22nd International Workshop on Laser Ranging

The Galileo for Science project: Fundamental Physics and Technology development for the Constellations of Galileo satellites

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Summary

- Introduction to the Galileo for Science Project (G4S_2.0)
- Fundamental Physics measurements
- Non-gravitational perturbations models
- First results
- Conclusions

Introduction to the Galileo for Science Project

Galileo FOC satellites on eccentric orbits

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. Subsequently, the orbits were corrected ($e \cong 0.16$).

	Nominal	***Injection***	***Resonant (19/10) (orbit 1)***	***Max.Perigee (orbit 2)***	***Resonant (37/20) (orbit 3)***
Semi-Major Axis [km]	**29600**	**26180.99**	**27484.8**	**27932.86**	**27977.9**
Eccentricity	**0.00027**	**0.2326**	**0.156**	**0.1563**	**0.1544**
Inclination	**55.12°**	**49.80°**	**49.8°**	**49.8°**	**49.8°**
RAAN	**100.66°**	**83.82°**	**83.82°**	**83.82°**	**83.82°**
Arg-Per	**241.98°**	**28.00°**	**28.00°**	**28.00°**	**28.00°**

Final choice of the recovery orbit

However, the incident offered a rare opportunity for **General Relativity** measurements.

Introduction to the Galileo for Science Project
Main goals

In this context, the **Galileo for Science Project** has several scientific goals:

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. Providing a **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.

Introduction to the Galileo for Science Project

Data analysis scheme for the Fundamental Physics measurements

Our **raw-data**: time-sequences of the clock-bias of the onboard Galileo FOC atomic clocks

Step 1: identification of «homogeneous» periods to process data.

Step 2: data cleaning procedure removing long-trend effects and daily rephrasing.

Gravitational redshift measurement

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

Dark Matter constraints

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

Fundamental Physics measurements
Gravitational redshift

Gravitational redshift is the relative frequency shift of an electromagnetic wave due to the gravitational field of a body.

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

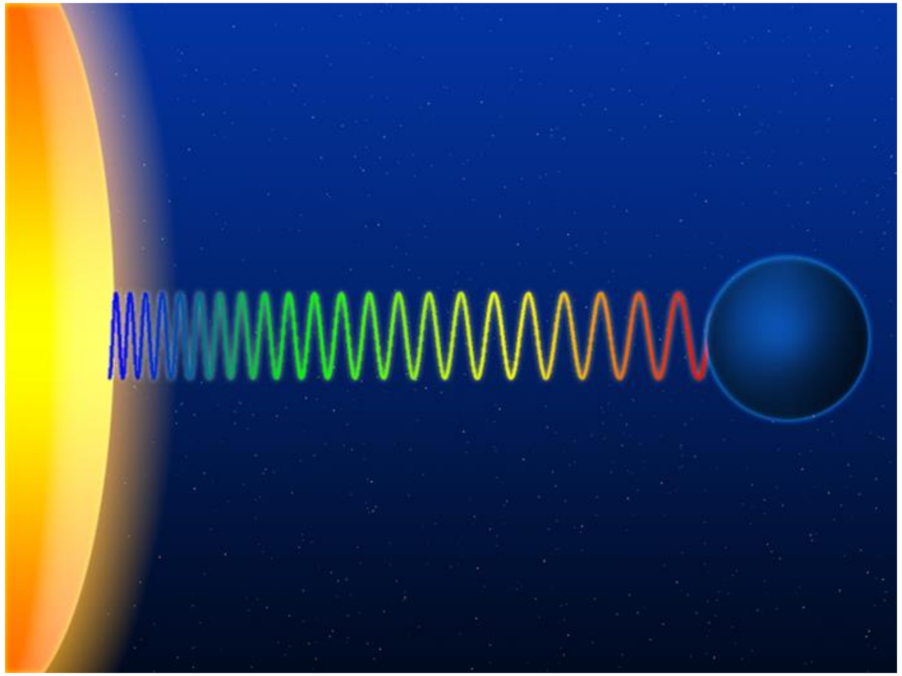
It is predicted by General Relativity but it is not a truly test of the Theory…

It can be measured through frequency shifts of the onboard atomic clocks

It is a **Local Position Invariance Test**:

$$\mathcal{Z} = (1 + \alpha)\frac{\Delta U}{c^2}$$

If GR is correct α should be zero.



A representation of the Gravitational redshift of the light emitted from the star surface.

Fundamental Physics measurements

Gravitational redshift: recent measurements

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

A deep analysis on systematic effects was conducted focusing mainly on:

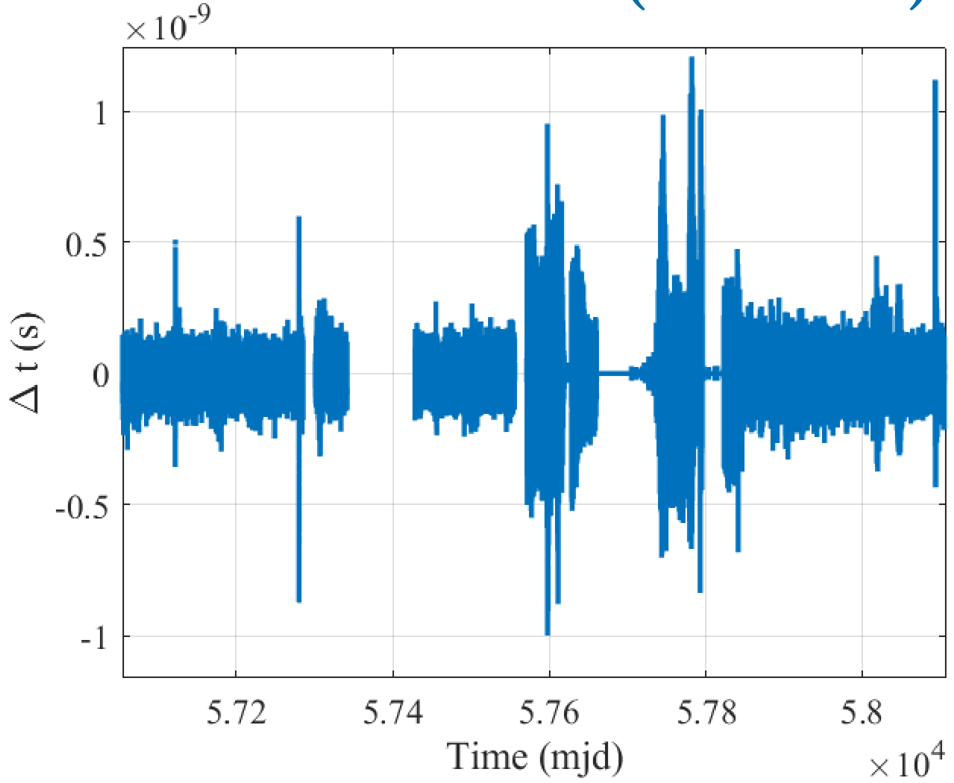
- **Earth's magnetic field** (atomic clocks are sensitive to magnetic field)
- **Temperature variation** (change of the orientation of the satellite with respect to the Sun)
- **Orbits and clocks solution**

Our goal is to constrain α down to a level of $< 2\times10^{-5}$

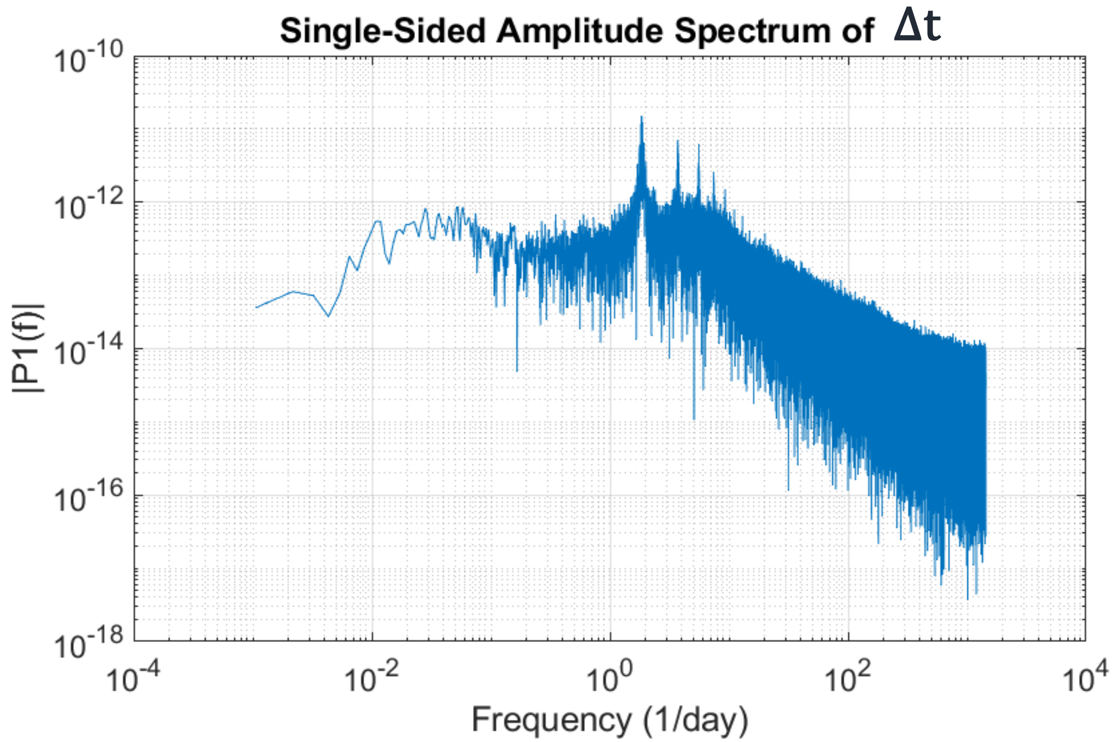
Fundamental Physics measurements

Gravitational redshift: analysis of GREAT clock-data

GSAT-0201 satellite (DORESA)



The resulting signal from all the pre-processed clock-data in the homogeneous periods, by substracting the moving average.



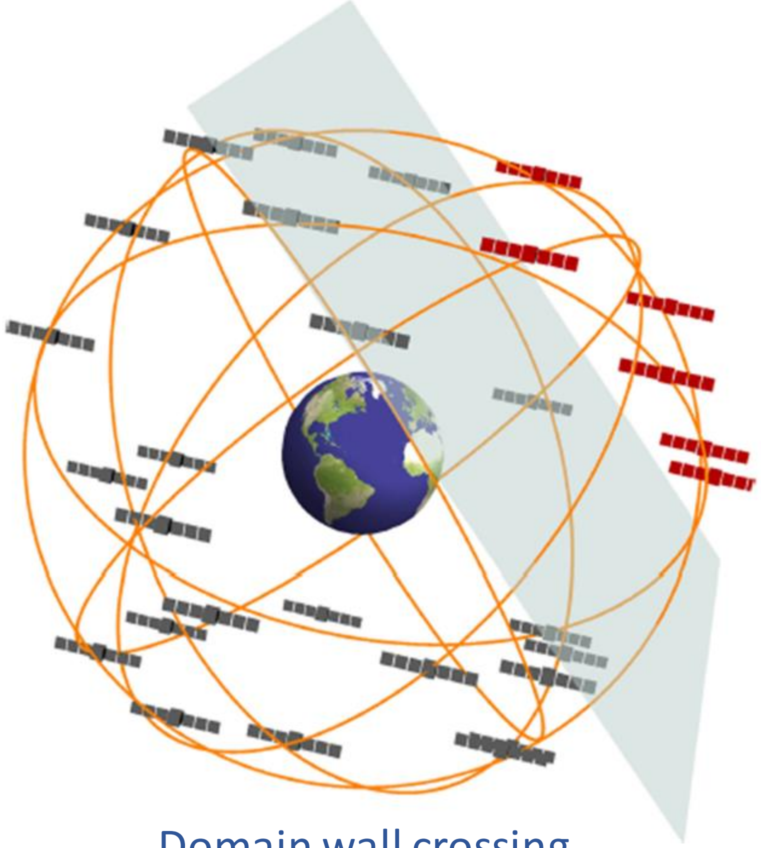
The spectrum of the final signal.

Fundamental Physics measurements
Constraints on Dark Matter

Dark Matter (DM) could be on the form of clusters or macroscopic structure. Examples of clumpy DM candidates are **topological defects**, such as domain walls.

Such structures could cross Earth's orbit and Galileo constellation. Interactions with domain walls could cause a sequence of atomic clock perturbations that propagate through the satellite constellation.

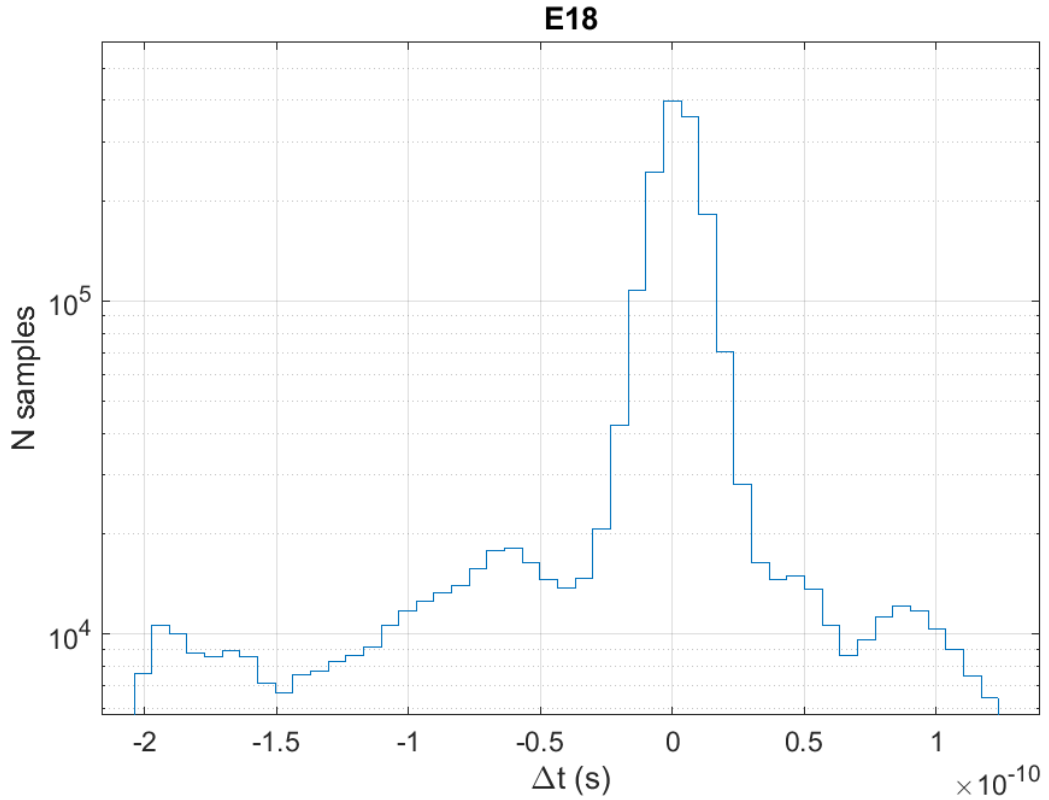
Our goal is searching for a succession of glitches of the Galileo onboard atomic clocks in case of crossing.


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

Fundamental Physics measurements

Constraints on Dark Matter

We are developing a pipeline to select the glitches in the different clocks and searching for their coincidences among them.



Amplitude distribution of the glitches in the clock of E18 satellite.

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).

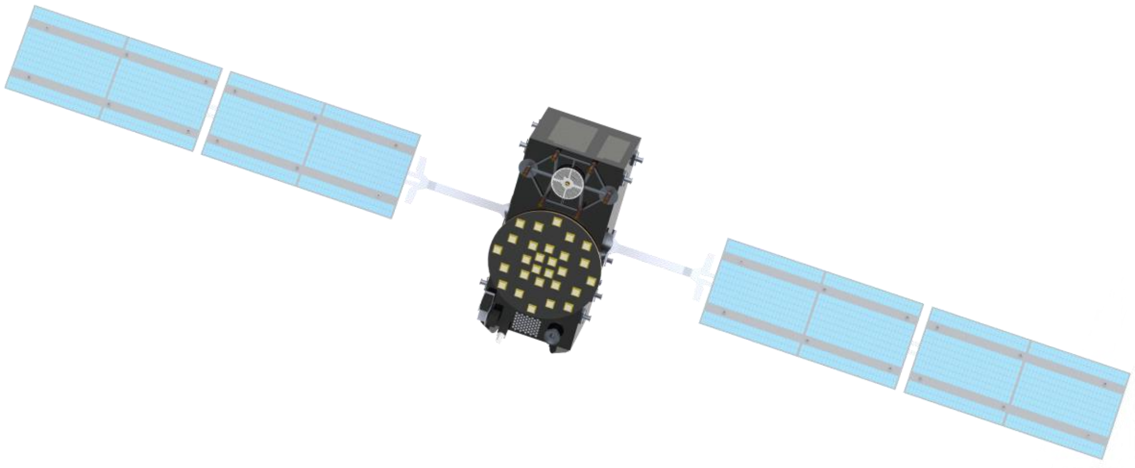
Main non-gravitational accelerations and their comparison with the monopole

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}

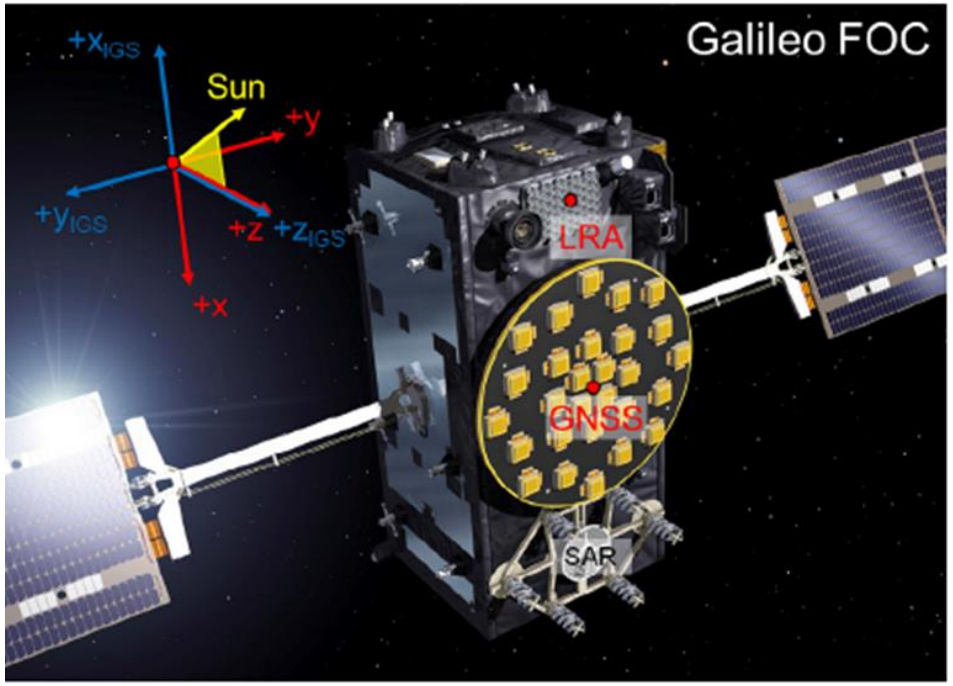
a more refined and reliable model for the direct SRP is the main challenge

Non-Gravitational Perturbations 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.



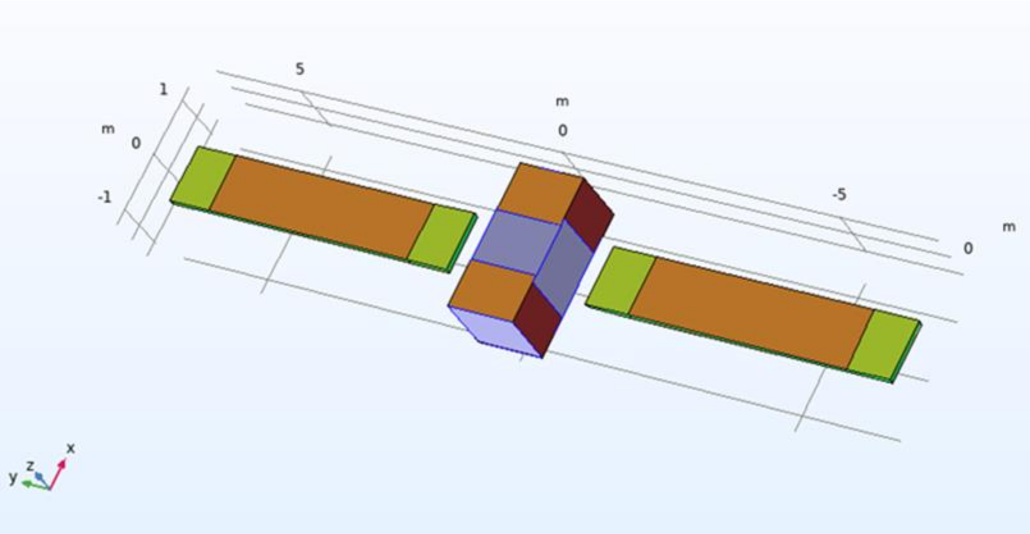
The Galileo FOC satellite. Credit: ESA.

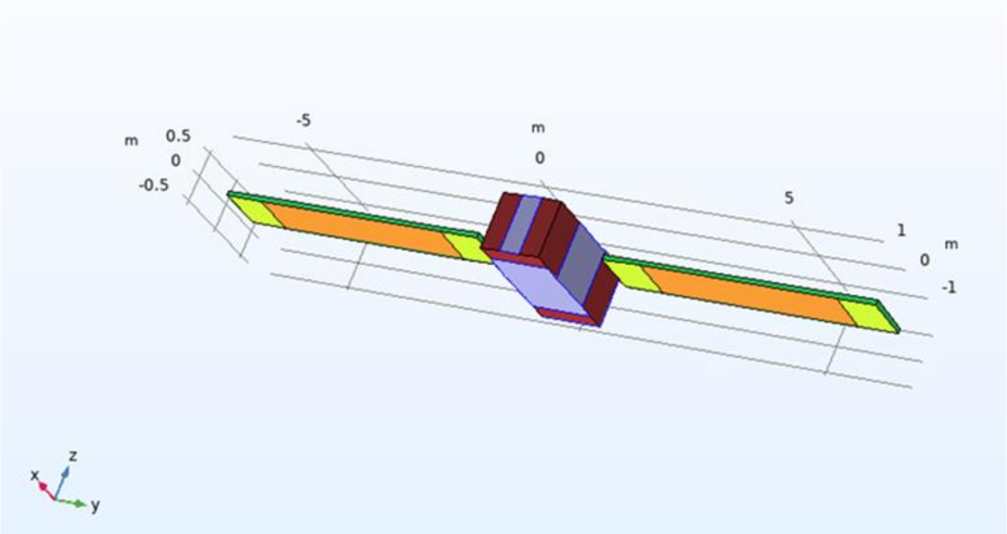
Non-Gravitational perturbations models

The Box-Wing Model

Preliminary to the Finite Element Model (FEM), we have developed a **Box-Wing** (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.

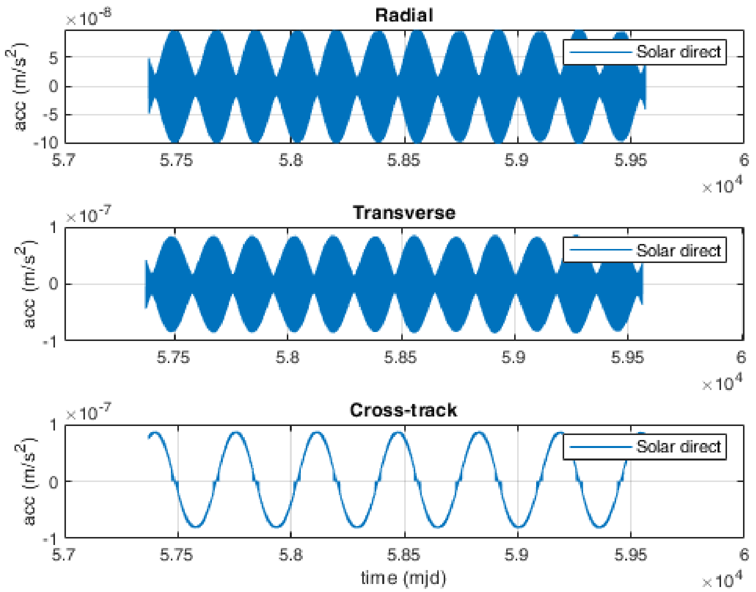
First results

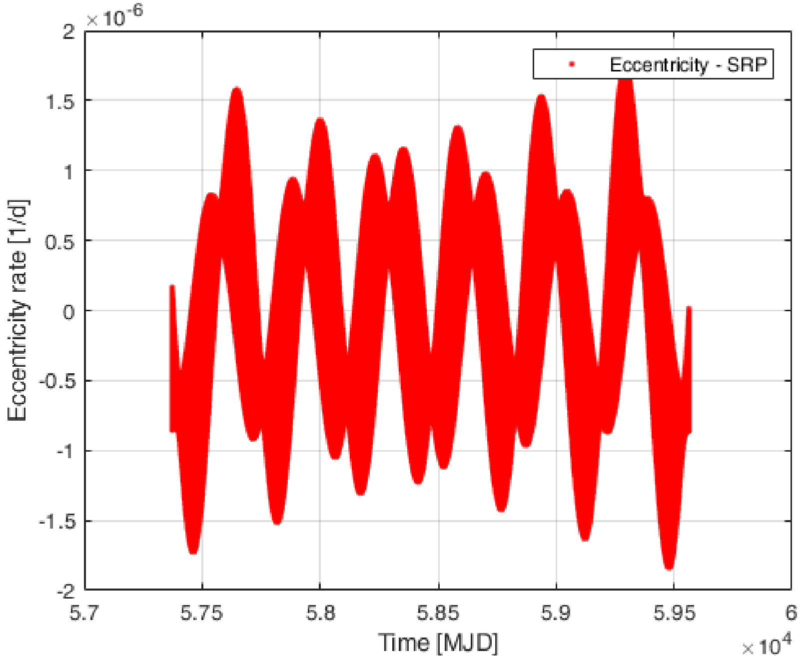
Preliminary results: *Box Wing for GSAT-0208 (ESA Galileo Metadata)*

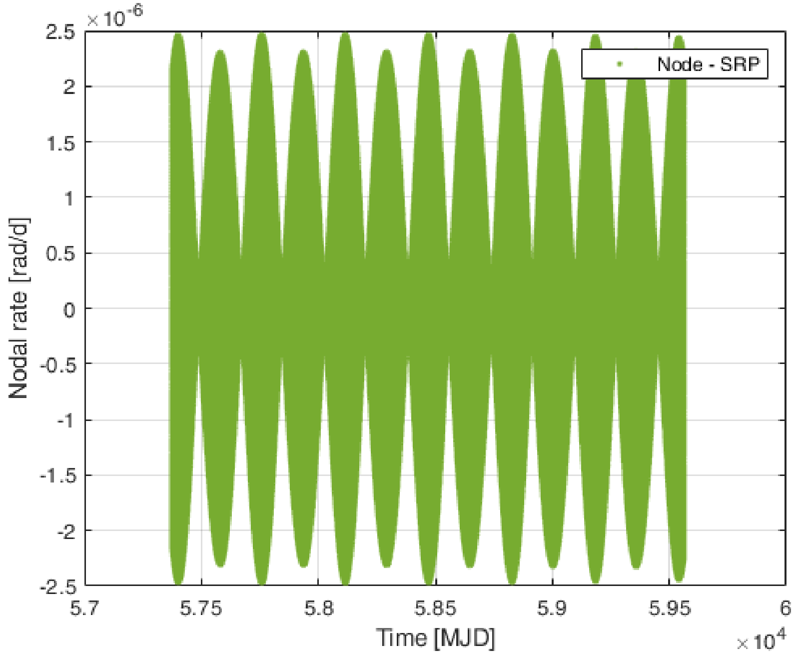
Gauss accelerations

$$\frac{de}{dt} = \frac{\sqrt{1-e^2}}{na}\left[R \sin f + T(\cos f + \cos u)\right]$$

$$\frac{d\Omega}{dt} = \frac{W}{H \sin i} r \sin(\omega + f)$$

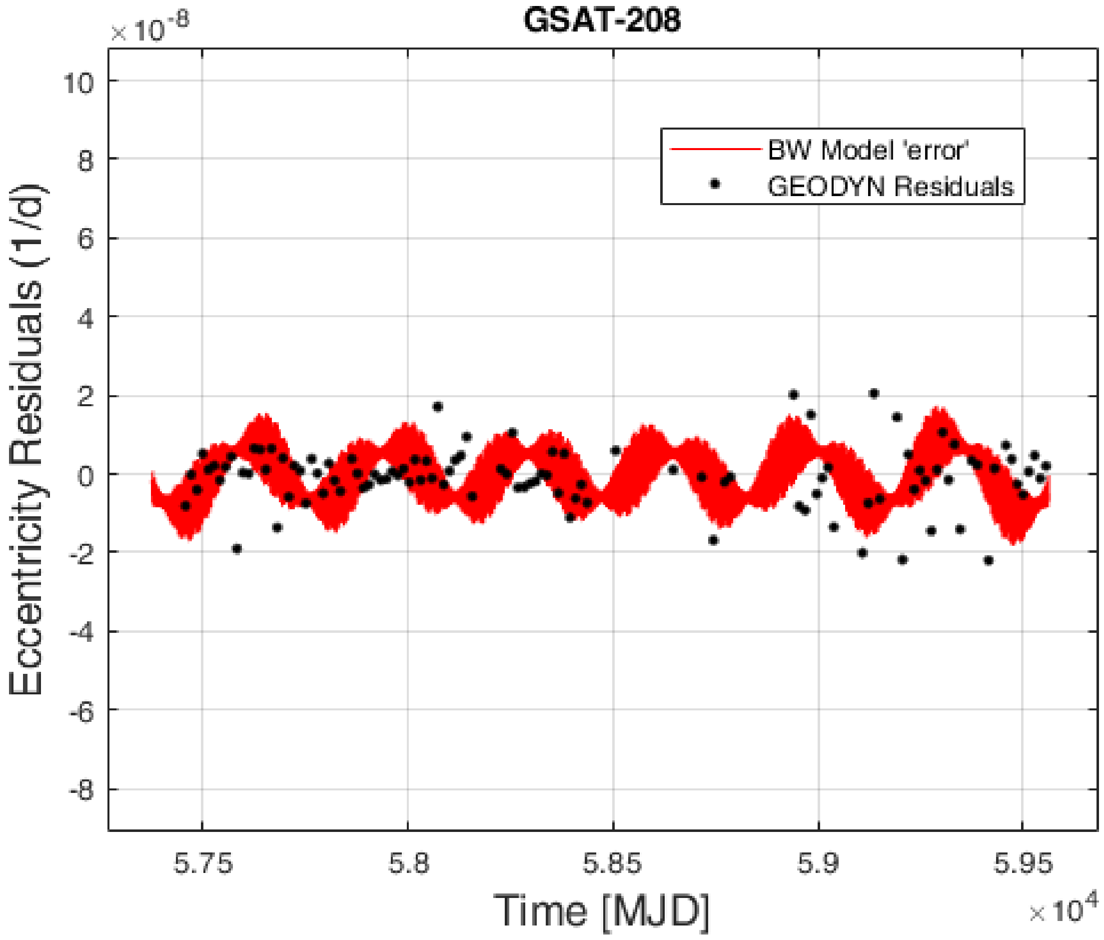






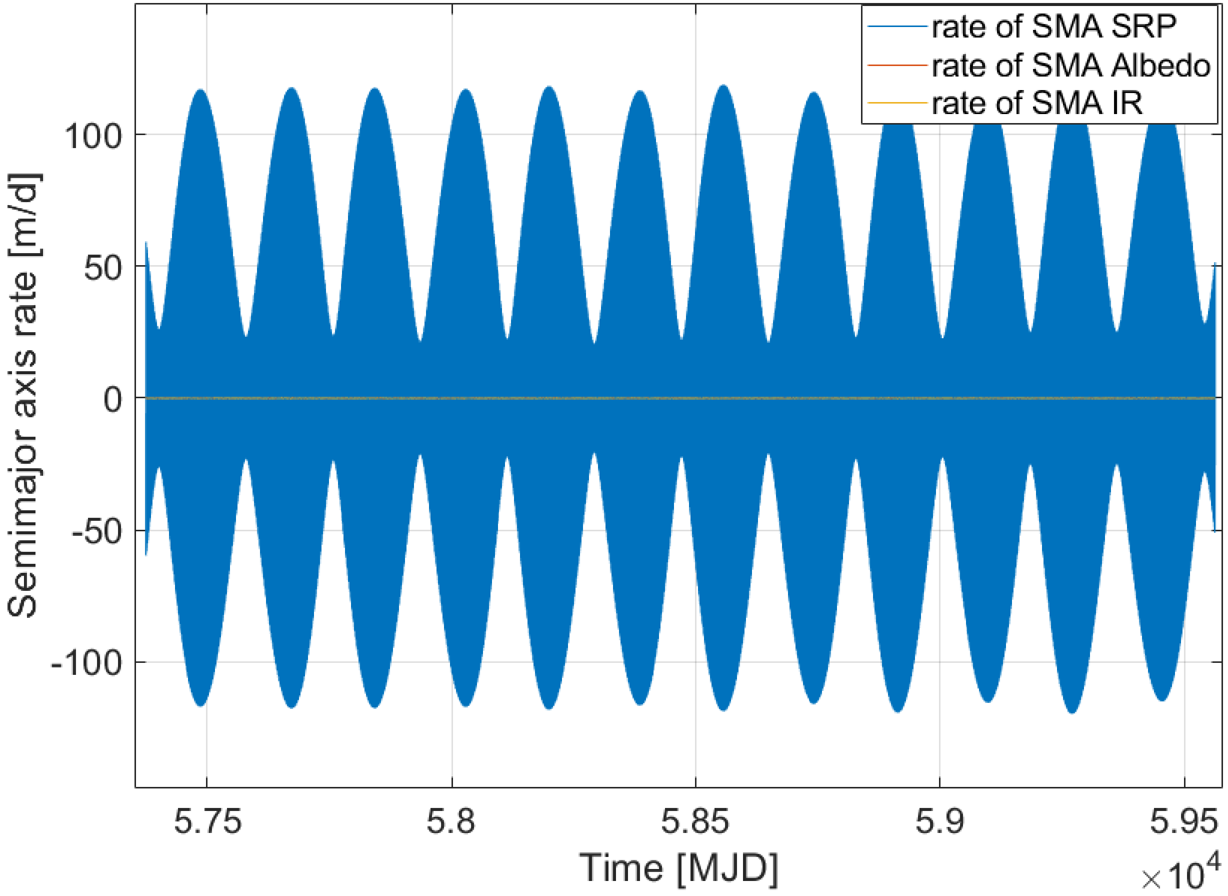
First results

Preliminary results: *Comparison with POD residuals*



First results

Preliminary results: *Box Wing for GSAT-0208 semimajor axis (ESA Galileo Metadata)*



Non-Gravitational Perturbations 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:

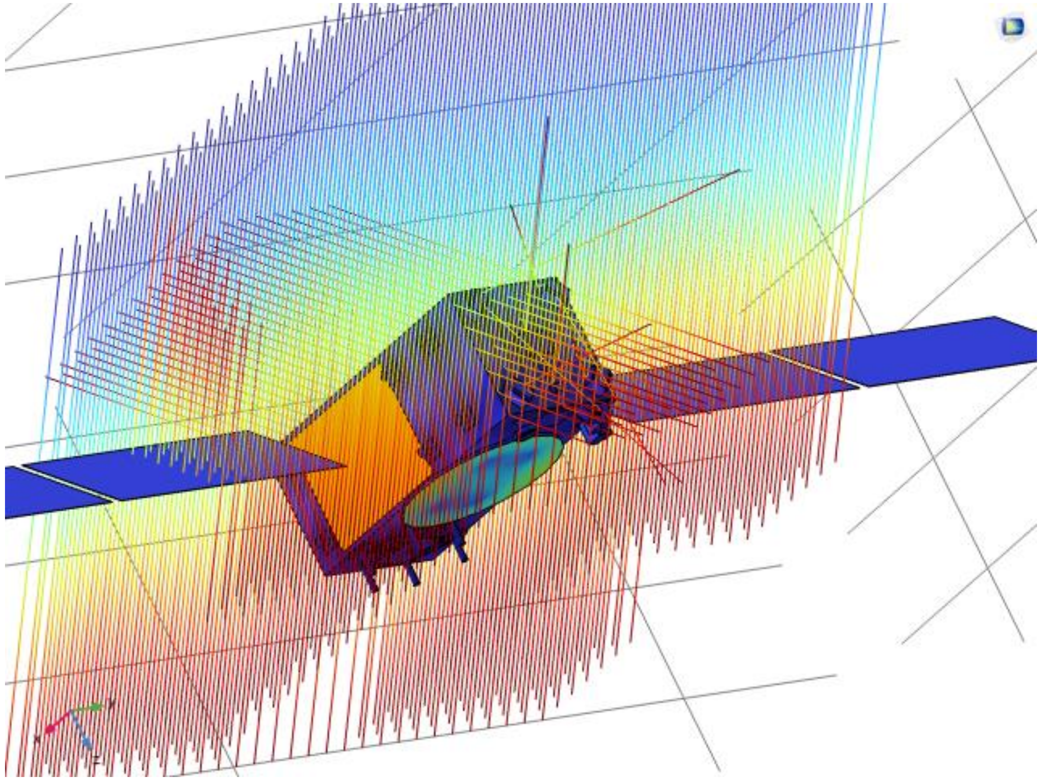
1. the complex geometry of the spacecraft
2. physical characteristics (such as optical and thermal) of each kind of surface and element (antenna, appendices, CCR, …) and their time-evolution
3. the spacecraft attitude-law

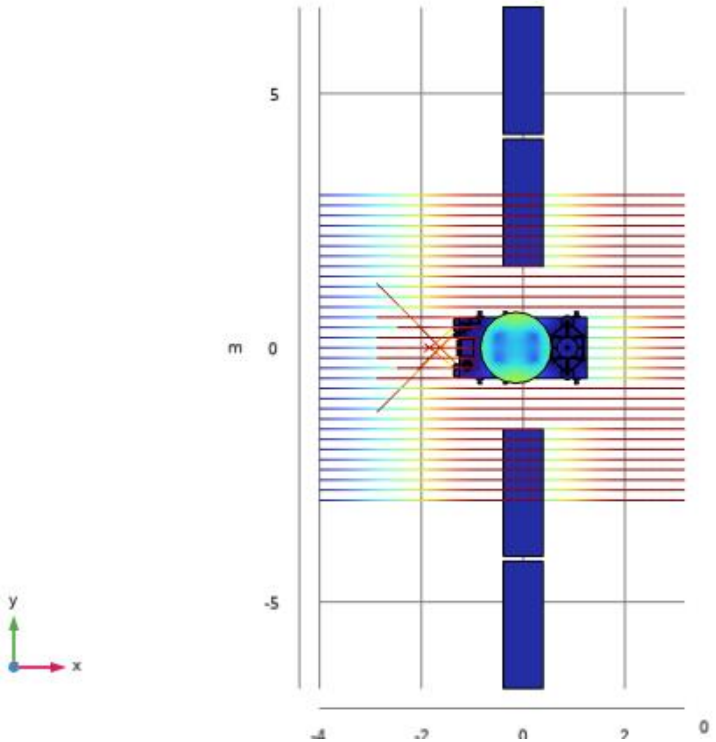
and to account for:

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

Non-Gravitational Perturbations Model
Finite Element Model: the Ray-Tracing technique

Moreover, we want to apply a **Ray-Tracing technique** to take into account umbra, penumbra and multiple reflections on the satellite itself.

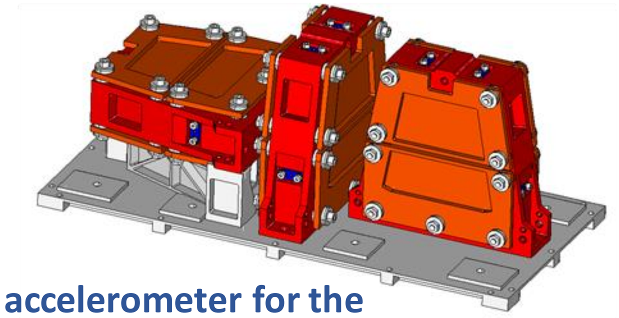




s/w COMSOL

Non-Gravitational perturbations models
A new accelerometer concept

The focus is to develop a **new concept of accelerometer** for a next generation of Galileo satellites.



ISA accelerometer for the ESA BepiColombo mission

It can be used as
- Scientific instrument
- Platform instrument

Main tasks:
- Overcoming the current limitations of the INAF-IAPS accelerometers
- Studying possible scientific goals that can be performed using an onboard accelerometer and the required measurement performance
- Studying suitable instrument configurations and identifying performance critical elements

Final goal:
Measuring the onboard non-gravitational accelerations down to a precision and accuracy of 10^{-10} m/s^2 and to a frequency of about 2×10^{-5} Hz.

Conclusions

We presented the main objectives and some of the ongoing activities within the G4S_2.0 project:

- A processement of GREAT clock-data by removing the various signal discontinuities (trend-effects, daily time rephrasing…) has been performed for the satellite DORESA (GSAT-0201). Now we are working to automate this procedure for all the Galileo FOC constellation. This will allow us to proceed on clock-data analysis.

- We have studied the NGPs using a preliminary BW model and we calculated their effects on the orbital elements. The preliminary results obtained with the BW and the POD of the satellites performed with GEODYN (analyzing only SLR data) are positive and encouraging.

- Our precise model on NGPs will be completed acquiring precise information about thermal and optical properties of the satellite and applying the Ray-Tracing technique, which we are developing. The corresponding perturbing accelerations will be used in the POD procedure.

Thanks for your attention