Albert Einstein Institute

Max Planck Institute for Gravitational Physics and
Leibniz Universität Hannover

lisa pathfinder

LPF Data Analysis & Operations

Martin Hewitson
for the LISA Pathfinder Team

LISA Symposium X
Gainesville, Florida
May 20th 2014

quest
Centre for Quantum Engineering and Space-Time Research

DLR
German Aerospace Center

We gratefully acknowledge support by the European Space Agency (ESA) (22331/09/NL/HB, 16238/10/NL/HB) and the German Aerospace Center (DLR) (50OQ0601, 50OQ1301) and thank the German Research Foundation for funding the Cluster of Excellence QUEST (Centre for Quantum Engineering and Space-Time Research).

Aims of operations

- Obtain the best geodesic motion possible
  - quietest differential acceleration of the two TMs
    - 3×10^{-14} m s^{-2} / $\sqrt{\text{Hz}}$ at 1 mHz
      - pm accuracy position measurement of TM-SC, TM-TM
  - **optimisation by changing system parameters**
    - determine best configuration by experiments

- Develop a noise model of the system
  - allows the **projection** of the performance of technologies to LISA

Structure of Mission Operations

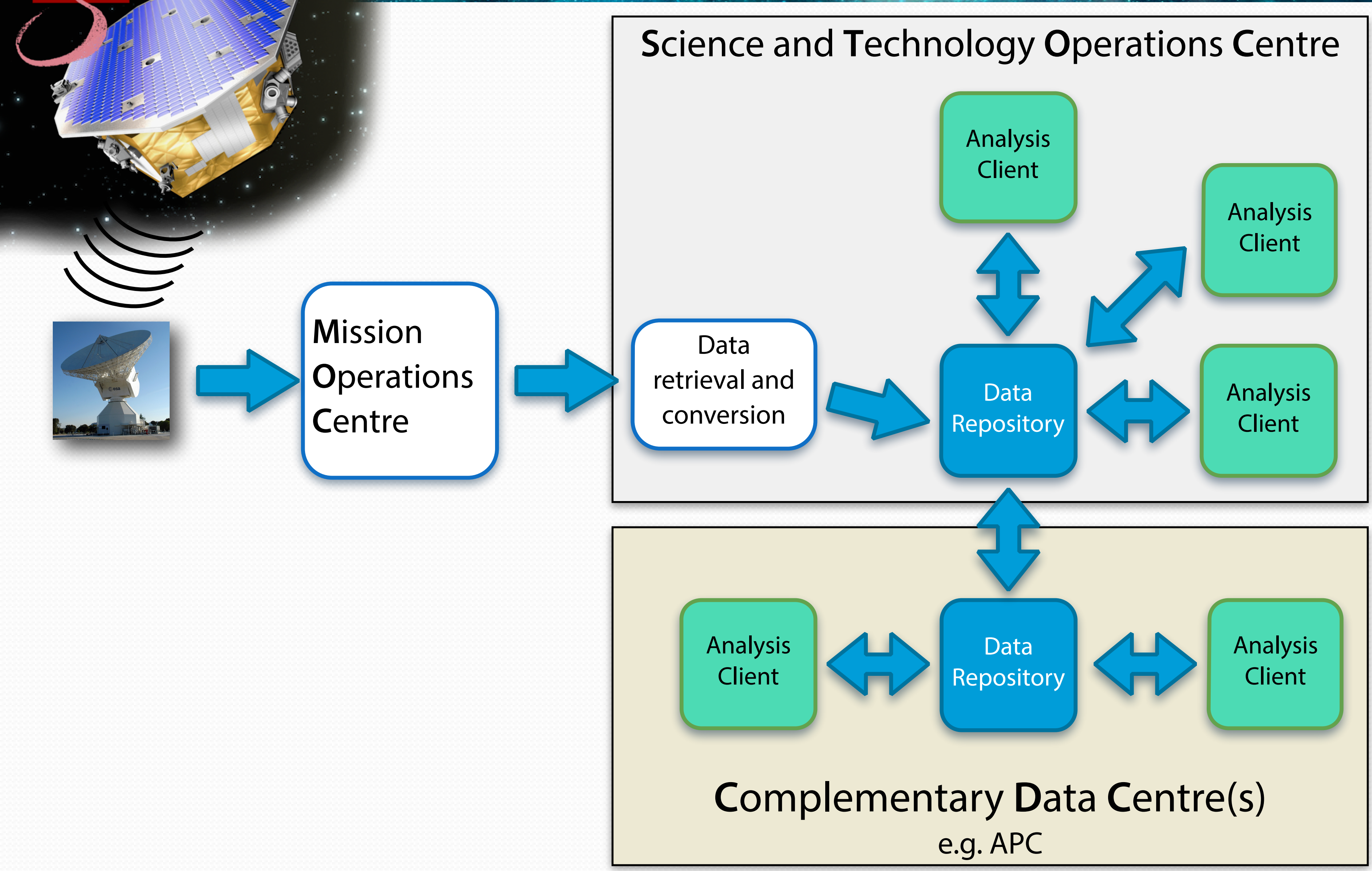
- LPF operations comprises many phases

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

	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				

Data Flow


Mission Operations Centre
Science and Technology Operations Centre
Data retrieval and conversion
Data Repository
Analysis Client
Analysis Client
Analysis Client
Data Repository
Analysis Client
Analysis Client
Complementary Data Centre(s)
e.g. APC

Running Operations

- Each day has two data deliveries:
  - early morning (10am Z): Instrument Configuration & Evaluation data (ICE)
    - a few key channels of data to allow 'quick look'
  - late afternoon (6pm Z): Full data set
- We have one team on duty to perform the quick-look and planned STOC front-line analysis
- A team comprises:
  - A senior scientist
  - A scribe
  - 2 data analysts
  - Operations Scientist

Example shifts

Online: Perform quick look and planned front-line analyses
Offline: Consolidate analysis and logbook from previous day
Travel: Commute to/from STOC
Off duty: Time at home

Day	N	N+1	N+2	N+3	N+4	N+5	N+6	N+7	N+8	N+9
Team 1	Online	Offline	Online	Offline	Travel	Off Duty	Off Duty	Travel	Online	Offline
Team 2		Online	Offline	Online	Offline	Travel	Off Duty	Off Duty	Travel	Online
Team 3					Online	Offline	Online	Offline	Travel	Off Duty
Team 4						Online	Offline	Online	Offline	Travel

Operational Constraints

- Investigations are time-line driven
  - no real-time / 'joystick' control
- Investigations are packed into 24 hour groups called **P**ayload **O**peration **R**equests
- 6 days of time-line are on-board LPF at all times
- Changing a POR has a 3-5 day lead-time
- Mid- and long-term plans will be generated before launch

Philosophy of Science Operations

1. Start out with low-risk, gentle probing of the system first to gain experience and to understand the state of the system

2. Move on to more invasive investigations and begin tuning the system

3. Higher risk investigations are planned to be later in the operations

Week 1: Gentle Probing

lisa pathfinder

- The first two weeks are all about gathering information and gaining experience
- This is our first interaction with the system

CE1	Charge estimate TM1
CE2	Charge estimate TM2
FD1	Fast Discharge TM1
FD2	Fast Discharge TM2

	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												run in Sci 1												
2	C											Noise run												
3	C																							
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	

The Crosstalk Experiment: A way to estimate the cross-coupling noise in LISA Pathfinder

Daniele Vetrugno, **Tuesday**

Optimizing Test Mass Position for the LISA- Pathfinder Optical Metrology System

Andreas Wittchen, **Thursday**

What is a noise run?

- Enter nominal science mode (DFACS mode Sci. 1.2)
  - SC following TM1
  - TM2 following TM1
- Put the system in the 'best' state we know
  - discharged TMs
  - optimal dc compensation voltages
  - best test-mass working point for OMS and GRS
  - ...
- Take data for, e.g., 10 hours

Estimating Residual Differential Acceleration

lisa pathfinder

- Understanding the purity of the free-fall we achieve, and what limits it, requires us to assess the residual forces acting on the TMs
  - what's left when we subtract the forces we can account for
- We compute the relative acceleration of the two TMs based on the observed relative position

$$g_{\mathrm{res}} = \ddot{x}_{12}$$

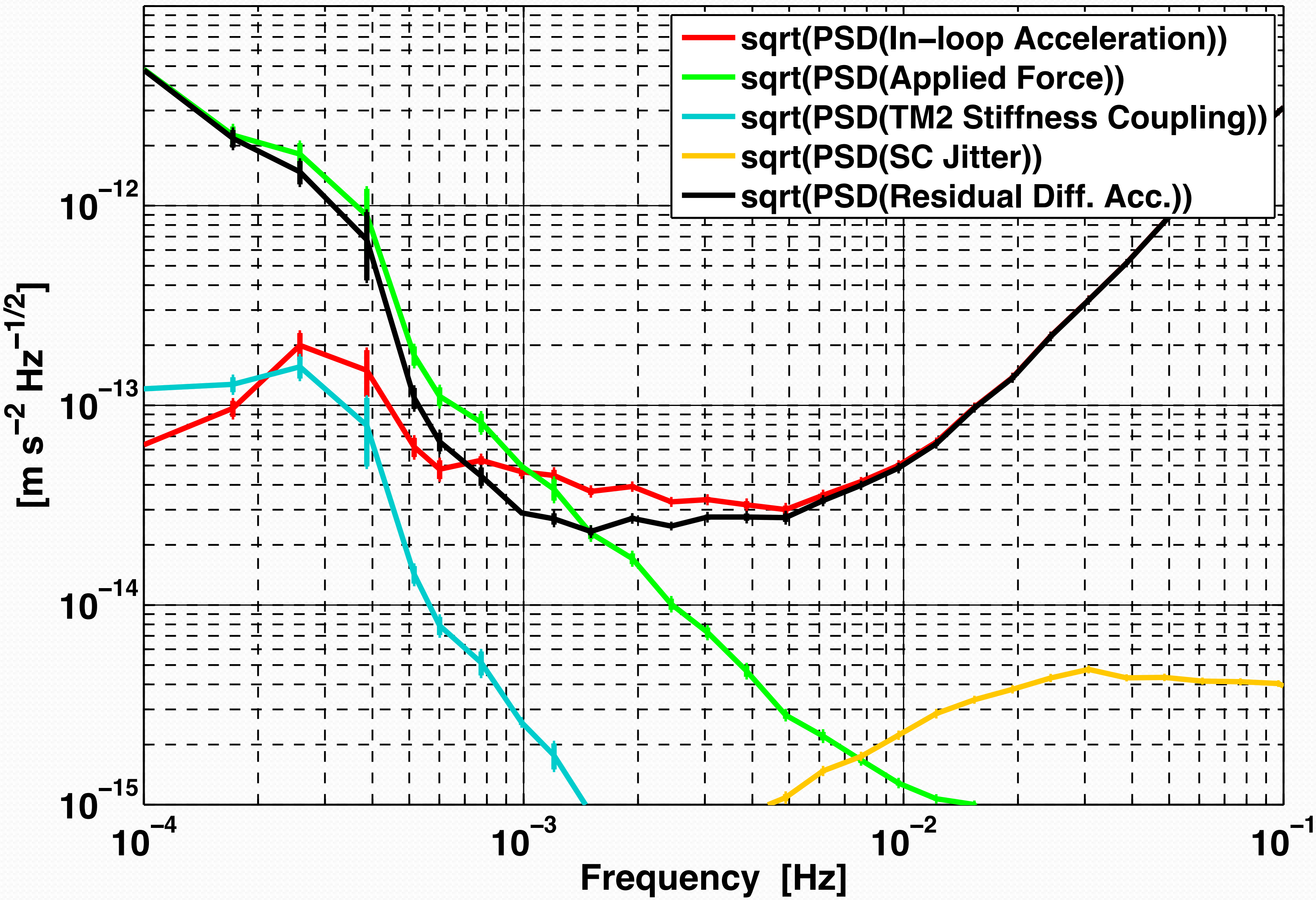
- Try to account for the contributions of g_res that we know
  - applied control forces
  - couplings due to force gradients

$$g_{\mathrm{res}} = \ddot{x}_{12} - g_{\mathrm{control}} - \omega_{\Delta}^2 x_1 - \omega_2^2 x_{12}$$

Analysing the data

1. Download the time-series
2. Assemble the current best estimate of the required system parameters
   - actuator gains, delays, stiffnesses, …
3. Form linear combination of the time-series
   - with delays, and filtering as necessary
4. Take spectrum of the residuals

The contributions

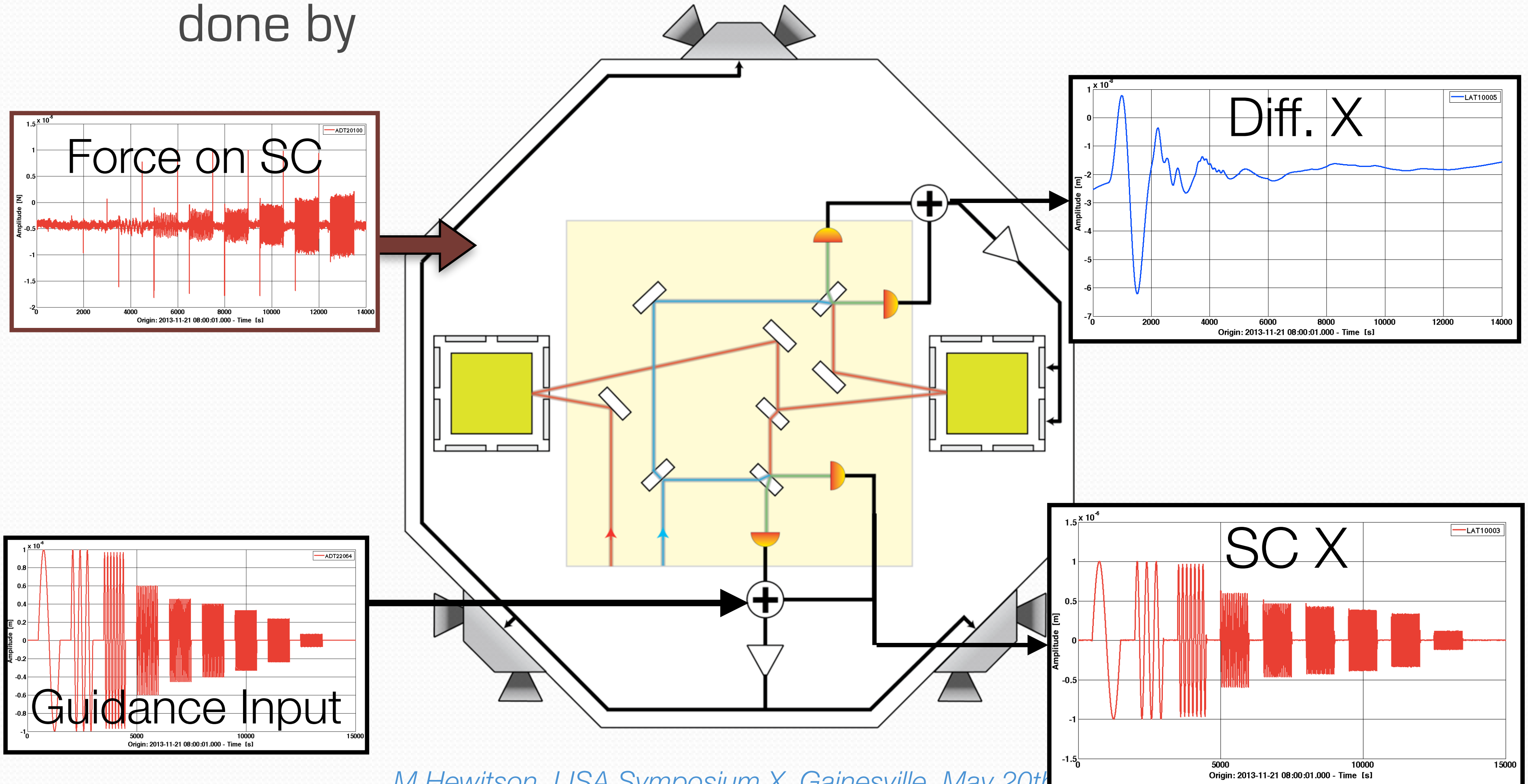


System Identification

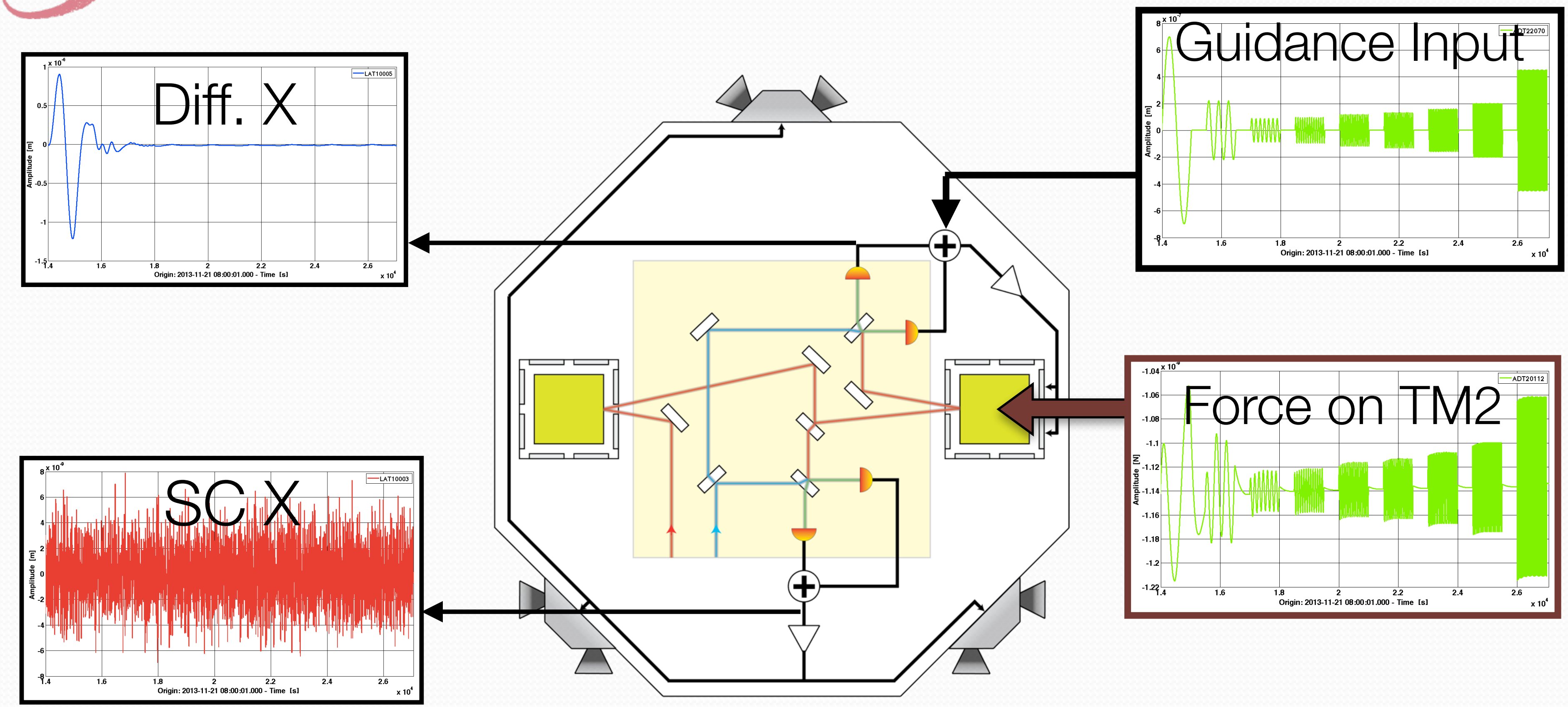
- Estimating our residual acceleration requires knowledge of certain system parameters
  - How do we gain that knowledge?
- At the beginning of operations, this comes from
  - ground measurements
  - system modelling
  - results of industrial commissioning campaign
- How do we improve and update that knowledge?
  - through dedicated investigations

x-axis system identification: part 1

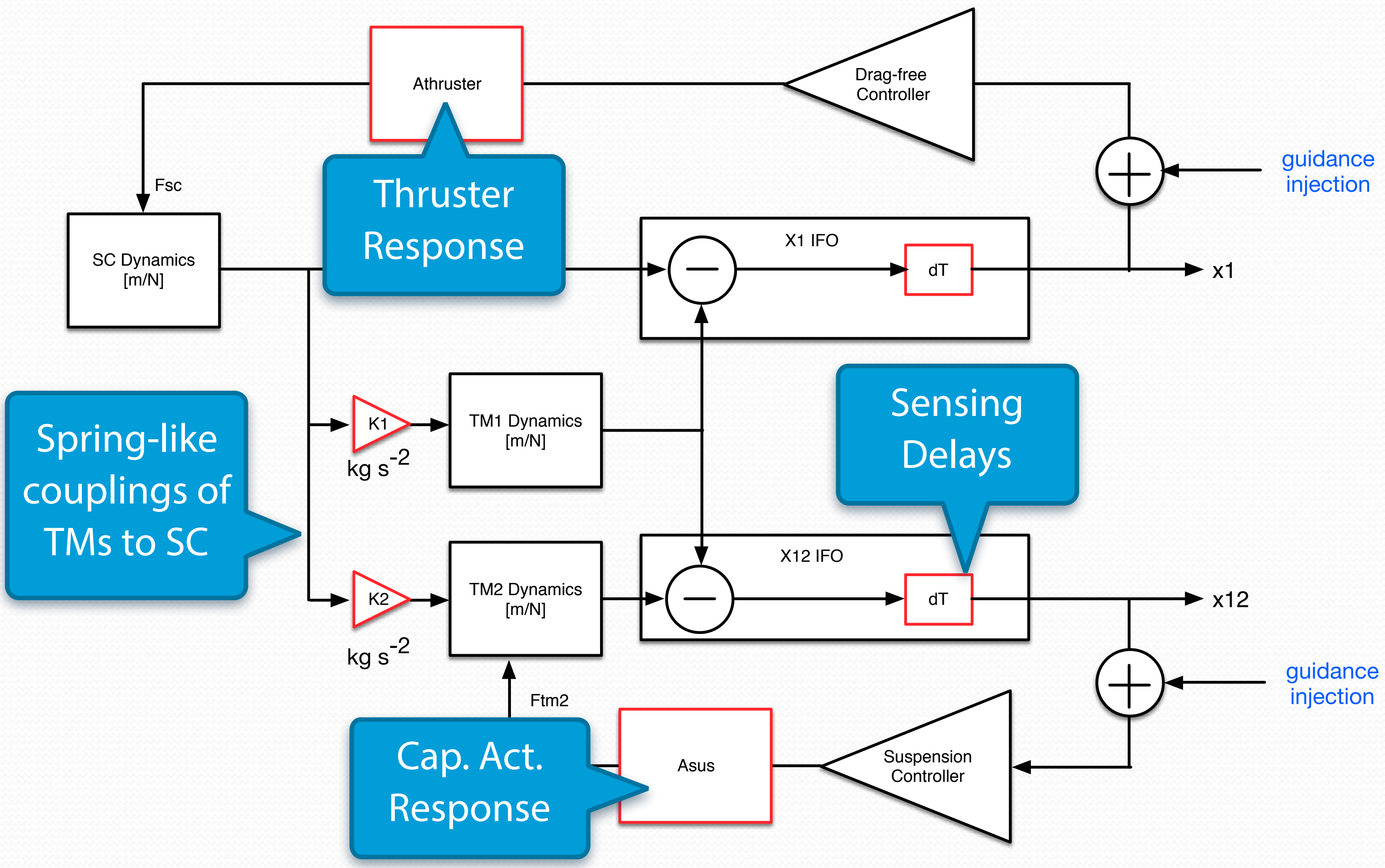
- Goal is to measure the key parameters needed for estimating the residual differential acceleration can be done by



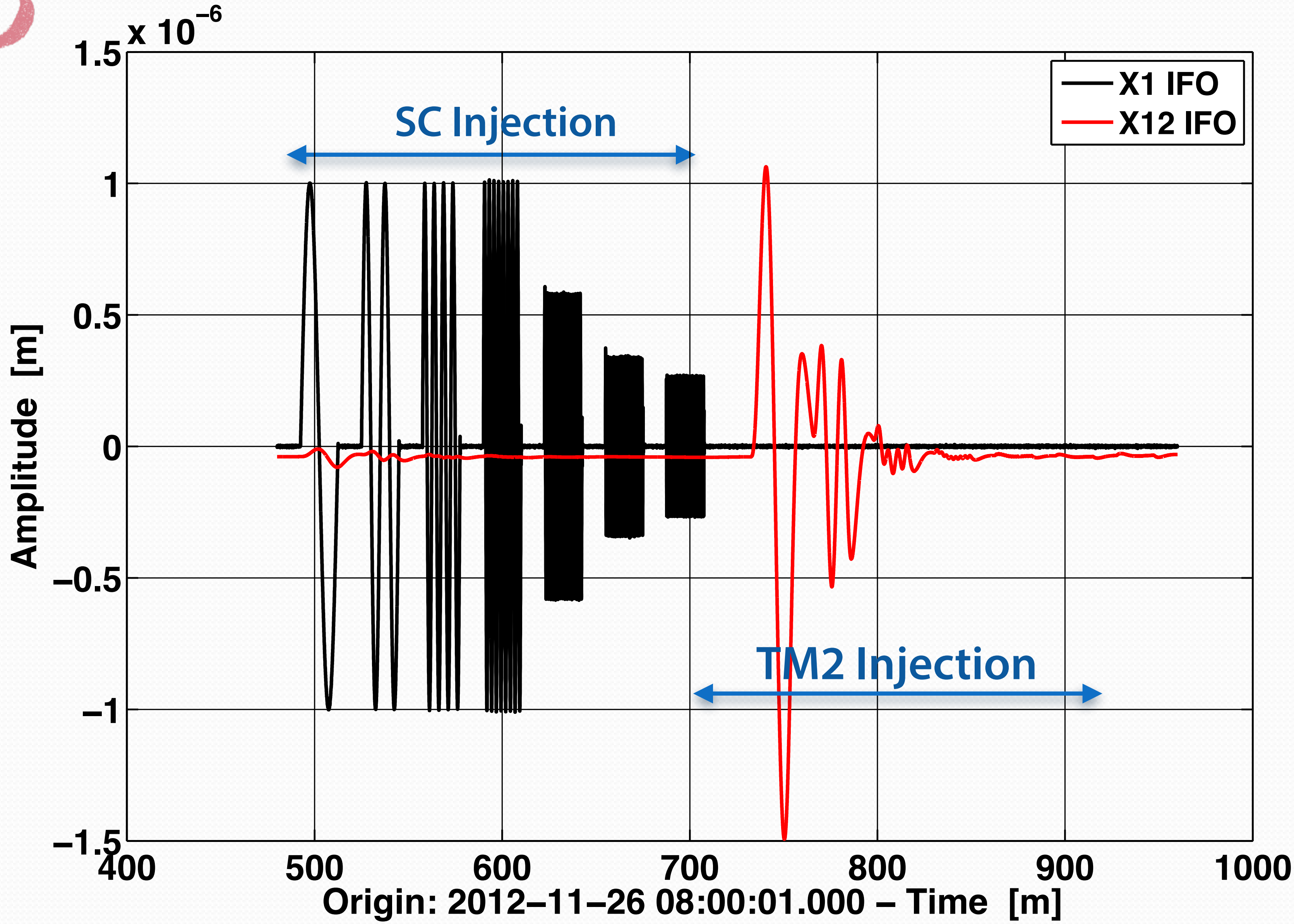
x-axis system identification: part 2



What do we learn from that?



The data

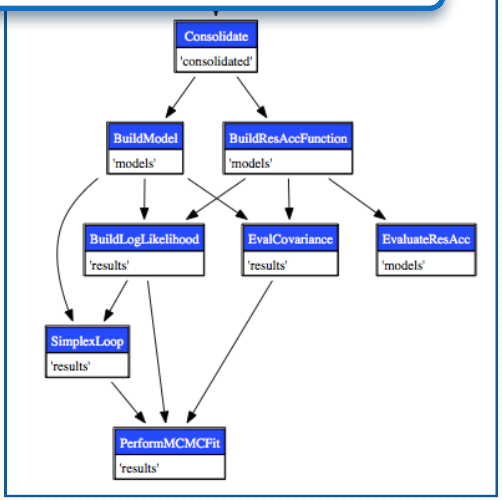

x 10^-6
1.5
1
0.5
0
–0.5
–1
–1.5
400
500
600
700
800
900
1000
Amplitude [m]
Origin: 2012–11–26 08:00:01.000 – Time [m]
X1 IFO
X12 IFO
SC Injection
TM2 Injection

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

Applying Bayesian Statistics to calibrate the LISA Pathfinder experiment

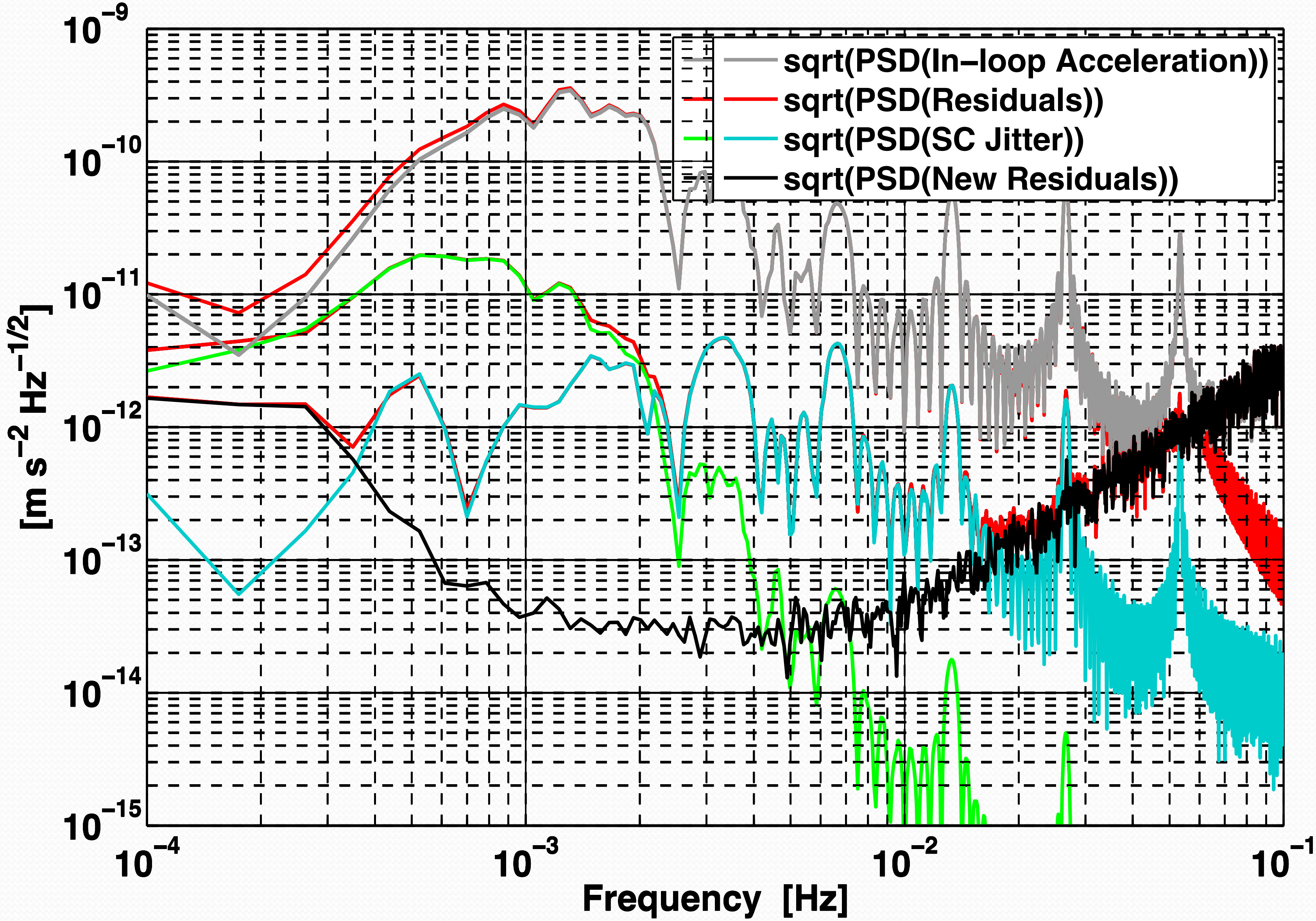
Nikos Karnesis, **Tuesday**



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


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

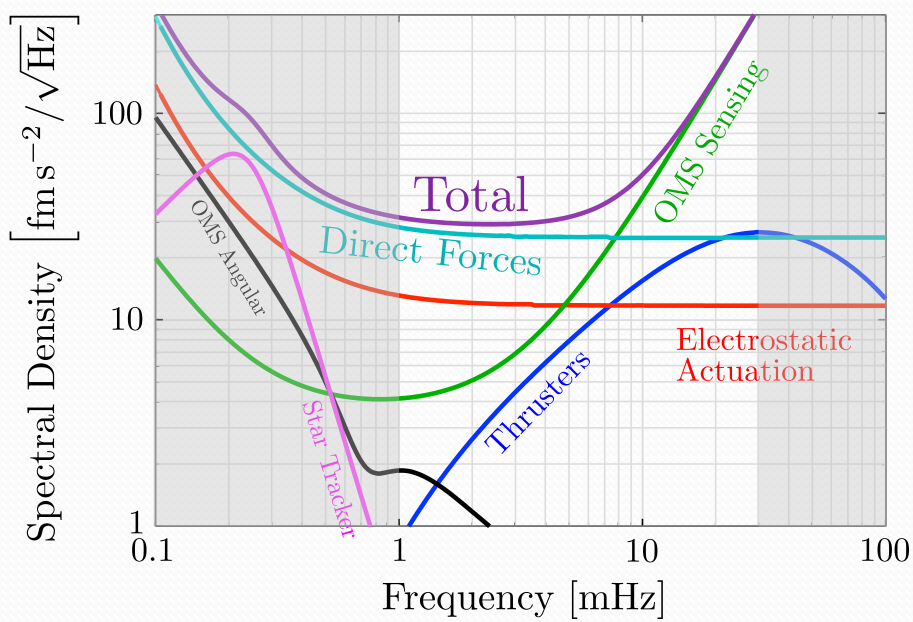
A general scheme

- **Balancing forces**:
  - improves physical modelling and interpretation
  - simplifies the analysis a great deal
- This 'acceleration' scheme can be used for other contributions
  - cross-talk
  - thermal
  - magnetic
  - free-flight experiments

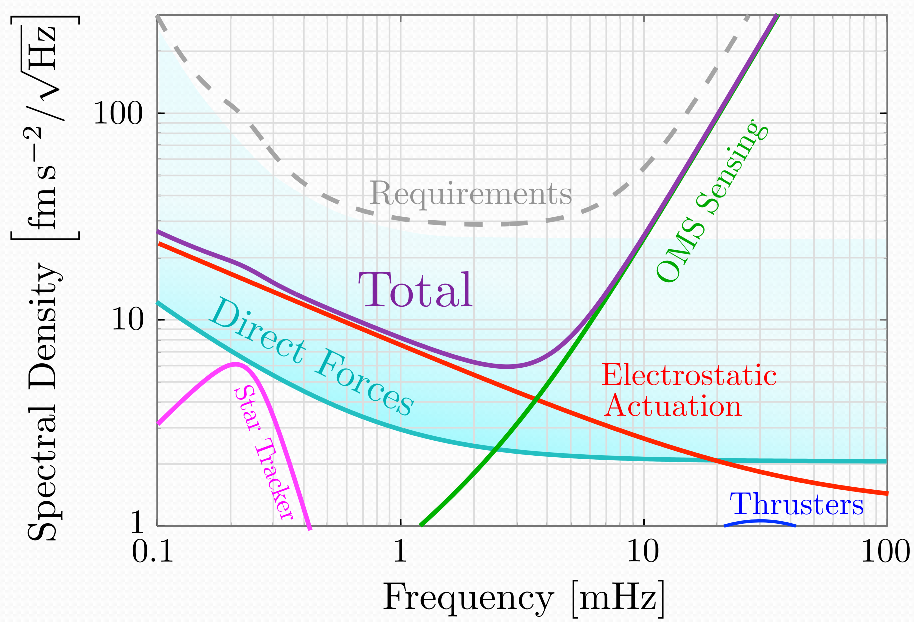
Noise Budget

- 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

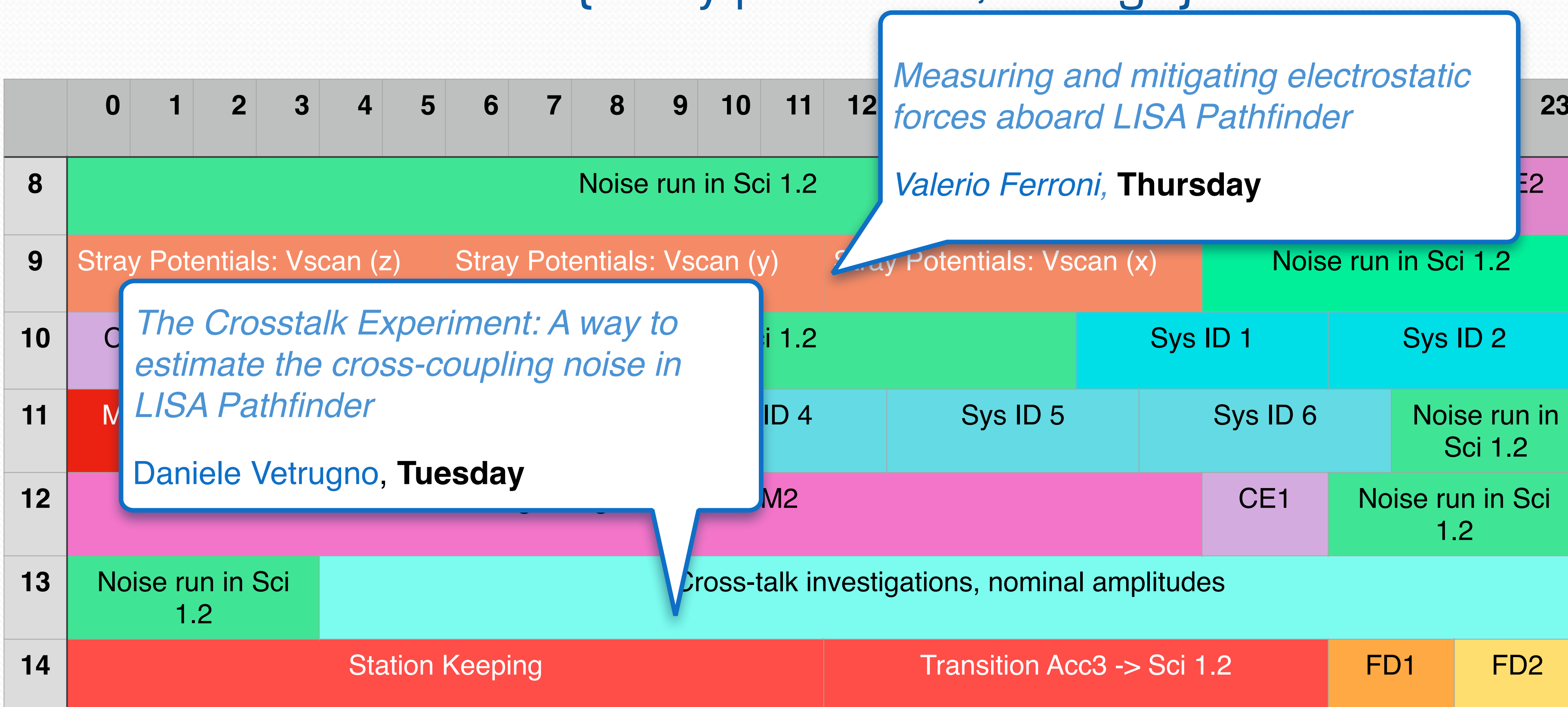


Current Best Estimate



Week 2: More Detailed Probing

- Focus on:
  - detailed system identification
  - state of TMs (stray potentials, charge)



Week 3: Exploration of the system

- Long noise run to look at low frequencies
- Alternative DFACS operation modes
- More detailed cross-talk investigations

<table>
<tr><th></th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th></tr>
<tr><td>15</td><td colspan="24">Noise run in Sci 1.2</td></tr>
<tr><td>16</td><td colspan="24">Noise run in Sci 1.2</td></tr>
<tr><td>17</td><td colspan="2">CE1</td><td colspan="2">CE2</td><td colspan="6">Transition from Sci1.2 to Sci2.0</td><td colspan="14">Noise run in Sci2.0</td></tr>
<tr><td>18</td><td colspan="4">Sys ID 1 (Sci2)</td><td colspan="4">Sys ID 2 (Sci2)</td><td colspan="4">Match stiffness</td><td colspan="4">Sys ID 3 (Sci2)</td><td colspan="4">Sys ID 4 (Sci2)</td><td colspan="4">Sys ID 5 (Sci2)</td></tr>
<tr><td>19</td><td colspan="4">Sys ID 6 (Sci2)</td><td colspan="2">CE1</td><td colspan="2">CE2</td><td colspan="16">Noise run in Sci2.0</td></tr>
<tr><td>20</td><td colspan="20">Cross-talk investigations, nominal amplitudes</td><td colspan="2">CE1</td><td colspan="2">CE2</td></tr>
<tr><td>21</td><td colspan="12">Station Keeping</td><td colspan="8">Transition Acc3 -> Sci 1.2</td><td colspan="2">FD1</td><td colspan="2">FD2</td></tr>
</table>

Longer term plan

lisa pathfinder

Main Activities

Early P…

w…

e…

Middle Phase

- OMS Optimisation
- IS Optimisation
- Thermal excitations
- Magnetic excitations
- Thruster characterisation

Late Phase

- Sensor characterisation
- Swapped test-mass operation
- Free-flight experiments
- Discharge tests

In-flight thermal experiments for LISA Pathfinder

Ferran Gibert, **Thursday**

Disentangling the magnetic force noise contribution in LISA Pathfinder

Miquel Nofrarias, **Tuesday**

Characterization of the micro-thruster system

Eric Plagnol, **Thursday**

Free-flight experiments in LISA Pathfinder

Ira Thorpe, **Tuesday**

Elements and Capabilities

- Successful science operations requires many elements
  - Ground segment infrastructure
  - Data analysis tools
  - Investigation designs
  - Analysis pipelines
- We also need many capabilities of the system
  - **DFACS configuration**: modes, gains, offsets, actuation algorithms
  - **Sensor configuration**: TM bias levels, GRM modes, laser temperature, OMS heterodyne frequency, OMS loop states, alignment
  - **Actuator configuration**: gains, biases
  - **Signal injections**: guidances, forces, torques, electrode voltages, OMS loop set points
  - **Environment**: TM discharge, UV lamp control, CMS configuration, thermal excitation, magnetic field excitation

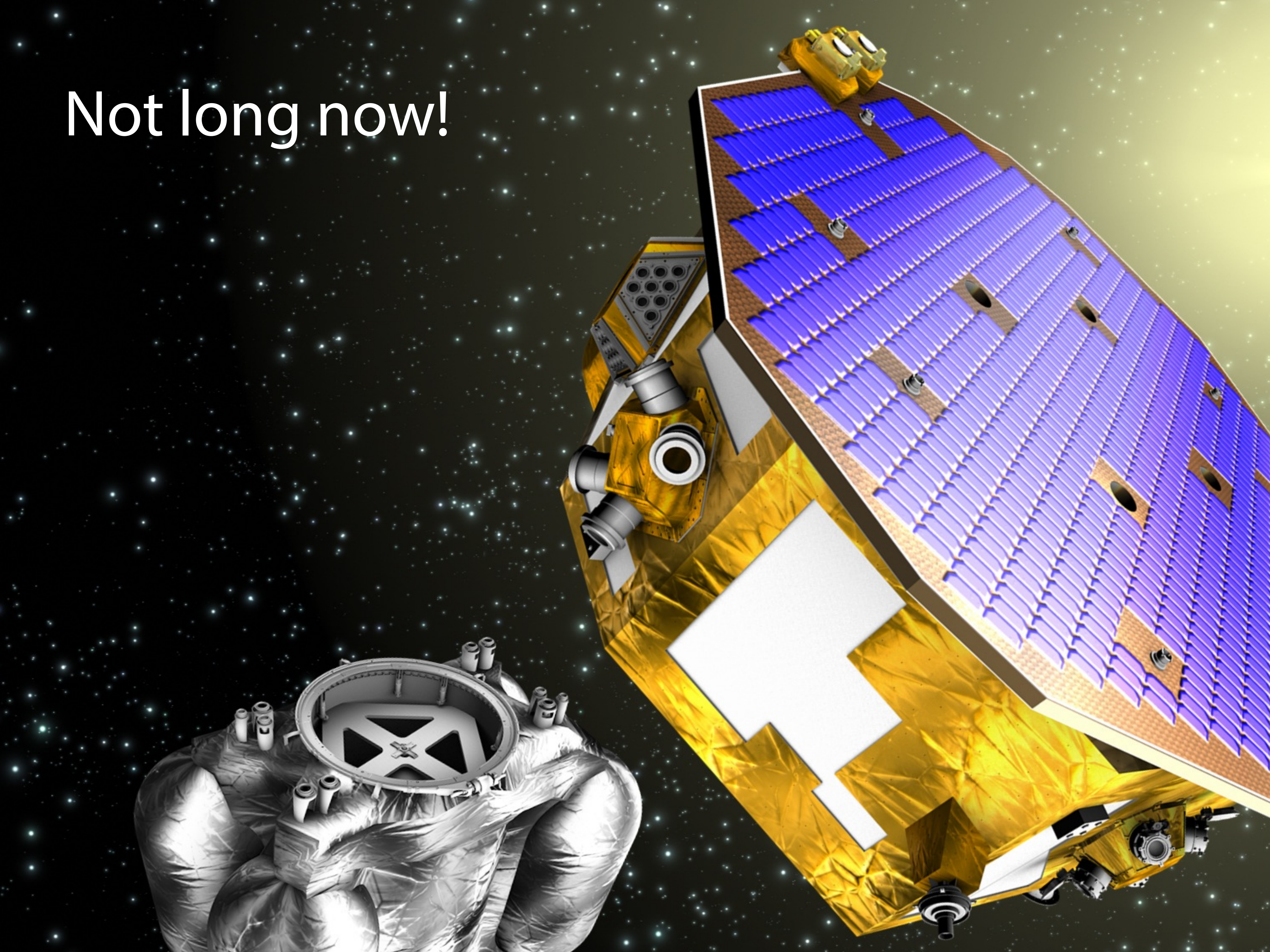
Where are we?

lisa pathfinder

- Components
  - Ground segment infrastructure
    - mostly all in place, some testing remains
  - Data Analysis Tools
    - LTPDA Toolbox is mature
  - Investigation design
    - we have generated and tested a large number of investigations
  - Analysis Pipelines
    - many exist already
    - some to be developed over the next year
- Training
  - We've had 3 dedicated training sessions
    - next one in June
  - We ran 4 large-scale mission simulations
    - tested many of the investigation designs and analysis pipelines on synthesised data in realistic operational environment
  - Participation in industrial hardware test campaigns
    - exposure to real data

Concluding thoughts

- LPF Operations is a **complex** and demanding schedule
- Packed full of detailed investigations which will allow us to:
  - **optimise** the system to achieve best possible TM free-fall
  - develop a **detailed physical model** of the system
- This all paves the way for **commissioning** of a LISA-like mission
  - we must design in the necessary capabilities from the start!


Not long now!