

G6.1 Open Session in Geodesy

The Galileo satellites DORESA and MILENA and their goals in the field of Fundamental Physics within the Galileo for Science (G4S_2.0) project

David Lucchesi, Emiliano Fiorenza, Carlo Lefevre, Marco Lucente, Carmelo Magnafico,

Roberto Peron, Francesco Santoli, Feliciano Sapio, Massimo Visco

Istituto di Astrofisica e Planetologia Spaziali (IAPS) – Istituto Nazionale di Astrofisica (INAF)

Tor Vergata, Roma, Italy

david.lucchesi@inaf.it

The High-level goals of G4S_2.0

SVN N.	PRN N.	
GSAT0201	E18	Doresa
GSAT0202	E14	Milena

1. A new measurement of the **Gravitational Redshift** exploiting the orbits of the **Galileo** satellites **GSAT0201** and **GSAT0202**
2. A measurement of the **General Relativity (GR) precessions** on the orbits of **GSAT0201** and **GSAT0202**
3. Constraints on **Dark Matter (DM)** in the Milky Way
4. Realize (in a reverse use) a pure **Relativistic Positioning System (RPS)**

Three research centers are involved in this project:

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

The following slides briefly summarize the main activities carried out at **IAPS/INAF**

Activities @ IAPS/INAF

1. Improve the dynamical model of the satellites orbits, in particular the modelling of the **Non-Gravitational Perturbations (NGPs)** and, among these, that of the direct solar radiation pressure, the largest **NGP** on **GNSS** satellites
2. Improve the **precise orbit determination (POD)** of the **Galileo FOC** satellites on eccentric orbit in relationship to the measurements to be performed in the field of **gravitation** and **fundamental physics**
3. Perform a set of measurements of the general relativistic effects on the orbits of the satellites with possible constraint to **alternative theories** of gravitation
4. Support the activities carried out by **ASI-CGS**, **OATO** and **POLITO**

Activities @ IAPS/INAF

Direct solar radiation pressure (SRP)

- It represents the largest **NGP** on the **Galileo FOC** satellites, about $1 \times 10^{-7} \text{ m/s}^2$ in magnitude, and about two orders-of-magnitude larger than the albedo and infrared radiation from the Earth
- Our ultimate goal is to develop a **Finite Element Model (FEM)** of the spacecraft and apply a ray-tracing technique to compute, first and foremost, the acceleration due to the direct **SRP** on the satellite
- Preliminary to the **FEM**, we have developed a **Box-Wing** model of the satellite based on current **Galileo Metadata** provided by **ESA**

Activities @ IAPS/INAF

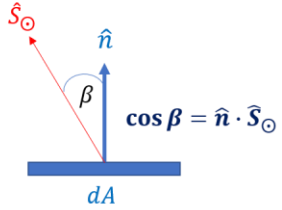
The direct **SRP** depends on:

1. the solar flux $\Phi_{\odot}$
2. the distance of the Earth-satellite system from the Sun
3. the satellite attitude and its shape/geometry
4. the physical properties (optical, thermal,...) of the various surfaces (constituents) and their time degradation

- We need to improve the modeling of the **NGPs** down to an acceleration level $\leq 10^{-10} \text{ m/s}^2$
- On the basis of our experience with **LAGEOS** satellites, 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
- We need almost all the physical information characterizing the S/C materials:

❑ The characteristics provided in the **FOC metadata** are not enough for a **FEM**

[Galileo Satellite Metadata | European GNSS Service Centre \(gsc-europa.eu\)](https://gsc-europa.eu)



$\cos \beta = \hat{n} \cdot \hat{S}_{\odot}$

The resulting elementary acceleration on a surface element

$$\alpha + \rho + \delta = 1$$

$$d\vec{a} = -\frac{\Phi_{\odot}}{mc} \left[(1 - \rho) \hat{S}_{\odot} + 2 \left(\frac{\delta}{3} + \rho \cos \beta \right) \hat{n} \right] dA |\cos \beta|$$

$$d\vec{a} = d\vec{a}_{\alpha} + d\vec{a}_{\rho} + d\vec{a}_{\delta}$$

Simplifying assumptions:

- a) the absorbed light is not-re-emitted
- b) for a given direction, the intensity of diffused light is proportional to the cosine of the angle with the unit vector $\hat{n}$ (**Lambert's law**, i.e. spherical diffusion lobe)
- c) the reflection is perfectly specular
- d) dA behaves like a linear combination of a black body, a perfect mirror and a Lambert diffuser

A. Milani, A.M. Nobili, P. Farinella, Adam Hilger, Bristol (1987)

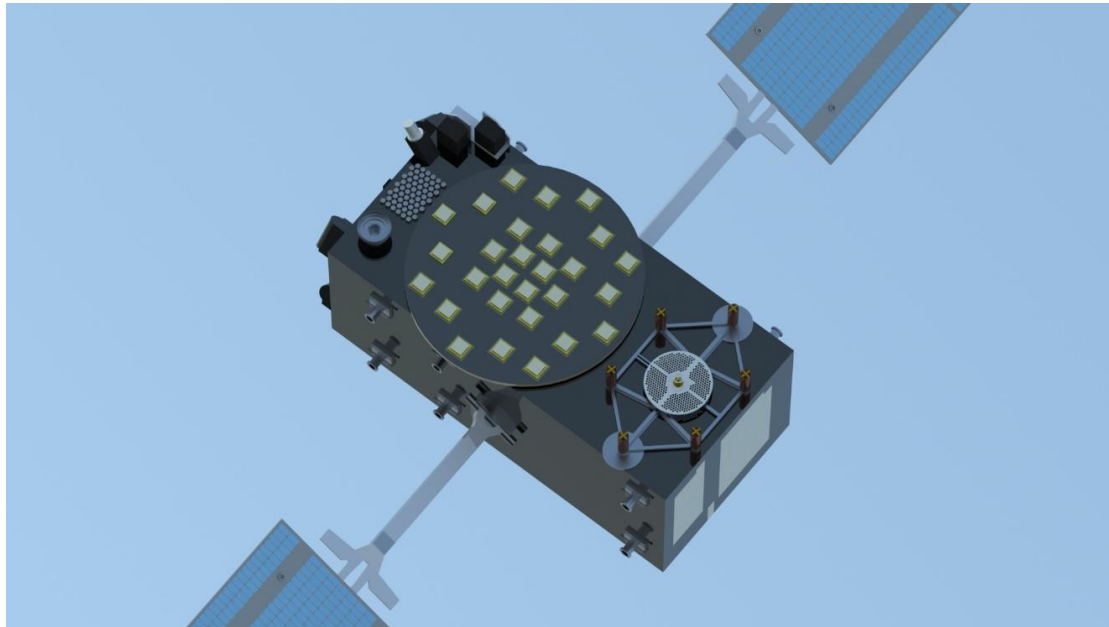
$$d\vec{a}_{\alpha} = -\frac{\Phi_{\odot}}{mc} \alpha dA |\cos \beta| \hat{S}_{\odot}$$

$$d\vec{a}_{\rho} = -\frac{\Phi_{\odot}}{mc} 2\rho \cos \beta dA |\cos \beta| \hat{n}$$

$$d\vec{a}_{\delta} = -\frac{\Phi_{\odot}}{mc} \delta dA |\cos \beta| \hat{S}_{\odot} - \frac{\Phi_{\odot}}{mc} \frac{2}{3} \delta dA |\cos \beta| \hat{n}$$

Activities @ IAPS/INAF

We developed a realistic **3D model** of the **Galileo FOC S/C**



Starting from this realistic model it is possible to build a simplified **FEM** model: a **Simplified Box-Wing (S-BW)** model at zero order

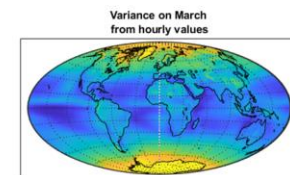
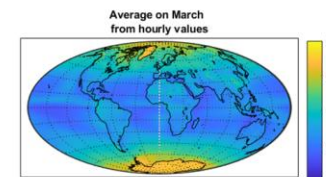
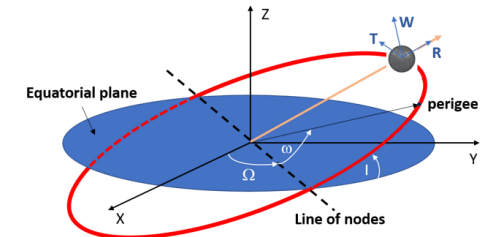
- In the following, we show the results for the perturbing accelerations due to direct **SRP**, Earth's Albedo radiation pressure (**ARP**) and Earth's Infrared radiation pressure (**IRP**) in the case of the **Galileo FOC E08** satellite
- The accelerations are given in the **Gauss co-moving** frame and plotted
 - in the time domain
 - as colour map as a function of the Sun height β above the orbital plane and of the difference Δu between the argument of latitude of the satellite with that of the Sun

$$\vec{a} = R\hat{r} + T\hat{t} + W\hat{w}$$

$$R = R(\beta, \Delta u)$$

$$T = T(\beta, \Delta u)$$

$$W = W(\beta, \Delta u)$$



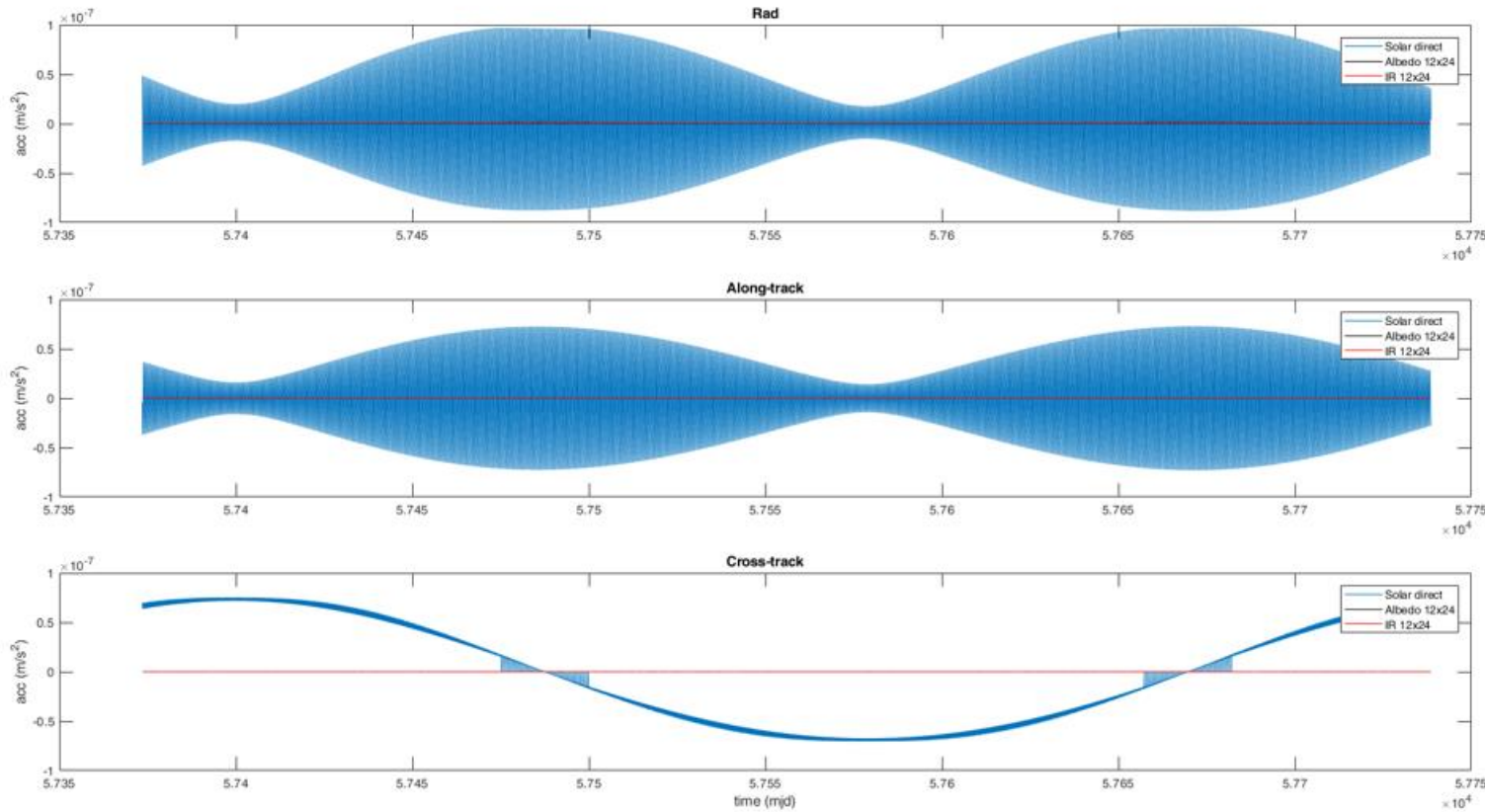
- **CERES (Clouds and Earth's Radiant Energy System)** measures in three bands solar-reflected and Earth-emitted radiation from the top of the atmosphere to the Earth's surface

- Using data from **CERES** we can calculate different averages (hourly, monthly, etc.) of Earth's Albedo and Infrared radiation

• <https://ceres.larc.nasa.gov/data/>

Activities @ IAPS/INAF

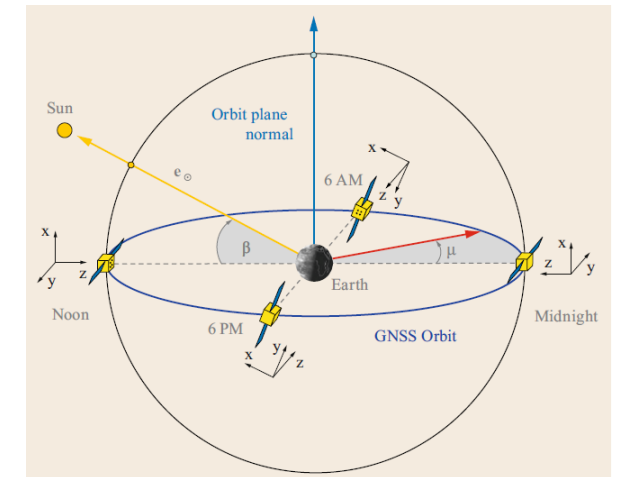
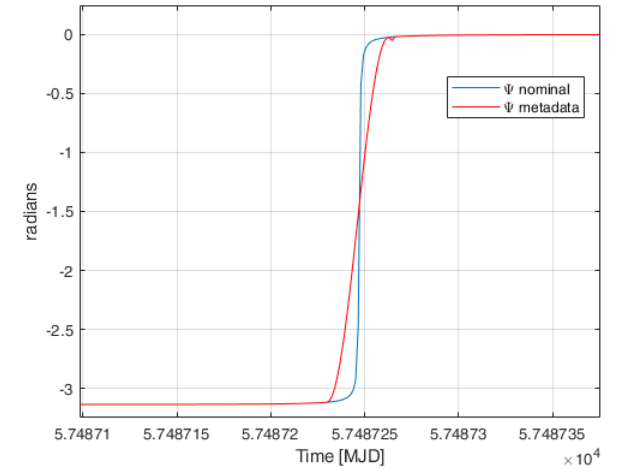
A 1-year simulation with the S-BW model



Galileo FOC E08

The attitude law:

Yaw Steering law of Galileo FOC satellites in agreement with the metadata

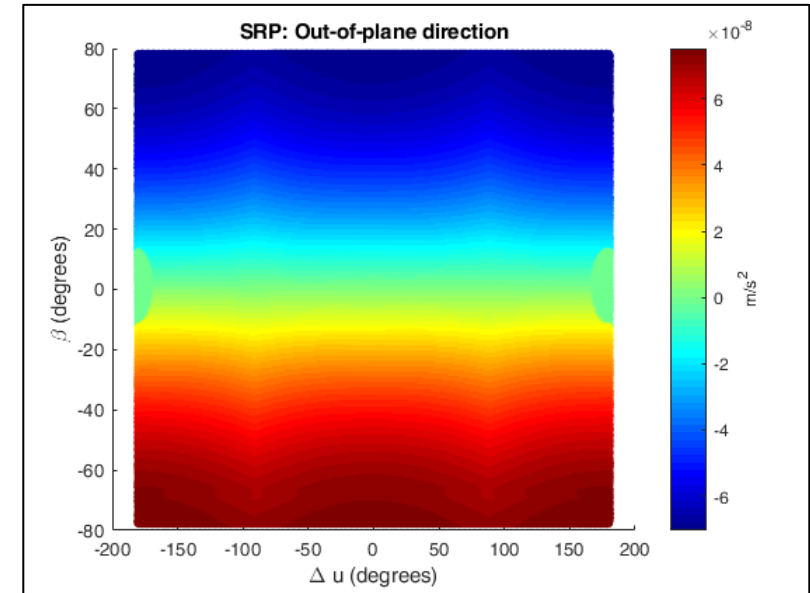
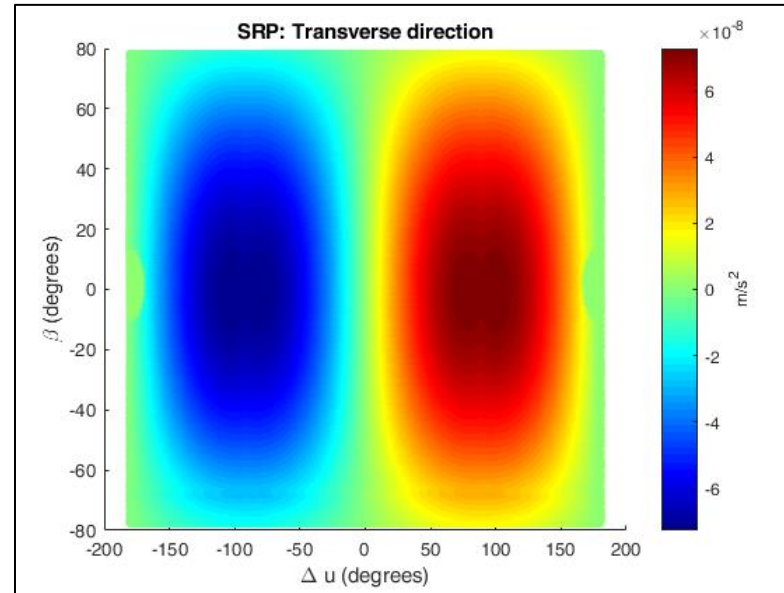
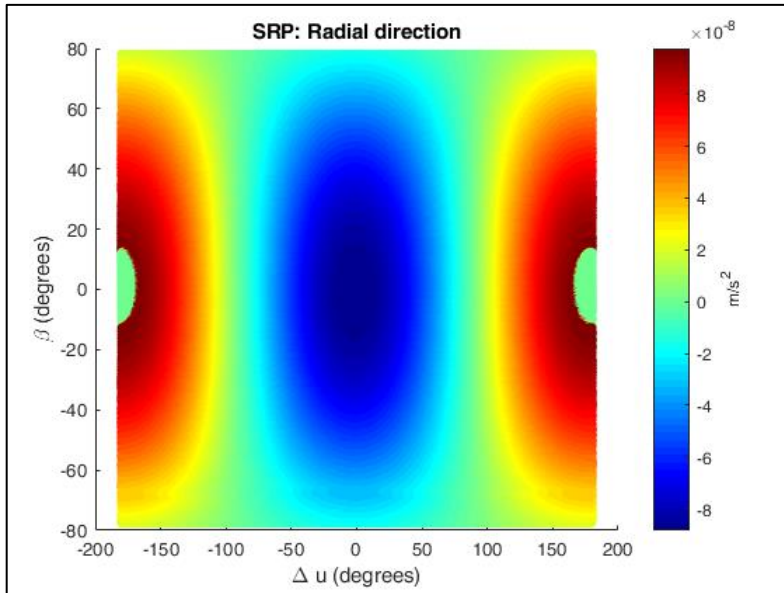


O. Montenbruck, et al., Adv. Space Res., 56, 1015, 2015

Activities @ IAPS/INAF

Solar Radiation Pressure acceleration

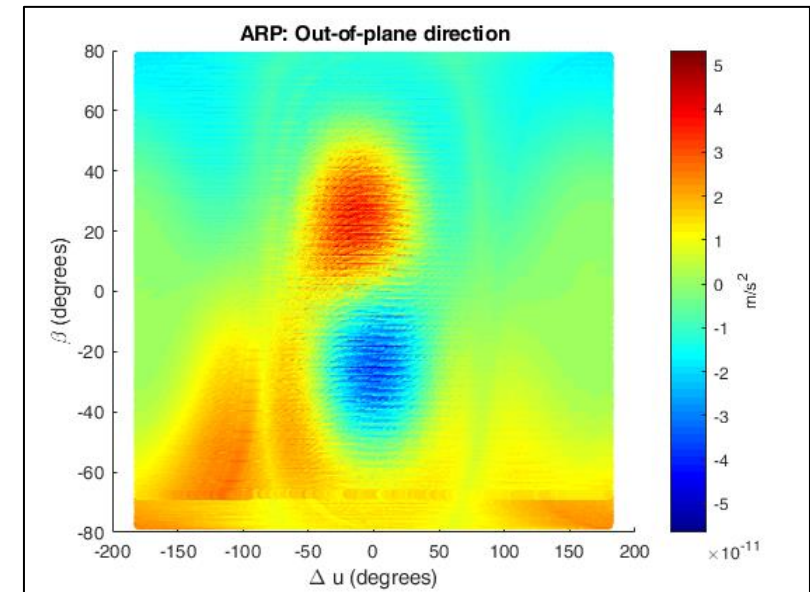
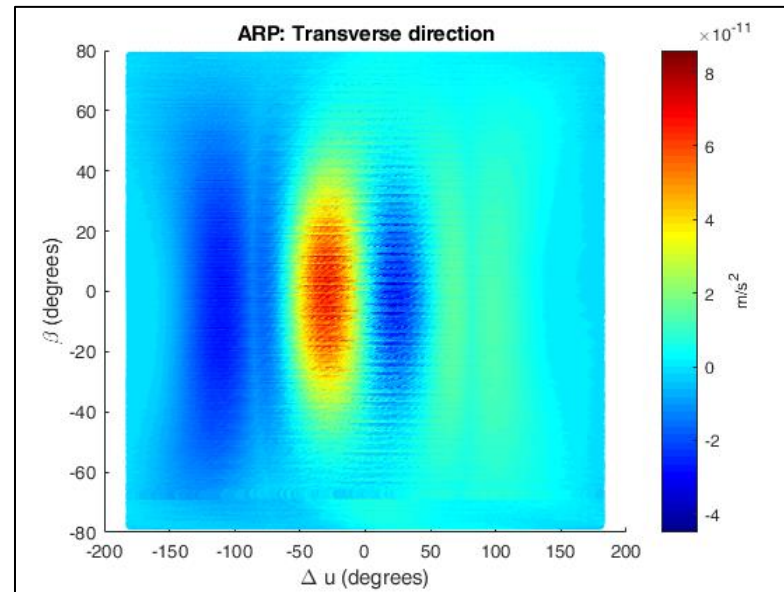
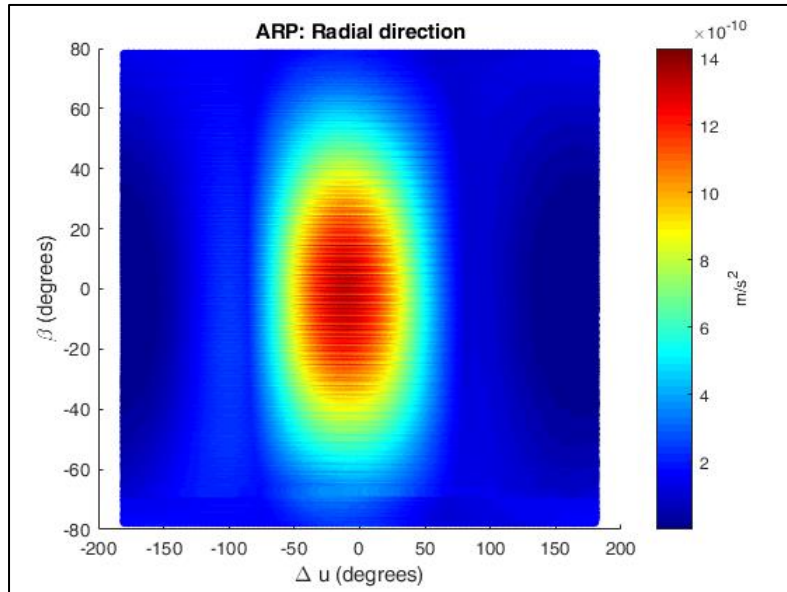
Galileo FOC E08



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Albedo Radiation Pressure acceleration

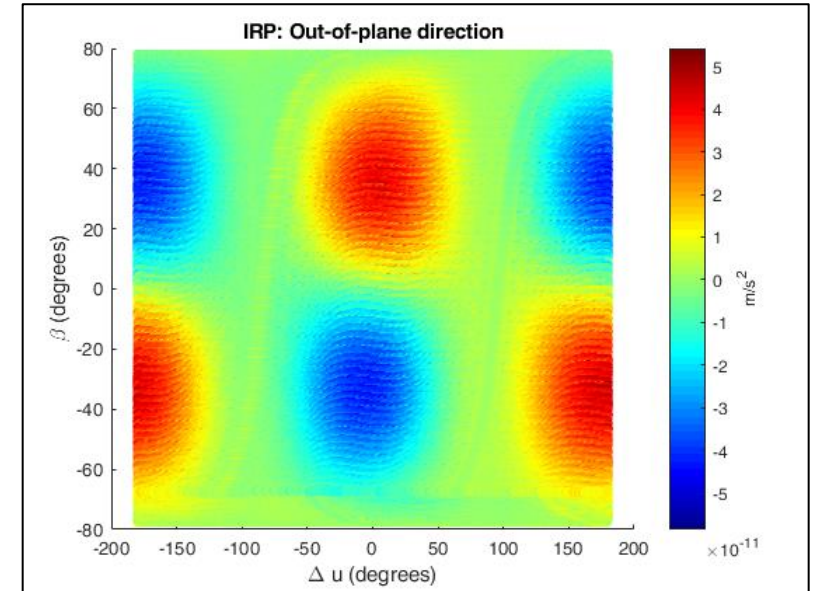
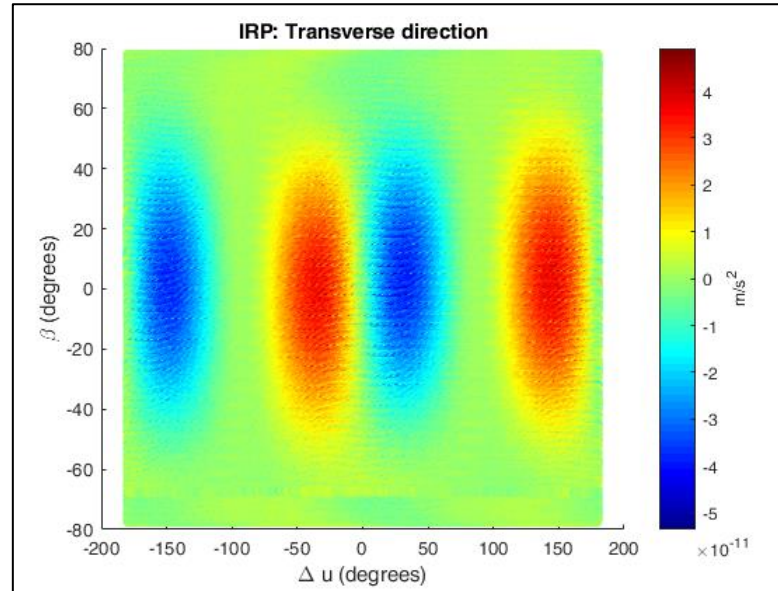
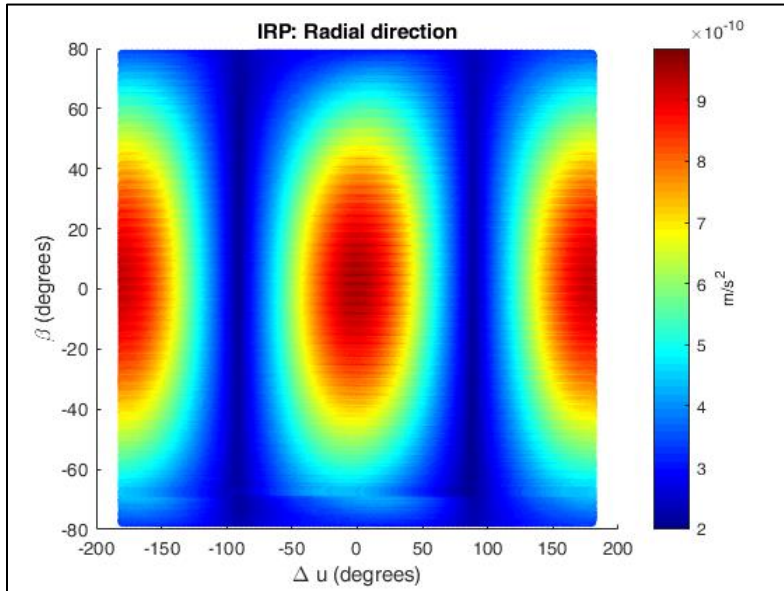
Galileo FOC E08



Activities @ IAPS/INAF

Infrared Radiation Pressure acceleration

Galileo FOC E08



Activities @ IAPS/INAF

- Precise orbit determination (**POD**)
 - The analyses will be mainly performed with **GEODYN II** (**NASA/GSFC**) s/w
 - The best setup with the current models implemented in the code needs to be established and improved with the models we will develop for the **NGPs**
 - We are evaluating the **optimal degree** ℓ and **order** m of the gravity field development in spherical harmonics that should be considered
 - Both **Satellite Laser Ranging (SLR)** normal points and full rate tracking data will be analyzed
 - The most favorable **arc length** must be established on the basis of the measurements to be made

Conclusions



- The general objectives of the **G4S_2.0** proposal and the main activities that will be carried out in Roma at **IAPS/INAF** have been introduced
- Modeling of **NGPs**, especially of direct **SRP**, with the aim of improving the current state of the art, is of utmost importance
- The next step is to apply the **S-BW** model to the **GSAT0201** and **GSAT0202** satellites and start their orbit determination
- In the future, an improved **BW** model is planned based both on:
 - a more in-depth information on S/C characteristics from an update (by ESA) of the **Galileo FOC** metadata
 - an independent analysis we initiated on the characteristics of the antennas and solar panels of these satellites



Many thanks for your kind attention