Fundamental Physics with GNSS satellites and the Galileo for Science Project

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Summary

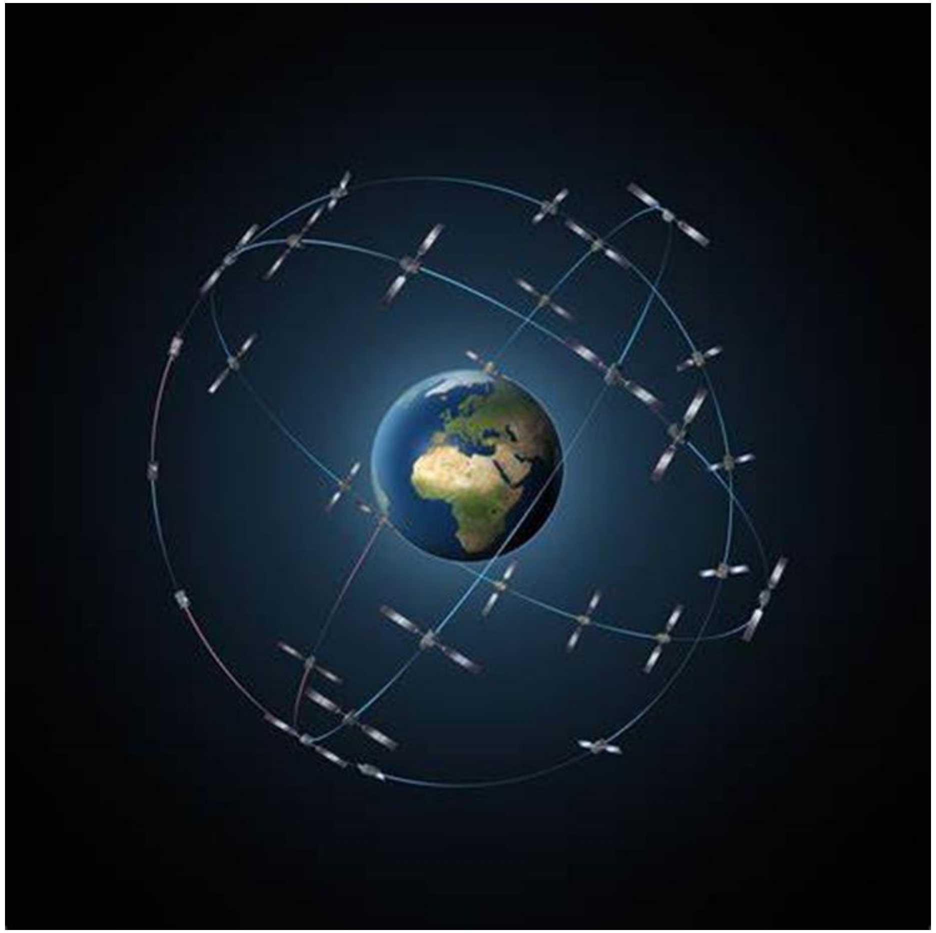
- Introduction to the Galileo for Science Project
- Fundamental Physics measurements
  - Gravitational redshift
  - Relativistic precessions
  - Constraints on galactic Dark Matter
- Data analysis scheme
- The role of the Precise Orbit Determination and dynamical model
- First results
- Conclusions

The Galileo FOC satellites

In August 2014, the **GSAT-0201** and **GSAT-0202** satellites of the European global navigation system Galileo were launched.

They were accidentally injected into wrong orbits of high eccentricity ($e \cong 0.23$), useless for navigation services. Subsequently, the orbits were corrected ($e \cong 0.16$).

However, the incident offered a rare opportunity to perform **Fundamental Physics experiments**.



Artistic representation of the Galileo FOC constellation with 30 satellites. Credits: ESA.

The Galileo for Science Project in a nutshell

Three research centers are involved in this project

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

High level goals of the project

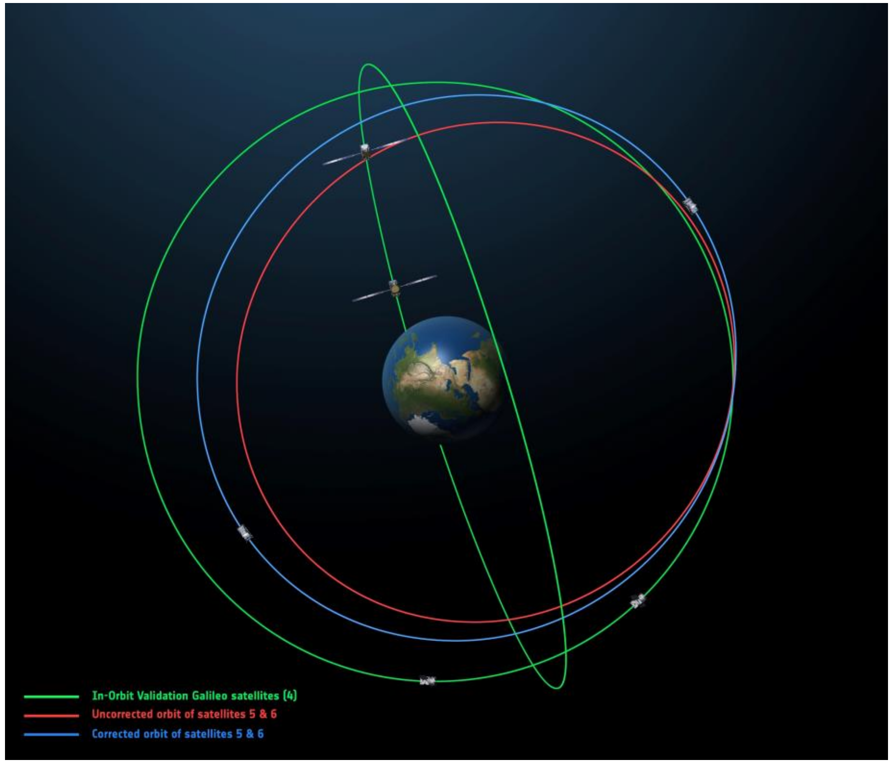
1. A new measurement of the **Gravitational Redshift**
2. A measurement of the **General Relativity precessions** on the orbits of GSAT-0201 and GSAT-0202 satellites
3. Constraints on (local galactic) **Dark Matter**
4. Realizing (in a reverse use) a pure **Relativistic Positioning System**
5. Developing a new **Accelerometer concept** for next generation of Galileo satellites

Fundamental Physics measurements
Gravitational redshift

The GSAT-0201 and GSAT-0202 satellites orbits are characterized by a relatively high eccentricity ($e \cong 0.16$) 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) via relative frequency variation:

$$\mathcal{Z} = \frac{\Delta\nu}{\nu} = \frac{\Delta U}{c^2}$$



The figure shows the wrong orbits in which the GSAT-0201 and GSAT-0202 satellites were injected (in red) and the corrected one (in blue). The green curve is the orbit of the previous generation of Galileo satellites. Credits: ESA.

Fundamental Physics measurements
Relativistic precessions

- **Schwarzschild precession** (Gravitoelectric field) *A. Einstein, Ann. Phys. (Berlin, Ger.) 354, 769 (1916)*
- **Lense-Thirring precession** (Gravitomagnetic field) *Lense, J.; Thirring, H. Phys. Z. (1918), 19, 156*
- **Geodetic precessions** (or De Sitter precession) *De Sitter, W. Mon. Not. R. Astron. Soc. (1916), 76, 699–728*

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

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

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

Cosmology
Constraints on Dark Matter

A fraction of Dark Matter (DM) in the Universe could be represented by Domain Walls (DW). These objects could arise, for instance, from ultra-light scalar fields predicted from theories beyond the Standard Model of particle Physics.

Such structures could cross Earth's orbit and Galileo constellation. The interaction of DW scalar field with a satellite atomic-clock generates a frequency **perturbation**.

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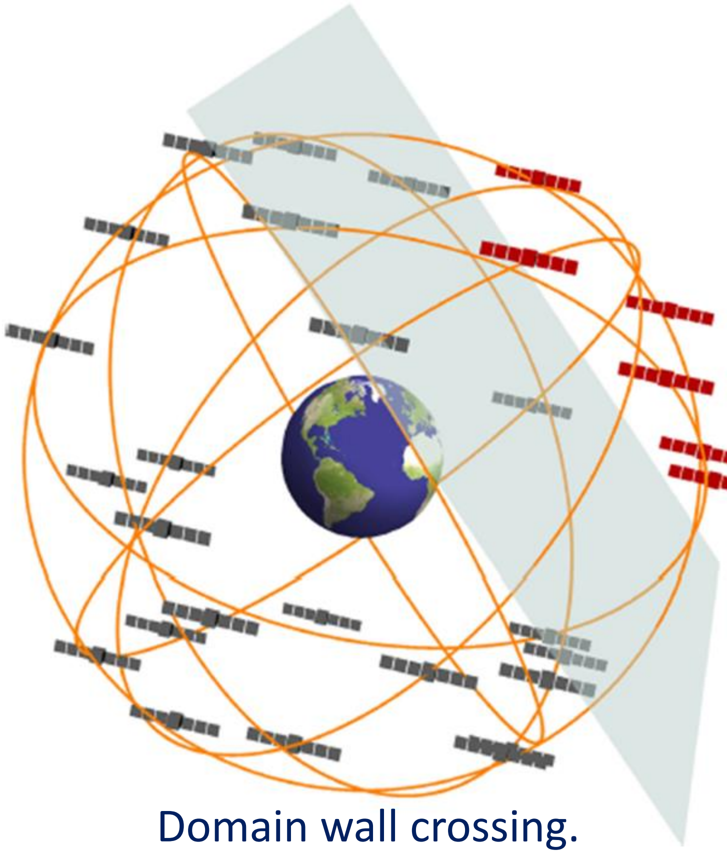
Our goal is searching for a succession of such glitches through the Galileo onboard atomic-clocks network.



Domain wall crossing.
Credits: Roberts et al., 2017

Data analysis scheme

Our **clock-data**: time-series of the difference between the time measured by the on-board clocks and the time measured by a clock on Earth (clock-bias).

Step 1: identification of «homogeneous» periods to process data.
Step 2: data cleaning procedure removing long-trend effects and daily rephasing.

Gravitational redshift measurement

- Satellites DORESA and MILENA
- Frequency analysis at orbital period
- Model for the redshift parameter α_{GRS}
- Study of systematic effects
- Further improvement of the precise orbit determination (POD)

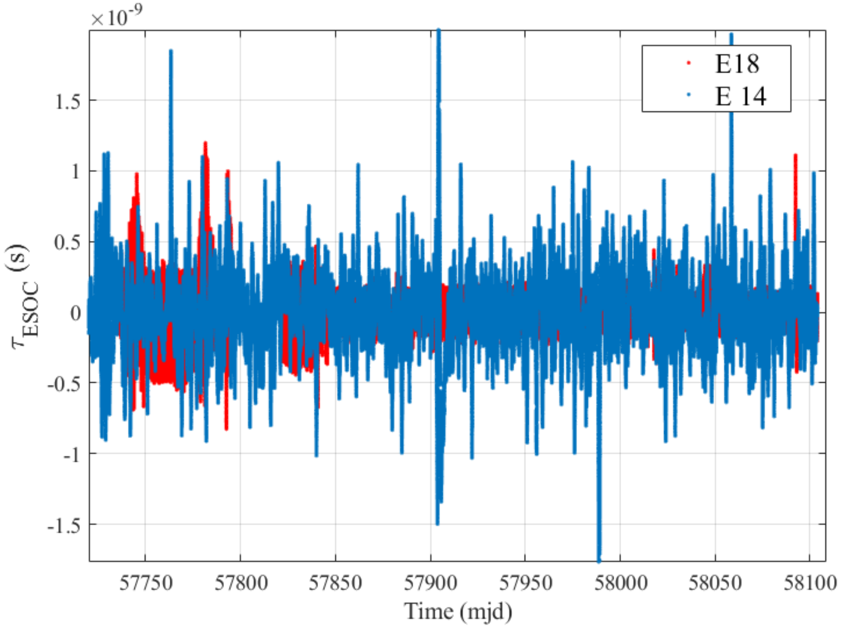
Dark Matter constraints

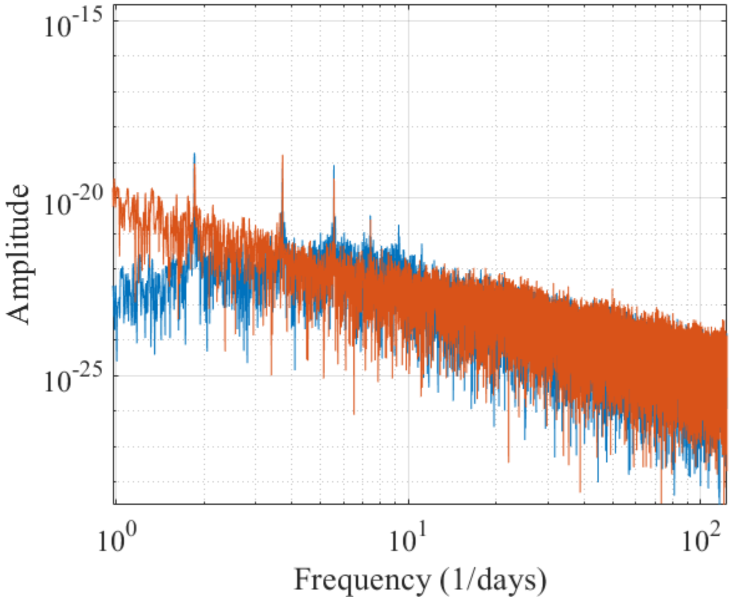
- Dark Matter model
- All the Galileo constellation
- Searching for δ-like signal in clocks-data
- Events simulation
- Pipeline for data selection
- Study of the background events

Data analysis
Gravitational redshift

The GRS represents a **Local Position Invariance Test** which is one of the ingredients of the Einstein Equivalence Principle. The deviation from General Relativity (GR) prediction is parameterized by

$\mathcal{Z} = (1 + \alpha_{GRS})\frac{\Delta U}{c^2}$. The α_{GRS} parameter can be constrained from the time series of the **clock-bias**.





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.

Data analysis
Gravitational redshift

The clock-bias (τ_{ESOC}) is a product of the Precise Orbit Determination. Its comparison with GR predictions can allow us to constrain α_{GRS}.

The "corrected" clock bias is calculated as

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

- τ_{corr}: Corrected raw clock bias
- τ_{ESOC}: Raw clock-bias from the ESA-ESOC POD
- τ_{Kepler}: Relativistic correction
- τ_{GR}: Proper time from General Relativity

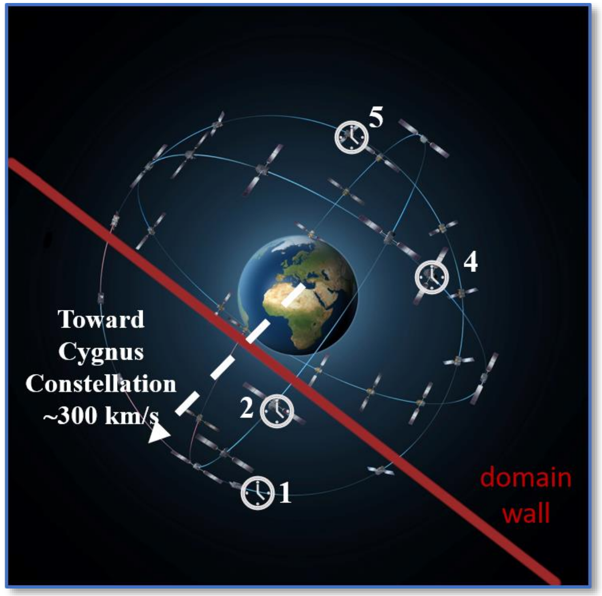
This measurement has already been performed by

- SYRTE (2018): $|\alpha_{\mathrm{GRS}}| = (0.19 \pm 2.48) \times 10^{-5}$ *P. Delva et al., Phys. Rev. Letter, 121, 231101 (2018)*
- ZARM (2018): $|\alpha_{\mathrm{GRS}}| = (4.5 \pm 3.1) \times 10^{-5}$ *S. Herrmann et al., Phys. Rev. Lett., 121, 231102 (2018)*

Data analysis
Constraints on Dark Matter

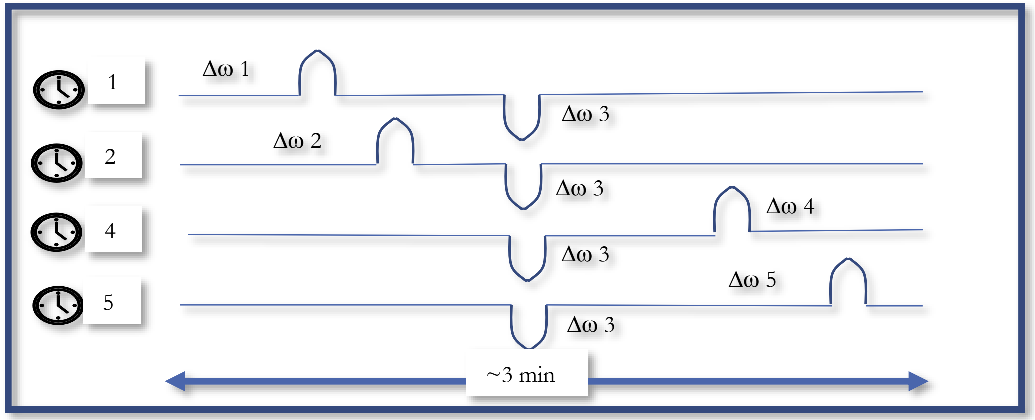
When a DW interacts with the atomic clocks of a satellite, a transient shift in frequency, $\delta\omega/\omega_0$, appears due to a transient variation in the physical constant X with a coupling factor K_X

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



We expect:

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



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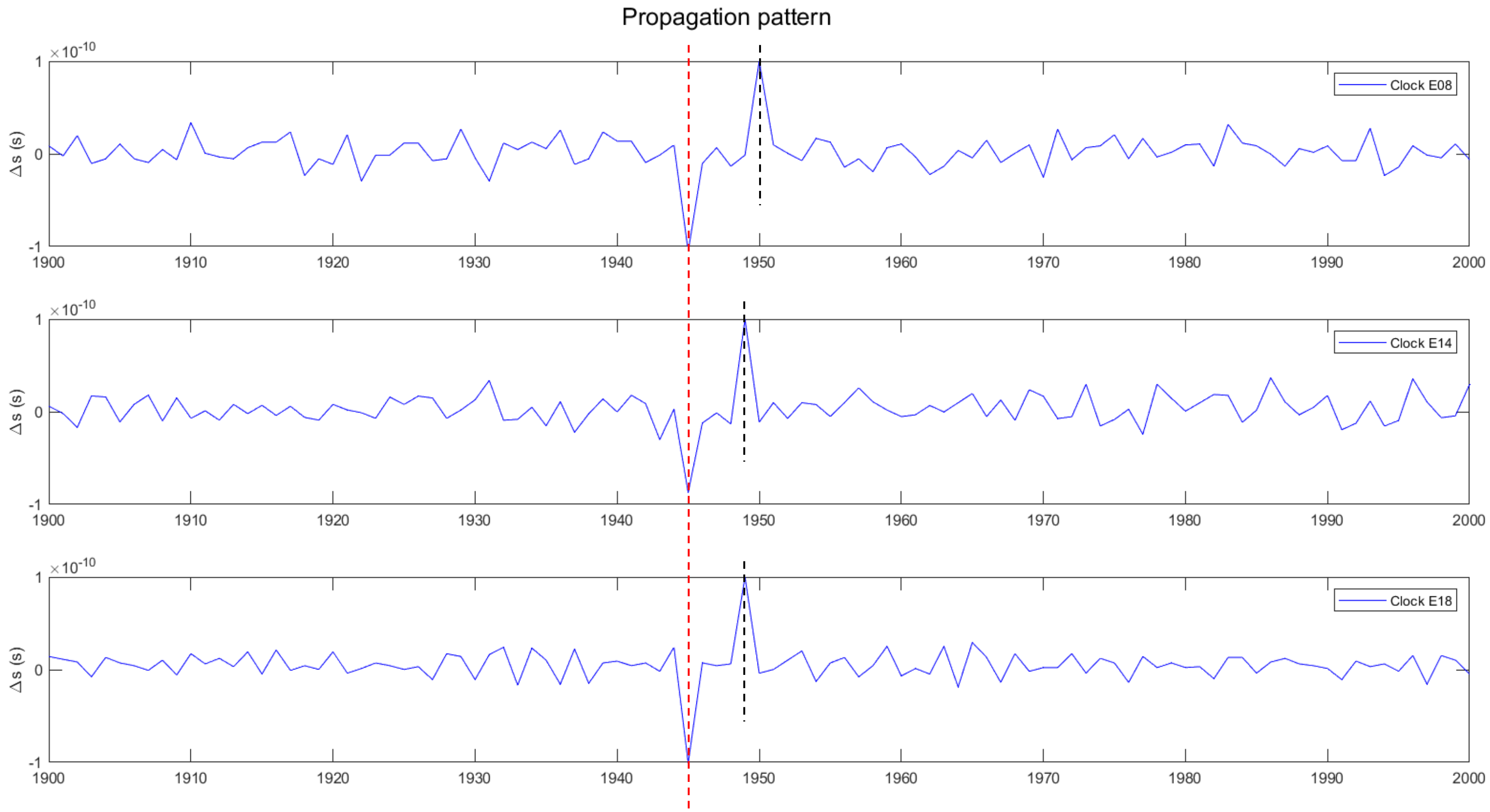
Simulation
Constraints on Dark Matter

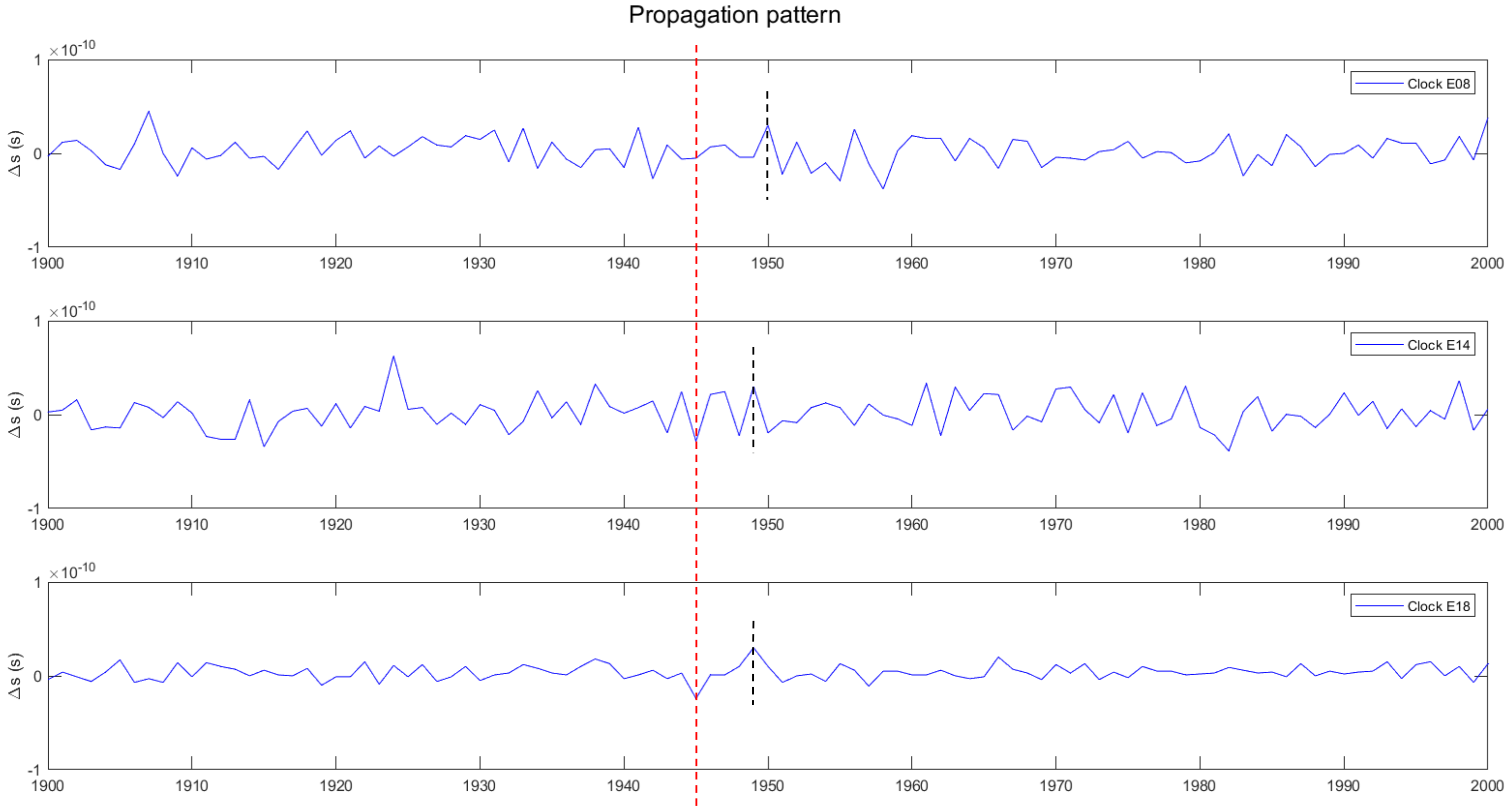
Simulations are fundamental to have an idea of the DW propagation pattern across the atomic-clocks network.



Simulation of a DW signal (amplitude = 10^{-10} s) in clock-data. The negative spike in coincidence with the three clock indicates the DW interaction with the reference clock. Positive spikes indicate the progressive interaction of DW with satellites clocks. The signal is clearly distinguishable from the background noise.

Simulation
Constraints on Dark Matter

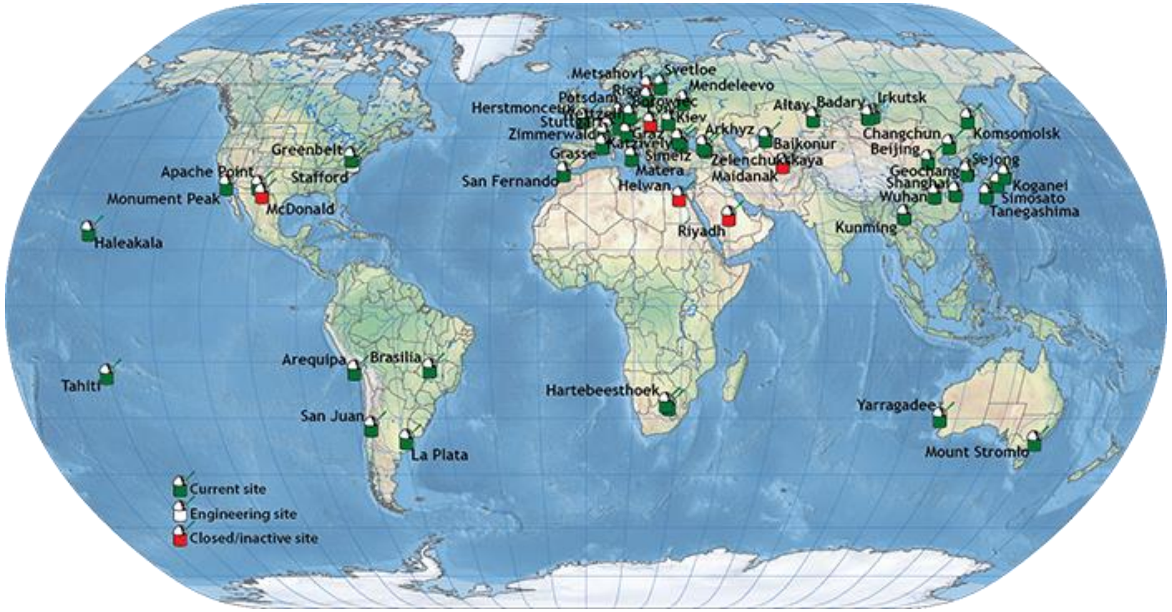
Simulations are fundamental to have an idea of the DW propagation pattern across the atomic-clocks network.



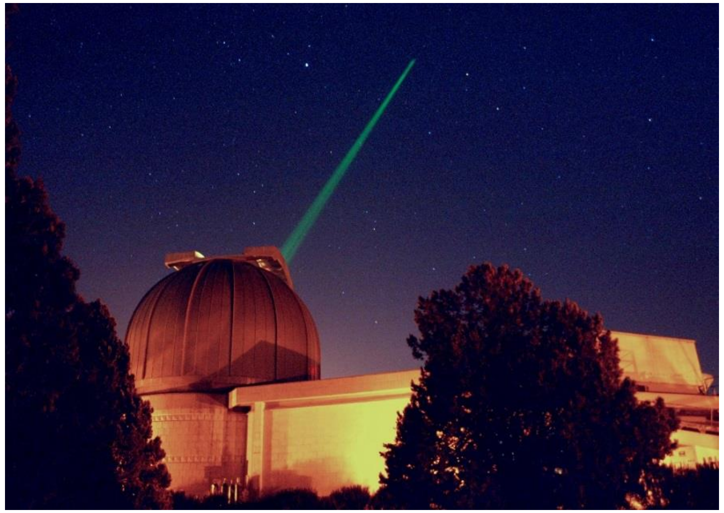
Simulation of a DW signal (amplitude = 0.3×10^{-10} s) in clock-data. In this case we can not distinguish the signal from the background noise.

Tracking-Satellite Laser Ranging

The **International Laser Ranging Service** (ILRS) provides global satellite and lunar laser ranging data and their related products to support scientific research activities.



Map of ILRS stations.
ilrs.gsfc.nasa.gov

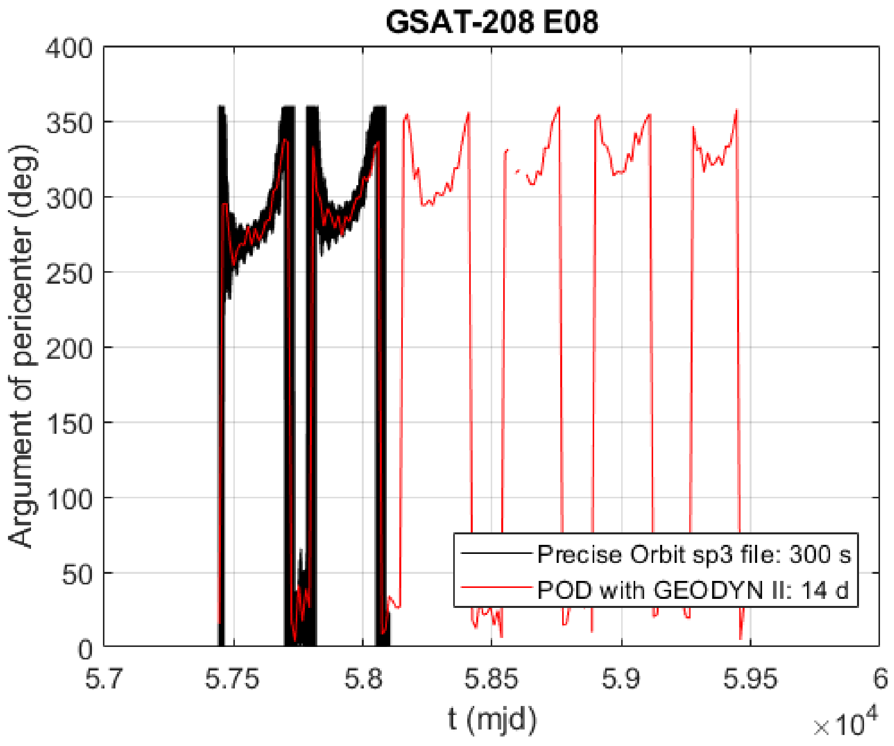


Picture of Franco Ambrico; courtesy of Giuseppe Bianco, ASI-CGS

Retroreflectors mounted on the satellite surface are the target for laser pulses, whose round-trip light time Δt is precisely measured.

$$\Delta s = \frac{c\Delta t}{2}$$

The Precise Orbit Determination



Our preliminary POD for the GSAT0208 satellite in nominal orbit with the ESA POD as comparison. Our POD was performed with the software GEODYN (NASA/GSFC) by using only the satellite laser ranging data.

In a very simplified scheme the **Precise Orbit Determination (POD)** is based on:

- Tracking observations data
- Theoretical Dynamical Model
- Least squares principle

The accuracy of the dynamic POD is highly dependent on the accuracy of physical force models used, in particular for the **Non-Gravitational Perturbations** (NGPs) such as solar radiation pressure, Earth's albedo and Earth's infrared radiation.

POD is also useful for **residuals**-computation.

Non-Gravitational perturbations models

The accuracy of the dynamic POD is highly dependent on the accuracy of physical force models used, in particular for the **Non-Gravitational Perturbations** (NGPs).

Main non-gravitational accelerations and their comparison with the monopole

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	$2\frac{A}{M}\frac{\Phi_{\odot}}{c}A_{\oplus}\frac{\pi R_{\oplus}^2}{4\pi r^2}$	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}

a more refined and reliable model for the direct SRP is the main challenge

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Dynamical Model

The Finite Element Model

Our ultimate goal is to develop a **Finite Element Model** (FEM) of the satellite.

The development of a really refined FEM requires a **detailed knowledge** of the following aspects:

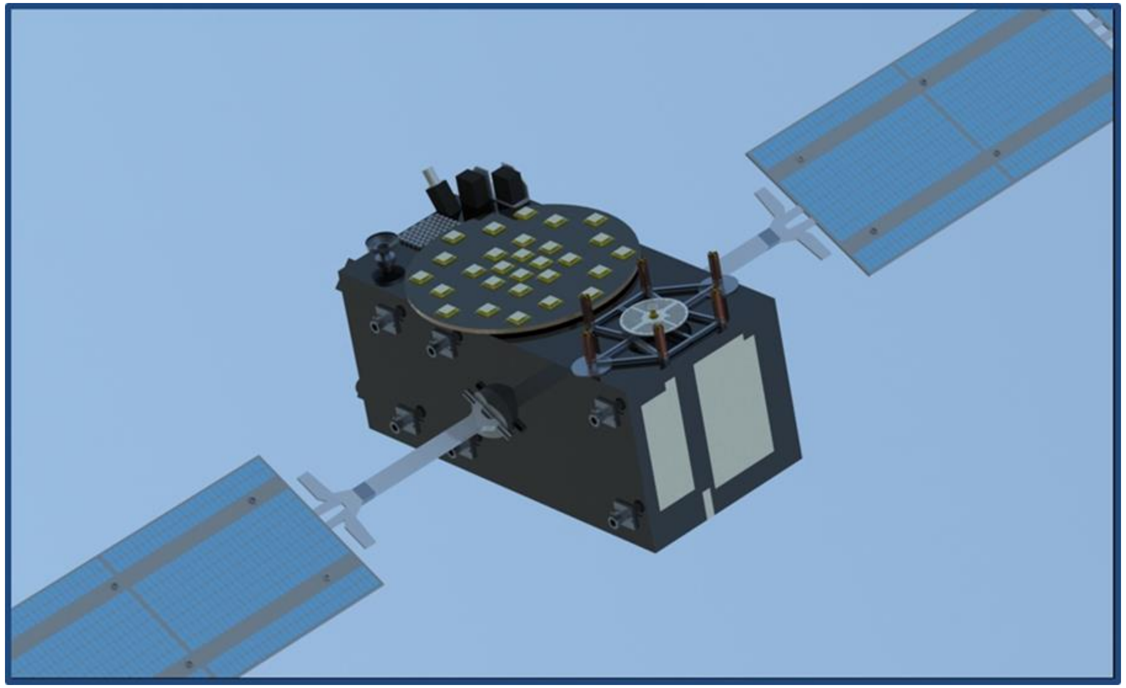
1. the complex geometry of the spacecraft
2. physical characteristics (such as optical and thermal) of each kind of surface and element (antenna, appendices, CCR, …) and their time-evolution
3. the spacecraft attitude-law

and to account for:

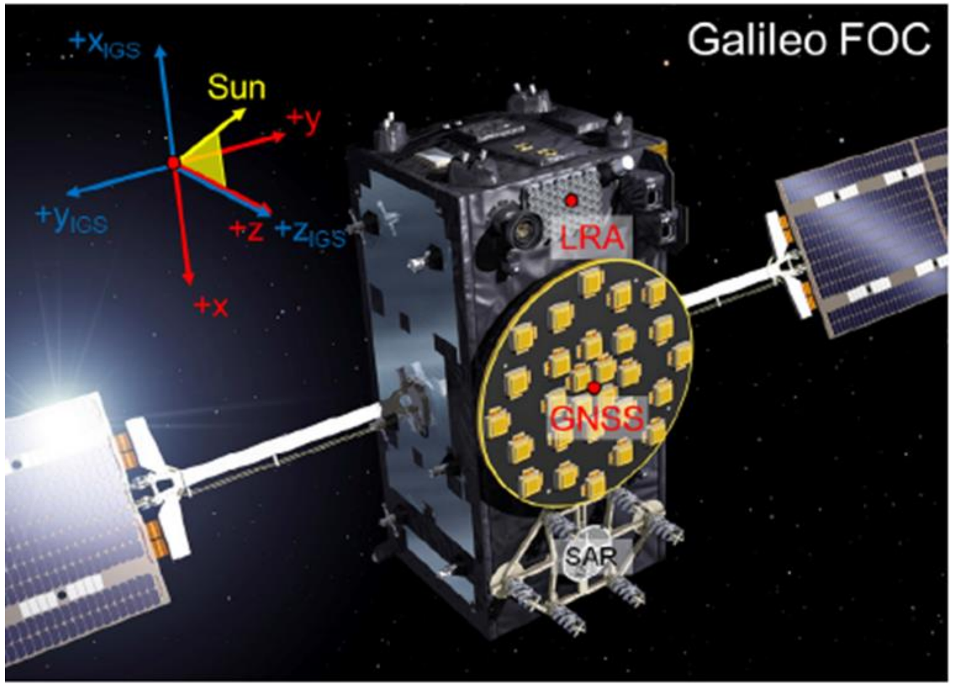
1. multiple reflections
2. mutual shadowing effects produced by the spacecraft surfaces and appendices

Dynamical Model
Preliminary activities to the Finite Element Model

As a starting point a **3D-CAD** of the satellite has been developed.



Our 3D-CAD of the FEM model.

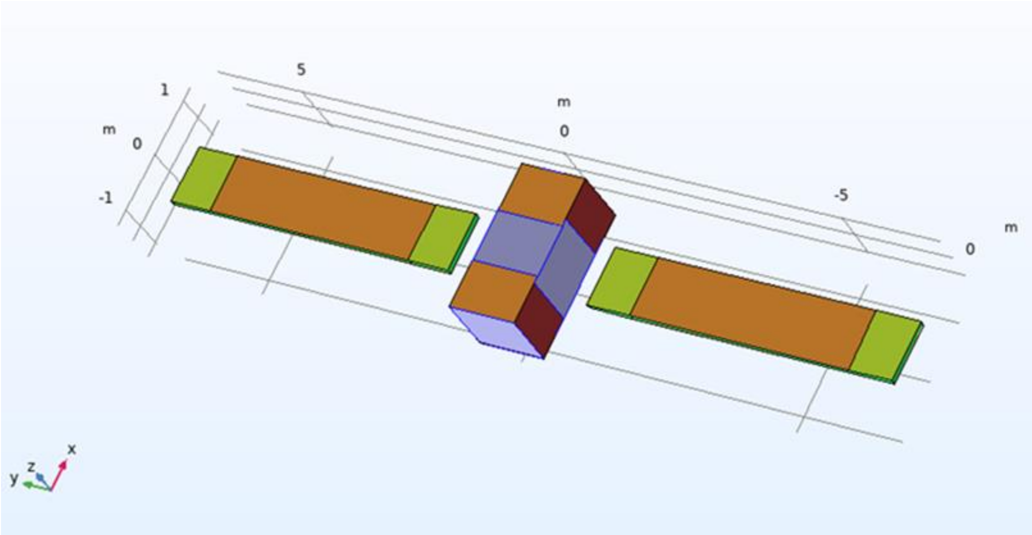


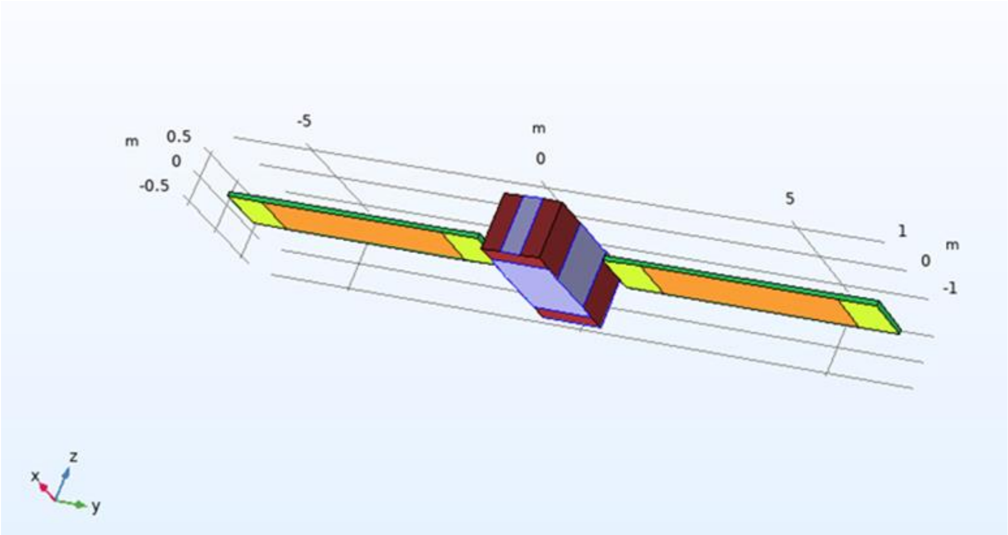
The Galileo FOC satellite.
Credits: Montenbruck et al., Adv. Space Res, 56, 6 (2015)

Dynamical Model
Preliminary activities to the Finite Element Model

We have developed a simplified **Box-Wing** (S-BW) model of the satellite based on current Galileo Metadata provided by ESA.
The ‘box-wing’ model simplifies spacecraft to the satellite bus (‘box’) and solar panels (‘wing’).

Galileo Satellite Metadata | European GNSS Service Centre (gsc-europa.eu)



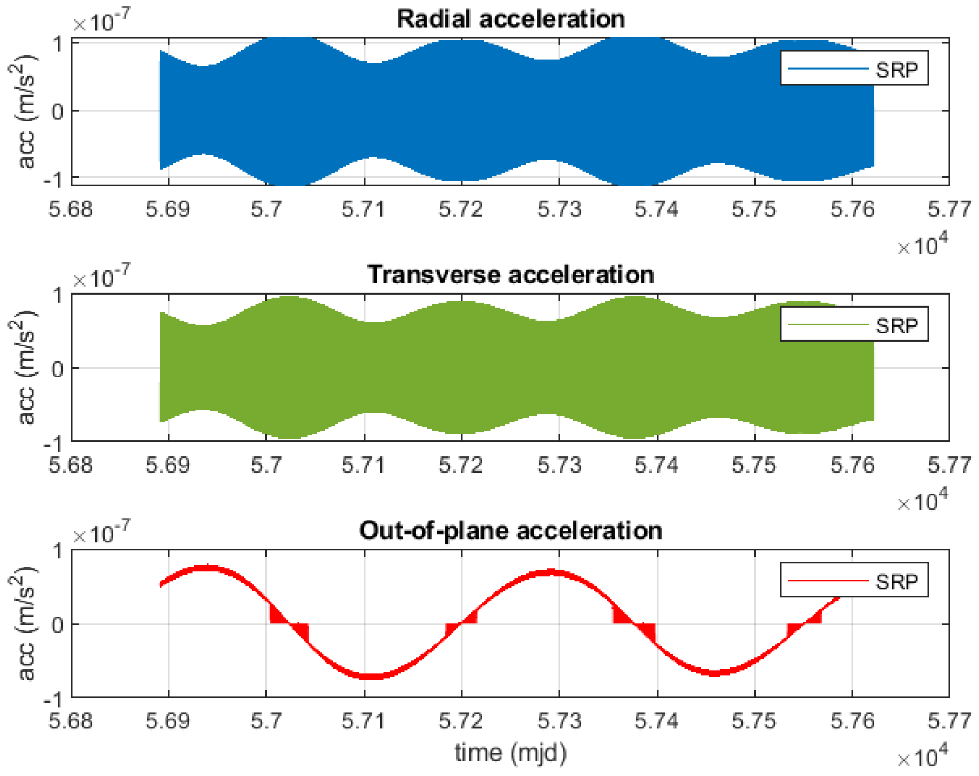


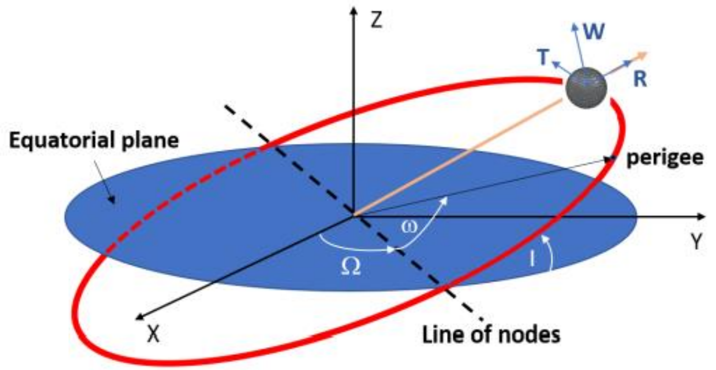
Our Box-Wing model with COMSOL.

Dynamical Model
Application with our S-BW

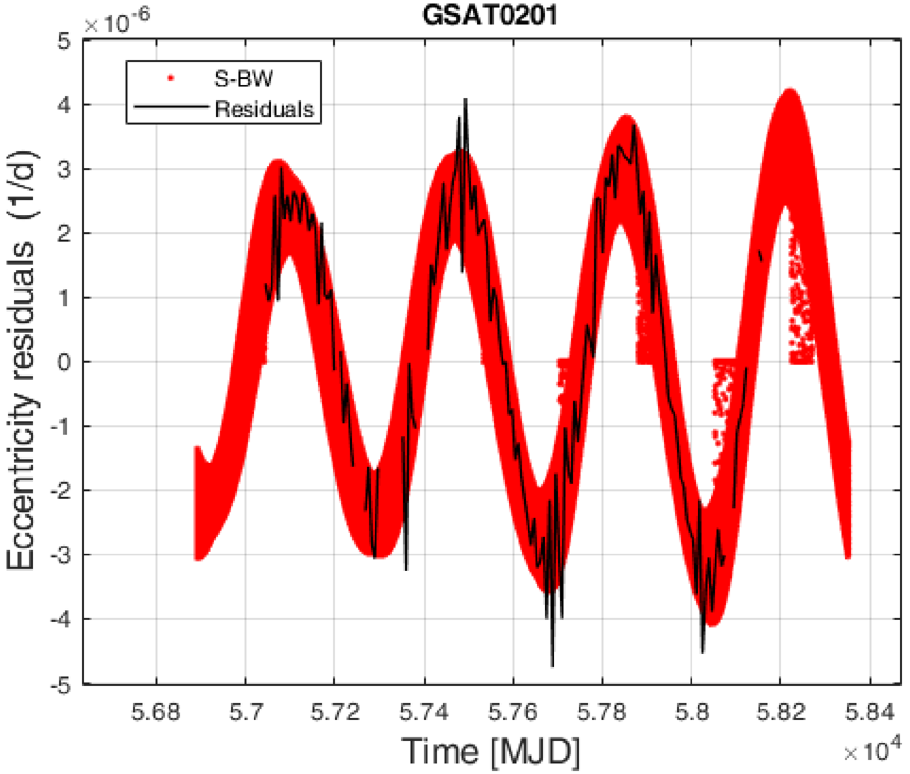
Interaction with the Solar Radiation Pressure (SRP)

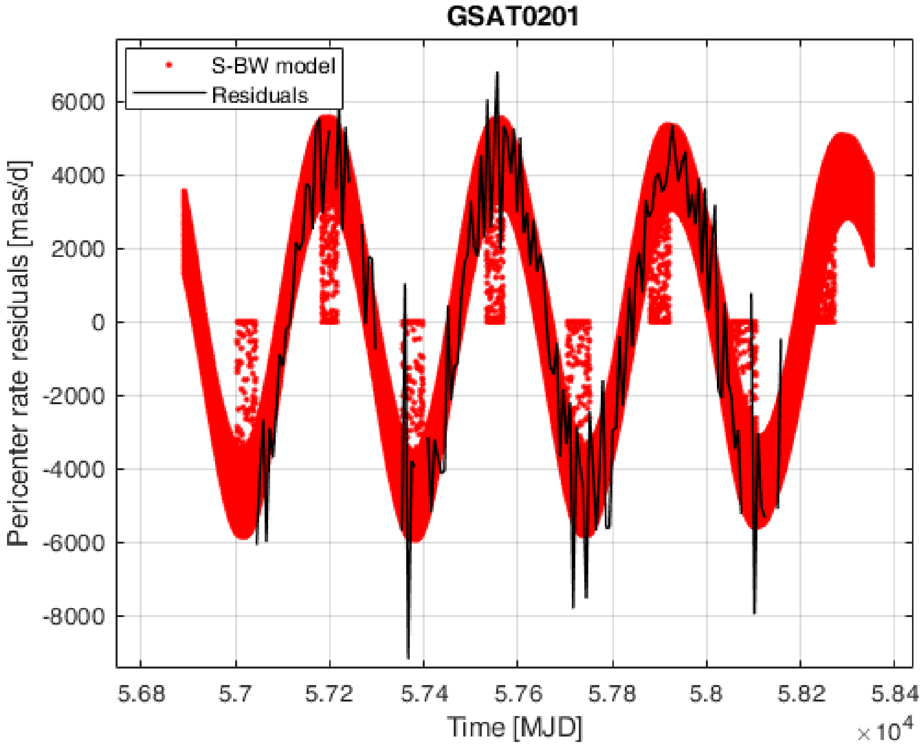
- Accelerations in the Gauss co-moving reference frame





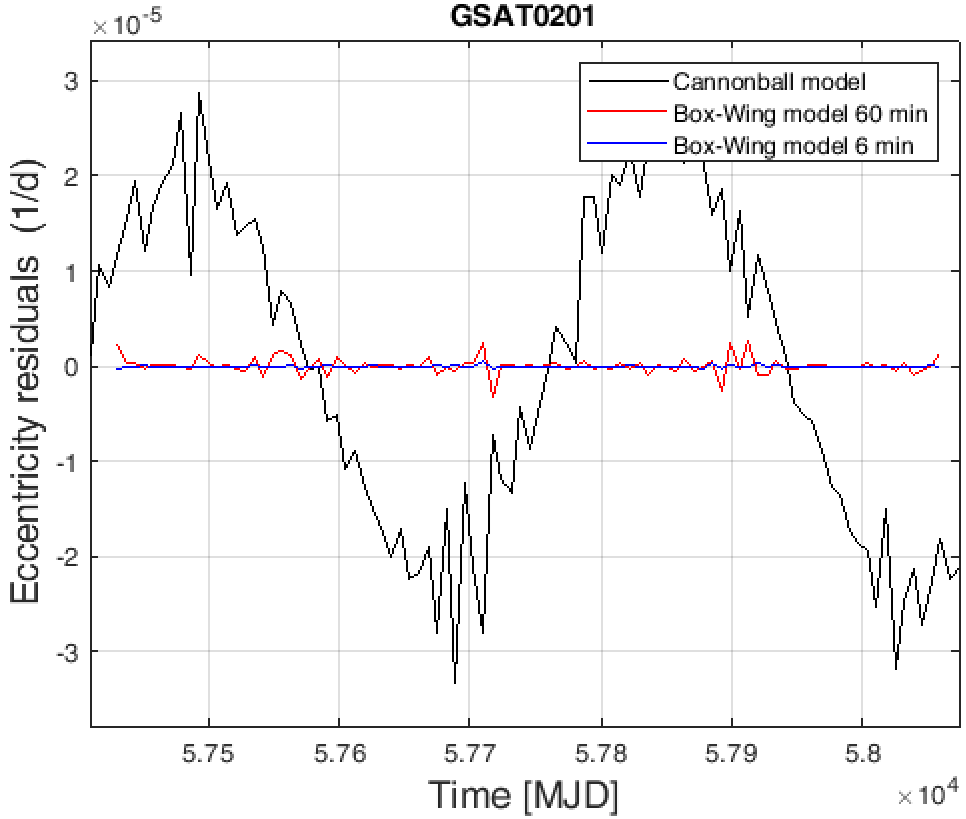
Dynamical Model
Application with our S-BW

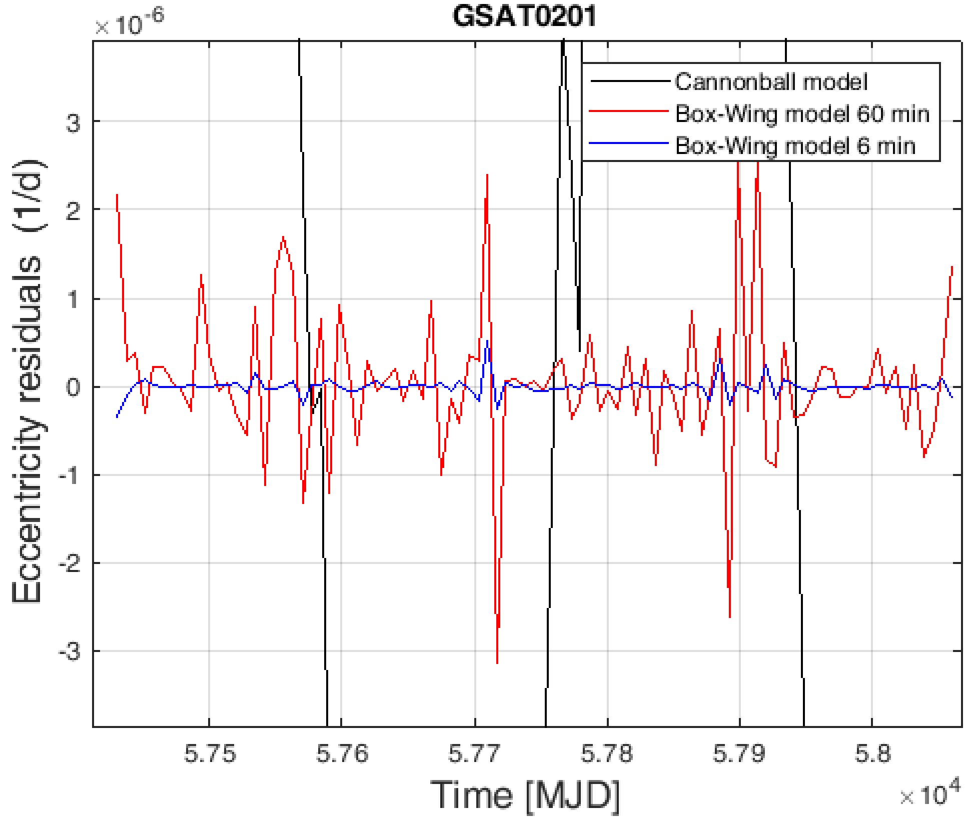




Comparison of the eccentricity and the argument of pericenter residuals with the corresponding prediction of the S-BW model on a 4 years timespan.

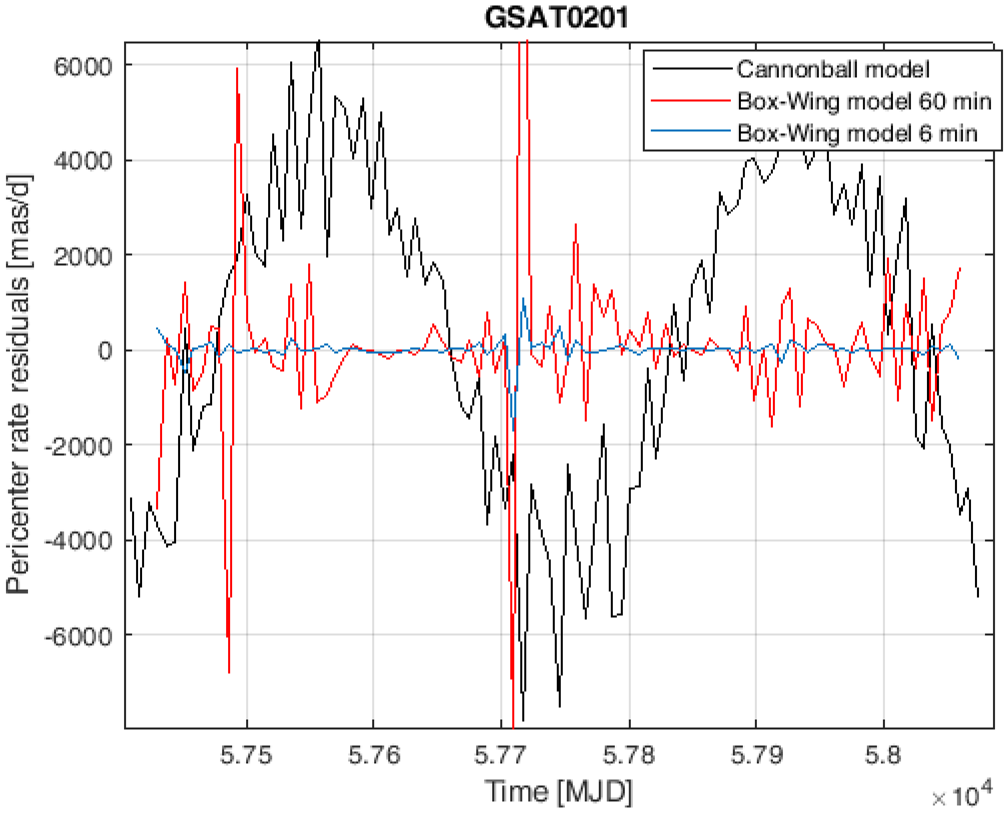
Dynamical Model
Application with our S-BW

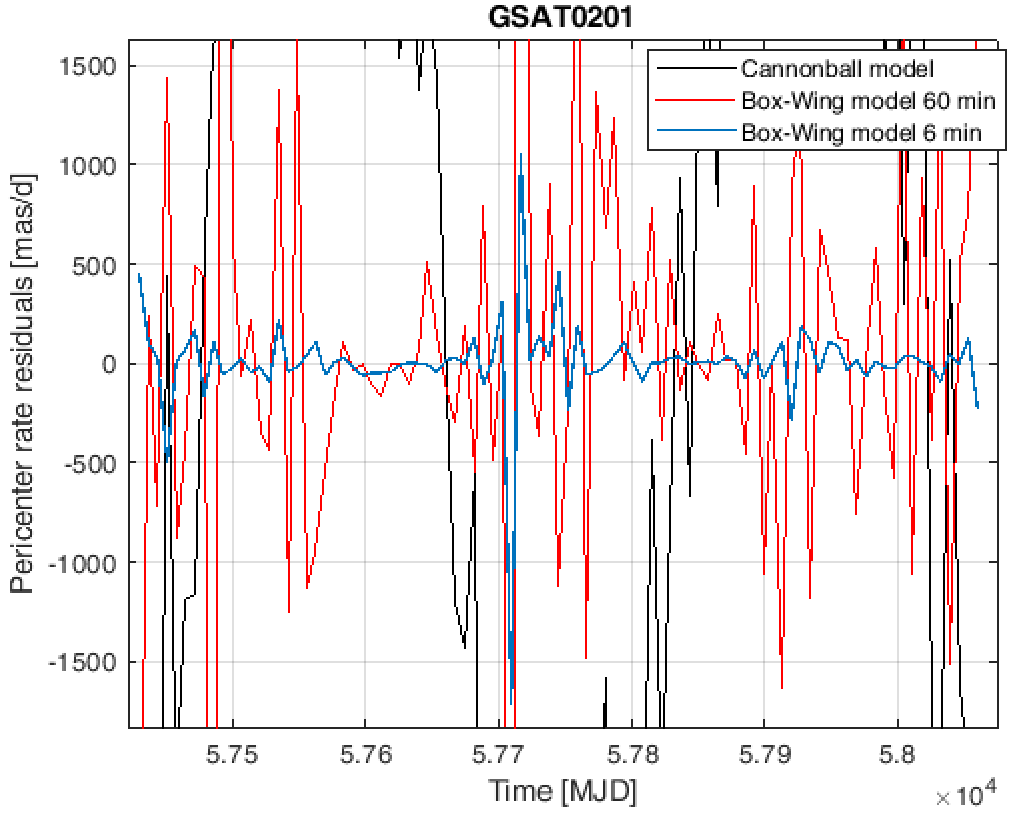




Comparison of the eccentricity residuals obtained with the cannon-ball model and with the accelerations calculated from the Box-Wing model every 60 minutes (red) and every 6 minutes (blue).

Dynamical Model
Application with our S-BW





Comparison of the argument of pericenter residuals obtained with the cannon-ball model and with the accelerations calculated from the Box-Wing model every 60 minutes (red) and every 6 minutes (blue).

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Conclusions

We underlined how the G4S_2.0 project is relevant in the field of Gravitation and Cosmology since it aims to

- improve the best available α_{GRS}-parameter measurements;
- obtain, for the first time, measurements of relativistic precessions of Galileo FOC satellites on eccentric orbits;
- constrain the presence of Dark Matter within our Galaxy.

In this context, modeling as better as possible the NGPs, in particular the SRP, is crucial to improve the POD of satellites for the main objectives of the project.

We built a S-BW according to ESA Galileo Metadata and we computed the SRP perturbing accelerations. These accelerations are used in the POD procedure to obtain a more reliable satellite orbit (as the residuals show) useful for our Fundamental Physics measurements.

Thanks for your attention

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