LPF Data Analysis

based on my personal recollection

Daniele Vetrugno

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AEI - Hannover

A few initial numbers of the LPF DA

- About 500 days of operations
- About 40 scientists involved

Courtesy of N. Karnesis

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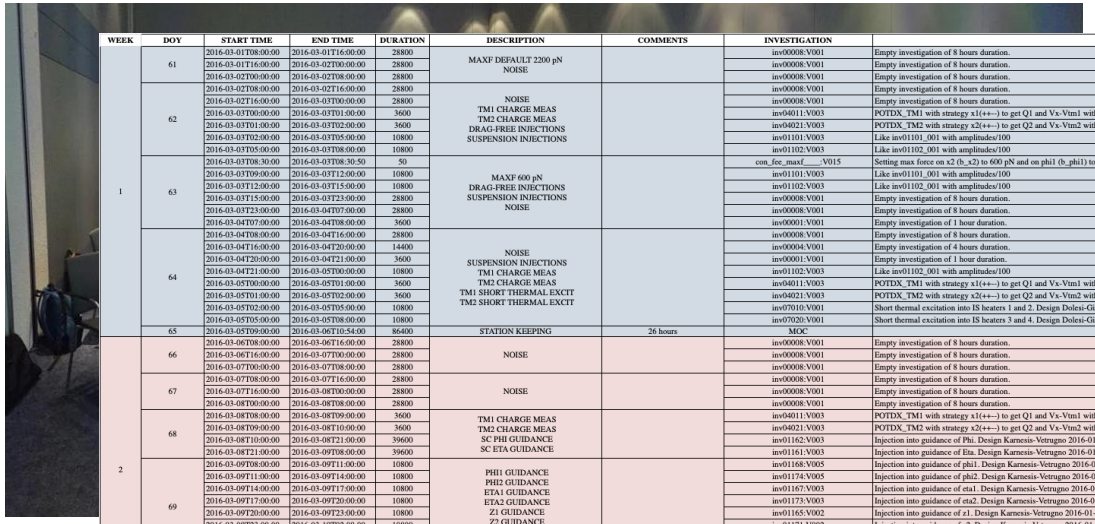

WEEK	DOY	START TIME	END TIME	DURATION	DESCRIPTION	COMMENTS	INVESTIGATION	INV DESCRIPTION
1	61	2016-03-01T08:00:00	2016-03-01T16:00:00	28800	MAXF DEFAULT 2200 pN NOISE		inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-01T16:00:00	2016-03-02T00:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-02T00:00:00	2016-03-02T08:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
	62	2016-03-02T08:00:00	2016-03-02T16:00:00	28800	NOISE TM1 CHARGE MEAS TM2 CHARGE MEAS DRAG-FREE INJECTIONS SUSPENSION INJECTIONS		inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-02T16:00:00	2016-03-03T00:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-03T00:00:00	2016-03-03T01:00:00	3600			inv04011:V003	POTDX_TM1 with strategy x1(++–) to get Q1 and Vx-Vtm1 with 0.05 V
		2016-03-03T01:00:00	2016-03-03T02:00:00	3600			inv04021:V003	POTDX_TM2 with strategy x2(++–) to get Q2 and Vx-Vtm2 with 0.05 V
		2016-03-03T02:00:00	2016-03-03T05:00:00	10800			inv01101:V003	Like inv01101_001 with amplitudes/100
		2016-03-03T05:00:00	2016-03-03T08:00:00	10800			inv01102:V003	Like inv01102_001 with amplitudes/100
	63	2016-03-03T08:30:00	2016-03-03T08:30:50	50	MAXF 600 pN DRAG-FREE INJECTIONS SUSPENSION INJECTIONS NOISE		con_fee_maxf____:V015	Setting max force on x2 (b_x2) to 600 pN and on phi1 (b_phi1) to 3.00 pN*m and on phi2 (b_phi2) to 3.00 pN*m
		2016-03-03T09:00:00	2016-03-03T12:00:00	10800			inv01101:V003	Like inv01101_001 with amplitudes/100
		2016-03-03T12:00:00	2016-03-03T15:00:00	10800			inv01102:V003	Like inv01102_001 with amplitudes/100
		2016-03-03T15:00:00	2016-03-03T23:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-03T23:00:00	2016-03-04T07:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-04T07:00:00	2016-03-04T08:00:00	3600			inv00001:V001	Empty investigation of 1 hour duration.
	64	2016-03-04T08:00:00	2016-03-04T16:00:00	28800	NOISE SUSPENSION INJECTIONS TM1 CHARGE MEAS TM2 CHARGE MEAS TM1 SHORT THERMAL EXCIT TM2 SHORT THERMAL EXCIT		inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-04T16:00:00	2016-03-04T20:00:00	14400			inv00004:V001	Empty investigation of 4 hours duration.
		2016-03-04T20:00:00	2016-03-04T21:00:00	3600			inv00001:V001	Empty investigation of 1 hour duration.
		2016-03-04T21:00:00	2016-03-05T00:00:00	10800			inv01102:V003	Like inv01102_001 with amplitudes/100
		2016-03-05T00:00:00	2016-03-05T01:00:00	3600			inv04011:V003	POTDX_TM1 with strategy x1(++–) to get Q1 and Vx-Vtm1 with 0.05 V
		2016-03-05T01:00:00	2016-03-05T02:00:00	3600			inv04021:V003	POTDX_TM2 with strategy x2(++–) to get Q2 and Vx-Vtm2 with 0.05 V
		2016-03-05T02:00:00	2016-03-05T05:00:00	10800			inv07010:V001	Short thermal excitation into IS heaters 1 and 2. Design Dolesi-Gibert 2016-01-13
		2016-03-05T05:00:00	2016-03-05T08:00:00	10800			inv07020:V001	Short thermal excitation into IS heaters 3 and 4. Design Dolesi-Gibert 2016-01-13
	65	2016-03-05T09:00:00	2016-03-06T10:54:00	86400	STATION KEEPING	26 hours	MOC	
2	66	2016-03-06T08:00:00	2016-03-06T16:00:00	28800	NOISE		inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-06T16:00:00	2016-03-07T00:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-07T00:00:00	2016-03-07T08:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
	67	2016-03-07T08:00:00	2016-03-07T16:00:00	28800	NOISE		inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-07T16:00:00	2016-03-08T00:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-08T00:00:00	2016-03-08T08:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
	68	2016-03-08T08:00:00	2016-03-08T09:00:00	3600	TM1 CHARGE MEAS TM2 CHARGE MEAS SC PHI GUIDANCE SC ETA GUIDANCE		inv04011:V003	POTDX_TM1 with strategy x1(++–) to get Q1 and Vx-Vtm1 with 0.05 V
		2016-03-08T09:00:00	2016-03-08T10:00:00	3600			inv04021:V003	POTDX_TM2 with strategy x2(++–) to get Q2 and Vx-Vtm2 with 0.05 V
		2016-03-08T10:00:00	2016-03-08T21:00:00	39600			inv01162:V003	Injection into guidance of Phi. Design Karnesis-Vetrugno 2016-01-12
		2016-03-08T21:00:00	2016-03-09T08:00:00	39600			inv01161:V003	Injection into guidance of Eta. Design Karnesis-Vetrugno 2016-01-12
	69	2016-03-09T08:00:00	2016-03-09T11:00:00	10800	PHI1 GUIDANCE PHI2 GUIDANCE ETA1 GUIDANCE ETA2 GUIDANCE Z1 GUIDANCE Z2 GUIDANCE Y1 GUIDANCE Y2 GUIDANCE		inv01168:V005	Injection into guidance of phi1. Design Karnesis-Vetrugno 2016-01-12
		2016-03-09T11:00:00	2016-03-09T14:00:00	10800			inv01174:V005	Injection into guidance of phi2. Design Karnesis-Vetrugno 2016-01-12
		2016-03-09T14:00:00	2016-03-09T17:00:00	10800			inv01167:V003	Injection into guidance of eta1. Design Karnesis-Vetrugno 2016-01-12
		2016-03-09T17:00:00	2016-03-09T20:00:00	10800			inv01173:V003	Injection into guidance of eta2. Design Karnesis-Vetrugno 2016-01-12
		2016-03-09T20:00:00	2016-03-09T23:00:00	10800			inv01165:V002	Injection into guidance of z1. Design Karnesis-Vetrugno 2016-01-12
		2016-03-09T23:00:00	2016-03-10T02:00:00	10800			inv01171:V002	Injection into guidance of z2. Design Karnesis-Vetrugno 2016-01-12
		2016-03-10T02:00:00	2016-03-10T05:00:00	10800			inv01164:V003	Injection into guidance of y1. Design Karnesis-Vetrugno 2016-01-12
		2016-03-10T05:00:00	2016-03-10T08:00:00	10800			inv01170:V003	Injection into guidance of y2. Design Karnesis-Vetrugno 2016-01-12
	70	2016-03-10T08:00:00	2016-03-11T07:00:00	82800	THERMAL INJECTIONS IN IS1/IS2 MAXF DEFAULT		inv07009:V004	Battery of injections into thermal IS heaters 1 and 2. Design Lobo-Nofrarias-Gibert
		2016-03-11T06:30:00	2016-03-11T06:30:20	20			con_fee_maxf_dft:V001	Reset all max forces and torques to MIB default
	71	2016-03-11T08:00:00	2016-03-12T08:00:00	86400	LAMP COMMISSIONING DAY		MOC	
	72	2016-03-12T09:00:00	2016-03-13T10:28:00	86400	STATION KEEPING	25.5 hours	MOC	Change to use of feed branch #2. Before feed branch #3 was used.
3	73	2016-03-13T08:00:00	2016-03-13T16:00:00	28800	MAXF 200pN NOISE		inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-13T16:00:00	2016-03-14T00:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-14T00:00:00	2016-03-14T08:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
	74	2016-03-14T08:00:00	2016-03-14T16:00:00	28800	NOISE		inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-14T16:00:00	2016-03-15T00:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-15T00:00:00	2016-03-15T08:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
	75	2016-03-15T08:00:00	2016-03-16T08:00:00	86400	WORKING POINT ENGINEERING		MOC	
	76	2016-03-16T08:00:00	2016-03-17T08:00:00	86400	WORKING POINT ENGINEERING		MOC	
	77	2016-03-17T08:00:00	2016-03-17T16:00:00	28800	NOISE		inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-17T16:00:00	2016-03-18T00:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.
		2016-03-18T00:00:00	2016-03-18T08:00:00	28800			inv00008:V001	Empty investigation of 8 hours duration.

Courtesy of N. Karnesis

A few initial numbers of the LPF DA

- About 500 days of operations
- About 40 scientists involved
- More than 100 Investigations, and pipeline, routines, catalogues
- A number of tiger teams: calibration team, Δg knights, pre-processing team, …

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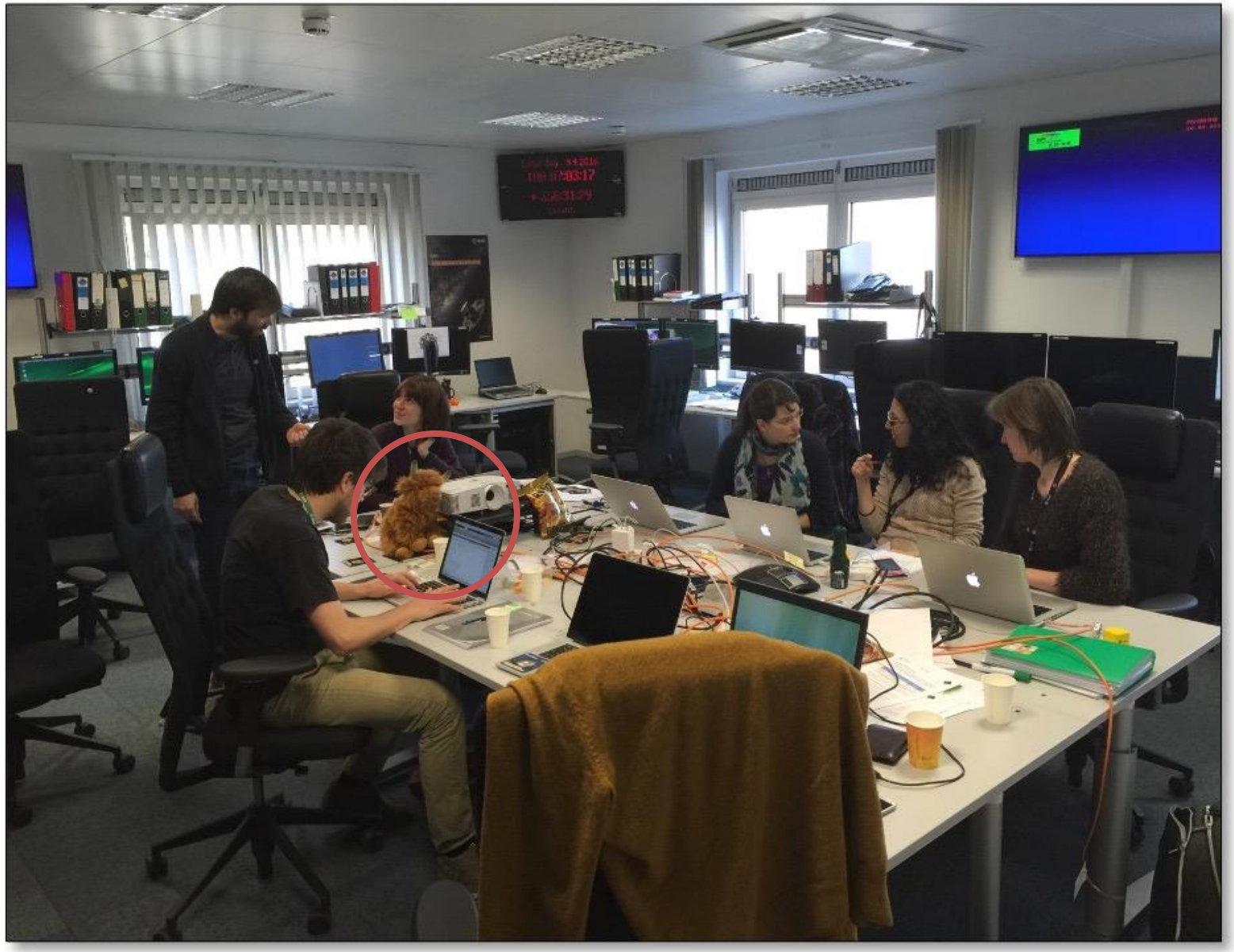
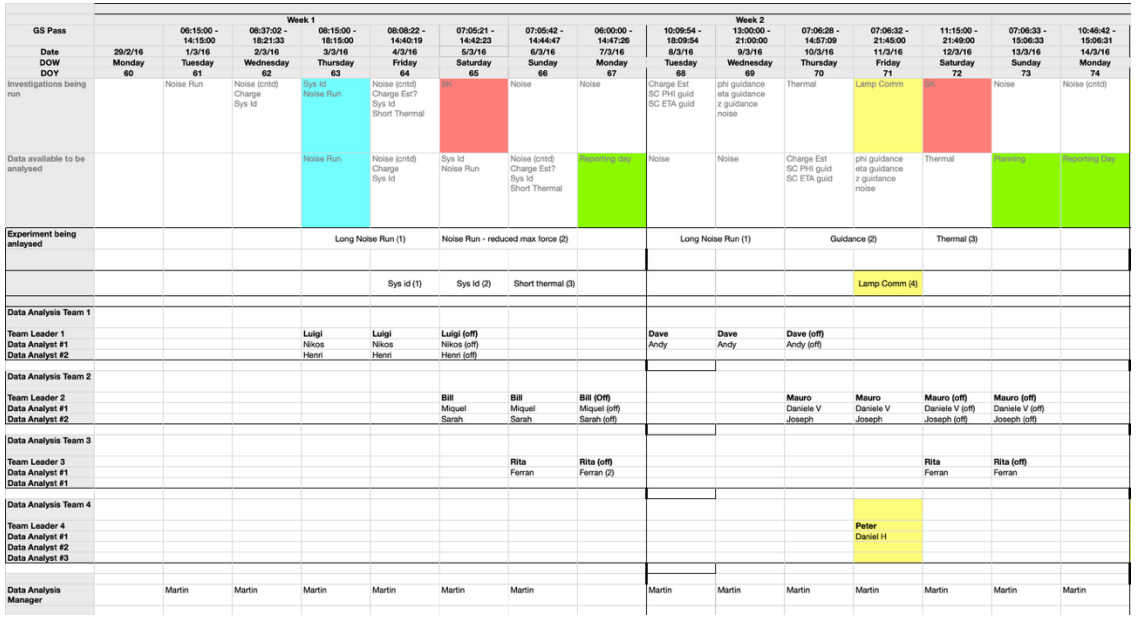


How it worked during operations

Rota was organized:

- Teams of 3 members: 1 team leader, 2 DA, partial overlapping



	Week 1								Week 2						
GS Pass		06:15:00 - 14:15:00	08:37:02 - 18:21:33	08:15:00 - 18:15:00	08:08:22 - 14:40:19	07:05:21 - 14:42:23	07:05:42 - 14:44:47	06:00:00 - 14:47:26	10:09:54 - 18:09:54	13:00:00 - 21:00:00	07:06:28 - 14:57:09	07:06:32 - 21:45:00	11:15:00 - 21:49:00	07:06:33 - 15:06:33	10:46:42 - 15:06:31
Date	29/2/16	1/3/16	2/3/16	3/3/16	4/3/16	5/3/16	6/3/16	7/3/16	8/3/16	9/3/16	10/3/16	11/3/16	12/3/16	13/3/16	14/3/16
DOW	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Monday
DOY	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74
Investigations being run		Noise Run	Noise (cntd) Charge Sys Id	Sys Id Noise Run	Noise (cntd) Charge Est? Sys Id Short Thermal	SK	Noise	Noise	Charge Est SC PHI guid SC ETA guid	phi guidance eta guidance z guidance noise	Thermal	Lamp Comm	SK	Noise	Noise (cntd)
Data available to be analysed				Noise Run	Noise (cntd) Charge Sys Id	Sys Id Noise Run	Noise (cntd) Charge Est? Sys Id Short Thermal	Reporting day	Noise	Noise	Charge Est SC PHI guid SC ETA guid	phi guidance eta guidance z guidance noise	Thermal	Planning	Reporting Day		
Experiment being anlaysed				Long Noise Run (1)		Noise Run - reduced max force (2)			Long Noise Run (1)		Guidance (2)		Thermal (3)		
					Sys id (1)	Sys Id (2)	Short thermal (3)					Lamp Comm (4)			
Data Analysis Team 1															
Team Leader 1				Luigi	Luigi	Luigi (off)			Dave	Dave	Dave (off)				
Data Analyst #1				Nikos	Nikos	Nikos (off)			Andy	Andy	Andy (off)				
Data Analyst #2				Henri	Henri	Henri (off)									
Data Analysis Team 2															
Team Leader 2						Bill	Bill	Bill (Off)			Mauro	Mauro	Mauro (off)	Mauro (off)	
Data Analyst #1						Miquel	Miquel	Miquel (off)			Daniele V	Daniele V	Daniele V (off)	Daniele V (off)	
Data Analyst #2						Sarah	Sarah	Sarah (off)			Joseph	Joseph	Joseph (off)	Joseph (off)	
Data Analysis Team 3															
Team Leader 3							Rita	Rita (off)					Rita	Rita (off)	
Data Analyst #1							Ferran	Ferran (2)					Ferran	Ferran	
Data Analyst #1															
Data Analysis Team 4															
Team Leader 4												Peter			
Data Analyst #1												Daniel H			
Data Analyst #2															
Data Analyst #3															
Data Analysis Manager		Martin	Martin	Martin	Martin	Martin	Martin		Martin	Martin	Martin	Martin	Martin	Martin	Martin

How it worked during operations

Rota was organized:

- Teams of 3 members: 1 team leader, 2 DA, partial overlapping
- Arrive few days in advance for Get Up To Speed

You must have G.U.T.S.*!!!

1. Landing is two days before on-duty.
2. *Get Up To Speed: starting from breakfast!
   - Set-up procedures
   - Discuss previous results
   - Read documents:
     - Previous analysis procedures
     - Logbooks
     - PI reports
     - …

28/11/25 LPF Ops Workshop - Lisbon 7

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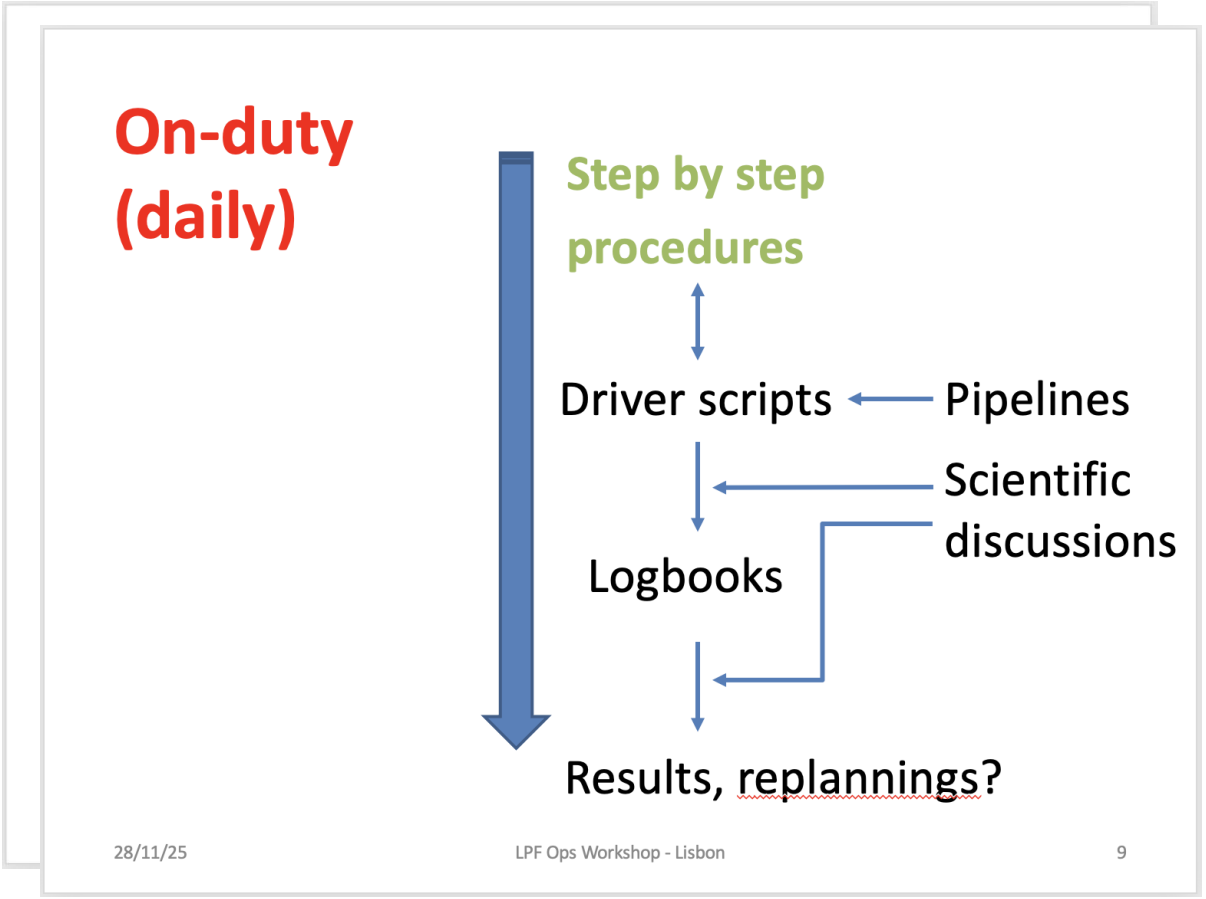

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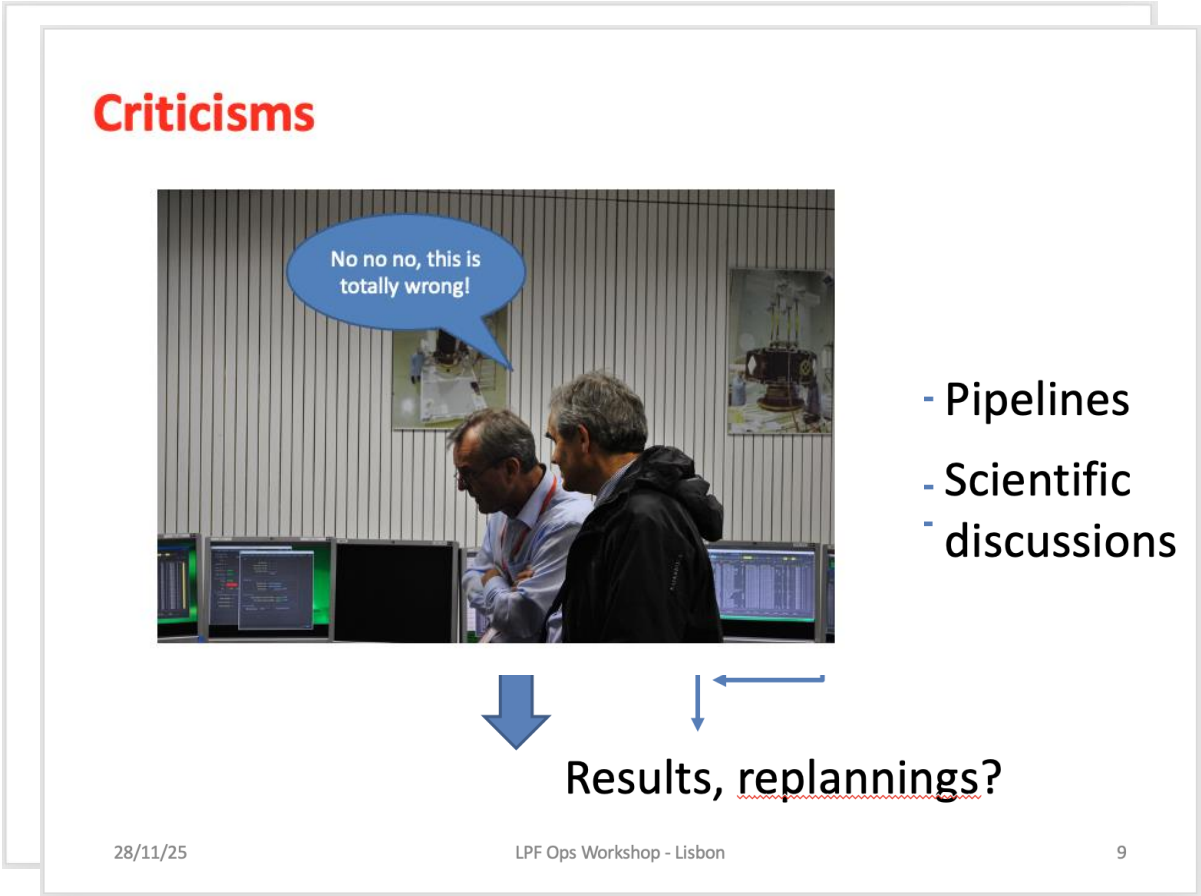

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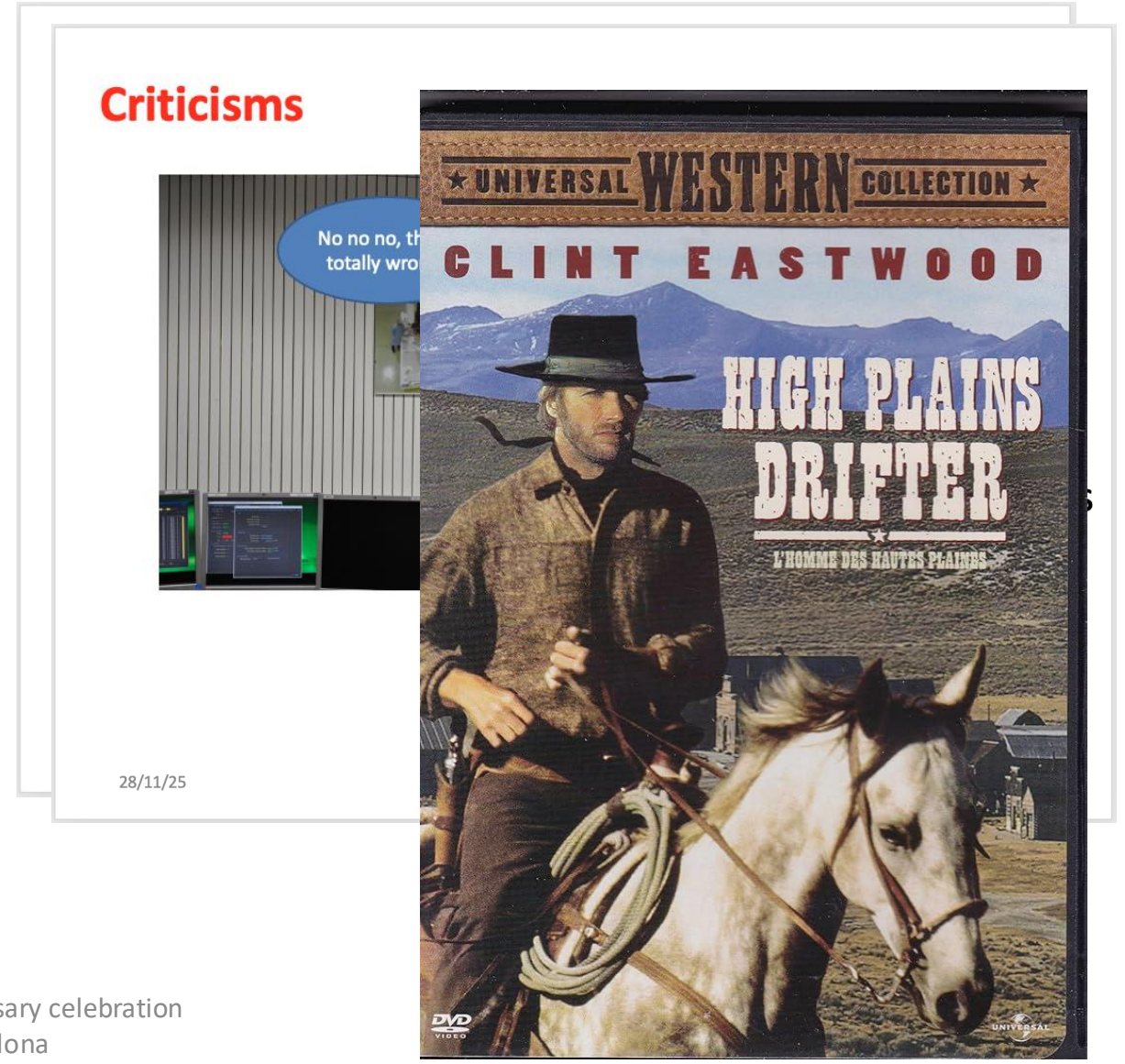
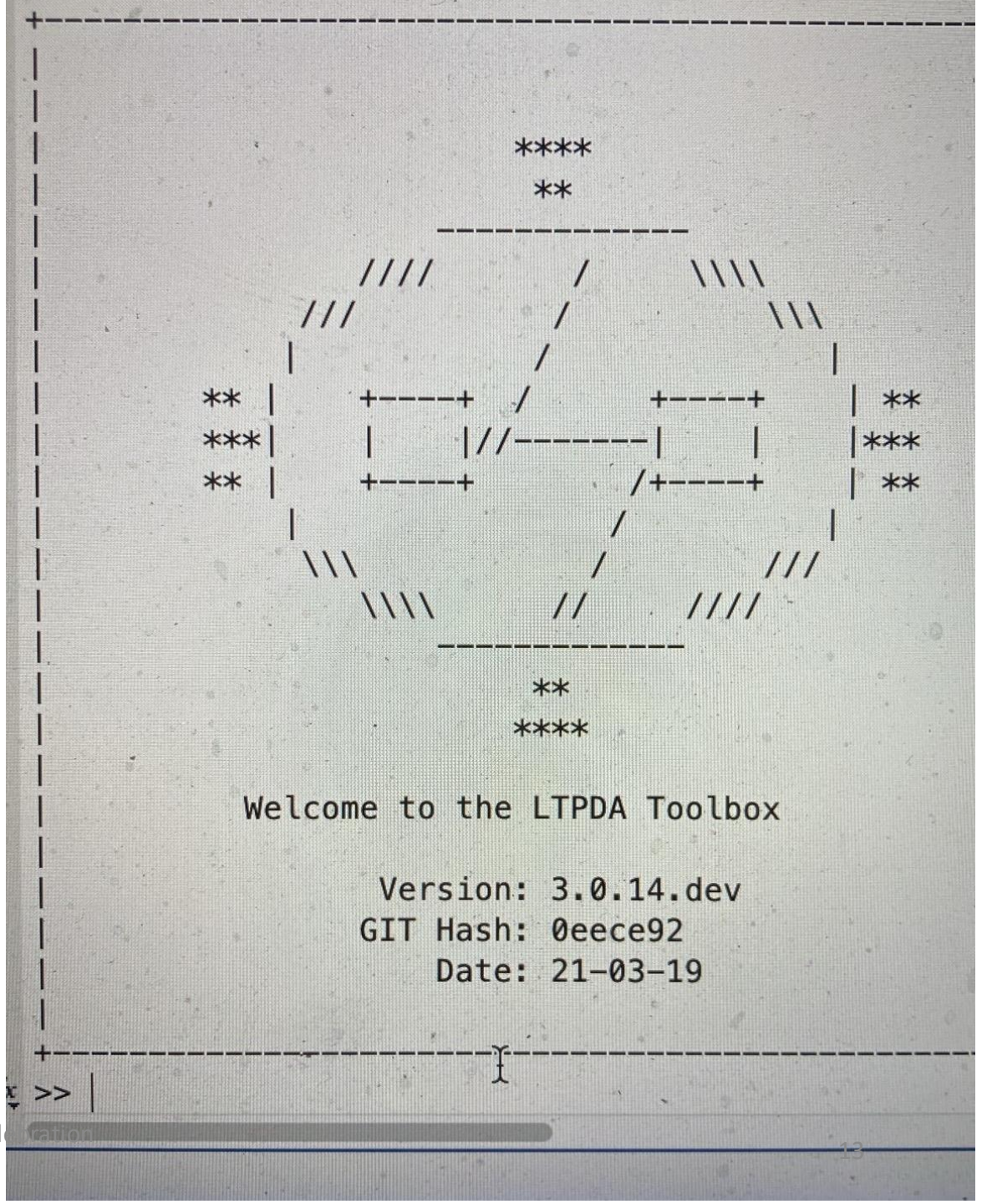


The ltpda toolbox

Prior to in-flight operations the ltpda (lisa technology package data analsys) tool was developed for them

- a lot of work to develop a common framework for the data analysis. Comparison easier between AOs
- Physical unites were always checked
- Pipeline and investigation created and tracked
- AOs history was tracked



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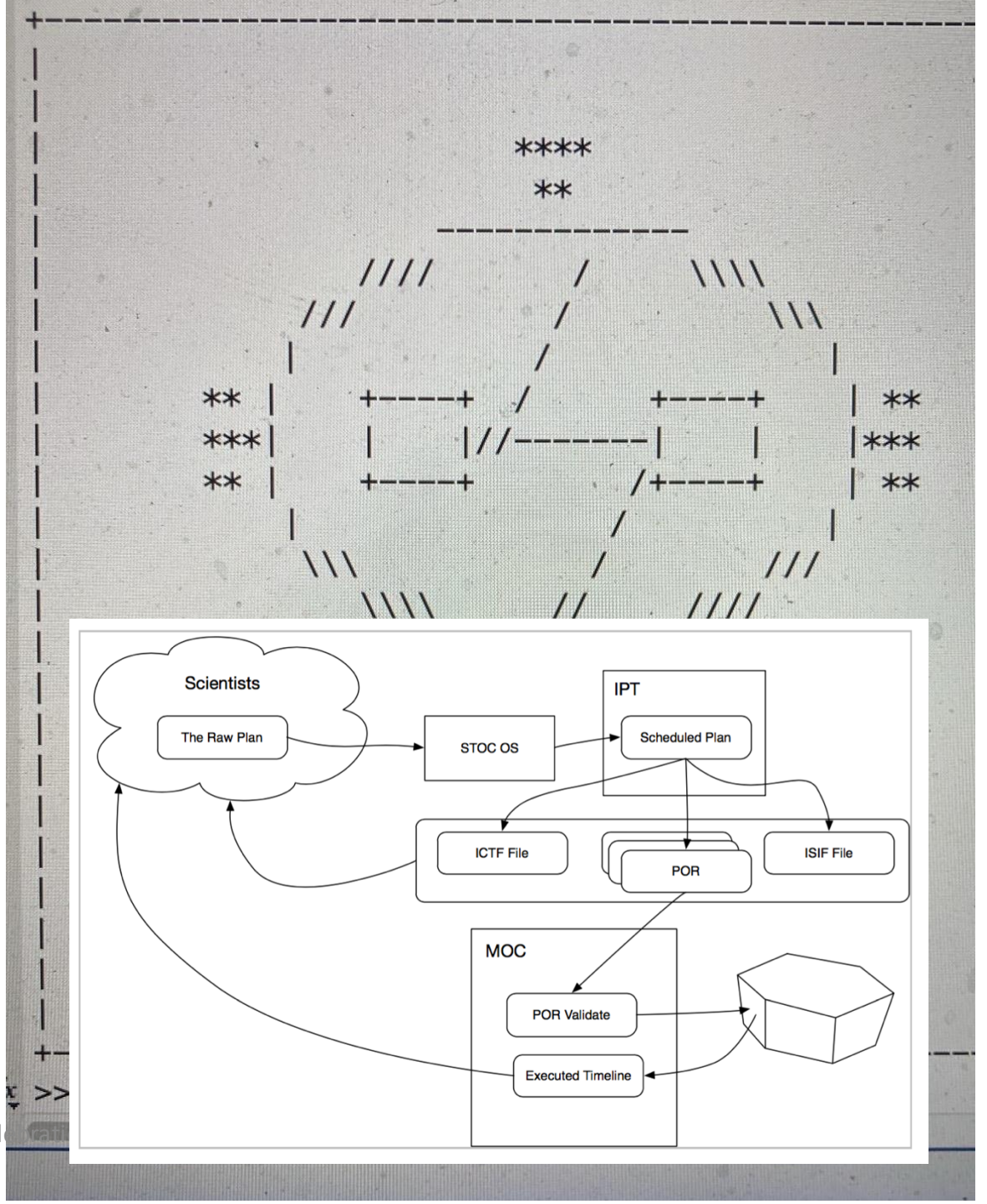
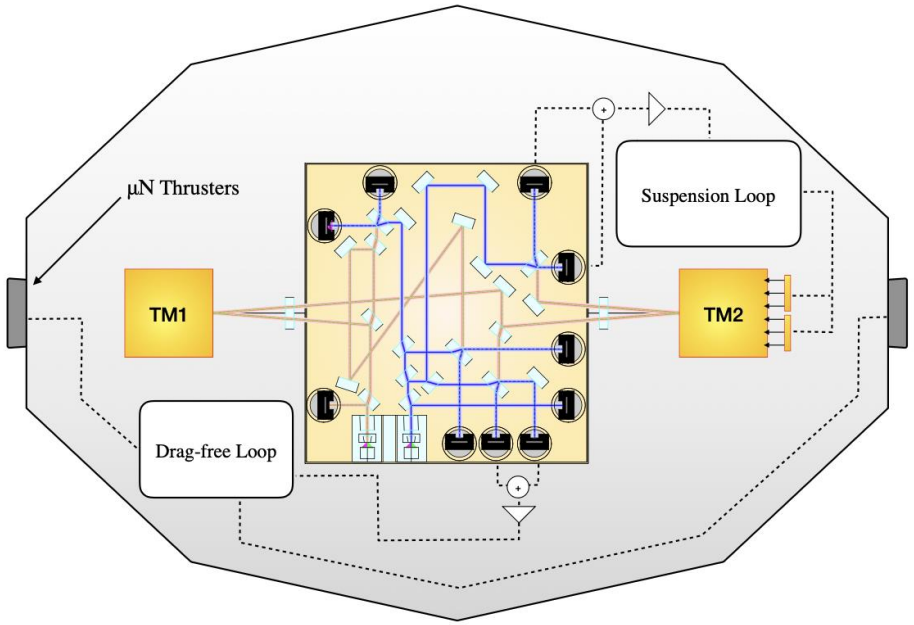
However

- “history” attached to AO made the data very heavy
- during operations, often needed quick estimation because of possible replanning
- we were forced to go “outside” the tool

It is important to have such a tool but the usability should be improved for LISA



Δg: the main objective of LPF data analysis



GOAL: to estimate the differential force per unit mass between the two test masses inside the SC

gain of the commanded force

delay

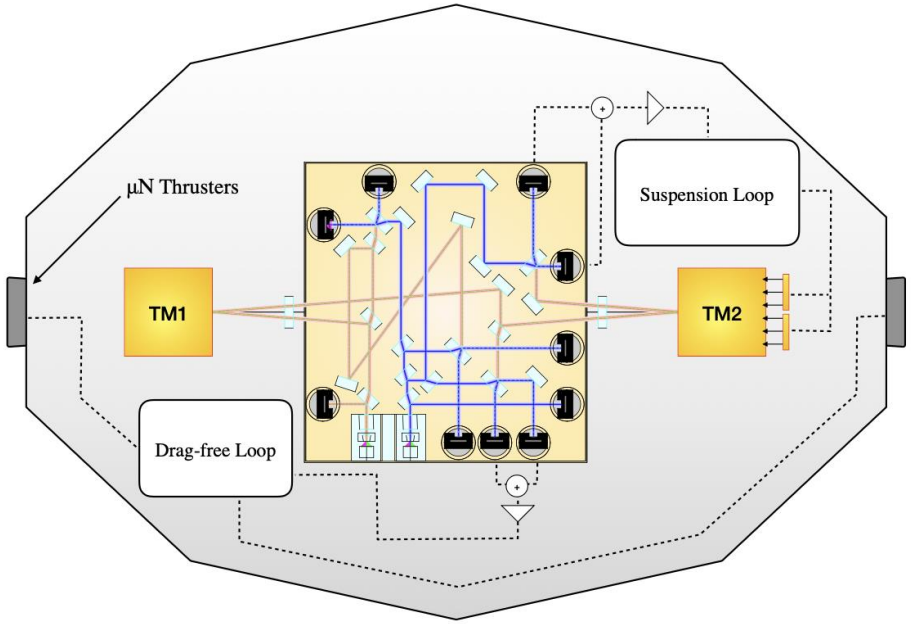
$$\Delta g(t) = \ddot{o}_{12}(t) + \omega_2^2 o_{12}(t) + \Delta\omega^2 o_1(t) - C_{sus} g_c(t) - c_1 \dot{g}_c(t) + \delta_1 \ddot{o}_1(t)$$

testmass 2 stiffness

differential stiffness

IFOX1X12

Δg can be calculated only after calibration…

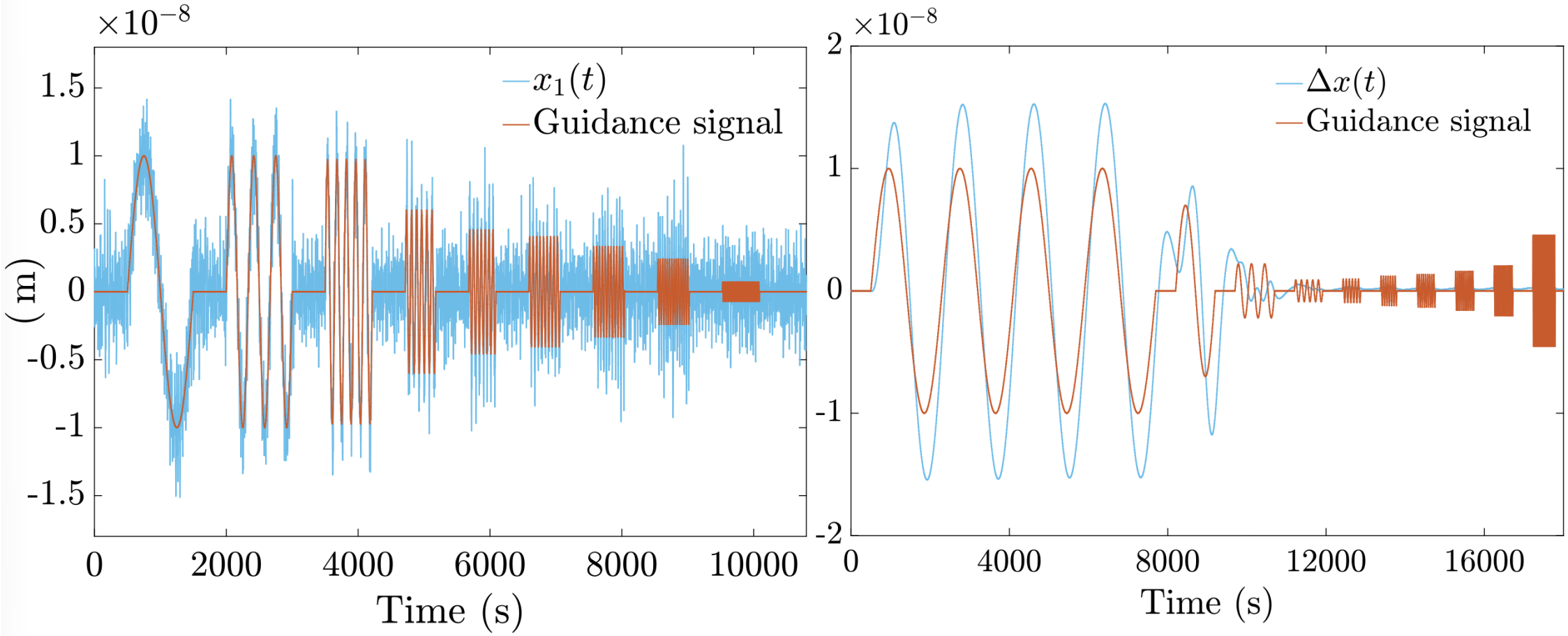


- We want to estimate the dynamical parameters of the three-body system.
- Produce the Δg differential residual force per unit mass between the two test masses.

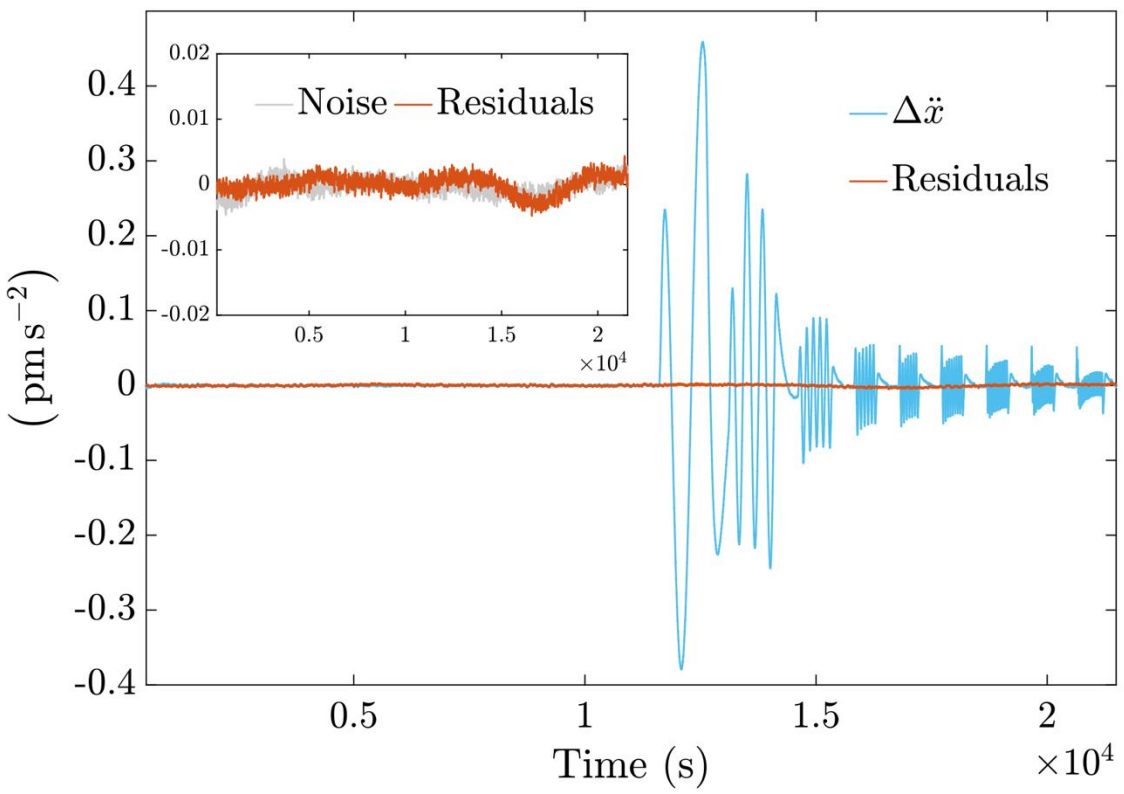
System identification experiments:

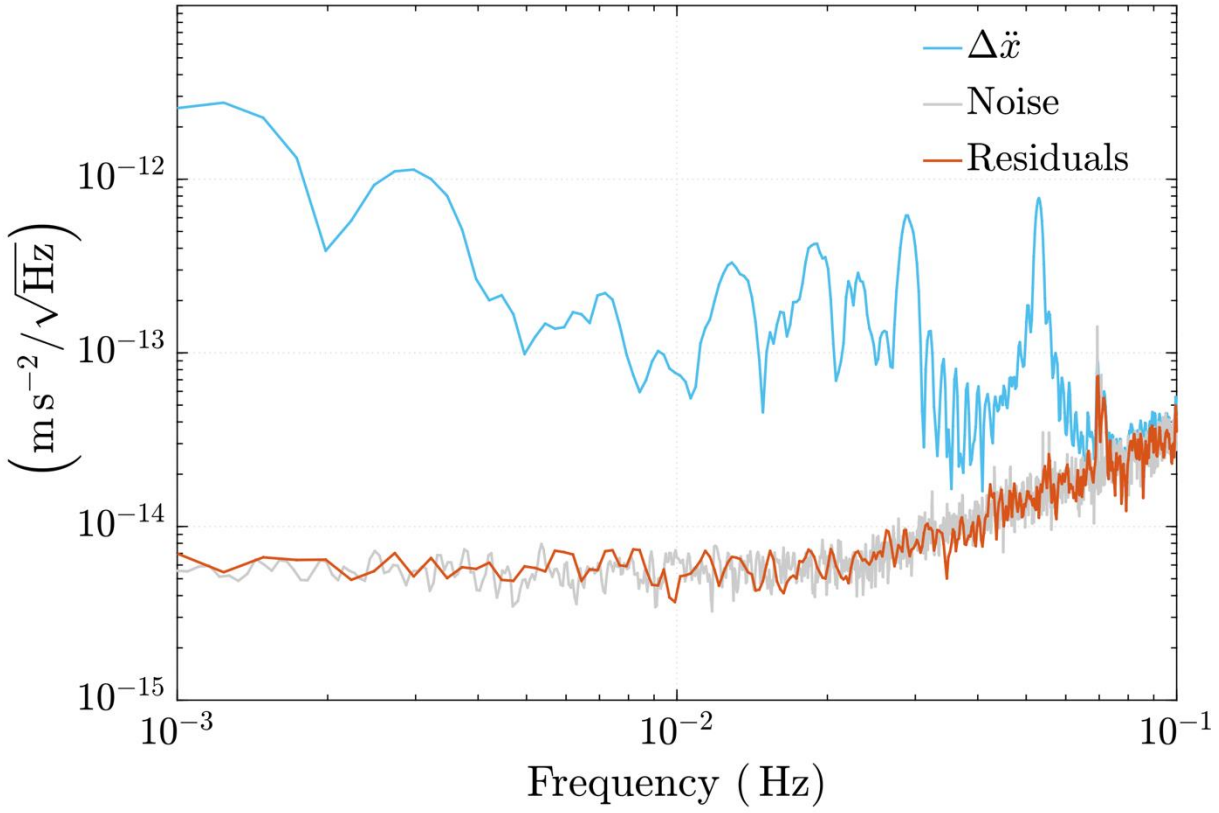
- Excite the system: Inject fake interferometric motion, let the system respond.
- Fit the system's response with our model and get the parameters' estimation.

System response was as expected…

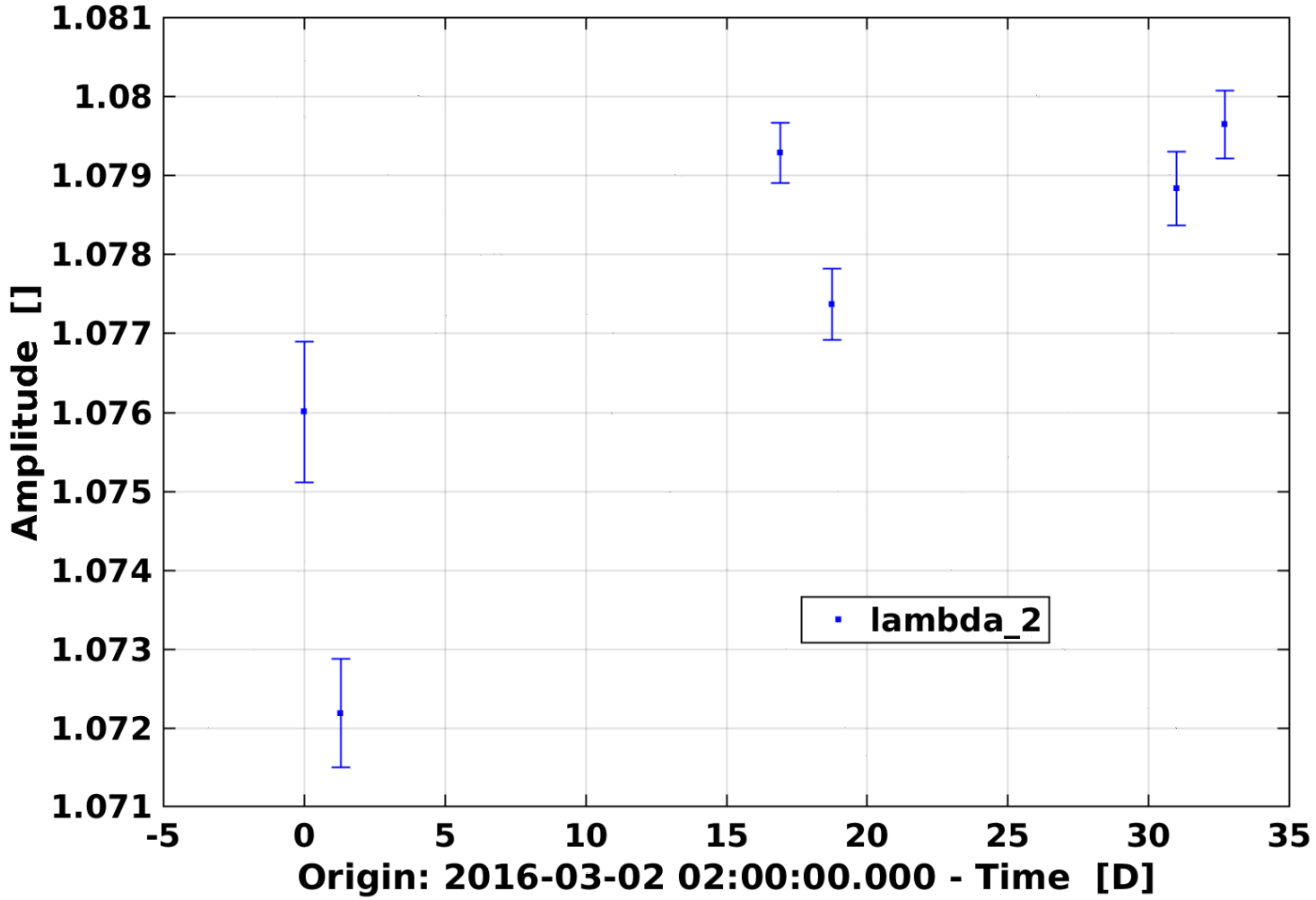


□ and signal was fully removed from the data

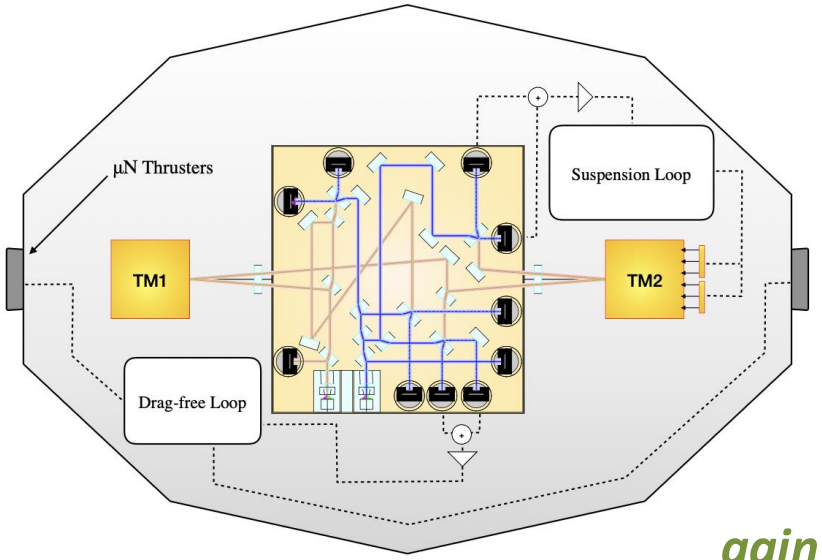


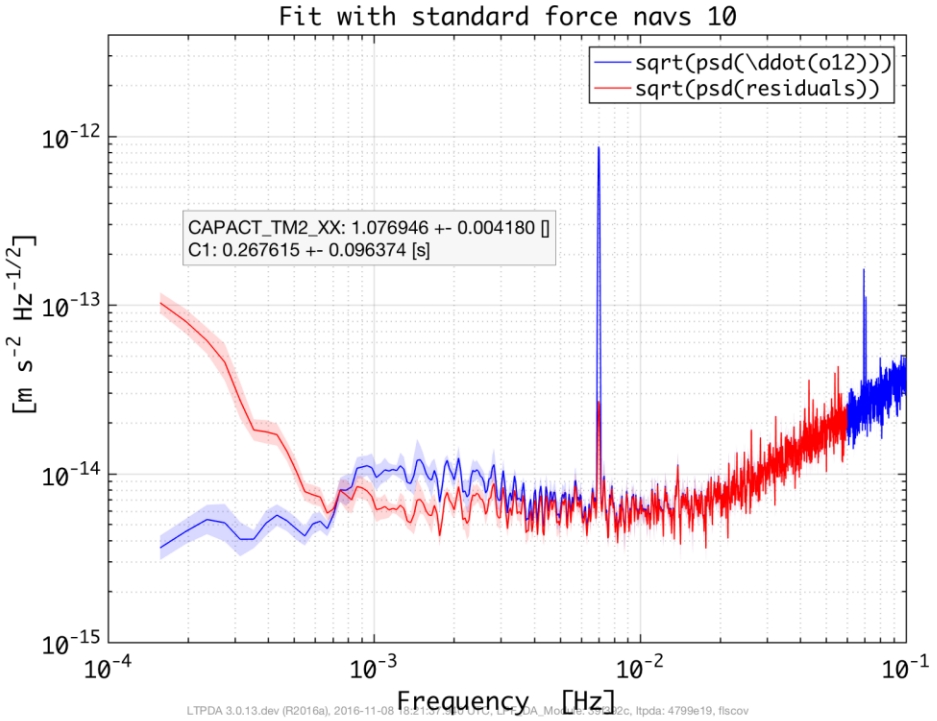


Wait a second? What? A variable actuation gain???



We need to design quickly an experiment to test this issue: the calibration tone





gain of the commanded force

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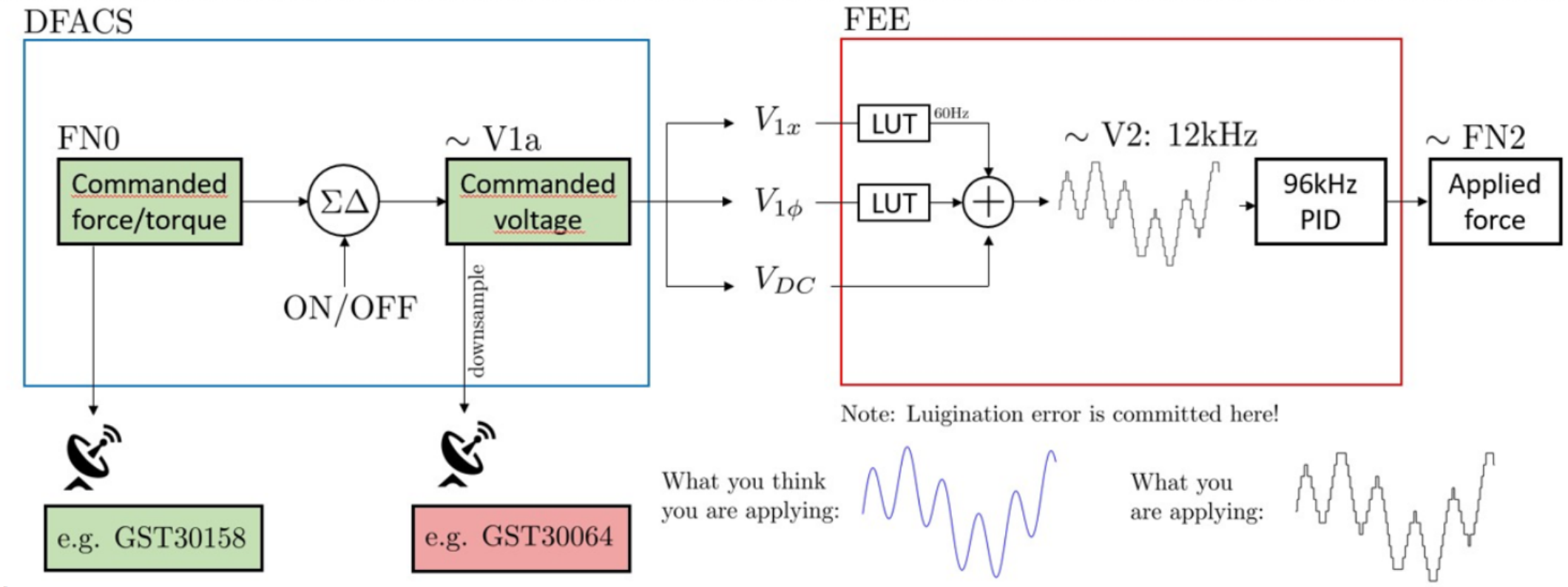
testmass 2 stiffness

differential stiffness

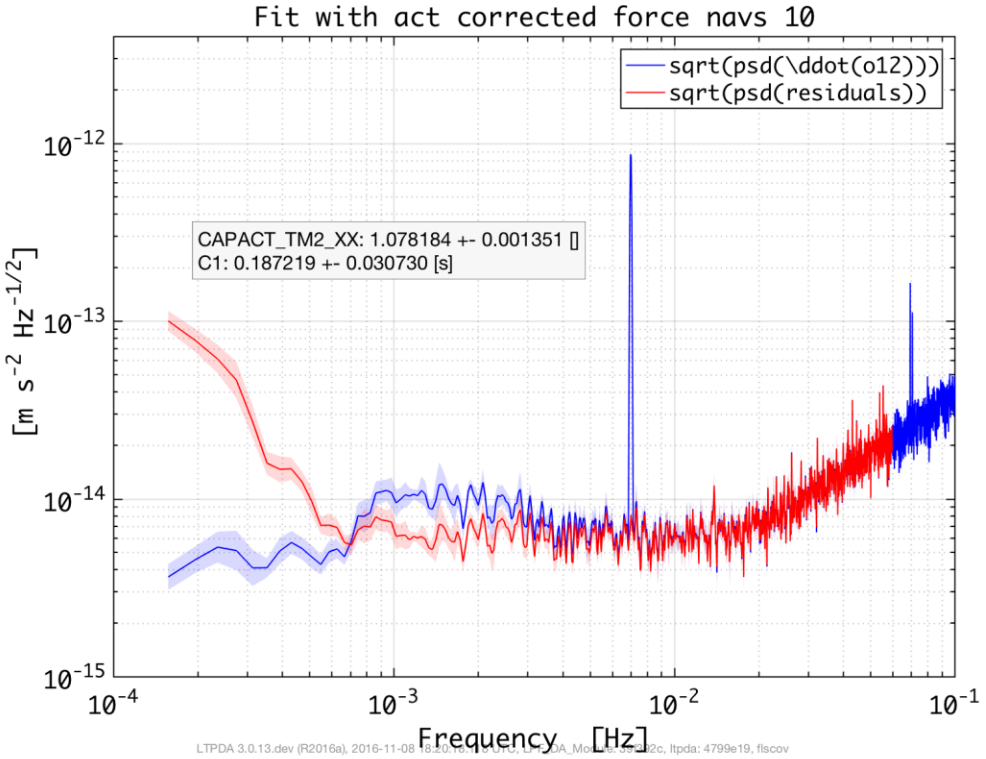
IFOX1X12

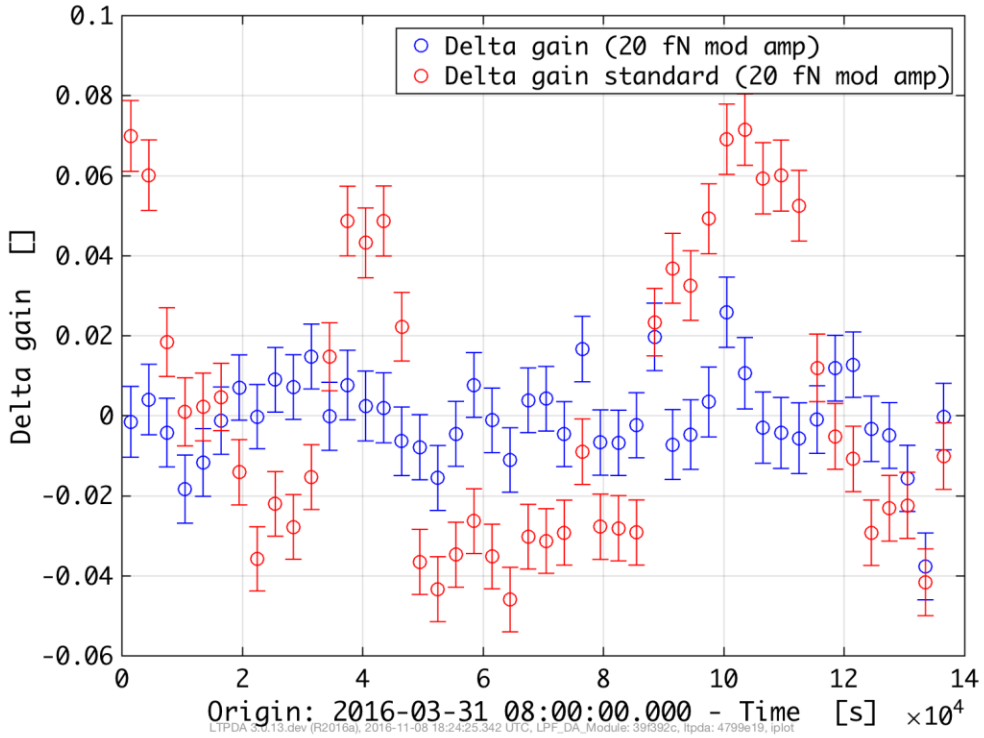
Commanded forces NOT EQUAL to Applied forces



Courtesy of V. Chiavegato PhD thesis

Demodulation of 20 fN @ 7 mHz with corrected forces





A few Lessons Learned

#1 Fast tools to see and work as soon as possible on possible issues was really important… e.g., IRLS vs MCMC

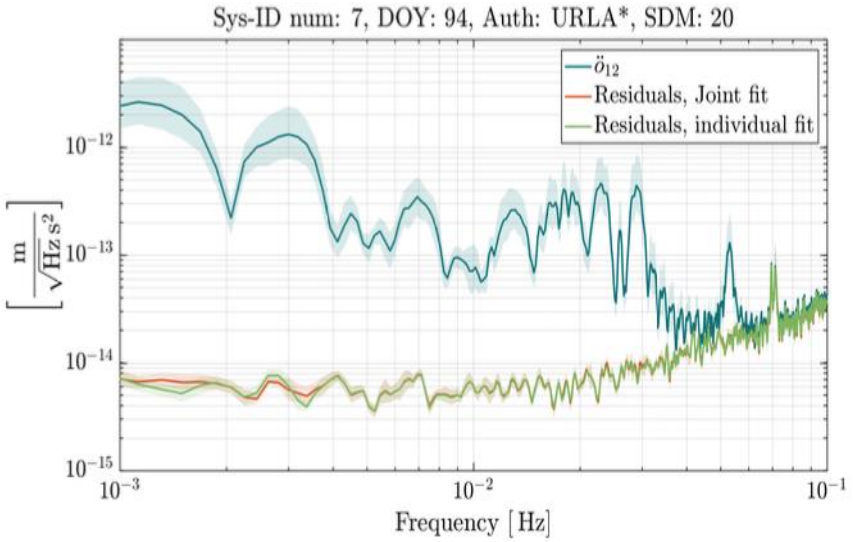
#2 Being able to replicate the subsystem behavior was also important (see also lowering authorities in Bill's presentation)

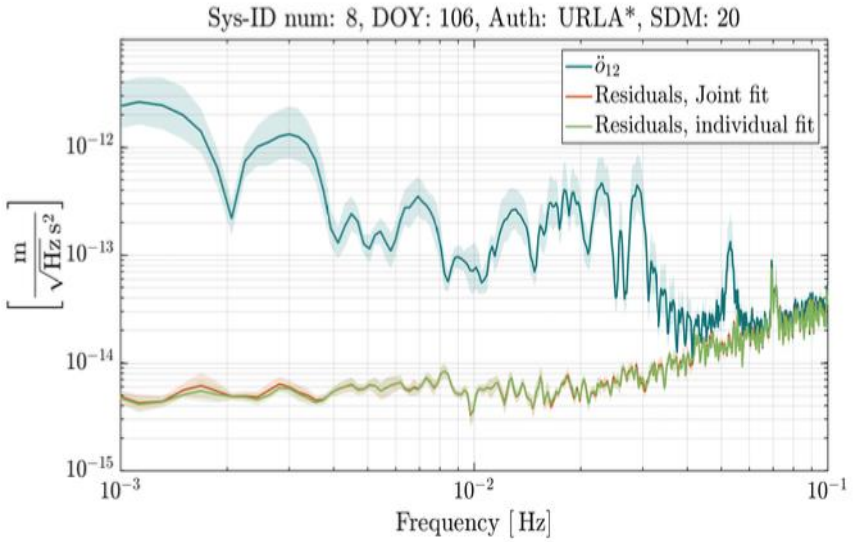
#3 flexibility in getting requested data from the SC: e.g., we needed to change telemetered sampling rate data from 1 Hz to 10 Hz

Name	Duration (hrs)	Type	Features
3045 default	6	Guidance	[1 -50 mHz] Drag Free (DF) and Suspension Loop (SL)
3045 short	3	Guidance	[1 -50 mHz] DF and SL
3045 long	9	Guidance	[0.55 -50 mHz] DF and SL
Calibration Tone 1	39	Ool force	20 fN - 7 mHz
Calibration Tone 2	3	Ool force	100 fN - 7 mHz
Calibration Tone 3	65	Ool force	100 fN - 10 mHz
IFOX1X12	1	Guidance	400 mHz – 1 nm
Low frequency calibration	16	Voltage modulation on Z	[++++] 0.25 V – 1 mHz 5 mHz 0.25 mHz

A global fit to a unique model can also be performed

$$
\begin{aligned}
\Delta g[t] =& \ddot{o}_1[t] - \lambda_2 F_{\mathrm{x2}}^{\mathrm{corr}}[t] + \lambda_1 F_{\mathrm{x1}}^{\mathrm{corr}}[t] \\
&+ (\omega_{2,\,\mathrm{bcgd}}^2 + a_{x2} F_{\mathrm{max},\,2} + a_{\phi 2} N_{\mathrm{max},\,2}) o_{12}[t] \\
&+ \left((\omega_{2,\,\mathrm{bcgd}}^2 + a_{x2} F_{\mathrm{max},\,2} + a_{\phi 2} N_{\mathrm{max},\,2}) - (\omega_{1,\,\mathrm{bcgd}}^2 + a_{x1} F_{\mathrm{max},\,1} + a_{\phi 1} N_{\mathrm{max},\,1})\right) o_1[t] \\
&- C_1 \dot{F}_{\mathrm{x1}}^{\mathrm{corr}}[t] + C_2 \dot{F}_{\mathrm{x2}}^{\mathrm{corr}}[t] - \delta_{\mathrm{ifo},\,\mathrm{k}} \ddot{o}_1[t].
\end{aligned}
$$





Estimated parameters compatible with expectations

Parameter	Estimated $\pm\sigma$
joint fit	
λ_1	0.8 ± 0.1
λ_2	$1.0776 \pm 1 \times 10^{-4}$
$\omega^2_{1,\,\mathrm{bcgd}}$ (s^{-2})	$-(4.21 \pm 0.08) \times 10^{-7}$
$\omega^2_{2,\,\mathrm{bcgd}}$ (s^{-2})	$-(4.24 \pm 0.04) \times 10^{-7}$
C_1 (ms)	-2 ± 1.2
C_2 (ms)	0.181 ± 0.004
a_{x1} ($\mathrm{s}^{-2}\,\mathrm{N}^{-1} \times 10^3$)	-0.327 ± 0.006
$a_{\phi 1}$ ($\mathrm{s}^{-2}\,\mathrm{N}^{-1}\,\mathrm{m}^{-1} \times 10^3$)	-26 ± 1
a_{x2} ($\mathrm{s}^{-2}\,\mathrm{N}^{-1} \times 10^3$)	-0.318 ± 0.006
$a_{\phi 2}$ ($\mathrm{s}^{-2}\,\mathrm{N}^{-1}\,\mathrm{m}^{-1} \times 10^3$)	-27 ± 1
$\delta_{\mathrm{ifo},\,1}$	$(-2.4 \pm 0.2) \times 10^{-5}$
$\delta_{\mathrm{ifo},\,2}$	$(-1.56 \pm 0.06) \times 10^{-5}$
$\delta_{\mathrm{ifo},\,3}$	$(-1.97 \pm 0.06) \times 10^{-5}$
$\delta_{\mathrm{ifo},\,4}$	$(1.79 \pm 0.09) \times 10^{-5}$

Expected values

$a_{x1} = a_{x2} = -319$

$a_{\varphi 1} = a_{\varphi 2} = -26400$

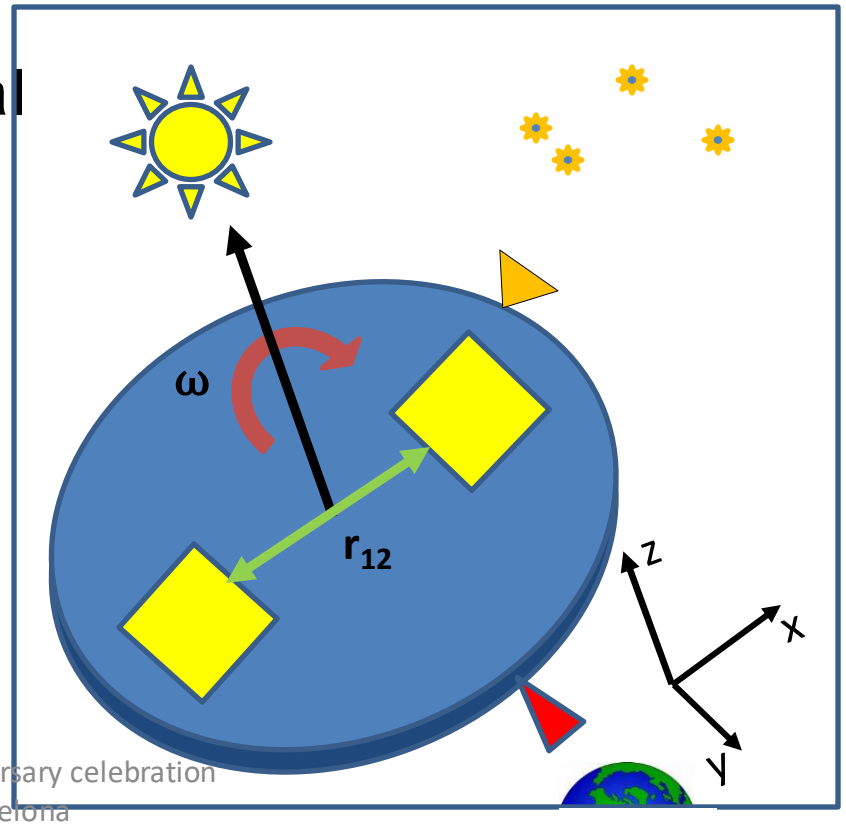
At very low frequency the spacecraft is a rotating reference frame

$$\Delta g(t) = a_{12} - \lambda f_{2,cmd} + \omega_2^2 o_{12} + \Delta\omega^2 o_1 \; +$$

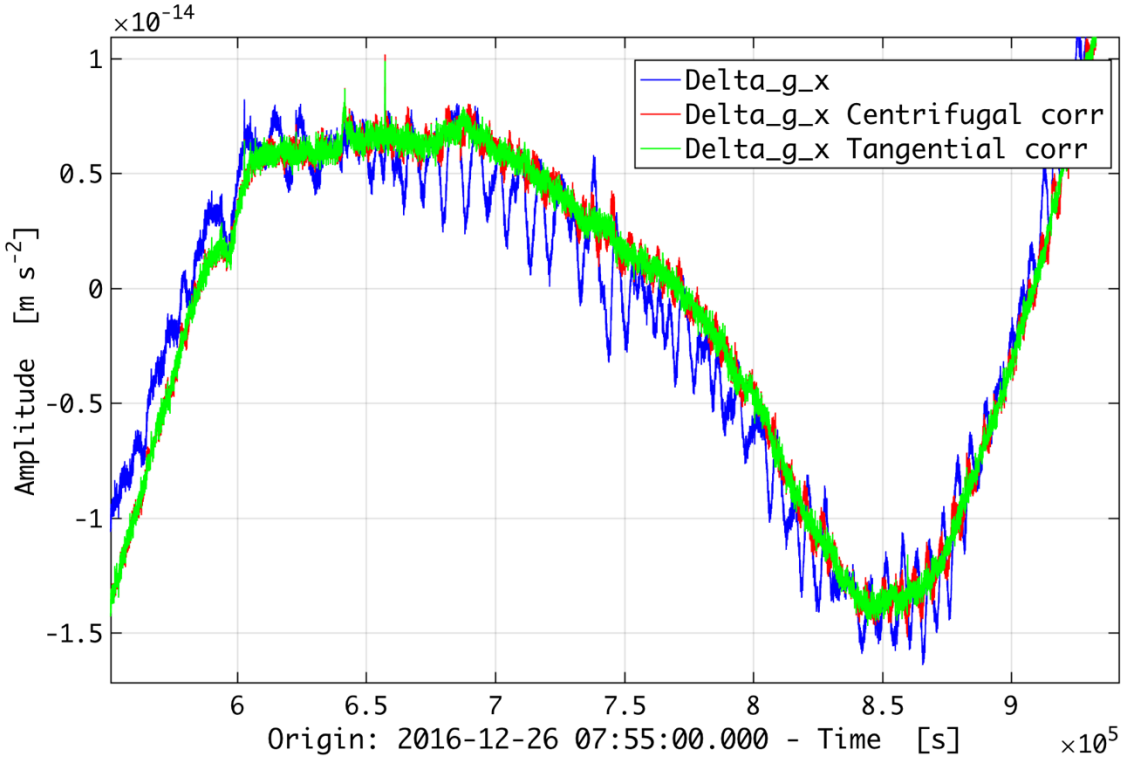
$-\vec{\omega} \times (\vec{\omega} \times \overrightarrow{r_{12}}) \cdot \hat{\imath}$ **Centrifugal**

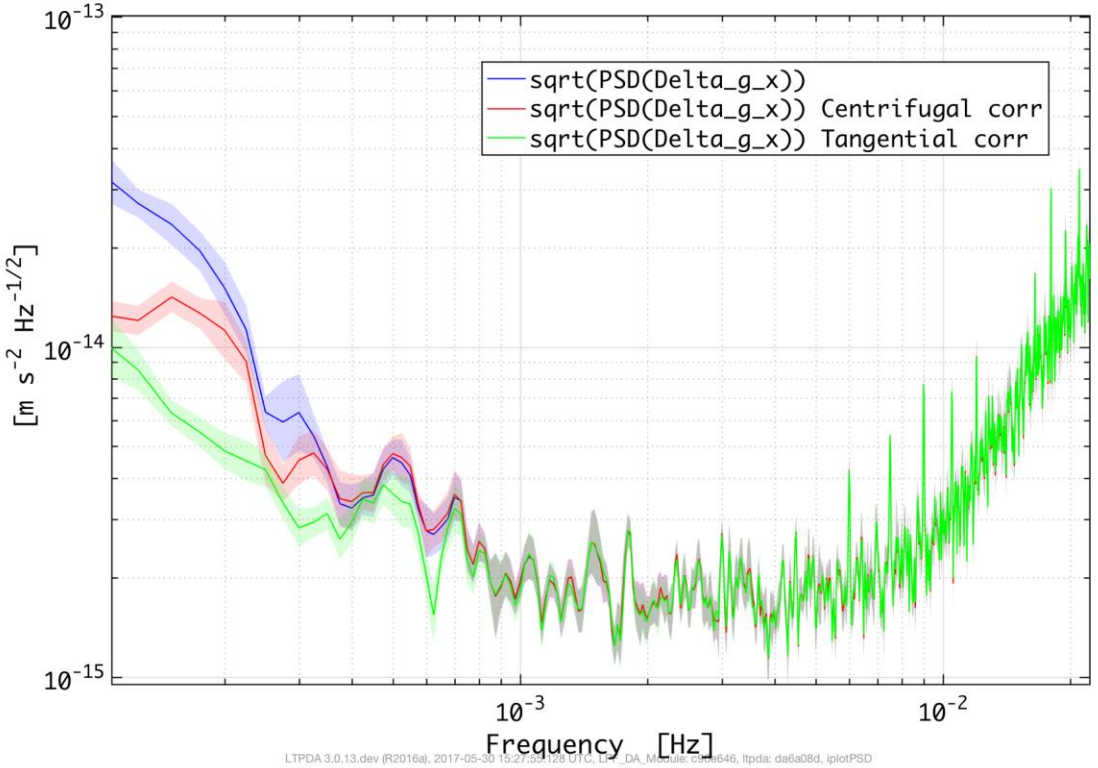
~~$-(\vec{\omega} \times \overrightarrow{v_{12}}) \cdot \hat{\imath}$~~ **Coriolis**

$-(\dot{\vec{\omega}} \times \overrightarrow{r_{12}}) \cdot \hat{\imath}$ **Tangential**

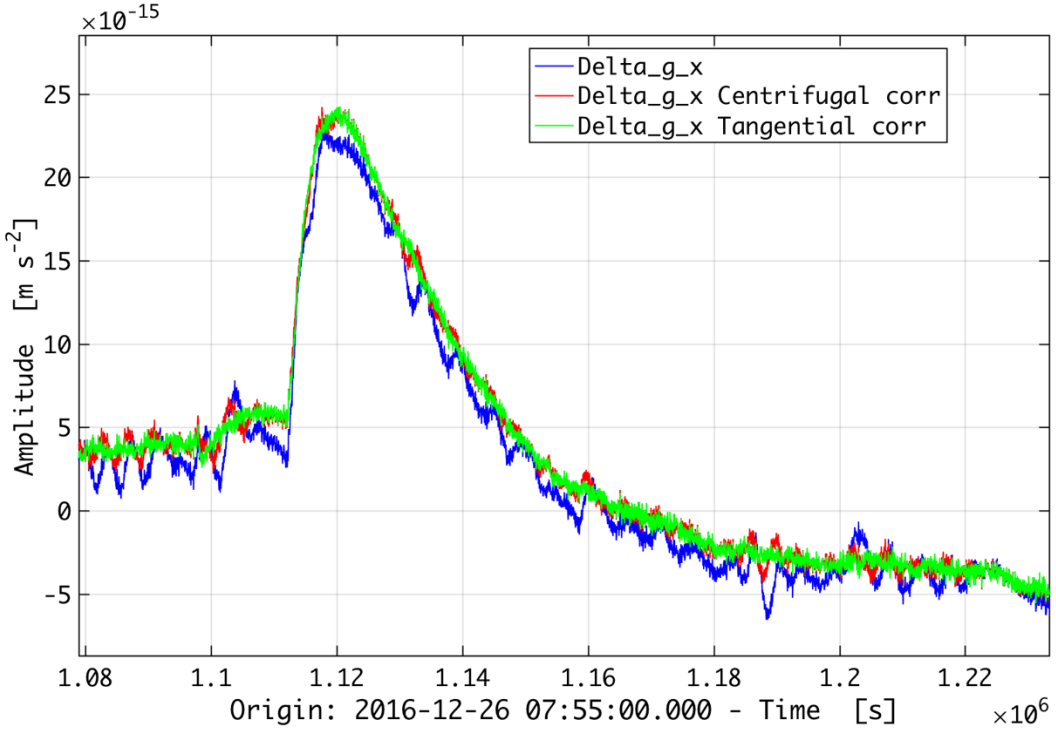


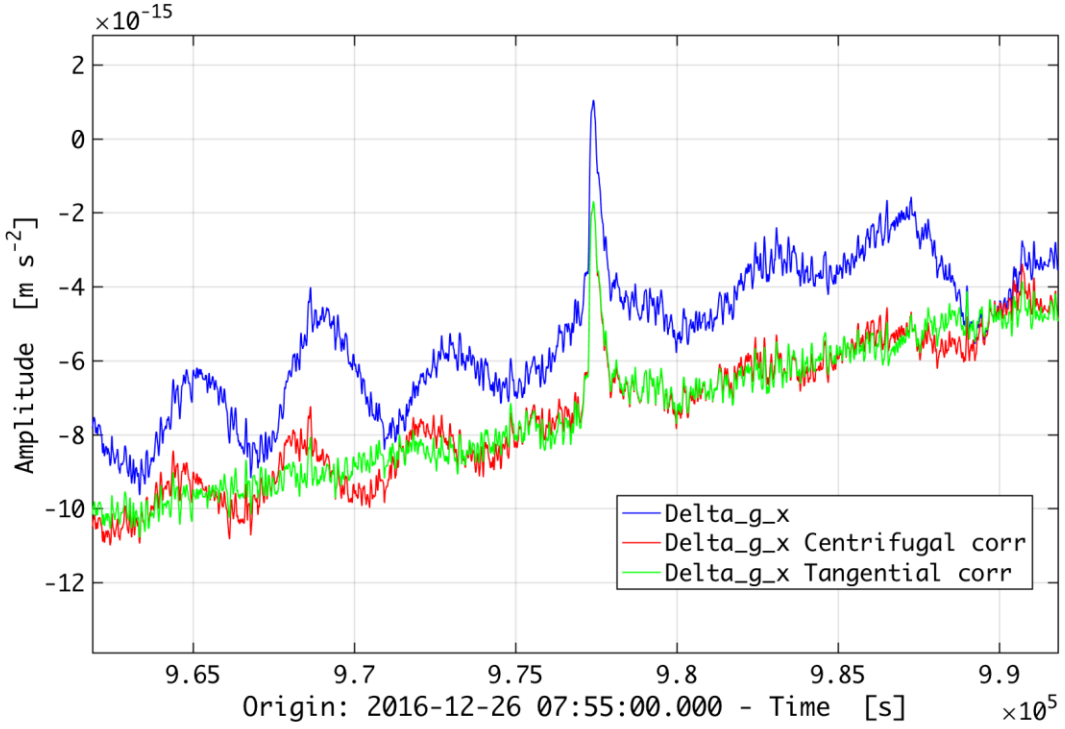
The centrifugal and tangential contributions smooth Δg(t)





Δg(t) shows also glitches, which are considered unknown signals and fitted away





The final Δg is the results of a series of corrections…

Delta g – L0

Centrifugal Corrected - L1

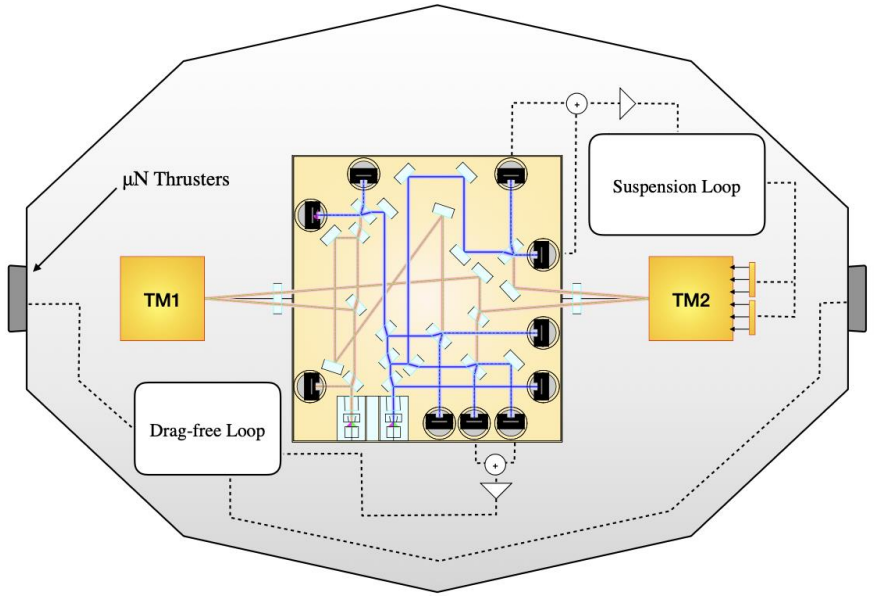
Debumped – L2

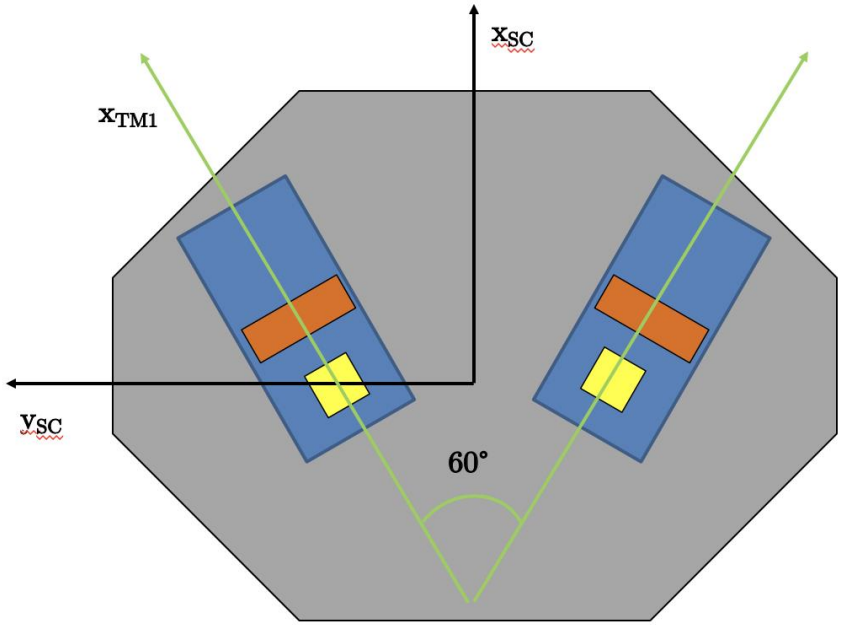
Tangential corrected - L3

…and, finally, we deglitch – L4

$$\Delta g(t) = a_{12} - \lambda f_{2,cmd} + \omega_2^2 o_{12} + \Delta\omega^2 o_1 + -\vec{\omega} \times (\vec{\omega} \times \overrightarrow{r_{12}}) \cdot \hat{\imath} + \alpha\bar{\phi} + \beta\bar{\eta} + \gamma\bar{y} + \delta\bar{z} + \delta_1 \ddot{o}_1 - (\dot{\vec{\omega}} \times \overrightarrow{r_{12}}) \cdot \hat{\imath}$$

Measuring Δg: from LPF to LISA





- We learnt how to characterize system dynamics in flight, and we discovered that we are able to do it.
- Unfortunately, in LISA no local measurement will be possible at the level of accuracy needed, and any small force experiments should go through TDI… it complicates a bit the things but, I think, not dramatically.
- Local calibration and measurement could be done, in principle, if not for the capacitive sensing and actuation noise in y and z

Conclusions

- LPF was a great success. Part of this success was a very well-prepared data analysis, allowing for running and analyzing many complex experiments in flight in a limited amount of time.

- In my opinion, it was also invaluable to have several scientists plus STOC and MOC together in the same place for days during operations, fully concentrated on the tasks, discussing and trying to solve problems. Will be important for LISA, at least in the initial phase, likely in close interaction with science data analysts (global fit, etc.)

- We have lessons learned, and I believe most of them are already being taken into account in the LISA project. Perhaps some are not… but there is still time for them to be heard.

- On a personal account, being part of the data analysis team during LPF operations was an amazing and professional life worth experience. Thanks for that opportunity!

- Finally, as a *Knight of* Δg I can only conclude by saying…

May the force be with you…

but below $3 \times 10^{-15}\ \mathrm{m/s^2/\sqrt{Hz}}$

from LISA Pathfinder to LISA…

and beyond…