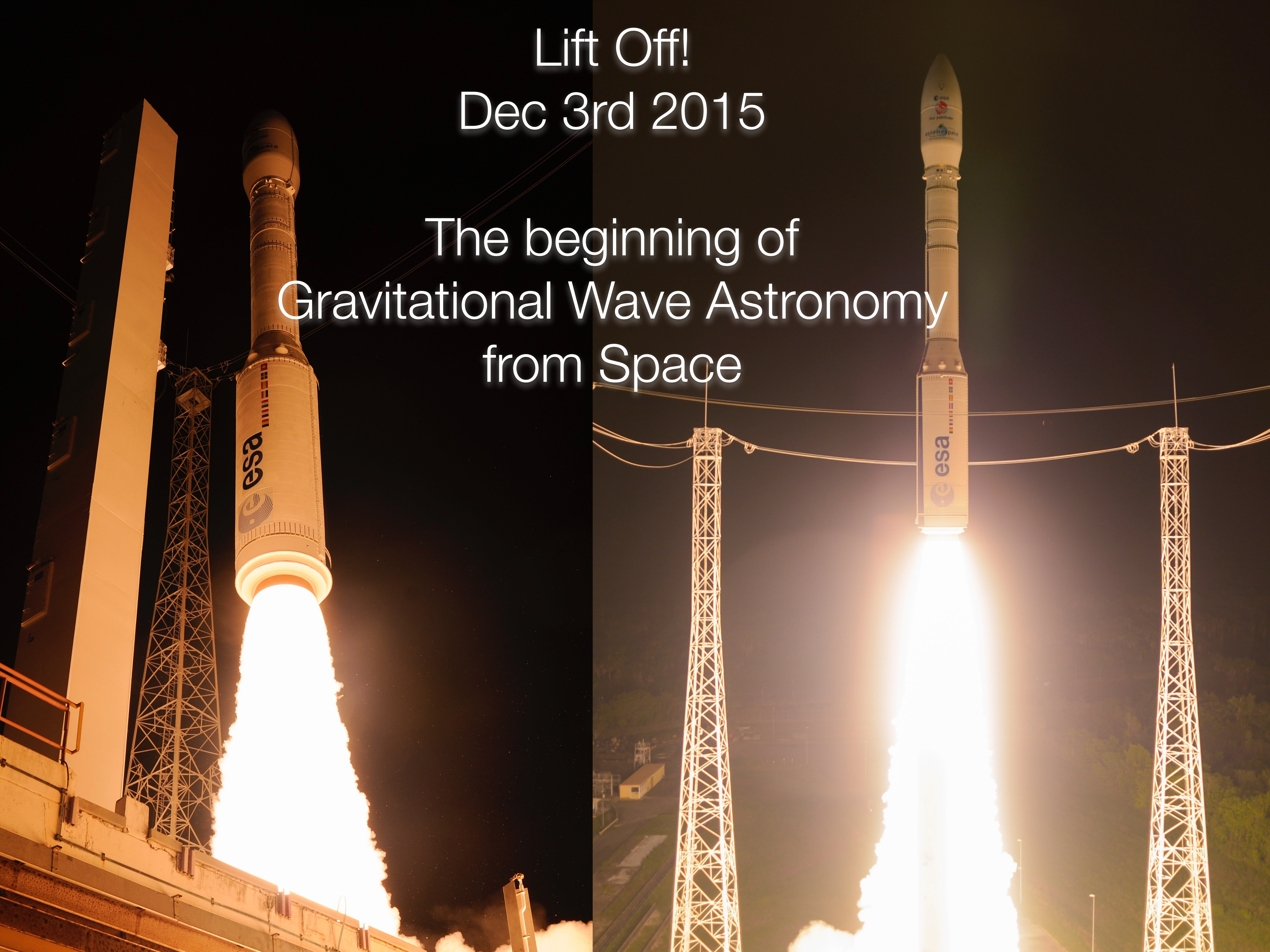

Lift Off!
Dec 3rd 2015
The beginning of
Gravitational Wave Astronomy
from Space

Sequence of events

Launch Dec 3rd 2015

Launch, Transfer

Industrial Commissioning

IOCR

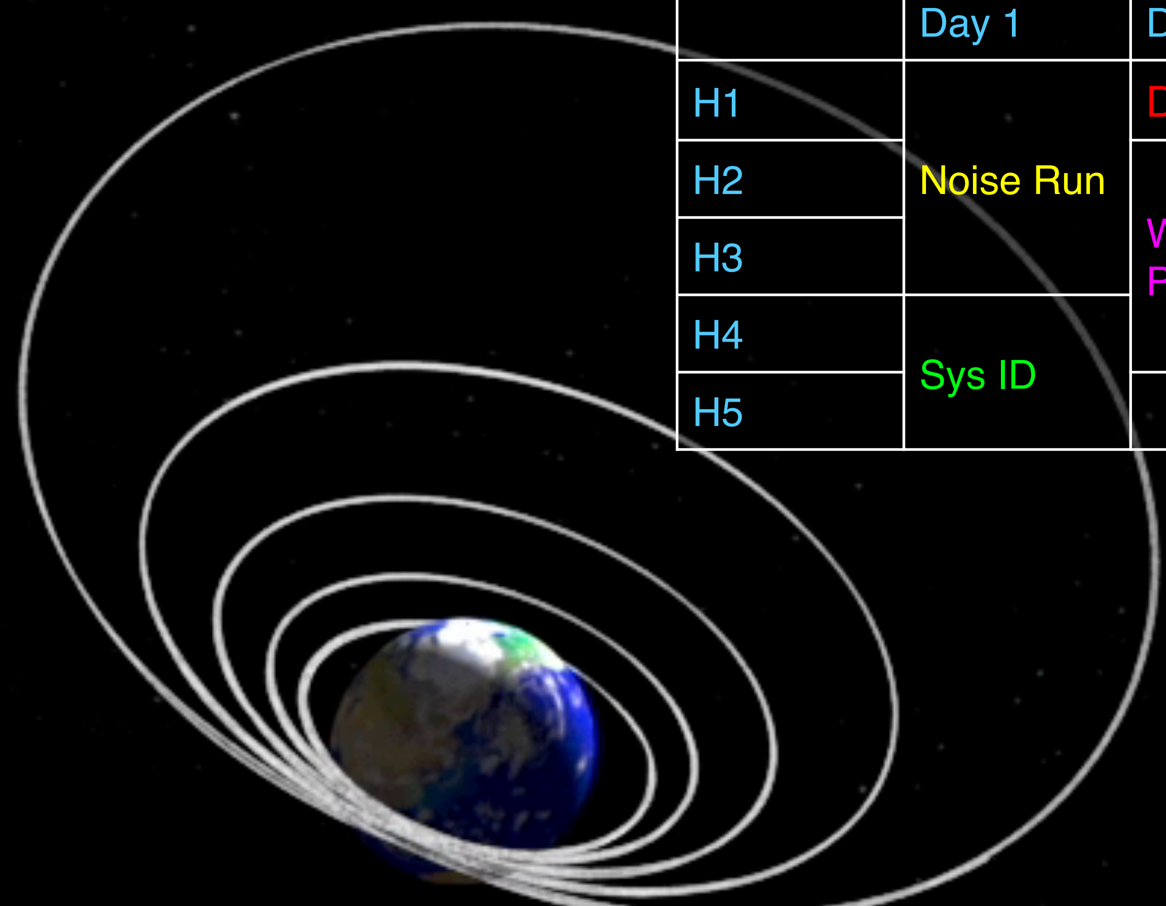
LTP Science Ops

03-01 to 06-25

NASA Payload Commissioning

NASA Operations

	Day 1	Day 2	Day 3	Day 4
H1	Noise Run	Discharge	Noise Run	Discharge
H2		Working Point		Stray Potentials
H3				
H4	Sys ID			
H5				



Understanding prior to launch

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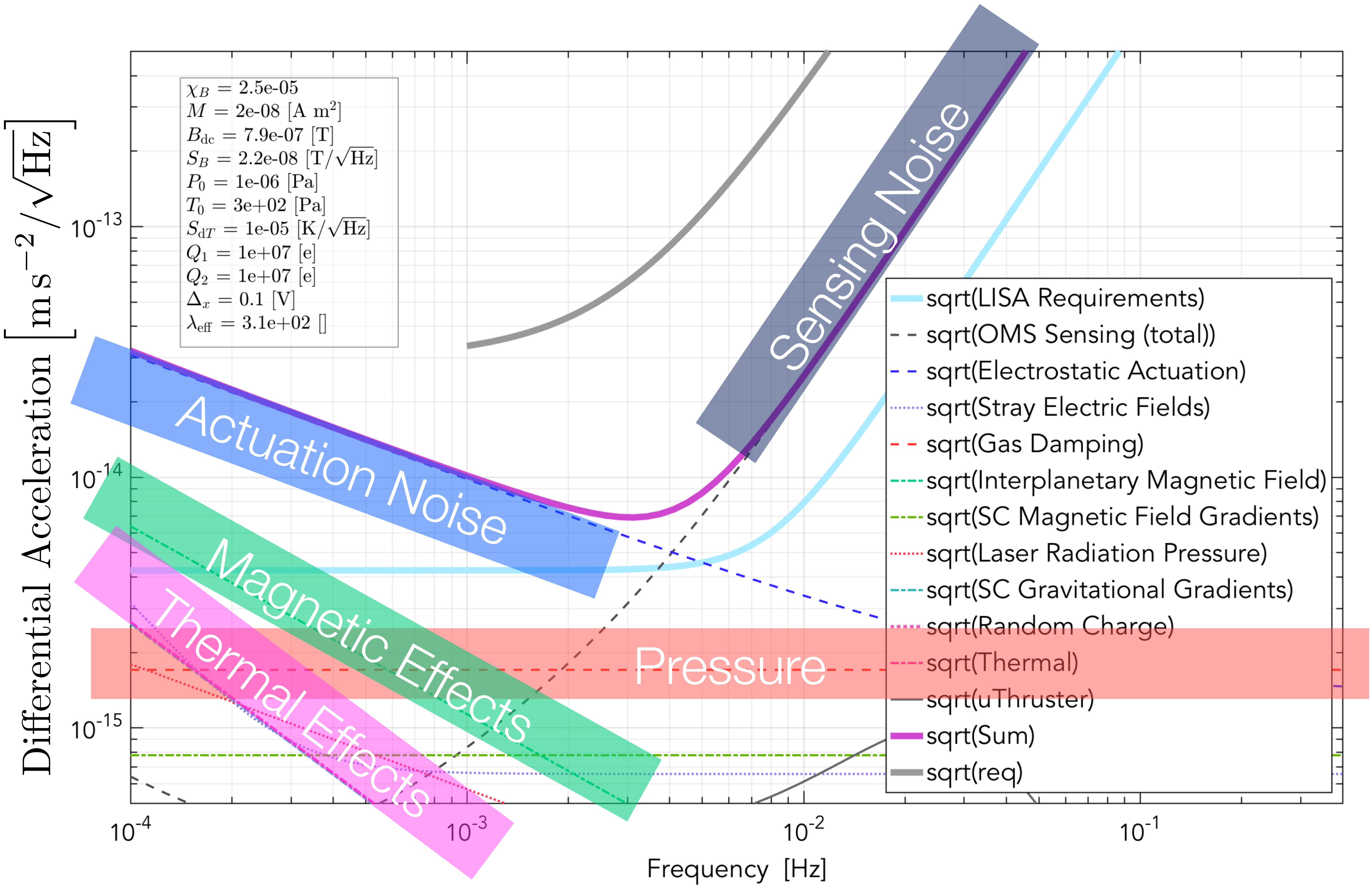

Status

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How did we get there?

- Step 1: Launch
  - successfully completed on December 4th 2015
- Step 2: Commissioning
  - Switch on and check-out all units
  - Discard propulsion module
  - Decage TMs
  - Release TMs
  - Align OMS
  - Commission Drag-free control system
- Step 3: Science Operations

Science Operations
&
Data Analysis

Science Operations

- In-flight experiments were designed, simulated and tested before flight
- Sequence of experiments evolves with time
  - further simulation of operational weeks run continuously
- Analysis teams are on-duty 7 days a week in ESA's Operations Centre (ESOC, Darmstadt)
- First two weeks of operations were run essentially as planned
- From week 3 onwards, the plan was tailored to fit the observations
  - aiming to achieve a full understanding of the (excellent) measured performance

Development

- 2011: Mock Data Challenges
  - help define algorithms
- 2012-2015: 45 STOC Exercises
  - face-to-face meetings between Scientists and ESA engineers
  - definition of interfaces, workflows in operations
  - technical details of all experiments
- 2012-2015: 5 STOC Simulations
  - simulate the operations scenario
  - from a few days to 2 weeks in length
  - involving full teams, including shifts
  - exercise all main experiments

Nominal Mission

- March 1st to June 26th
- 12 station keeping manoeuvres
- 31 unique configuration blocks
- 85 unique investigations

Nominal Phase

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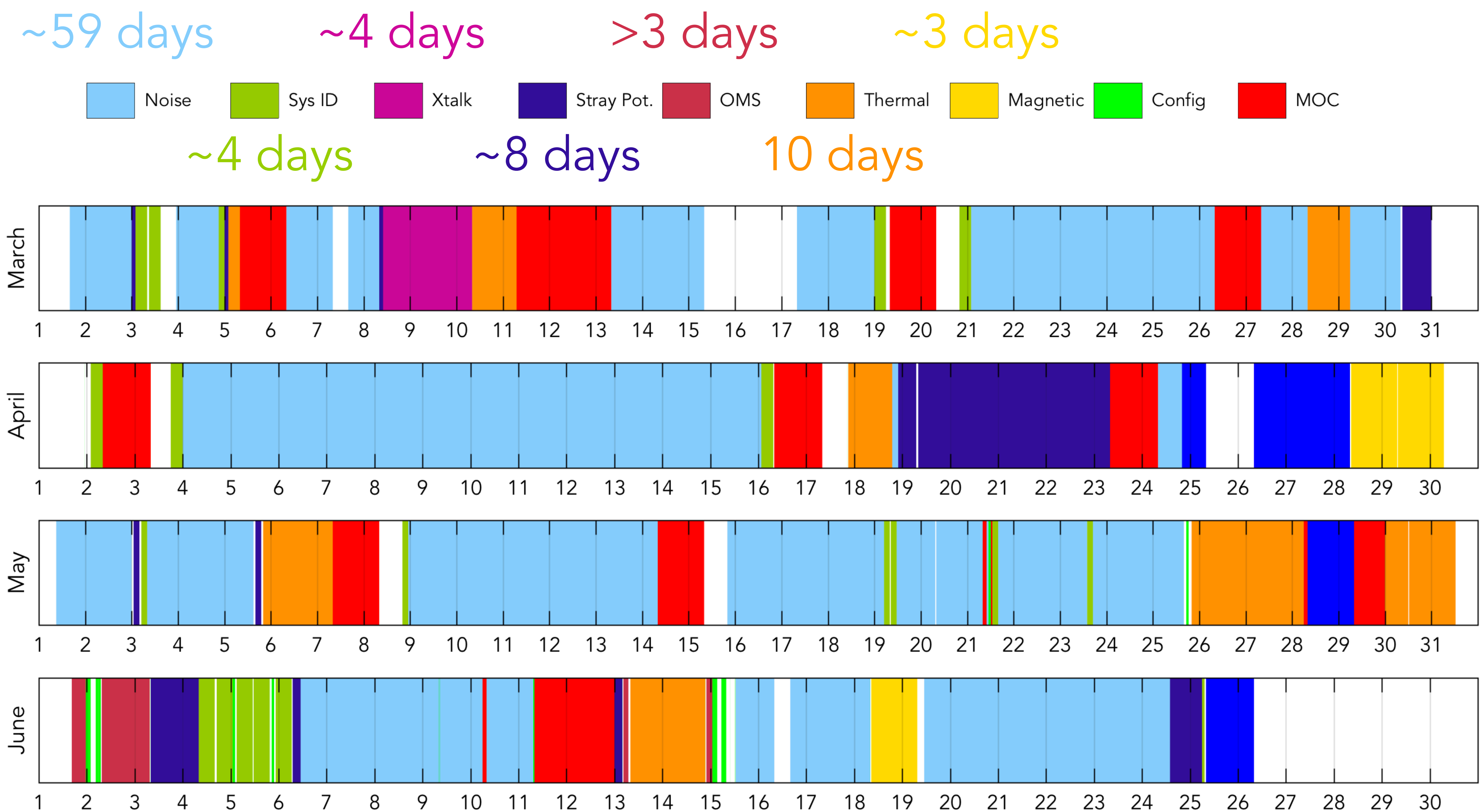
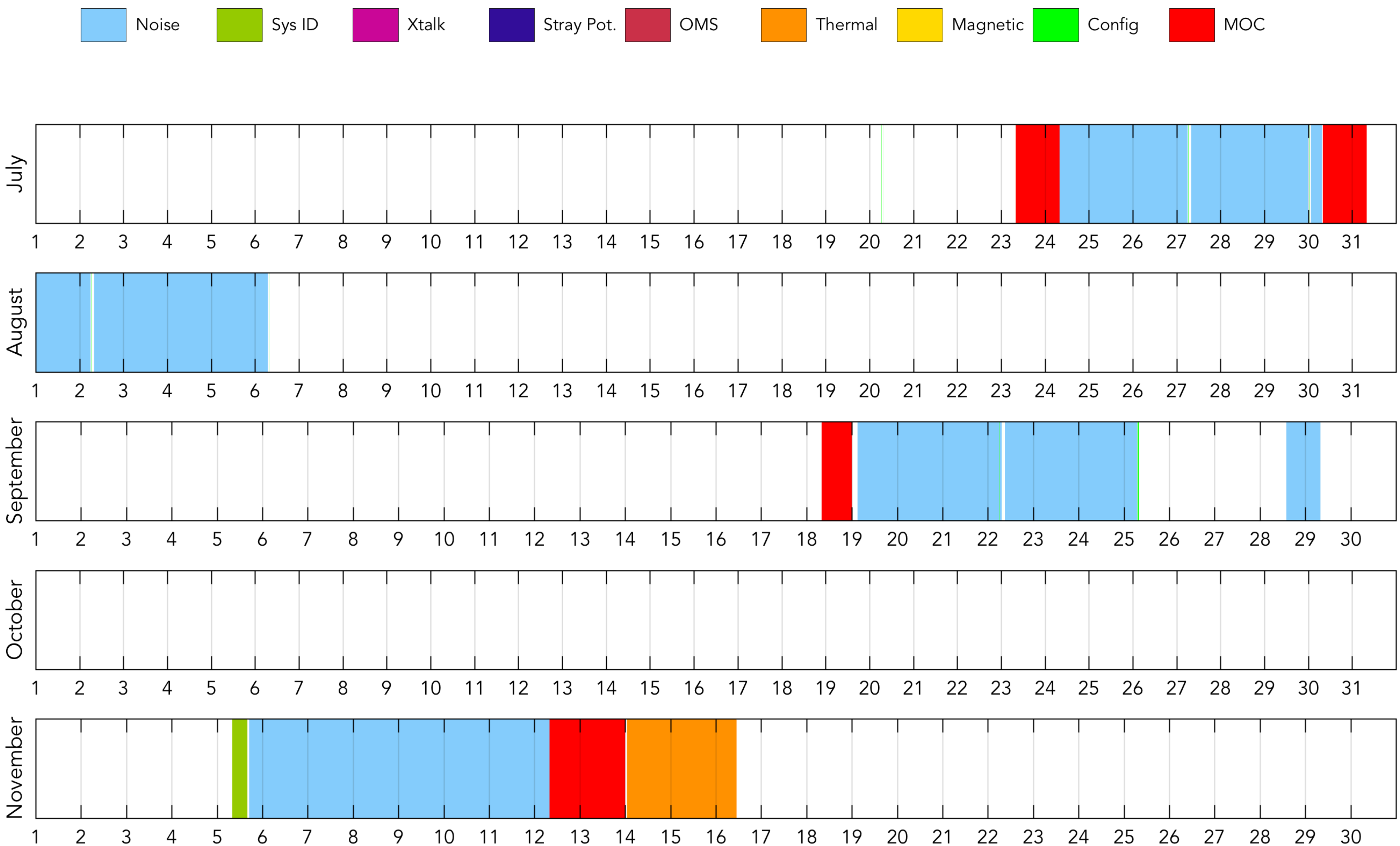


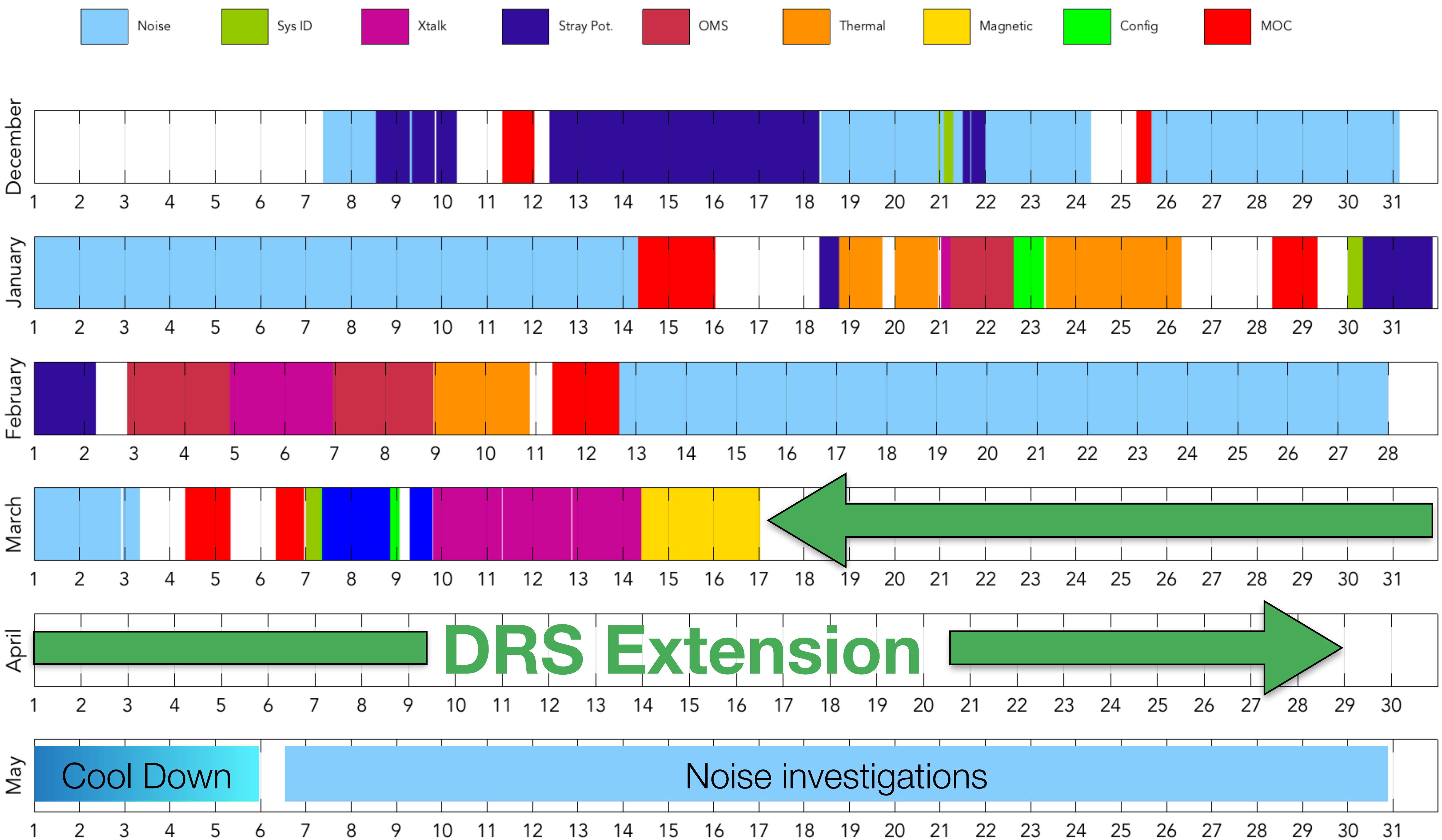
DRS Phase



Noise
Sys ID
Xtalk
Stray Pot.
OMS
Thermal
Magnetic
Config
MOC
July
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
August
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
September
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
October
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
November
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30

Extension

- Hand-back to LTP around Dec 7th



Primary science measurement

Differential test mass acceleration

- The relative acceleration of the two test masses along the sensitive x-axis
- Representative of the force noise as it appears in a long LISA arm
- Estimated from the observation of the relative motion
  - made using the X12 interferometer
- Different corrections/calibrations made

Evolution of Δg

- Raw Δg
- Inertial correction
  - centrifugal force on TMs due to the rotating and jittering SC
- Further correction
  - Debumped (cross-talk correction)
    - despite TM alignments done in hardware, we can still remove effects of SC jitter leaking into Δg
  - leakage of angular acceleration of SC

Raw Δg

$$\Delta g^{\mathrm{raw}} = \ddot{o_{12}} - G_{x_2}\delta(F_{\mathrm{app}_2}, \tau)/M - \omega_2^2 o_{12}$$

- in-loop differential acceleration
- corrected for *applied* forces
  - gain correction factor (estimated from sys id)
  - commanded AC voltages
  - account for quantisation effects in FEE
- corrected for stiffness of TM2
  - estimated from dedicated system identification campaigns

Return to inertial frame

- correct for centrifugal forces arising from the rotation of the observer frame
  - steady rotation of SC together with SC jitter gives in-band noise
  - not present in LISA

$$\Delta g^{\text{inertial}} = \Delta g^{\text{raw}} + \Delta g^{\text{cent}}$$

$$\Delta g^{\text{cent}} = \vec{\Omega} \times \vec{\Omega} \times \vec{r}$$

$$\vec{\Omega} = \vec{\Omega_{\text{dc}}} + \vec{\Omega}_{\text{noise}}$$

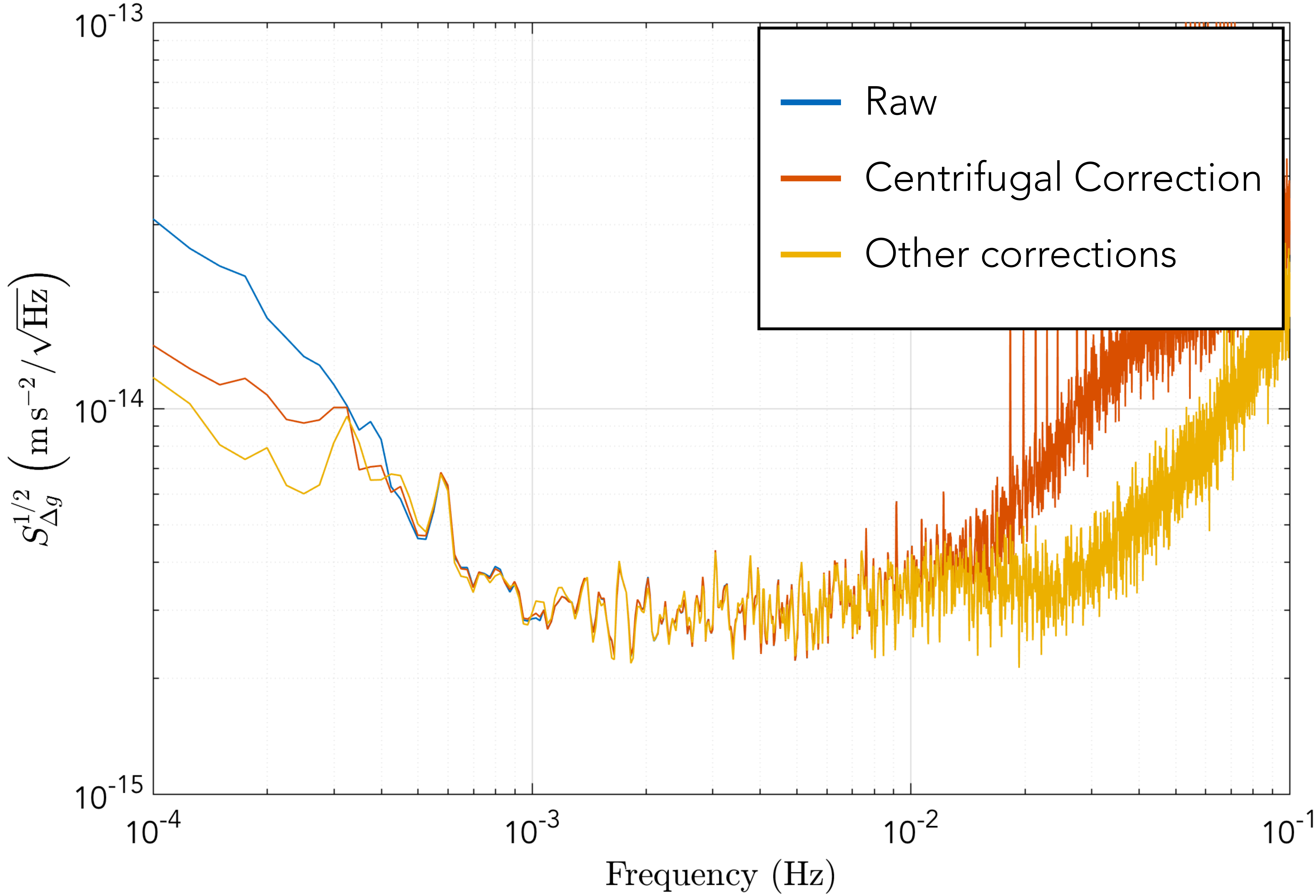
$$\vec{\Omega}_{\text{noise}} = \int G_\phi \frac{(N_{\phi_1} + N_{\phi_2})}{2I_{\text{zz}}} \text{d}t$$

$\vec{\Omega}_{\text{dc}}$ from low frequency SC angular, estimated from AST quaternions

Other corrections

- De-bumping:
  - subtraction of SC jitter leaking into Δg
  - mitigate in hardware and post-processing:
    - Hardware de-bumping via test mass alignment
    - Post-processing: subtract a linear combination of other measured degrees-of-freedom
      - ad-hoc, but effective
- Tangential acceleration and actuation cross-talk
  - mis-alignment of optical axis and the mechanical axis joining the TMs
  - leakage of phi actuation along x (shared electrodes)
- Glitch removal
  - we have some relatively rare (~1/Day) glitches
  - big enough to disturb spectral estimation
  - fit with simple model and subtract

Δg products



Raw
Centrifugal Correction
Other corrections
10^{-13}
10^{-14}
10^{-15}
$S_{\Delta g}^{1/2}\ \left(\mathrm{m\,s^{-2}}/\sqrt{\mathrm{Hz}}\right)$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Frequency (Hz)

Calibration of the x-axis

System model

second derivative of observed position (from IFO)

- numerical computation
- needs corrected time-stamping

$$\Delta g^{\text{raw}} = \ddot{o_{12}} - G_{x_2}\delta(F_{\text{app}_2}, \tau)/M + \omega_2^2 o_{12}$$

spring coupling to S/C

- estimate of the gravitational and electrostatic couplings
- modelled depending on actuation authority

estimate of applied force

- commanded force not enough
- need modelling of actuation electronics
- delay in actuation
- gain in actuation

Parameter estimation: the experiment

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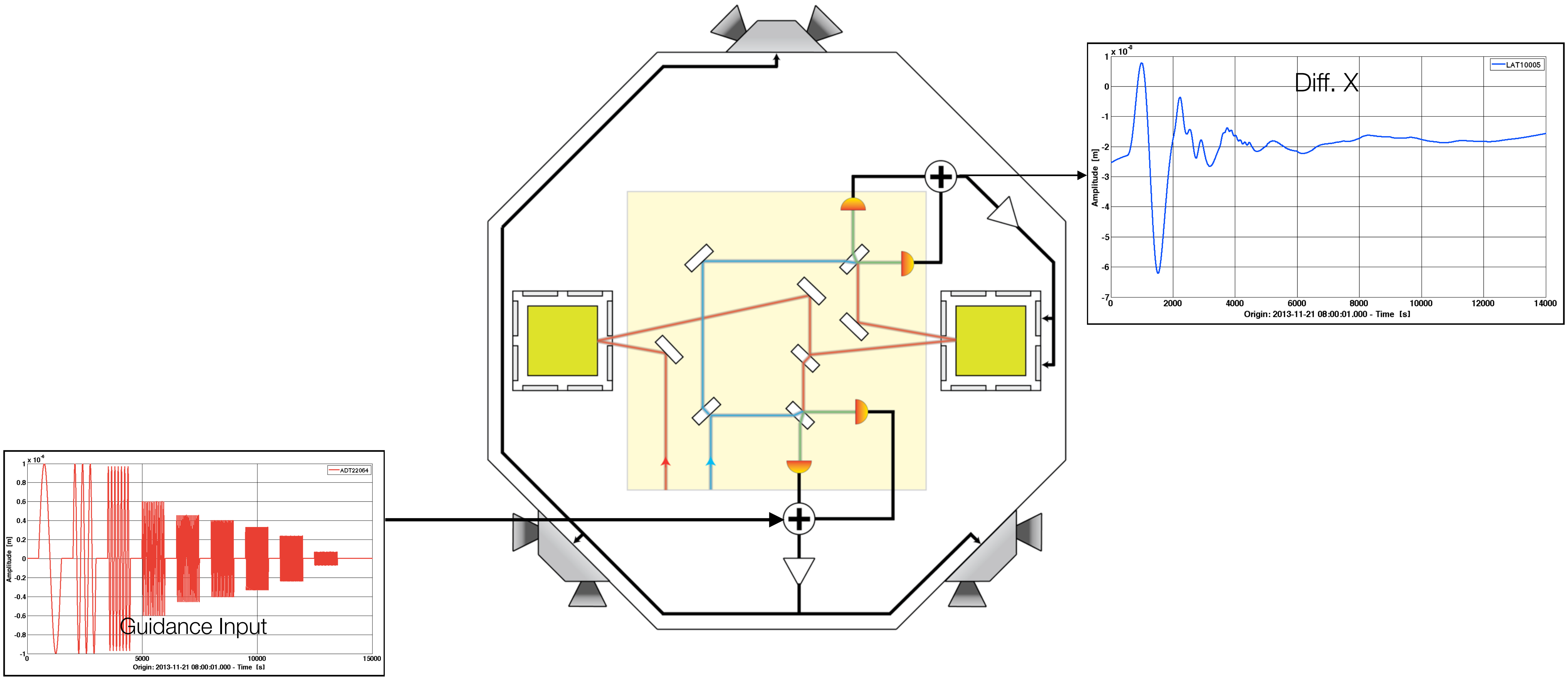
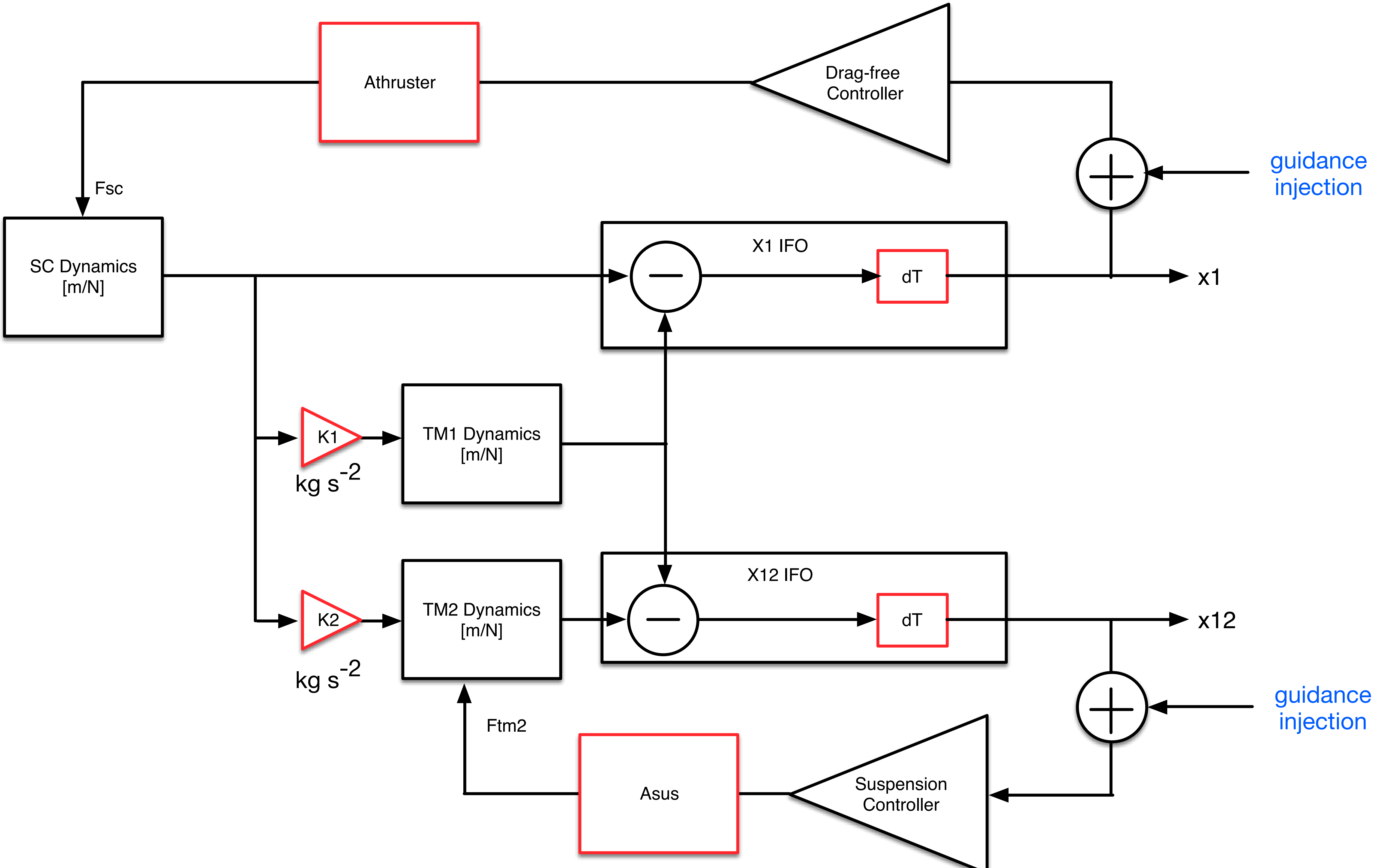
Goal is to measure the key parameters needed for estimating the residual differential acceleration



System control



Inputs and outputs

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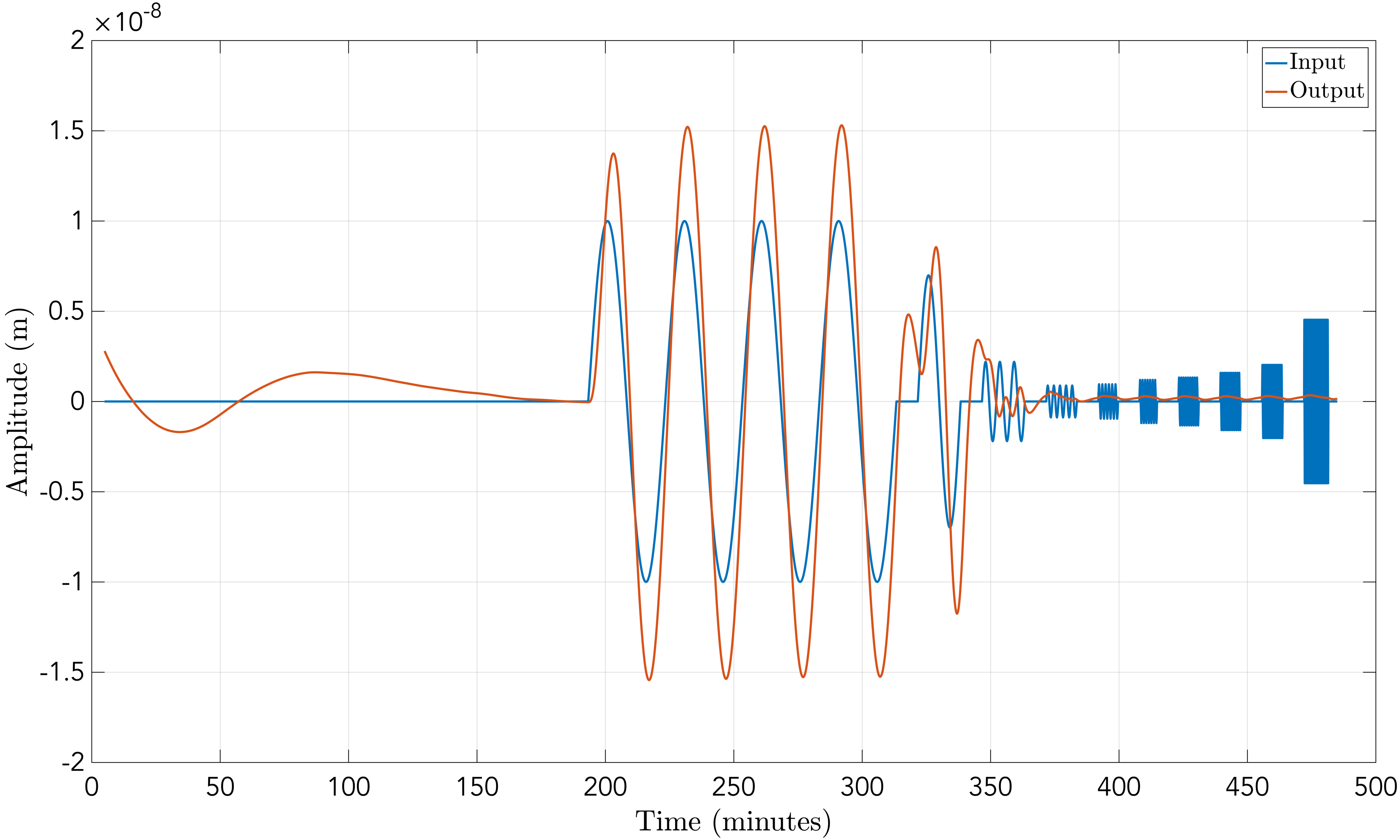
signals on the x-axis suspension loop



Residuals after model fit

$$\Delta g^{\mathrm{raw}} = \ddot{o_{12}} - G_{x_2}\delta(F_{\mathrm{app}_2}, \tau)/M - \omega_2^2 o_{12}$$

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Evolution of the noise

Noise properties

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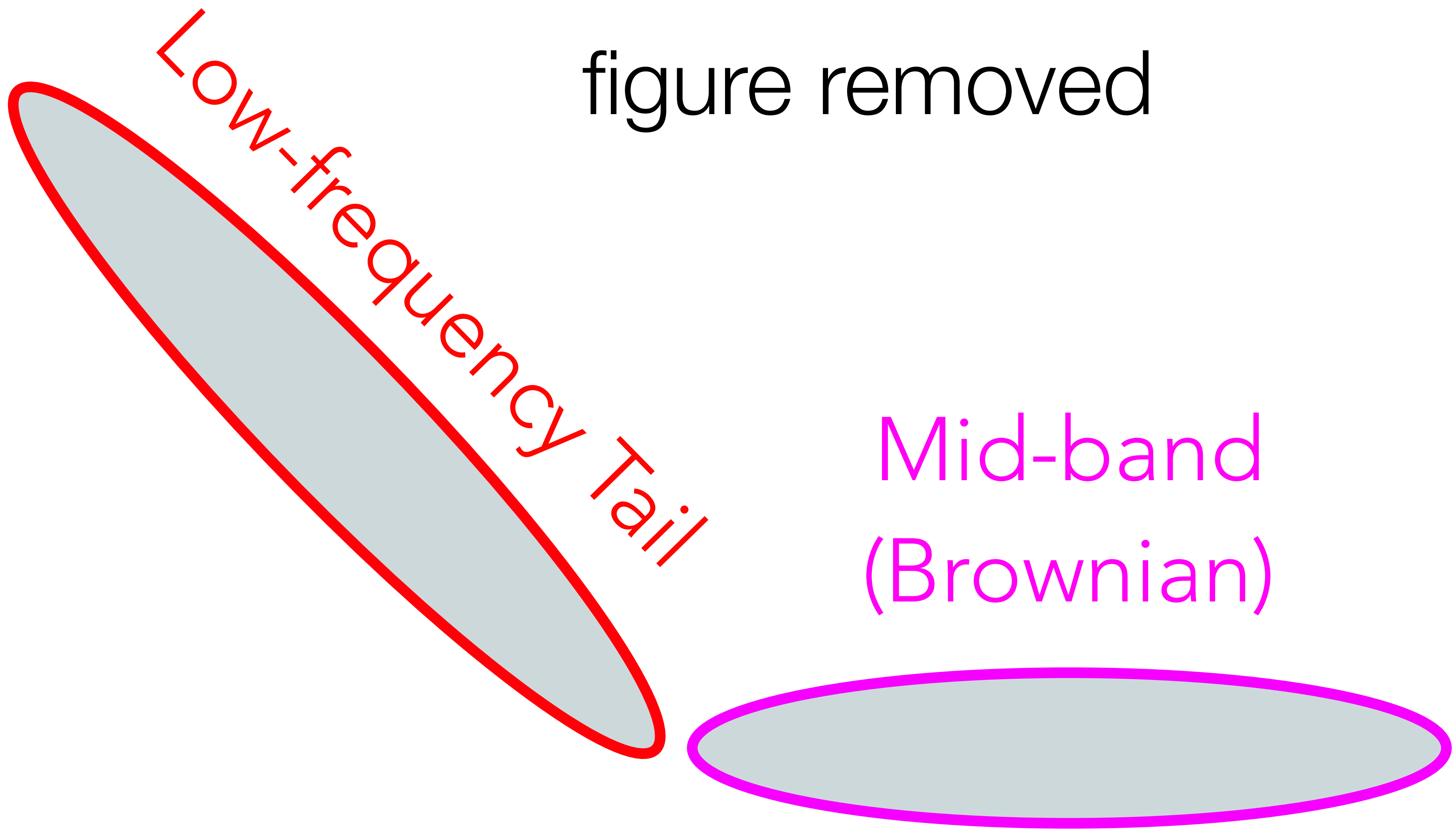

Mid-band (Brownian)

- Mid-band: 1–10 mHz
- Dominated by residual gas around TMs
- Varies with temperature
- Varies with pressure
  - venting, outgassing

Noise evolution

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Evolution of low frequency tail

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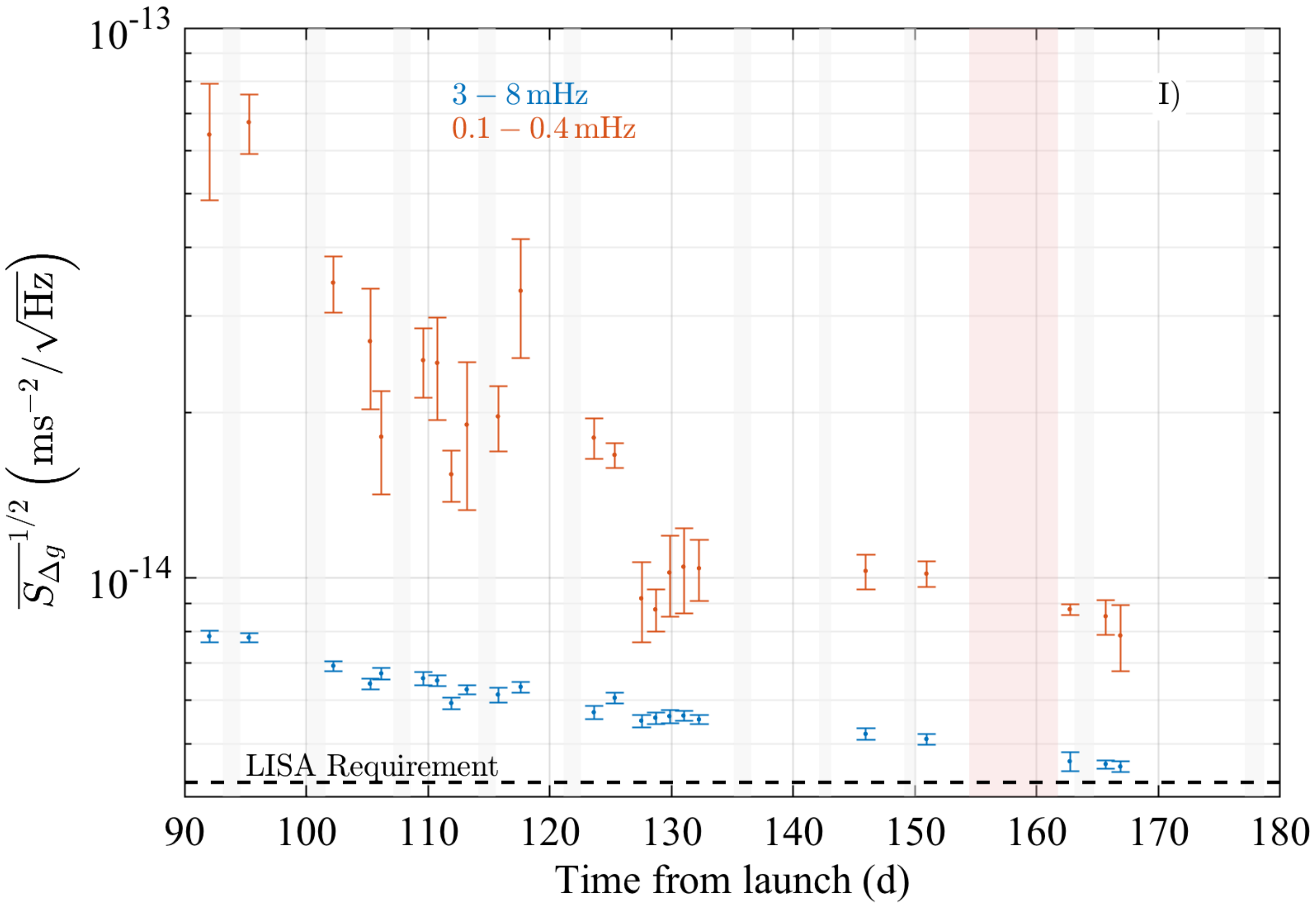
- In the early days, looked like it was improving with time
- In reality, our estimation of applied forces was not sufficient

$$\Delta g^{\text{raw}} = \ddot{o_{12}} - G_{x_2}\delta(F_{\text{app}_2}, \tau)/M - \omega_2^2 o_{12}$$

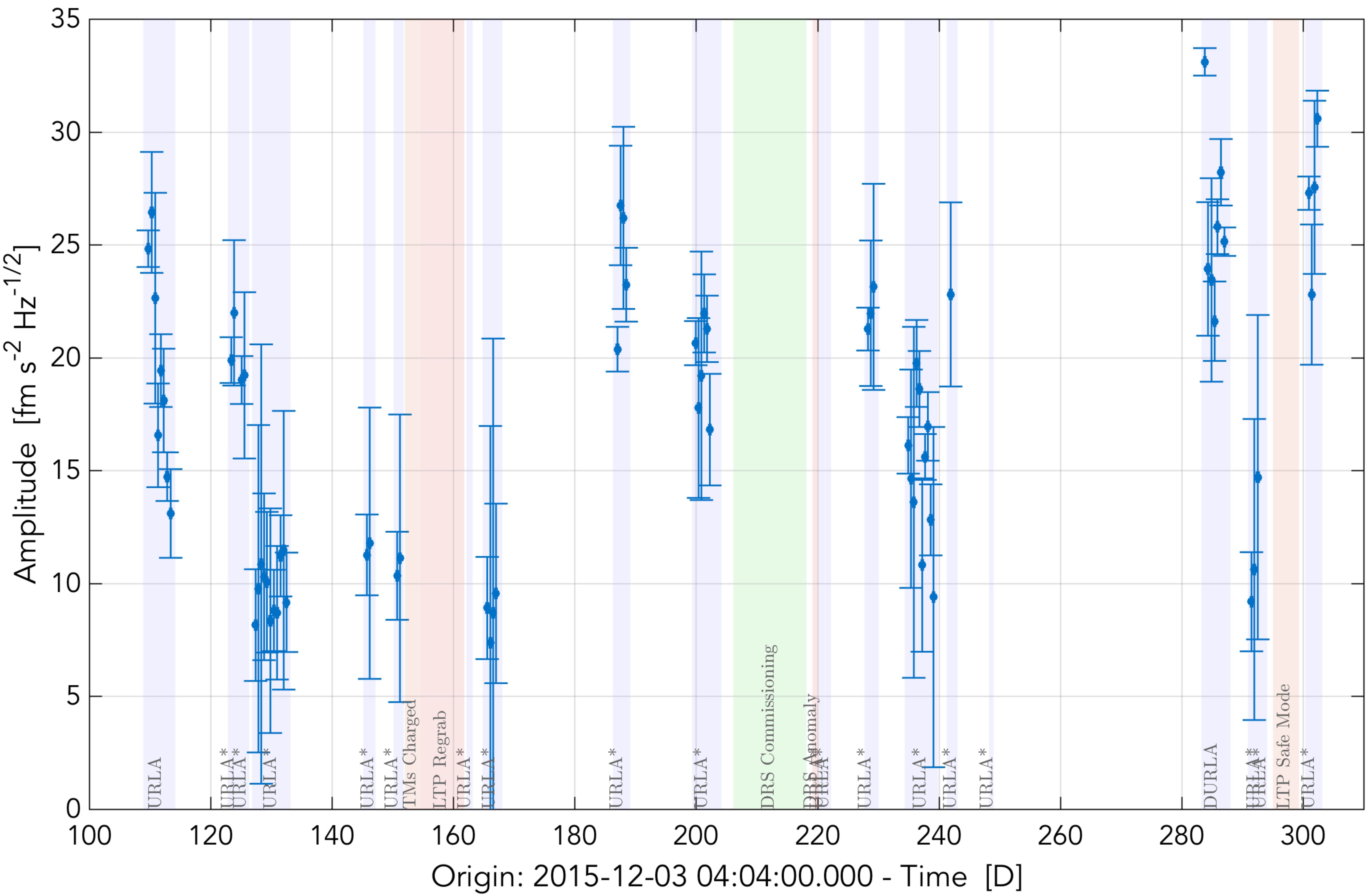
- We were fooled by the decreasing rate of change of the applied force
  - error in estimate of applied force reduced
- Applied force is properly estimated now
- Data is being fully reanalysed

In the early days…

- During nominal operations we observed a decay of a low frequency noise
- Possible causes:
  1. thermo-mechanical relaxation of the system
  2. out-gassing effects creating pressure gradients which lead to forces if temperature drifts
  3. un-modelled actuation noise which depends on *slope* of dc force



with more data…



Then with correctly estimated applied forces

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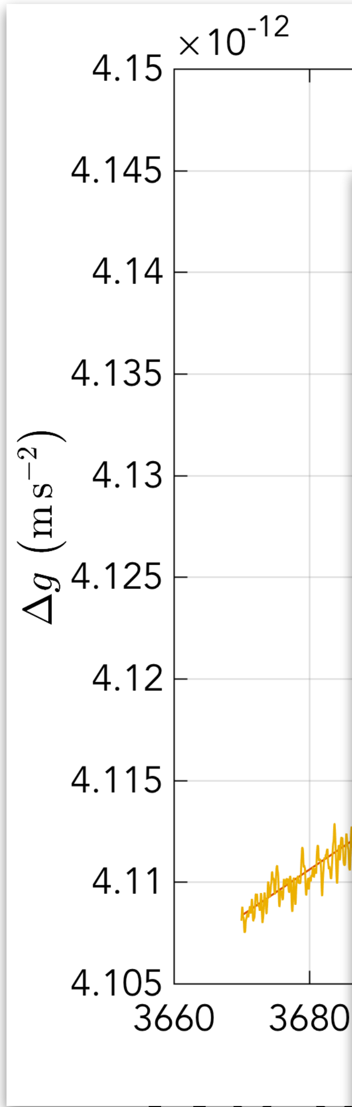
Glitches, glitches everywhere, …

…s of glitches



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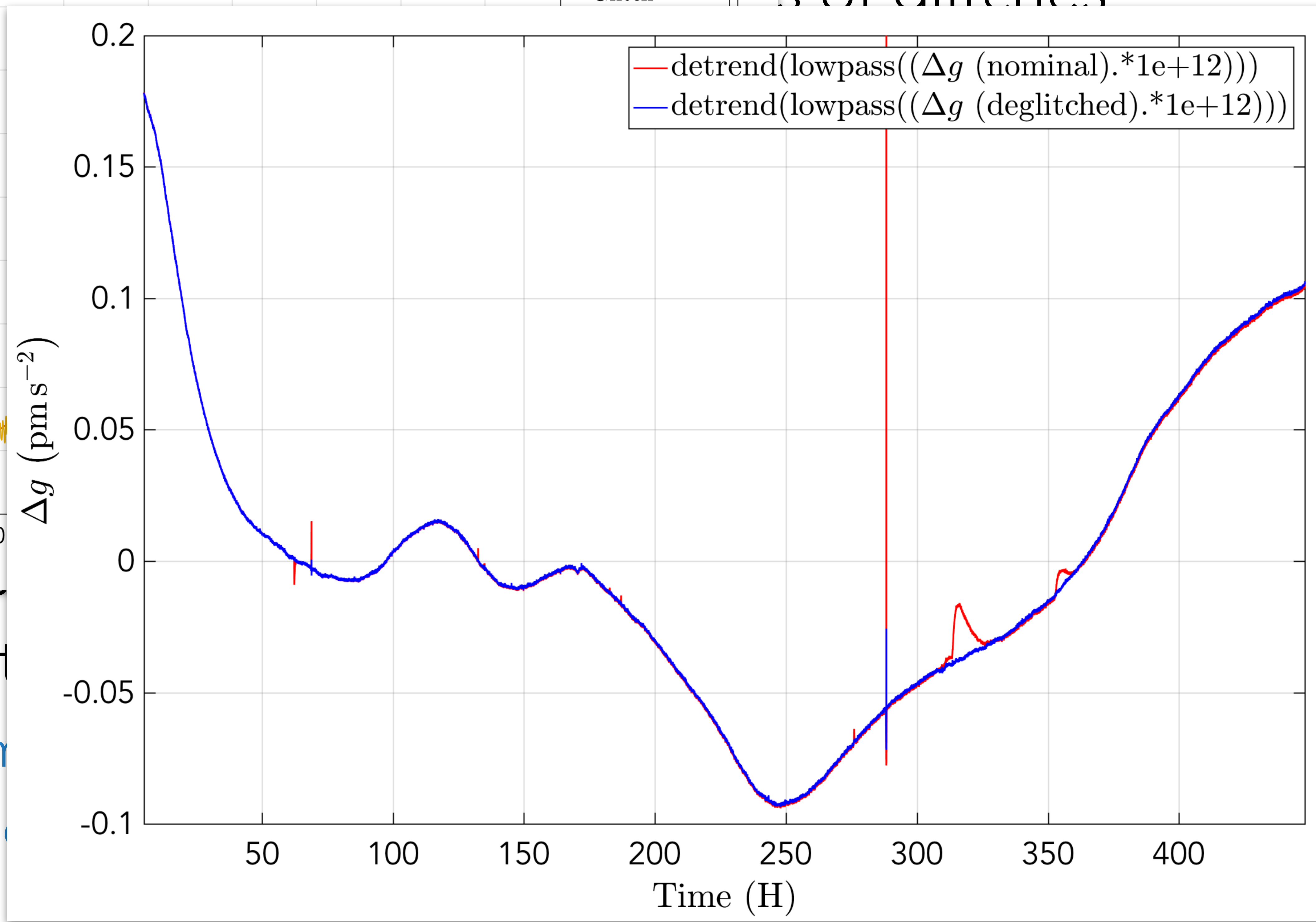


Next steps

- Full re-analysis of delta-g segments underway
- Formal de-glitching pipeline is developed
- Final results to be summarised in up-coming publications
- Expectation is that the low frequency tail is rather stationary
  - still some decay
  - maybe associated with pressure and outgassing?

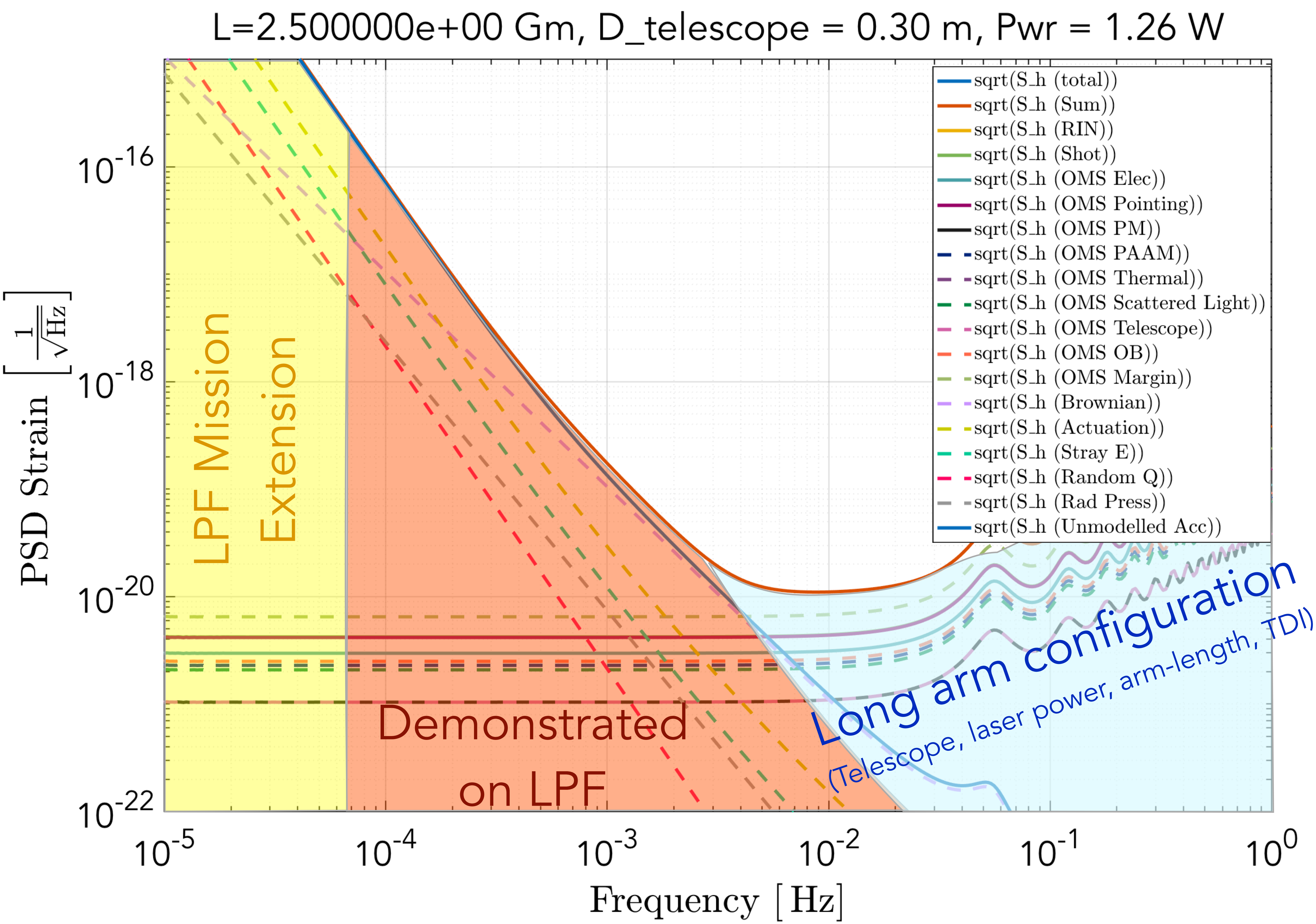
Summary

- All data to date is in the process of being reanalysed now our estimate of applied forces has improved
  - significant improvement to low frequency stationarity
- We made good use of slots in DRS phase to monitor performance and prepare for extension
- Extension is now nearly finished
  - began with our best long noise run
  - de-orbiting burn is complete - no more station keeping
  - first cool-down of LCA is complete, everything went well
  - 2nd cool-down yielded lots of glitches
  - return now to higher temperature
- Most other themes are well covered
  - thermal and gas environment of TMs
  - charge behaviour
  - OMS performance and noise budget
  - magnetic couplings
  - …

Looking forward

- low frequency excess noise remains top priority
  - seems fairly stationary for whole mission
  - unchanged by changes we've done (?)
  - some slight correlation with time and/or temperature?
  - how do we attack this?
    - cool-down again (done) and measure (underway)
    - heat-up again and measure
      - break correlation of temperature and time
- glitches
  - sources remain unknown
  - rates and zoology still being investigated
  - difficult to affect the rate/populations without hypotheses for the origin(s)
- Satellite to be decommissioned in early July and switched off on July 18th

Projection to LISA sensitivity



Thanks!