EGU General Assembly 2022

The Galileo for Science (G4S_2.0) project: Precise Orbit Determination for Fundamental Physics and Space Geodesy

(extended version)

EGU22 session G2.1:
'Precise Orbit Determination for Geodesy and Earth Science'

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Summary

- Galileo satellites on eccentric orbits and G4S_2.0 main goals
- The role of the Precise Orbit Determination
- First results
- Conclusions

Galileo satellites on eccentric orbits and G4S_2.0

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 ($e \cong 0.16$).

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

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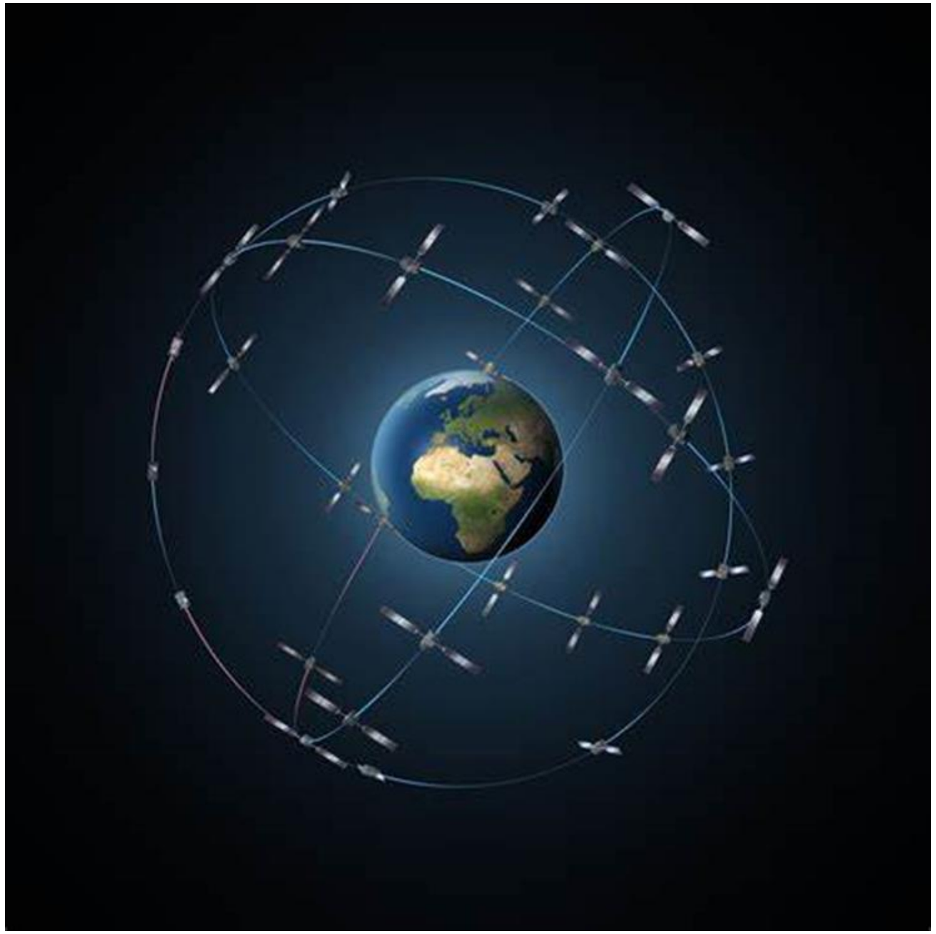
In this context, the Galileo for Science Project aims to perform a set of Fundamental Physics measurements with these two satellites.



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

Main scientific goals

1. A new measurement of gravitational redshift
2. A measurement of relativistic precessions on the orbits of the two eccentric satellites
3. Constraints on Dark Matter in the Milky Way
4. 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

Gravitational redshift

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

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

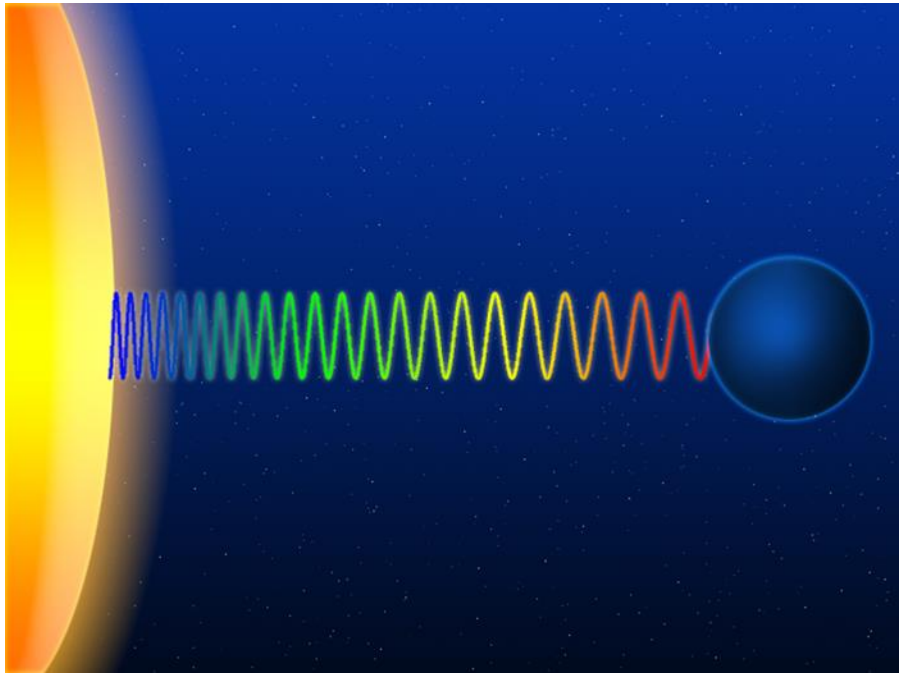
It is predicted by General Relativity but it is not a truly test of the Theory…

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.

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 $< 2\times10^{-5}$

Relativistic Precessions

- **Schwarzchild 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

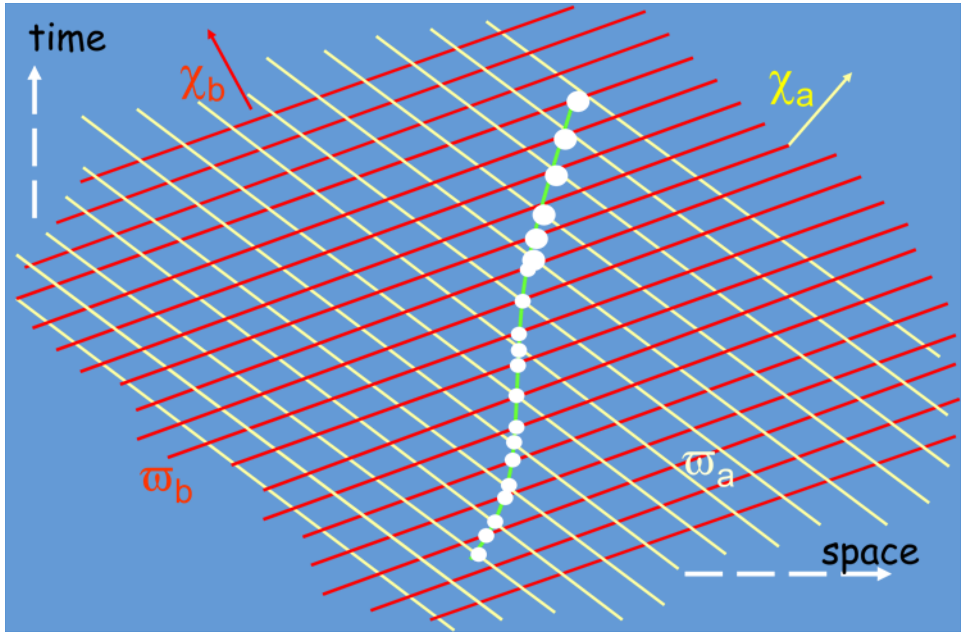
Relativistic Positioning System

The idea is to provide a precise orbit determination from Earth exploiting **Special Relativity** and **General Relativity**.
To this purpose, a set of Earth-stations emitting e.m. signals to satellites are required.

From the **proper-time intervals** measurements of the sequence of the arriving signals from the Earth-stations, it is possible to obtain the position of the receiver.

The **null emission** (or light) **coordinates**, for the receiver on a satellite, is obtained from a set of different emitters whose positions on the Earth and periods are assumed to be known.

Angelo Tartaglia, Acta Astronautica, 67, 539-545 (2010)
Angelo Tartaglia, Acta Futura, issue 7, 111-124 (2013)

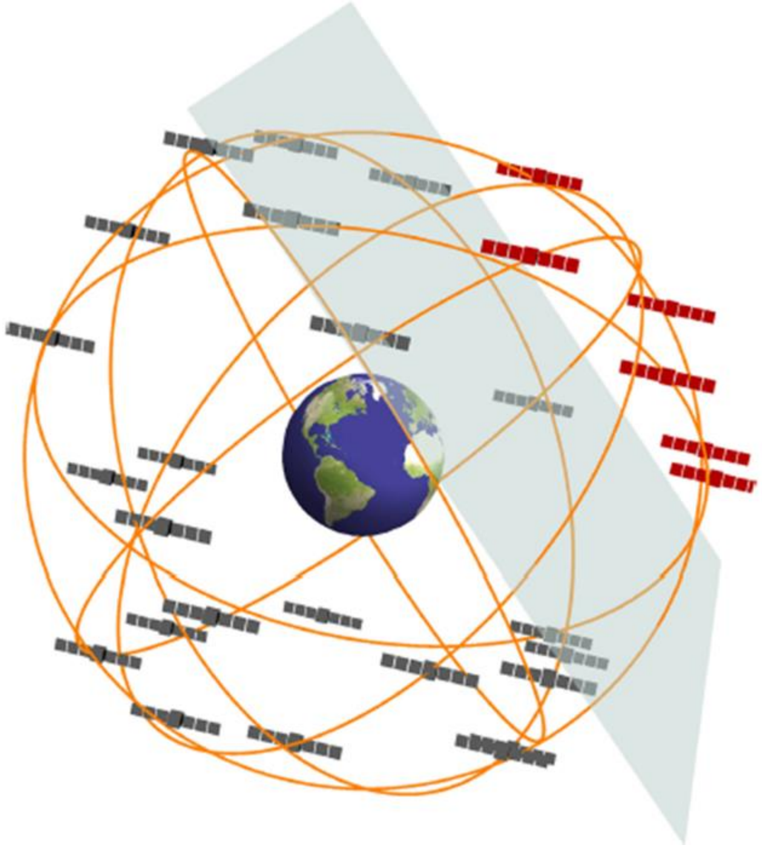


The wave fronts emitted by two ground stations (ω_a, ω_b) intersect with the position of the satellite (white dots).

Constraints on Dark Matter

DM could arise from very light quantum fields that form macroscopic objects or clumps. Examples of clumpy DM candidates are topological defects (TDs), such as domain walls.

As the Earth moves through the galactic dark matter halo, interactions with domain walls could cause a sequence of atomic clock perturbations that propagate through the satellite constellation.

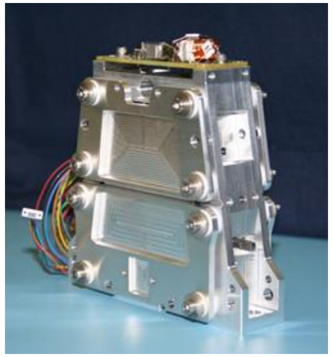
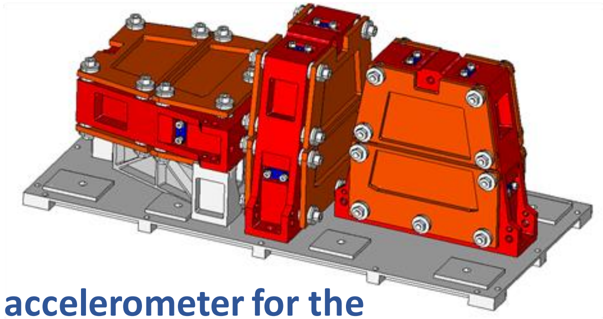


- Analyzing 16 years of GPS-data, Roberts et al. (2017) have found no evidence for the existence of domain walls (see also the ESA GASTON Project).

- The current constellation of Galileo FOC satellites can allow an improvement of this constrain exploiting the higher sensitivity of the onboard atomic clocks.

A new concept of accelerometer

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.

The role of the Precise Orbit Determination

To achieve these significant results, a fundamental point is obtaining a satellite orbit solution precise as far as possible

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An accurate **Precise Orbit Determination** (POD) has to be performed

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It requires an enhancement of the Non-Gravitational Perturbations models, in particular for the solar radiation pressure (SRP), to derive the perturbative accelerations

To this purpose, our ultimate goal is to develop a **Finite Element Model** (FEM) of the satellite. Moreover, we want to apply a Ray-Tracing technique to take into account umbra, penumbra and multiple reflections on the satellite itself.

The role of the Precise Orbit Determination

Main non-gravitational accelerations

Physical effects	*Formula*	*LAGEOS II*	*Galileo FOC*
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	$\frac{2}{3}\frac{\sigma}{c}\frac{A}{M}(\epsilon_1 T_1^4-\epsilon_2 T_2^4)$	—	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}

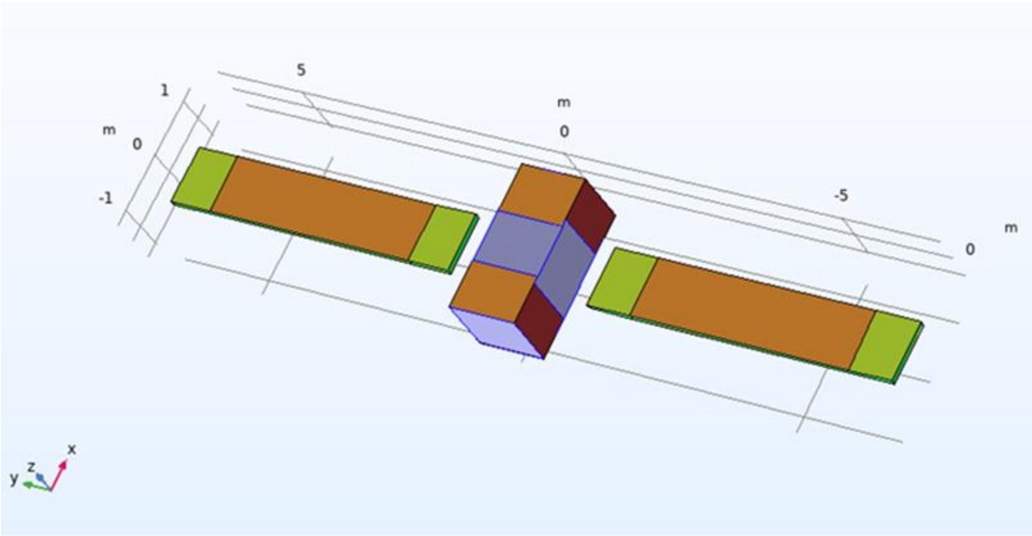
The role of the Precise Orbit Determination

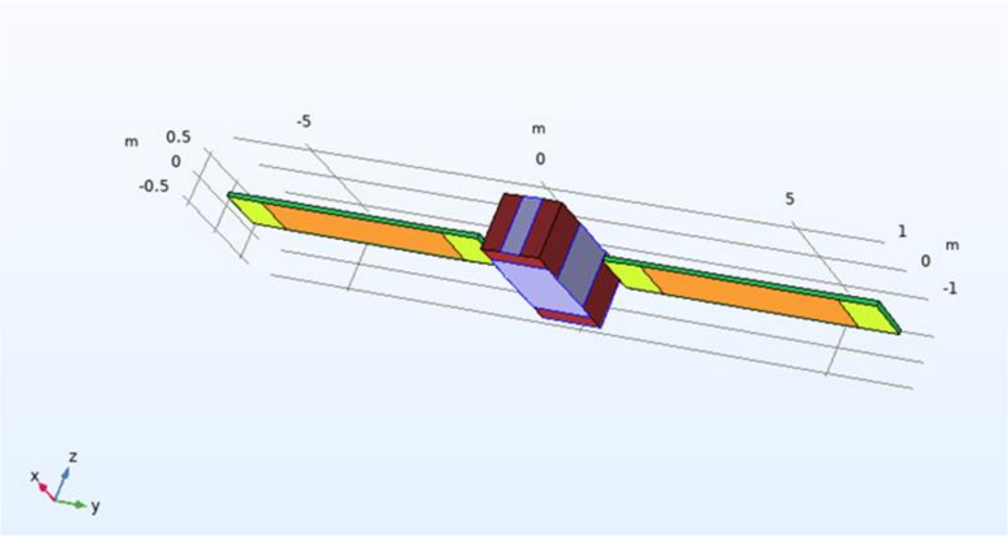
Box-Wing Model

Preliminary to the final 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)](https://www.gsc-europa.eu)





Our Box-Wing model with COMSOL.

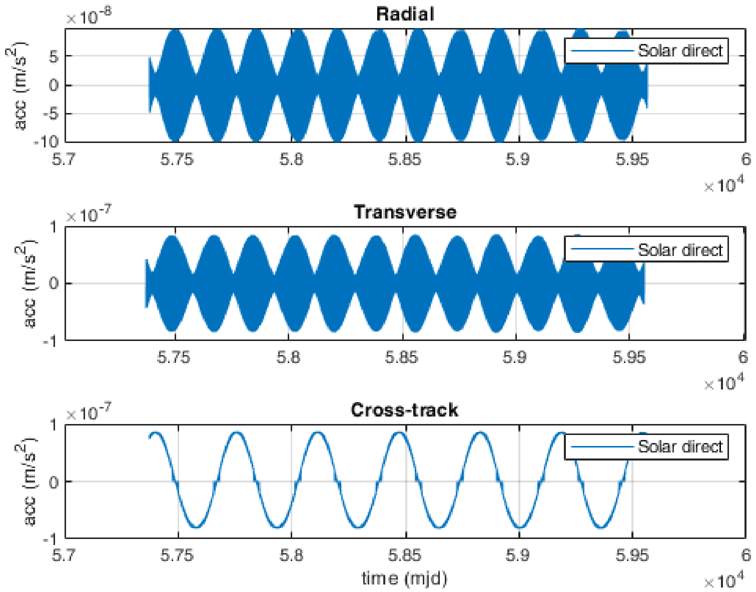
First results

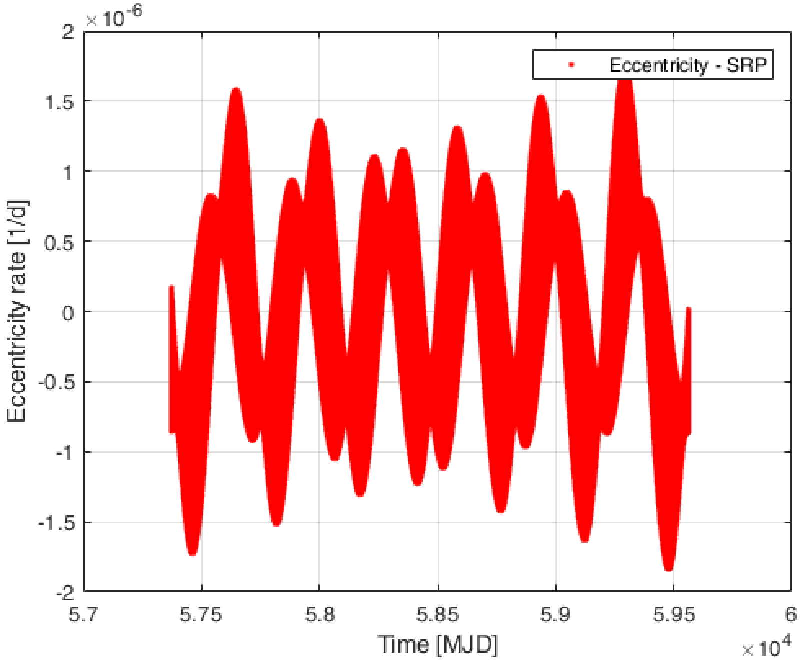
Preliminary results: *Box Wing for GSAT-0208 (ESA Galileo Metadata)*

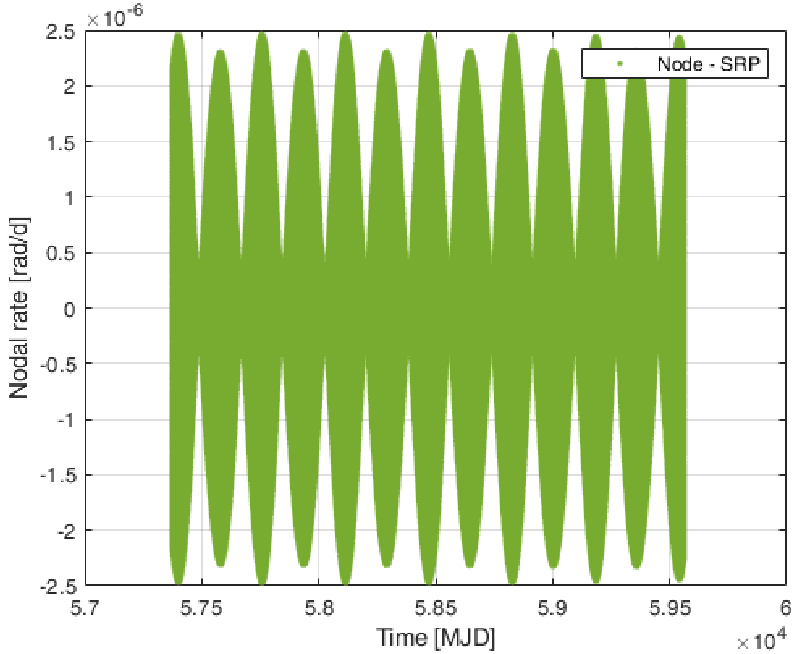
Gauss accelerations

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

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



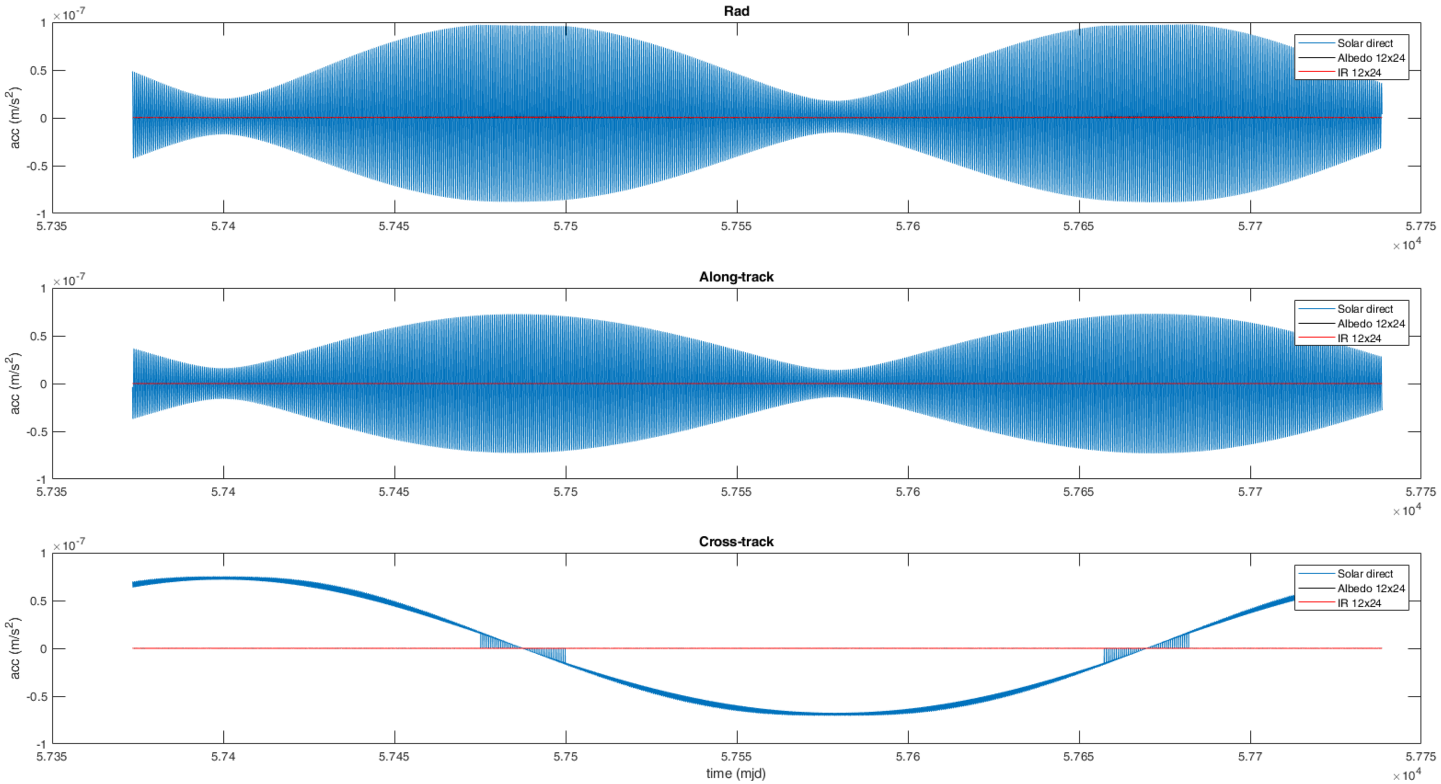


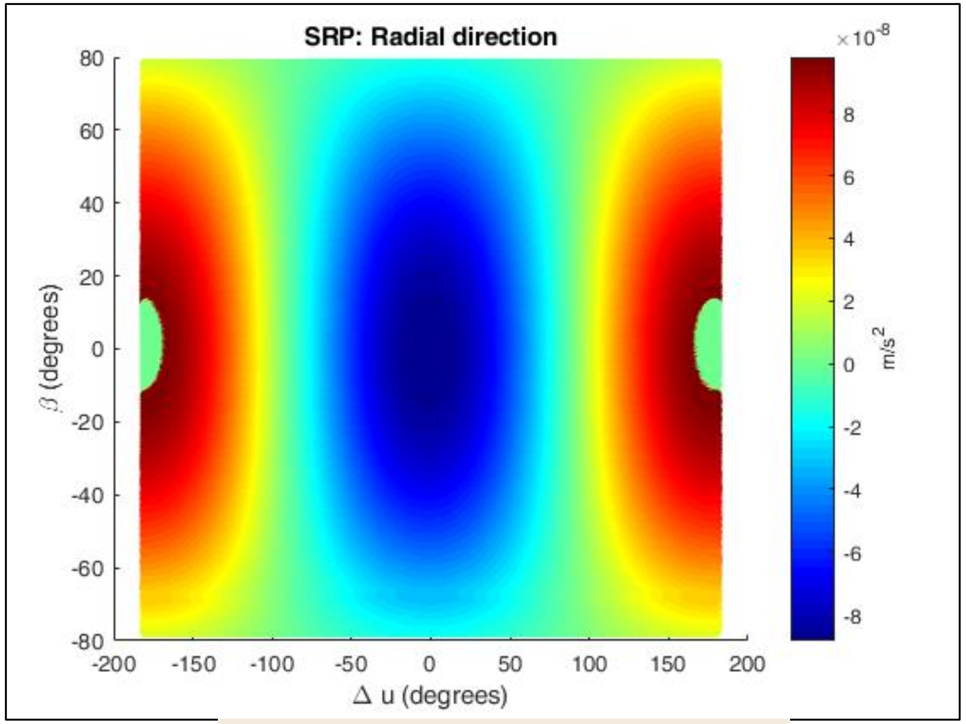


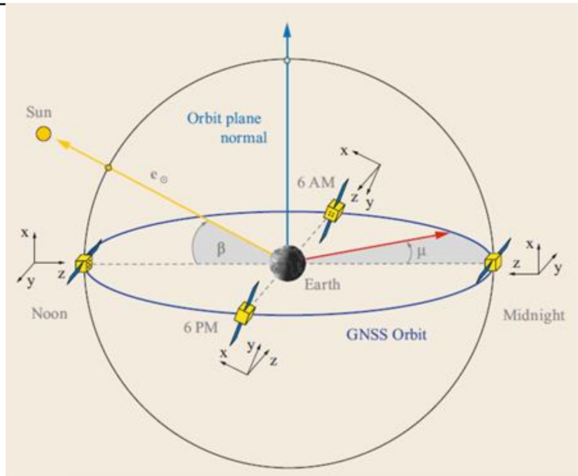
First results

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

A 1-year simulation with the BW model



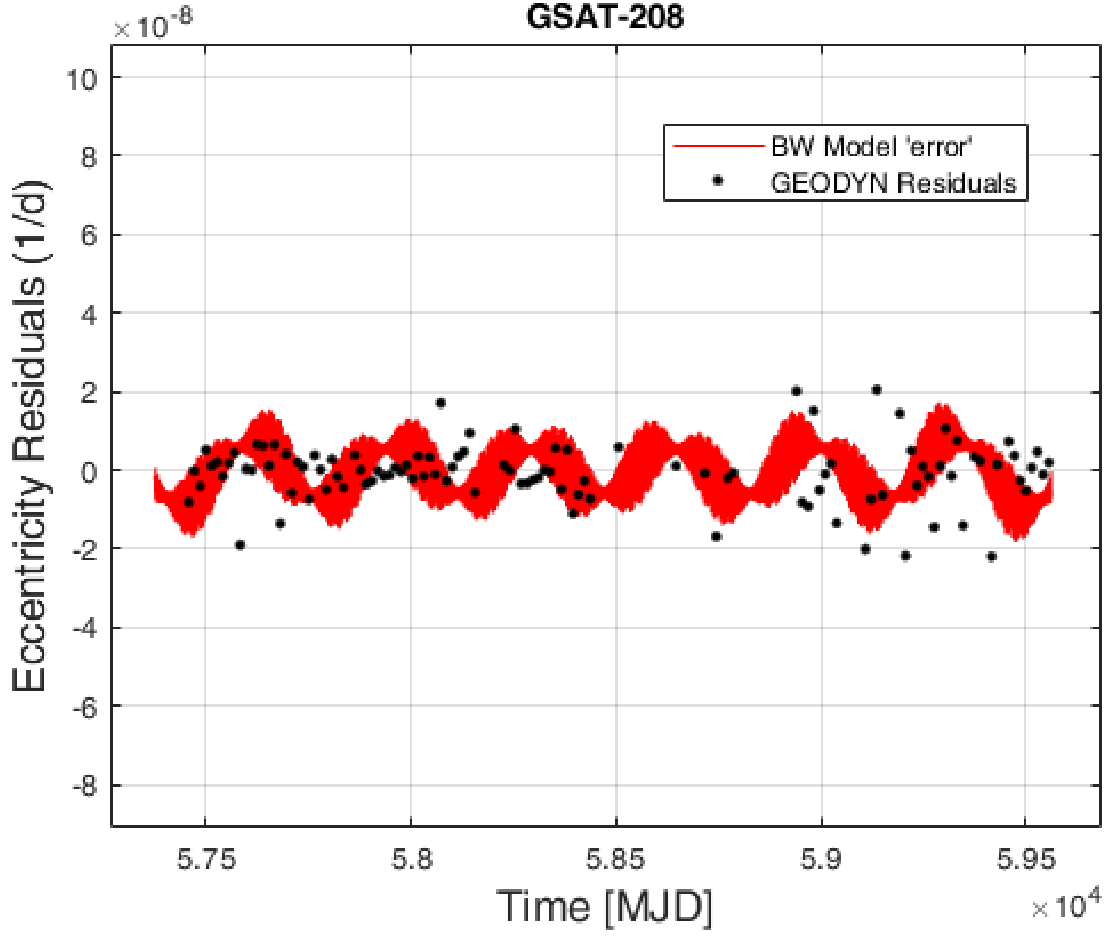




Radial, along track and cross track accelerations due to Solar Radiation Pressure, Albedo and Infrared Radiation.

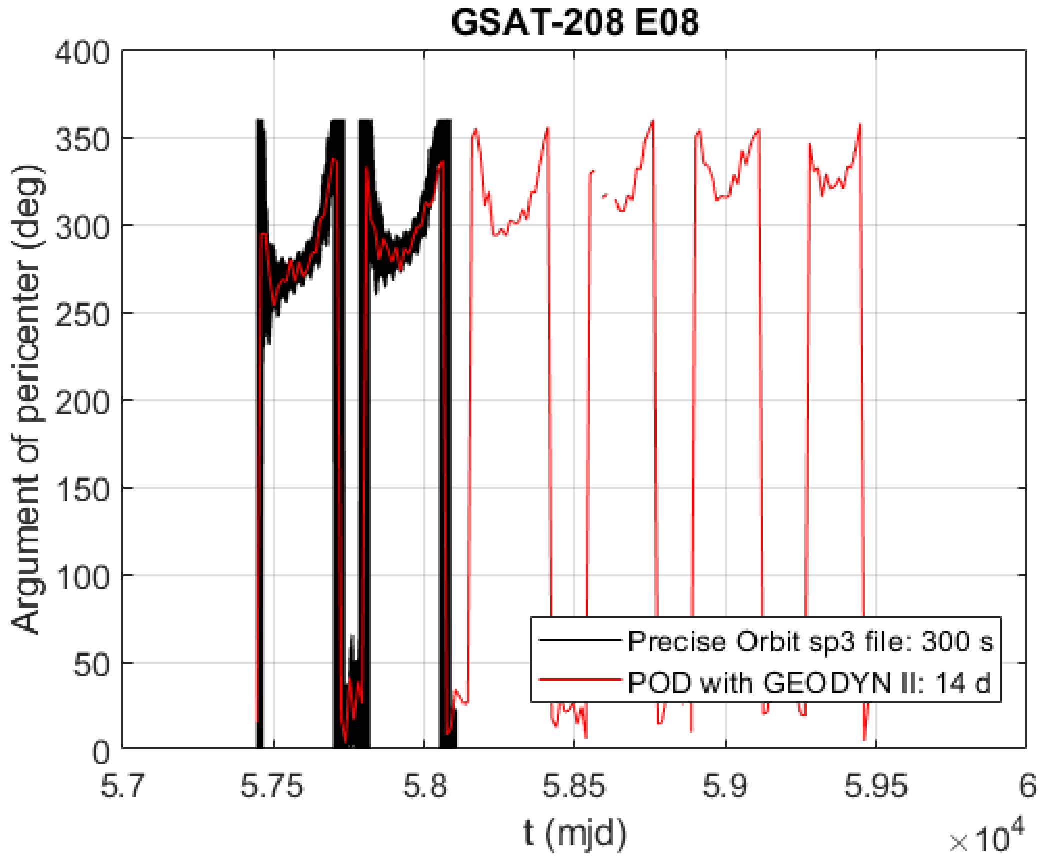
First results

Preliminary results: *Comparison with residuals*



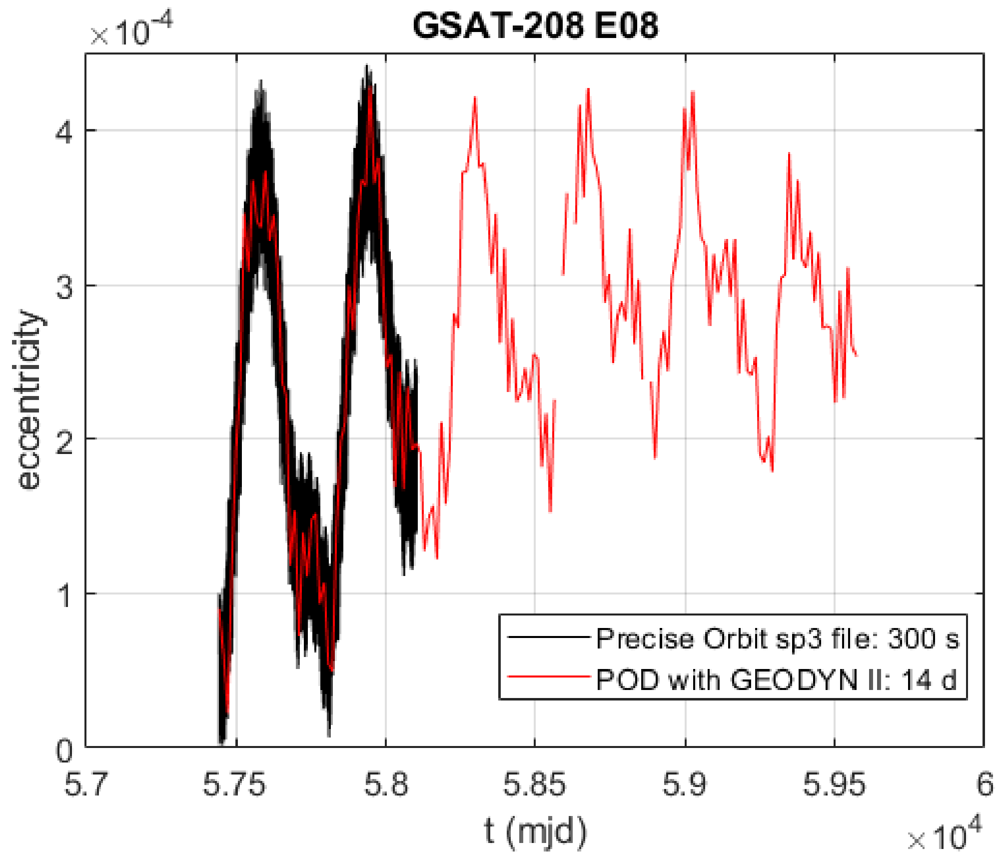
First results

Preliminary results: *GEODYN POD vs sp3*



First results

Preliminary results: *GEODYN POD vs sp3*



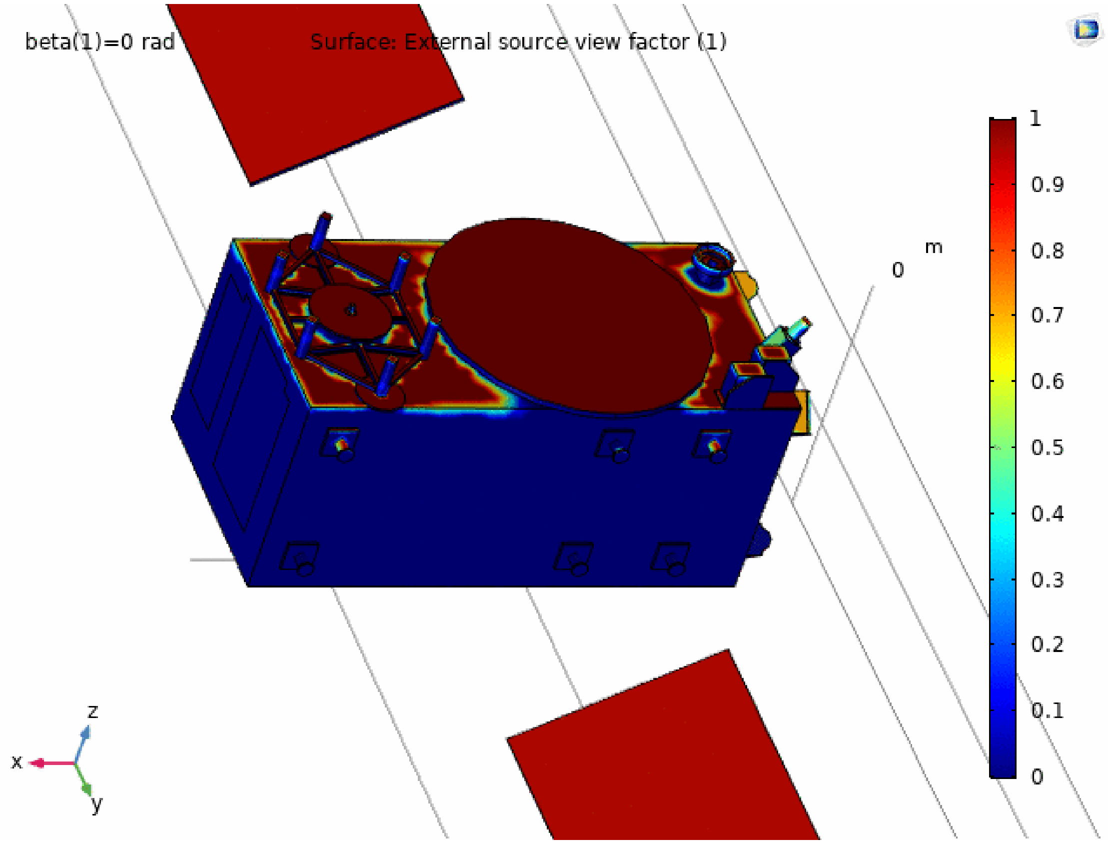
Finite Element Model

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

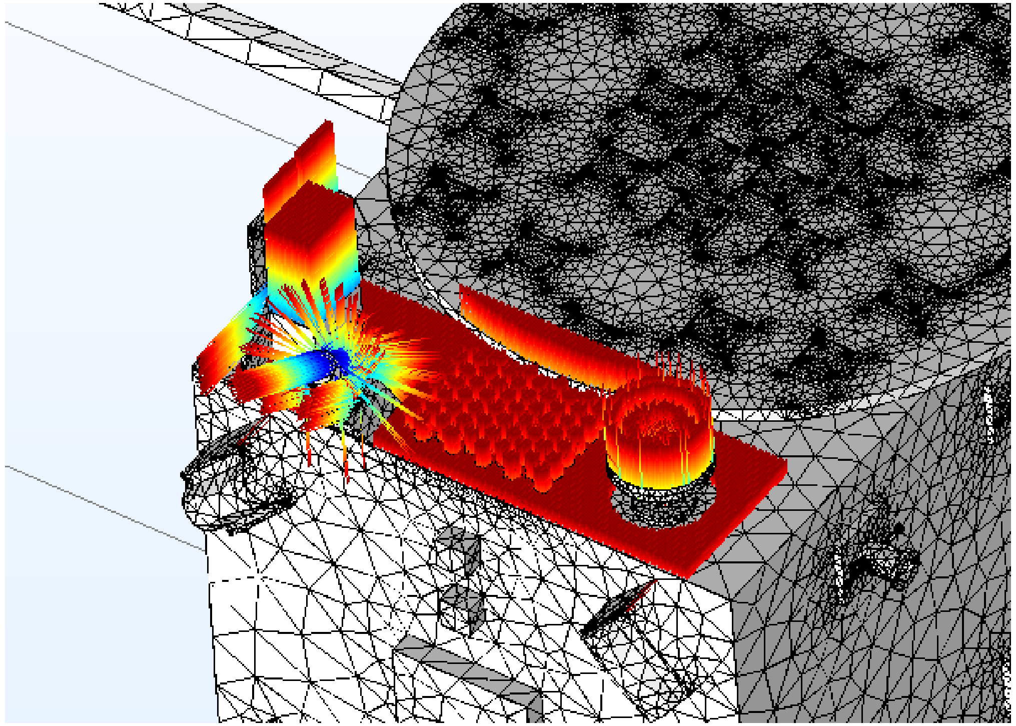
The development of a really refined FEM requires:

1. a very accurate representation of the complex geometry of the spacecraft
2. the knowledge of the physical characteristics (such as optical and thermal) of each kind of surface and element (antenna, appendices, CCR, …) that constitute the spacecraft
3. the knowledge of how these characteristic (especially the optical ones) evolve in time and how they are function, for instance, of the illumination conditions
4. to account for multiple reflections
5. the knowledge with high accuracy of the spacecraft attitude-law
6. to model the mutual shadowing effects produced by the spacecraft surfaces and appendices, in order to account for umbra and penumbra effects

Ray-Tracing preliminary activities



s/w
COMSOL



Conclusions

- We presented part of the ongoing activities within the G4S_2.0 project focusing on the BW model and on the POD of the satellites obtained with GEODYN (analyzing only SRL data). The preliminary results are positive and encouraging in both cases.

- We plan to develop an improved Box-Wing (IBW) model based on more in-depth information on the optical characteristics of Galileo FOC satellites and to begin the application of the Ray-Tracing technique to this model.

- In addition to GEODYN, the Bernese software will also be used for the Fundamental Physics measurements of the project:
  - gravitational redshift, as a test of Local Position Invariance
  - GR precessions, with consequent constraints to possible alternative theories of gravitation.

Thanks for your attention