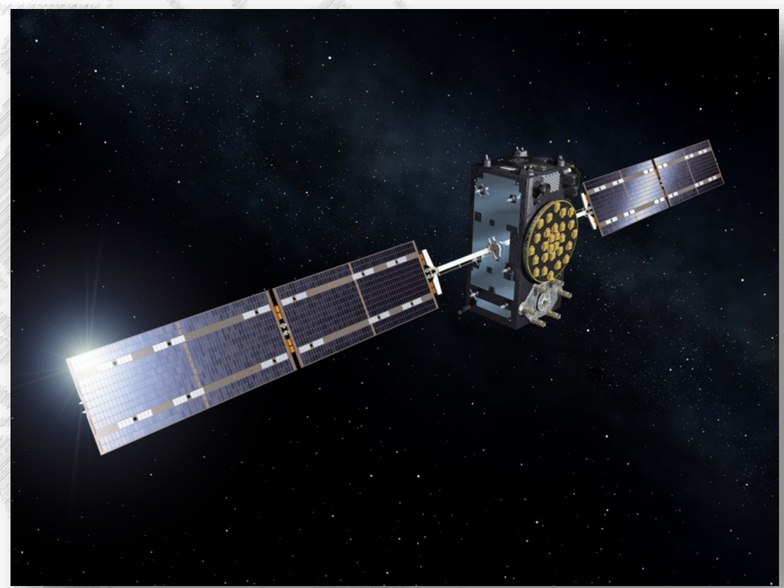
INCREASE GEOworkshop
28-29.03.2019

Wrocław University of Environmental and Life Sciences



Towards 1-cm Galileo orbits

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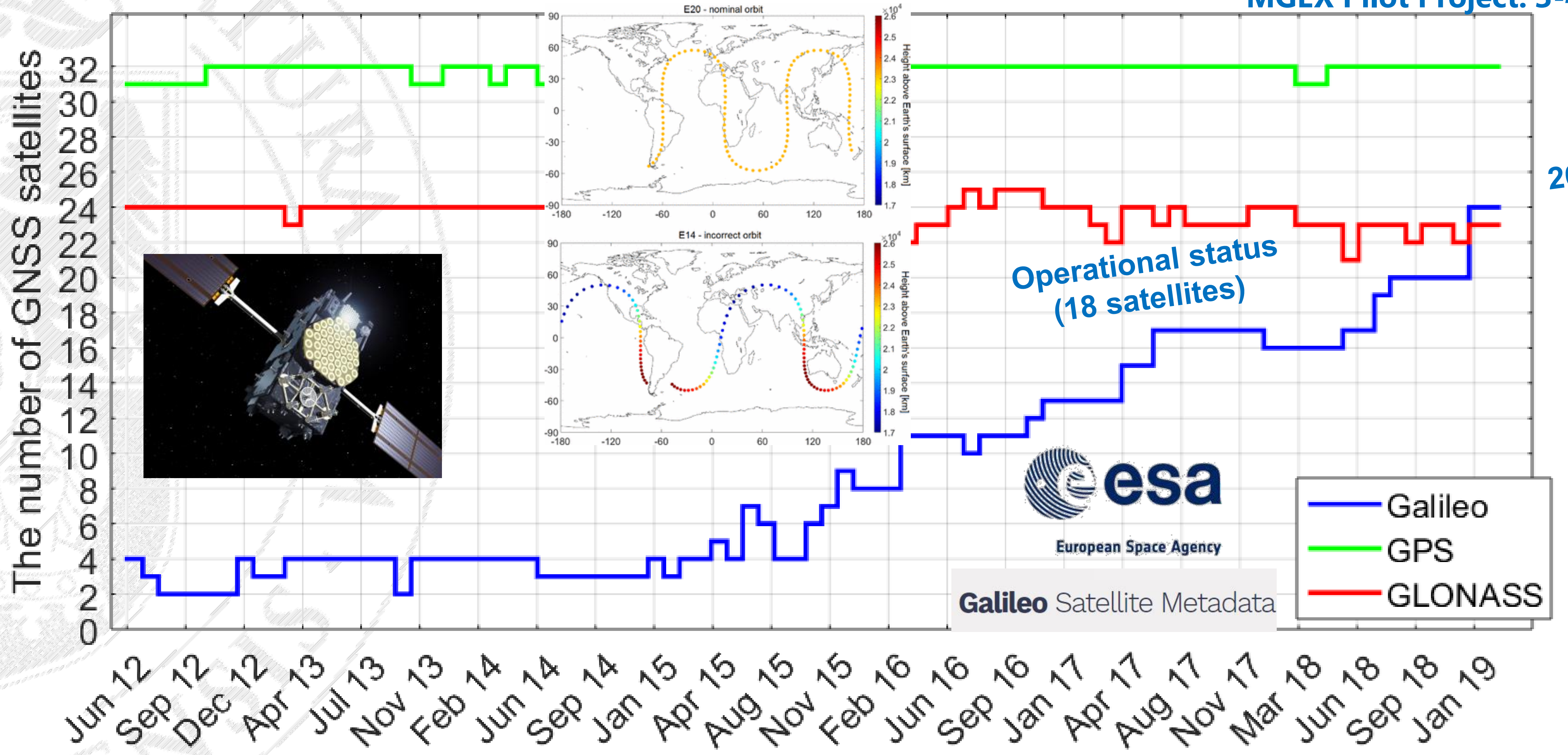
Galileo constellation status

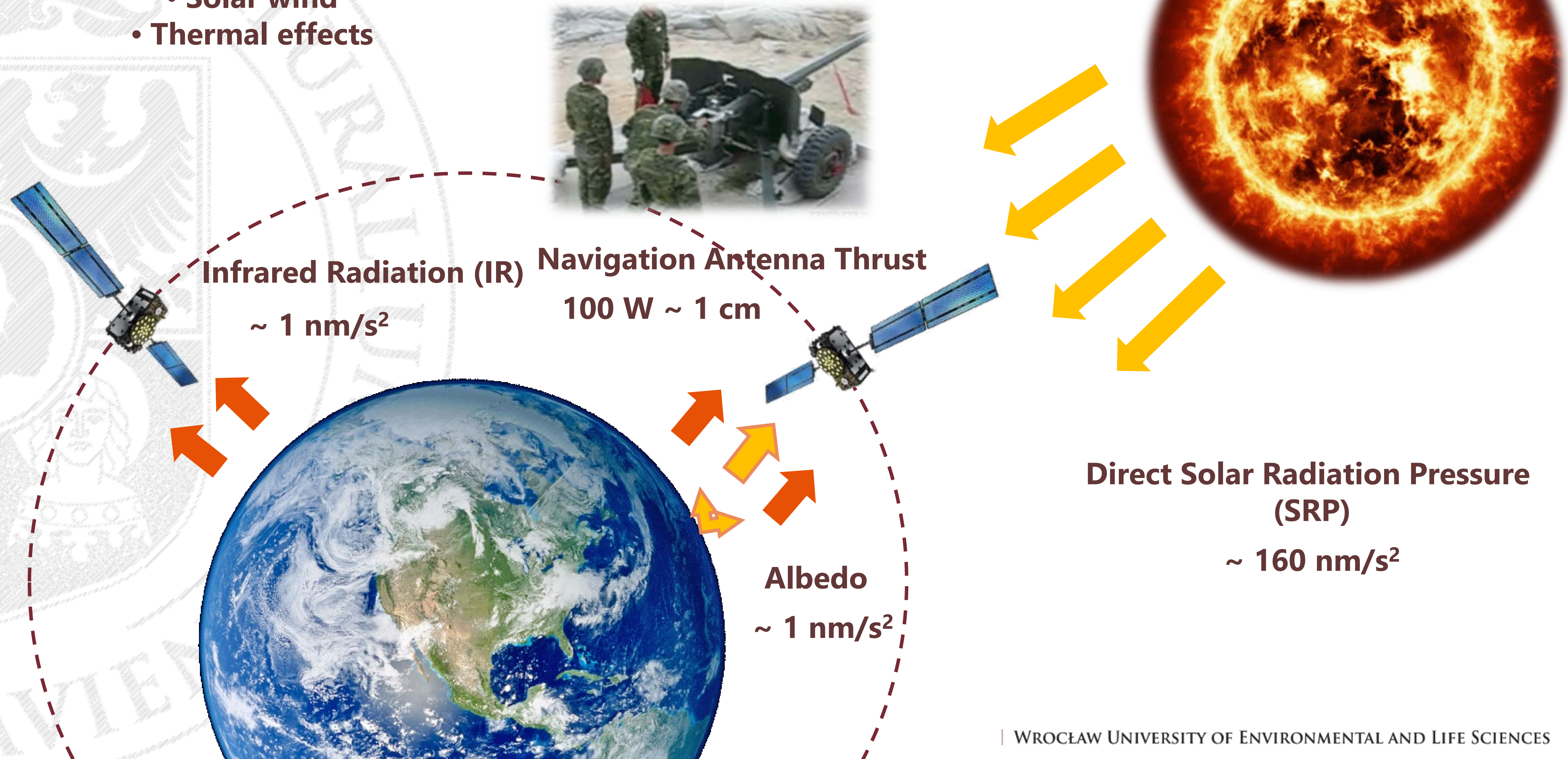
Accuracy of the final orbits:
GPS: 2.5 cm
GLONASS: 3.0 cm
Galileo: ???
MGEX Pilot Project: *3-4 cm*



26 satellites on orbit

Non-gravitational forces acting on GNSS

- Solar wind
- Thermal effects



Coping with direct Solar Radiation Pressure

Empirical models ⇐ Widely used in the GNSS community, i.e., ECOM2 (Arnold et al. 2015)

- Based on physical interaction betw...

solar radi...

Adjustable box-wing model for GPS and GLONASS (Rodriguez-Solano et al. 2012)

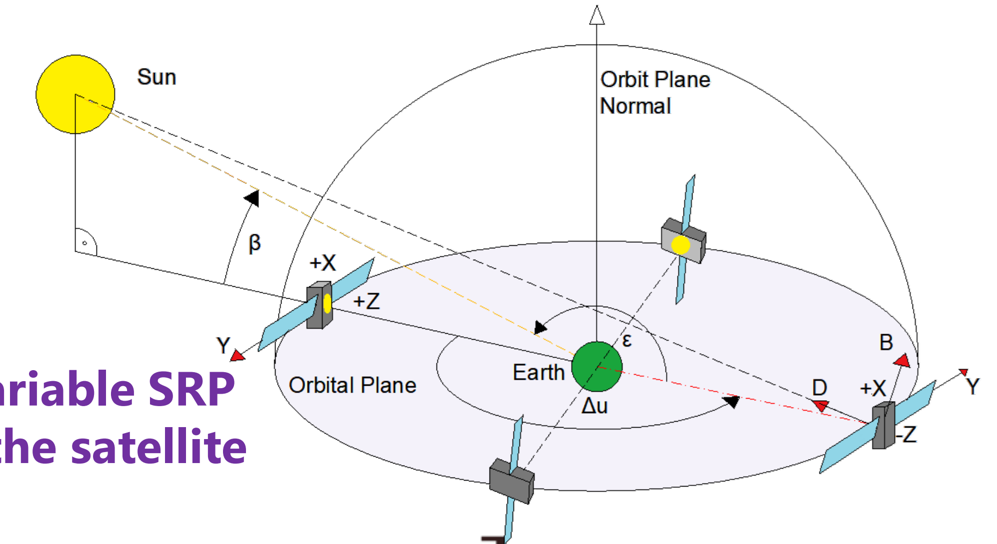
...of empirical and analytical models

Hybrid models

Ray-tracing ⇐ Tests for GPS, Galileo, QZSS (Li et al. 2018; Darugna et al. 2017)

Test, which set of the ECOM parameters used together with the Box-wing model provides the best orbit determination results?

Empirical CODE Orbit Model (ECOM2)



Absorbs direct SRP acting on the solar panels and mean SRP acting on the satellite bus, and the solar wind

Absorbs variable SRP acting on the satellite bus

$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C} \cos 2\Delta u + D_{2S} \sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C} \cos \Delta u + B_{1S} \sin \Delta u \end{bmatrix}$$

Absorbs thermal effects

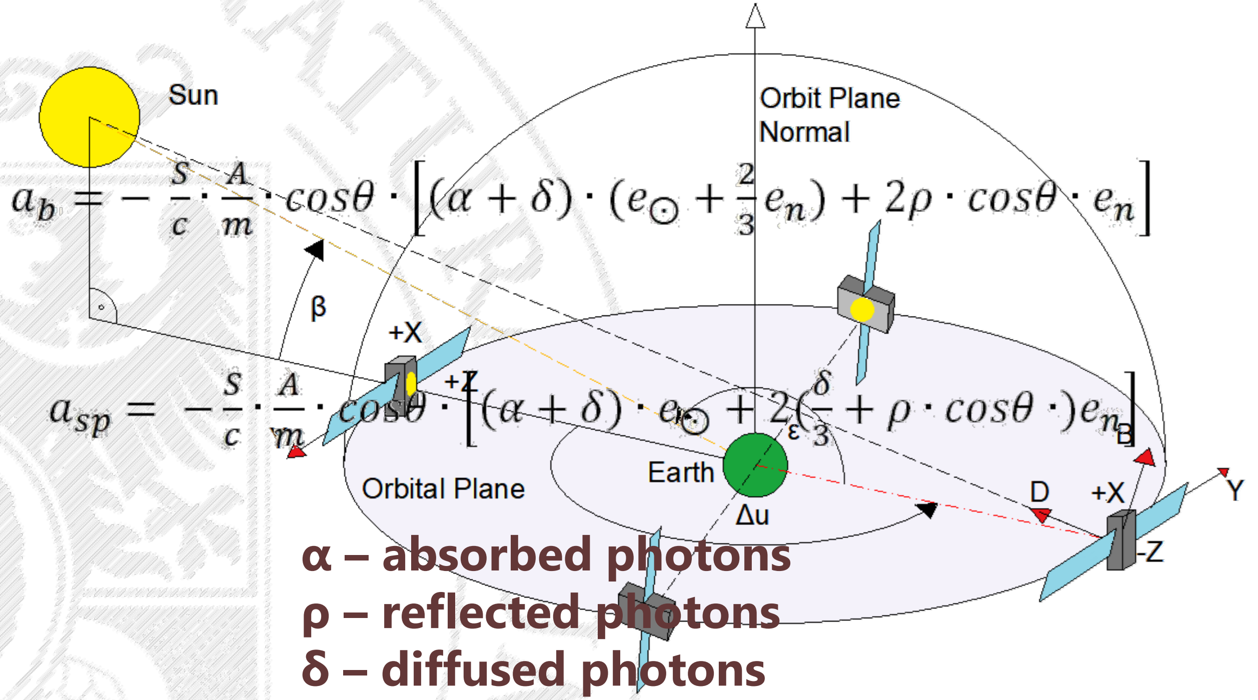
Absorbs Y-bias and B-bias Which appear due to misalignment of solar panels

Arnold, D., Meindl, M., Beutler, G. et al. J Geod (2015) 89: 775. https://doi.org/10.1007/s00190-015-0814-4

Limitations:

- **Not adjusted for albedo absorption**
- **Antenna thrust is neglected (constant radial acceleration)**
- **Considers the „yaw-steering"**
- **Orbit modelling problems when the satellite enters the Earth shadow (ECOM parameters = 0)**

GNSS satellites characteristics –„Box-wing" model



$$a_b = -\frac{S}{c}\cdot\frac{A}{m}\cdot cos\theta\cdot\left[(\alpha+\delta)\cdot(e_\odot+\frac{2}{3}e_n)+2\rho\cdot cos\theta\cdot e_n\right]$$

$$a_{sp} = -\frac{S}{c}\cdot\frac{A}{m}\cdot cos\theta\cdot\left[(\alpha+\delta)\cdot e_\odot+2(\frac{\delta}{3}+\rho\cdot cos\theta\cdot)e_n\right]$$

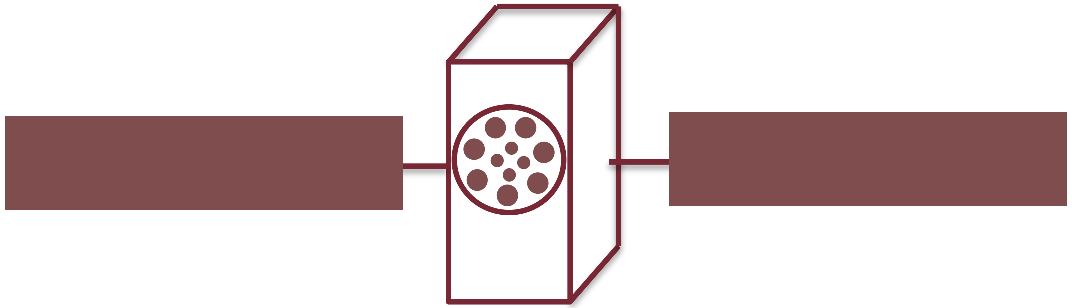
α – absorbed photons
ρ – reflected photons
δ – diffused photons

α + ρ + δ = 1

European Space Agency

Galileo Satellite Metadata

Bernese GNSS Software 5.2



GPS X:Z area ratio = 5.7 : 5.4
Galileo X:Z area ratio = 1.3 : 3.0

System	Type	Solar panels area [m²]	Bus area [X/Y/Z] [m²]	Altitude above the Earth surface [km]	Mass [kg]
GPS	Block IIF	13.60	**5.72**/7.01/**5.40**	20 200	1555
Galileo	IOV	**10.82**	**1.32**/3.00/**3.00**	**23 200**	**695**
	FOC / FOC ecc.	**10.82**	**1.32**/2.78/**3.04**	**23 200 / 17 000-26 000**	**708/645**

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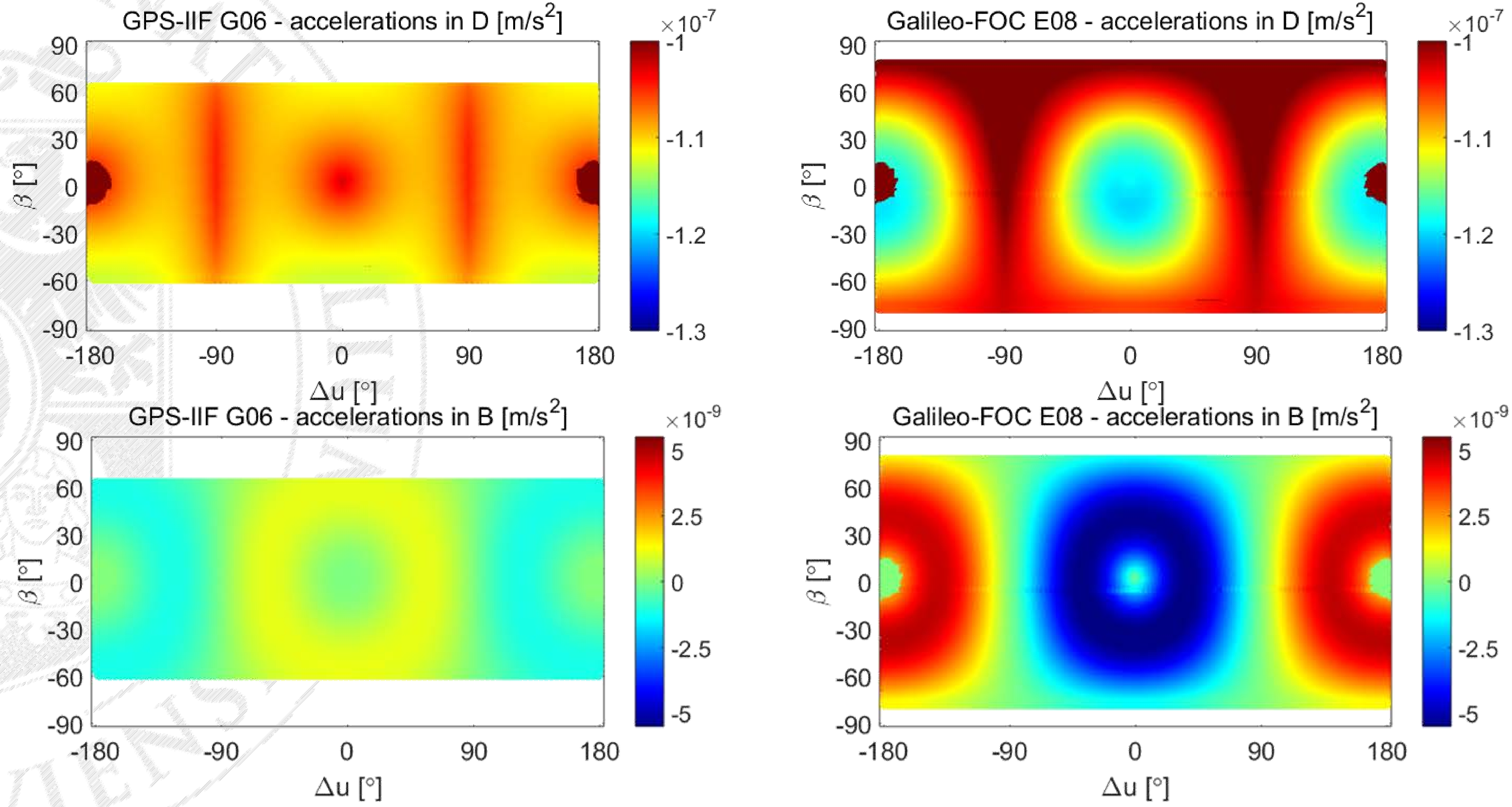
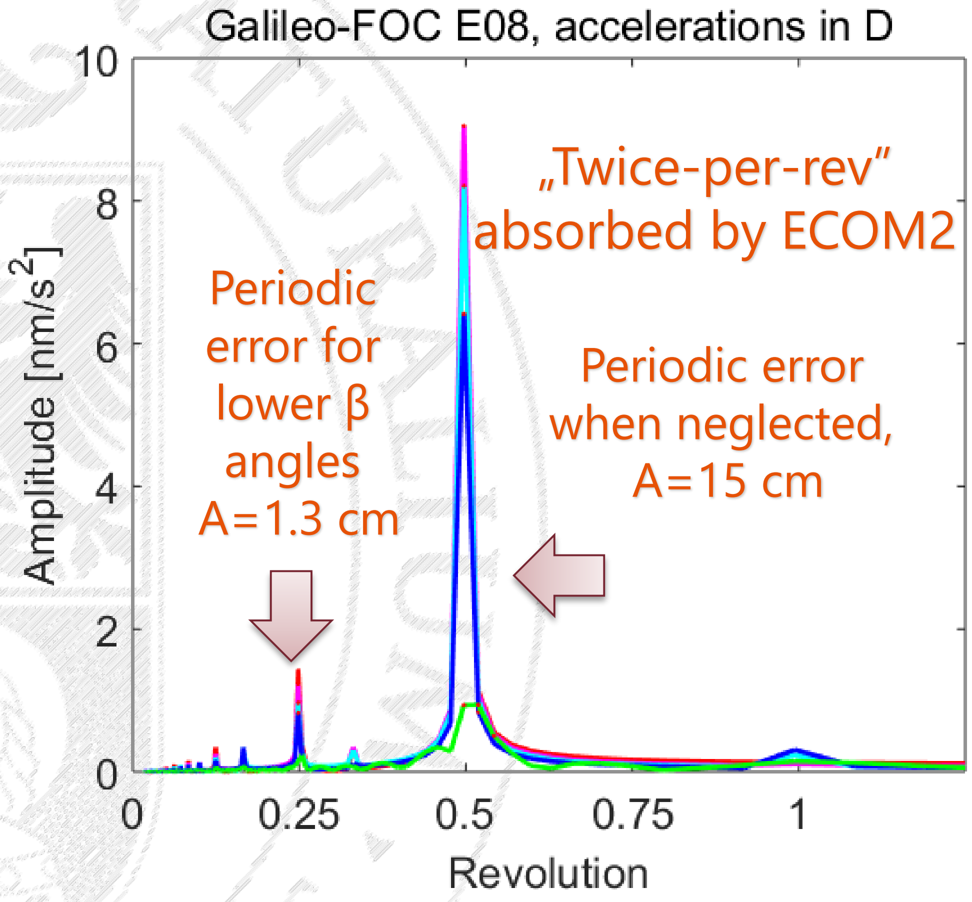
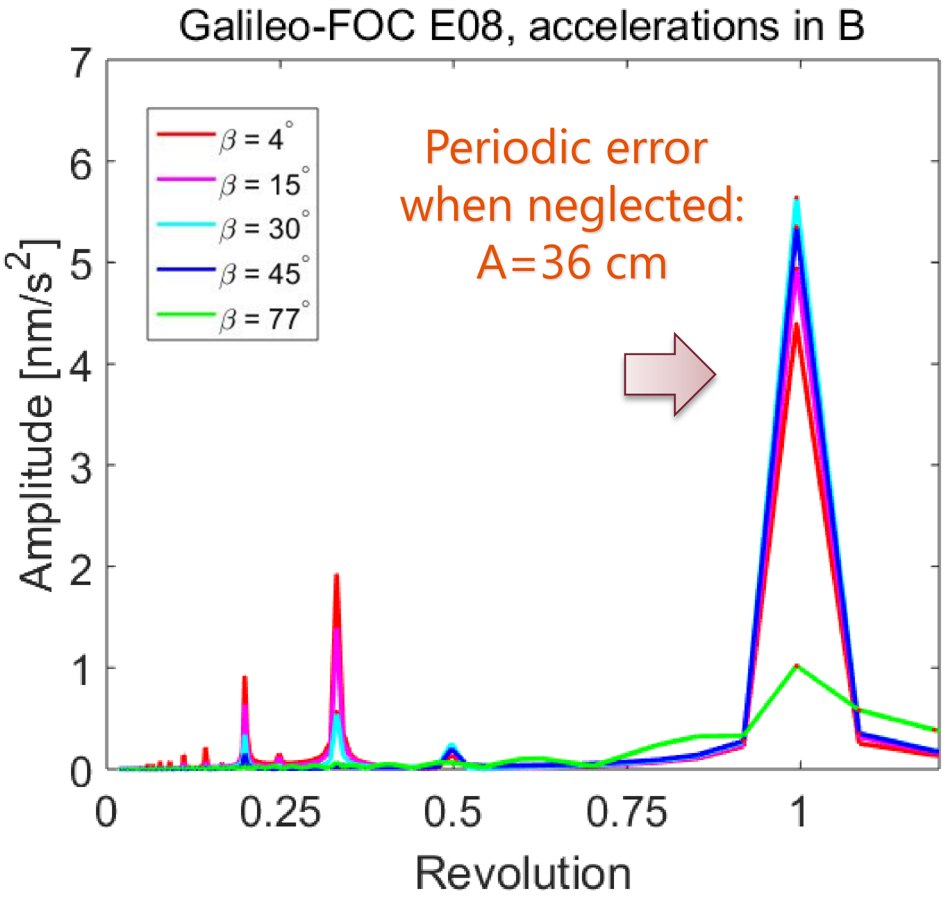
Accelerations resulting from SRP, albedo and IR based on the analytical box-wing model

SRP –„Box wing” model – accelerations in D and B directions



SRP – spectral analysis – Galileo E08 – nominal orbit

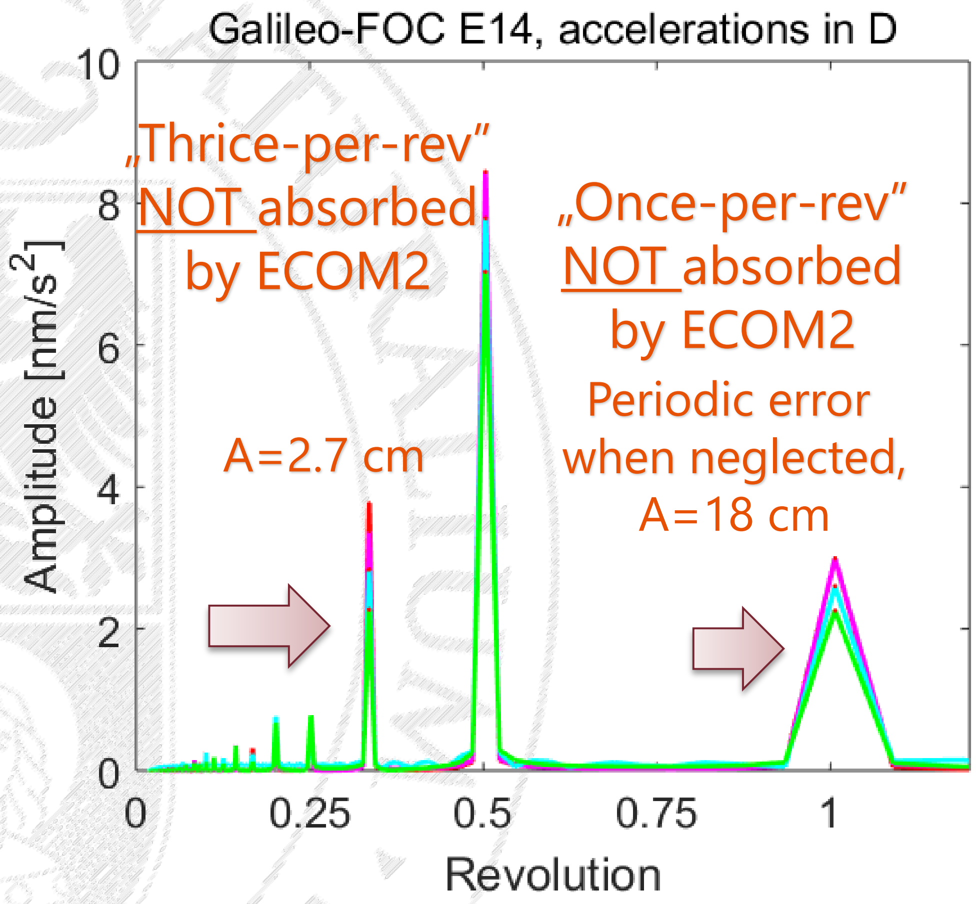


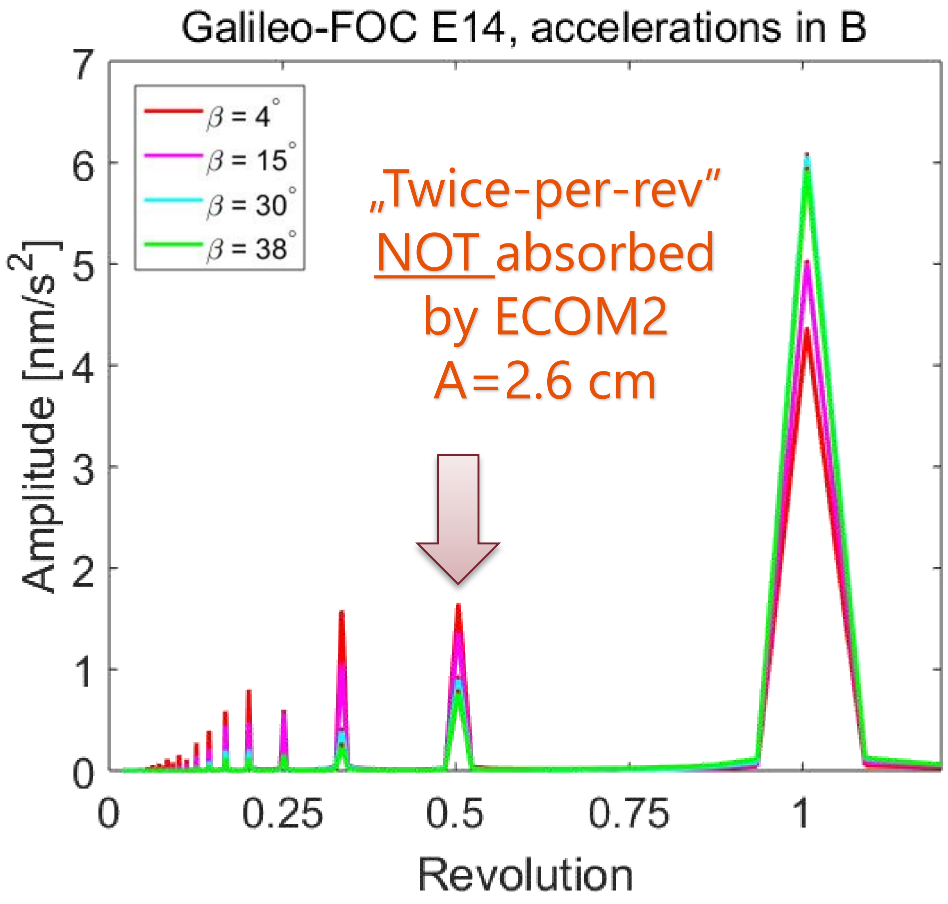


- **ECOM absorbs most of the direct SRP**
- **„Thrice-per-rev" are not estimated, thus cause errors for lower β angles**

$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C}\cos \Delta u + B_{1S}\sin \Delta u \end{bmatrix}$$

SRP – spectral analysis – Galileo E14 – elliptic orbit

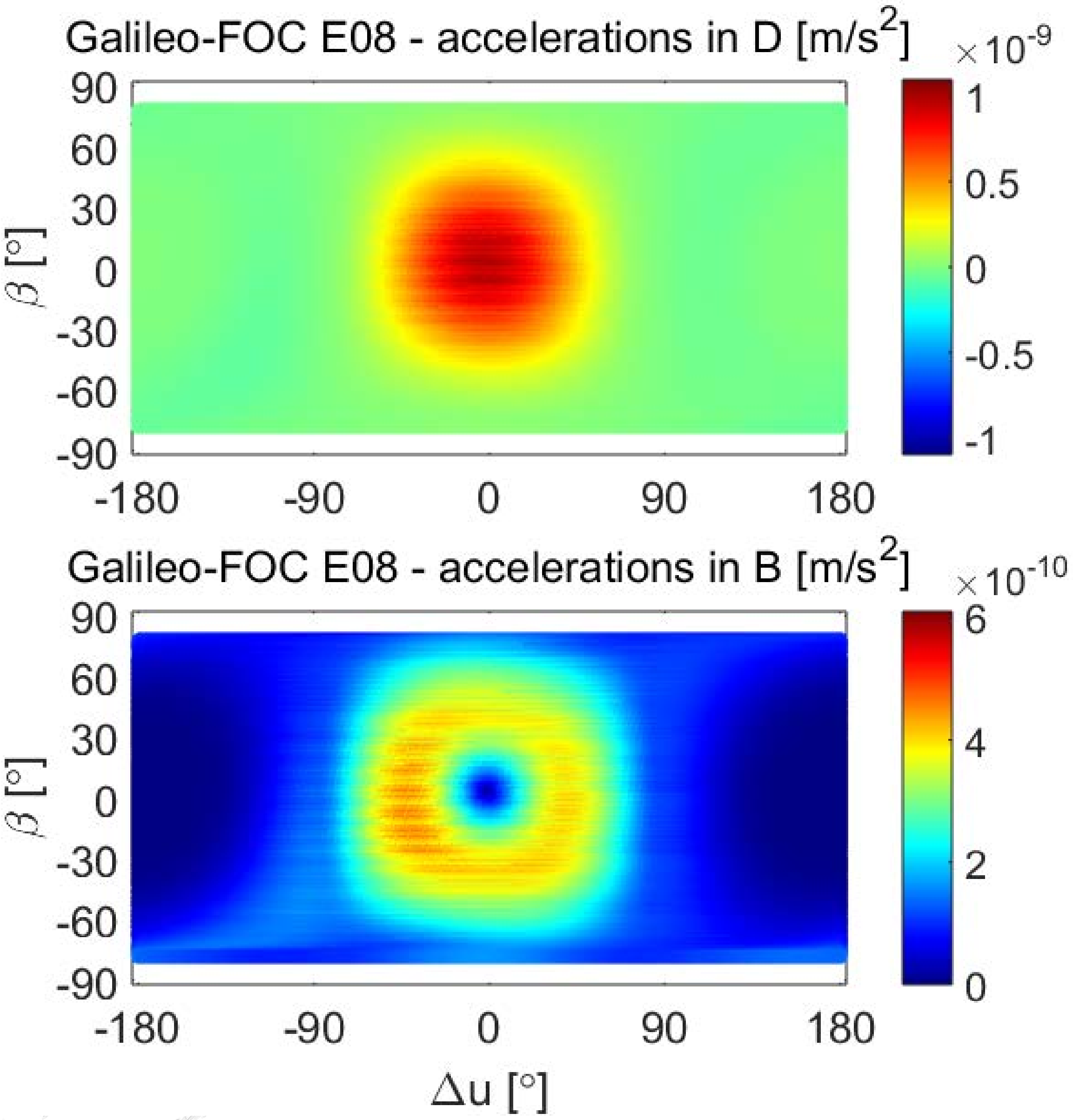




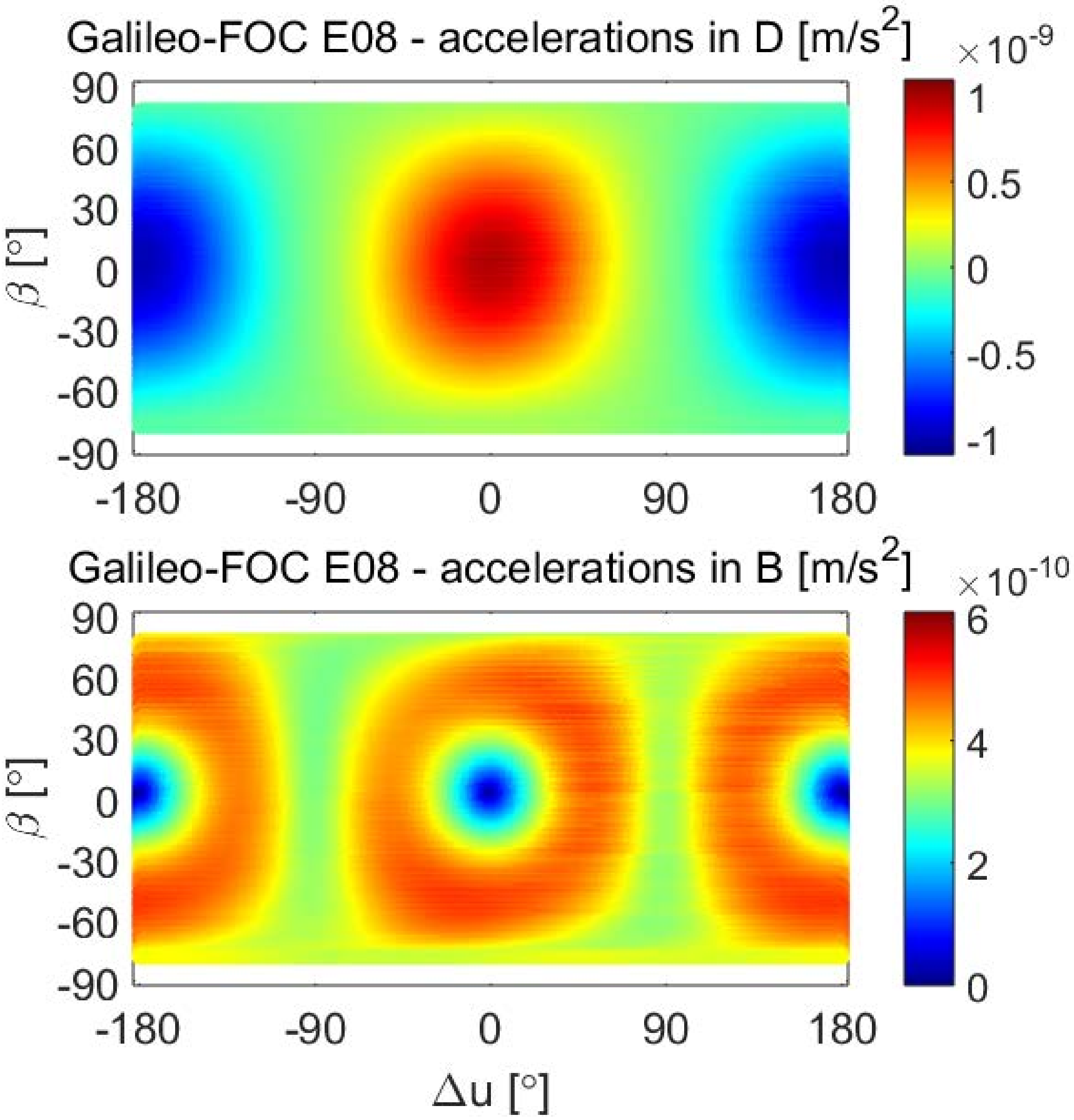
ECOM does not absorb perturbations resulting from SRP for the Galileo satellites launched into elliptic orbits. How about the albedo and IR?

$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C}\cos \Delta u + B_{1S}\sin \Delta u \end{bmatrix}$$

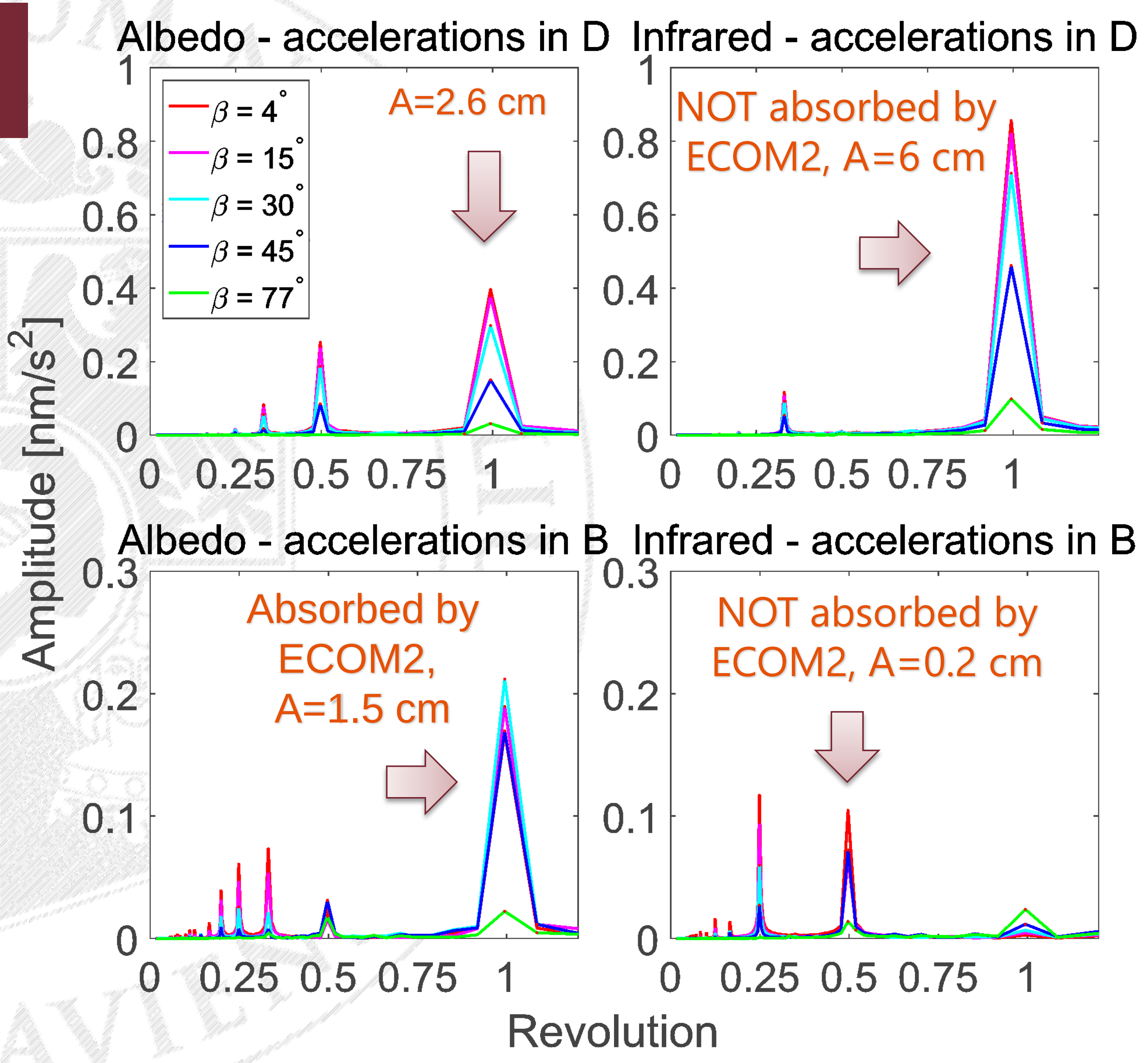
Albedo



Infrared radiation



Albedo and IR – spectral analysis – Galileo E08 – nominal orbit



- **ECOM2 does not absorb the whole albedo influence**
- **Not only the periodic perturbations, but also the constant accelerations resulting from IR has an impact on the GNSS satellites**

$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C}\cos \Delta u + B_{1S}\sin \Delta u \end{bmatrix}$$

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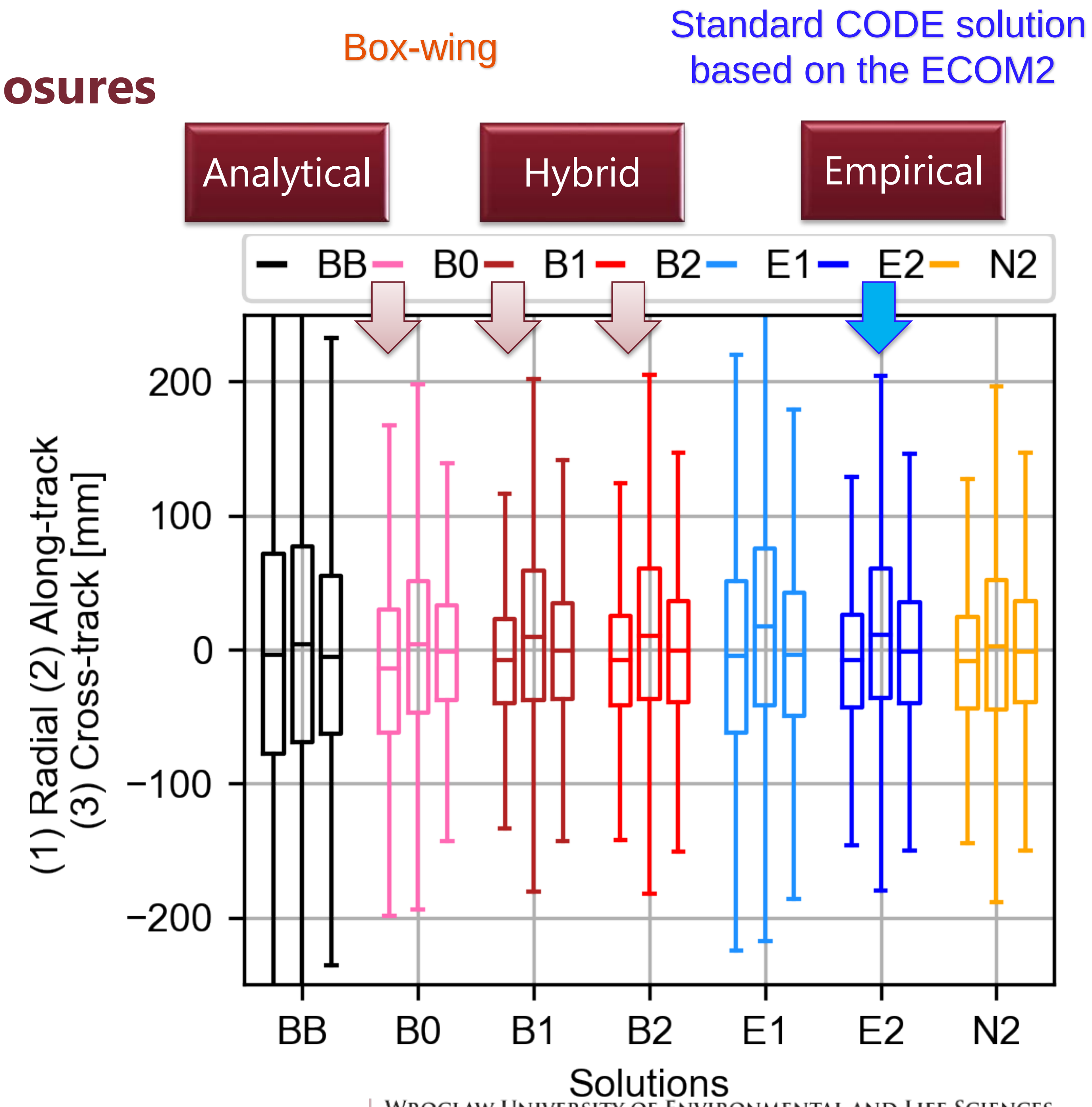
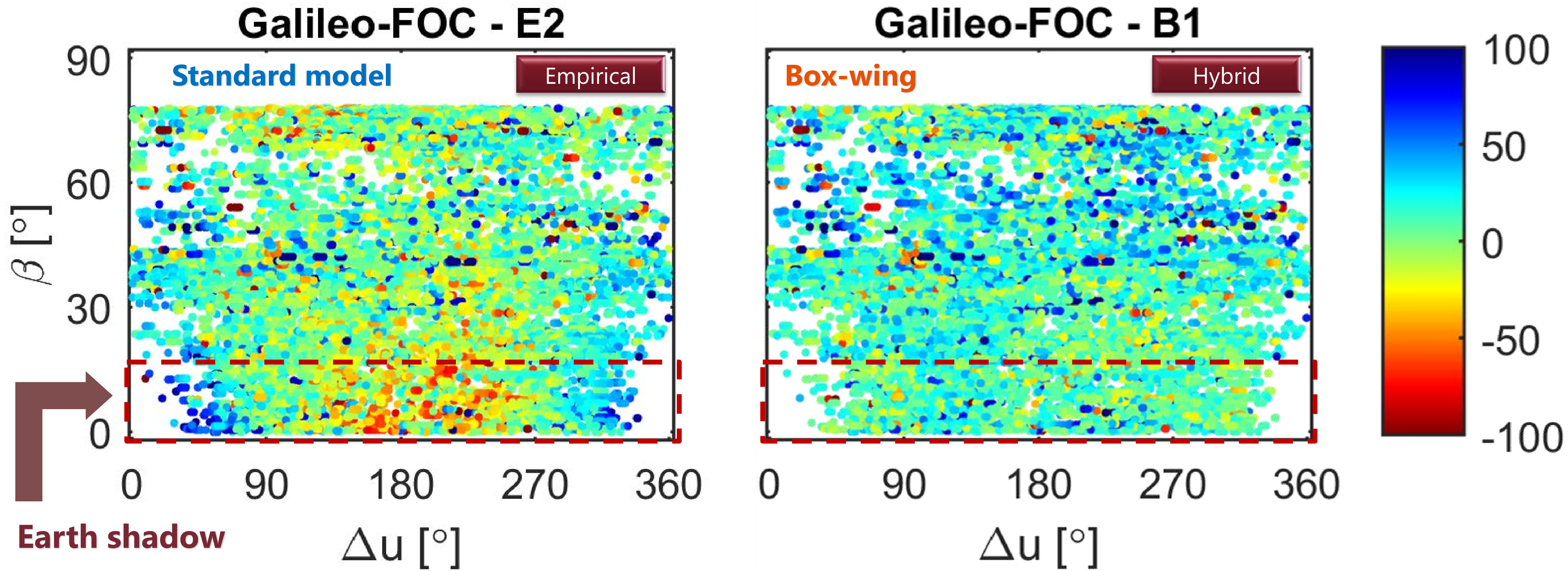
Estimation of the Galileo orbit parameters

Internal quality control – orbit misclosures

Solution	Box-wing	Empirical parameters	Albedo + IR + antenna thrust
B0	YES	------------	YES
B0	YES	D0,Y0,B0	YES
B1	YES	D0,Y0,B0, B1S,B1C	YES
B2	YES	D0,Y0,B0, B1S,B1C,D2C, D2S	YES
E1	NO	D0,Y0,B0, B1S,B1C	YES
E2	NO	D0,Y0,B0, B1S,B1C,D2C, D2S	YES
N2	NO	D0,Y0,B0, B1S,B1C,D2C, D2S	NO



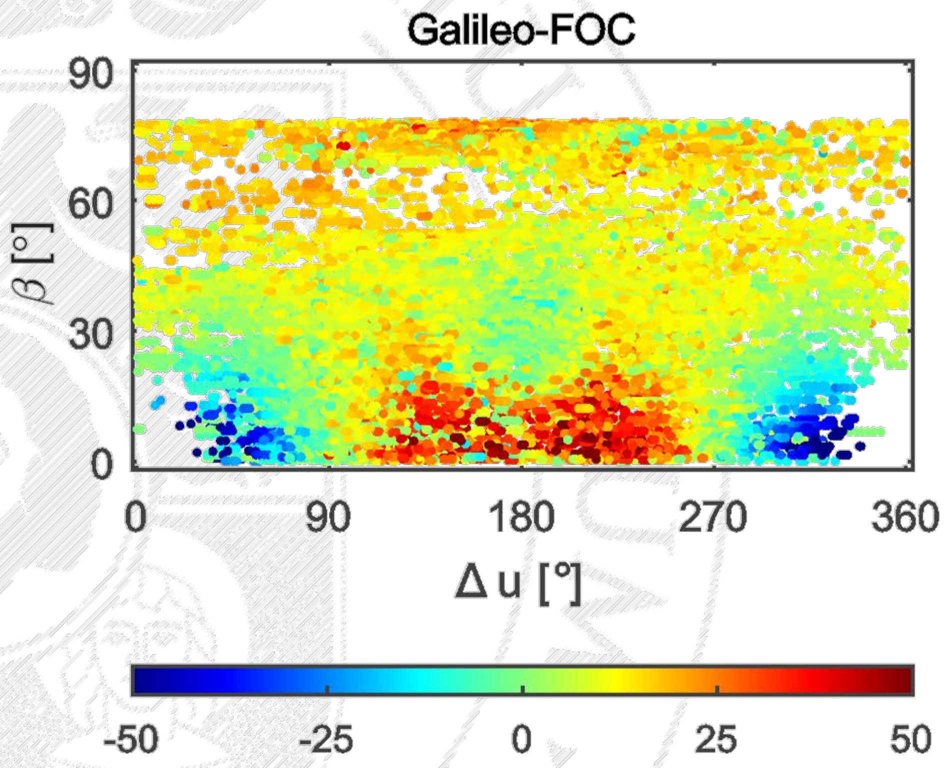
External quality control – SLR validation



Significant decrease of STD of the SLR residuals for |β| < 12.3°, i.e., when the satellites enters the Earth shadow

	B0	B1	E2
Mean [mm]	5.5	6.4	0.4
STD [mm]	24.7	24.7	29.5
STD [mm] |β| < 12.3°	24.0	24.7	37.2

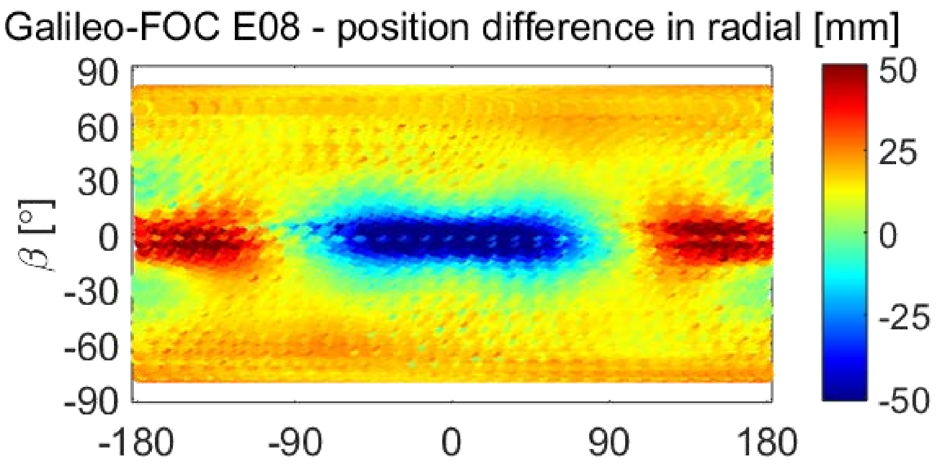
What is not absorbed by ECOM2?



SLR residual differences (B2-E2)

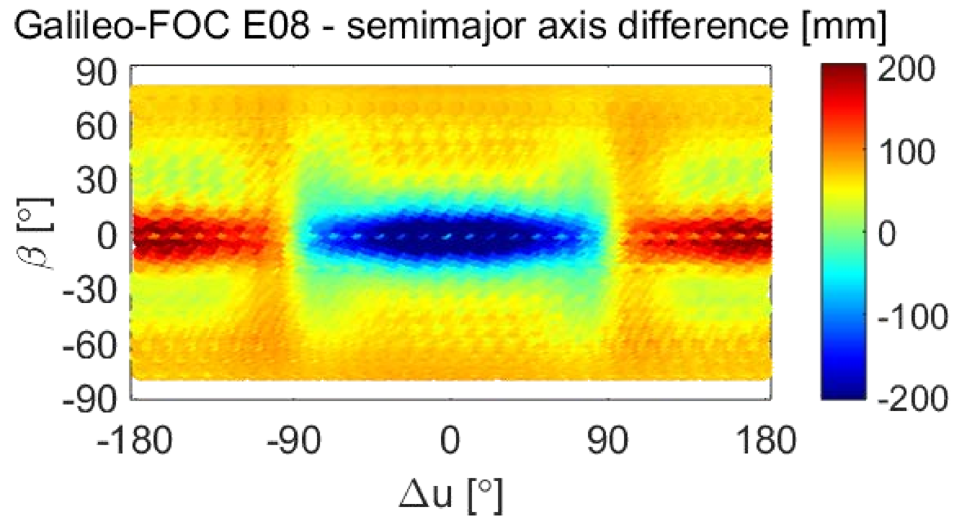
Satellite position differences (B2-E2)

$$\Delta r \approx -\frac{1}{3}\frac{a^3 R_0}{GM}$$



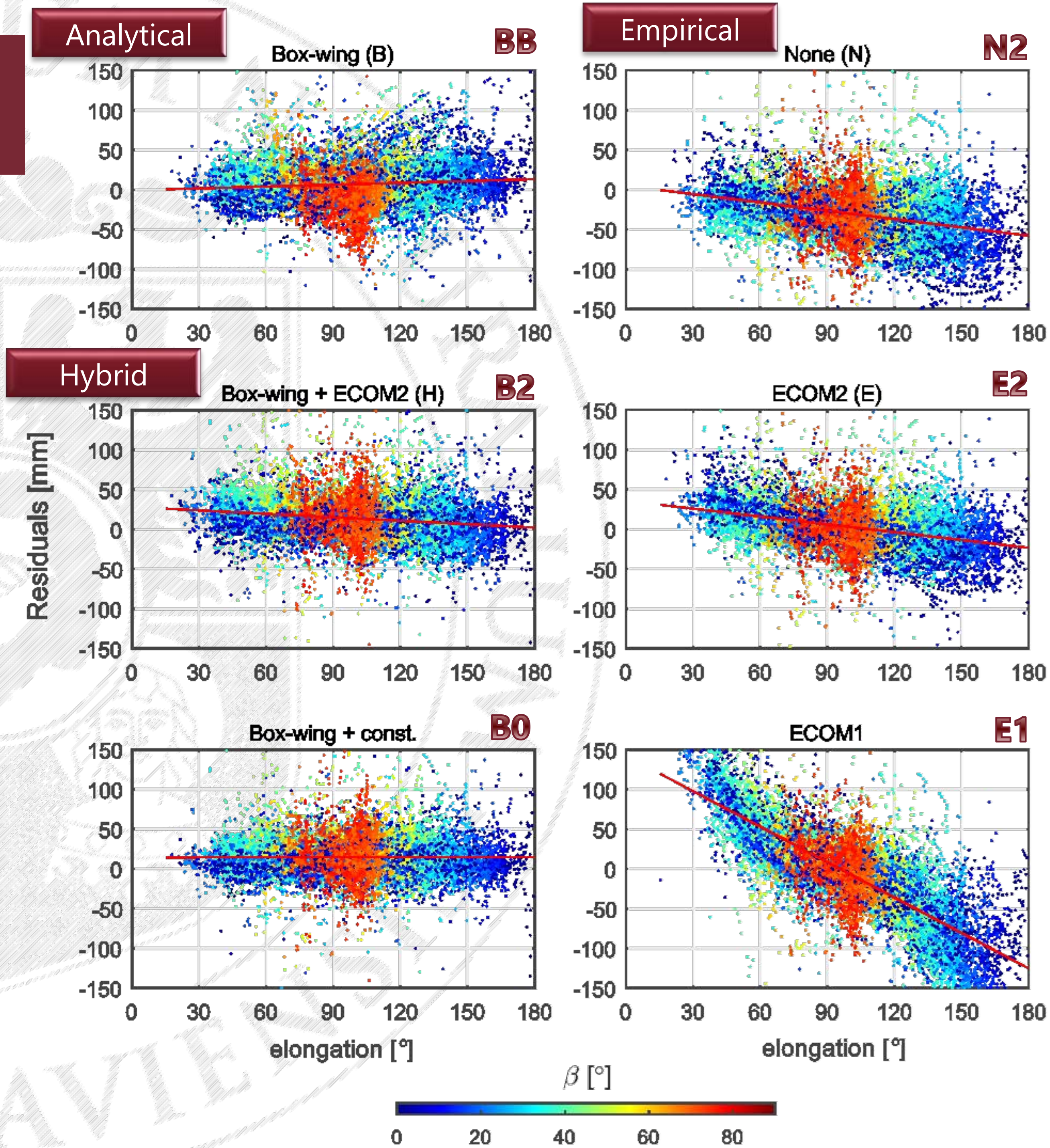
Semi-major axis differences (B2-E2)

$$\Delta a \approx -\frac{4}{3}\frac{a^3 R_0}{GM}$$

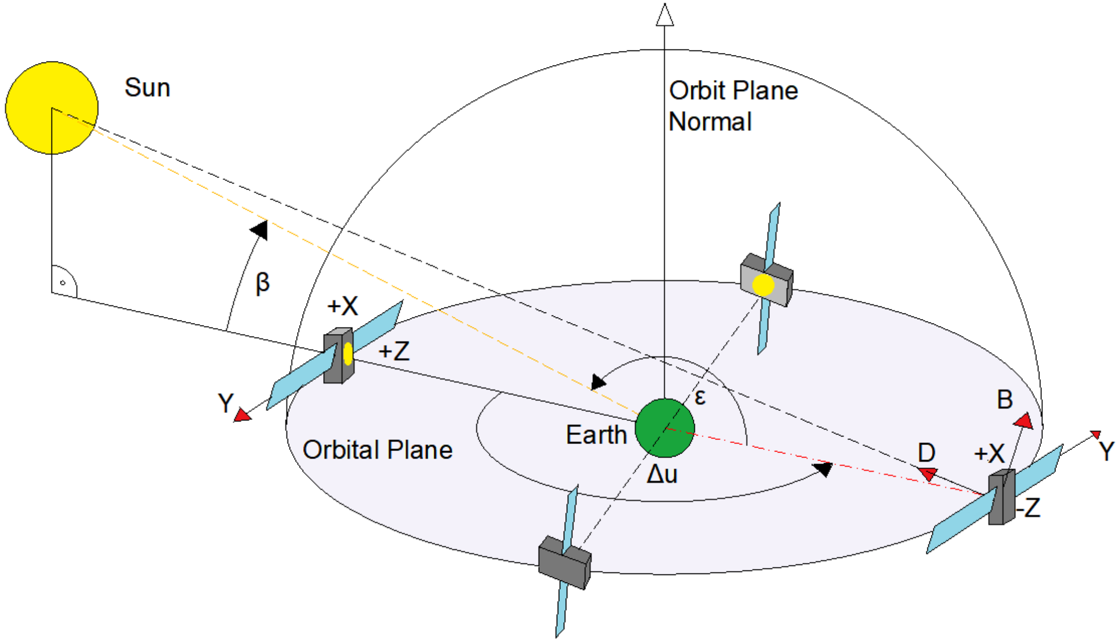


- **Box-wing model absorbs the higher order SRP terms,**
- **The maximum effect for the radial component exceeds 50 mm, and for the orbit semi-major axis 200 mm.**

SLR residual dependence on the elongation angle



	BB	B0	E2
Slope [mm/°]	0.077	0.003	-0.328
STD [mm]	27.3	24.7	29.5



Summary

Precise orbit determination for Galileo is more challenging than for GPS due to the lower mass of the Galileo satellites and the higher X:Z area ration than for the GPS satellites.

In order to absorb the influence of albedo and IR (especially for the Galileo on the elliptic orbits), it is necessary to estimate the higher order terms of the empirical models or usage of the box-wing model.

The usage of the box-wing model significantly improves the Galileo orbit solution when the satellites enter the Earth shadow, i.e., the **SLR residuals decrease from 37 to 25 mm for the HYBRID solution.**

Moreover, the reduction of the empirical parameters stabilizes the solution.

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Thank you for your attention!

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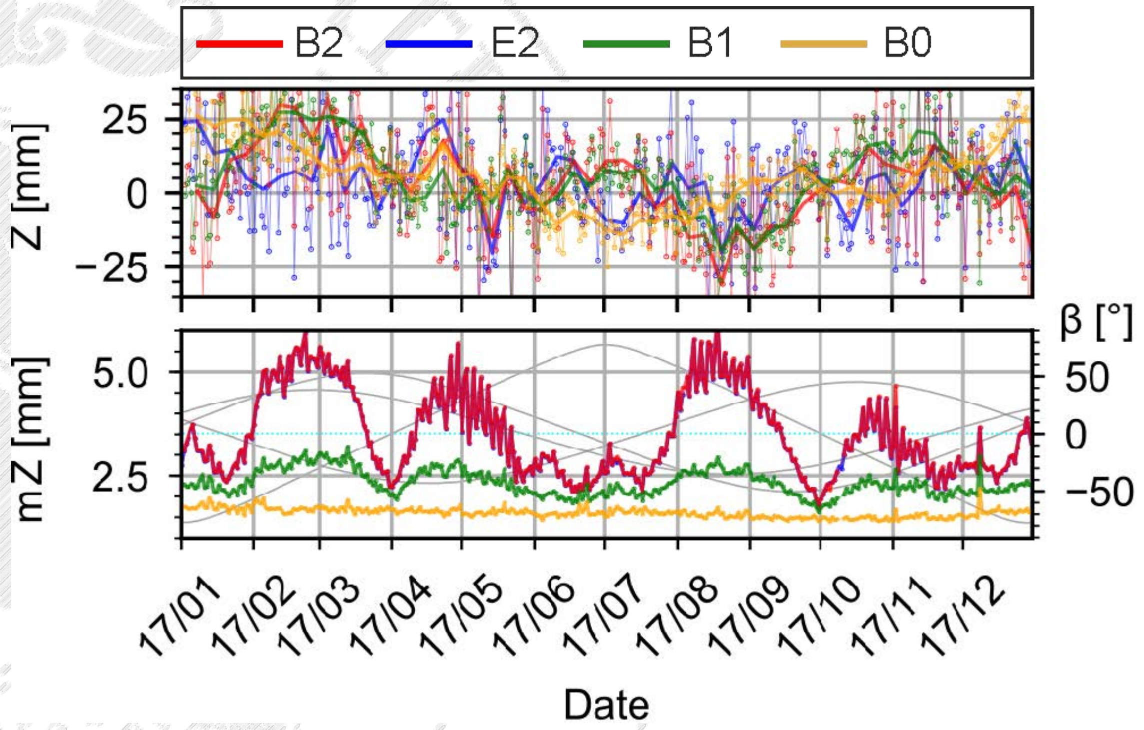
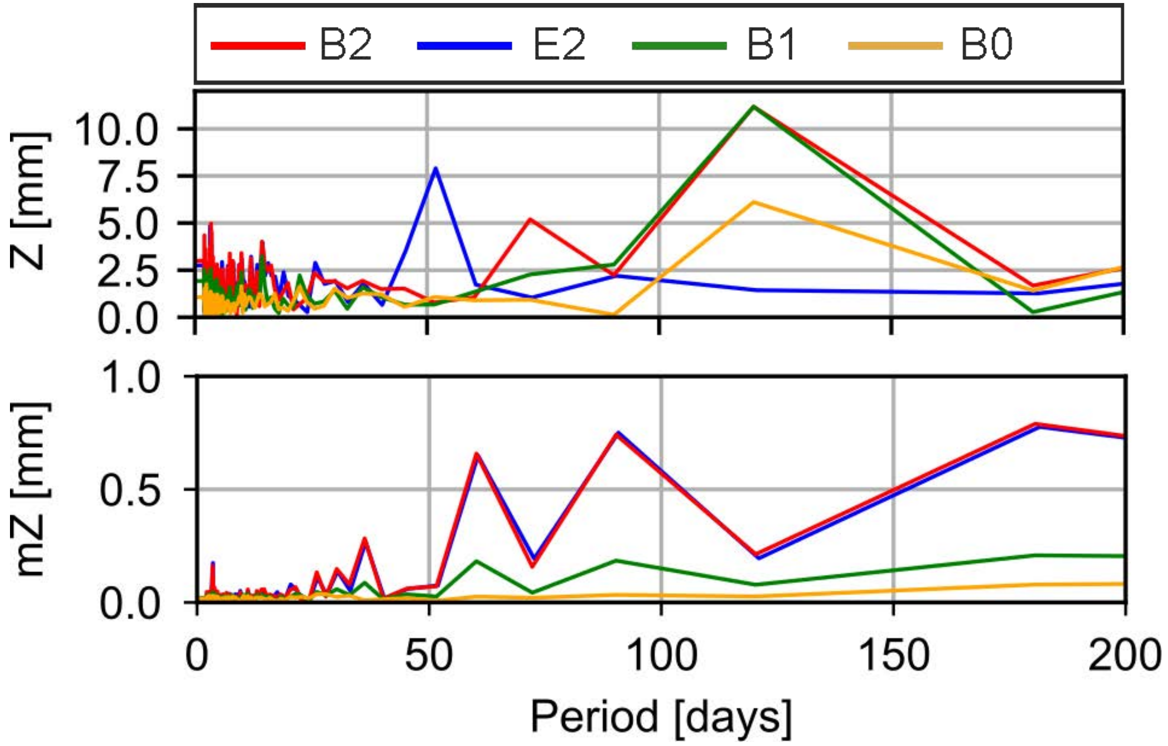
Backup slides…

The impact of the box-wing model on the global geodetic parameters (Geocenter)



'Z ' geocenter coordinate

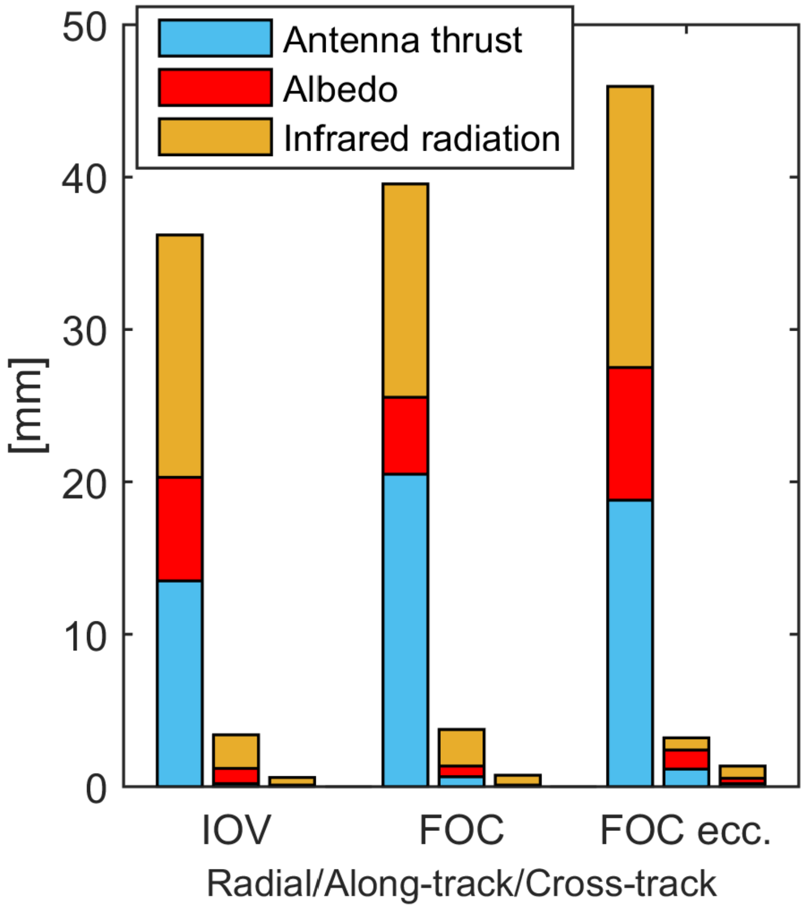


Spectral analysis 'Z ' coordinate of geocenter

- **Reduction of the dependence of the error of the Z component of geocenter estimates on the orbit plane orientation w.r.t the Sun with the reduction of the estimated empirical orbit parameters**

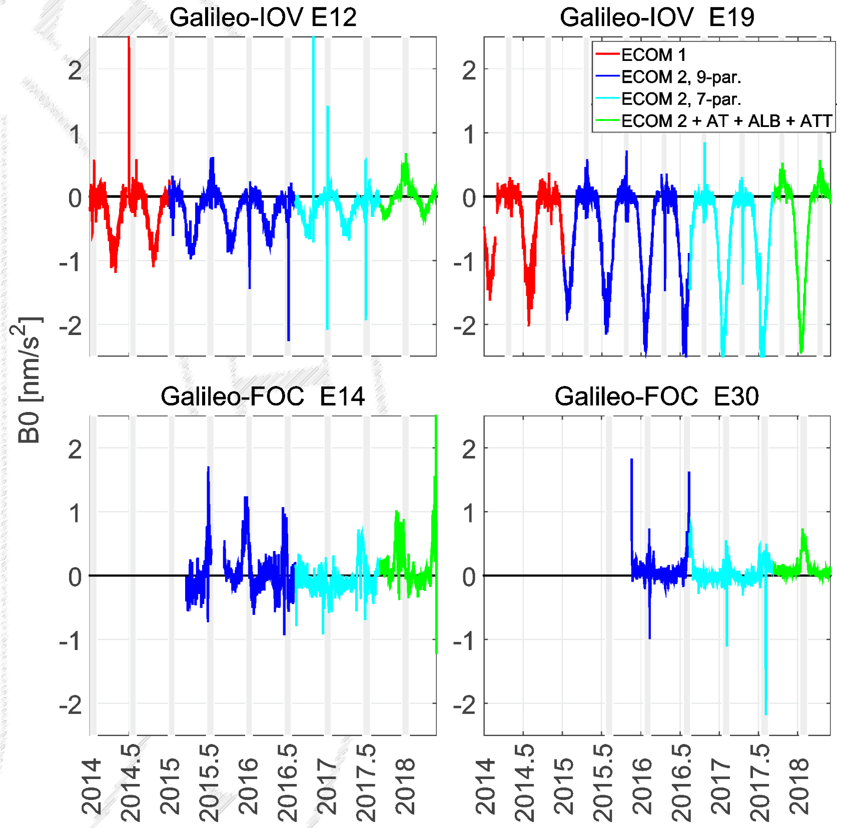
Impact of non-gravitational perturbing forces on Galileo satellites

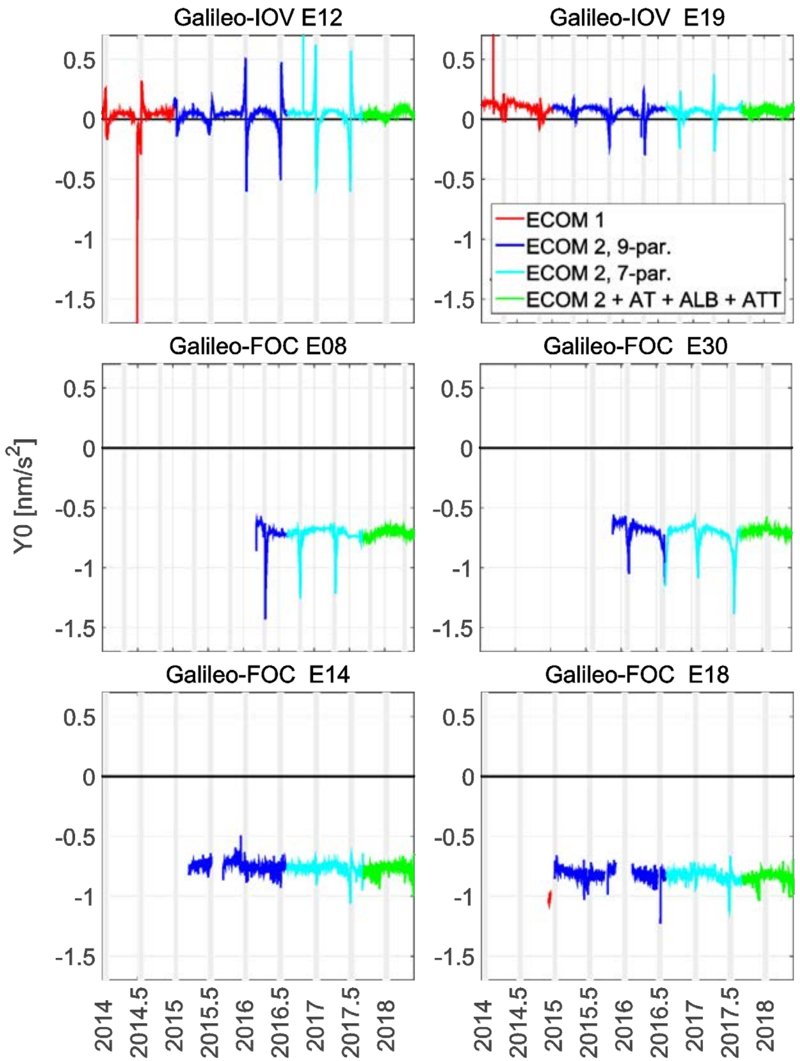
[mm]	IOV	FOC	FOC ecc.
Antenna thrust	13.5	30.5	18.8
Albedo	6.9	5.1	8.8
Infrared radiation	16.1	14.2	18.5



- **The higher values of the satellite position differences for the Galileo on elliptic orbits come from their orbit characteristics (relativistic effects)**

Empirical orbit parameters (CODE)

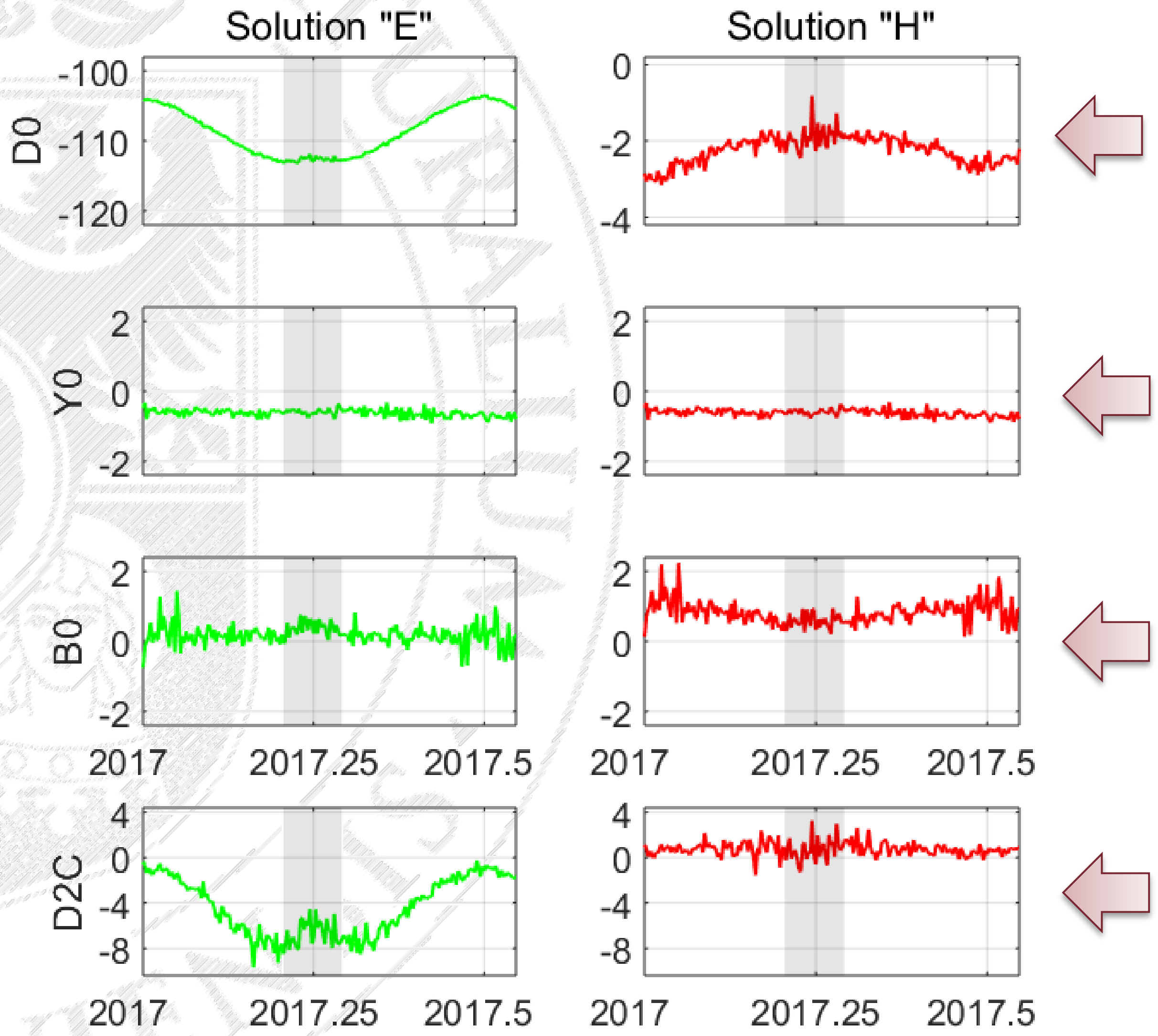




- **Galileo-IOV satellites are characterized with the B accelerations dependence on the β angle (max 3.6 nm/s^2)**
- **Galileo-FOC satellites are characterized with the constant acceleration in the Y direction at the level of (0.7 nm/s^2)**

$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C}\cos\Delta u + B_{1S}\sin\Delta u \end{bmatrix}$$

Empirical parameters estimates

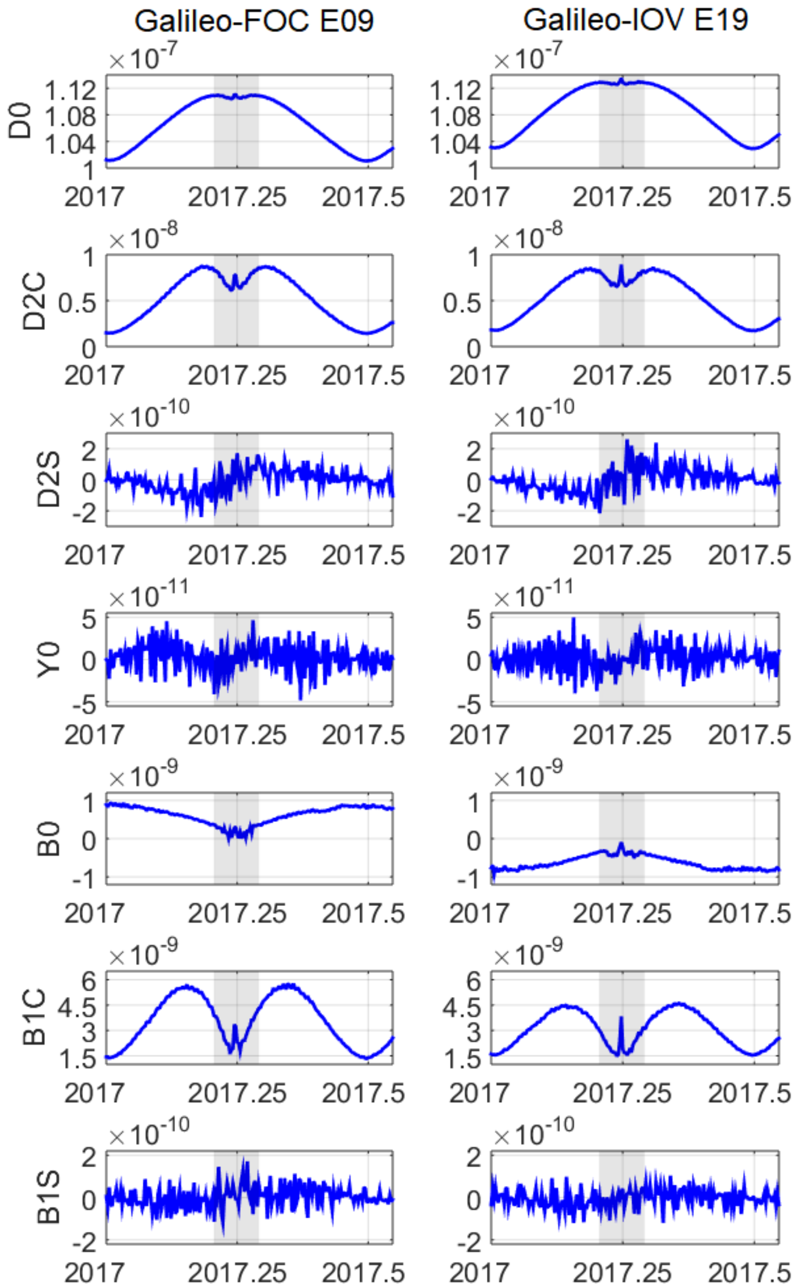


$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C}\cos\Delta u + B_{1S}\sin\Delta u \end{bmatrix}$$

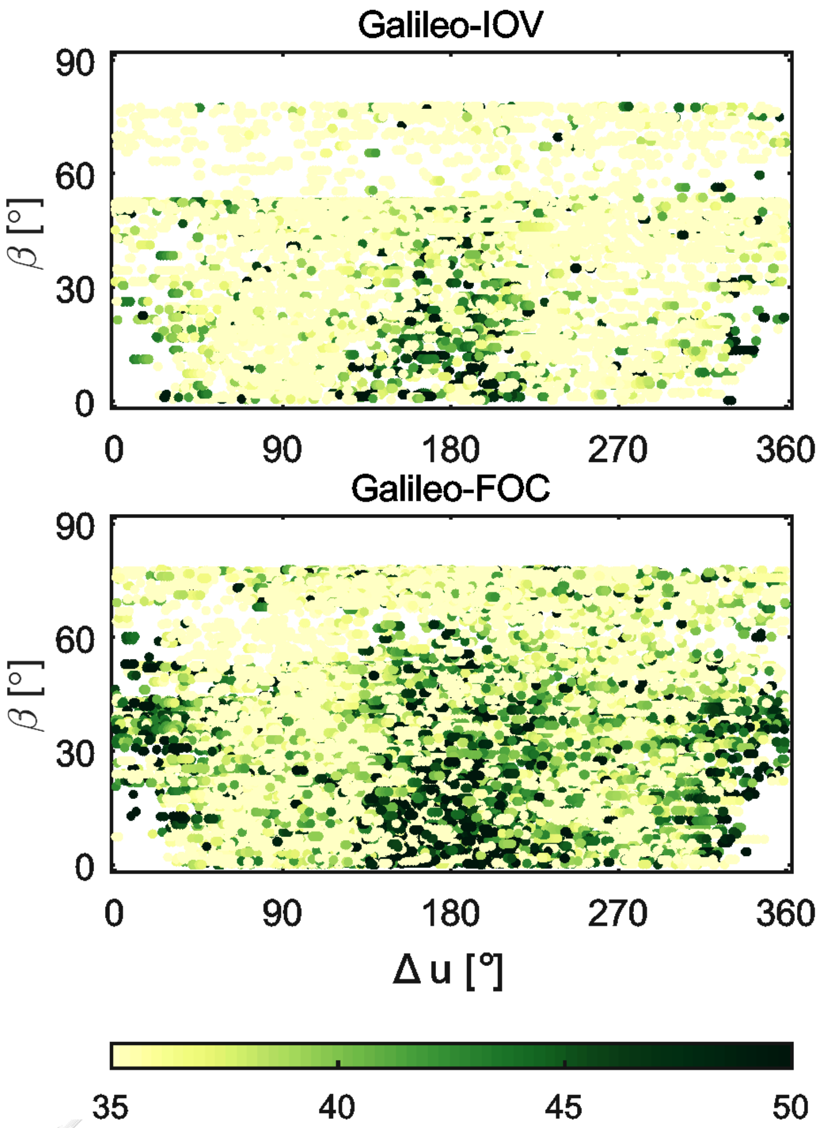
- **Box-wing absorbs up to 97% of the direct SRP and other „µ"-accelerations acting on the Galileo satellites.**
- **The constant accelerations result from the misalignment of the solar panels w.r.t the Sun.**
- **Box-wing model diminishes the dependence of the empirical parameters estimates on the β angles.**

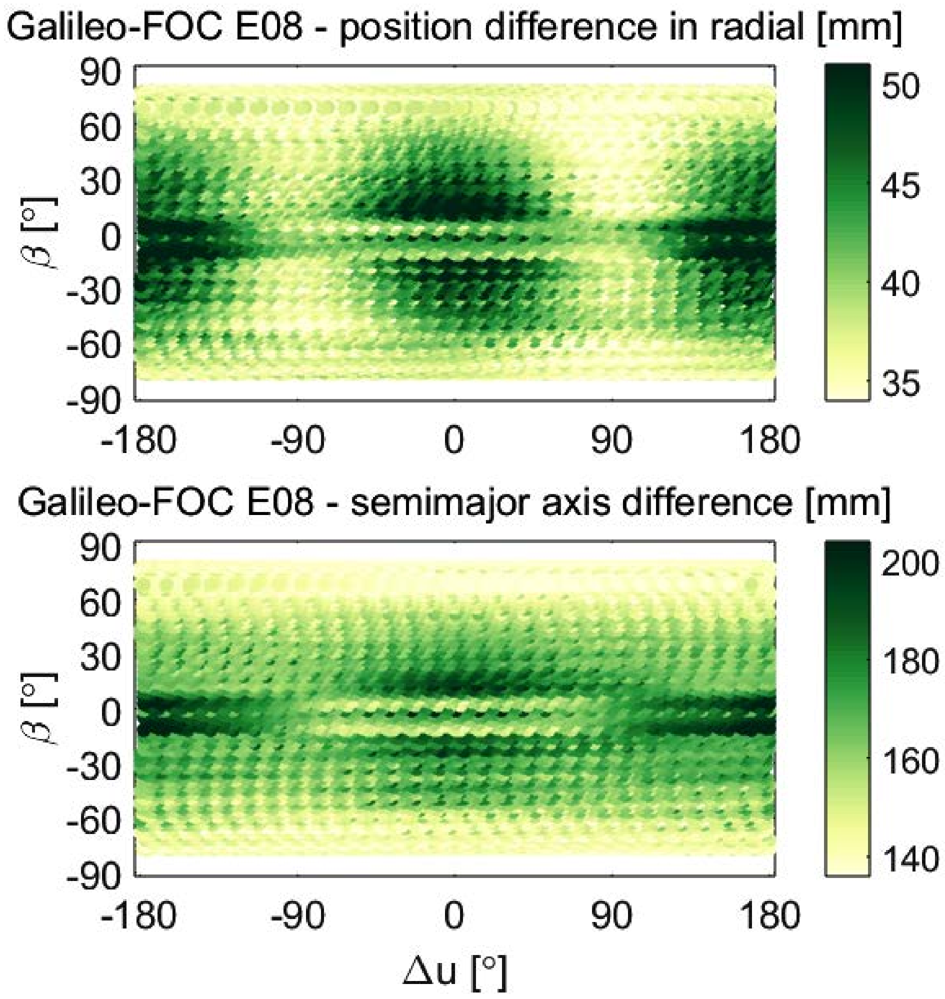
Empirical parameters estimates differences

Source	Magnitude [nm/s²]
Direct SRP	122.0
Albedo	1.0
Infrared radiation	1.0
Antenna thrust	1.2
D_0 variability	0.4
Y – bias (FOC)	0.7
B – $bias_{max}$ (IOV)	3.6
Thermal effect (D_{2S} variability)	0.8



Impact of albedo, IR, and antenna thrust





Quality of the Galileo orbit predictions