Workshop sulla Gravitazione Sperimentale: misure laser, fisica fondamentale e applicazioni in INFN-CSN2
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Fundamental Physics with Galileo Satellites

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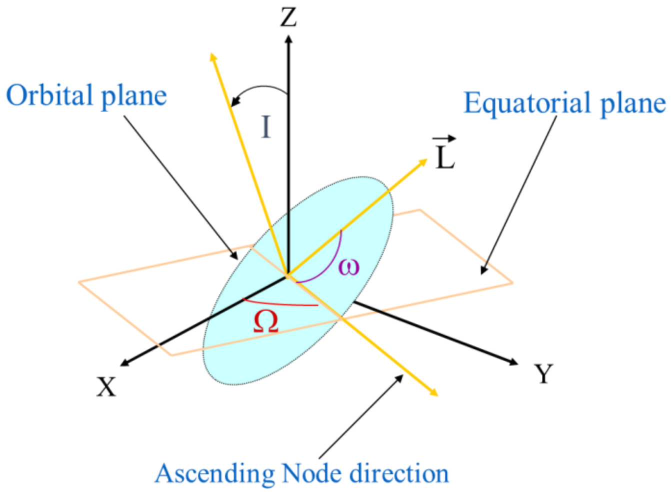
GENERAL GOAL

- To perform reliable measurements of Fundamental Physics with the two FOC Galileo S/C (GNSS) on eccentric orbits:
    - DORESA and MILENA (corrected orbits)



Satellite	SV ID	Slot	a(Km)	e	I (°)	RAAN (°)	ARGP (°)	MA (°)
GSAT0201	18	Ext01	27977.6	0.162	49.850	52.521	56.198	316.069
GSAT0202	14	Ext02	27977.6	0.162	49.850	52.521	56.198	136.069
GSAT0203	E26	B08	29599.8	0.0	56.0	77.632	0.0	150.153

GENERAL RELATIVITY MEASUREMENTS

- Relativistic measurements to be performed on the eccentric orbits of GSAT-201 and GSAT-202:
  - Gravitational red shift using clock
  - Secular effects on the orbit elements (not easy indeed)
  - Periodic effects on the orbit elements (much more demanding than the first ones…)
- Work is done in the linear approximation of General Relativity (GR):
  - Weak-field and slow-motion (WFSM) limit

$$\frac{m}{r} = \frac{GM_{\oplus}}{rc^2} \ll 1 \qquad \frac{GJ_{\oplus}}{c^3 r^2} = \frac{j}{r^2} \ll 1 \qquad \frac{j}{mr} \ll 1 \qquad \frac{v}{c} \ll 1$$

SCHWARZSCHILD PRECESSION OF THE ORBIT

Gravitoelectric field produces the Schwartzschild secular precession of two Keplerian parameters

Precession of the argument of perigee	$$\left\langle \frac{d\omega}{dt} \right\rangle = \left(\frac{2 + 2\gamma - \beta}{3} \right) \frac{3\left(GM_{\oplus}\right)^{3/2}}{c^2\, a^2 (1 - e^2)}$$
Precession of mean anomaly	$$\left\langle \frac{dM}{dt} \right\rangle = \left(\frac{2 + 2\gamma - \beta}{3} \right) \frac{3\left(GM_{\oplus}\right)^{3/2}}{c^2\, a^{5/2} (1 - e^2)^{1/2}}$$

The orbit rotates in its plane without changing shape.

DE SITTER EFFECT

De Sitter o geodetic secular precession drag the orbital plane as an enormous gyroscope. The effect is due to the curvature induce by the central mass (Sun).

Precession of the longitude of ascending node.

$$\left\langle \frac{d\Omega}{dt} \right\rangle = \left(\frac{1}{2} + \gamma \right) \frac{G M_{\odot}}{c^2 R^3_{\odot\oplus}} \left| \left(\vec{v}_{\oplus} - \vec{v}_{\odot} \right) \times \vec{x}_{\odot\oplus} \right| \cos \varepsilon_{\odot}$$

The value is the same for all the satellite orbiting around the Earth: **17.6 mas/yr**

LENSE THIRRING EFFECT ON THE ORBIT

Above Schwartzschild or Einstein precession, the Lense Thirring secular precession on two keplerian parameters appears.

Precession of the longitude of the ascending node	$$\left\langle \frac{d\Omega}{dt} \right\rangle = \left(\frac{1+\gamma}{2}\right) \frac{2\,G}{c^2\,a^3} \frac{J_\oplus}{(1-e^2)^{3/2}}$$
Precession of the argument of perigee	$$\left\langle \frac{d\omega}{dt} \right\rangle = \left(\frac{1+\gamma}{2}\right) \frac{-6GJ_\oplus}{c^2\,a^3(1-e^2)^{3/2}} \cos I$$

- The angular momentum of central body $J_\oplus$ *drags* the orbiting mass current.
- The orbital plane acts as an enormous gyroscope dragged by the rotation of the central body.
- The plane of the orbit precedes around the central body.

RELATIVISTIC PRECESSIONS

Numerical values for the relativistic precessions on the argument of pericenter and node of the two LAGEOS satellites and of GSAT-201/202 and 203:

Rate (mas/yr)	LAGEOS II	LAGEOS
	1 mas = 1 milli arc sec	
$\Delta\dot{\omega}_E$	+ 3351.95	+ 3278.77
$\Delta\dot{\omega}_{LT}$	– 57.00	+ 32.00
$\Delta\dot{\Omega}_{LT}$	+ 31.50	+ 30.67
$\Delta\dot{\Omega}_{dS}$	+ 17.60	+ 17.60

Rate (mas/yr)	GSAT-201/202	GSAT-203
	1 mas = 1 milli arc sec	
$\Delta\dot{\omega}_E$	+ 428.88	+ 362.74
$\Delta\dot{\omega}_{LT}$	– 5.21	– 3.67
$\Delta\dot{\Omega}_{LT}$	+ 2.69	+ 2.18
$\Delta\dot{\Omega}_{dS}$	+ 17.60	+ 17.60

The measurements are much more challenging in the case of the Galileo satellites

- In particular in the case of the LT effect (the GR precession is more than a factor of 10 smaller than the LAGEOS one)
- However, the measurement of Schwarzschild precession is favorable, particularly if LAGEOS II is also considered
- Consequently, also the constraints in Yukawa-like interactions are promising

GRAVITATIONAL AND NOT GRAVITATIONAL ACCELERATIONS

		Accelerations [m/s²]	
Physical effect	**Formula**	**LAGEOS II**	**Galileo FOC**
Earth's monopole	$\frac{GM_\oplus}{r^2}$	2.6948	0.4549
Earth's oblateness	$3\frac{GM_\oplus}{r^2}\left(\frac{R_\oplus}{r}\right)^2 \bar{C}_{2,0}$	1.08×10^{-3}	3.1×10^{-5}
Low-order geopotential harmonics:	$3\frac{GM_\oplus}{r^2}\left(\frac{R_\oplus}{r}\right)^2 \bar{C}_{2,2}$	5.4×10^{-6}	1.5×10^{-7}
Low-order geopotential harmonics:	$7\frac{GM_\oplus}{r^2}\left(\frac{R_\oplus}{r}\right)^6 \bar{C}_{6,6}$	3.7×10^{-9}	3.0×10^{-12}
High-order geopotential harmonics:	$13\frac{GM_\oplus}{r^2}\left(\frac{R_\oplus}{r}\right)^{12} \bar{C}_{12,12}$	3.7×10^{-11}	1.4×10^{-16}
Moon	$2\frac{GM_m}{r_m^3}r$	2.2×10^{-6}	5.3×10^{-6}
Sun	$2\frac{GM_\odot}{r_\odot^3}r$	9.6×10^{-7}	2.3×10^{-6}
Third body: Venus	$2\frac{GM_v}{r_v^3}r$	1.2×10^{-10}	3.0×10^{-10}
Indirect oblation	$3\frac{GM_\oplus}{r_m^2}\left(\frac{R_\oplus}{r_m}\right)^2 \frac{M_m}{M_\oplus}\bar{C}_{2,0}$	1.4×10^{-11}	1.4×10^{-11}
GR correction	$\frac{GM_\oplus}{r^2}\frac{GM_\oplus}{c^2}\frac{1}{r}$	9.8×10^{-10}	6.8×10^{-11}
Dynamic solid tide	$3k_2\frac{GM_m}{r_m}\left(\frac{R_\oplus}{r_m}\right)^2\frac{R_\oplus^3}{r^4}$	3.9×10^{-8}	1.1×10^{-9}
Dynamic oceanic tide	0.1 of the dynamic solid tide	3.9×10^{-9}	1.1×10^{-10}
Kinematic solid tide	$h\left(\frac{2\pi}{T_{syn}/2}\right)^2$	5.8×10^{-7}	5.8×10^{-7}
Kinematic solid tide	$h_L\left(\frac{2\pi}{T_{syn}/2}\right)^2$	9.7×10^{-8}	9.7×10^{-8}

		Accelerations [m/s²]	
Physical effect	**Formula**	**LAGEOS II**	**Galileo FOC**
Neutral drag	$\frac{1}{2}C_D\frac{A}{M}\rho V^2$	2.6×10^{-13}	—
Charged drag	Andrés (2007), Chap 5	2.0×10^{-12}	NA
Solar radiation pressure	$C_r\frac{A}{M}\frac{\Phi_\odot}{c}$	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 IR	$\frac{A}{M}\frac{\Phi_{IR}}{c}\frac{R_\oplus^2}{r^2}$	1.5×10^{-10}	1.1×10^{-9}
Power radiated by the antennas	$\frac{P}{Mc}$	—	1.2×10^{-9}
ISL Antenna	$\frac{P}{Mc}$	—	—
Solar Yarkovsky-Schach	$\frac{16}{9}\frac{A}{M}\frac{\varepsilon\sigma}{c}T_0^3\Delta T$	1.0×10^{-10}	NA
Earth Yarkovsky	$0.41\frac{4}{9}\frac{A}{M}\frac{\varepsilon\Phi_{iR}}{c\alpha}\frac{f_0 R_\oplus^2}{r^2}$	2.5×10^{-11}	NA
Asymmetric reflectivity	$\frac{1}{4}\frac{A}{M}\frac{\Phi_\odot}{c}\delta_a$	1.2×10^{-11}	NA
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}
Thermal effects from solar panels	$\frac{2}{3}\frac{\sigma A}{Mc}\left(\varepsilon_1 T_1^4-\varepsilon_2 T_2^4\right)$	—	1.9×10^{-10}
Y-bias	Y_0: empirical acceleration	—	7.0×10^{-10}

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STRATEGIES OF MEASUREMENTS

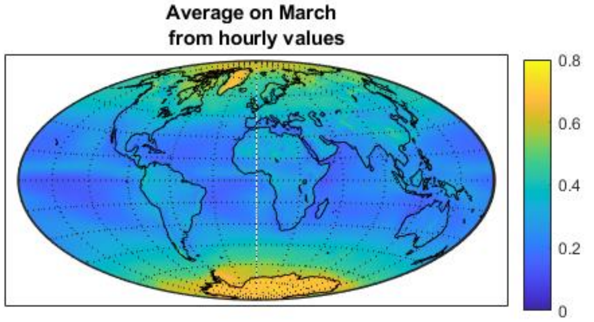
- In order to highlight the GR periodic effects on the orbit of the GSAT-201 and 202 we need to improve modeling of the NGP down to an acceleration level $\leq 10^{-10}$ m/s^2
- For instance, the bulk of the acceleration due to the direct solar radiation pressure (SRP) on the solar panels is about 350 times larger than the acceleration produced by the main GR effect due to Schwarzschild's contribution
- On the basis of our experience with LAGEOS satellites, one of the main challenge is represented by the knowledge of the temperature distribution of the S/C and the development of a reliable model for the thermal perturbations
- POD based on very short arcs and use of different software

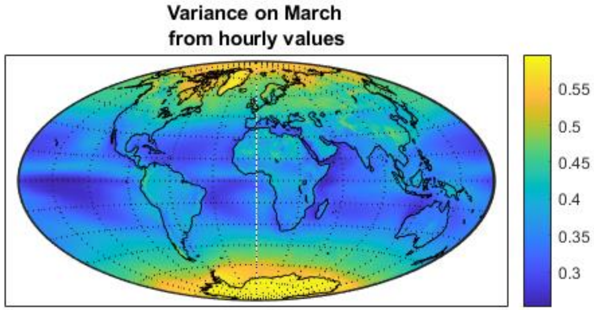
REQUIREMENT TO MODEL MAIN NGP

To model the acceleration due to radiation on the satellite one needs:

- A model of the source (solar flux, Earth albedo, Earth IR)
- Satellite shape and surface properties and time degradation
- Satellite orbit and attitude

USE OF CERES DATA FOR THE SOURCES





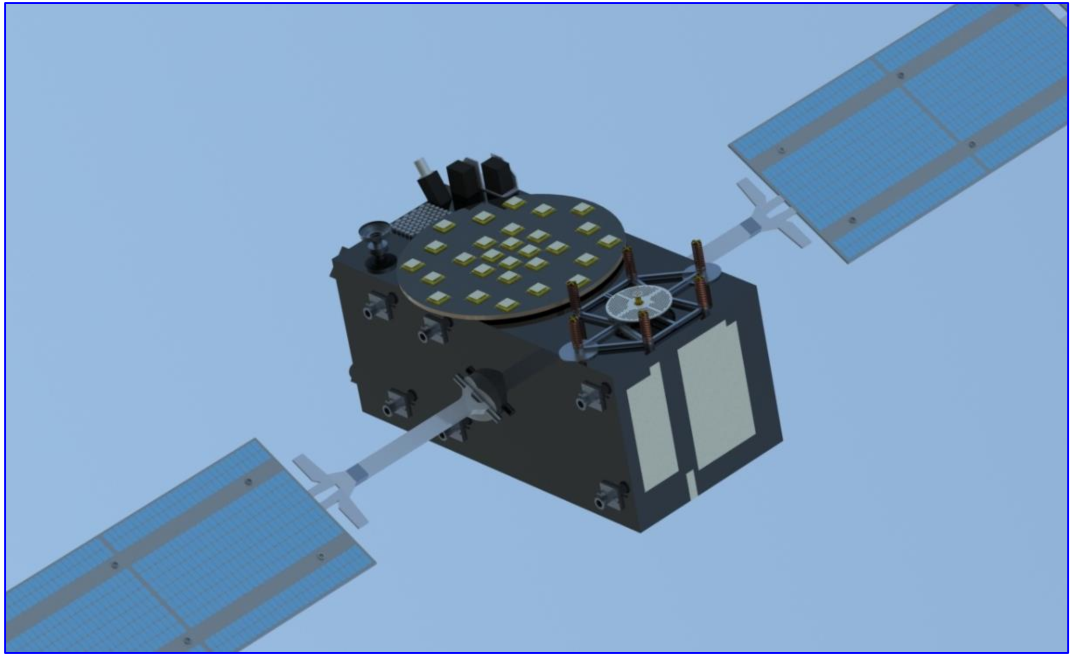
CERES (Clouds and Earth's Radiant Energy System) measures in three bands solar-reflected and Earth-emitted radiation from the top of the atmosphere to the Earth's surface.

Using the CERES data we can :

- calculate different averages (hourly, montly etc) of Earth Albedo and Earth IR.

https://ceres.larc.nasa.gov/data/

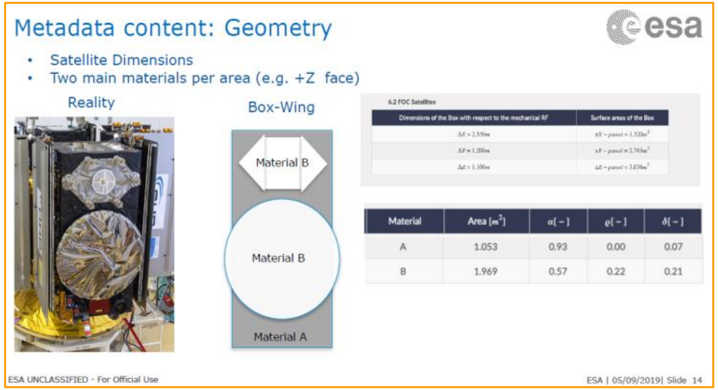
REALISTIC 3D MODEL

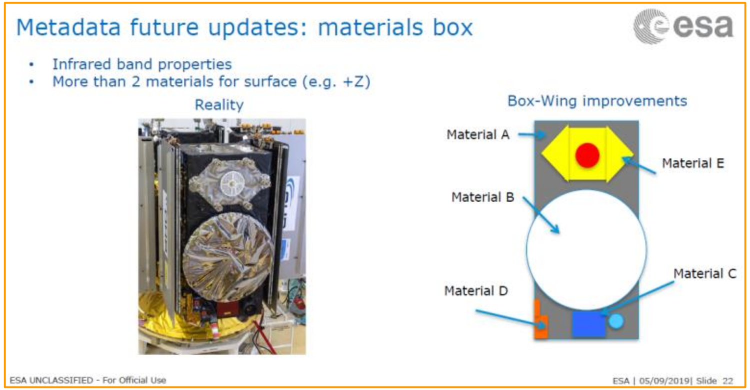


Starting from this realistic model a simplified FEM model can be calculated

GALILEO METADATA

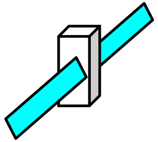
Creating a complete model is made difficoult by the lack of information about surface materials and their characteristics





Slides from: Gonzalez, F., Dilssner, F.: Galileo Satellite Metadata: Galileo Metadata for scientific products, source and future updates. 7th International Colloquium on Scientific and Fundamental Aspects of GNSS. ETH Zurich, 4-6 September (2019)

We started developing a simple BOX-WING MODEL



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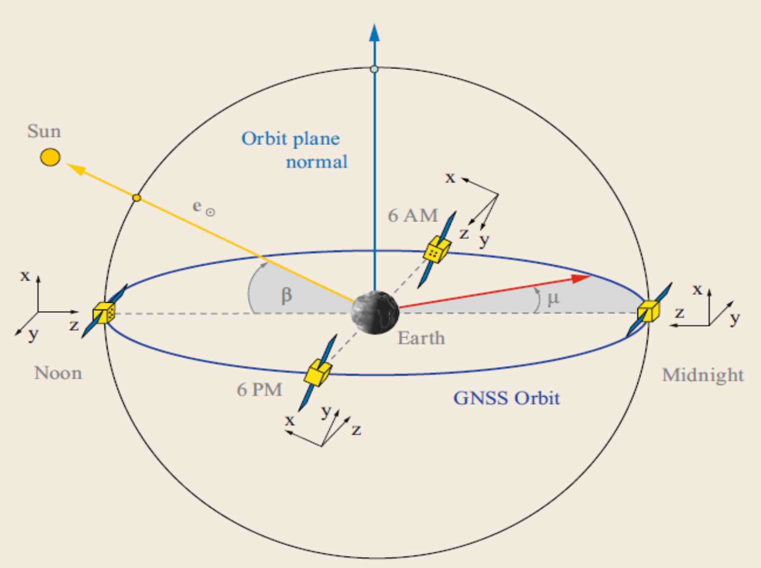
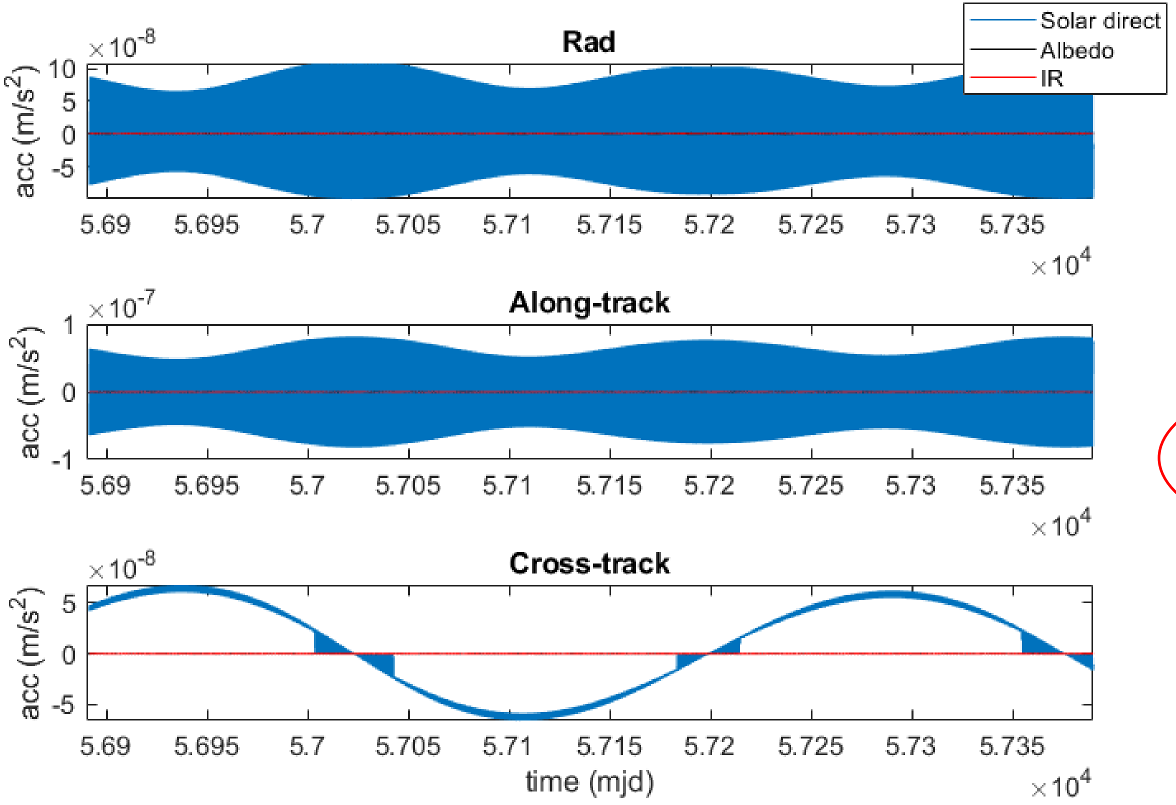
ATTITUDE

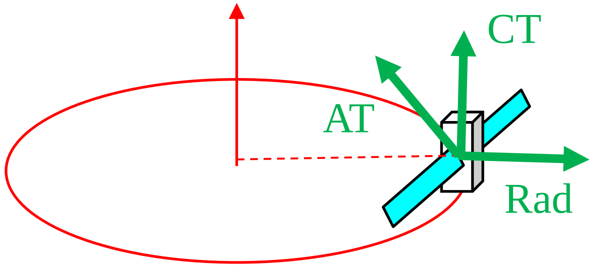


We adopted the nominal attitude law: the satellite rotate around the direction of the sun maintaining the best possible solar panel orientation

O. Montenbruck, R. Schmid, F. Mercier, P. Steigenberger, C. Noll, R. Fatkulin, S. Kogure, A.S. Ganeshan, Adv. Space Res., 56, 1015, 2015

ACCELERATION ON THE SATELLITE





PERSPECTIVES

- We need to improve the models for the non-conservative forces with the development of a refined Box Wing model with the final aim of a Finite Element Model

- We are evaluating the best combinations of observables to be used to extract the various relativistic precessions

- Concerning the Precise Orbit Determination (POD):
  - We are evaluating what degree and order of the gravity field harmonics should be considered
  - We are evaluating the best arc-length to be used in the Precise Orbit Determination (POD) for the various possible measurements