Fundamental Physics with the Galileo Constellation: the Galileo for Science Project

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Abstract

The project The Galileo for Science Project (G4S_2.0) is an Italian Project funded by the Italian Space Agency (ASI) that aims to provide Fundamental Physics measurements with the Galileo-FOC constellation. These concern both the analysis of atomic-clocks data and that of satellite orbits.

Main goals A new accurate analysis of the satellites onboard atomic-clocks can lead to two significant results: i) measuring the gravitational redshift and, consequently, making a local position invariance (LPI) test, and ii) searching for possible Dark Matter Domain-Wall of Galactic origin. Conversely, precise orbit determination (POD) of satellites allows the relativistic precessions of satellite orbits to be measured at a much higher altitude than previous measurements with passive geodetic satellites.

A focus on the Fundamental Physics measurements The two satellites E14 and E18 in elliptical orbits will be exploited for the measurement of the gravitational redshift, as the onboard atomic clocks frequency is periodic-modulated with respect to on-ground clocks. Whereas for the Dark Matter constraints, the entire Galileo constellation will be considered: the goal is searching for interactions with possible Dark Matter candidates, such as Domain Wall, that would cross the whole constellation. If this happens, on-board clocks would impulsively change their frequency relative to a reference clock on Earth. Finally, measuring the relativistic precessions will allow to study possible deviations from General Relativity and to compare its prediction with those of other theories of gravitation.

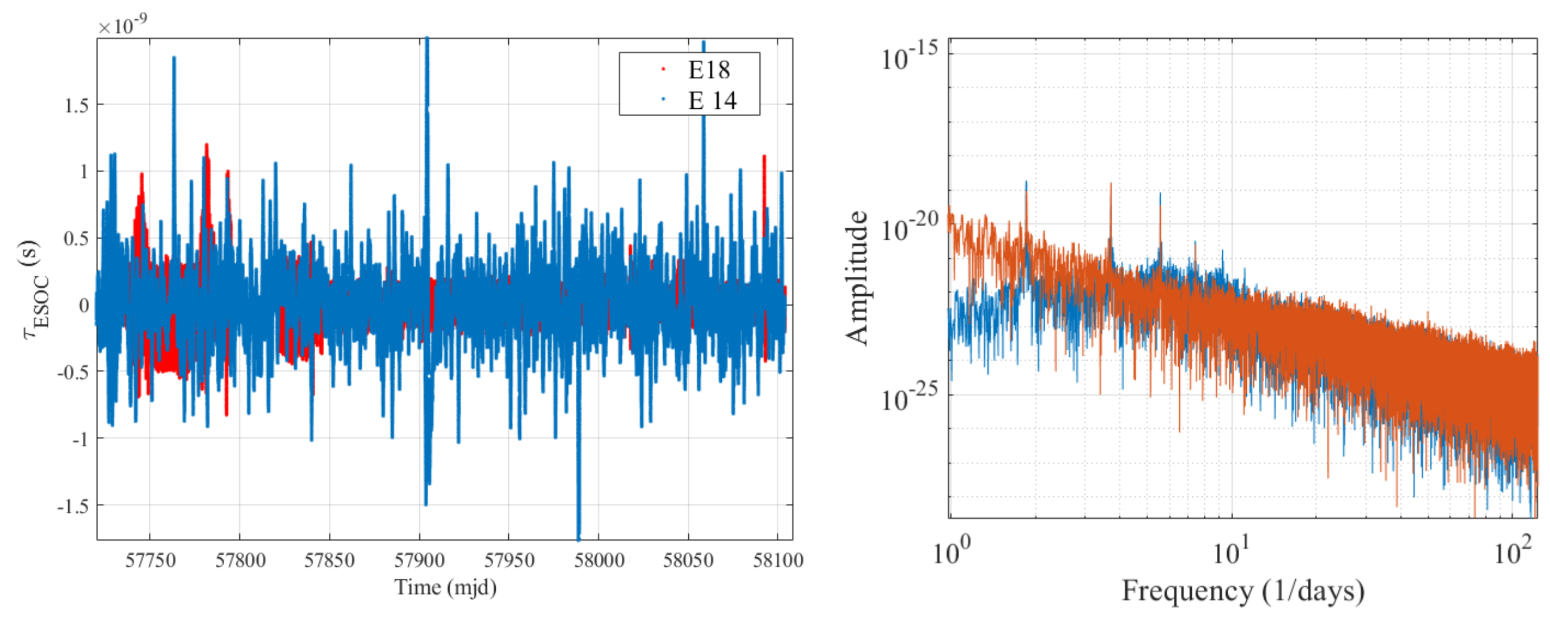
Methods To pursue the goals of G4S_2.0, a fundamental key point in our analysis is obtaining the satellite's position as a product of the POD. Consequently, modeling as better as possible the complex effects of the Non-Gravitational Perturbations (NGPs), such as the direct solar radiation pressure (SRP), is essential. Many of our efforts go in this direction. The state of the art will be presented, both as regards the measurements of Fundamental Physics and the development of new models for NGPs.

Gravitational redshift

The E14 and E18 orbits are characterized by a relatively high eccentricity (about 0.16) suitable for gravitational measurements. In particular, as the gravitational potential changes along the orbit, these satellites can be exploited to measure the gravitational redshift (GRS).

The GRS represents a Local Position Invariance Test (LPI) which is one of the ingredients of Einstein Equivalence Principle. To this purpose, an α parameter is introduced and it is non-zero in the case of LPI violation: $\mathcal{Z} = (1+\alpha)\frac{\Delta U}{c^2}$

The α parameter can be constrained from the time series of clock bias, i.e the difference in the time reading between the satellite and the terrestrial reference clock in a given sample time.



The resulting signal after the cleaning procedure of clock-data (on the left) and its spectrum (on the right). The peaks are related to the orbital frequency and its harmonics.

The clock-bias is a product of the POD. Its comparison with GR predictions can allow us to constrain α.

$$\tau_{GR} = \int \frac{d\tau}{dt}dt = \int \left[1 - \frac{v^2}{2c^2} - \frac{U_S}{c^2}\right]dt$$

$$\tau_{corr} = \tau_{ESOC} + \tau_{Kepler} - \tau_{GR}$$

$$\tau_{Kepler} = -\frac{2\boldsymbol{x}\cdot\boldsymbol{v}}{c^2}$$

Relativistic precessions

- **Schwarzschild precession or Einstein precession** (gravitoelectric field) → secular effect on ω
- **Lense-Thirring precession** (gravitomagnetic field) → secular effects on ω and Ω
- **De Sitter precession or geodetic precession** → secular effect on Ω

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

$$\dot{\Omega}^{LT} = \frac{2\,GJ_\oplus}{c^2\,a^3(1-e^2)^{3/2}}$$

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

Rate (mas/yr)	E18	E08	LAGEOS II
$\dot{\omega}^{Ein}$	+428.63	+362.72	+3351.95
$\dot{\omega}^{LT}$	–5.15	–3.77	–57.33
$\dot{\Omega}^{LT}$	+2.39	+2.18	+31.51
$\dot{\Omega}^{dS}$	+17.64	+17.64	+17.64

We intend to extract the relativistic precessions from the analysis of the orbit residuals using a refined POD for E14 and E18. Because of the small relativistic effects and of the larger non-gravitational perturbations, these measurements are very challenging in the case of Galileo satellites.

References

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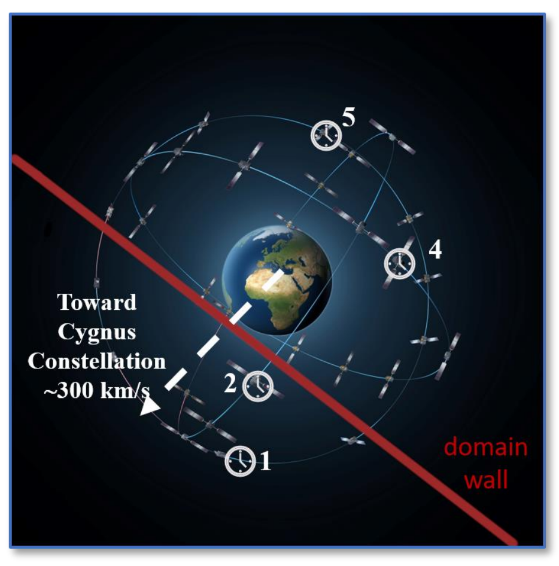
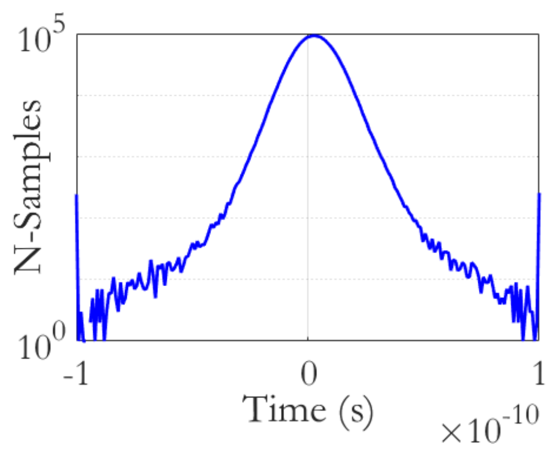
Searching for Domain-Wall Dark Matter

The Galileo-FOC constellation can be used to search for possible Dark Matter (DM) candidates such as Domain-Walls (DW). These macroscopic objects would arise from ultra-light scalar fields predicted from theories beyond the Standard Model. Such exotic objects could represent a fraction of DM in the Universe.



Domain Wall crossing on the Galileo-FOC constellation.

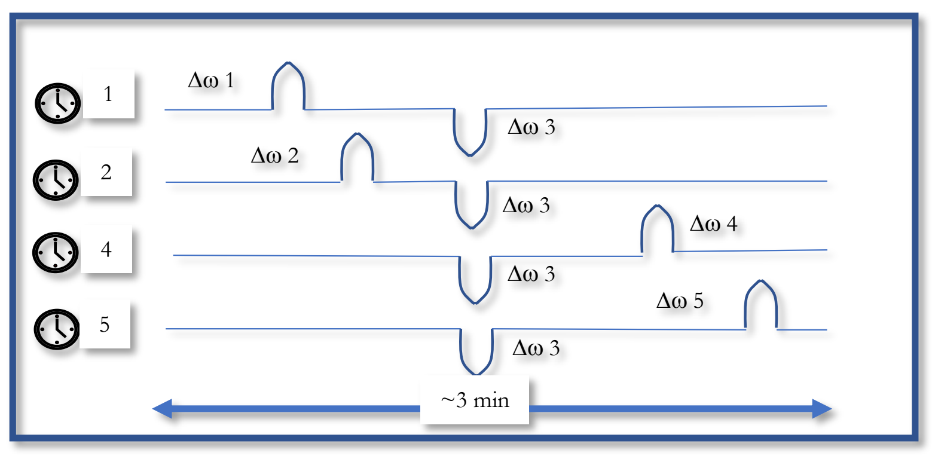


Example of distribution of the discrete derivative of the clock-bias (satellite E08).

When a DW interacts with the atomic clocks of a satellite, a transient shift in frequency, $\delta\omega/\omega_0$, appears due to a transient variation in the physical constant X with a coupling factor K_X

$$\frac{\delta\omega(r,t)}{\omega_0} = \sum_X K_X \frac{\delta X}{X} \qquad \text{with X} = \begin{cases} \alpha \\ m_e, m_p \\ m_q/\Lambda_{QCD} \end{cases}$$

We expect a sequence of delta-like signals in clocks-data as the DW propagates across the whole satellite constellation, and negative delta-like signals in coincidence in all the satellites clocks when the reference clock on the Earth is invested by the DW.



We intend to perform an analysis in two steps:
- looking for time-coincidences in signals of all the clocks when the reference clock is invested (trigger event).
- looking for signals of the singles clocks within a time-window around the trigger.

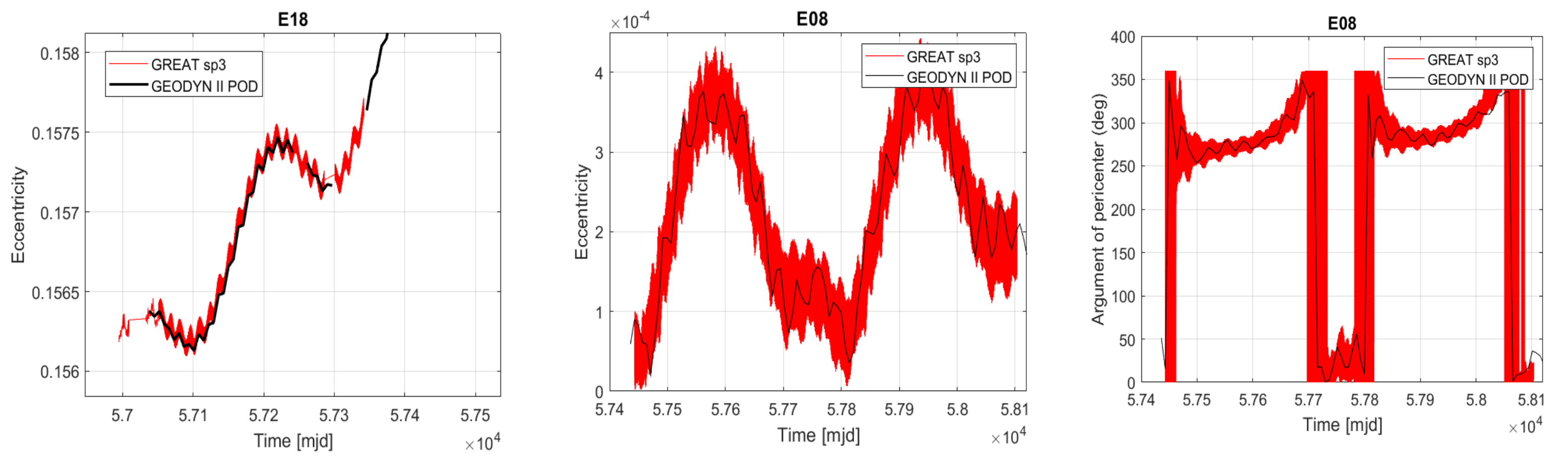
Dynamic model

A key aspect, to attain such measurements in the field of Fundamental Physics, is to perform an accurate POD to derive the satellite orbit. This can be achieved by enhancing the dynamic model, implemented in the POD, for the non-conservative forces acting on the Galileo-FOC satellites.

Physical effects	*Formula*	*LAGEOS II (m/s²)*	*Galileo FOC (m/s²)*
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	$2\frac{A}{M}\frac{\Phi_\odot}{c}A_\oplus\frac{\pi R^2_\oplus}{4\pi r^2}$	1.3×10^{-10}	7.0×10^{-10}
Earth's infrared radiation	$\frac{A}{M}\frac{\Phi_{IR}}{c}\frac{R^2_\oplus}{r^2}$	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	$\frac{1}{4}\frac{A}{M}\frac{\Phi_\odot}{c}\frac{R^2_\oplus}{r^2}\frac{v}{c}$	4.2×10^{-15}	1.9×10^{-14}

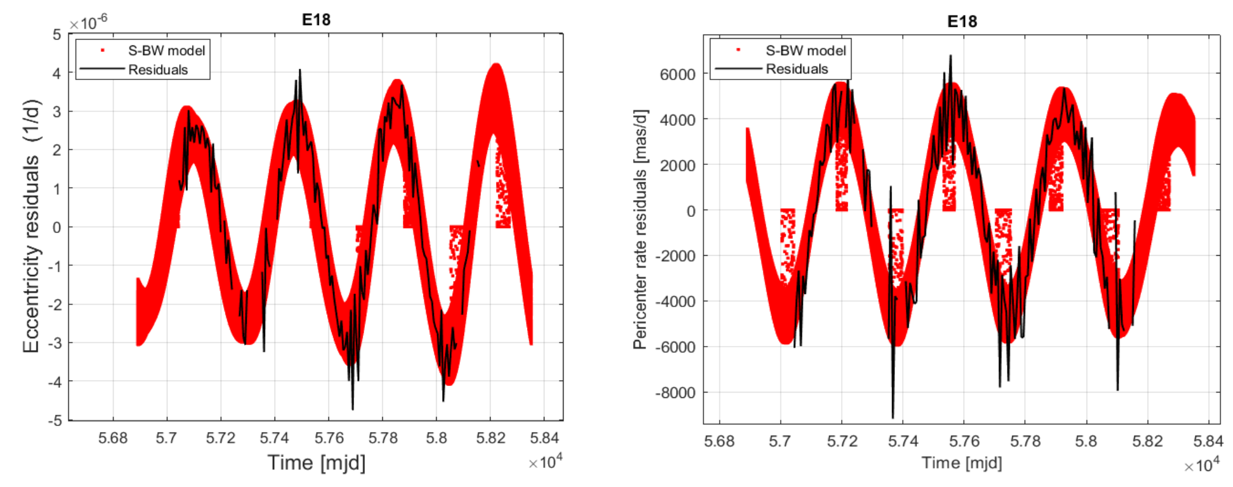
The table shows the value of the monopole acceleration of the Galileo-FOC satellites with the values of the main non-gravitational accelerations. For comparison are shown the corresponding accelerations of the LAGEOS II, one of the best tracked geodetic satellites and successfully used for Fundamental Physics measurements.

We studied the long-term evolution of the keplerian elements of E18 and E08 by performing a preliminary POD with the software GEODYN II with a cannonball model for the satellite.



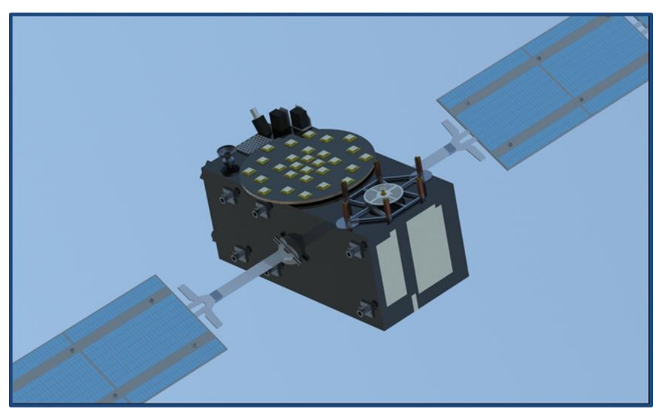
Comparison between our GEODYN II POD (black) and GREAT sp3 precise orbit (red): long-term evolution of the eccentricity of the satellites E18 and E08 and of the argument of pericenter of E08.

We developed a Box-Wing (BW) model of the satellite based on ESA Galileo Metadata. The corresponding perturbing accelerations will be used in the POD to improve the satellite orbit reconstruction. Then, we performed a POD without empirical accelerations and we compared its orbit residuals with the predictions of our BW model.

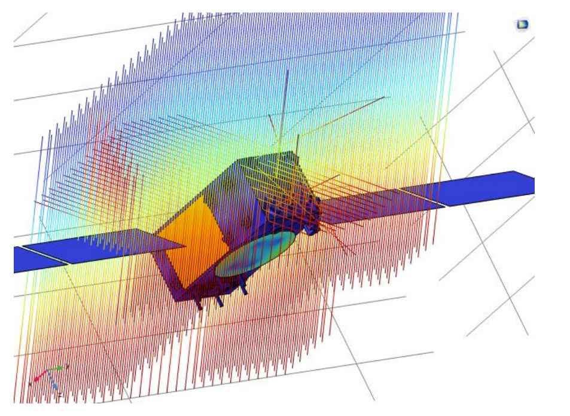


Comparison of the eccentricity and the argument of pericenter residuals with the corresponding prediction of the BW model on a 4 years timespan. This model is able to explain the annual oscillation due to the non-optimal modeling of direct solar radiation pressure in the residuals.

The final purpose is to best characterize the various elements of the Galileo spacecraft and to apply the so-called Ray Tracing technique. This will allow to improve the modeling of the NGPs, first of all the SRP, by taking into account umbra and penumbra effects as well as multiple reflections.



We built a sophisticated 3D-CAD model (on the left) and we started the application of the Ray-Tracing technique on it.



We plan to build more sophisticated Box-Wing and FEM models as we receive from ESA more detailed information on the attitude, thermal, and optical properties of the Galileo-FOC satellites.