The Galileo for Science 2.0 Project: SLR Campaign and Project Status

Alessandro Di Marco

Istituto Nazionale di Astrofisica,
Istituto di Astrofisica e Planetologia Spaziali di Roma (INAF-IAPS), Roma

Gruppo di Gravitazione Sperimentale
Alessandro Di Marco, Feliciana Sapio, Massimo Visco, David Lucchesi, Marco Cinelli, Emiliano Fiorenza, Carlo Lefevre, Pasqualino Loffredo, Marco Lucente, Carmelo Magnafico, Roberto Peron, Francesco Santoli, and Francesco Vespe

23rd International Workshop on Laser Ranging - GGOS
Kunming, China 20 - 26 October 2024

SLR for Gravitation and Relativity Session

Table of contents

Galileo GNSS Mission

The Galileo mission dates back to 1999 to develop a GNSS[1] with the scope to make independent the EU from the GPS (USA) and GLONASS (RUS).
The Galileo system is characterized by the three standard segments:

- Space Segment (GSS): network of satellites;
- Ground Segment (GGS): ground control system, remote terrestrial stations;
- User Segment (GUS): user community.

The Space Segment provides:

- 30 satellites distributed on 3 plane orbits;
- medium Earth orbit (MEO), $h \sim 23200$ Km;
- lifetime ~ 12 years;
- **onboard atomic clock (AC): 2 Passive Hydrogen Maser (PHM) and 2 Rubidium (RAFS)**.

The preliminary phase known as **GIOVE mission**, designed to test the Galileo technology, dates back to the period 2005-2008 (GIOVE-A, GIOVE-B) while the **Full Operational Capability (FOC)** phase started in 2014.

[1] Global Navigation Satellite System

DORESA and MILENA Satellites

The FOC phase started with the launch of two satellites, *i.e.* GSAT0201 and GSAT0202 also known as DORESA and MILENA, respectively. They were injected into an incorrect orbit and

- expected inclination 55.0°, final inclination 49.8°.
- expected eccentricity 0.0 (circular), final eccentricity 0.23 (elliptical, useless for navigation).
- Recovery manoeuvres were applied in order to reduce the eccentricity to navigation purposes, $e \sim 0.156$.
- The final configuration allows investigations in the field of **fundamental physics** [see GREAT project: *P. Delva et al 2018*, *S.Herrmann et 2018*]

GSAT-0201 = E18 = Sat 5

GSAT-0202 = E14 = Sat 6

Figure: Official Logo on the ESA's rocket for DORESA and MILENA launch

Final Orbit - Equatorial plane

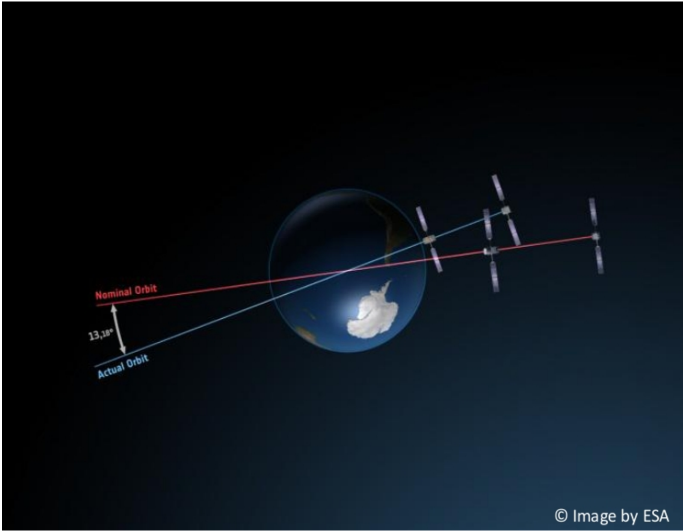


Figure: Current equatorial inclination compared to the designed one (ESA Credit)

Final Orbit - Orbit shape

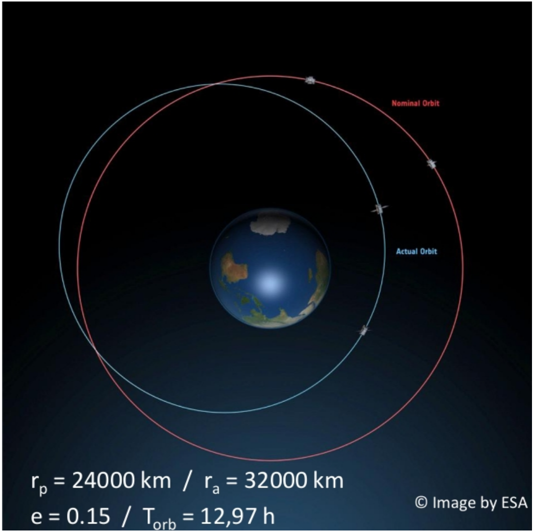


Figure: Current elliptic shape of the orbit compared to the designed one (ESA Credit)

G4S 2.0 - Overview

The Galileo for Science project (G4S 2.0) is funded by the Italian Space Agency (ASI) and started its activities on June 4, 2021.

1. Three **italian centers**
   - Center for Space Geodesy (ASI-CGS) in Matera;
   - Istituto di Astrofisica e Planetologia Spaziali (INAF-IAPS) in Rome;
   - Politecnico (POLITO) in Turin
2. The **nominal duration** of the project was three years (from 06/2021 to 06/2024), but it has recently been extended until the end of 2026
3. The project aims to use the Galileo GNSS to face a series of challenges from **fundamental physics measurements to tech-developments**

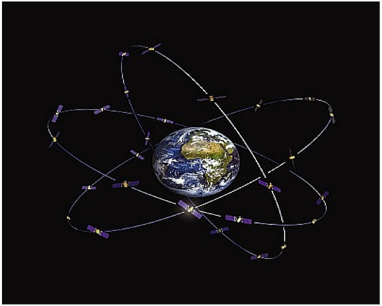


Figure: The Galileo GNSS allows to explore several fundamental physics questions (image credit: ESA)

G4S 2.0 - Main Goals

The G4S project aims to address a series of challenges:

1. Develop new and more accurate models for:
    - The Non Gravitational Perturbations (NGPs) acting on the satellite spacecraft, *e.g* Solar Radiation Pressure (for details: Dr. D.M.Lucchesi)
    - The spacecraft itself, *i.e.* Box-Wing model and Finite Element Model (for details: C.Lefevre, D.M.Lucchesi)

    In principle, this ensures to get high quality *orbit* results, *i.e* robust **Precise Orbit Determination (POD) and atomic clocks data**.

2. New measurements in the context of fundamental physics, i.e.:
    - measurement of the Gravitational Redshift - via satellites 5 and 6;
    - measurement of the General Relativity precessions (and deviations from Newton inverse-square law) - via satellites 5 and 6;
    - constraints on the Dark Matter (DM) content in the Milky Way - via all constellation satellites;

3. Develop new technologies:
    - realize a pure Relativistic Positioning System (RPS) (reverse use);
    - develop a new accelerometer concept for the next generation of Galileo satellites.

G4S Campaign - Motivation

How can we properly complete this recipe and get our fundamental physics goals?

- Surely, we need to apply our models (NGPs and spacecraft) to a set of Galilelo satellites orbit observations, see *F.Sapio et al. 2024, D.Lucchesi 2024*,
- In principle, one could require to access data of other campaign, *i.e.* the **GREAT** project or more recently, **GASTON** Project.
- However, in order to achieve the ambitious goals of the project, **we requested to the International Laser Ranging Service (ILRS) a dedicated SLR Campaign** to increase the number of NPs of the Galileo satellites

This new campaign would allow to improve the **number of normal points (NPs)** for the (requested) Galileo satellites. As a result we can

- Get a better characterization of the satellites trajectory during the so called **penumbra transitions**, *i.e* light-shadow and shadow-light passages
- Get a better determination of the satellites **spacecraft attitude**
- Get a very improved POD results and atomic clocks data, so to **reduce the systematic errors** in the measurements we want to perform.

Campaign details:

- It started on January 20, 2024 and it will last 2 years for elliptic satellites and 3 months (+3 months) for circular ones.
- G4S 2.0 SLR campaign website (Dr.Carmelo Magnafico) : `https://g4s-duepuntozero.iaps.inaf.it/`

What is the **current structure of the campaign**?

G4S Campaign - State of the art I

Galileo satellites: 3 IOV (bold) and 11 FOC

1. Satellites in elliptical orbits: GSAT0201 (E18), GSAT0202 (E14)
2. Satellites in nominal orbits:
    - Orbital Plane A: GSAT210 (E01), GSAT206 (E30), GSAT205 (E24), GSAT211 (E02)
    - Orbital plane B: **GSAT0101 (E11)**, **GSAT0102 (E12)**, GSAT0221 (E15), GSAT0203 (E26)
    - Orbital plane C: GSAT0209 (E09), GSAT0208 (E08), **GSAT0103 (E19)**, GSAT0212 (E03)
3. GSAT102, GSAT209 and GSAT210 are the most tracked!

Let us see a report (Dr.D.M. Lucchesi) for the **first 6 months** of campaign considering 15 **stations** and the two **satellites GSAT0201 and GSAT0202 as examples**.

16 ILRS Stations:

- 7237 Changchun
- 7090 Yarragadee
- 8834 Wettzell
- 7845 Grasse
- 7839 Graz
- 7821 Shangai
- 7396 Wuhan
- 7819 Kunming
- 7810 Zimmerwald
- 7840 Hertsmonceux
- 7825 Mt. Stromlo
- 7249 Beijing
- 7841 Postdam
- 7941 Matera
- 7105 Greenbalt
- 7701 Izana

G4S Campaign - State of the art II

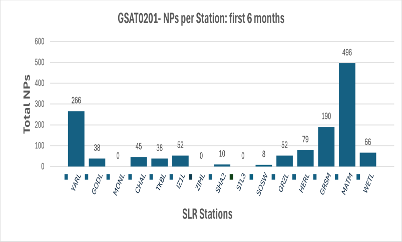
Preliminary analysis performed with Geodyn II software (D.M.Lucchesi, Roberto Peron) using GREAT obs data, have shown that **at least 10 NPs** per day are required to obtain a reliable and sufficiently robust POD **for a given satellite**. As a consequence

- The **expected NPs** on 6 months$\sim$186 days should be $\sim$ 1860...
- so the **required, average number of NPs for a given station should be** $\sim$ 124...
- or a minimum of $\sim$ 5 **NPs per week!**

Currently we count

- NPs of GSAT0201 : 1340
- NPs of GSAT0202 : 1391

In particular, 3 Stations have reached the minimum number of NPs for GSAT0201 and 4 Stations for GSAT0202! Let us see in details the evolution per **each weeks**...



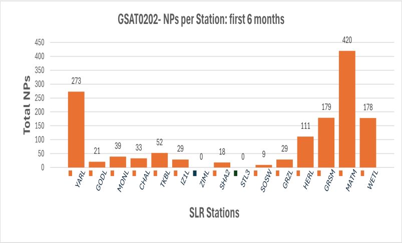
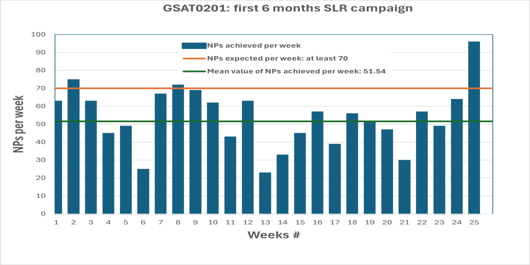


Figure: Summary for GSAT0201 and GSAT0202

G4S Campaign - State of the art III



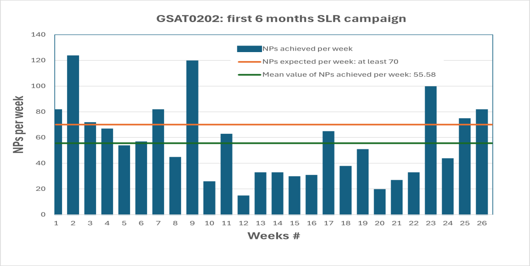


Figure: Details for all the weeks: most of the time we are below the threshold

G4S Campaign - State of the art IV

For each station we expect at least 5 NPs per week. However, only three stations have satisfied this requirement

- Matera : GSAT0201 mean value per week $\sim$ 19.08, GSAT0202 mean value per week $\sim$ 16.15
- Grasse : GSAT0201 mean value per week $\sim$ 7.31, GSAT0202 mean value per week $\sim$ 6.88
- Yarragadee : GSAT0201 mean value per week $\sim$ 10.23, GSAT0202 mean value per week $\sim$ 10.05

We will soon present the details of this analysis to the ILRS Central Bureau to try to increase, if possible, the number of NPs by some Stations. As we have shown, in the case of 15 stations an average of 5 NPs-Station-week is sufficient for the objectives of G4S 2.0.

Figure: Matera has provided the most relevant contribution to the G4S campaign so far!

Dark matter and domain walls

- The *dark matter* is a mysterious form of matter that has been introduced to *catch* a large number of *astronomical and cosmological observations*
- The most known realization is given by specific particles called Weakly Interacting Massive Particles (WIMP) but...no convincing detection up to now!
- It has been proposed that *extended and almost* 2-dimensional **(ultralight) scalar field Domain Walls (DW)** could represent a **detectable** fraction of the galactic DM[2]
- These objects can assume a planar geometry and are characterized by a scalar field that varies along the finite, transverse size. They are just the "cosmological version" of the domain walls comparing in the **physics of ferromagnets**. Here fundamental quantity is a scalar field ϕ instead of the (orientation of) magnetic moments.
- If a Domain wall interacts with a GNSS atomic clock, it induces a frequency variation with respect the nominal one ν_0, that depends on microphysics and macrophysics

  $$\frac{\Delta\nu}{\nu_0} = \frac{\Delta\nu}{\nu_0}(\text{Particle phyics parameters}, \text{Astrophyisical parameters}) \qquad (1)$$

  In some cases, it has been shown the variation will provide a **time localized spike[3] in the derivative of the clock bias, *i.e.* the standard GNSS clock data.**
- What does happen if a DW interacts with a network of GNSS (satellites and station) clocks?

[2] *A.Derevianko and M.Pospelov 2014*, *P.Wcislo et al.2016*, *B.M.Roberts et al. 2017*, *B.M.Roberts et al. 2018*, *B.Bertrand et al. 2024* (ESA-GASTON)

[3] *B.M.Roberts et al. 2017*

Clock bias and domain wall spike II

In this context, it is possible to show that the DW will provide a **general pattern for the timeseries derivative of the clocks data**. In particular:

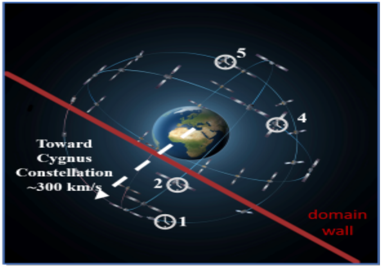
- a common **negative** spike in coincidence in all the considered clocks, *i.e* **trigger event** (interaction with the ground clock).
- a cloud of **positive** spikes around the trigger (interaction with the clocks);
- Simple estimation of the bias derivate spike (*A.Derevianko and M.Pospelov 2014*, *B.M.Roberts et al. 2017*):

$$S^{(1)}_{\text{avg}} \simeq \Gamma_{\text{eff}} \rho_{\text{DW}} d^2 T \qquad (2)$$

How many encounters? Model dependent!

T (years)	Λ_{eff} (GeV)	S_{avg} (ns)
10	10^{10}	2.5×10^{-1}
15	2×10^{10}	9.3×10^{-2}
20	3×10^{10}	5.5×10^{-2}

Here $\rho_{\text{DW}} \sim 0.4$ GeV/cm^3, DW size $d \sim 10^3$ km and $\Lambda_{\text{eff}} = 1/\sqrt{\Gamma_{\text{eff}}}$ (DW-clock interaction strenght.)



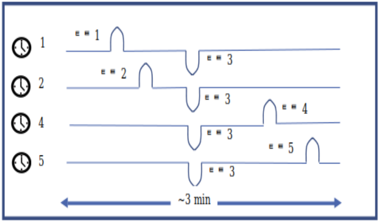


Figure: Schematic DW-clocks interaction example.

Clock network properties II

The first method to catch DW patterns has been proposed by *Roberts et al 2017*.

- Currently, does not exist any characterization of the clock network;
- a reliable characterization of the clock network turns out to be crucial in order to statistically describe the likelihood of an observed pattern.

Galileo 4 science project 2.0: we have cleaned six bias timeseries[4] (sampling time $\tau \sim 30$ s), we have computed the corresponding timeseries of the bias derivative and then performed

- a **false alarm analysis**: to study the occurrence of **accidental** negative spikes or trigger events in the data, above some thresholds;
- a development of a MATLAB code to simulate **DW dynamics across the constellation** (F.Sapio, M.Visco);
- a **detection efficiency analysis**: test of the network capability to exhibit injected (trigger) events, above some thresholds.

The detection efficiency has been realized by

- assuming DW couples only to the electron field, so that PHM and RAFS show the same frequency response;
- simulating $k \sim 10^4$ DW events over the real data and $A \sim 10^{-10}$ seconds.

[4] Data source: online archive, courtesy of L.Mendes

Clock network properties IV - False alarm

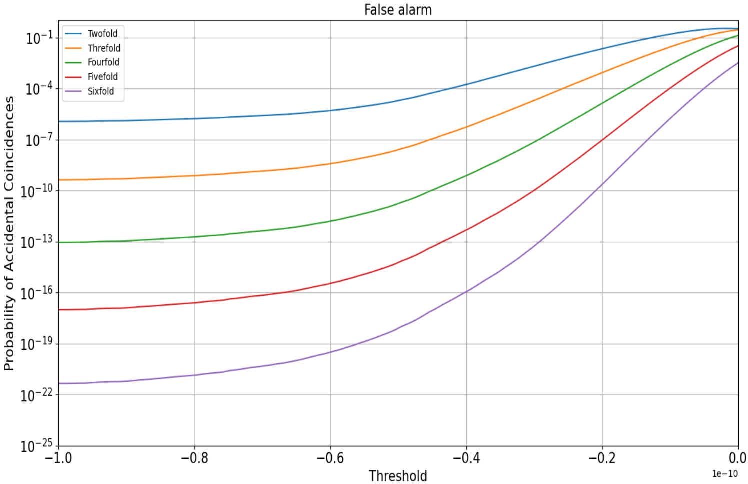


Figure: False alarm curves. The probability to find a sixfold coincidence above a large threshold is almost negligible.

Clock network properties V - Detection efficiency

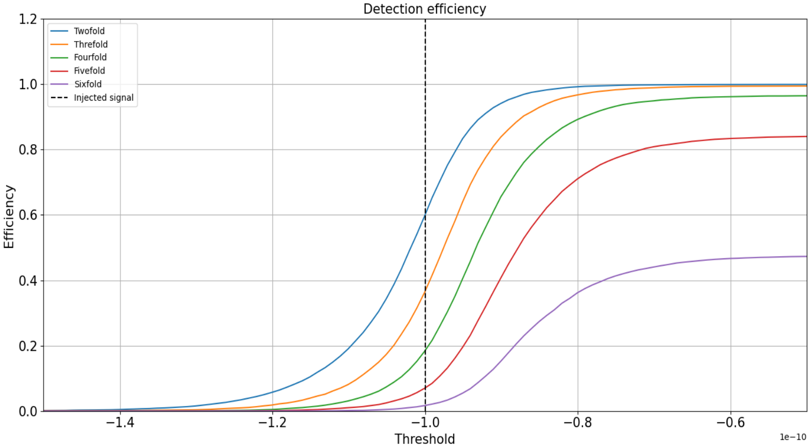


Figure: Detection efficiency curves for $k \sim 10^4$ events with $A \sim -10^{-10}$ s. As the number of clocks becomes 6, the probability that a DW hits the ground clock and a satellite one (within 30 s) gets larger and the sixfold is missing.

Conclusions and prospects

The G4S 2.0 project is essentially based on two fundamental pillars or aspects

- The development of NPG and spacecraft models
- The SLR campaign

These activities are crucial in order to have

- Robust and high quality POD data and
- Clock solutions

and so to perform fundamental physics measurement with low impact of systematic errors and also improve current preliminary results like the impact of the background noise for searching Domain Walls. Currently we have

- the probability that a large number of clock (> 6) exhibit **accidental large values** ($|A| < 0.2 \times 10^{-10}$ s) is very low ($P < 10^{-10}$);
- the probability for a **six-clock trigger event** should be affected by the GNSS setup and the adopted sampling time of 30 s.

These studies have been realized using the current available (online) clock solutions. **We expect to improve them via our SLR Campaign!**

Thank you for the attention!

Bibliography

- D. Lucchesi et al. "Fundamental physics measurements with Galileo FOC satellites and the Galileo for science project. I. A 3D-CAD and a box wing for modeling the effects of nonconservative forces," Phys. Rev. D **109**, no.6, 062004 (2024)
- F. Sapio, et al. "Fundamental physics measurements with Galileo FOC satellites and the Galileo for science project. II. A box wing for modeling direct solar radiation pressure and preliminaries orbit determinations," Phys. Rev. D **109**, no.6, 062005 (2024)
- P. Delva et al. "Gravitational Redshift Test Using Eccentric Galileo Satellites," Phys. Rev. Lett. **121**, no.23, 231101 (2018) [arXiv:1812.03711 [gr-qc]].
- S. Herrmann et. "Test of the Gravitational Redshift with Galileo Satellites in an Eccentric Orbit," Phys. Rev. Lett. **121**, 231102 (2018) [arXiv:1812.09161 [gr-qc]].
- A. Derevianko and M. Pospelov, "Hunting for topological dark matter with atomic clocks," Nature Phys. **10**, 933 (2014) [arXiv:1311.1244 [physics.atom-ph]].
- P.Wcislo, et al. "Experimental constraint on dark matter detection with optical atomic clocks," Nature Astronomy, 2397-3366, 0009 (2017)
- B. M. Roberts et al. "Search for domain wall dark matter with atomic clocks on board global positioning system satellites," Nature Commun. **8**, no.1, 1195 (2017) [arXiv:1704.06844 [hep-ph]].
- B. M. Roberts et al. "Search for transient ultralight dark matter signatures with networks of precision measurement devices using a Bayesian statistics method," Phys. Rev. D **97**, no.8, 083009 (2018) [arXiv:1803.10264 [astro-ph.IM]].
- B. Bertrand et al. "Searching for large dark matter clumps using the Galileo Satnav clock variations," [arXiv:2403.17890 [astro-ph.CO]].

BackUp I - Non Gravitational Perturbations and Spacecraft models

The Precise Orbit Determination recipe and the related optimal results depend on two fundamental points

- A good model for the NGP, in particular the **Solar Radiation Pressure (SRP)**, that represents the largest NGP for the Galileo satellites and in general, all navigation satellites $\sim 10^{-7} \mathrm{m/s}^2$
- A good characterization of the spacecraft and the attitude law

As part of the G4S 2.0 activities **we have developed** two models for the management of the NGPs and in particular the SRP, acting on a Galileo FOC spacecraft:

- A **Box-Wing (BW)** model based mainly on the information provided in the ESA metadata on the main characteristics of the Galileo FOC satellites
- A **3D-CAD model** to be used as a basis for a **Finite Element Model (FEM)** to be physically characterized at a higher level of sophistication than the BW and to be used for the application of the Raytracing technique.

The details of these models and the relative and preliminary studies related to the modeling of nonconservative forces can be found in

- D. Lucchesi *et al.* "Fundamental physics measurements with Galileo FOC satellites and the Galileo for science project. I. A 3D-CAD and a box wing for modeling the effects of nonconservative forces," Phys. Rev. D **109**, no.6, 062004 (2024)
- F. Sapio *et al.* "Fundamental physics measurements with Galileo FOC satellites and the Galileo for science project. II. A box wing for modeling direct solar radiation pressure and preliminaries orbit determinations," Phys. Rev. D **109**, no.6, 062005 (2024)

BackUp II - Preliminary Precise Orbit Determination

We performed some preliminary analyses with GEODYN II to test some performances of the POD, as the **state-vector convergence**, in relation to the number of NPs available. Three Galileo FOC satellites were considered over a time span of several years in order to also include the period of the analysis carried out by GREAT

- GSAT0201 and GSAT0202, in elliptical orbit: $\sim$ 8 years
- GSAT0208, in nominal orbit $\sim$ 7 years

We realized two POD, both with a simplified **cannonball** model for the spacecraft

- POD 1 : Empirical acceleration + modeled GR effects
- POD 2 : No Empirical acceleration + GR not modeled

The GREAT campaign provided an improved number of normal points and this trigger a **convergence of the state vector**.