The G4S_2.0 Project:
state of the art and SLR campaign

2023 Virtual International Workshop on Laser Ranging

Session 01 Scientific analysis of SLR observation: past, current and future challenges and possibilities

16th October 2023

Feliciana Sapio

David Lucchesi, Massimo Visco, Alessandro Di Marco, Marco Cinelli, Emiliano Fiorenza, Carlo Lefevre, Pasqualino Loffredo, Marco Lucente, Carmelo Magnafico, Roberto Peron, Francesco Santoli and Francesco Vespe.

feliciana.sapio@inaf.it

Introduction to G4S_2.0
Main objectives

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

Data analysis scheme

Our **clocks-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

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

The Precise Orbit Determination

Precise Orbit Determination (**POD**) has the **goal** of accurately determining the **position** and **velocity vectors** of an orbiting satellite. In a very simplified scheme the **POD** is based on:

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

In the case of **SLR**, the **observable** to be minimized in a least squares process is a **quadratic function** of the **range residuals** R:

$$R_i = O_i - C_i = -\sum_j \frac{\partial C_i}{\partial P_j} dP_j + dO_i$$

- O_i and C_i are, respectively, the SLR range observations and their computed (from the dynamical models) values,
- dP_i represent the corrections to the vector P of parameters to be estimated,
- dO_i are the errors associated with each observation.

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

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:

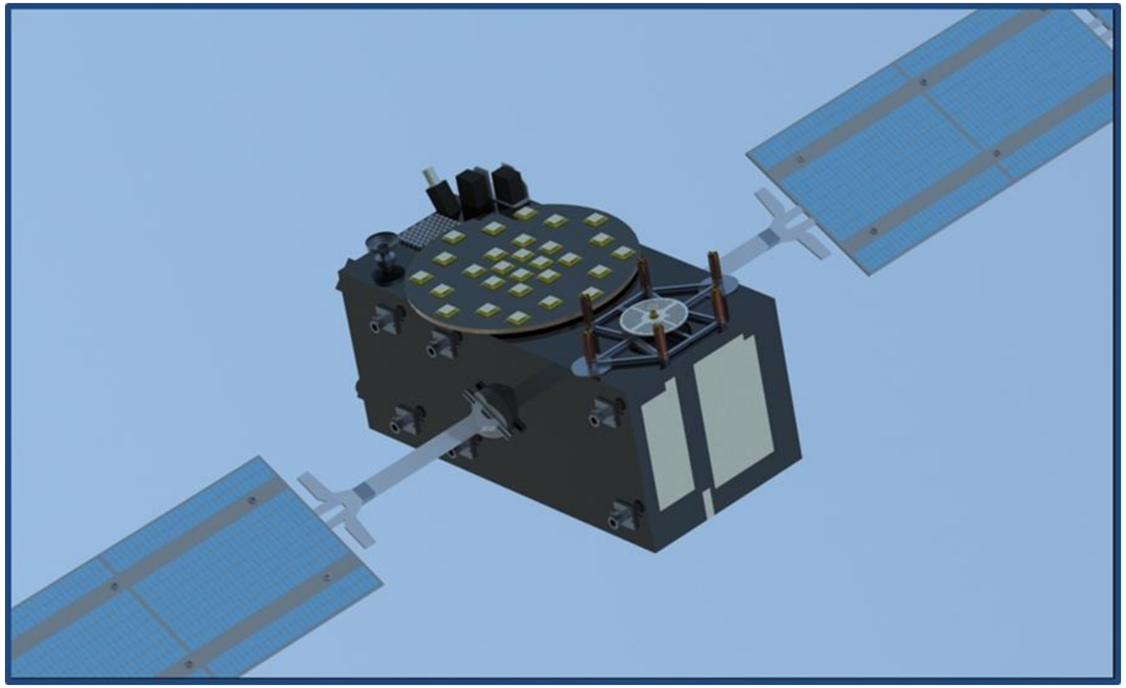
1. the complex geometry of the spacecraft
2. physical characteristics (such as optical and thermal) of each kind of surface and element (antenna, appendices, CCR, …) and their time-evolution
3. the spacecraft attitude-law

and to account for:

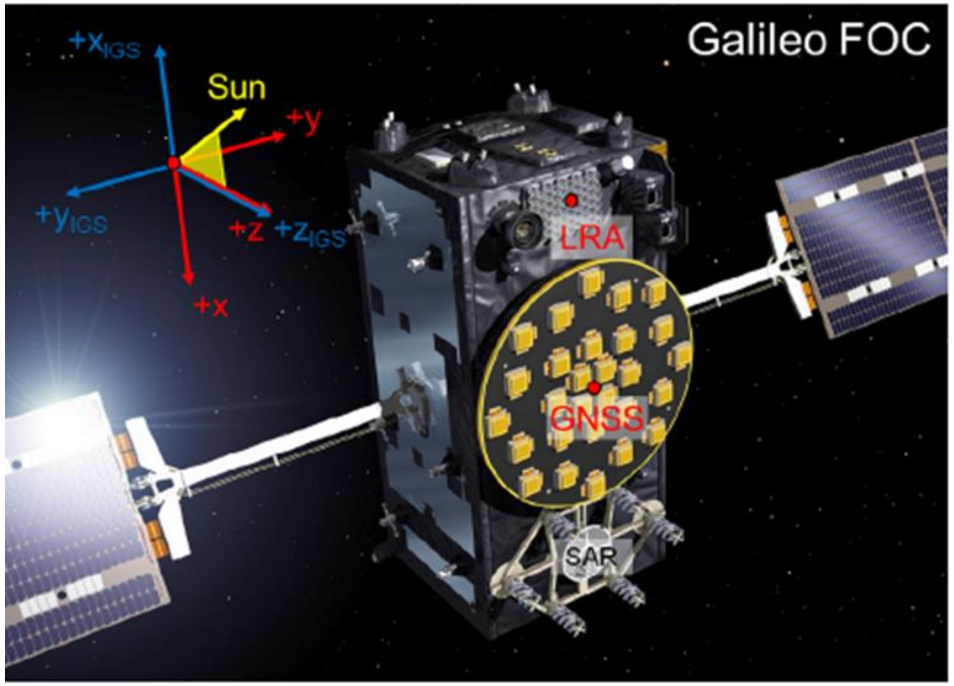
1. multiple reflections
2. mutual shadowing effects produced by the spacecraft surfaces and appendices

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.

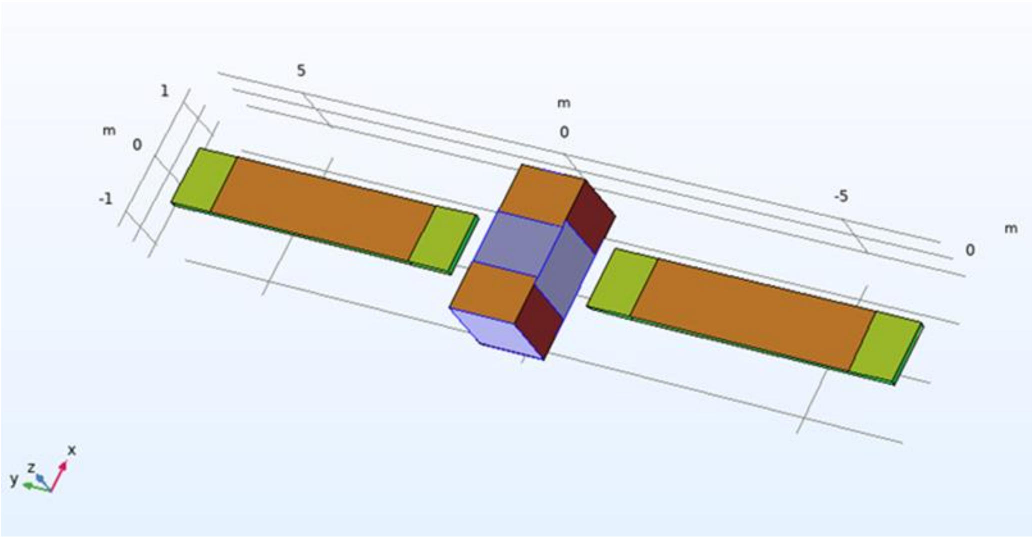


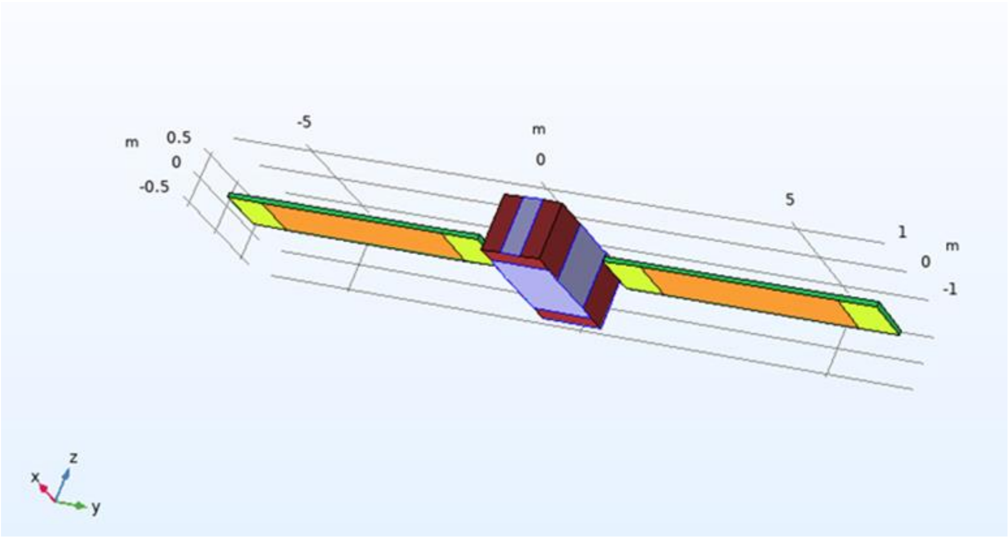
The Galileo FOC satellite.
Credits: Montenbruck et al., Adv. Space Res, 56, 6 (2015)

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)]



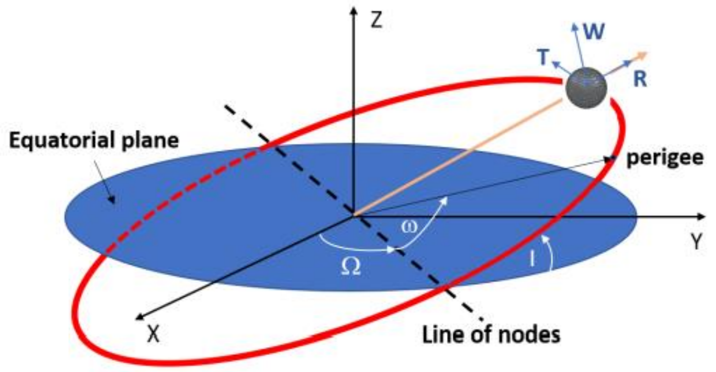


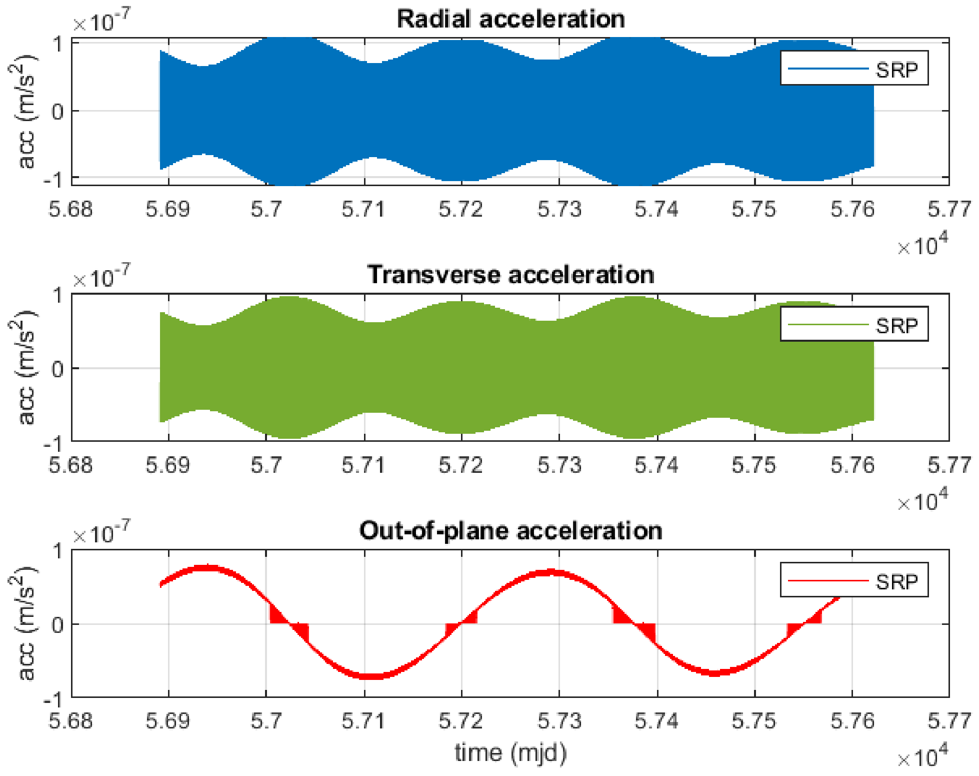
Our Box-Wing model with COMSOL.

Dynamical Model
Application with our S-BW

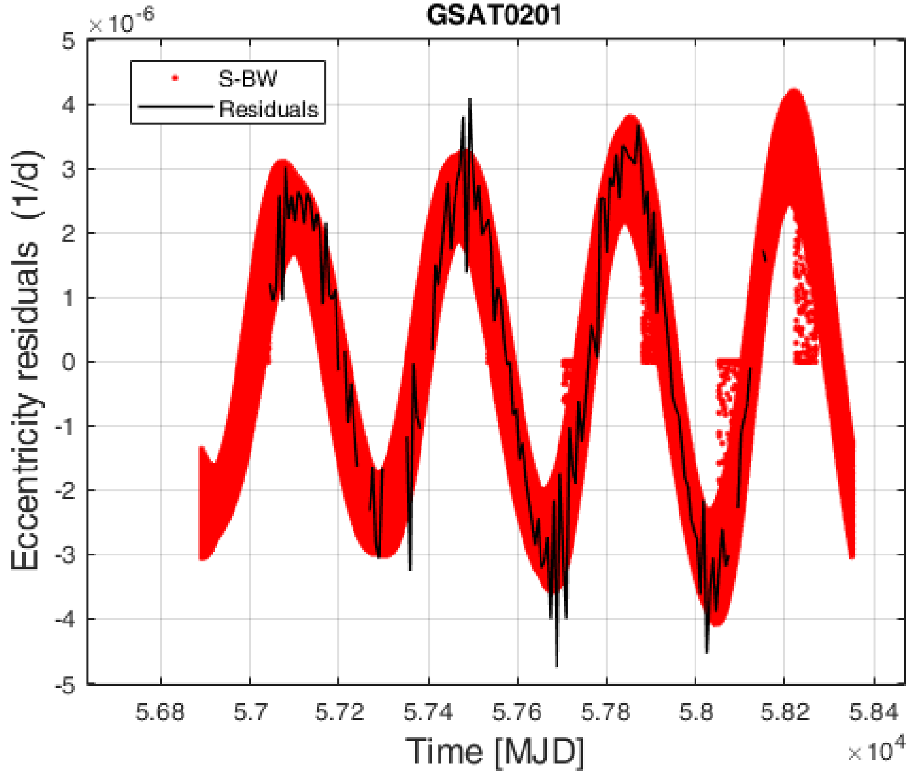
Interaction with the Solar Radiation Pressure (SRP)

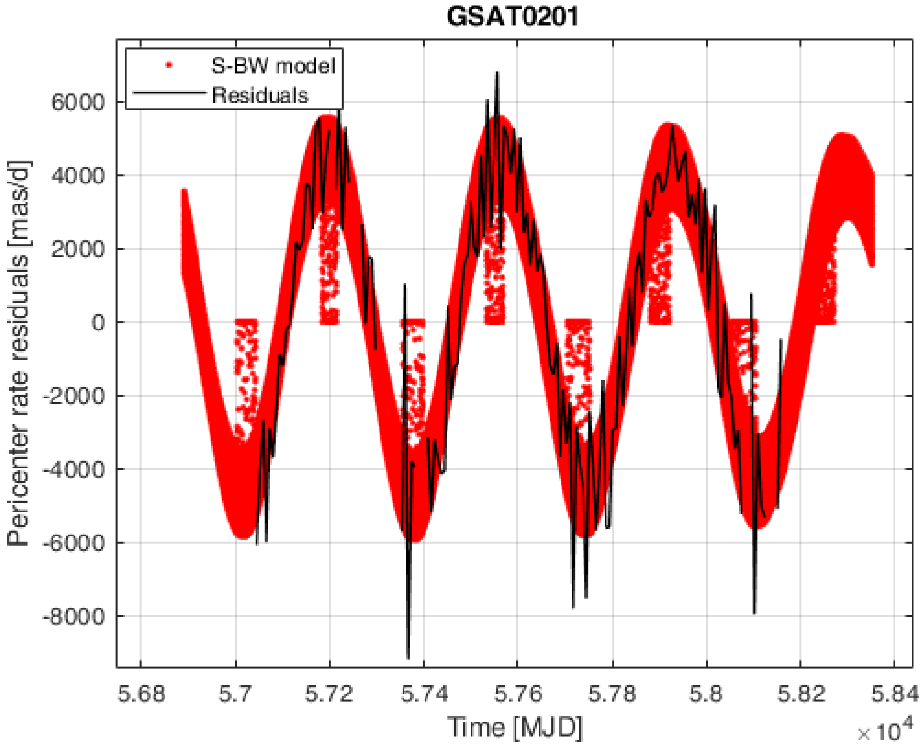
- Accelerations in the Gauss co-moving reference frame





Dynamical Model
Application with our S-BW

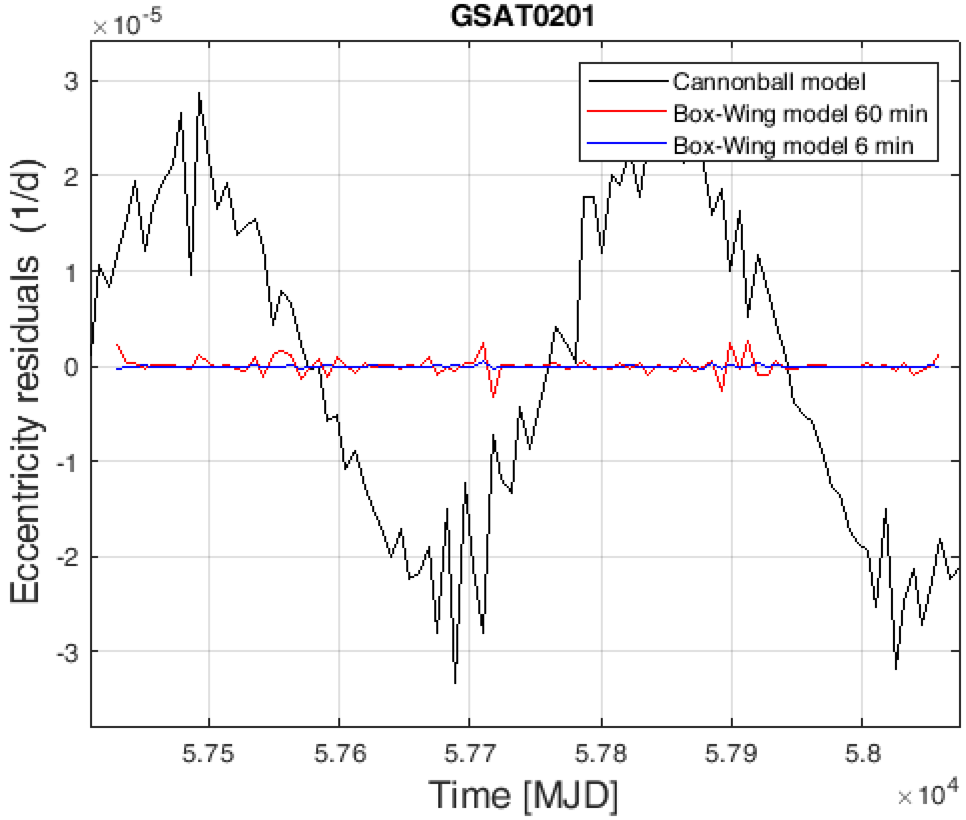


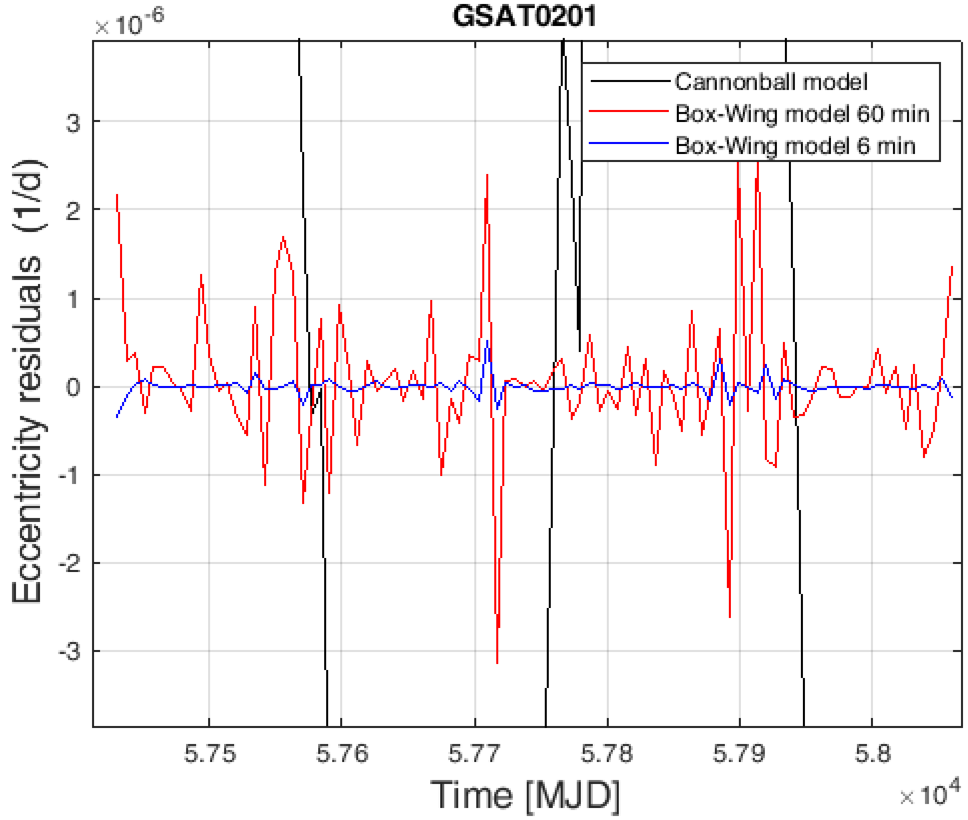


Comparison of the eccentricity and the argument of pericenter residuals with the corresponding prediction of the S-BW model on a 4 years timespan.

Dynamical Model

Application with our S-BW





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

A dedicated SLR Tracking Campaign for the Galileo for Science Project

Main motivation for more SLR observations

Improving the POD of the satellites
(Orbit modeling errors are strongly correlated to the clock solutions)

Reducing systematic errors
(mainly due to the SRP mismodeling)

The **SLR campaign** consists of:

1. a 2-years campaign for the two Galileo FOC on elliptical orbit for the gravitational measurements (gravitational redshift and relativistic precessions)
2. a 3-months campaign for a larger set of satellites (11 FOC + 3 IOV = 14 Galileo) to constrain Galactic Dark Matter
   - this campaign will be limited to 5 hours per week to limit the Stations burden (with 2 NPs per pass instead of 3 NPs)

A dedicated SLR Tracking Campaign for the Galileo for Science Project

Results: normal points average number per year and per day

Normal Points	GSAT0201	GSAT0202	GSAT0208
Number of NPs	13,244	18,923	15,249
NPs/yr	1661	2462	2235
NPs/day	4.4	6.7	6.1
NPs/day (no-GREAT)	2.7	6.6	5.1
NPs/day (GREAT)	10.9	7.2	9.0

From our GEODYN analysis we can deduced that at least 10 NPs per day are required to obtain a reliable and sufficiently robust POD.

A dedicated SLR Tracking Campaign for the Galileo for Science Project

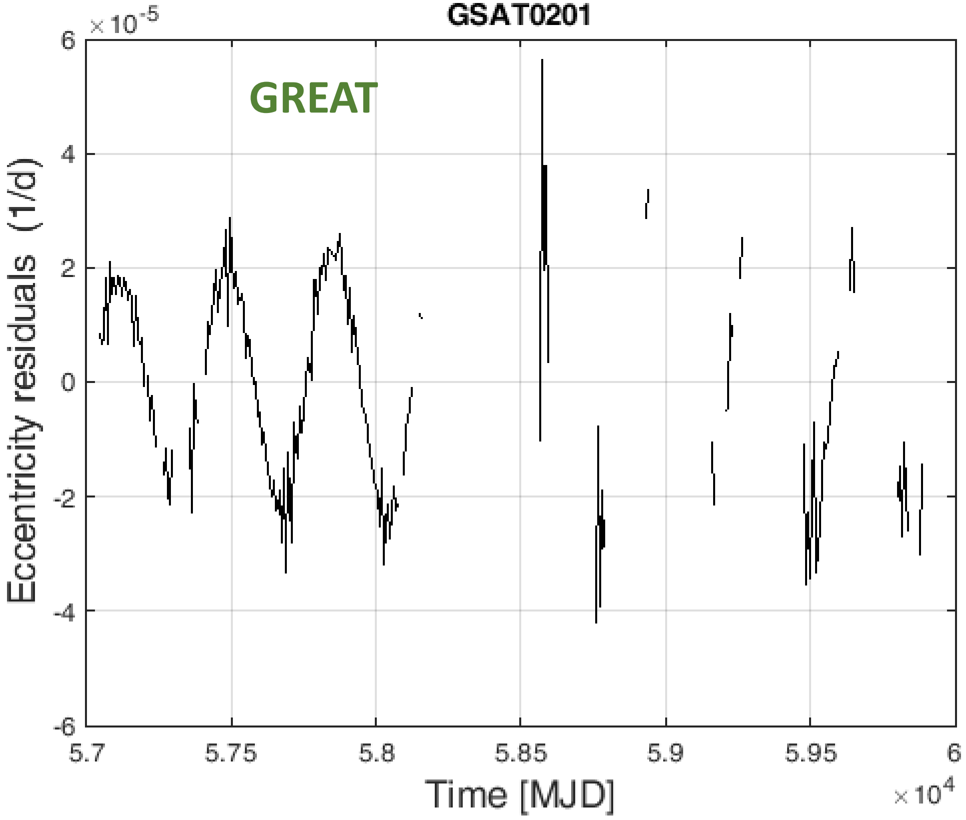
12-09-2014 — 02-25-2023

57000 MJD — 60000 MJD

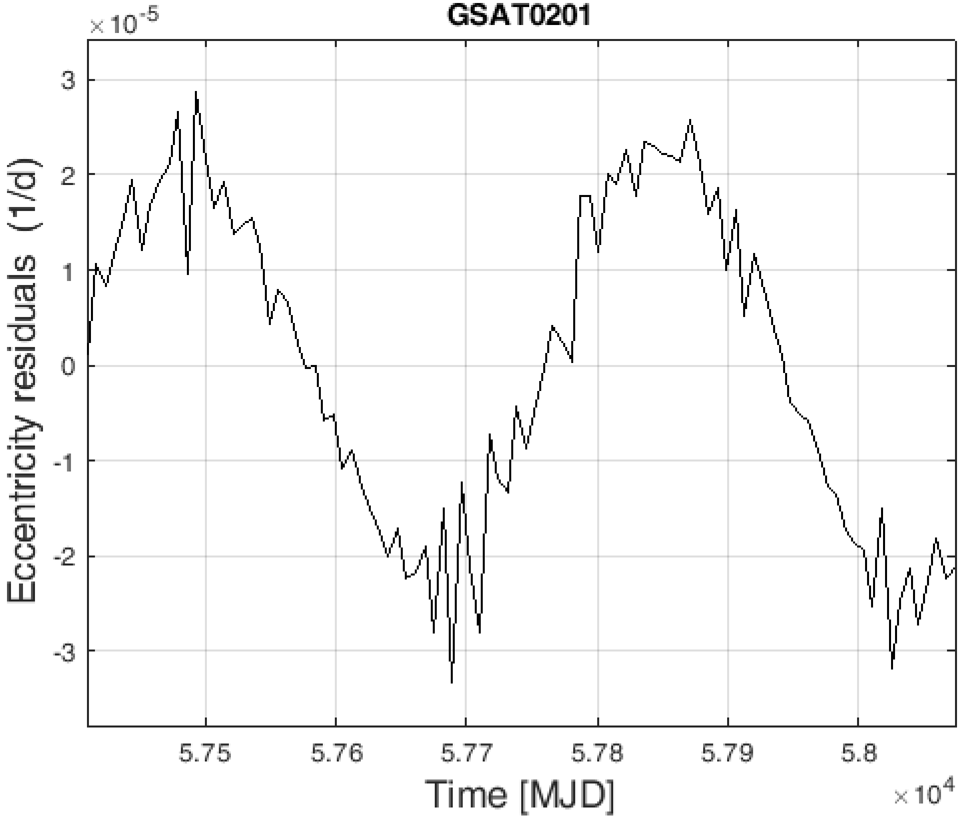
Average number NPs/day = 4.4

Results: orbits residuals and state-vector convergence GSAT0201

No gaps: 10.9 NPs



The whole period of the analysis: 8-years



The GREAT period of the analysis: 2-years

Conclusions and prospects

- G4S_2.0 project aims to provide several measurements in the field of Fundamental Physics by exploiting the Galileo FOC constellation.
- We built a S-BW according to ESA Galileo Metadata and we computed the SRP perturbing accelerations as well as those related with terrestrial albedo and infrared radiation pressure. These accelerations are used in the POD procedure to obtain a more reliable satellite orbit (as the residuals show).
- We asked for a dedicated SLR campaign that has been approved by the ILRS Governing Board.

Next steps:

- Building a more refined model of the spacecraft on the basis of available more detailed information and calculate updated, more refined accelerations due to NGPs;
- Performing a more accurate POD on the basis of the new data available from the dedicated SLR campaign;
- Performing the G4S_2.0 measurements.

Thanks for the attention