Debris Laser Ranging Experiments
with Transmitting / Receiving-Stations 333km Apart

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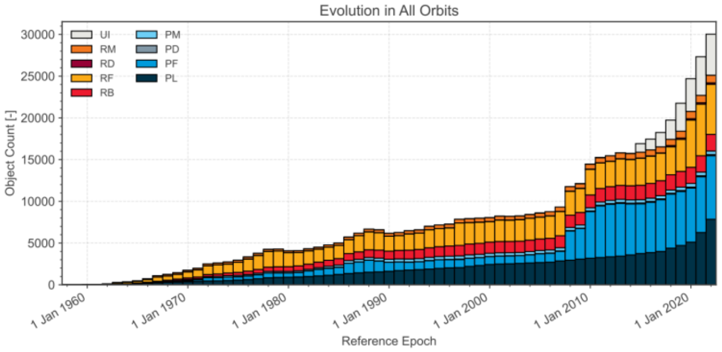
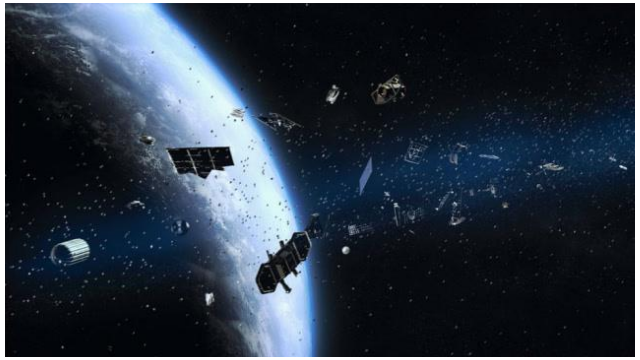
The NESC meeting 2023.02.02

The Debris' Problem



Source: ESA – Space Environment Report



The pioneering DLR experiment

- Laser fired from Graz station
- Received by Graz, Wettzell (400km), Zimmerwald(600km) and Herstmonceux(1200km)

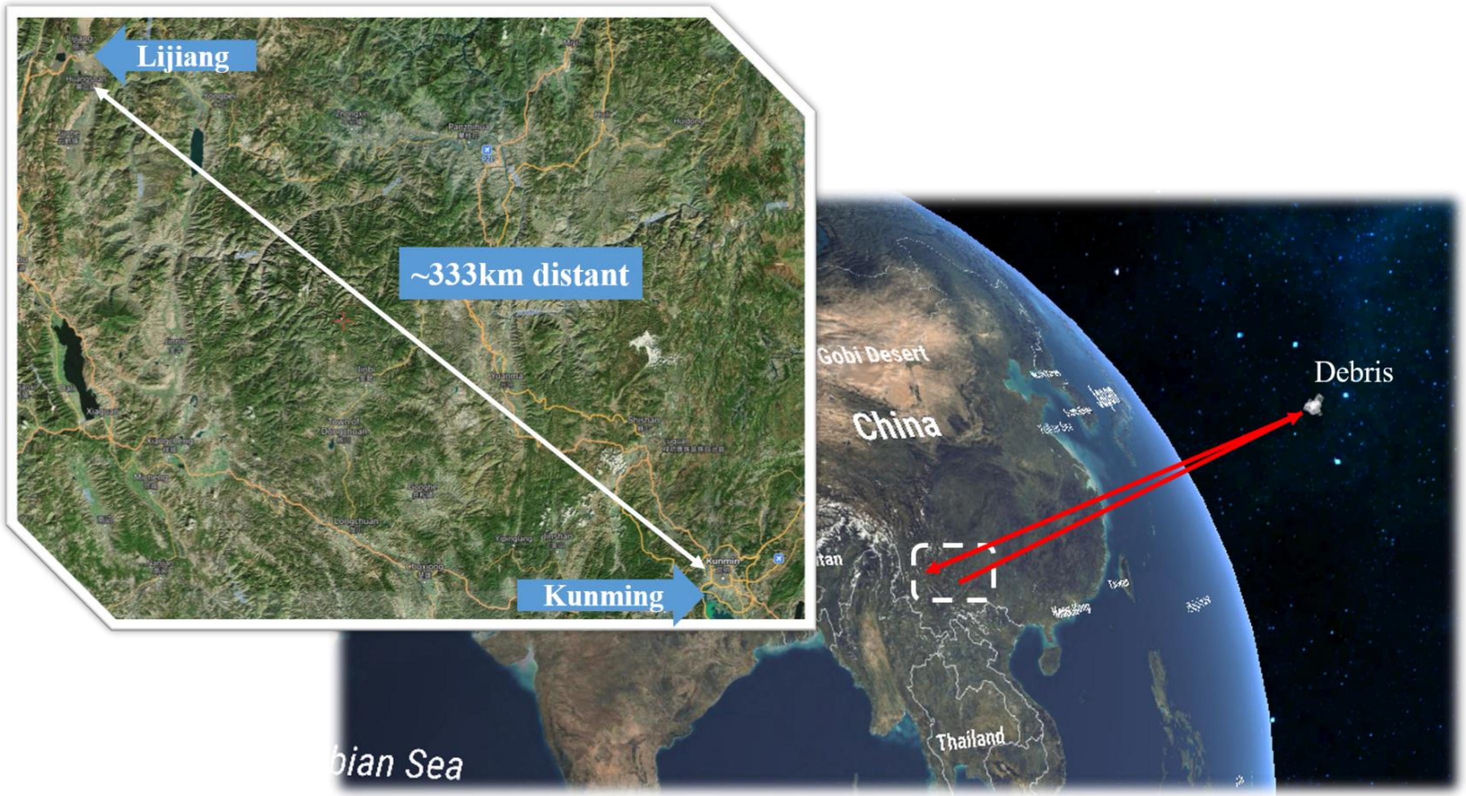
Source: Kirchner, G., Koidl, F. et al. Multistatic Laser Ranging to Space Debris. (2014).

The Debris are posing threats…

- Large amount
- Small size
- Orbit resource
- Collision with other space objects

Precise observation required

Stations in Kunming and Lijiang



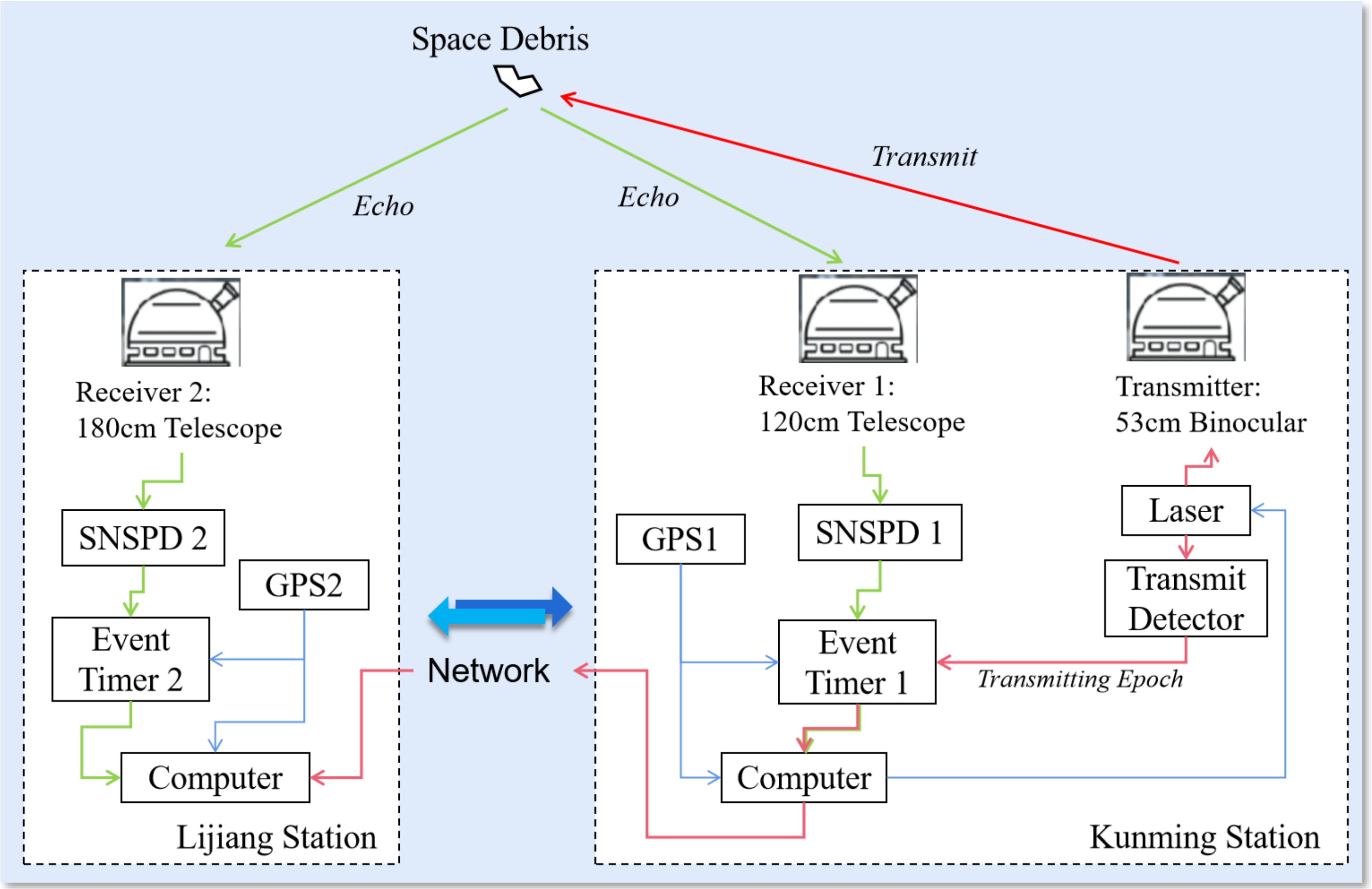
Main facilities in Kunming

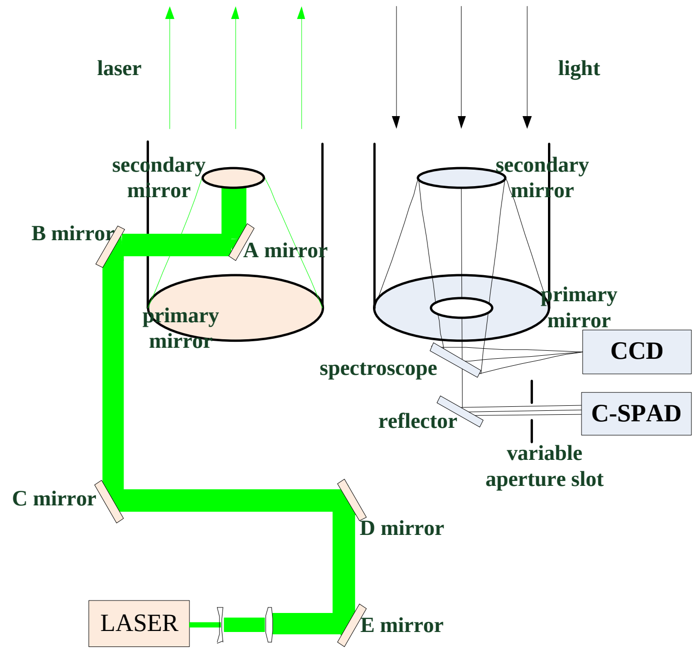

The 120cm Telescope


The 53cm Binocular

- 1064nm Laser @ 100Hz
- Laser fired from the 53cm Binocular of Kunming station
- Received by both the 120cm Telescope in Kunming and the 180cm Telescope in Lijiang

Experiment Setups

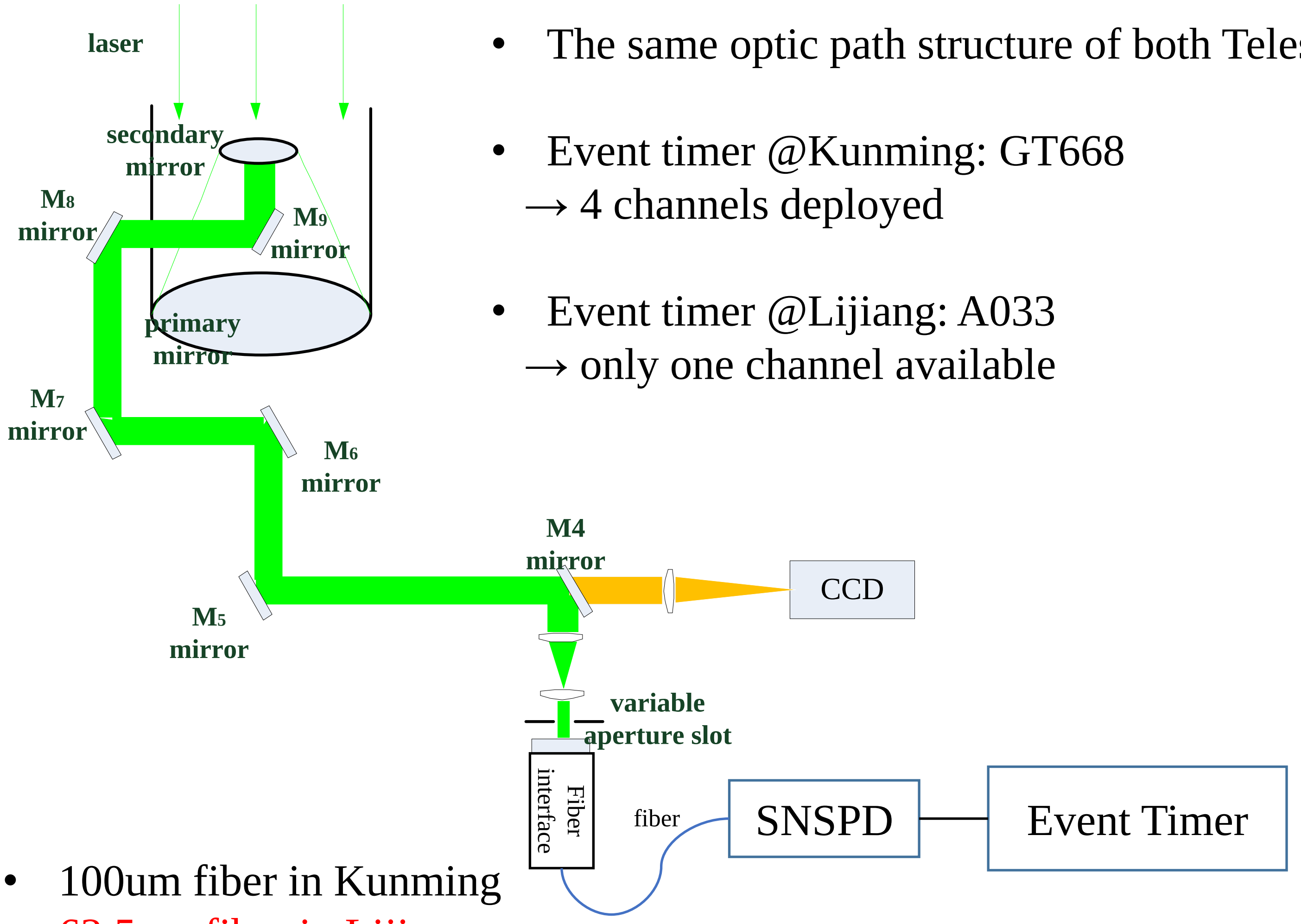




- the firing epoch was sent immediately to Lijiang Station via internet

Transmitter Parameter	Value
Wavelength	1064 nm
Repetition rate	100Hz
Pulse Width	6.7ns
Pulse Energy	≤3J/pulse

Experiment Setups: Receiving



- The same optic path structure of both Telescopes
- Event timer @Kunming: GT668
  → 4 channels deployed
- Event timer @Lijiang: A033
  → only one channel available

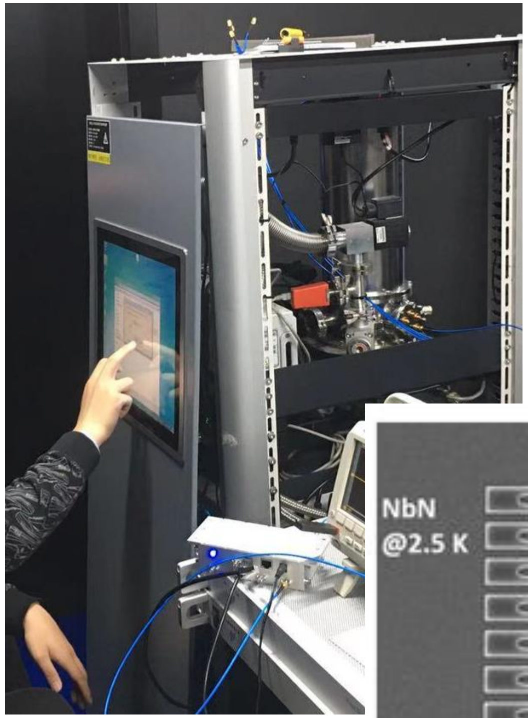
- 100um fiber in Kunming
- 62.5um fiber in Lijiang

The GT668 Event Timer

The A033 Event Timer

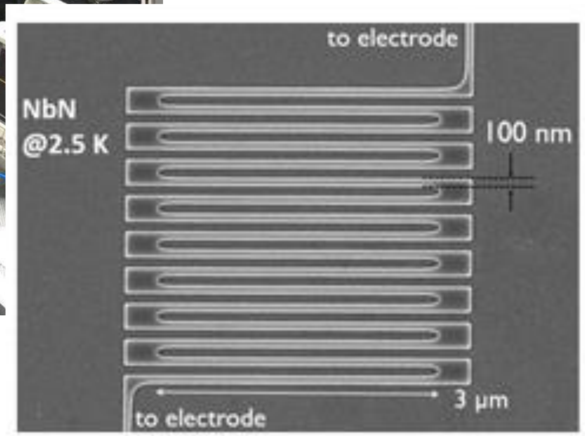
Experiment Setups: SNSPDs

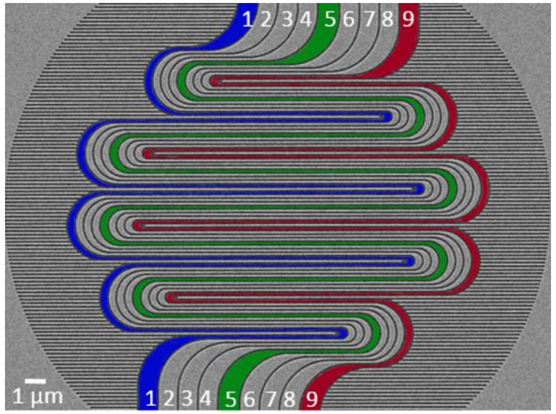
- Super-conducting Nano-wire Single Photon Detector
- SNSPD deployed at both stations
- Integrated signal in Lijiang due to limited ET input

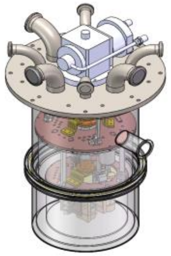


SNSPD
@Kunming Station

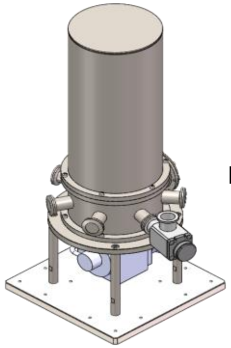
a 4-channel SNSPD developed by Nanjing University





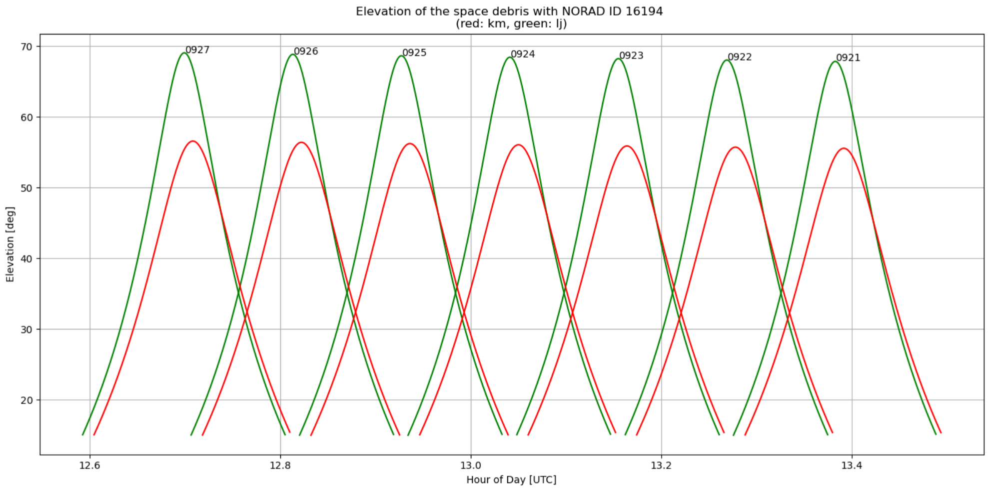


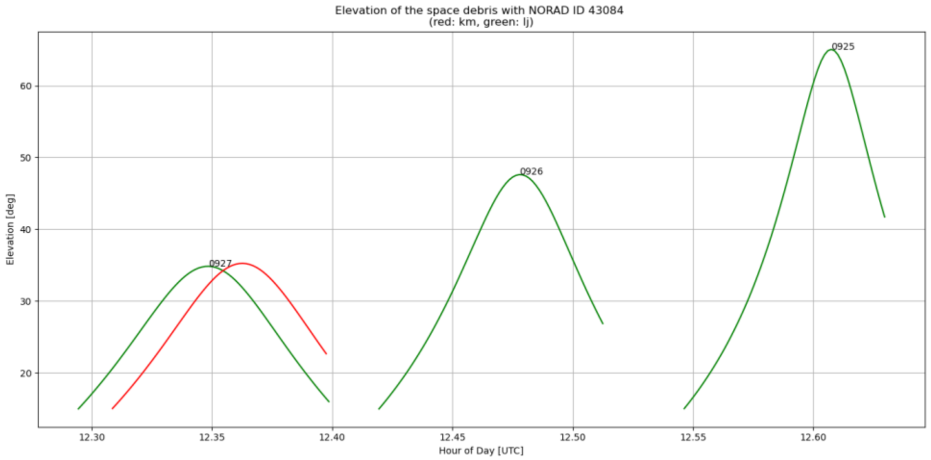
SNSPD @ Lijiang Station: a Multi-channel-integrated type developed by SIMIT (Shanghai Institute of Microsystem and Information Technology)

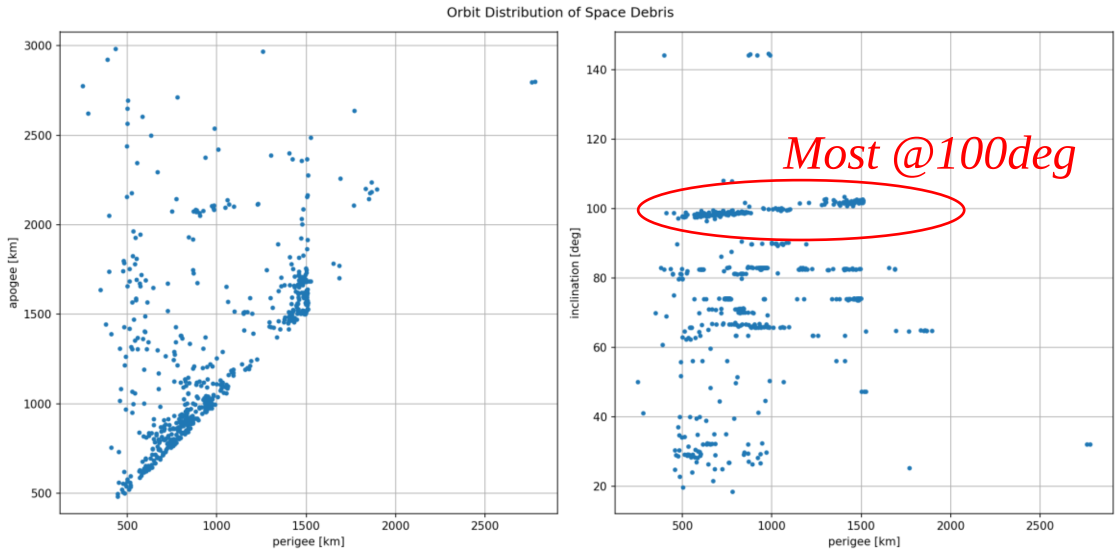


Target Selection

- Simultaneous visibility for both stations







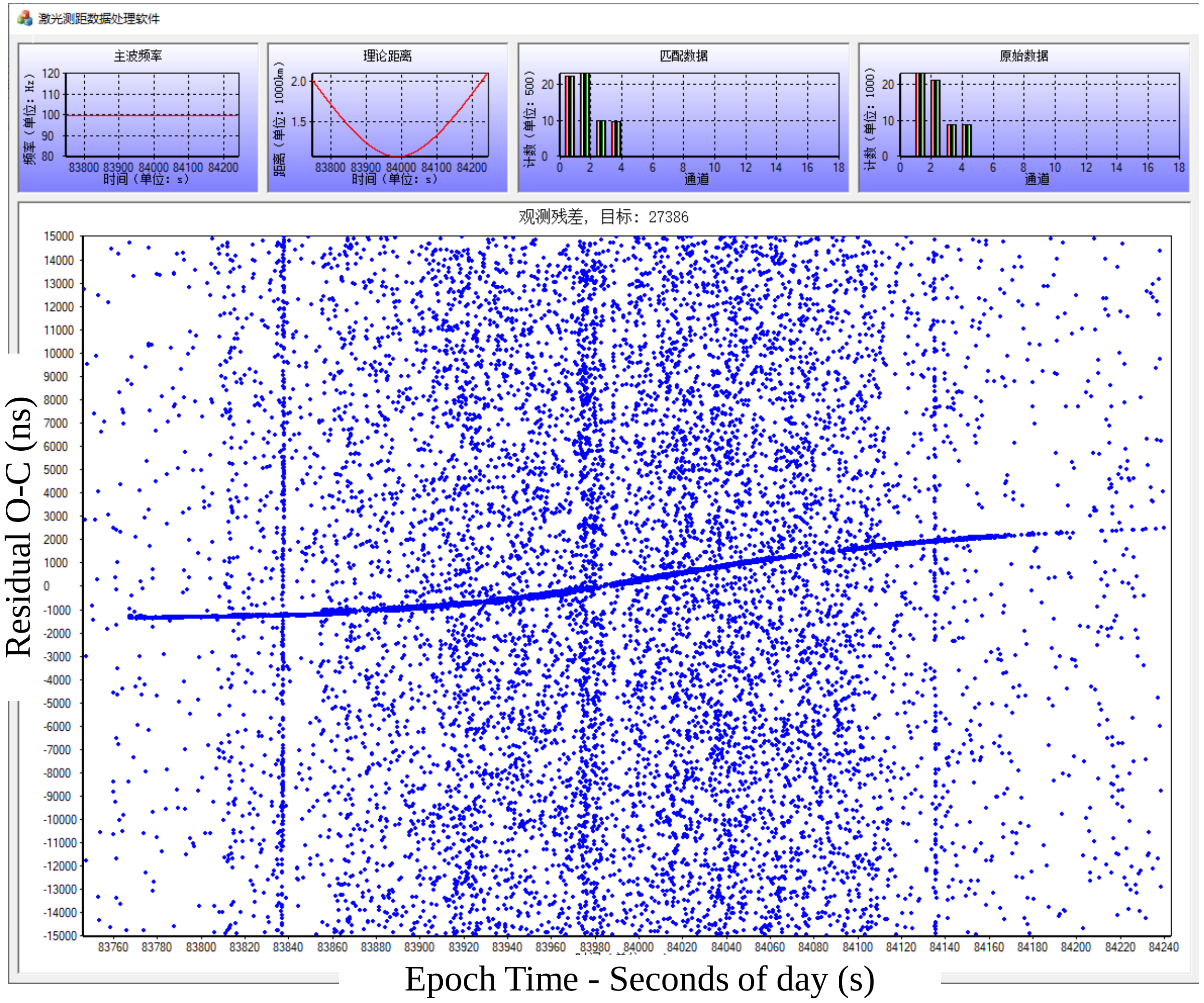
- Red: Kunming Green: Lijiang
- Analysis on orbit data of 7 days
- E.g. ID: 16194, SL-14 R/B, 1248km×1224km@82.57°. RCS-4.8m^2. In the 7 days its passes were visible by both stations.
- E.g. ID: 43084, CZ-2C R/B, 620km×481km@34.67°. RCS为8.73m^2. Visible only on Sep.27th.
- 697 debris, 3277passes, averagely visible for 10 min

⇨ Plenty to choose

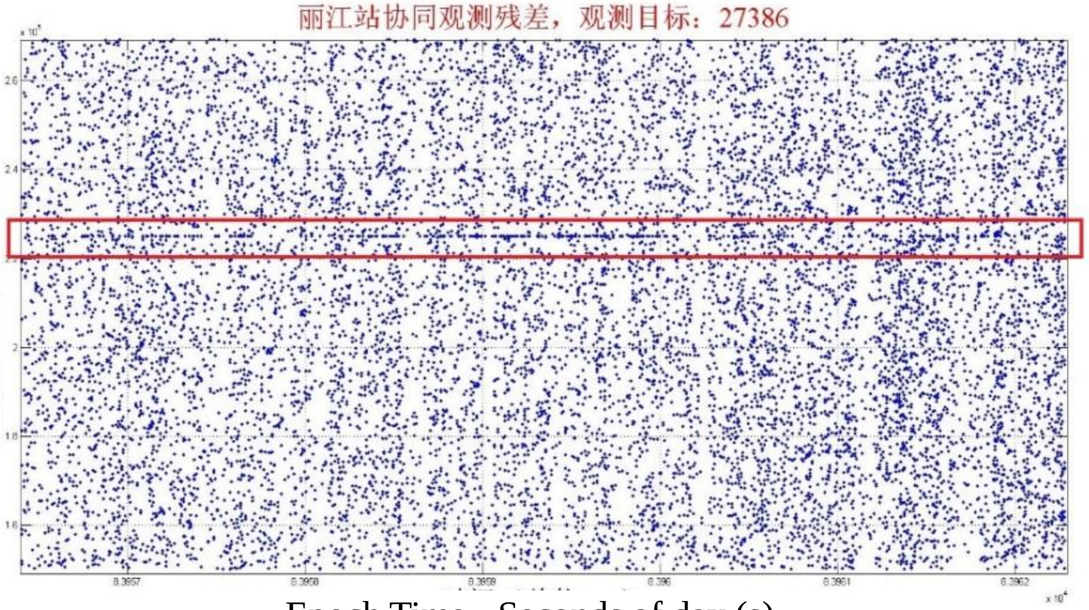
Experiment Results

Target ID: 27386 ENVISAT

- Screenshot in Kunming



- Screenshot in Lijiang



Residual O-C (ns)

Epoch Time - Seconds of day (s)

The session RMS of NPT @ meter-level

Problems and the following works

- The clock **synchronization** problem

  Fiber-transferring technology

- The **calibration** of multi-station system delay

  New calibration method, SNSPD (low jitter)

- Limited **field of view**: Fiber diameter – 62.5um, corresponding field of view – 3″

  Tracking with Fast Steering Mirror (FSM), 2-d tracking strategy

ILRS Networks and Engineering Standing Committee
February 2, 2023

G4S_2.0: Motivations for a SLR Campaign

David Lucchesi

On behalf of the G4S_2.0 Project

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Summary

- G4S_2.0 Project
- Main motivation: systematic errors
- Preliminary POD
- The proposal for a SLR campaign
- MOU between ASI and ESA

G4S_2.0 Project

The **G4S_2.0** project, financed by the **Italian Space Agency** (**ASI**), aims to perform a set of measurements in the field of **gravitation** with the **Galileo** satellites of the **Full Operational Capability** (**FOC**) constellation taking advantage of the accuracy of their on-board atomic clocks. In particular of **GSAT0201** and **GSAT0202** exploiting their relatively high eccentricity (≅0.16).

Three research centers in Italy are involved in this project:

- **ASI-CGS** (Center for Space Geodesy) in Matera
- Istituto di Astrofisica e Planetologia Spaziali (**IAPS/INAF**) in Roma and **OATO/INAF** in Torino
- Politecnico (**POLITO**) in Torino

Agenzia Spaziale Italiana

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA
E PLANETOLOGIA SPAZIALI DI ROMA

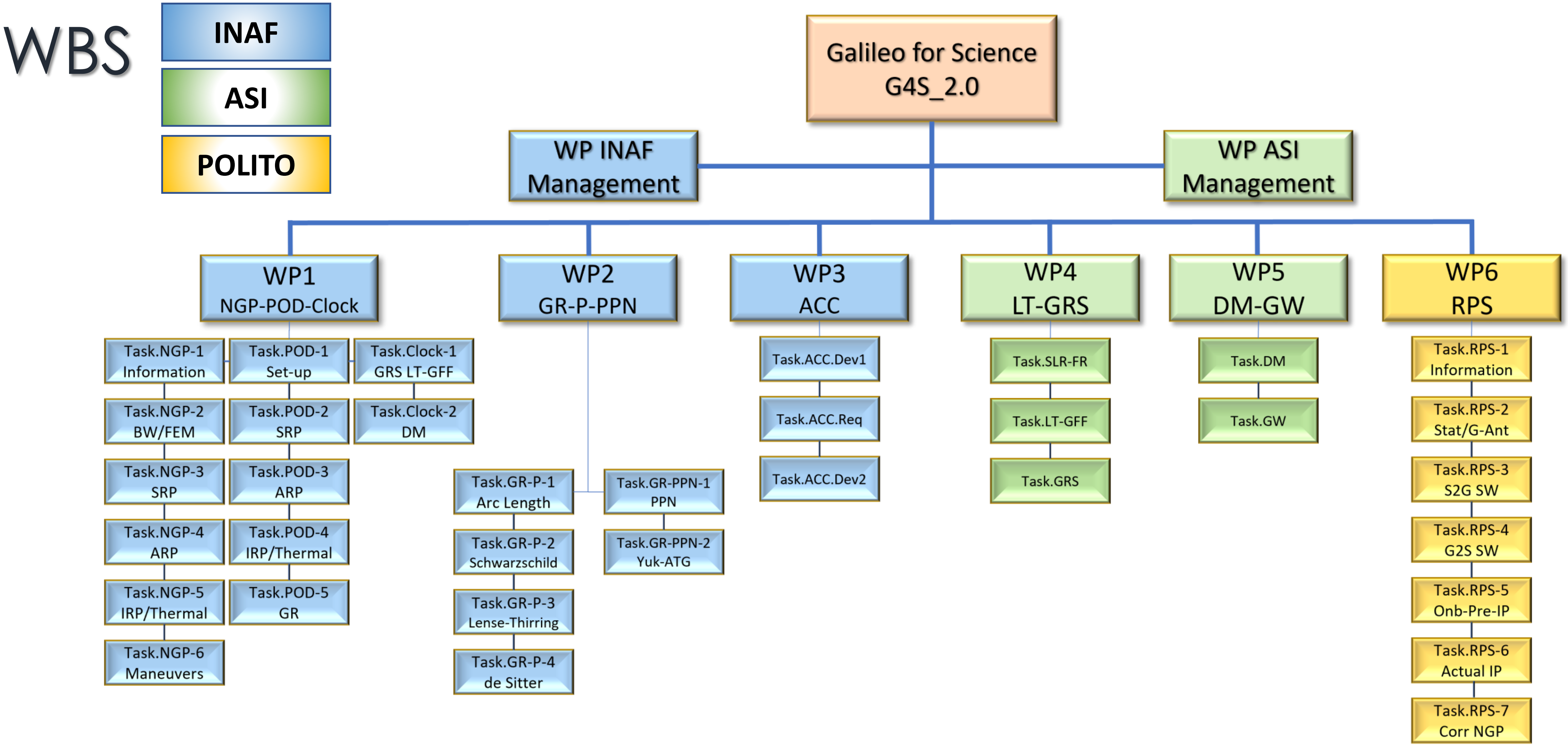
POLITECNICO DI TORINO 1859 1906

G4S_2.0 Project

Main goals of the **G4S_2.0** project.

1. A new measurement of gravitational redshift
2. A measurement of relativistic precessions on the two satellites in eccentric orbit
3. Constraints on Dark Matter in the Milky Way
4. Relativistic Positioning System
5. Development of new models for non-gravitational forces
6. Development of a new accelerometer concept for a next generation of Galileo satellites.

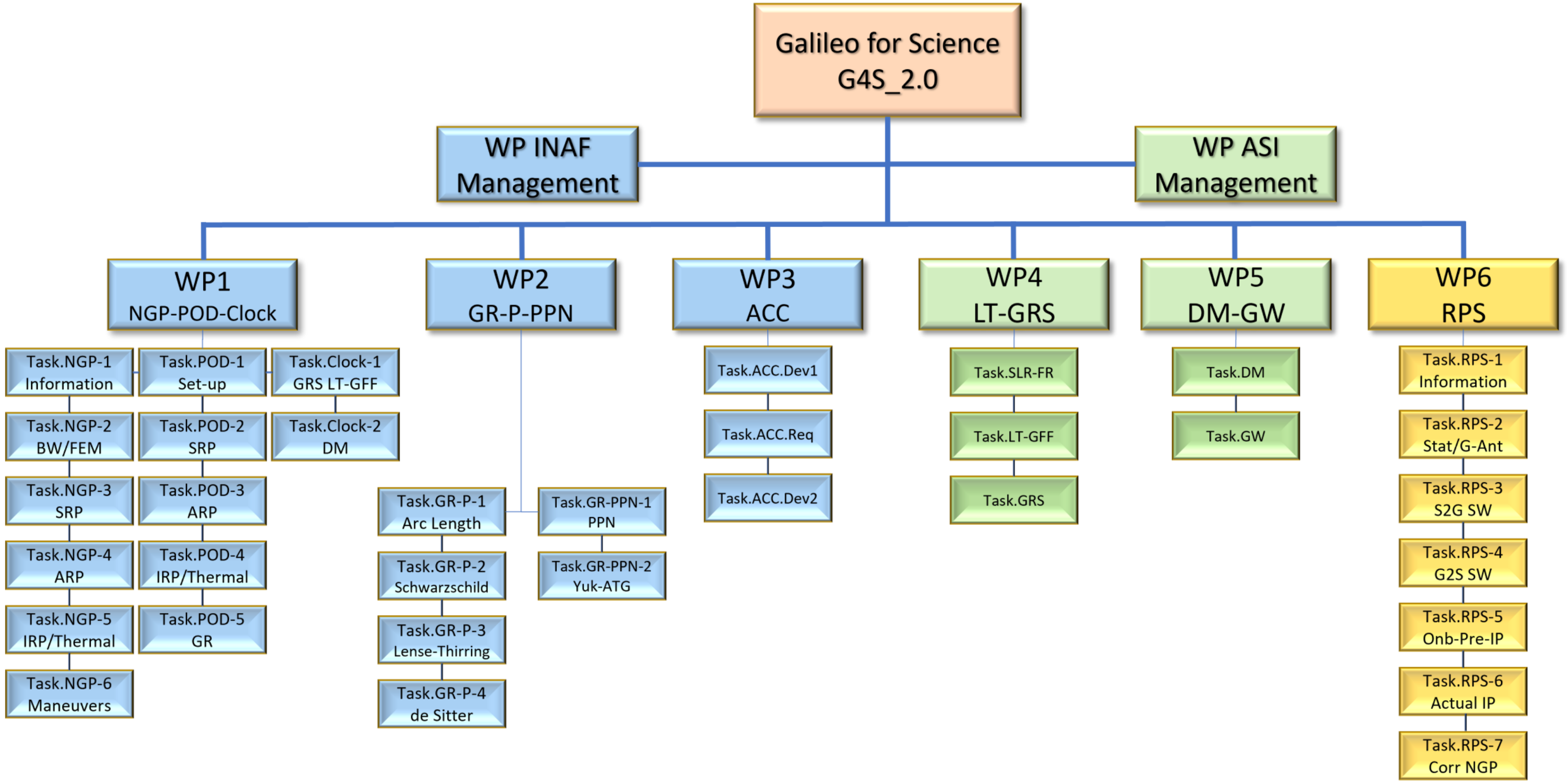
G4S_2.0 Project



G4S_2.0 Project

Il Team scientifico di IAPS-INAF

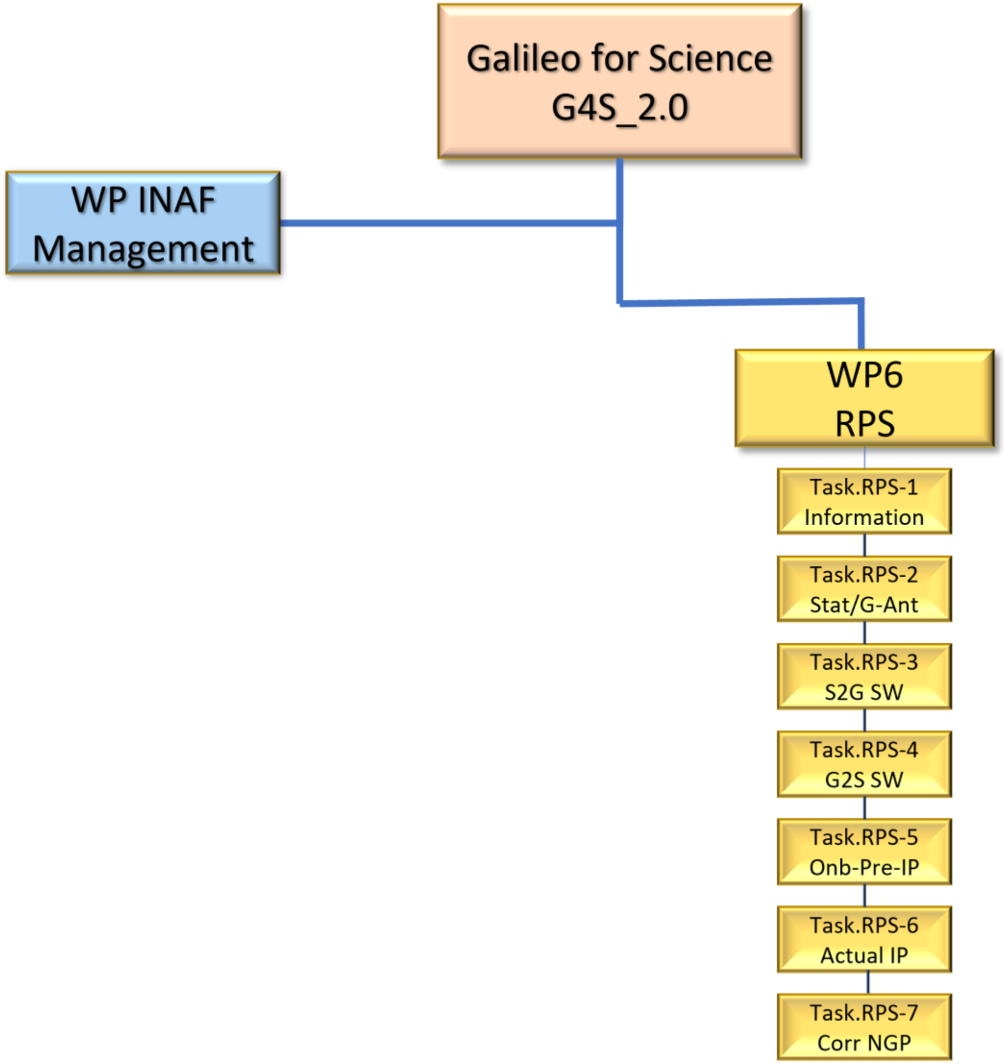
1. Marco Cinelli (AdR)
2. Claudia Di Geronimo (Tecnologo)
3. Alessandro Di Marco (AdR)
4. Emiliano Fiorenza (Tecnico)
5. Natalia Gatto (CTER)
6. Carlo Lefevre (Tecnologo)
7. David Lucchesi (Primo Ricercatore)
8. Marco Lucente (Tecnologo)
9. Carmelo Magnafico (Tecnologo)
10. Roberto Peron (Ricercatore)
11. Francesco Santoli (Primo Tecnologo)
12. Feliciana Sapio (Dottoranda)
13. Angelo Tartaglia (Professore in quiescenza: OATO-INAF)
14. Massimo Visco (Ricercatore)



G4S_2.0 Project

Il Team scientifico di POLITO

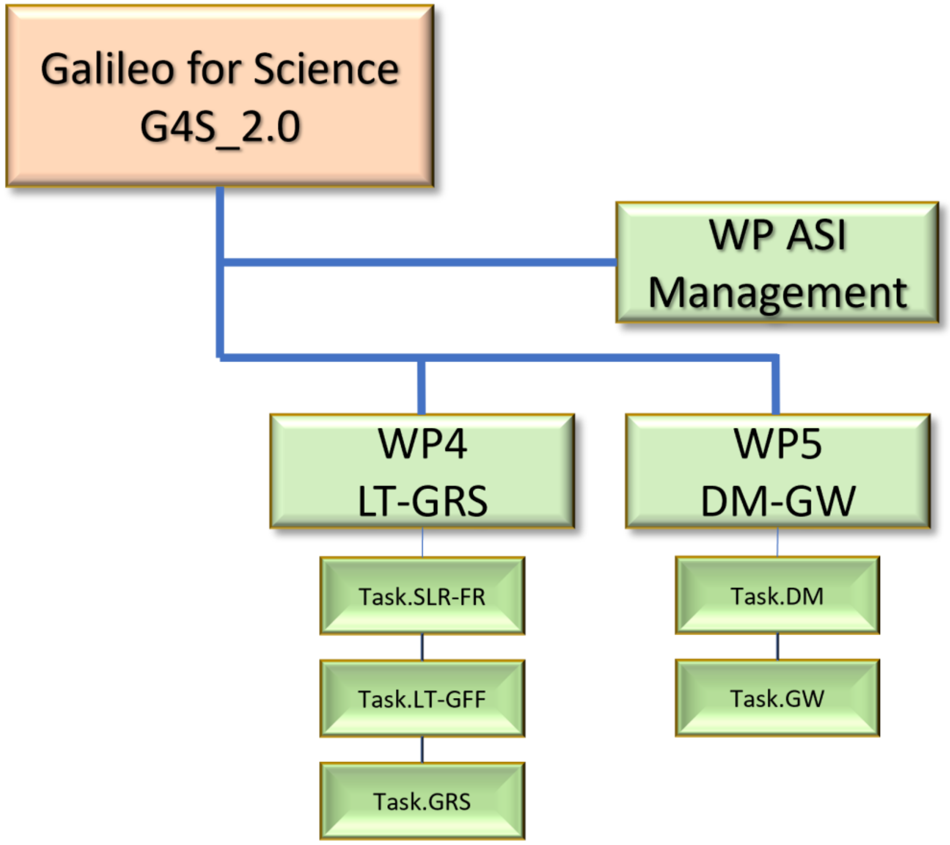
1. **Lorenzo Casalino** (Professore Ordinario)
2. Matteo Luca Ruggiero (Ricercatore): ex AdR
3. Angelo Tartaglia (Professore in quiescenza: OATO-INAF)
4. BdR-1
5. BdR-2
6. BdR-3



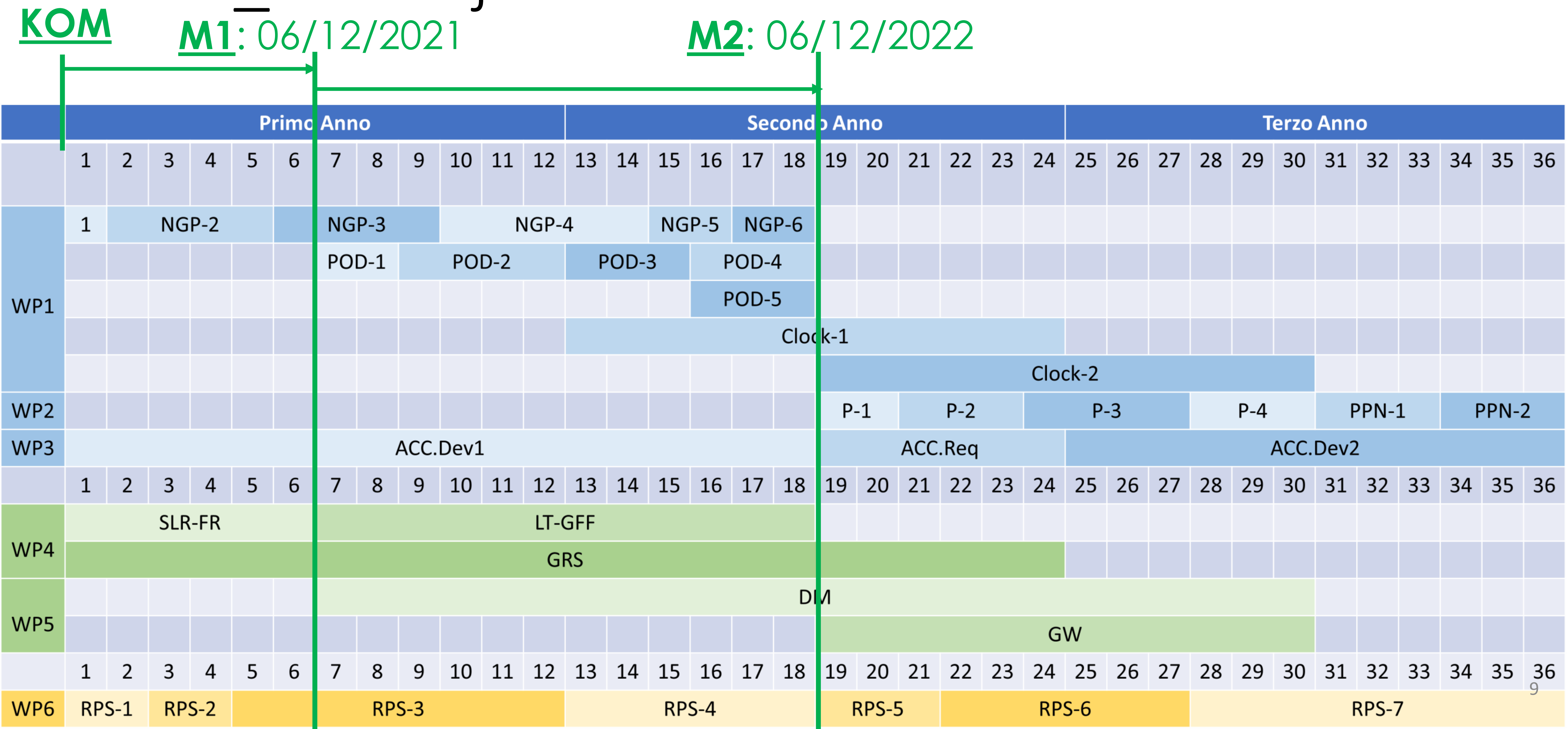
G4S_2.0 Project

Il Team scientifico di ASI-CGS

1. **Francesco Vespe** (Dirigente Tecnologo)
2. Patrizia Sacco (Tecnologo)
3. Daniele Dequal (Ricercatore)
4. Luigi Santamaria-Amato (Ricercatore)
5. Andrea Andrisani (Ricercatore)



G4S_2.0 Project: schedule



G4S_2.0 Project: funding

IAPS-INAF winner of the Bando Premiale di ASI (2019) with the G4S_2.0 project

- **ASI** financial support to **G4S_2.0**: 580 k€ (40 k€ **ASI-CGS**)
- **INAF** Prime of the contract with **ASI**: 540 k€
  - ❑ **460** k€ **@IAPS-INAF**
  - ❑ **80** k€ **@POLITO**

Main motivation: systematic errors

In the context of navigation satellites of the **GNSS**, there are three aspects that are strongly linked to each other:

- Dynamical model: **NGPs** $\rightarrow$ direct **SRP**
- **POD**
- **Clock-bias**

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An increased number of **SLR** data is important to reduce systematic errors in the measurements to be performed:

- Orbit modeling errors are strongly correlated to the clock solutions
- **SLR** data are essential to characterize orbital radial errors in the **IGS** Analysis Centers Solutions
  - radial systematic errors are 1:1 correlated with the onboard clock solution
- Since these systematic errors are mainly due to the mismodeling of the direct **SRP**, it will be useful to have a campaign long enough to account for the variation of the so-called β angle (the Sun height with respect to the orbital plane), whose period of variation is equal to the Draconit year $\approx$ 365 days.

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Main non-gravitational accelerations

Physical effects	Formula	LAGEOS II	Galileo FOC
Earth's monopole	$G\frac{M_\oplus}{r^2}$	2.6948	0.4549
Direct SRP	$C_R\frac{A}{M}\frac{\Phi_\odot}{c}$	3.2×10^{-9}	1.0×10^{-7}
Earth's Albedo	$2\frac{A}{M}\frac{\Phi_\odot}{c}A_\oplus\frac{\pi R_\oplus^2}{4\pi r^2}$	1.3×10^{-10}	7.0×10^{-10}
Earth's infrared radiation	$\frac{A}{M}\frac{\Phi_{IR}}{c}\frac{R_\oplus^2}{r^2}$	1.5×10^{-10}	1.1×10^{-9}
Power from antennas	$\frac{P}{Mc}$	—	1.2×10^{-9}
Thermal effect solar panels	$\frac{2}{3}\frac{\sigma}{c}\frac{A}{M}(\epsilon_1T_1^4-\epsilon_2T_2^4)$	—	1.9×10^{-10}
Poynting-Robertson	$\frac{1}{4}\frac{A}{M}\frac{\Phi_\odot}{c}\frac{R_\oplus^2}{r^2}\frac{v}{c}$	4.2×10^{-15}	1.9×10^{-14}

The current *noise level* of **NGPs** accelerations is in the range $(10^{-9} \div 10^{-10})\, m/s^2$

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The current *noise level* of **NGPs** accelerations to understand and model is in the range $0.1 \div 1$

Main motivation: systematic errors

Therefore, **SRP** modeling must achieve much better than 1% accuracy to adequately account for perturbing effects due to terrestrial **albedo** and **infrared** radiation pressure.

For this reason, we are working hard to improve the modeling of direct **SRP**:

- We have developed a **Box-Wing** model of the S/C on the basis of **ESA** Galileo Metadata
  - an improved **Box-Wing** model is now under investigation
- We have developed a **3D-CAD** of the S/C (i.e. a **FEM**) to be used for **Ray-Tracing** technique
  - this will be, hopefully, our final goal.

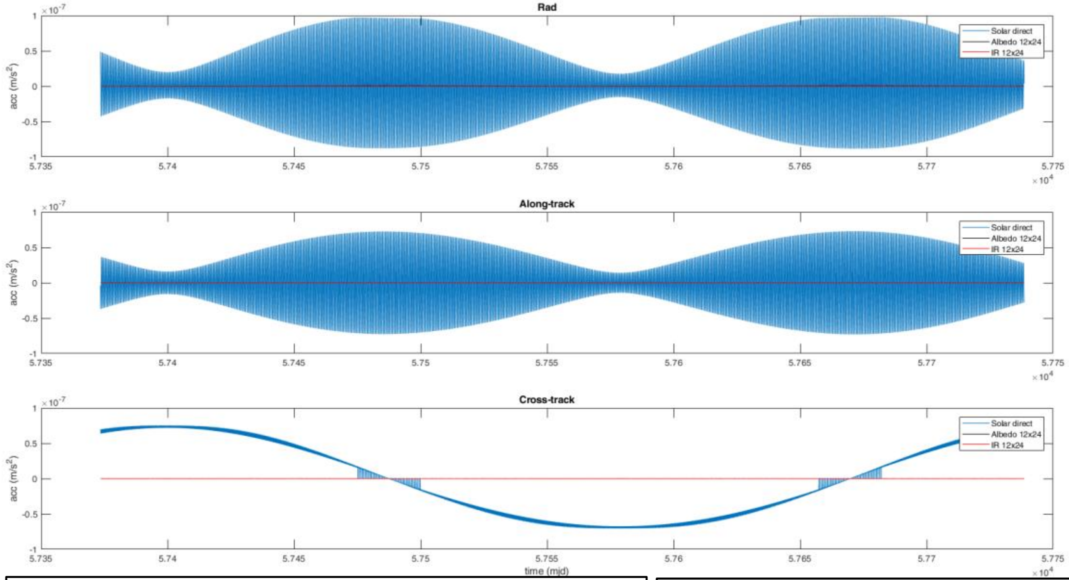
The perturbing accelerations obtained from these new models will be used in the **POD** as input data for our forthcoming measurements within G4S_2.0.

We have a great experience (well documented in the literature) in the development of **perturbation models** related to **non-gravitational forces** in the case of the **LAGEOS** and **LARES** geodetic satellites.

Main motivation: systematic errors

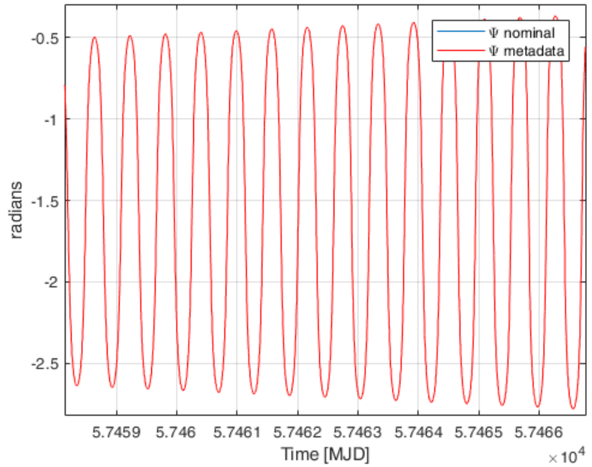
$$\psi(t) = atan2[\hat{s} \cdot \hat{n}, \hat{s} \cdot (\hat{r} \times \hat{n})]$$

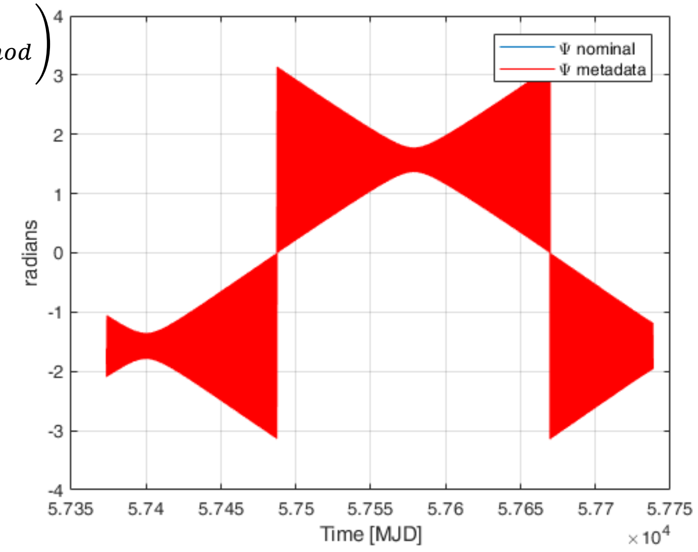
A 1-year simulation with the S-BW model



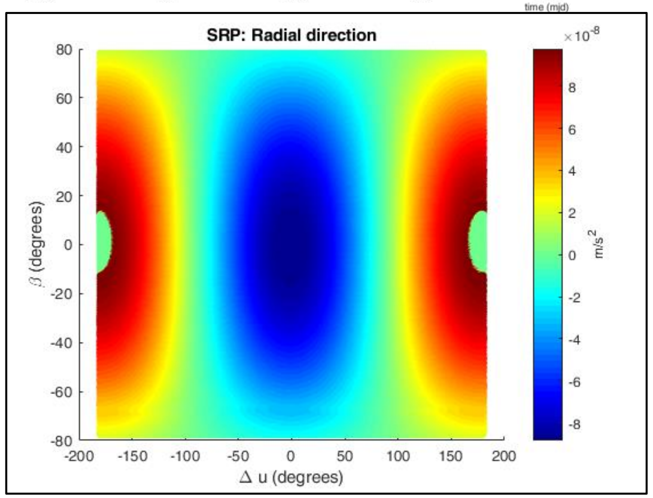
$$\psi_{mod}(t_{mod}) = \frac{\pi}{2} sign\psi + \left(\psi - \frac{\pi}{2} sign\psi\right) cos\left(\frac{2\pi}{5656} t_{mod}\right)$$

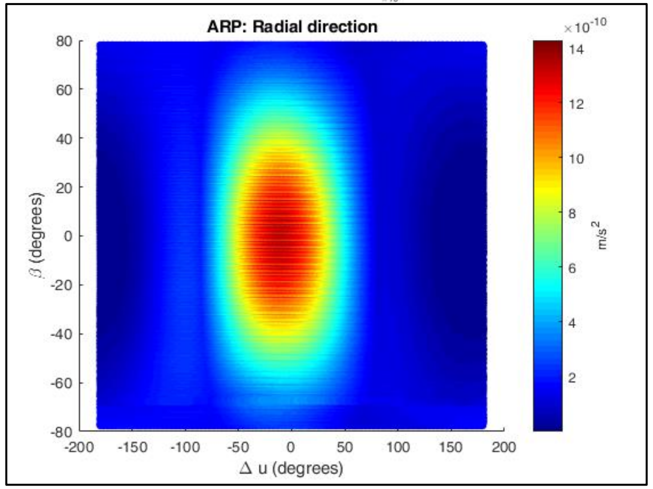
Particular 1

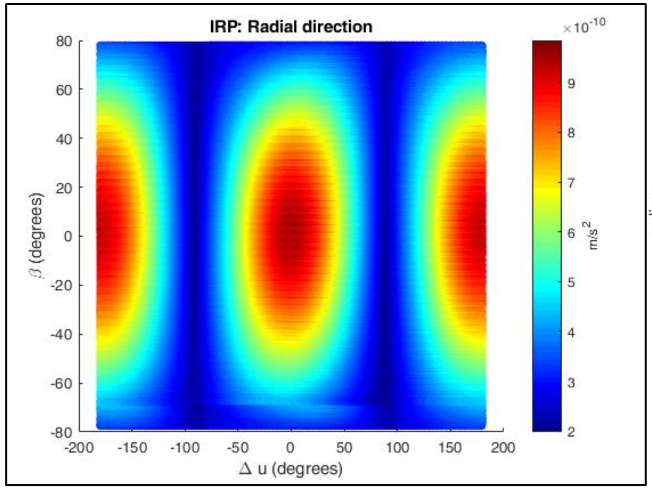


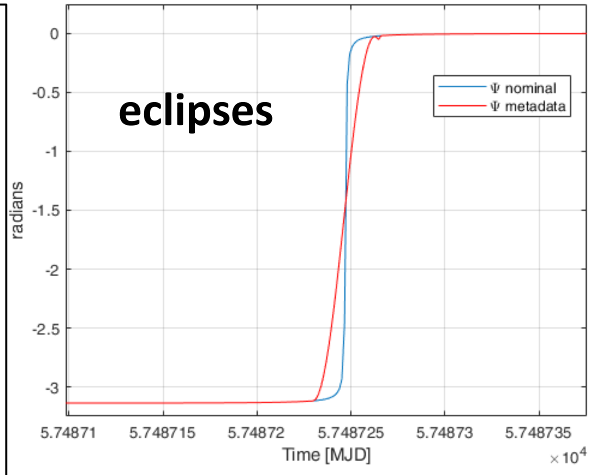


Particular 2



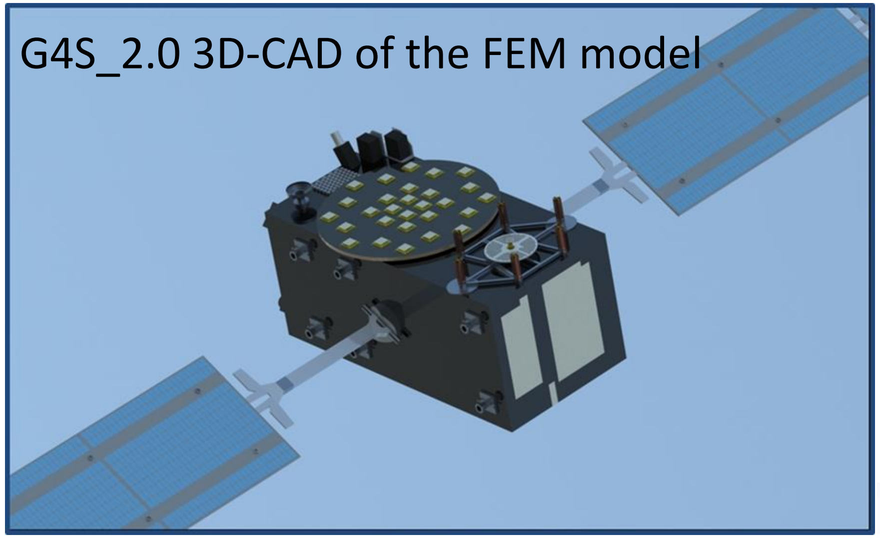


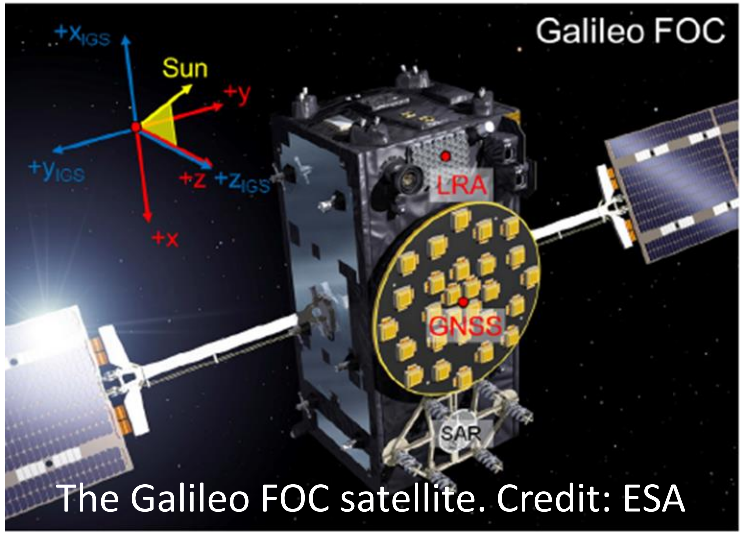




Main motivation: systematic errors

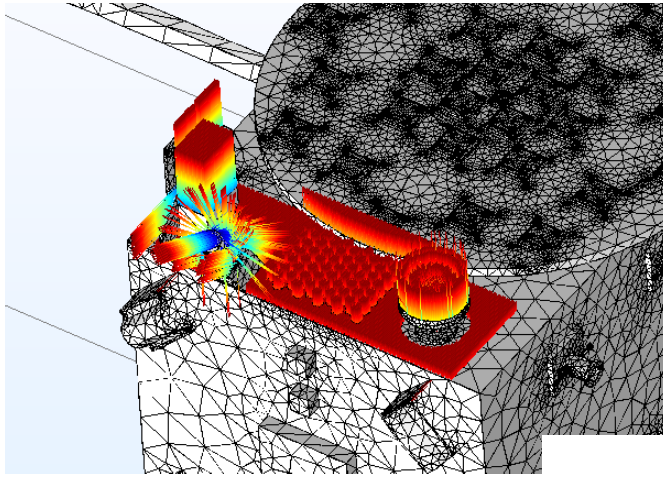
3D-CAD, FEM and Ray-Tracing





The Galileo FOC satellite. Credit: ESA

COMSOL



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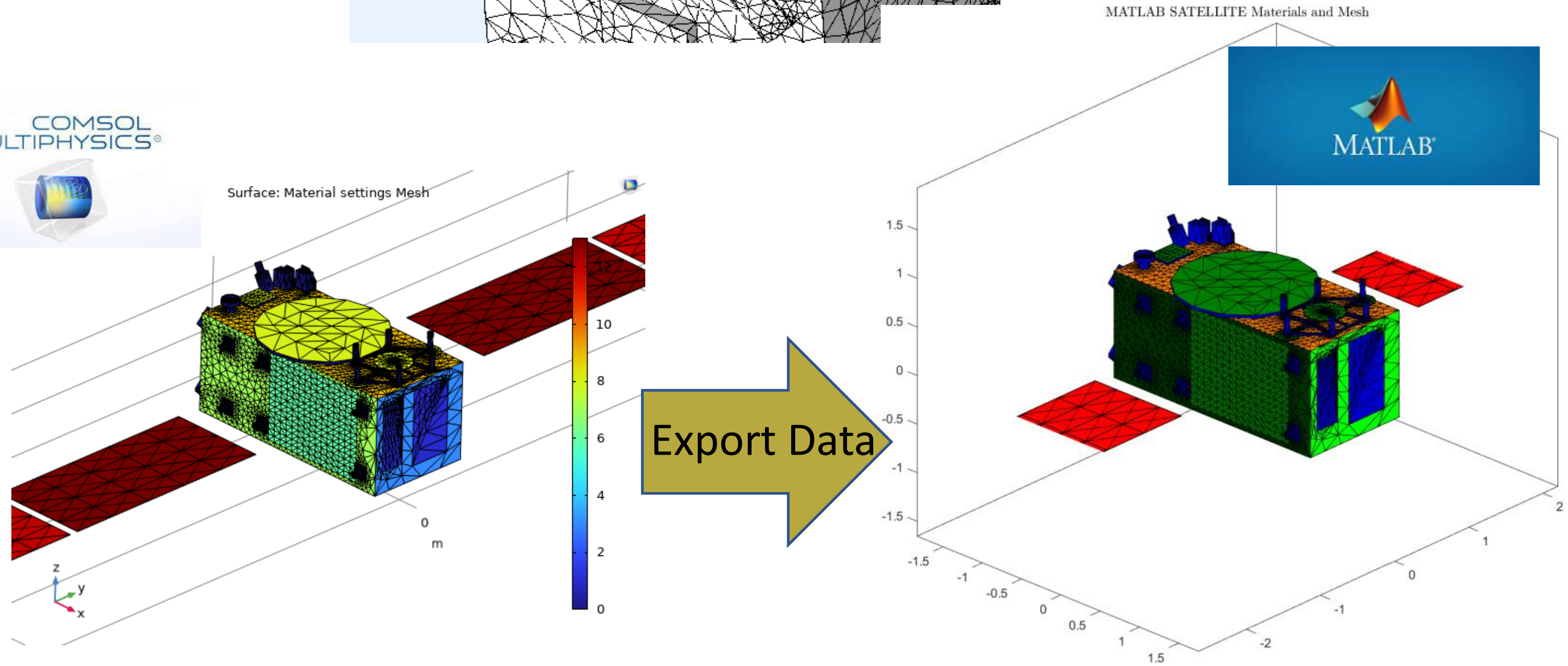

Main motivation: systematic errors

Systematic errors must be carefully estimated in order to obtain a reliable and robust **Error Budget** in the **Fundamental Physics** measurements we will perform:

1. **Relativistic precessions**
   - Schwarzschild
   - Lense-Thirring
   - De Sitter
2. **Local Position Invariance** (**LPI**), via a measurement of the **Gravitational Redshift**
3. **Dark Matter** constraints

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Goal of GREAT Project

Goal of GASTON Project

Main motivation: systematic errors

Relativistic precessions:

Rate (mas/yr)	*GSAT-201/202*	*GSAT-203*	*LAGEOS II*	*LAGEOS*
$\dot{\omega}^{Ein}$	**+428.88**	**+362.74**	**+3351.95**	**+3278.77**
$\dot{\omega}^{LT}$	**-5.21**	**-3.67**	**-57.00**	**+32.00**
$\dot{\Omega}^{LT}$	**+2.69**	**+2.18**	**+31.50**	**+30.67**
$\dot{\Omega}^{dS}$	**+17.60**	**+17.60**	**17.60**	**+17.60**

$$\dot{\omega}^{Ein} = \frac{3\left(GM_{\oplus}\right)^{3/2}}{c^2\, a^{5/2}(1-e^2)} \qquad \dot{\omega}^{LT} = \frac{-6\, GJ_{\oplus}}{c^2\, a^3(1-e^2)^{3/2}}\cos i \qquad \dot{\Omega}^{LT} = \frac{2\, GJ_{\oplus}}{c^2\, a^3(1-e^2)^{3/2}}$$

$$\dot{\Omega}^{dS} = \frac{3}{2}\frac{GM_{\oplus}}{c^2\, R^3_{\oplus\odot}}\left|(V_{\oplus} - V_{\odot}) \times R_{\oplus\odot}\right| \cos\varepsilon_{\odot}$$

Main motivation: systematic errors

Violations of the inverse-square law by very weak NLRI are usually described by means of a Yukawa-like potential with strength α and range λ and mediated by a field of very small mass $\mu = \hbar/\lambda c$.

$$V_{Yuk} = -\alpha \frac{G_\infty M_\oplus}{r} e^{-r/\lambda}$$

$$\alpha = \frac{1}{G_\infty}\left(\frac{K_\oplus}{M_\oplus}\frac{K_s}{m_s}\right)$$

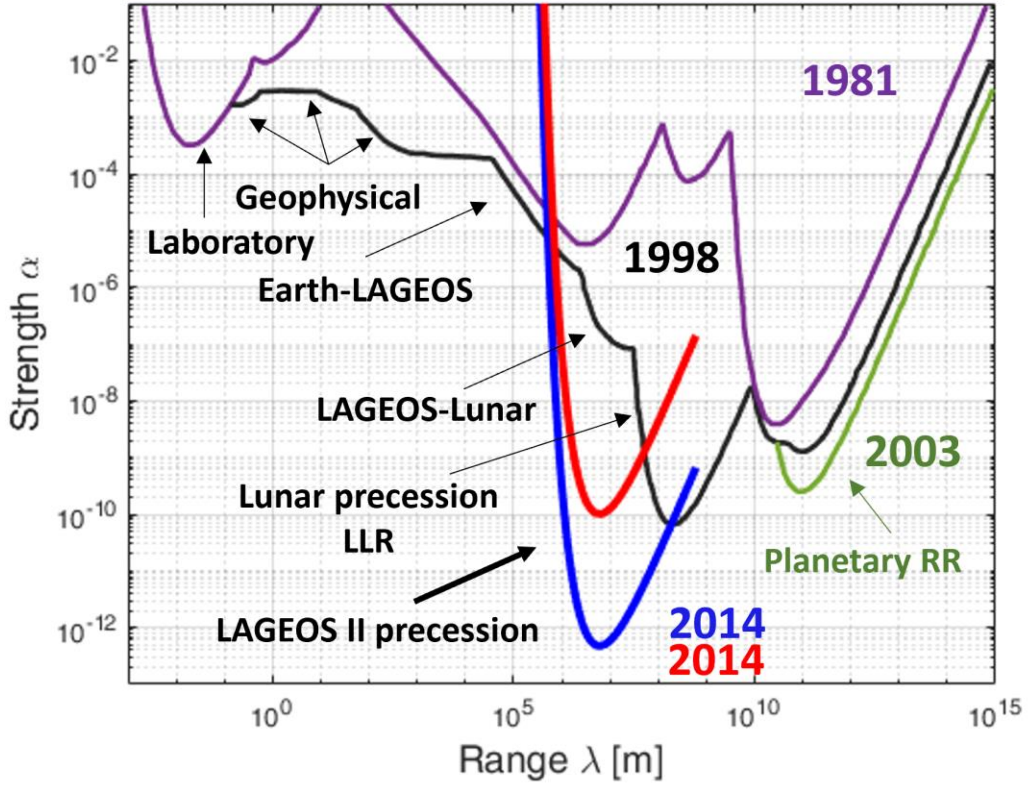
$$\boxed{\varepsilon = 1 - (0.12 \pm 2.10)\cdot 10^{-3} \pm 2.5 \cdot 10^{-2}}$$

$$|\boldsymbol{\alpha}| \cong \left|(\mathbf{0.5} \pm \mathbf{8})\cdot \mathbf{10^{-12}} \pm \mathbf{101 \cdot 10^{-12}}\right|$$

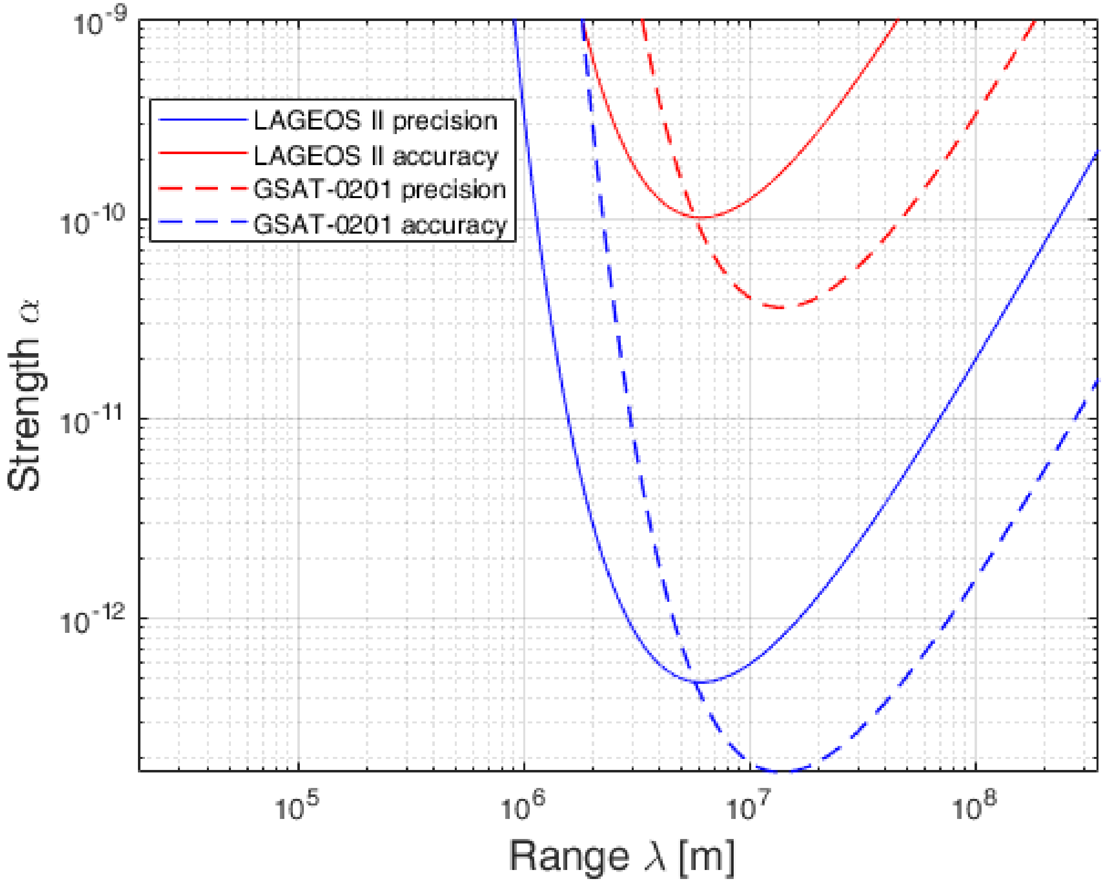
Lucchesi & Peron, in Phys. Rev. D (2014), 89, 8, 082002

The region above each curve is ruled out at the 95.5% confidence level.

Composition independent experiments



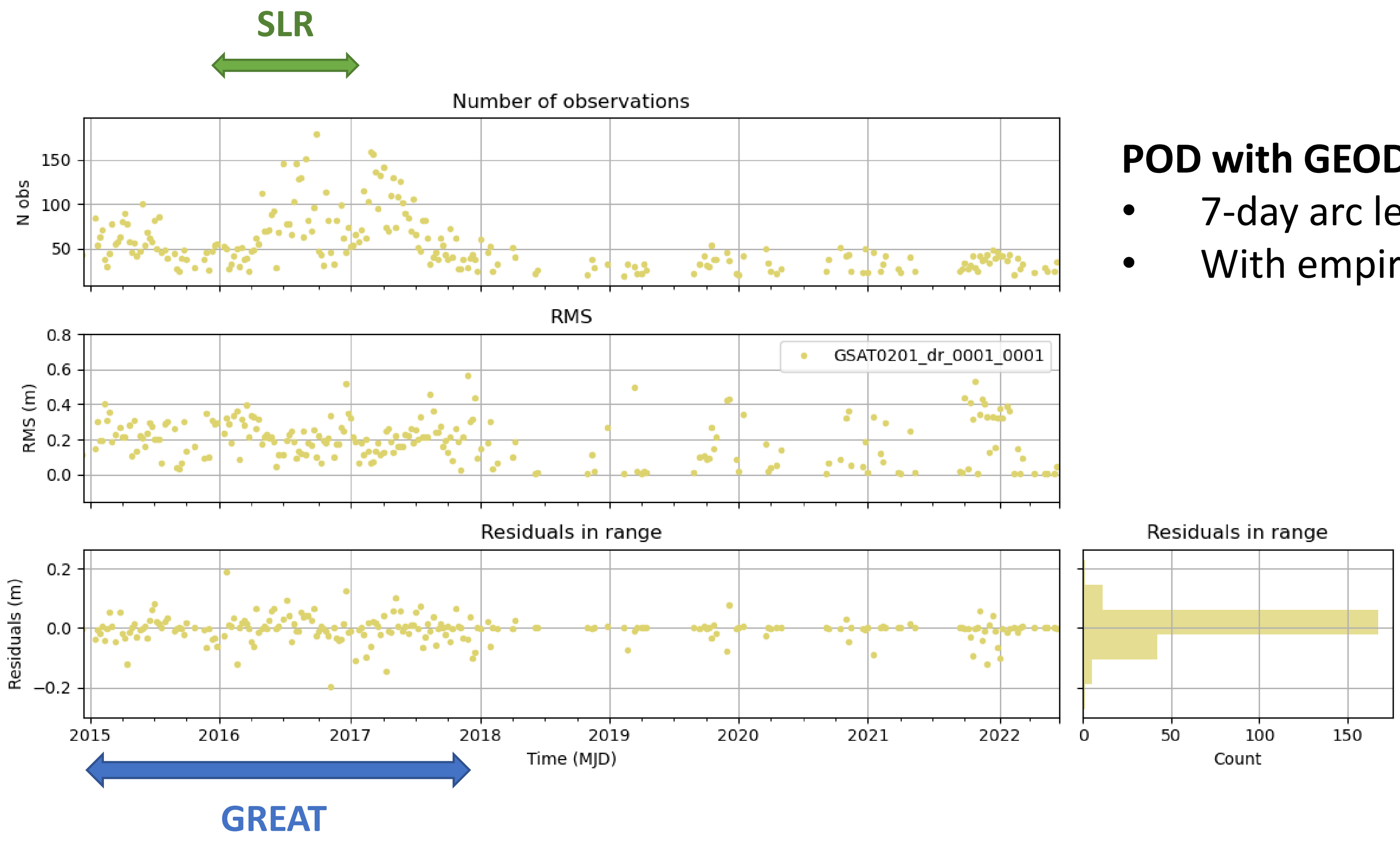
Main motivation: systematic errors



Constraints of α and λ for LAGEOS II satellite and for the GSAT-0201 Galileo satellite, evaluated in the case it had the same precision and accuracy of LAGEOS II in the measurement of the relastivistic precession of its pericenter.

Preliminary POD

GSAT0201

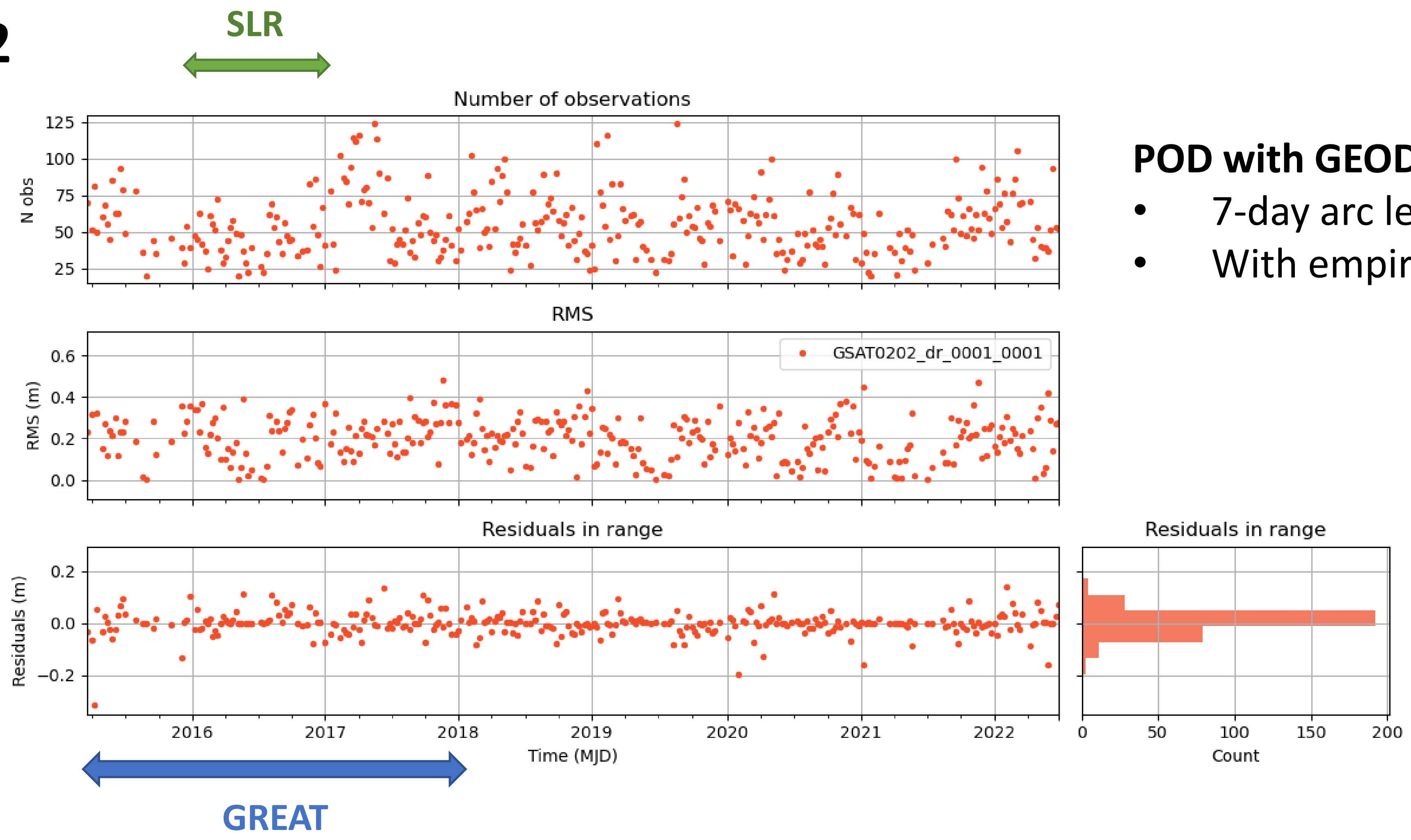


POD with GEODYN II

- 7-day arc length
- With empirical accelerations

Preliminary POD

GSAT0202



POD with GEODYN II

- 7-day arc length
- With empirical accelerations

Preliminary POD

GSAT0201
GSAT0202
GSAT0206
GSAT0208

POD Statistics

POD statistics for the various analyses. The "Average" column contains average values for the analysis periods.

		Average (m)	+/-
GSAT0201	RMS	0.220	0.282
	Mean	-0.002	0.089
GSAT0202	RMS	0.243	0.510
	Mean	0.006	0.087
GSAT0206	RMS	0.179	0.183
	Mean	0.001	0.019
GSAT0208	RMS	0.172	0.111
	Mean	0.001	0.012

POD with GEODYN II

- 7-day arc length
- With empirical accelerations

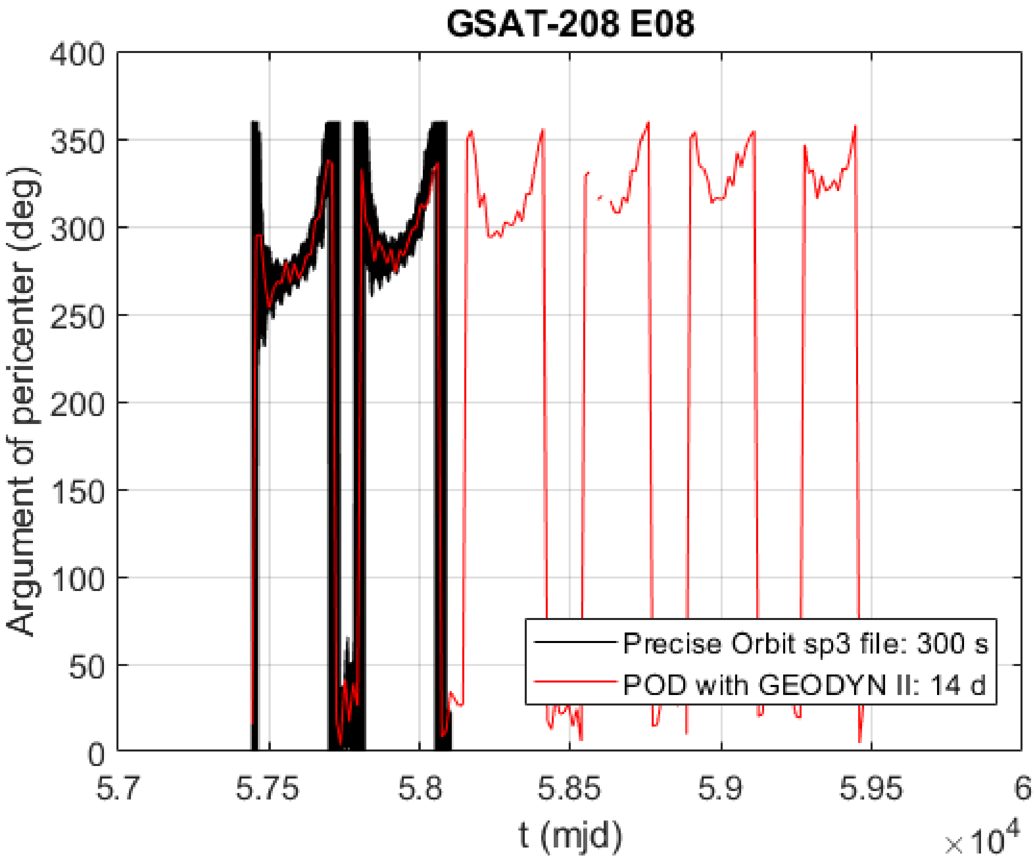
Preliminary POD

A few considerations.

- We will improve these results with a more refined **POD** based on the use of our improved **Box-Wing** model and with our final **FEM** model of the S/C, instead of using empirical accelerations
- We are interested in Full Rate data to better characterize the penumbra transition during the eclipses season
  - More refined and reliable models are useful in these cases
  - Clock-bias estimate could improve
- The **Bernese** S/W will be used to estimate the clock-bias for **LPI** and **DM** tests
- Anyway, current preliminary results are encouraging when looking to the long-term orbital effects

Preliminary POD

Preliminary results: GEODYN POD vs sp3



The proposal for a SLR campaign

Satellites in elliptical orbit (GSAT0201 and GSAT0202)

In the case of the measurements related to the **relativistic precession** and the possible **LPI violation** test, we proposed:

1. To observe the two satellites over a **2-year time span**: at least two weeks per month (to increase the tracking during these two weeks with respect to that currently in progress).

2. The two weeks of tracking will necessarily concern the periods in which the **beta angle is maximum and minimum and when this is close to zero**, i.e. with particular attention to the epochs of penumbra transitions.

The proposal for a SLR campaign

Satellites in nominal orbit (e≈0)

In the case of the satellites in nominal orbit we propose a **6-month SLR campaign** to limit the possible presence of **Dark Matter** in the Milky Way. In particular:

1. The campaign should be as intensive as possible: daily observations.
2. The 6 months of observations must be held in two cycles of 3 months each at 6 months from each other (see Remark #3 of point 8 below).
3. It will not be necessary to extend the requested increased number of observations to all the satellites of the constellation (see point 7 below).

The proposal for a SLR campaign

Satellites in nominal orbit ($e \approx 0$)

In the case of the satellites in nominal orbit we propose a **6-month SLR campaign** to limit the possible presence of **Dark Matter** in the Milky Way. In particular:

1. The campaign should be as intensive as possible: daily observations.
2. The 6 months of observations must be held in two cycles of 3 months each at 6 months from each other (see Remark #3 of point 8 below).
3. It will not be necessary to extend the requested increased number of observations to all the satellites of the constellation (see point 7 below).

Remark #3. A project named **GASTON** and funded by **ESA** has already obtained from **ILRS a 3-month intensive SLR campaign** to put constraints on the Dark Matter with the Galileo-FOC constellation. If this 3-month campaign has characteristics very close to the one we asked for (to be verified), <u>we ask for a campaign of only 3 months</u> and postponed by 6 months with respect to the period of the year carried out for the **GASTON** project.

The proposal for a SLR campaign

Satellites in nominal orbit (e≈0)

In the case of the satellites in nominal orbit we propose a **6-month SLR campaign** to limit the possible presence of **Dark Matter** in the Milky Way. In particular:

1. The campaign should be as intensive as possible: daily observations.
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7. Priority in observations. As for the satellites in nominal orbit and the measures to constrain DM, we can limit the observations to **4 satellites for each orbital plane** of the constellation, which we remember is of the Walker type 24/3/1, for a total of **12 satellites**. In this case we should identify a priori the satellites that use the **PHM** as clocks and those that use the **RAFS**, in order to specify which satellites should be tracked.

The proposal for a SLR campaign

ASI-CGS MLRO station will **fully support** the **G4S_2.0 SLR campaign**.

MOU between ASI and ESA

A collaboration with **ESA** is currently underway and **ASI** is finalizing a **MOU** with **ESA** (between the two Navigation Office) to obtain a collaboration equal to that of the previous **GREAT** and **GASTON** projects. Some points of the **MOU** concern a support for:

- a dedicated **SLR** campaign
- major insight into the **physical properties** of the Galileo-FOC satellite
- **POD** with ESA S/W **NAPEOS**
- …

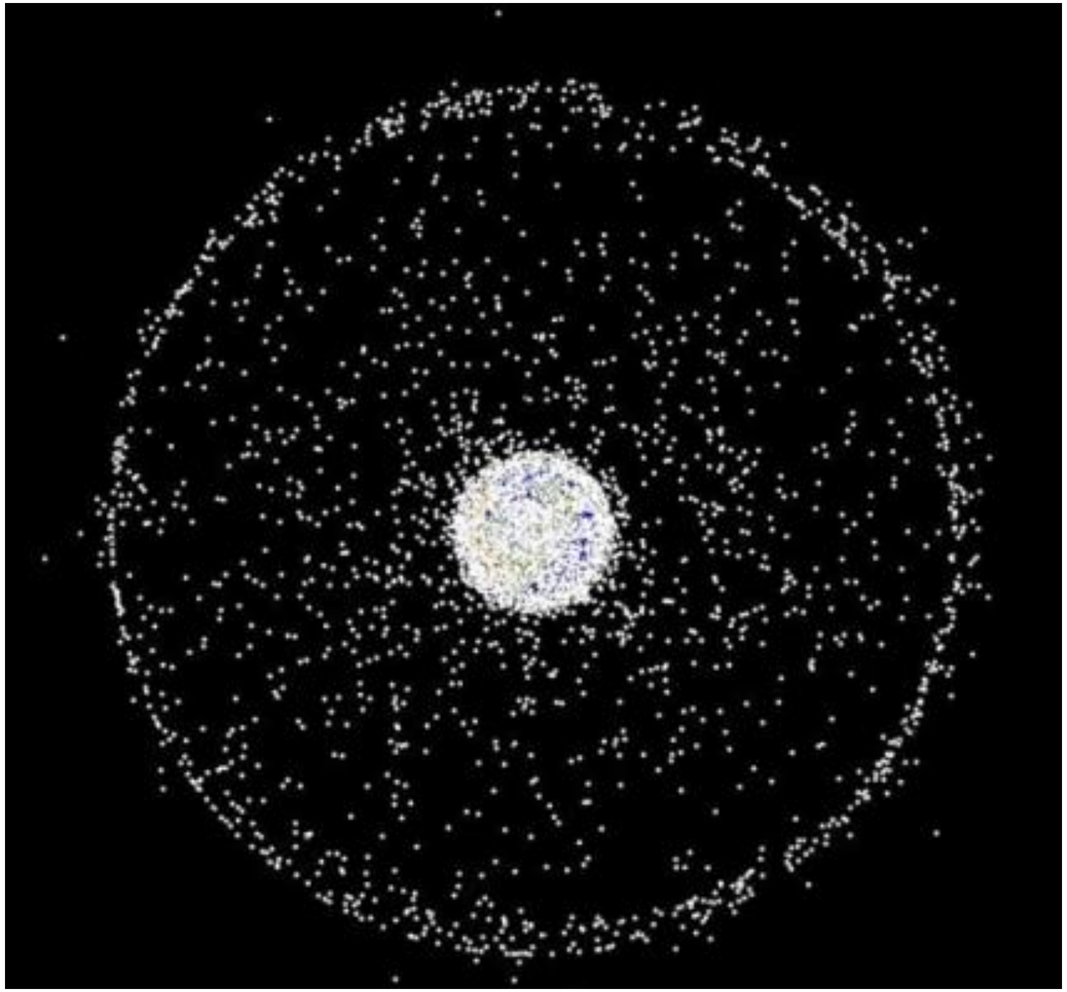
Space Debris Laser Ranging with range-gate-free Superconducting Nanowire Single-Photon Detector

reduce the effect of the inaccurate orbital prediction of targets

Haitao Zhang,
Yuqiang Li *, Zhulian Li, Xiaoyu Pi, Yongzhang Yang, Rufeng Tang

Yunnan Observatories, CAS
Online NESC meeting, Feb. 02, 2023

1 Introduction



DLR (Space Debris Laser Ranging)

- developed from SLR (Satellite Laser Ranging)
- non-cooperative targets (without retro-reflectors)

Difficulties

- the low reflectivity
- the inaccurate orbital prediction

Solutions

- improving the echo detection capability
- improving the accuracy of orbital prediction ?

→ reducing the effect of the inaccurate orbital prediction

2 Why Laser Ranging requires high accurate orbital prediction ?

SLR

The **accurate** orbital prediction is required :

- to calculate the pointing of telescope (to aim at the target)
- **to calculate the opening time of the range gate (to find the signal)**

The detection probability (the probability of detecting an echo photon at the time of its arrival) [1, 2] :

$$p_s = \left(1 - e^{-(n_s + n_n \tau)}\right)\left(\frac{n_s}{n_s + n_n \tau}\right)$$

n_s - the number of echo photons reaching the detector.

n_n - the noise-photon rate reaching the detector.

τ - the response time of the detector.

The false alarm probability (the probability of the detector being triggered by noise photons during the period when the detector is waiting for the echo photons after the range gate is opened) [1, 2] :

$$p_n = 1 - e^{-n_n t_{rg}}$$

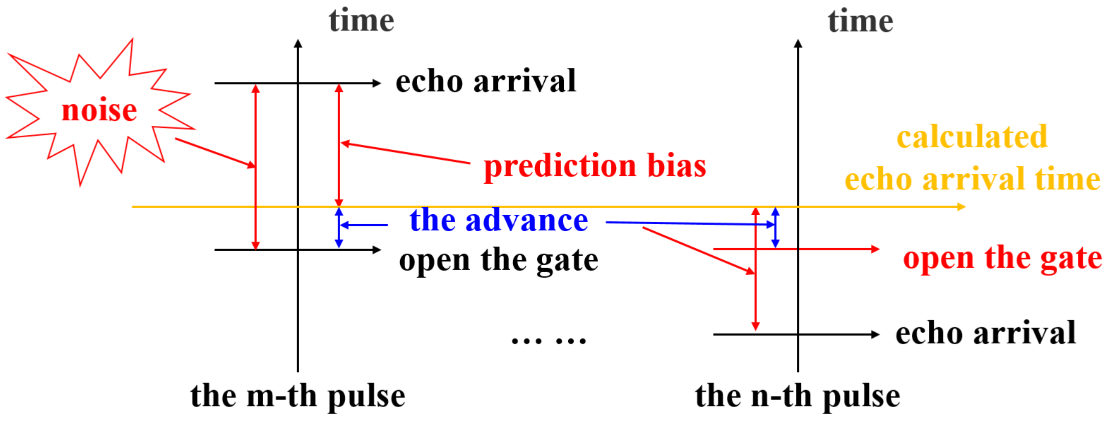
accurate
$t_{pb} \approx 0$

t_{rg} - the advance of the opening time of the range gate.

The success probability of laser ranging [1, 2] :

$$p = (1 - p_n)\, p_s$$

DLR



- respond once for each laser pulse.
- the m-th pulse : it is possible to detect an echo photon only if the detector is not triggered by noise photons during the period (from the opening time of the range gate to the echo arrival time).
- the n-th pulse : the range gate opens after the arrival of the echo due to the orbit-prediction bias.

The false alarm probability :

$$p_n = 1 - e^{-n_n (t_{pb} + t_{rg})}$$

t_{pb} - the orbit-prediction bias.

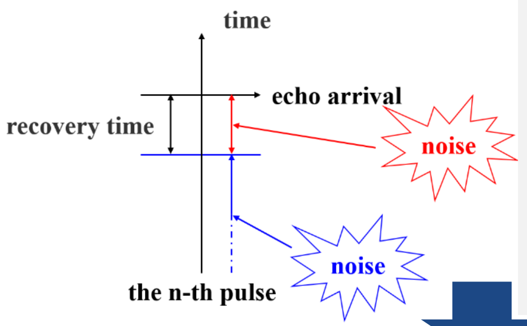
inaccurate

t_{rg} - the advance of the opening time of the range gate.

3 DLR in Normal mode and Range-gate-free mode

SNSPD (Superconducting Nanowire Single-Photon Detector) :

- The SNSPD can **automatically recover its working state** in range-gate-free mode. [3-6].
- For each laser pulse, the SNSPD can respond multiple times.

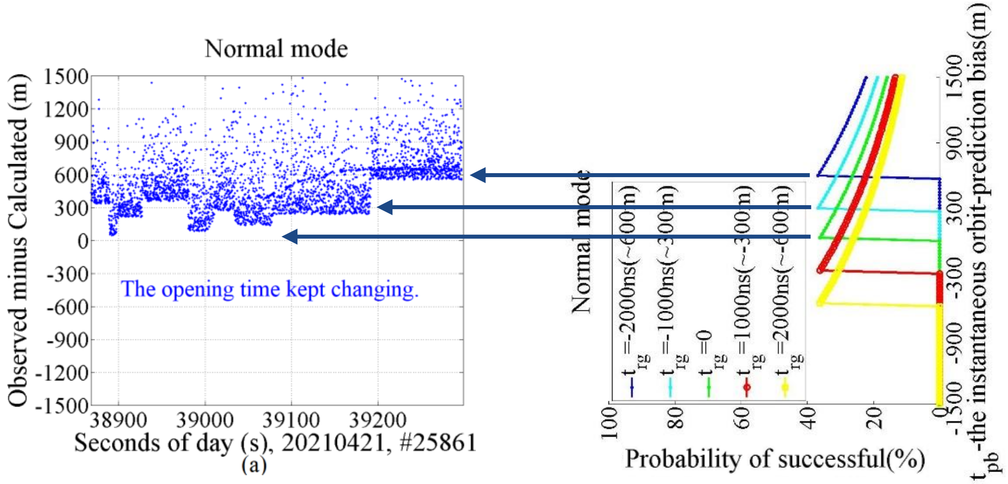


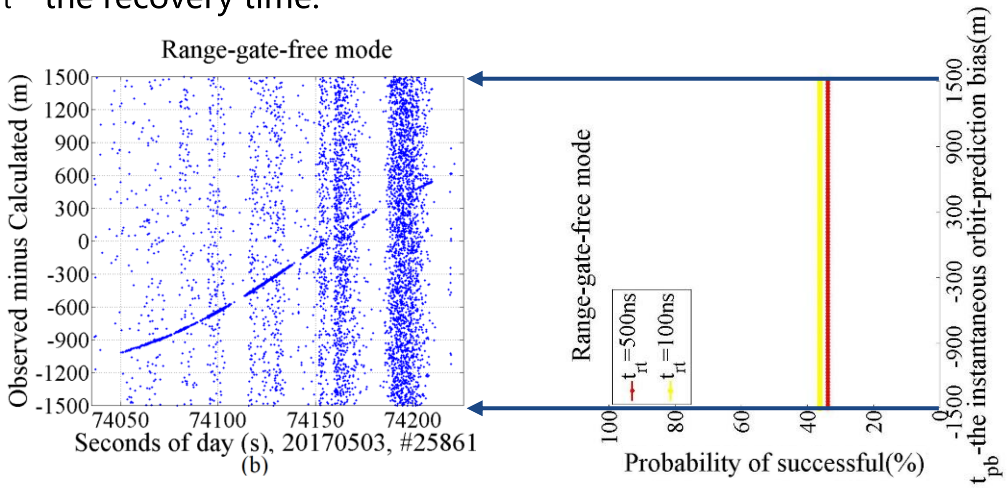
As long as the detector is not triggered by noise photons during recovery time, it is possible for the SNSPD to detect an echo photon

The false alarm probability (**normal**) : $p_n = 1 - e^{-n_n(t_{pb} + t_{rg})}$

The false alarm probability (**range-gate-free**) : $p_n = 1 - e^{-n_n t_{rt}}$

t_{rt} - the recovery time.





1.Keep searching for target position.

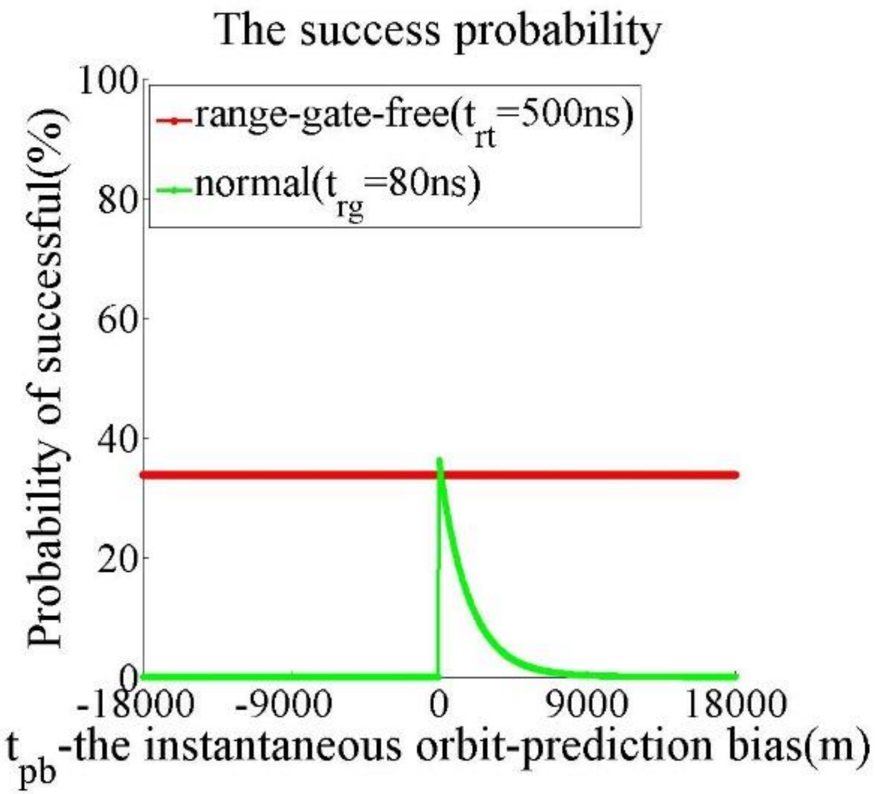
2.Keep searching for the opening time of range gate

t_{rg}↘↗ : (t_{pb} + t_{rg}) > 0 & (t_{pb} + t_{rg}) → 0

1. Just search for target position.
2. No need to do anything. (**reduce the effect of the prediction**)

t_{rt} : constant

4 DLR with range-gate-free SNSPD



- the success probability is not affected by the accuracy of the orbital prediction : the echo photons are within the threshold of Observed-minus-Calculated (O-C).
- the maximum threshold of O-C can be set to ±60000ns (**≈±18000m,** related to data processing capability).
- **greatly reduce the effect (the RB in the radial direction, max.~±18km) of the inaccurate orbital prediction.**

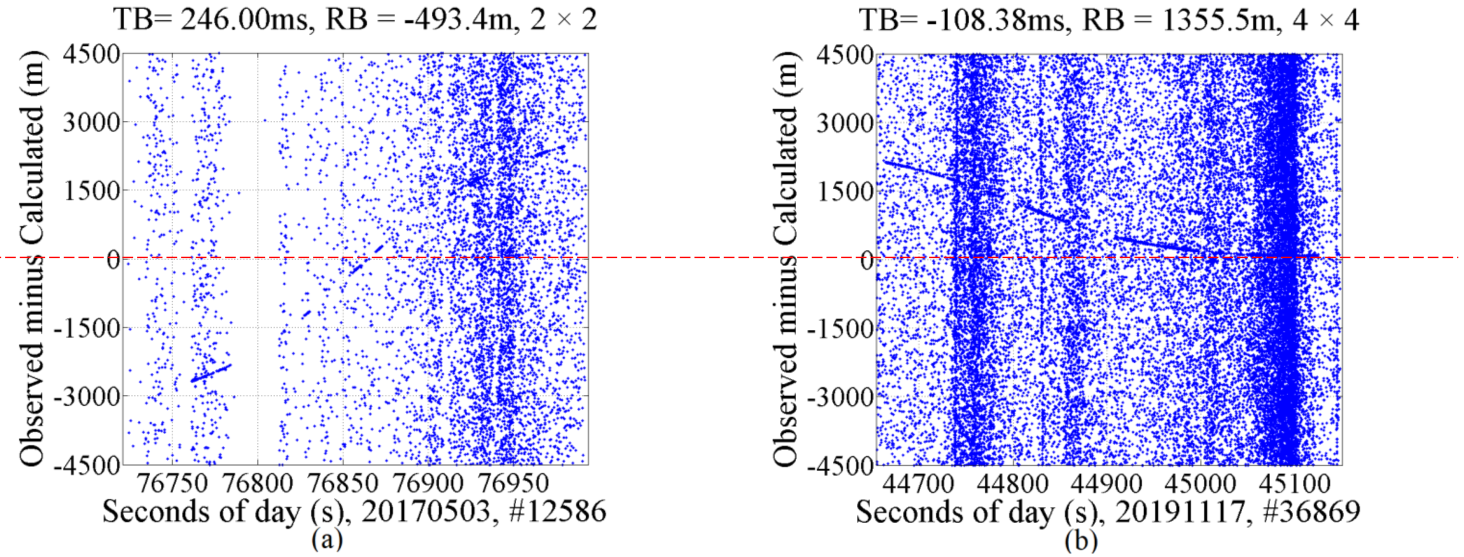
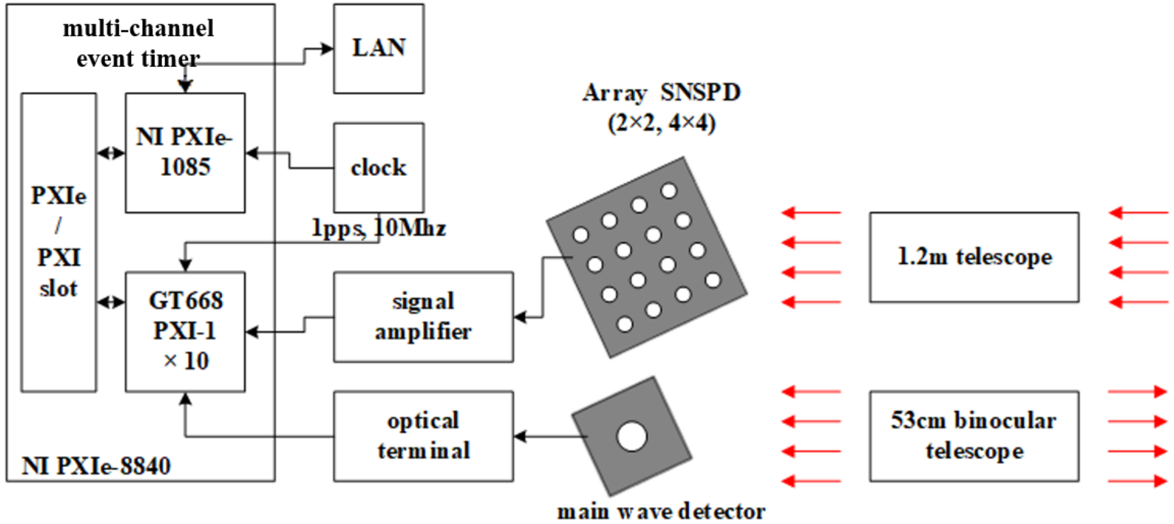


Fig (a) : TB (Time Bias) = 246.00ms, RB (Range Bias) = -493.4m
Fig (b) : TB = -108.38ms, RB = 1355.5m

5 Experiment and Results

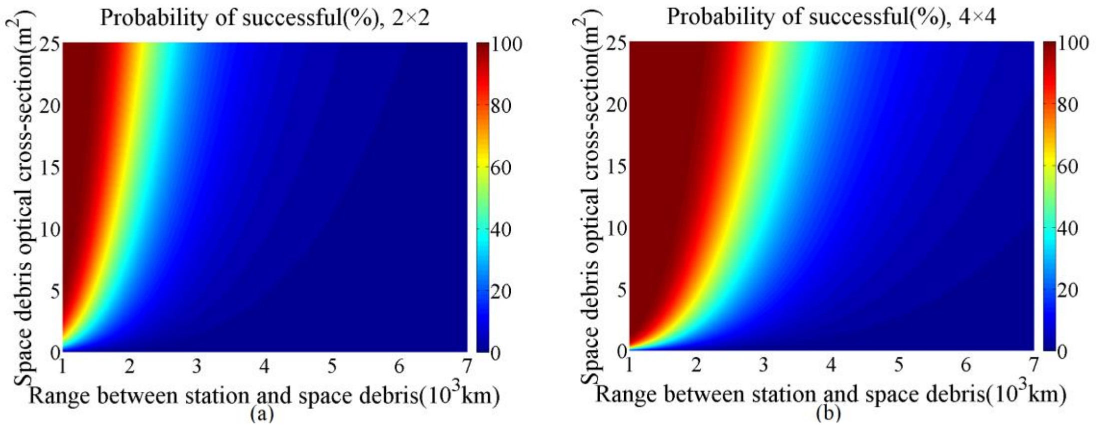


In order to further improve the success probability of DLR :

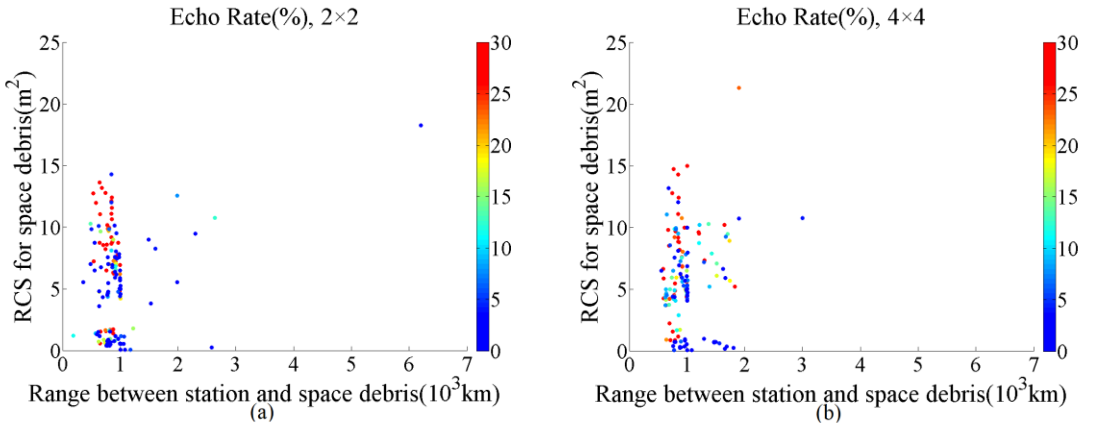
- a **range-gate-free SNSPD array** [6, 7].
- a **multi-channel event timer** [6, 7].
- laser wavelength is **1064nm**, laser power is **40 W-300 W (generally using 40W)**, laser repetition rate is **100Hz** [6, 7].

Results (2017-2020)

Number of days of observation	Number of targets	Number of passes
87	249	532

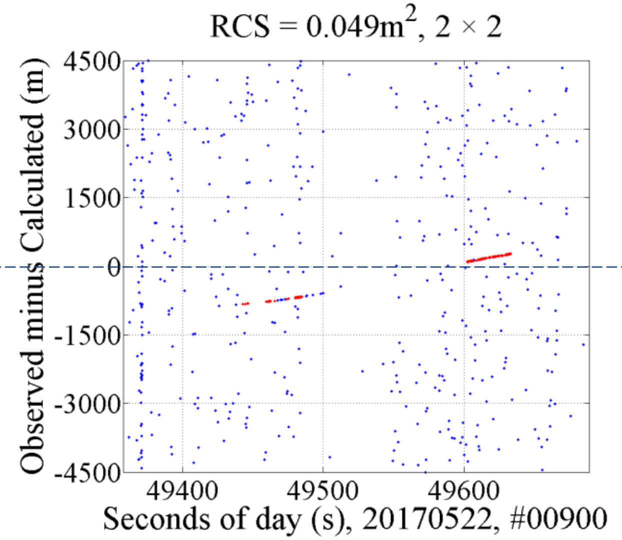


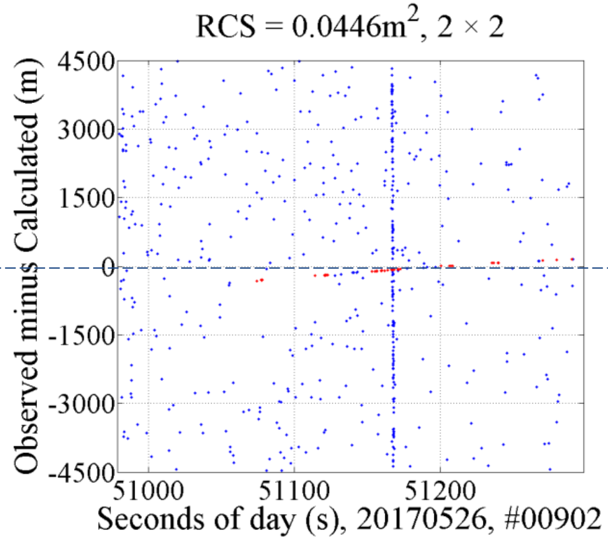
success probability of DLR for different targets.
a) 2×2 SNSPD array. b) 4×4 SNSPD array.

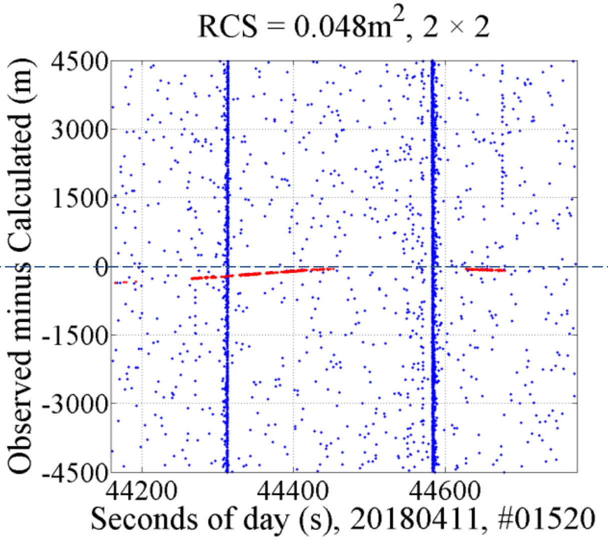


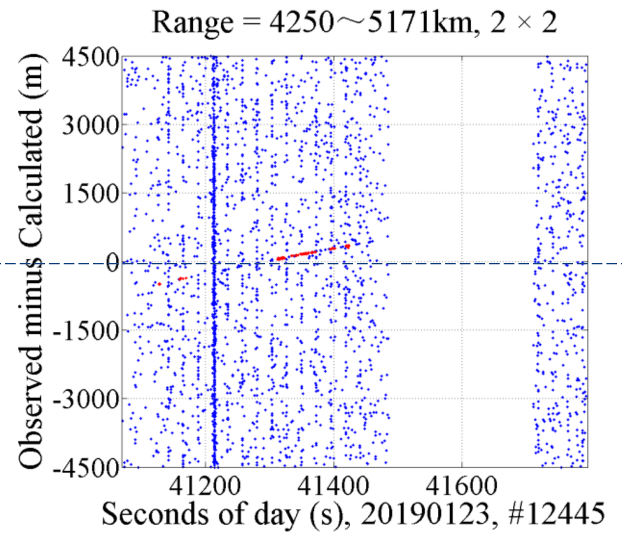
the echo rate statistics for different targets.
a) 2×2 SNSPD array. b) 4×4 SNSPD array.

5 Experiment and Results (the smallest & farthest)









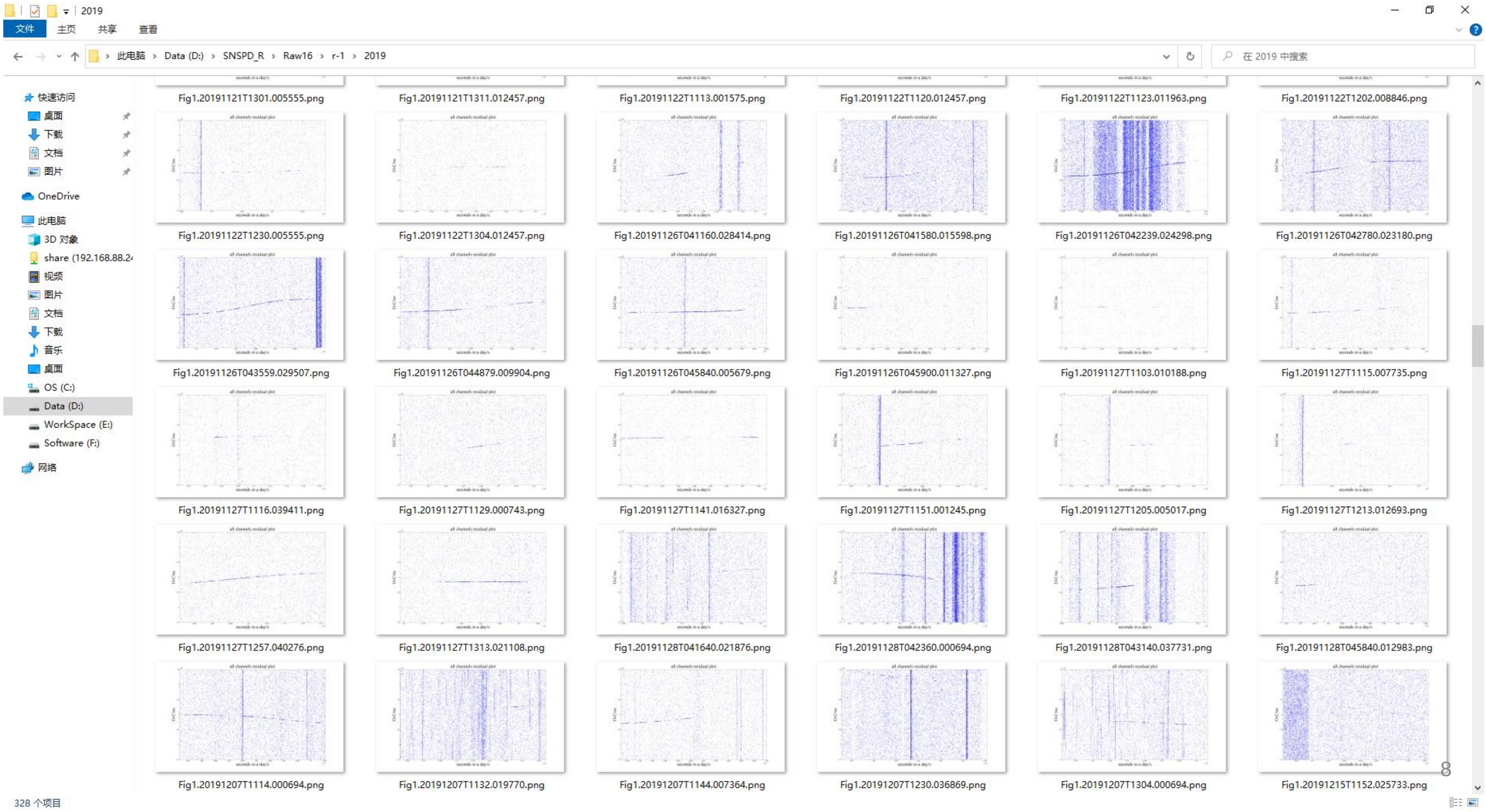
the smallest targets detected in the experiment

	Apogee / km	RCS / m²	Size / m	RMS / m	Laser power / W
900	1006	0.0490	spherical 0.36	<1.5	~70—150W
902	1075	0.0446	spherical 0.36	<1.5	~70—150W
1520	1175	0.0480	spherical 0.36	<1.5	~70—150W

the farthest target (12445, RCS~18.2505m²) detected in the experiment

date	Range / km	RMS / m	Laser power / W
Jan. 23, 2019	~4250—5171	2.32	~200
Jan. 27, 2019	6260.805 (NPT)	2.12	~200

5 Experiment and Results (residual plots of some data)



6 Conclusion

Conclusion

- the SNSPD array running in automatic-recoverable range-gate-free mode : **greatly reduce the effect (the RB in the radial direction) of the inaccurate orbital prediction.**
- increasing the success probability of space debris laser ranging : increases the probability of detection (array) & **reduces the false alarm probability** (range-gate-free).
- application : Space Debris Laser Ranging Experiments with Transmitting / Receiving - Stations 333km Apart. (Next Report - Xiaoyu Pi).

In the future

We will devote to applying the method to :

- **daylight** space debris laser ranging.
- space debris laser ranging **without range prediction.**

Main References

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4. C L Lv, H Zhou, H Li, L X You, X Y Liu, Y Wang, W J Zhang, S J Chen, Z Wang and X M Xie, "Large active area superconducting single-nanowire photon detector with a 100μmdiameter," Supercond. Sci. Technol. 30, 115018 (2017).
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7. Zhang Haitao, Li Zhulian, Tang Rufeng, Zhai Dongsheng, Li Rongwang, Pi Xiaoyu, Fu Honglin, Li Yuqiang, "Application of array detection technology in laser ranging," Infrared and Laser Engineering. **49**(10), 20200006, (2020).
8. Michael A Steindorfer, Georg Kirchner, Franz Koidl, Peiyuan Wang, Beatriz Jilete and Tim Flohrer, "Daylight space debris laser ranging," Nat Commun. 11(1), 3735 (2020).

Thanks !

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Online NESC meeting, Feb. 02, 2023

Riga ITRF 2014 Solution Problem

NESC Meeting 2023/02/02

K. Salmins, J. del Pino

SLR Riga 1884

UNIVERSITY OF LATVIA
INSTITUTE OF ASTRONOMY

Background information:

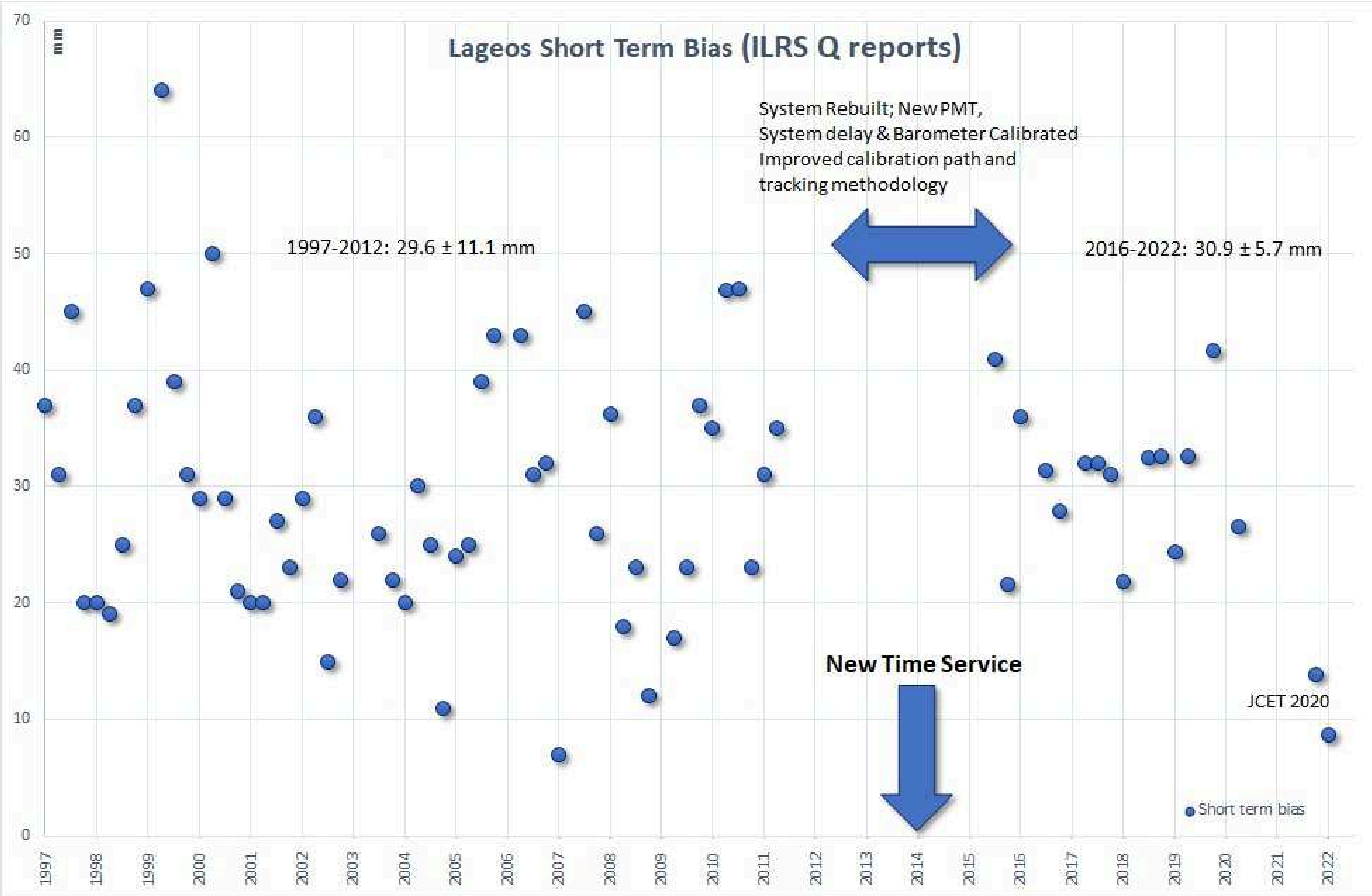
- The current team took charge of the SLR station in 2013.
- The previous Team leader retired earlier due to bad health and passed away in May, 2013. No chance to know-how transfer or asking for clarifications.
- In many cases poor or non-existent documentation.
- Many technical problems:
  - Good part of the SLR hardware was obsolete, some parts older than 30 years.
  - Need to replace/upgrade the tracking, filtering, calibration, data storage and information procedures.
  - SLR building needed repairs.
  - Fast degradation of the tracking capabilities, in early 2013 no returns from Lageos 1,2.

Upgrading the SLR Riga 1884:

- In 2012 a local ties check was done as a BSc dissertation.
- The Fotonika project (EU FP7 GRANT REGPOT-CT-2011-285912-FOTONIKA) allowed funding for the SLR initial equipment upgrade and for personnel secondment.
- In February 2014 enters in operation a new SLR time service based on the Spectracom SecureSync timing unit with GNSS steering with a new time & frequency distribution network.
- The new equipment was extensively calibrated. Parts of the old time service were also calibrated (E. Hoffman et al. Annapolis 2014).
- During 2015-2016 practically all SLR blocks, building and procedures were upgraded, replaced and if needed, recalibrated.
- Two quarantines releases: 2016/04/16 and 2017/02/01.

First hint of a problem:

After all the upgrades, the Lageos short and long term biases did not improved.



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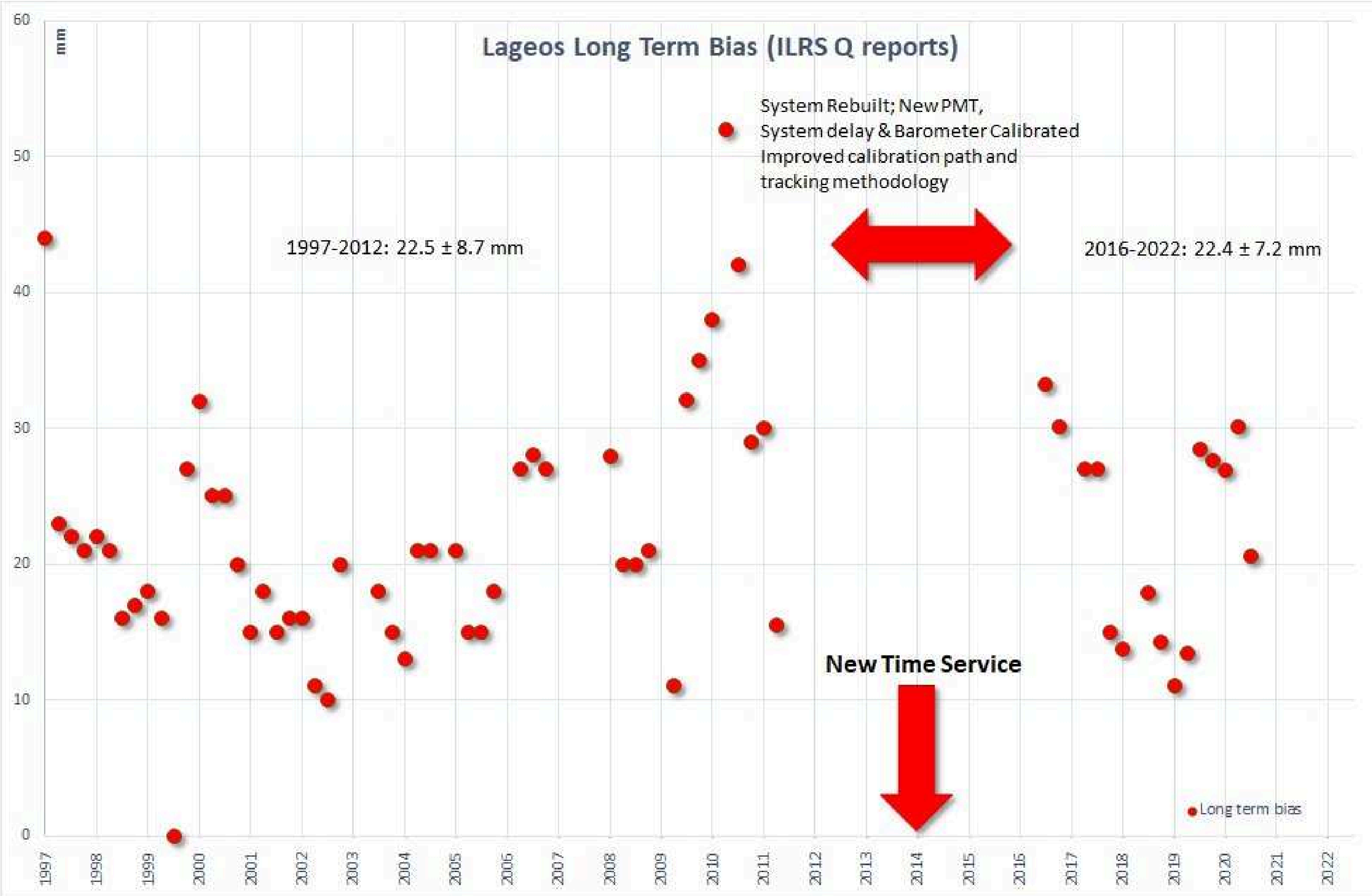


Riga, we have a problem:

In early 2020, the papers by:

Guo et al. Estimation of SLR station coordinates by means of SLR measurements to kinematic orbit of LEO satellites, Earth, Planets and Space (2018) 70:201 https://doi.org/10.1186/s40623-018-0973-7

Arnold, et al. Satellite laser ranging to low Earth orbiters: orbit and network validation, Journal of Geodesy (2019) 93:2315–2334 https://doi.org/10.1007/s00190-018-1140-4

used GNSS derived orbits (Guo: GraceA from Jan-Dec 2012 and Arnold: Swarm-C, TerrasarX, Sentinel 3A, Jason 2 Jan-Dec 2016) and the SLR Ranges from selected stations to calculate the SLR reference points position errors.

Gave that:

Riga has the biggest Up error, and the "Up/RB" errors increased **after the 2014-2016 upgrades**.

	Riga	n(mm)	±	e(mm)	±	u(mm)	±	RB(mm)	±	#NP
2012	Guo	-10.3	2.7	-7.1	1.6	**83.7**	5.4	**57.4**	5.1	377
2016	Arnold	-11.6	0.8	-8.8	0.9	**185.2**	2.3	**172.9**	1.5	2191

Steps to understand the problem:

- All the 2013-2016 SLR calibrations were revised, both in concept and experimental values, all results were consistent.
- As the n,e,u errors were calculated comparing the ITRF X,Y,Z station coordinates against the calculated X,Y,Z values, we decided to revise the Riga ITRF solutions.
- Things became interesting...

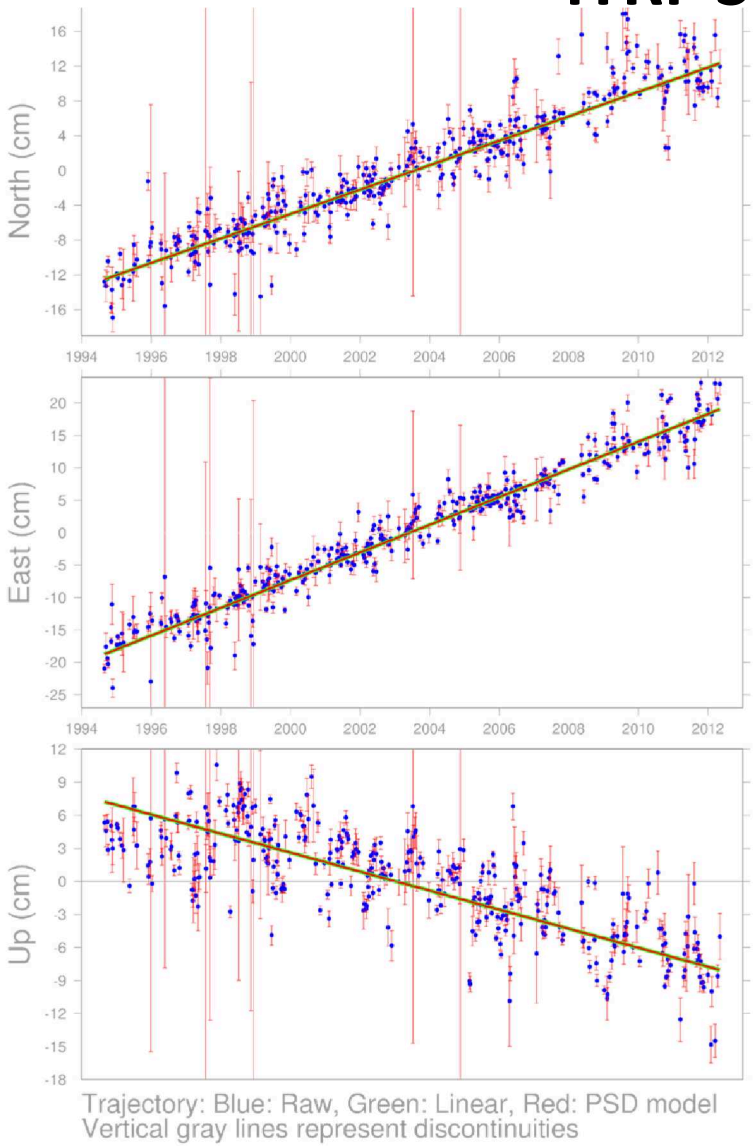
The ITRF problem:

- Up to ITRF2005 the Vx, Vy, Vz for a multisystem site were a common value for all the systems on site.
- No 2005 GNSS solution for Riga.
- Starting with ITRF2008, each local system had its own independent Vx, Vy, Vz solution values, in the case of Riga, **we found significative discrepancies at the mm/year level between the SLR and GNSS velocities**.

ITRF	VxSLR-VxGNSS (m/y)	VySLR-VyGNSS (m/y)	VzSLR-VzGNSS (m/y)
1996	0.00000	0.00000	0.00000
1997	0.00000	0.00000	0.00000
2000	0.00000	0.00000	0.00000
2008	-0.00630	-0.00290	-0.01030
2014	-0.00593	-0.00159	-0.00786
2020	-0.00037	-0.00007	-0.00060

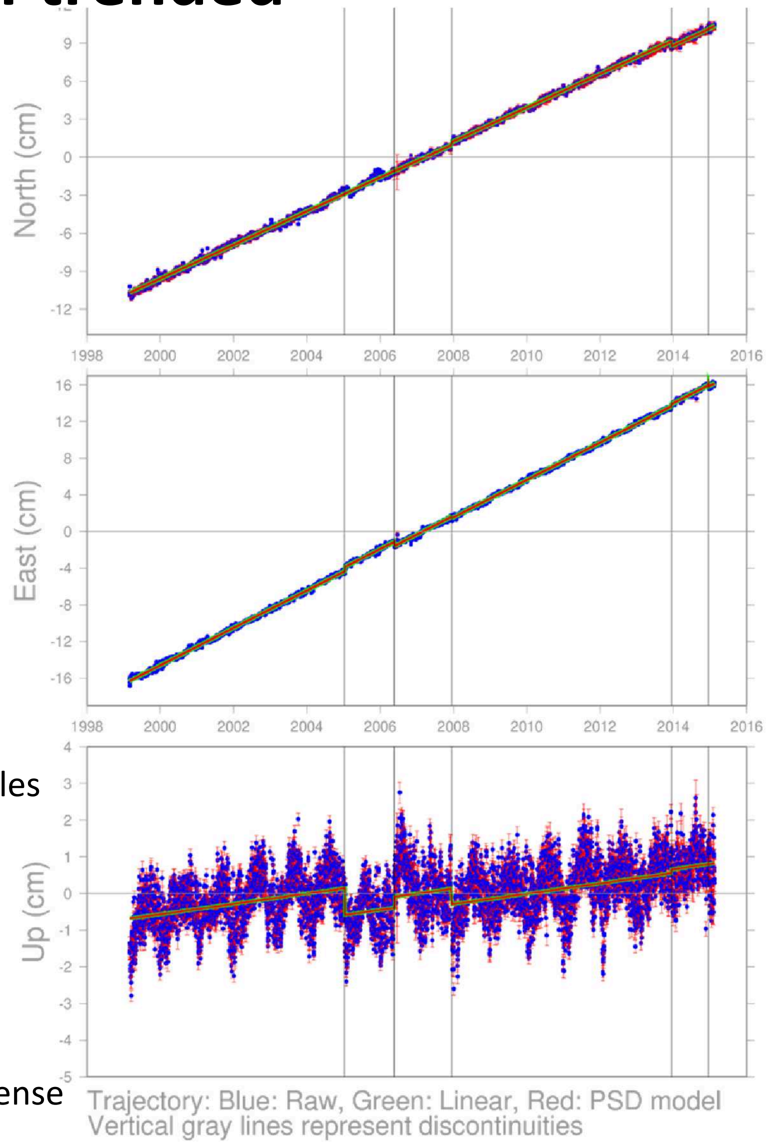
- For Riga, the first ITRF solution with a trended plot available was for ITRF 2014, so we decided to concentrate on it. Even if the Guo paper used the ITRF 2008.

ITRF Solution 2014 trended



different vertical scales

opposite movement sense



The ITRF problem:

According to the 2014 trended plot:

- The SLR is sinking in relation to the GNSS (before 1998 no „up“ movement).
- If the sinking is true, then the slope distance SLR-GNSS should be growing.
- The 2012 local ties re-measure did not found any significative change at the mm level on the slope distance. The 2021 local ties solution confirmed this.
- There is no indication that the SLR building has sunk in the ground.

- **Hypothesis**: the ITRF 2014 solution was wrong because the Riga SLR data before 2014 was wrong.
- We went back to the 2014 E. Hoffman et al. ILRS Annapolis presentation.

The ITRF problem:

- The Rb frequency source was built in the early 80‘s, the original Rb cell was never replaced.
- When calibrating the un-steered soviet built Rb 5 MHz source, E. Hoffman found that the Rb drift was ~2-3 orders of magnitude higher than typical.
- In that moment, no one noticed the Rb drift implications for the ToF measurements.
- The event timer electronics (and processing software) assumes that the ET incoming frequency signal is **exactly** 5 Mhz, if not, the ToF values measured are wrong.
- This ToF value error will grow with time because of the Rb drift.
- As the local time scale was synchronized at least daily against the GNSS receiver pps, the local UTC time scale was kept between limits. The GNSS receiver frequency output was 10 MHz.
- There was no control if the 5 MHz signal feeding the event timer was **REALLY** 5MHz.
- We revised the operation notes and logs before 2013 and interviewed old observers, there is no information of any attempt to calibrate and/or correct the 5Mhz signal.

The ITRF problem:

- When calibrating the un-steered Soviet built Rb 5 MHz frequency source in 2014, E. Hoffman found that the Rb drift was ~2-3 orders of magnitude higher than typical.

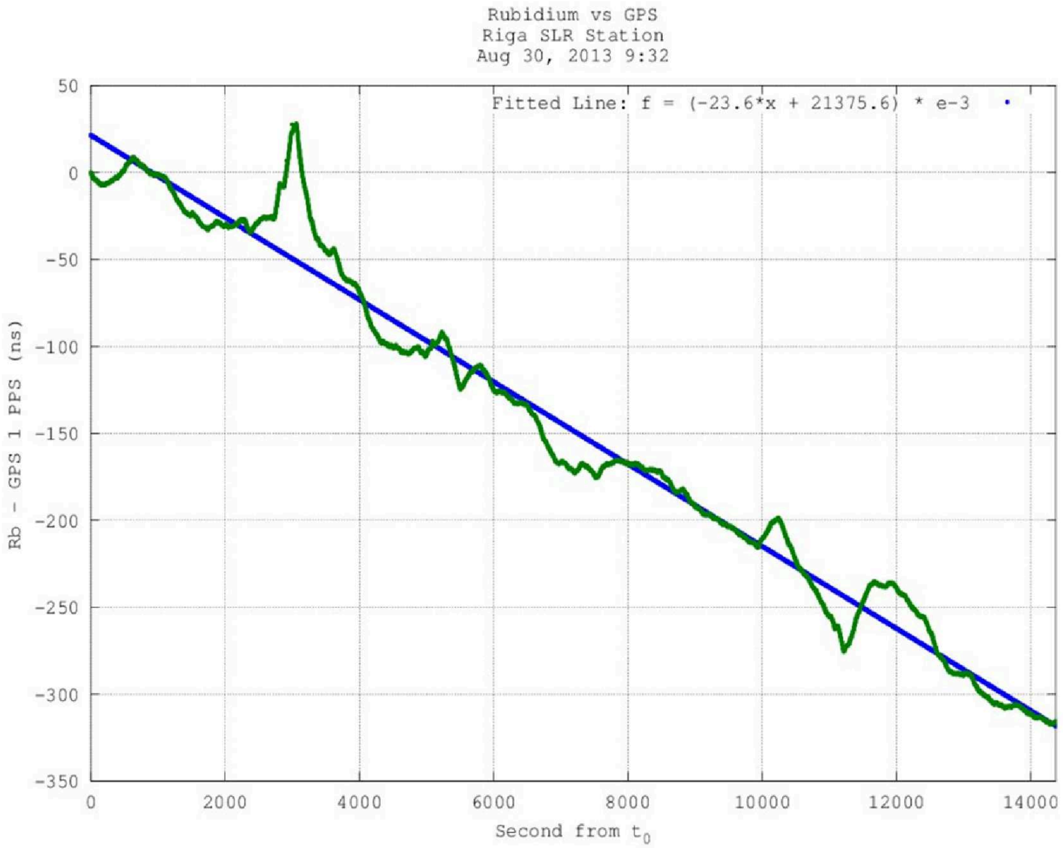


Figure 2: Long Term Drift Shown by old Rb

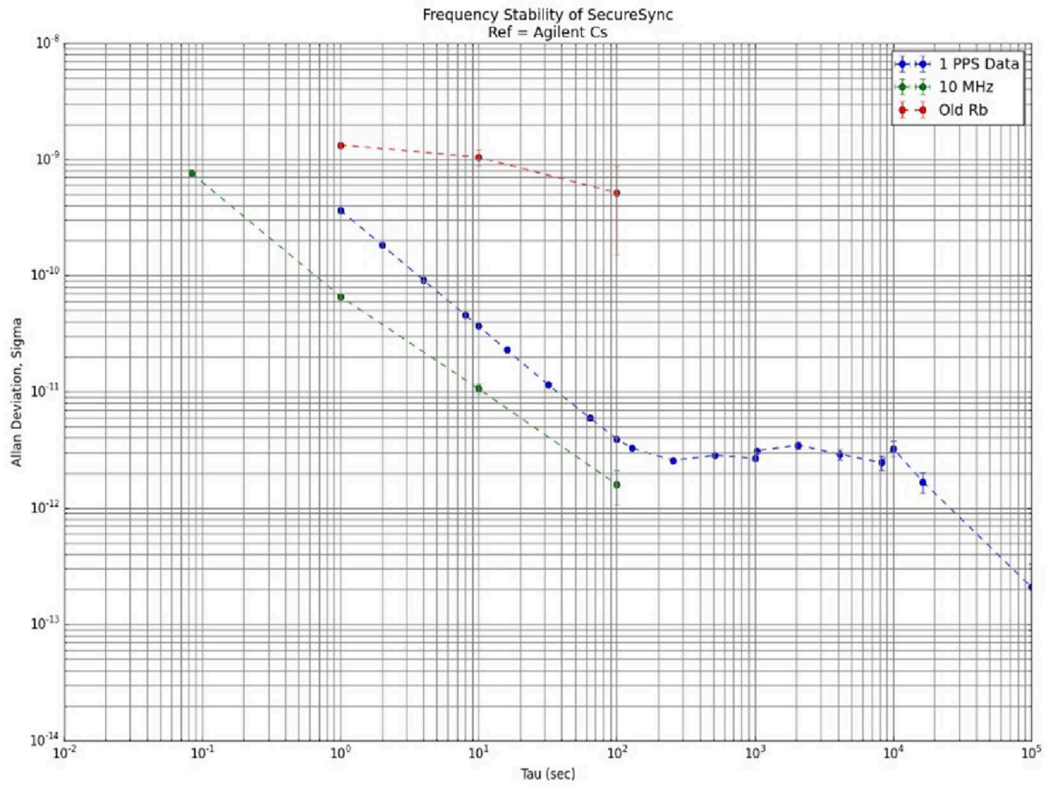
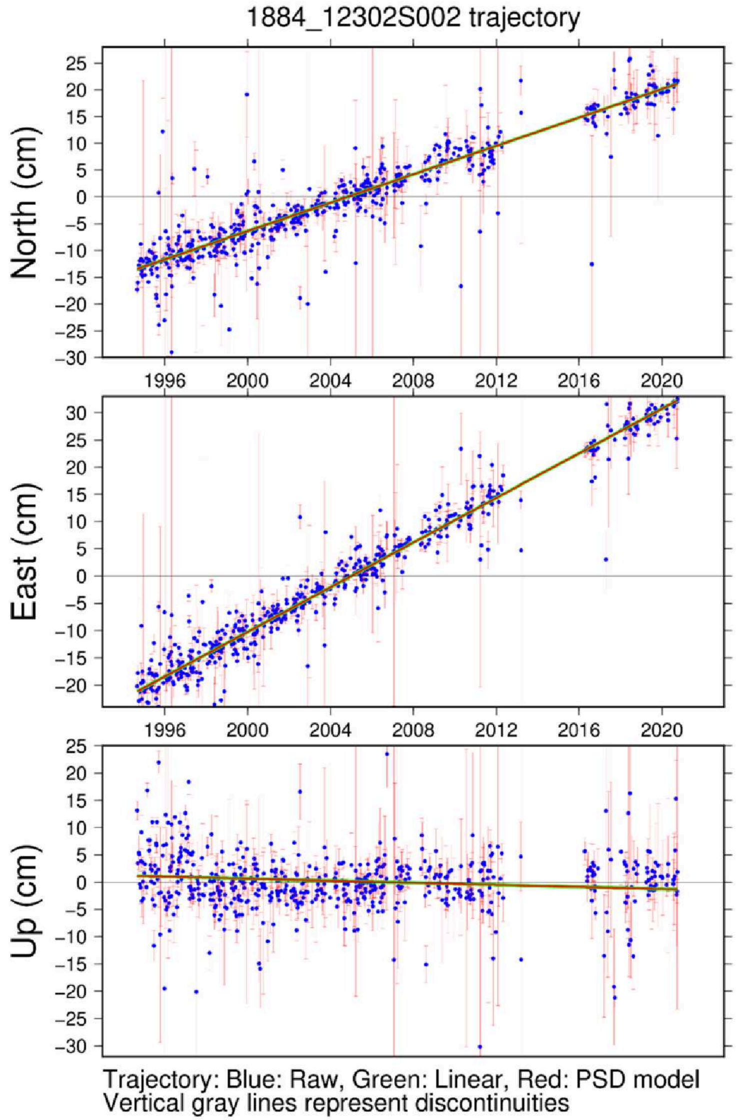


Figure 5: Allan Deviation of Frequency Sources

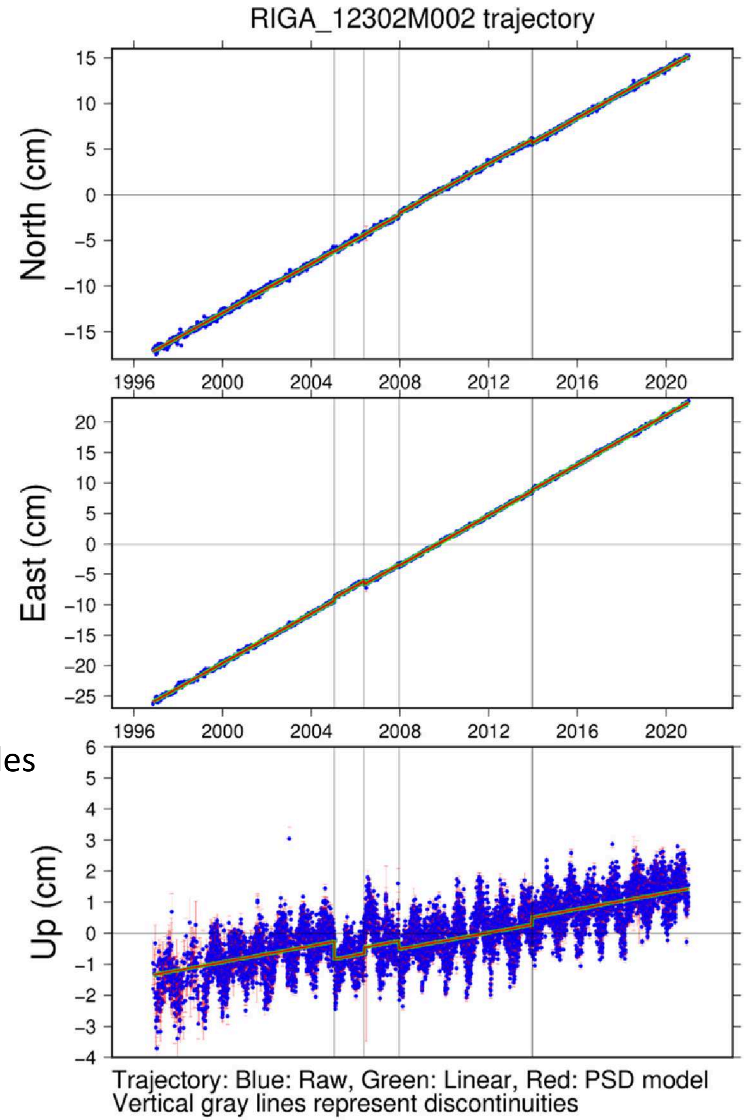
Hypothesis:

- If the ITRF solutions errors were caused by corrupted ToF values before the 2014 Time service exchange, then the 2020 solution will have SLR V_i values closer to the GNSS V_i values.
- If this proven true, then either the Riga ITRF 2020 SLR solution should be recalculated using ONLY the data after 2014, or to ask to do so for the next ITRF solution.
- This problem could has been detected starting with the Riga 2008 solution.
- Any Station check his solutions for V_i discrepancies?

ITRF Solution 2020 trended



different vertical scales

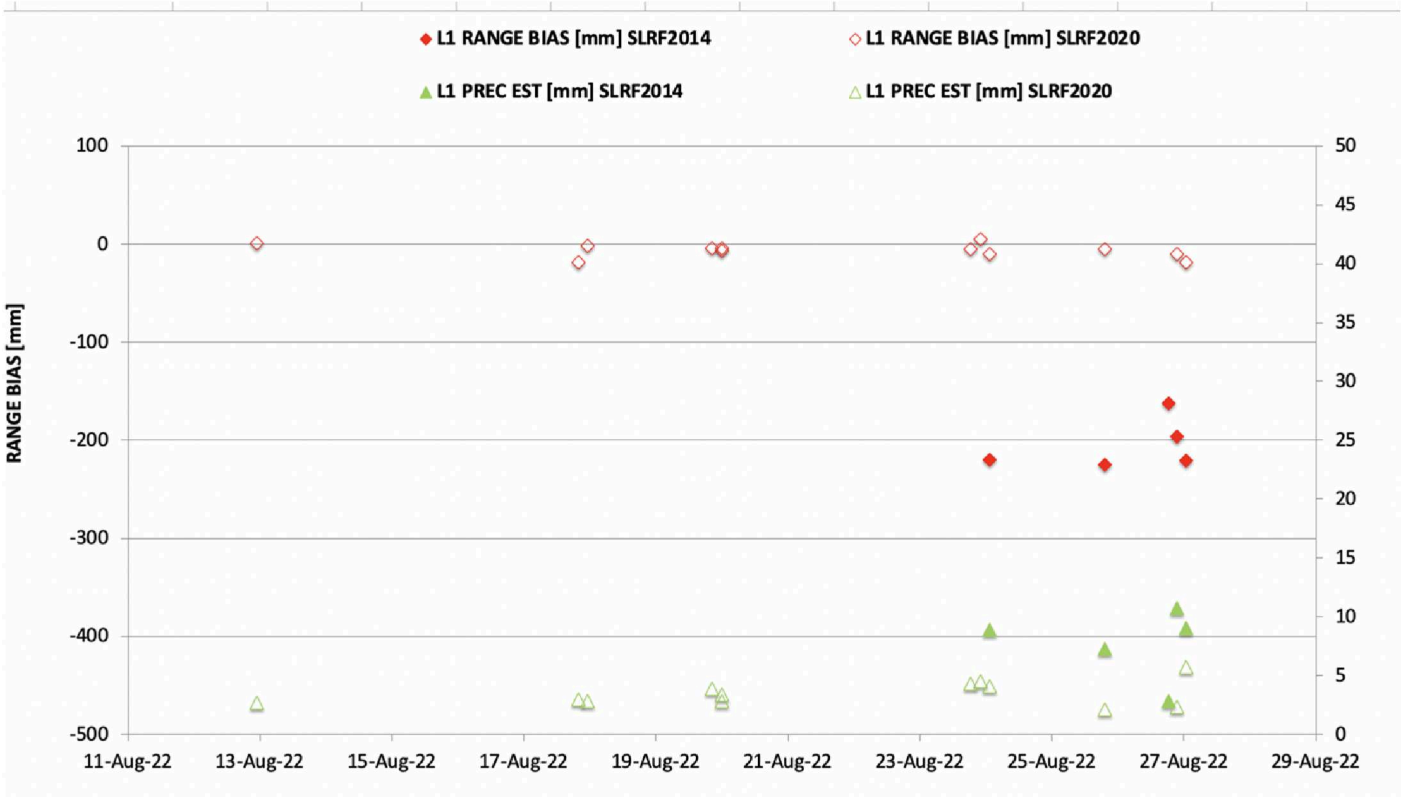


The ITRF problem:

- Starting in 2021 the SLR system was upgraded to add space debris and photometric capabilities.
- At the same time the expanded local ties were measured and the results published:

  K. Salmins, V. Sprois, I. Biļinskis, J. del Pino. Local Ties at SLR Station Riga, International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2022_157.
- This allowed the recalibrate the SLR system delay with high confidence.
- We restarted observing in the summer 2022, we are now on quarantine.
- We contacted E. Pavlis, explained our hypothesis and agreed to ran initially the quarantine analysis using both ITRF 2014 and ITRF 2020.
- We contacted T. Otsubo, He is doing the analysis using ITRF 2014 only.

The ITRF problem: Quarantine 2014 against Quarantine 2020



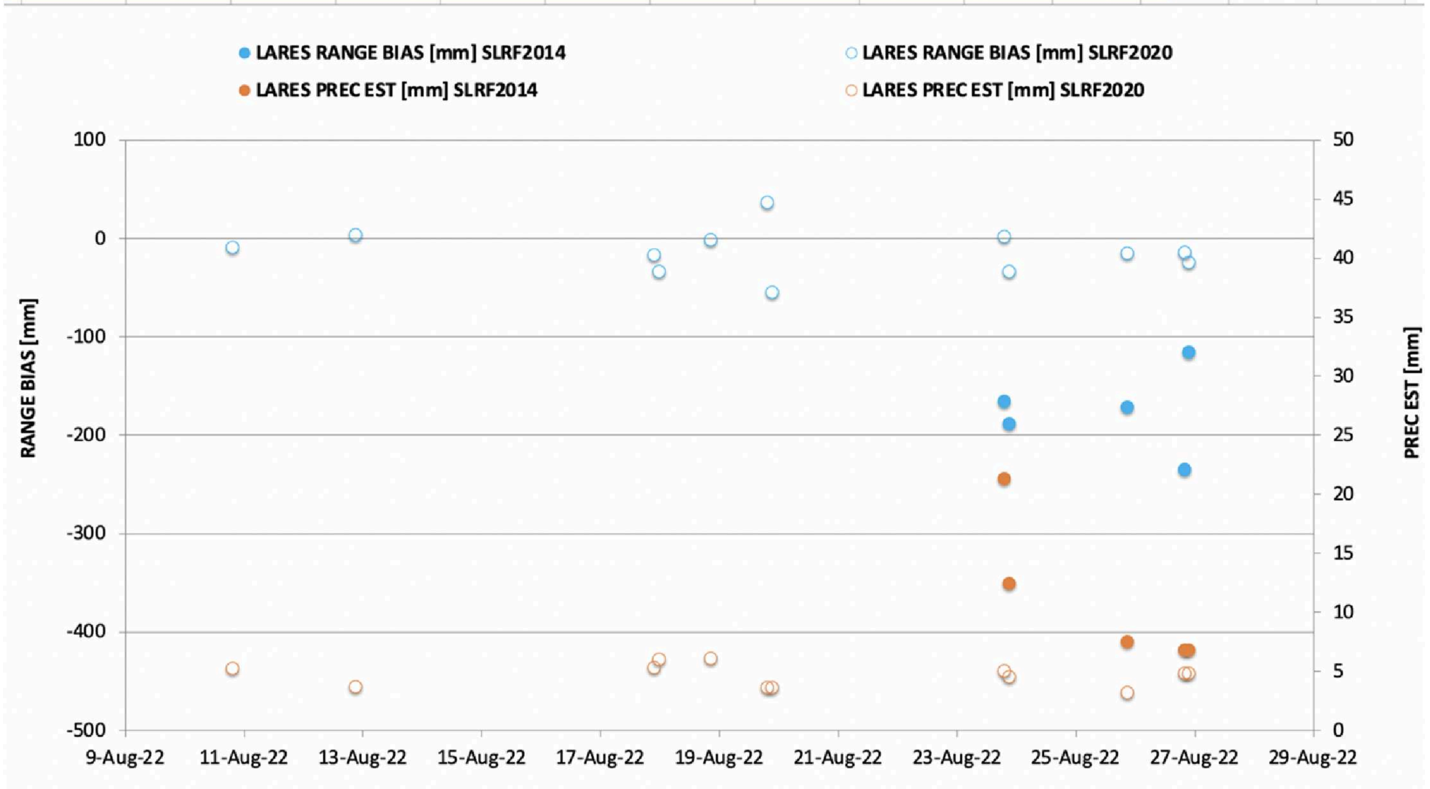
18844401SL RF2014	PREC EST [mm]	RANGE BIAS [mm]
Mean	7.7	-204.9
STD	3.0	26.3
RMS	8.2	206.2
Passes	5	5

18844401SL RF2020	PREC EST [mm]	RANGE BIAS [mm]
Mean	11.0	-175.5
STD	6.2	43.2
RMS	12.3	179.7
Passes	5	5

Values	L1	LR
Accpted	39	207
Obs.	16	12
Passes	5	5

Courtesy E. Pavlis

The ITRF problem: Quarantine 2014 against Quarantine 2020



18844401SLRF2020	PREC EST [mm]	RANGE BIAS [mm]
Mean	3.5	-6.6
STD	1.1	7.1
RMS	3.6	9.5
Passes	12	12

18844401SLRF2020	PREC EST [mm]	RANGE BIAS [mm]
Mean	4.7	-13.6
STD	1.0	23.0
RMS	4.7	25.9
Passes	12	12

Values	L1	LR
Accpted Obs.	148	207
Obs.	2	12
No. of Passes	13	12

Courtesy E. Pavlis

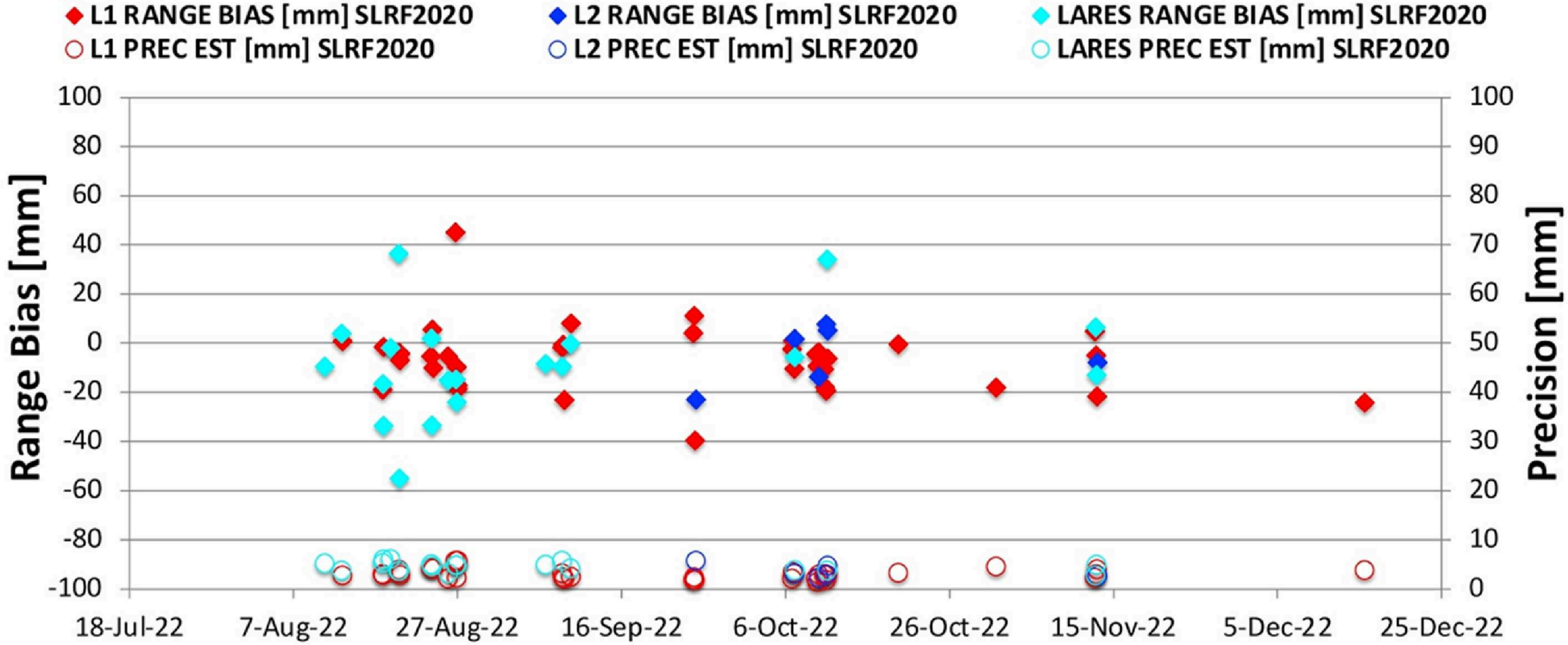
The ITRF problem: Quarantine using ITRF 2020

LAGEOS 1 | LARES | LAGEOS 2

QC L1 18844401SLRF2020	PREC EST [mm]	RANGE BIAS [mm]
Mean	3.1	-6.6
STD	1.1	13.6
RMS	3.3	14.9
Passes	37	37

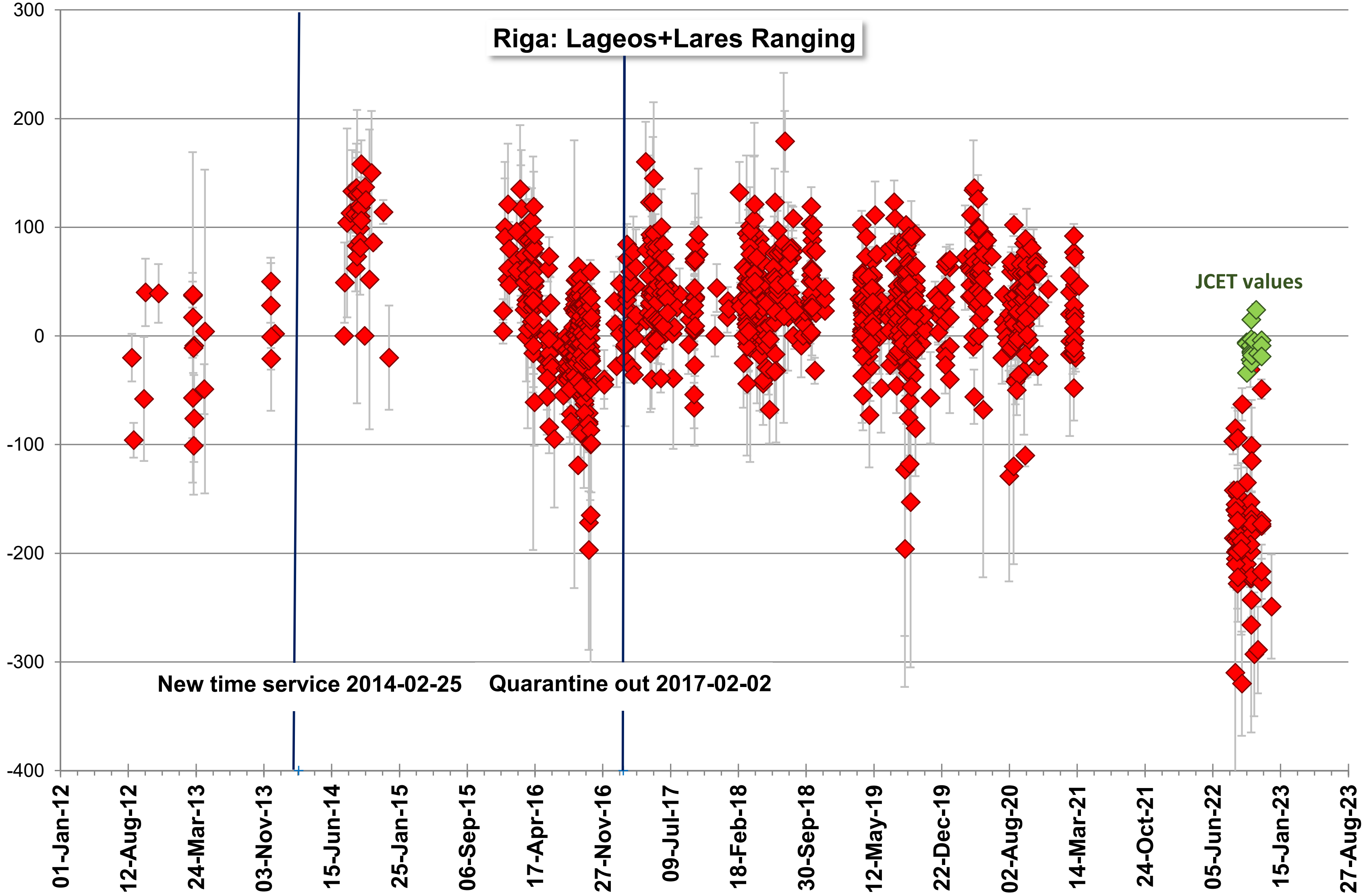
QC LR 18844401SLRF2020	PREC EST [mm]	RANGE BIAS [mm]
Mean	4.5	-8.4
STD	1.0	21.4
RMS	4.6	22.5
Passes	19	19

QC L2 18844401SLRF2020	PREC EST [mm]	RANGE BIAS [mm]
Mean	3.6	-5.2
STD	1.3	11.9
RMS	3.8	12.1
Passes	6	6

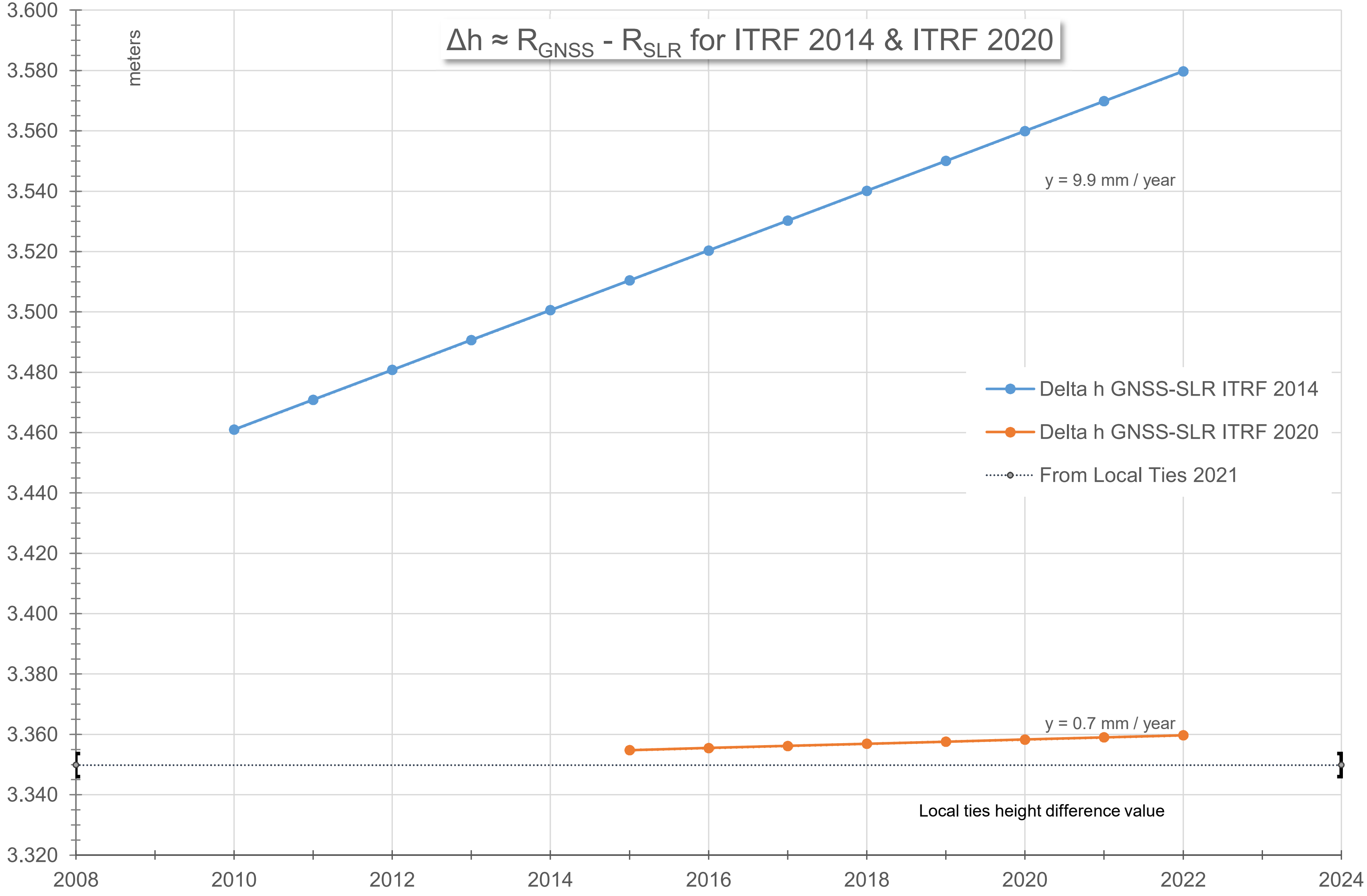


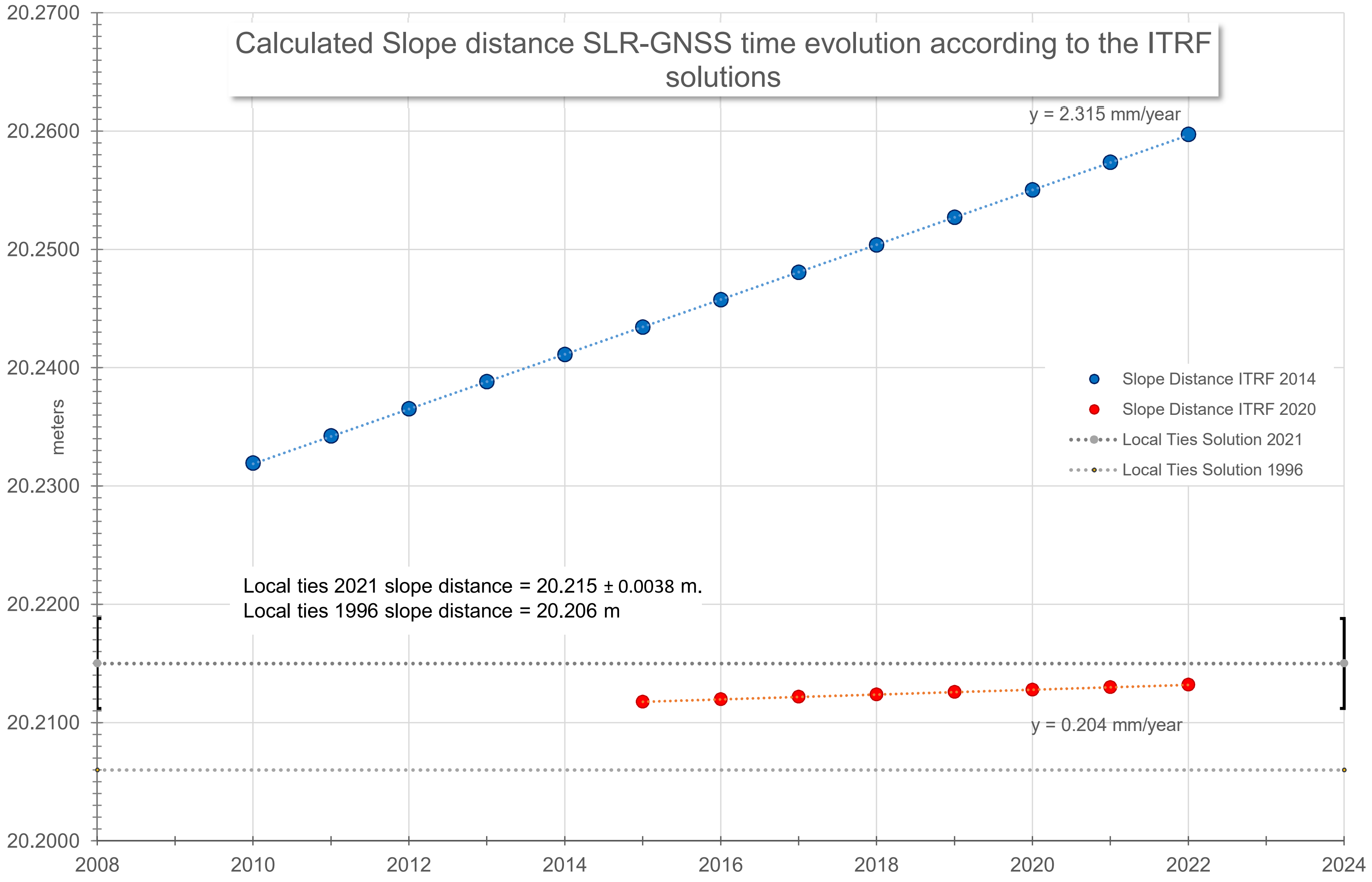
Courtesy E. Pavlis

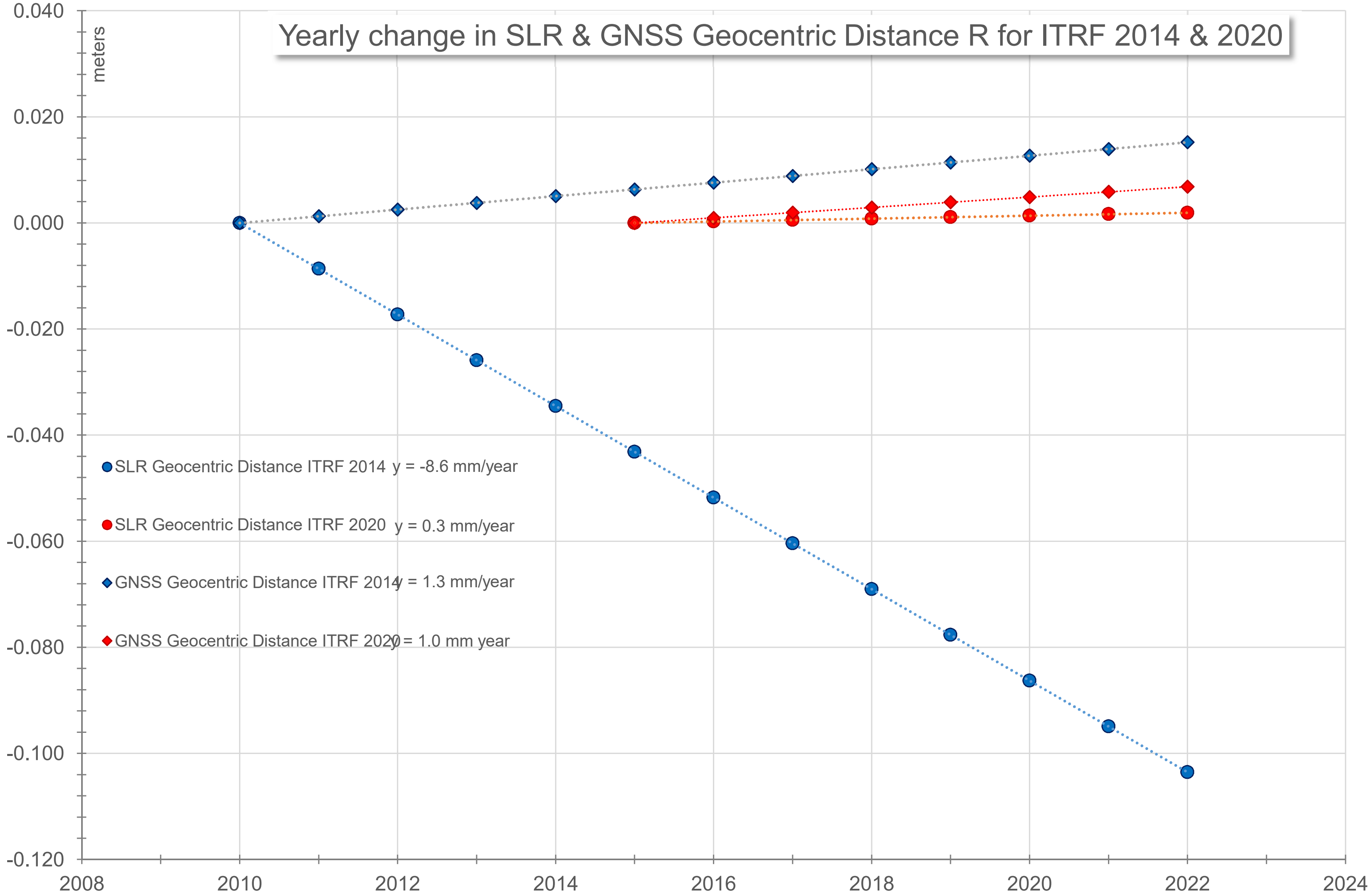
The ITRF problem: Otsubo plot 2012-2020



Modeling the ITRF solutions against local ties


Δh ≈ R_GNSS - R_SLR for ITRF 2014 & ITRF 2020
meters
3.600
3.580
3.560
3.540
3.520
3.500
3.480
3.460
3.440
3.420
3.400
3.380
3.360
3.340
3.320
2008
2010
2012
2014
2016
2018
2020
2022
2024
y = 9.9 mm / year
y = 0.7 mm / year
Delta h GNSS-SLR ITRF 2014
Delta h GNSS-SLR ITRF 2020
From Local Ties 2021
Local ties height difference value


Calculated Slope distance SLR-GNSS time evolution according to the ITRF solutions
y = 2.315 mm/year
y = 0.204 mm/year
Slope Distance ITRF 2014
Slope Distance ITRF 2020
Local Ties Solution 2021
Local Ties Solution 1996
Local ties 2021 slope distance = 20.215 ± 0.0038 m.
Local ties 1996 slope distance = 20.206 m
meters
20.2700
20.2600
20.2500
20.2400
20.2300
20.2200
20.2100
20.2000
2008
2010
2012
2014
2016
2018
2020
2022
2024


Yearly change in SLR & GNSS Geocentric Distance R for ITRF 2014 & 2020
meters
0.040
0.020
0.000
-0.020
-0.040
-0.060
-0.080
-0.100
-0.120
2008
2010
2012
2014
2016
2018
2020
2022
2024
SLR Geocentric Distance ITRF 2014 y = -8.6 mm/year
SLR Geocentric Distance ITRF 2020 y = 0.3 mm/year
GNSS Geocentric Distance ITRF 2014 y = 1.3 mm/year
GNSS Geocentric Distance ITRF 2020 y = 1.0 mm year


CAUTION
LASER
AREA
Thanks!