21ST INTERNATIONAL WORKSHOP ON LASER RANGING

5 – 9 NOVEMBER 2018
CANBERRA, AUSTRALIA

WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

Galileo precise orbit determination based on GNSS and SLR observations

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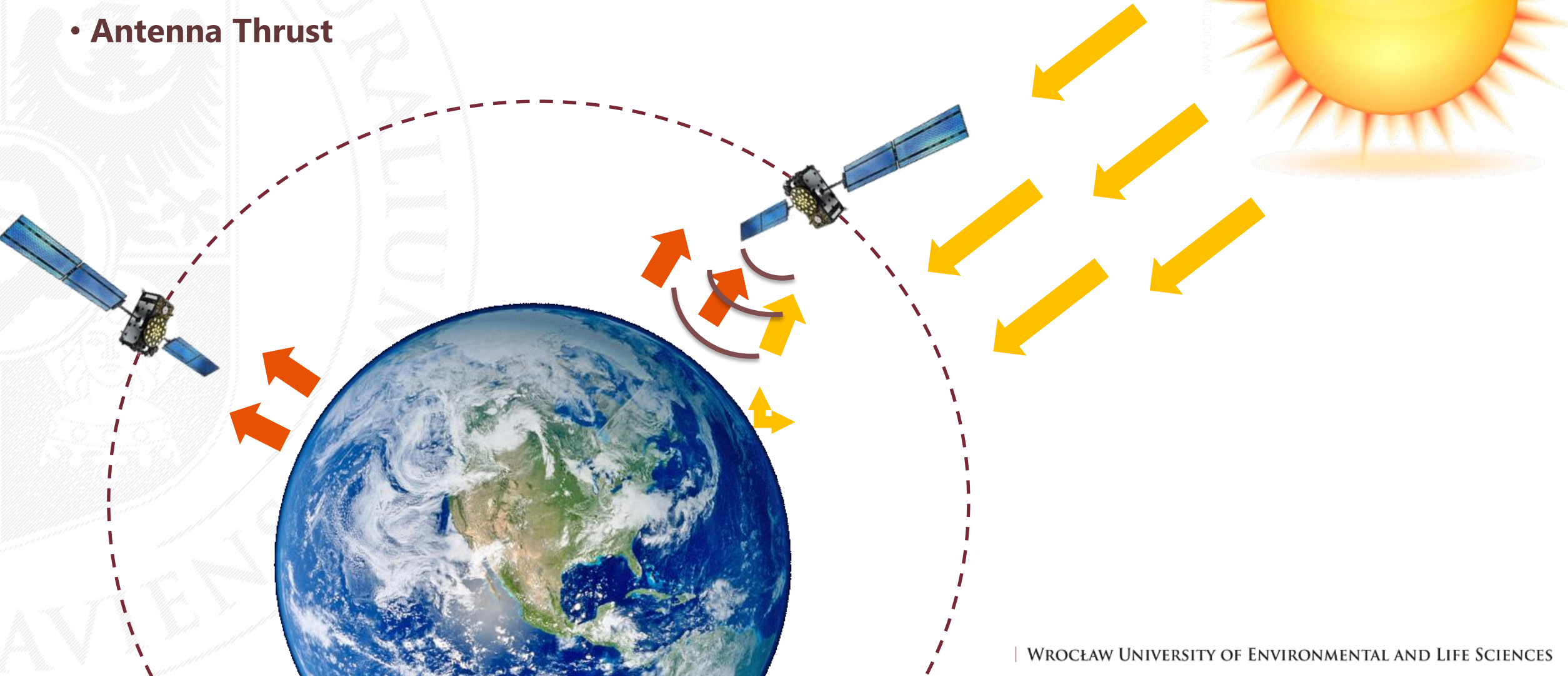
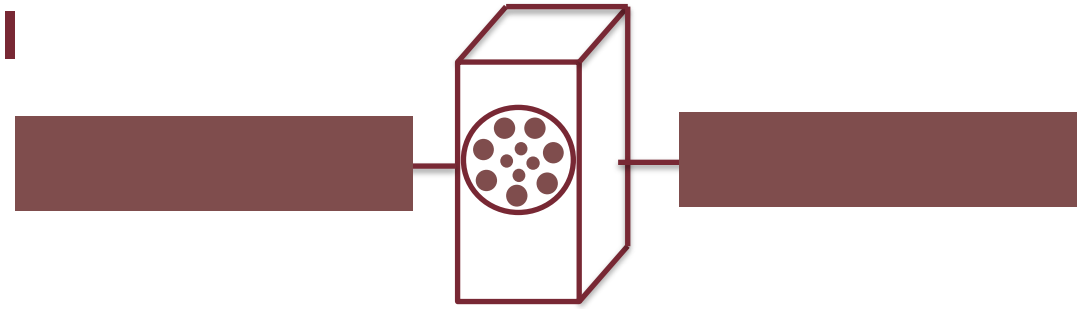
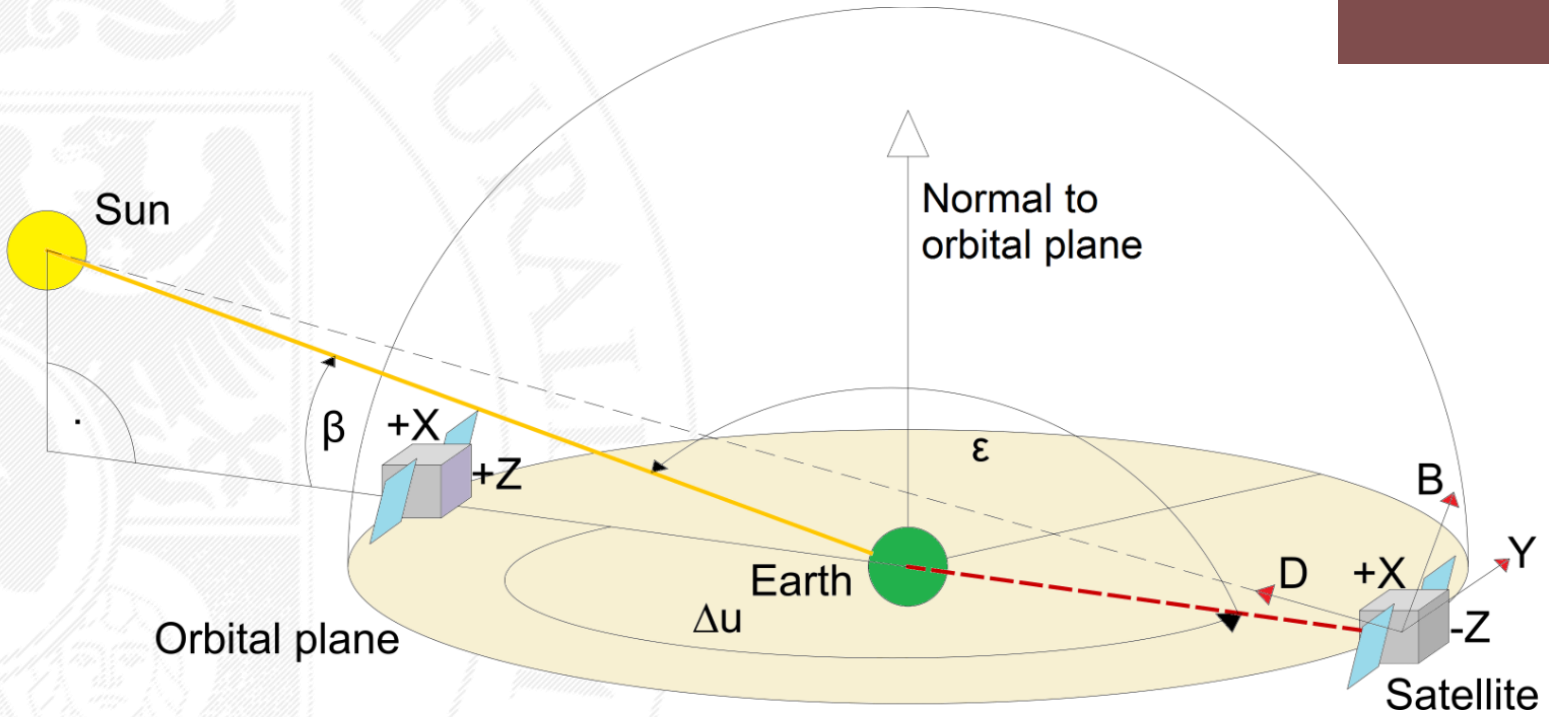
- Direct Solar Radiation Pressure
- Albedo
- Infrared Radiation
- Antenna Thrust
- Solar wind
- Thermal effects
- Y-bias, B-bias



GNSS characteristics – the „Box-wing" model





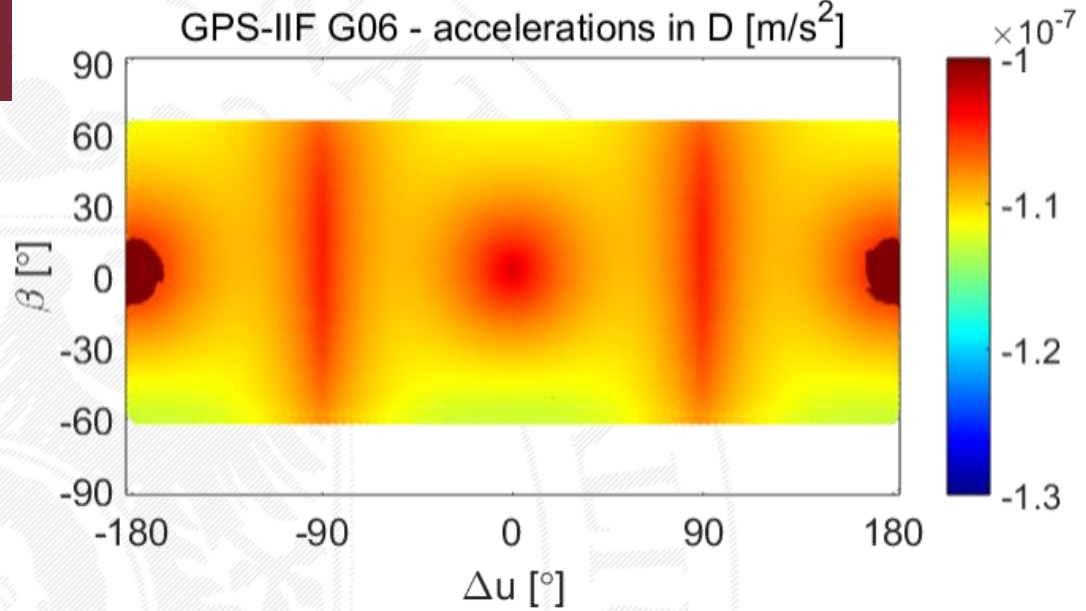
Galileo Satellite Metadata

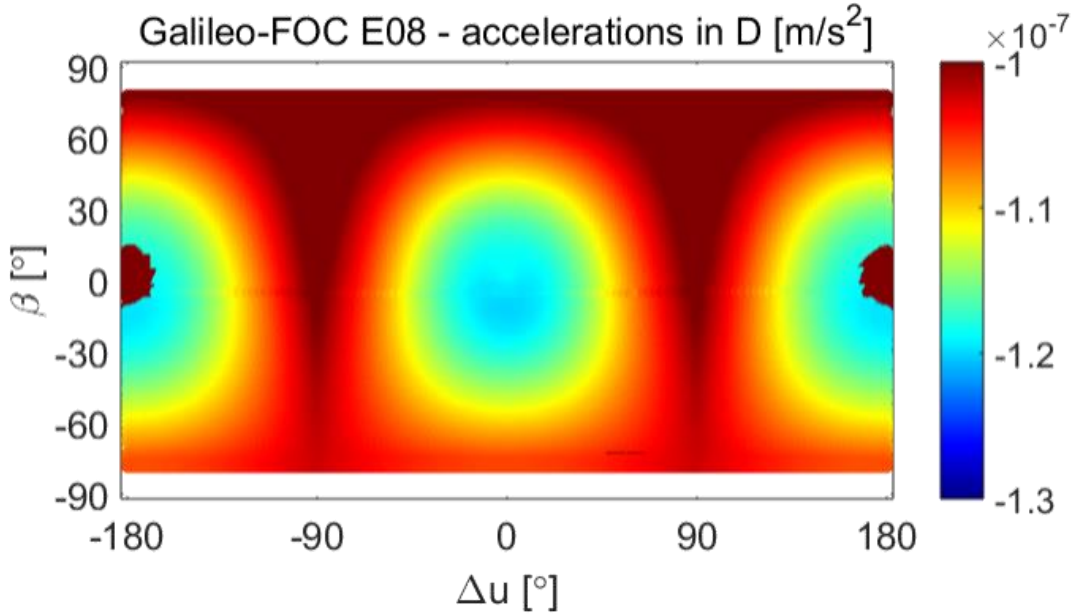
https://www.gsc-europa.eu/support-to-developers/galileo-satellite-metadata

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

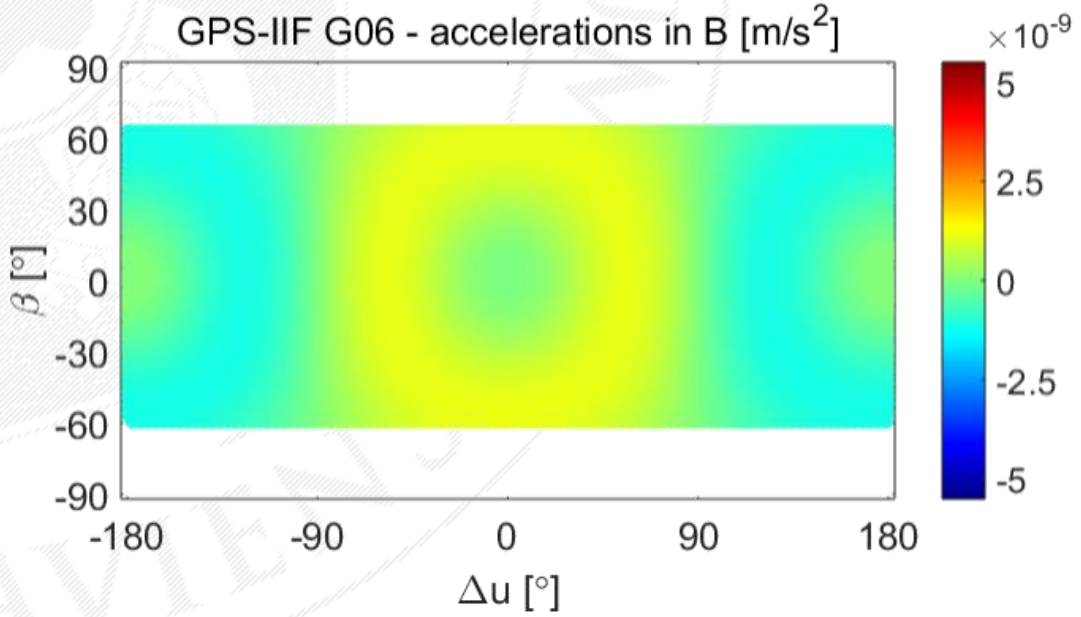
System	Type	Solar panels area [m²]	Box surface area [X/Y/Z] [m²]	Altitude [km]	Mass [kg]
GPS	Block IIF	13.60	**5.72**/7.01/**5.40**	20 200	1555
Galileo	IOV	**10.82**	**1.32**/3.00/**3.00**	**23 200**	**695**
	FOC / FOC ecc.	**10.82**	**1.32**/2.78/**3.04**	**23 200 / 17 000-26 000**	**708/645**

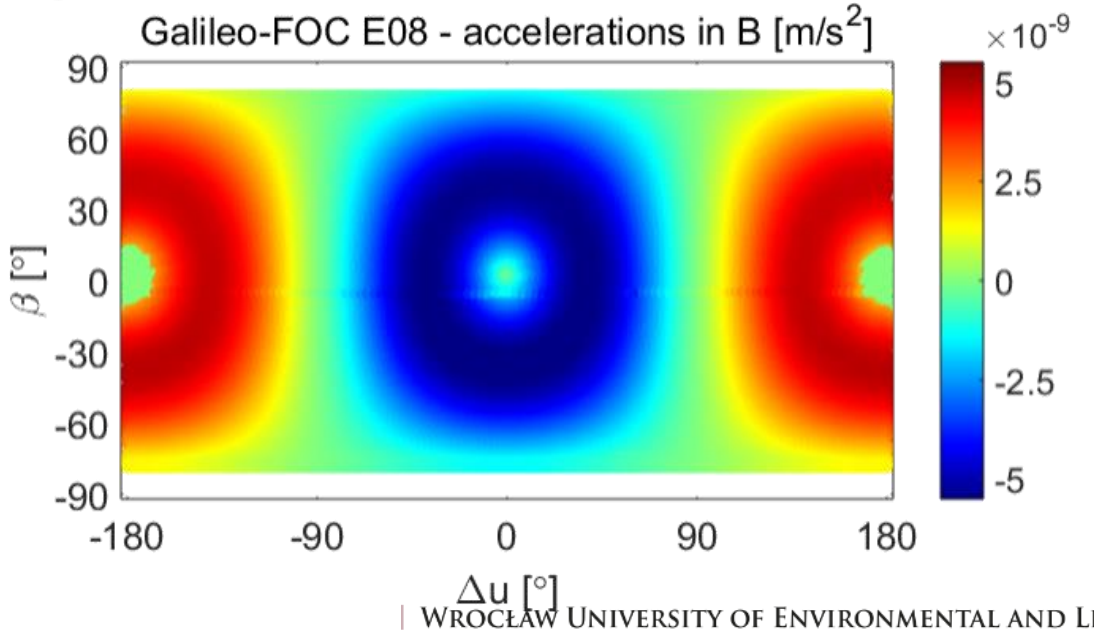
SRP –„Box wing" model – accelerations in D and B





Galileo orbit modelling is more challenging than for the GPS satellites





New Empirical CODE Orbit Model (ECOM2)

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

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

Absorb variations of direct SRP acting on the bus

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

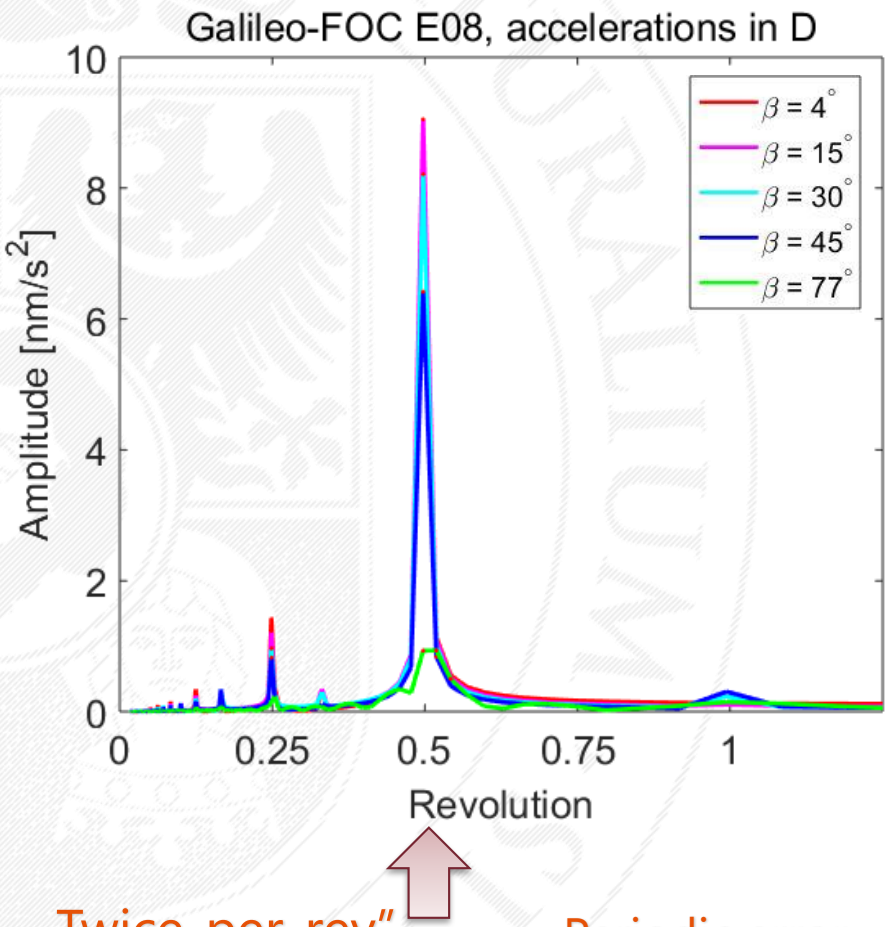
Absorb thermal effects to some extent (temperature lags)

Absorb Y-bias and B-bias due to the misalignment of the solar panels w.r.t. the Sun

Limitations:

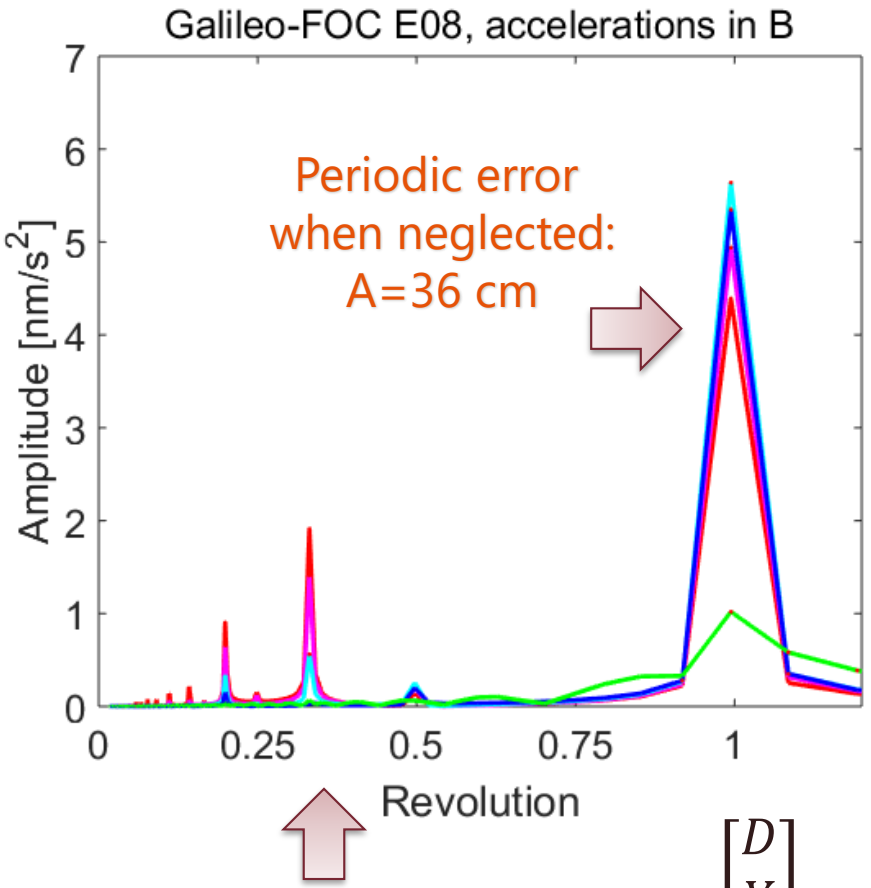
- Albedo is not included
- Antenna thrust is not included (constant radial acceleration)
- Assumes yaw-steering (accounts only for the Y-bias and B-bias)
- Problems with eclipsing satellites (ECOM parameters = 0 in Earth's shadows & dynamic yaw-steering)

SRP –„Box wing" model – spectral analysis



„Twice-per-rev" absorbed by ECOM2

Periodic error when neglected: A=15 cm



Periodic error for the low β angles A=1.3 cm

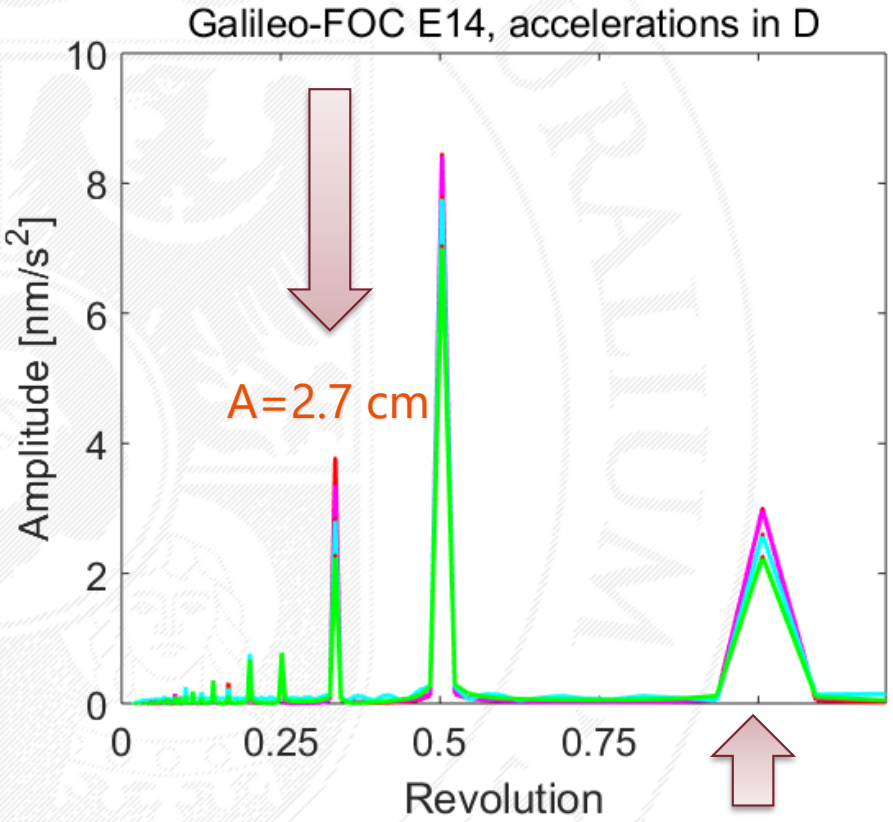
- „Once-per-rev" are always estimated in ECOM1/ECOM2
- „Thrice-per-rev" are not usually estimated although they cause systematic errors during low β angles

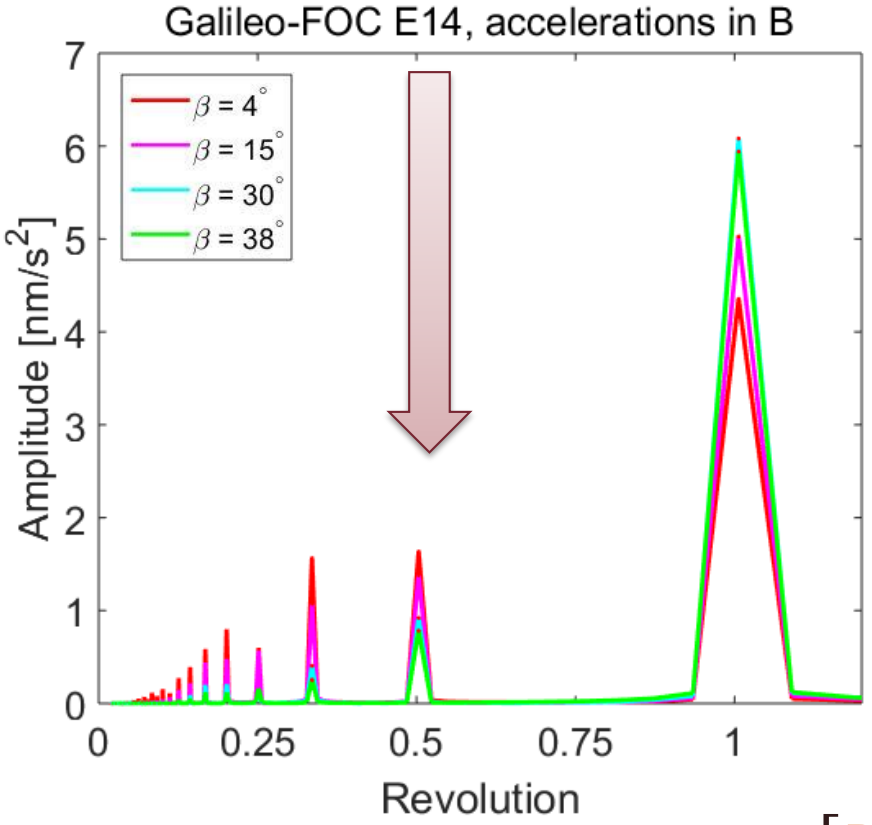
$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C}\cos \Delta u + B_{1S}\sin \Delta u \end{bmatrix}$$

SRP –„Box wing" model – spectral analysis

„Thrice-per-rev" NOT absorbed by ECOM2

„Twice-per-rev" NOT absorbed by ECOM2 A=2.6 cm





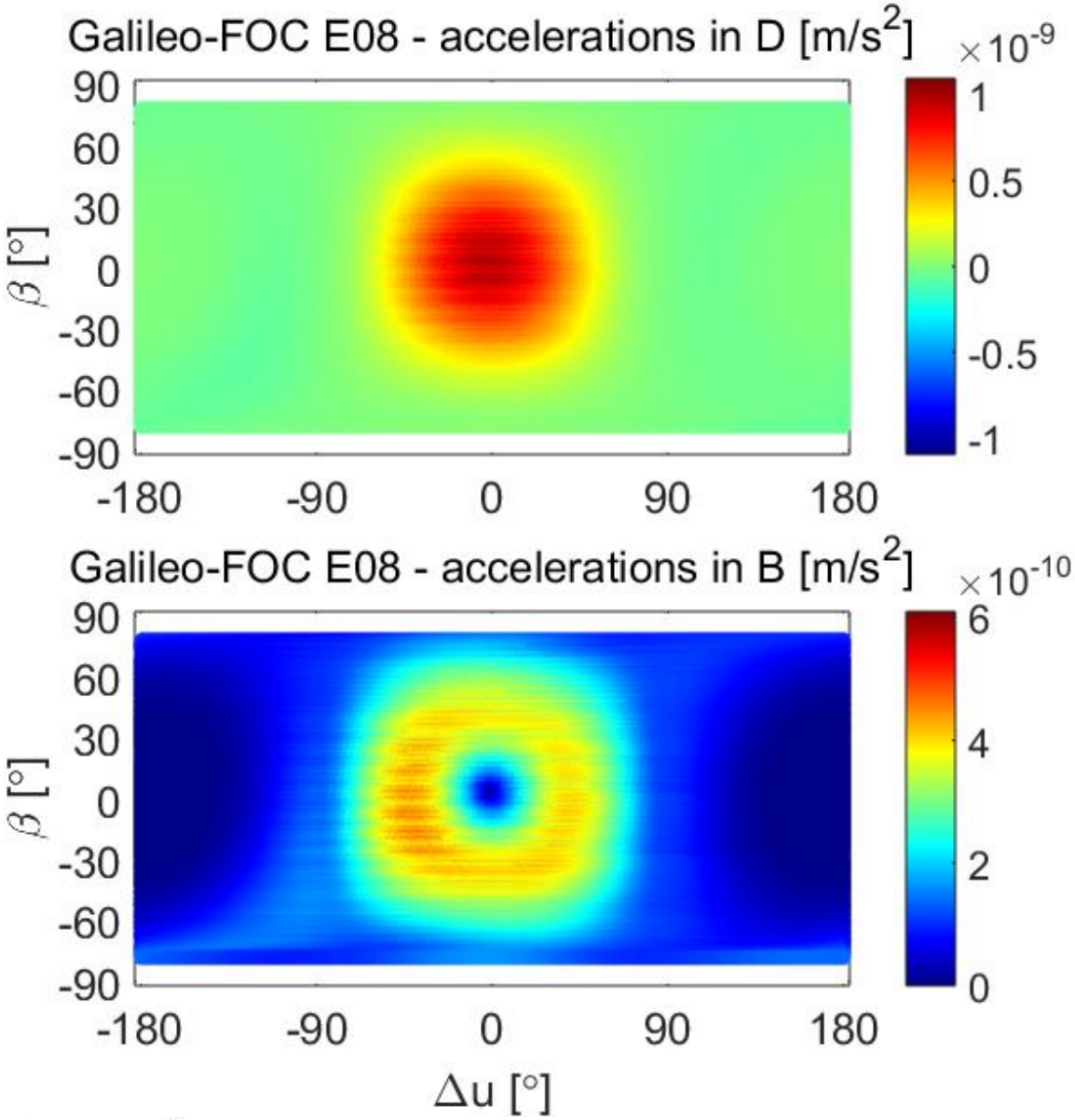
The current form of the ECOM2 absorbs the „Twice-per-rev" accelerations in the D - direction –> insufficient for the elliptic Galileo

„Once-per-rev" NOT absorbed by ECOM2

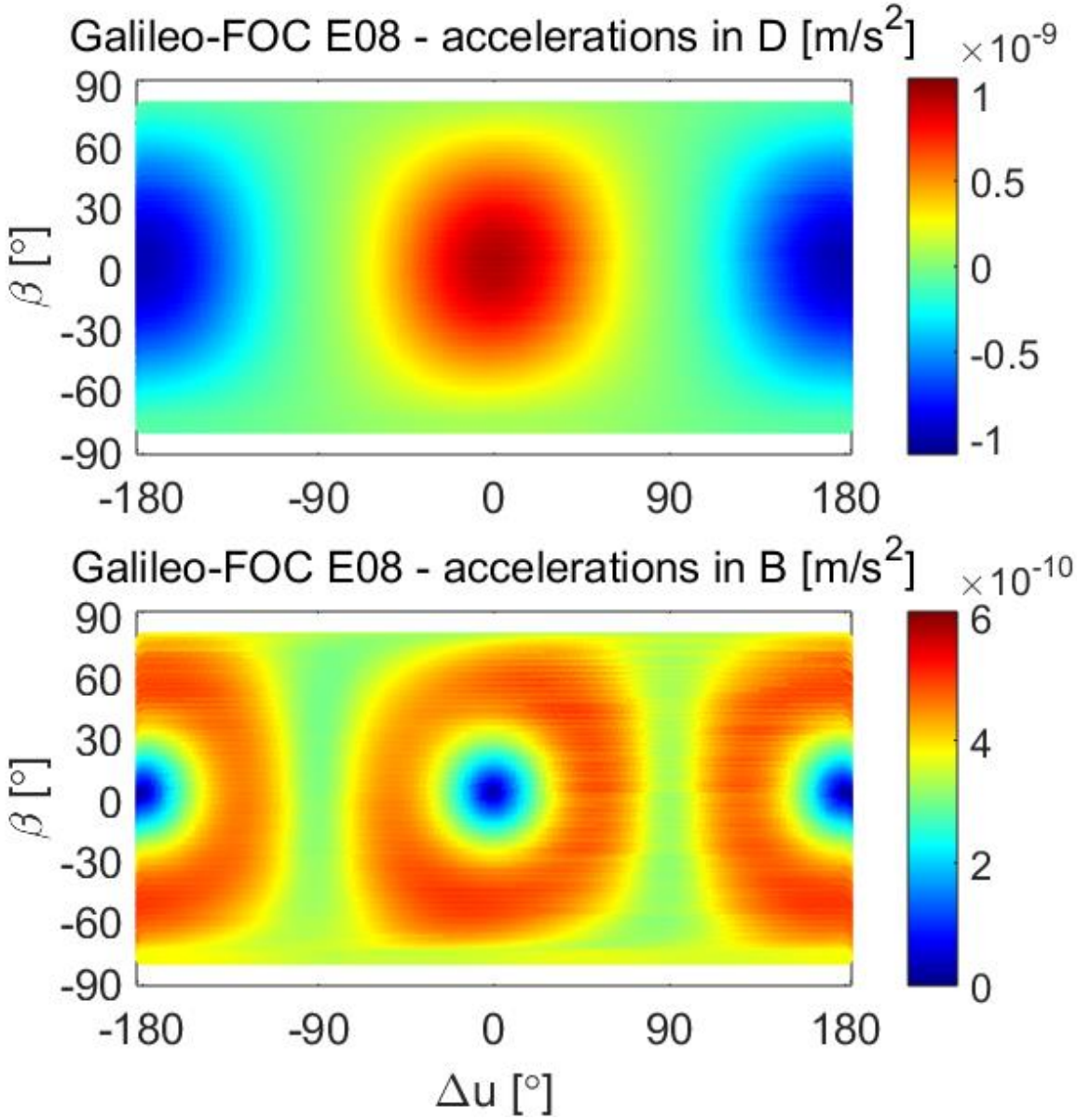
Periodic error when neglected: A=18 cm

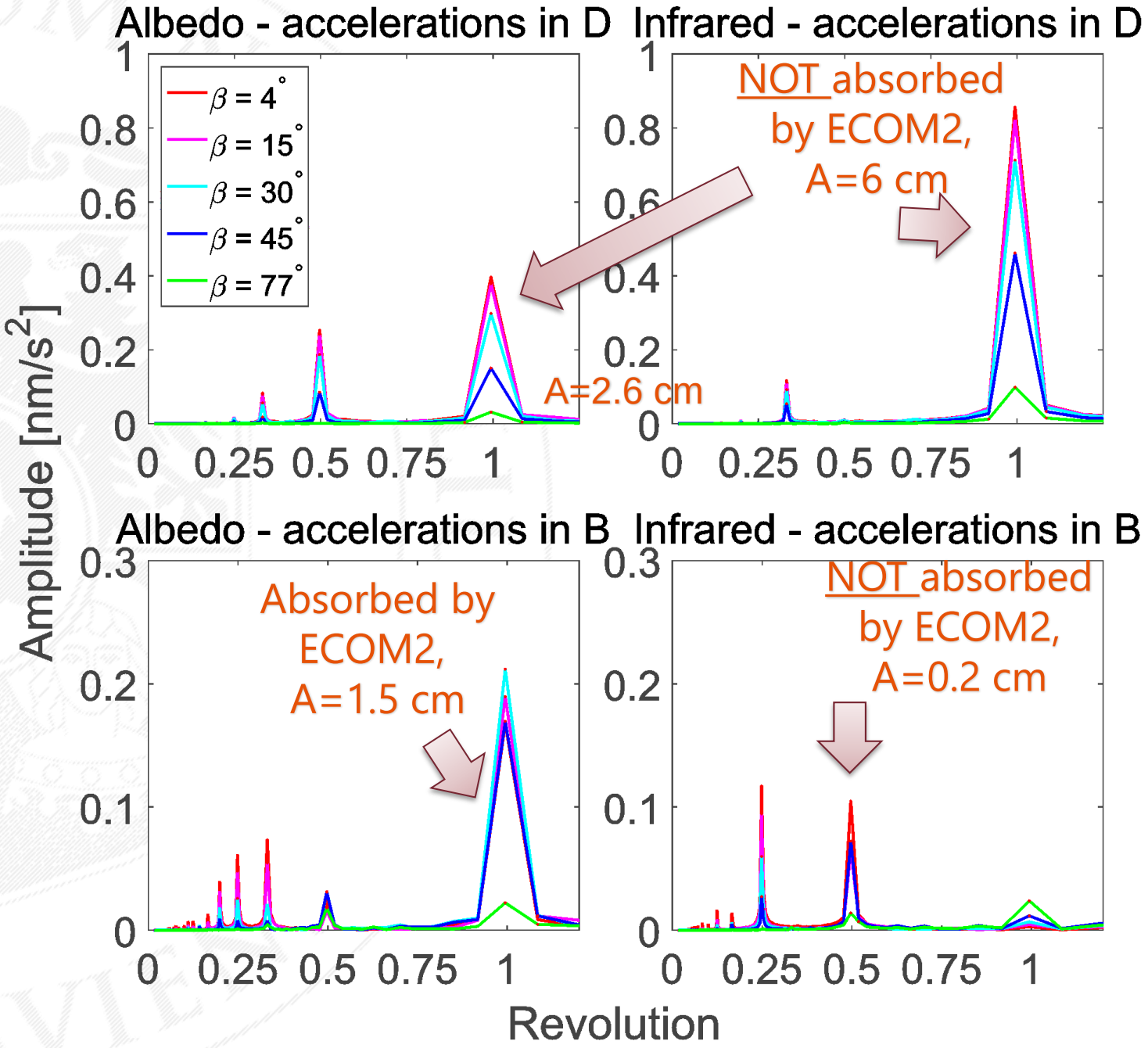
$$\begin{bmatrix} D \\ Y \\ B \end{bmatrix} = \begin{bmatrix} D_0 + D_{2C}\cos 2\Delta u + D_{2S}\sin 2\Delta u \\ Y_0 \\ B_0 + B_{1C}\cos \Delta u + B_{1S}\sin \Delta u \end{bmatrix}$$

Albedo



Infrared radiation

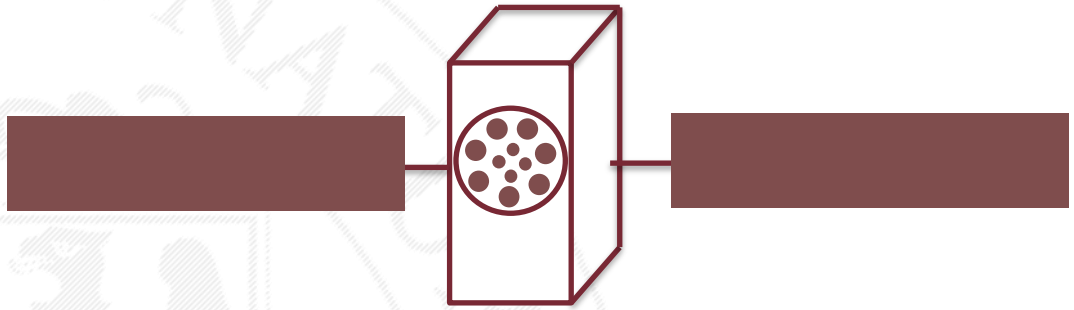




Albedo & IR – spectral analysis

- ECOM2 does not fully absorb the albedo
- Not only the periodic perturbations, but also the constant accelerations resulting form IR has an impact on 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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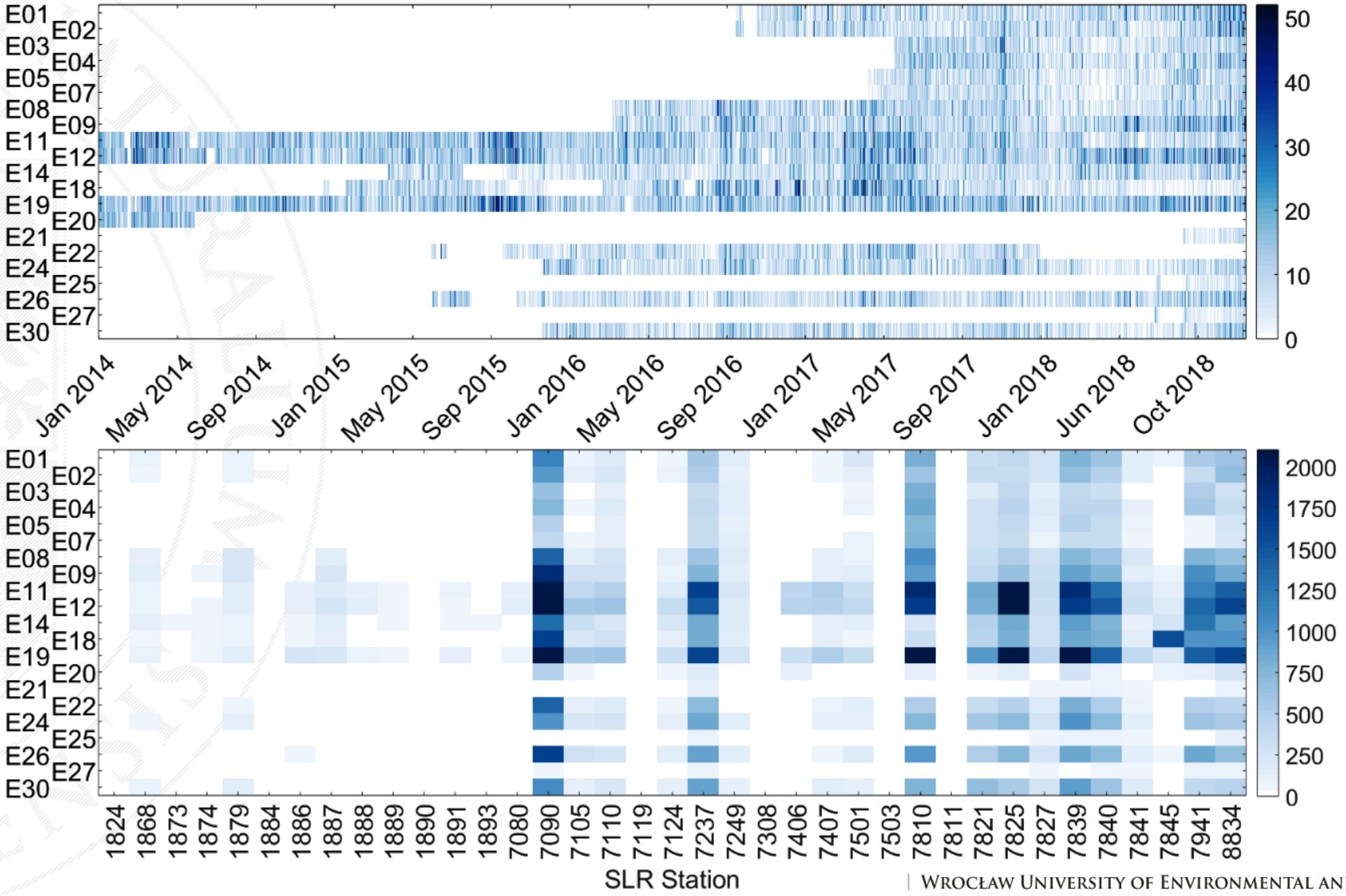
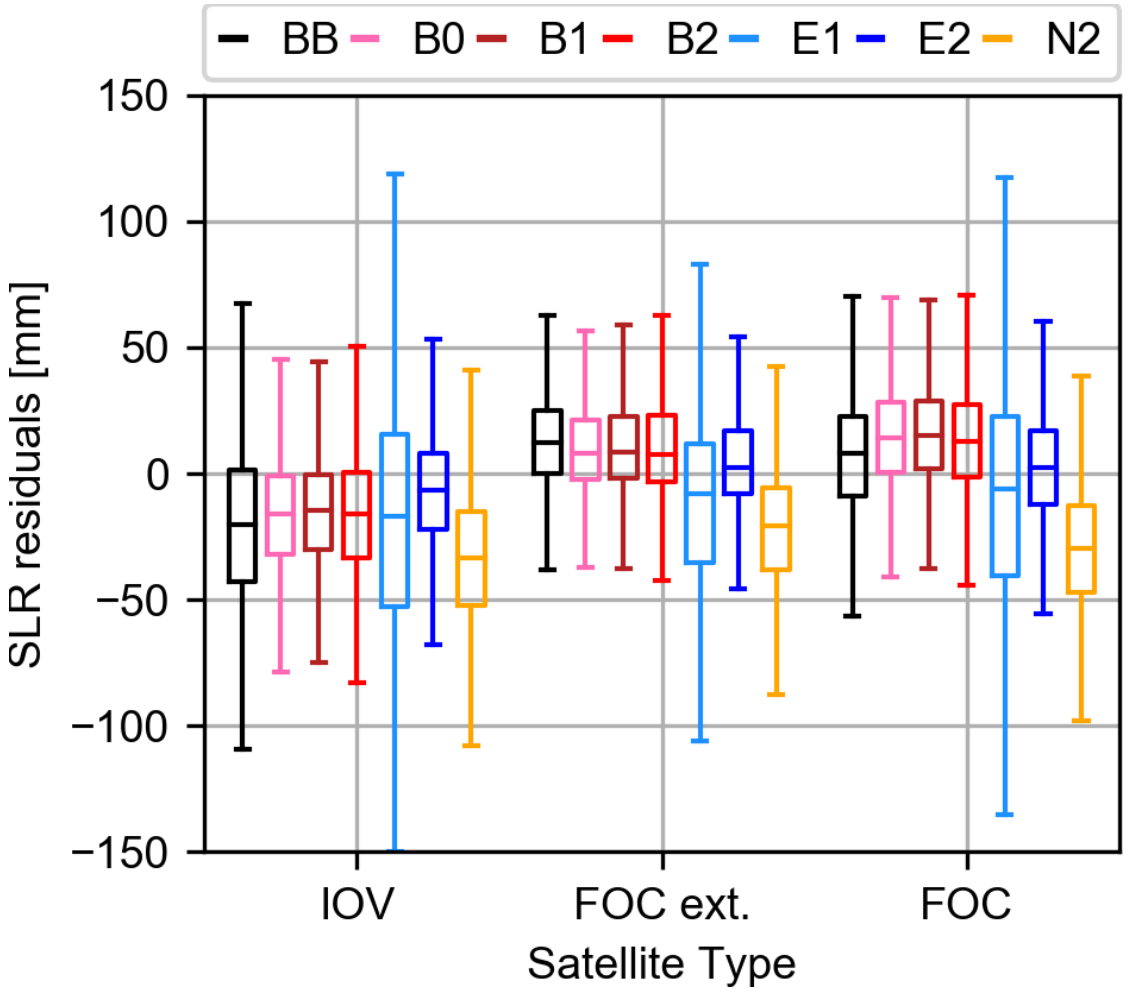
Precise orbit determination using the box-wing model

The number of SLR observations to Galileo



SLR residuals microwave orbit validation using SLR data
1-day arcs for 0-200 doy 2017

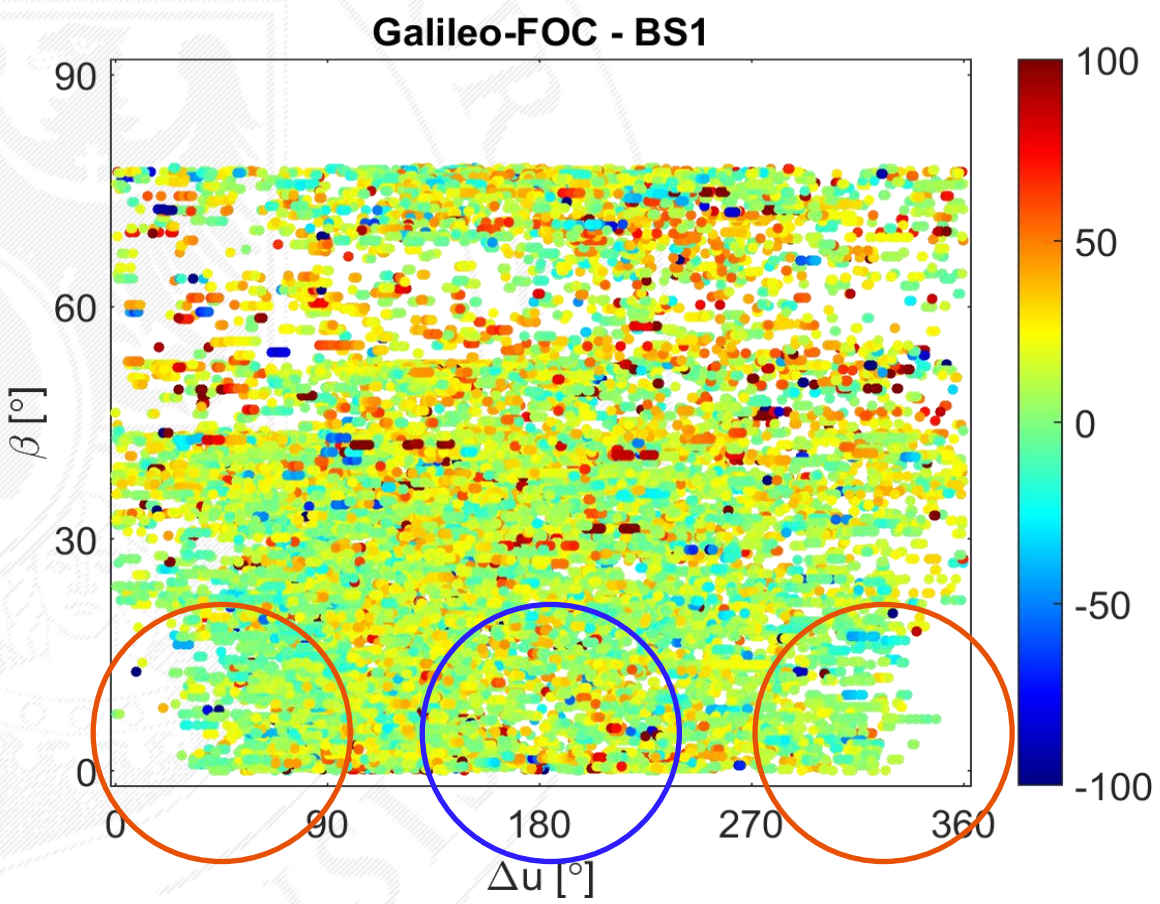
Solution	Box-wing	Empirical Orbit Parameters	Albedo + Antenna thrust
BB	**YES**	NONE	**YES**
B0	**YES**	D0,Y0,B0	**YES**
B1	**YES**	D0,Y0,B0, B1S,B1C	**YES**
B2	**YES**	D0,Y0,B0, B1S,B1C,D2C, D2S	**YES**
E1	NO	D0,Y0,B0, B1S,B1C	**YES**
E2	NO	D0,Y0,B0, B1S,B1C,D2C, D2S	**YES**
N2	NO	D0,Y0,B0, B1S,B1C,D2C, D2S	NO



FOC[mm]	BB	B0	B1	B2	E1	E2	N2
Mean	**7.2**	**15.3**	**16.1**	**13.9**	**-8.7**	**3.1**	**-29,1**
RMS	**28.9**	**25.3**	**25.0**	**27.0**	**53.7**	**27.3**	**30.8**

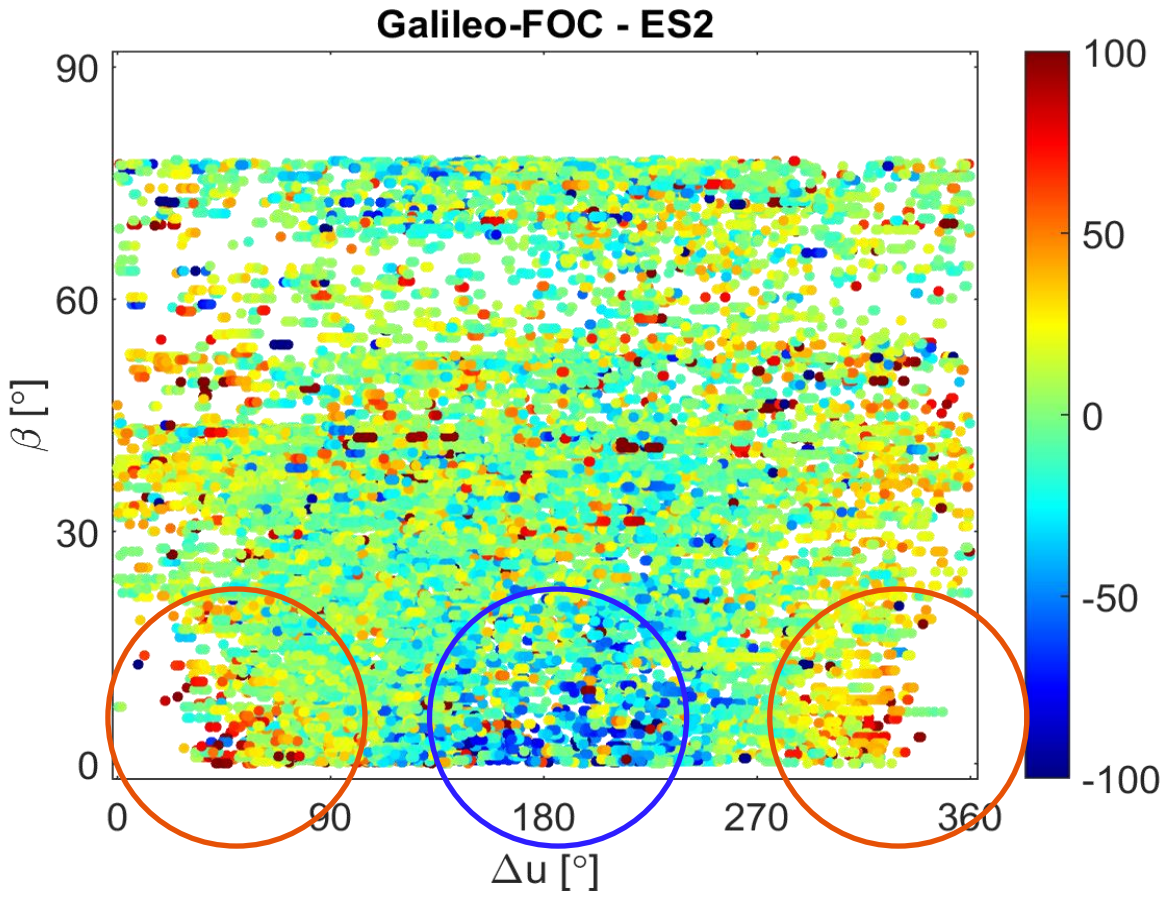
SLR residuals to microwave orbit solution [mm]

Box-wing (B1)



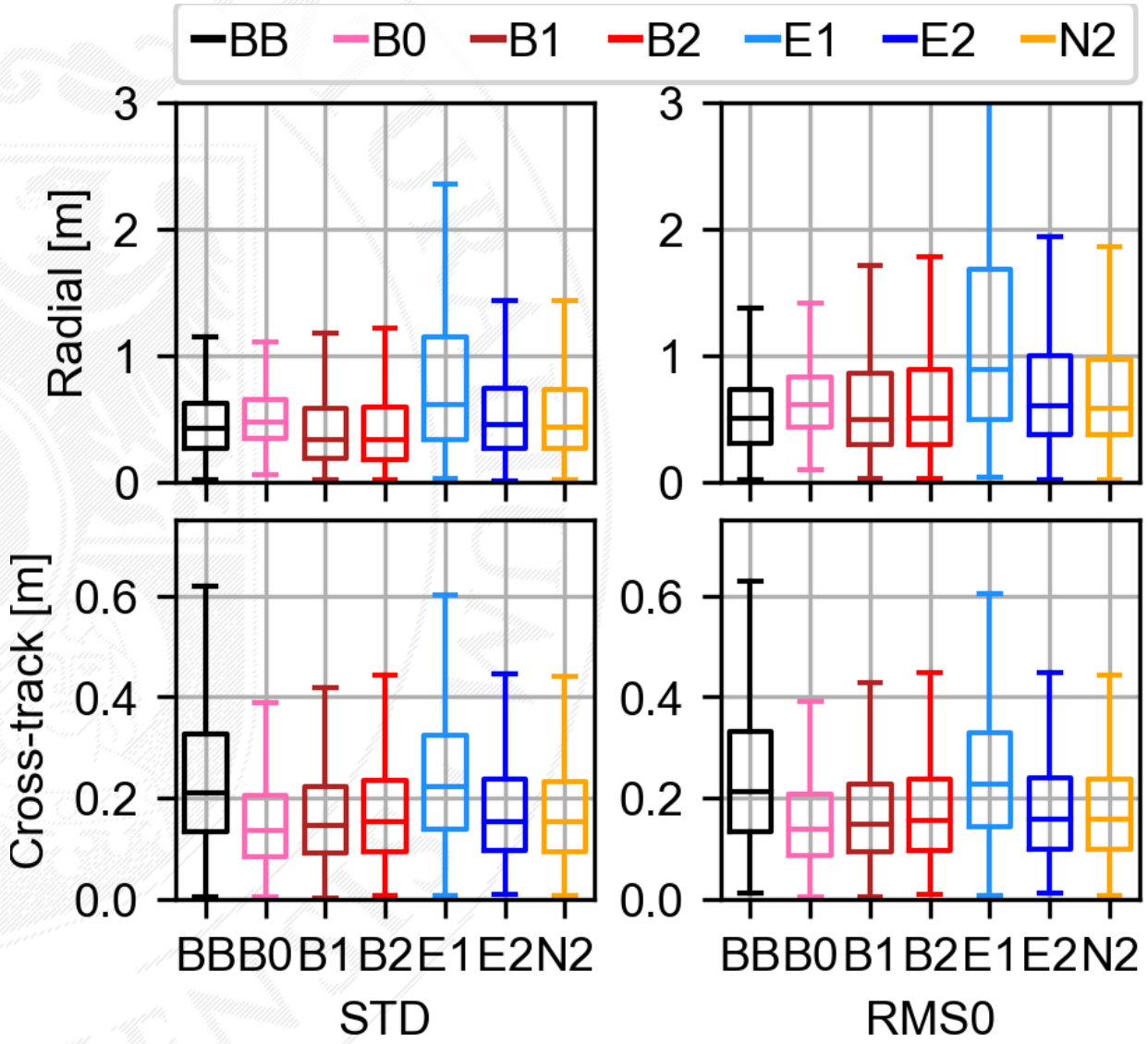
β < 14˚ RMS: 26 mm

Standard ECOM2 solution (E2)

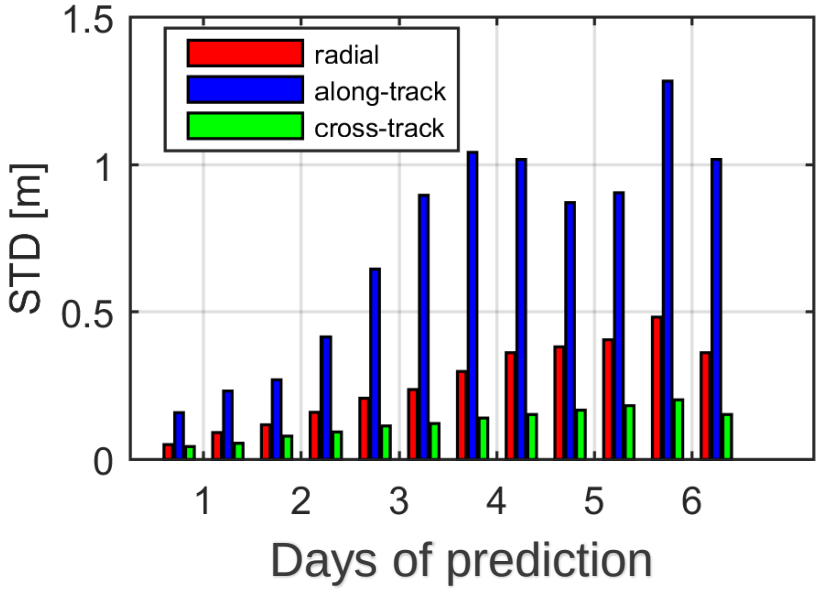


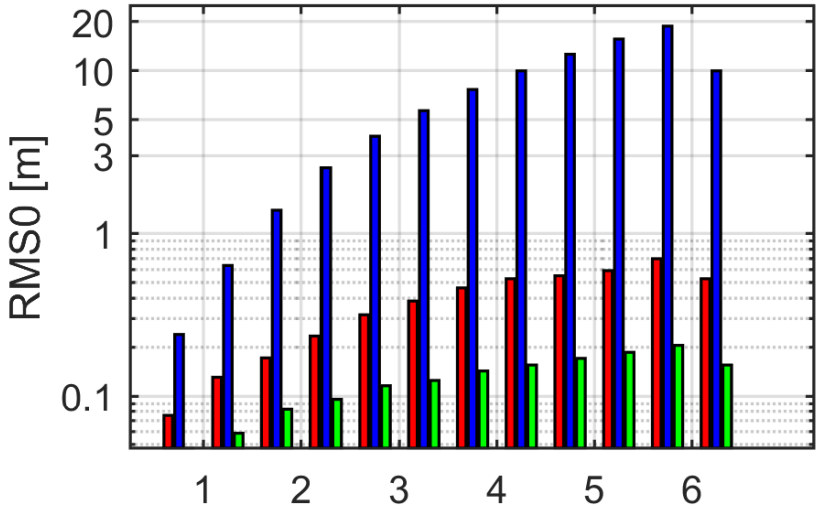
β < 14˚ RMS: 42 mm

The quality of Galileo orbit predictions



Quality of the 5-day orbit predictions





Quality of the orbit predictions in the 12-hour interval

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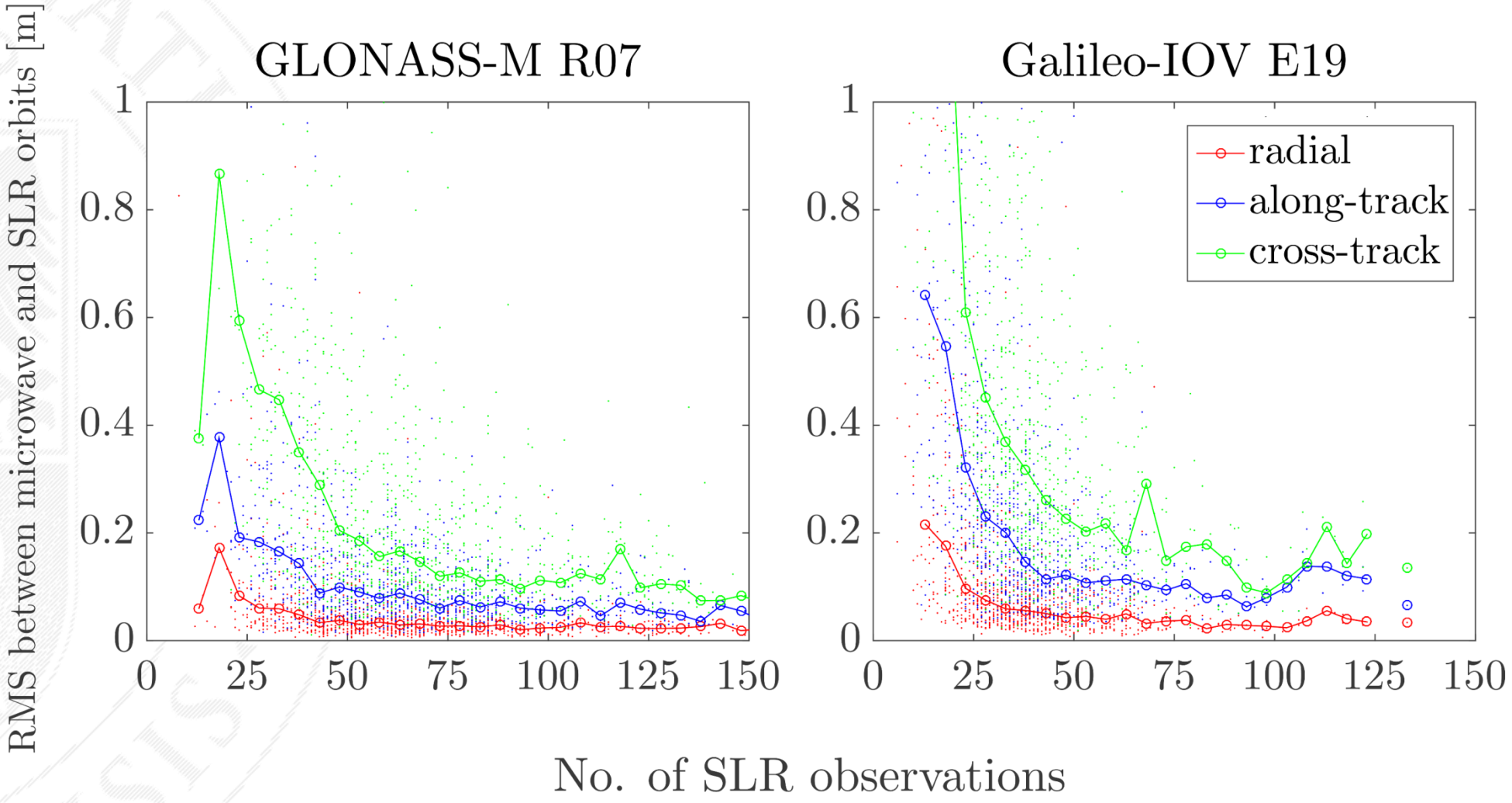
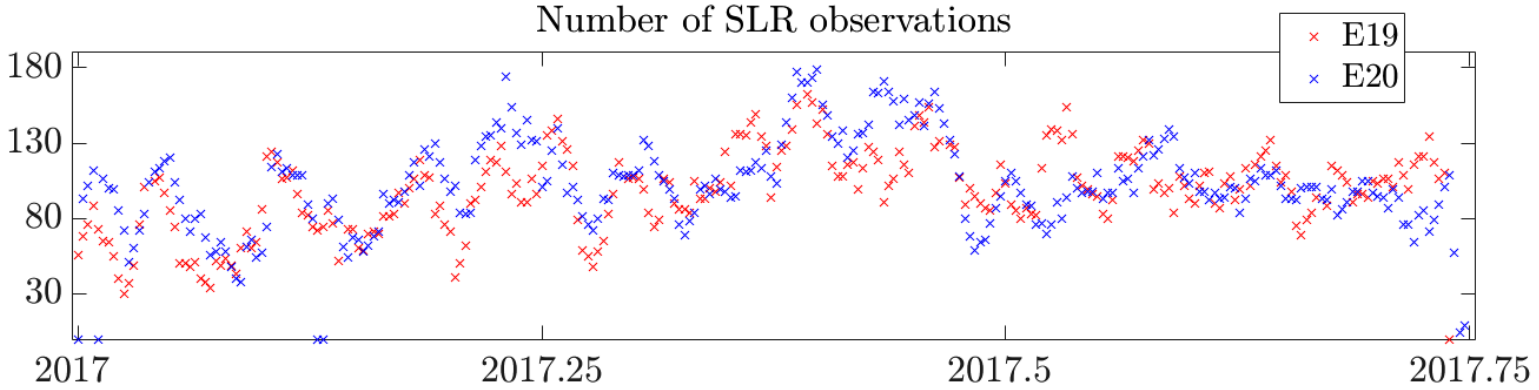
Precise orbit determination using solely SLR observations

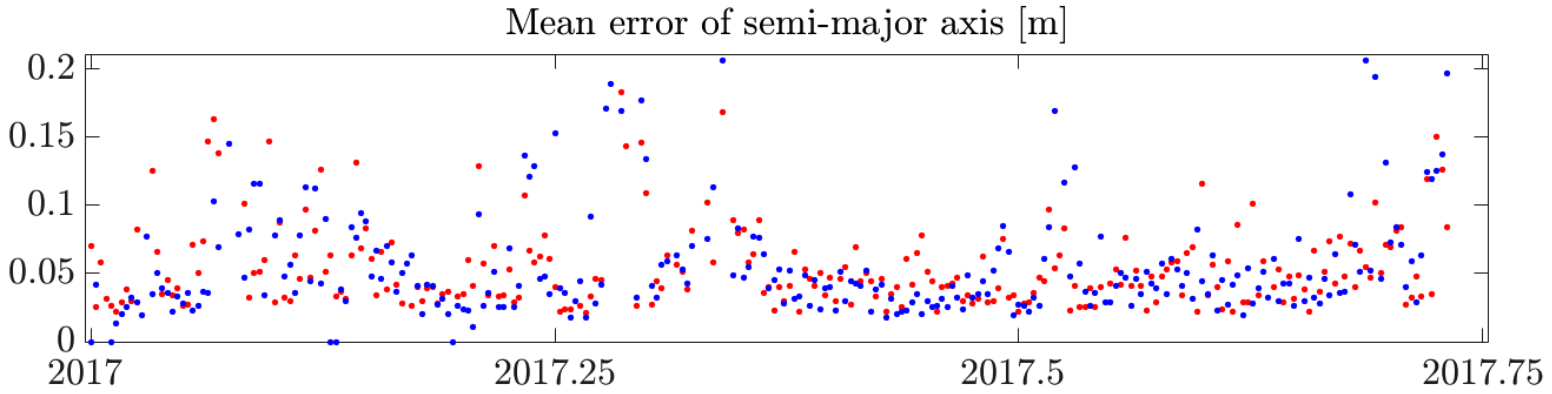
Not only the Galileo satellites ...



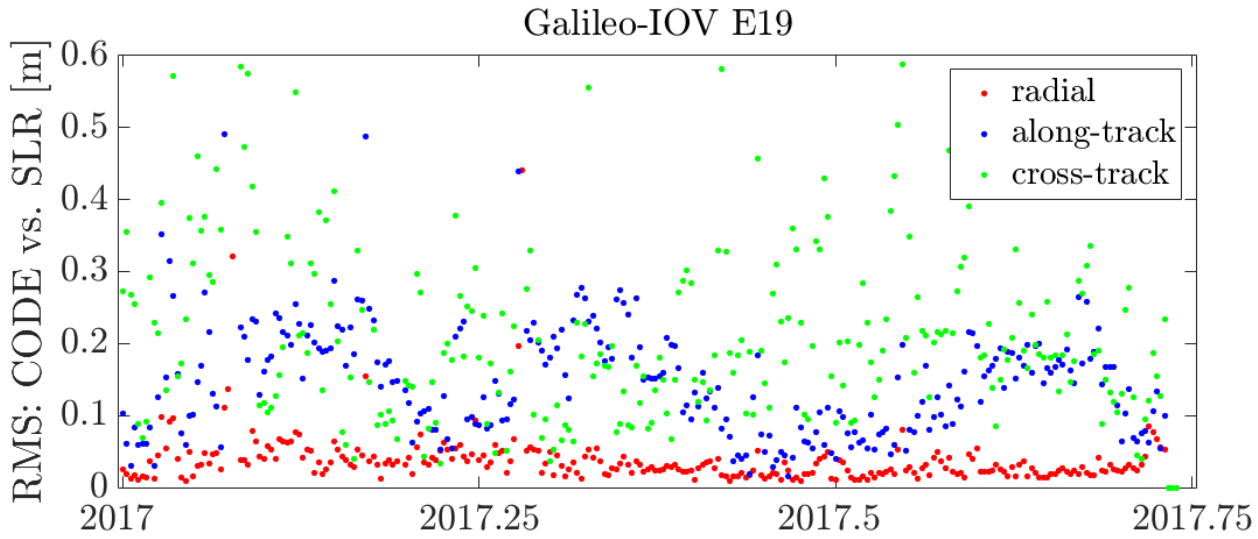
3-day orbital arcs / No. of observations obtained in the 3-day interval (E2 model used)
Microwave orbits form the CODE-MGEX solution

Galileo E20 orbit determination using solely SLR observations



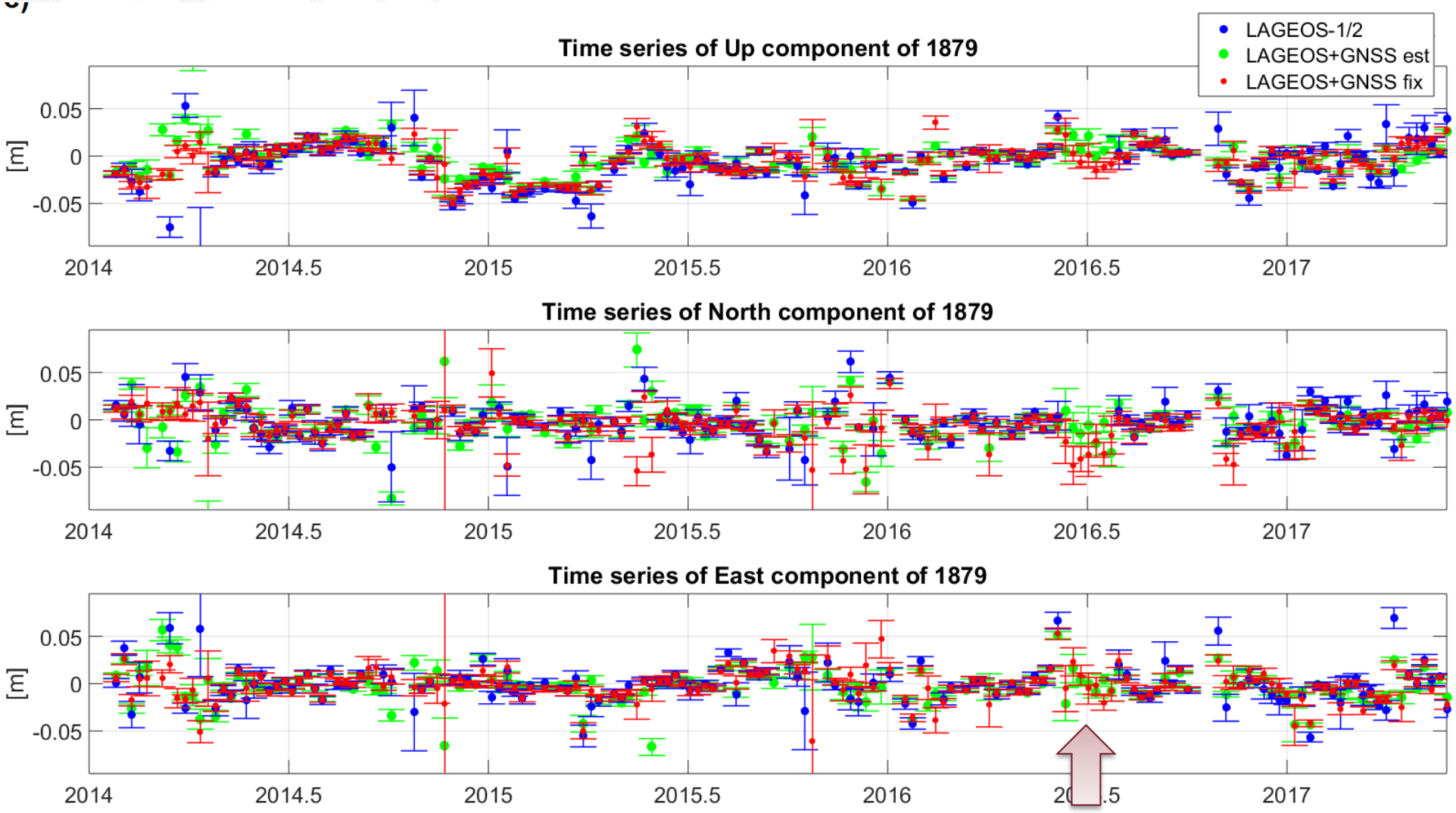


Based on the orbit predictions as an a priori,
Determined using solely SLR



Comparison of E19 orbit determined using SLR with the CODE-MGEX product

Station coordinates



GNSS-only solution

Altay (Russia) :

RMS: 31.1 19.8 24.3 mm for North, East, Up, resp. in LAGEOS-1/2

RMS: 17.1 16.5 16.6 mm for North, East, Up, resp. in LAGEOS+GNSS fix

132 solutions in LAGEOS-1/2

161 solutions in LAGEOS+GNSS (23% more solutions)

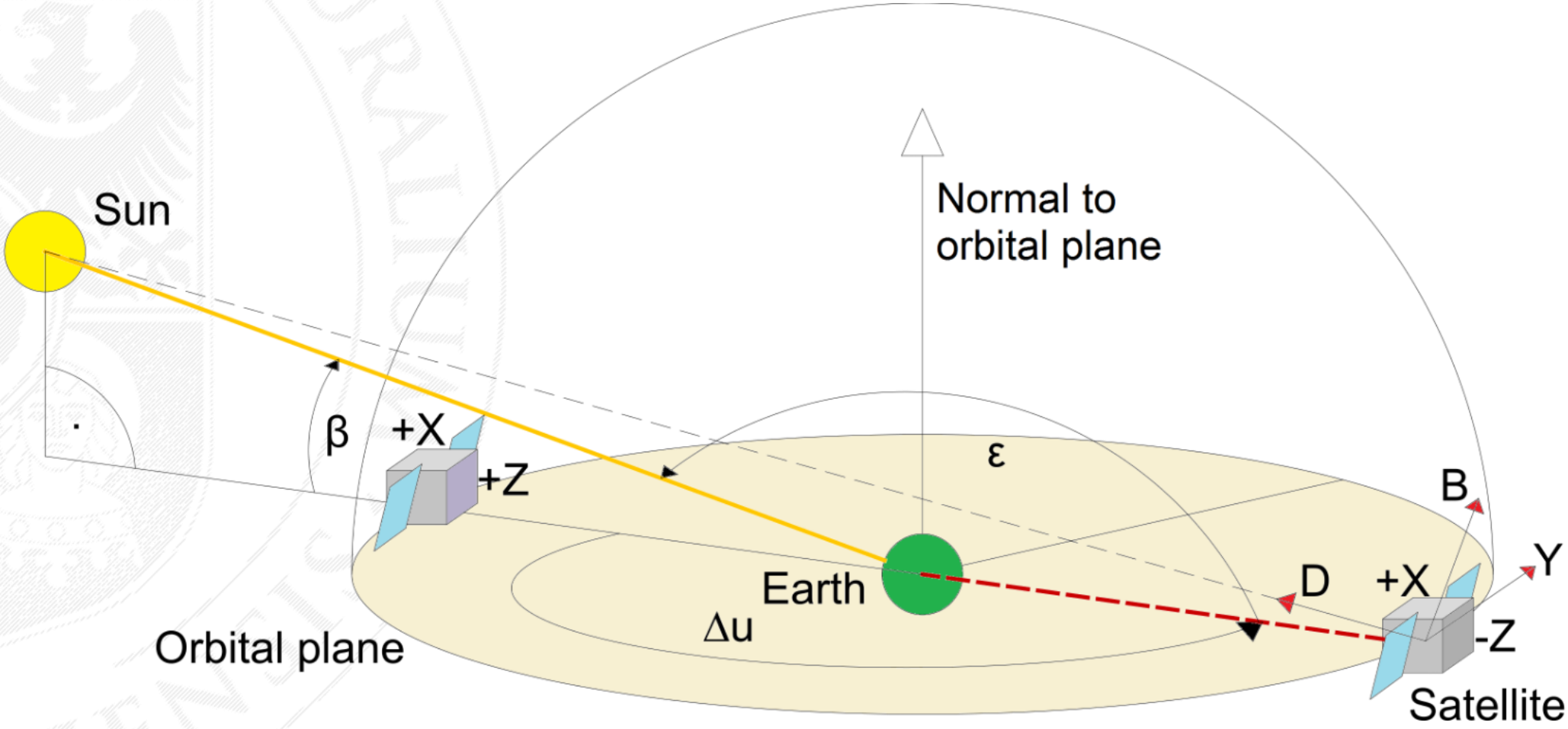
Summary

Precise orbit determination of Galileo is more challenging than in case of GPS due to lower masses and the higher X:Z bus surface ratio. POD of Galileo in eccentric orbits needs more coefficients to absorb all SRP effects (ECOM2 is insufficient).

Using the a priori box-wing model gives similar POD results to ECOM2, but:
(1) fewer coefficents have to be estimated (twice-per-rev are not needed),
(2) orbit predictions become more stable than in case of ECOM2.

The number of SLR observations to Galileo is being increasing due to the intensive ILRS tracking campaigns which allow for: (1) GNSS orbit validation, (2) POD of Galileo, (3) determination of SLR-derived parameters, such as SLR station coordinates, geocenter motion and Earth rotation parameters.

Thank you for your attention



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Back-up slides

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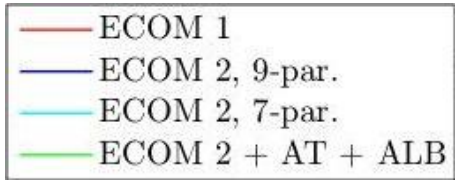
Y-bias & B-bias

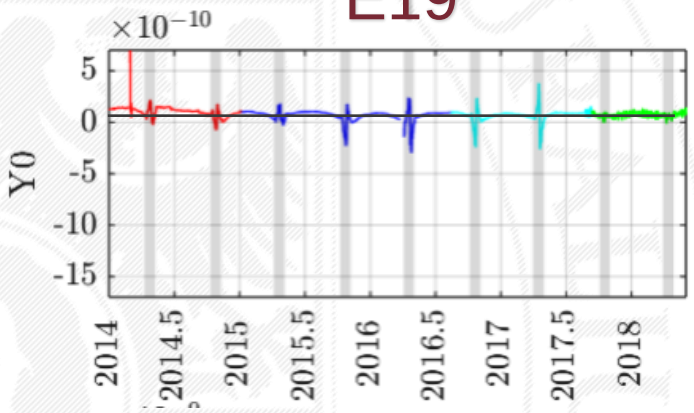
Do Galileo have any problems with the Y-bias?



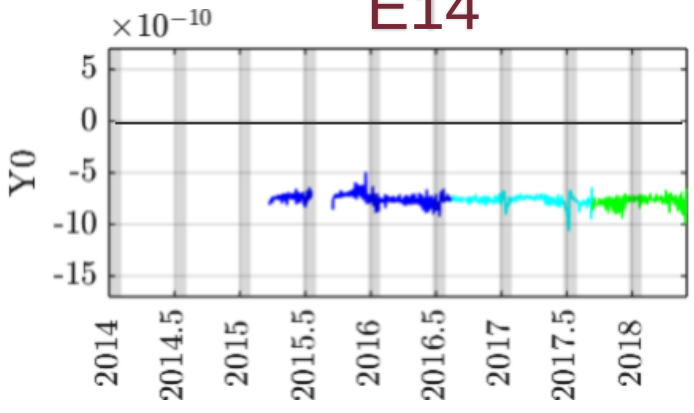
All Galileo FOC have problems with the Y-bias

Based on CODE MGEX orbits

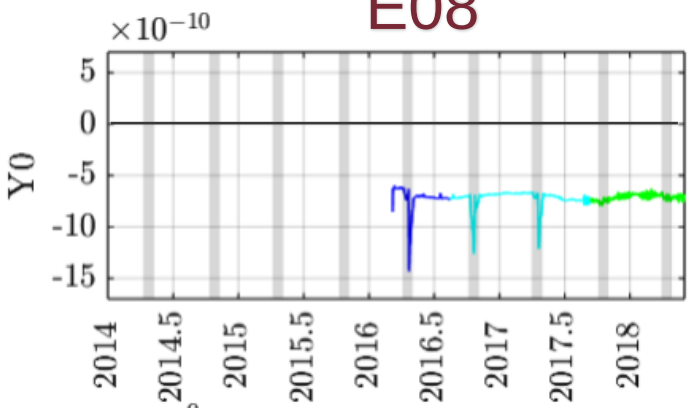
E19



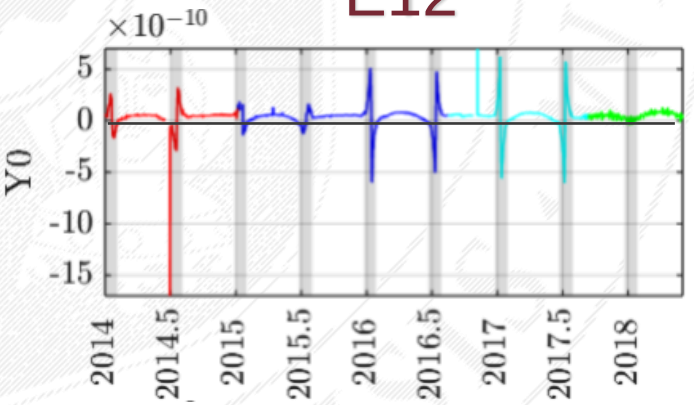
E14



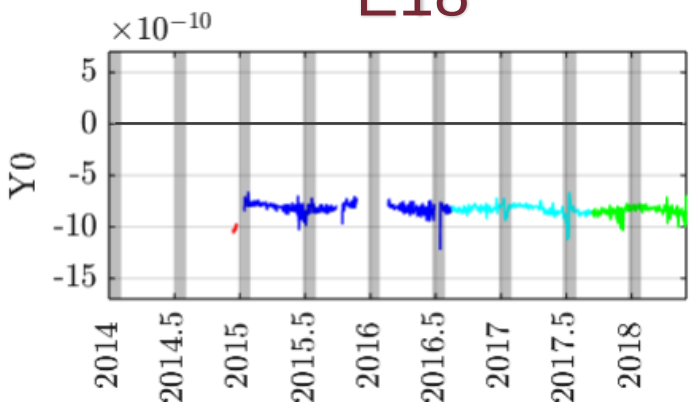
E08



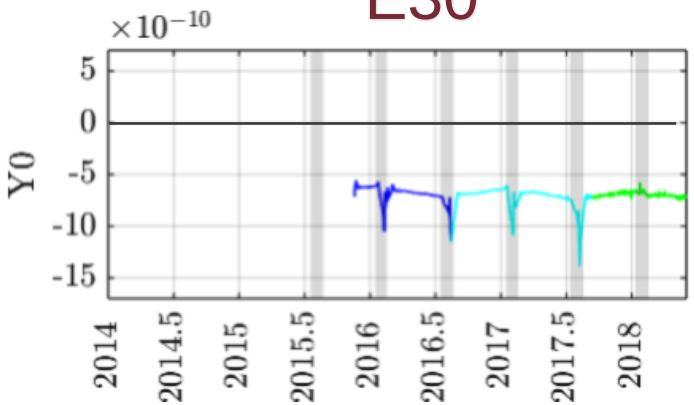
E12



E18

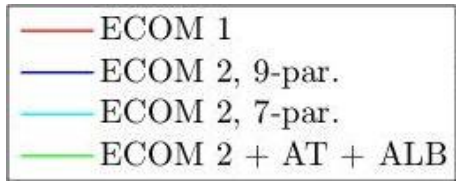


E30

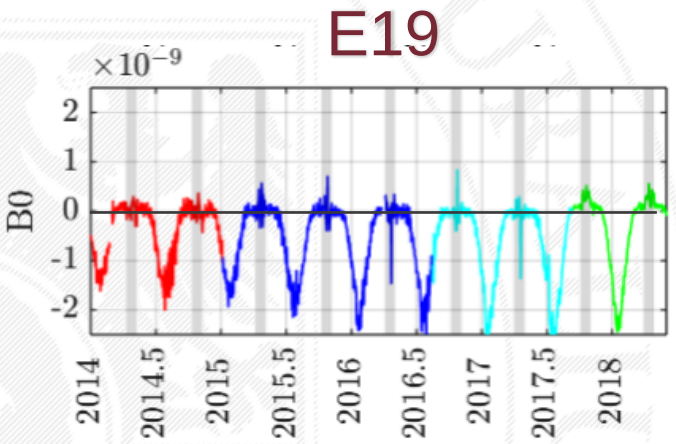


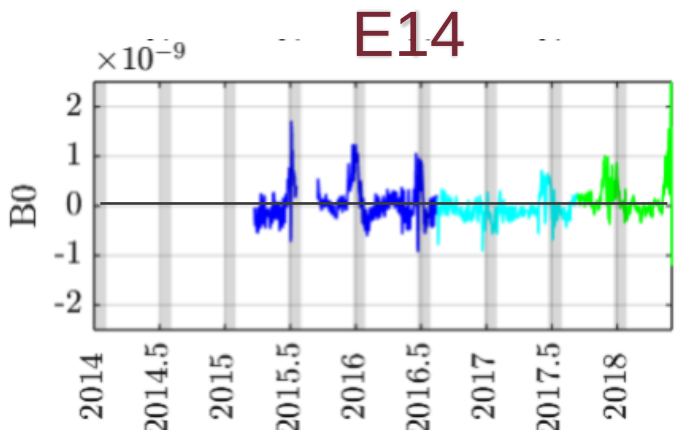
Galileo IOV – Y-bias close to 0 Galileo ecc. – Y-bias=~-8x10^{-10}m/s^2 Galileo FOC – Y-bias=~-7x10^{-10}m/s^2

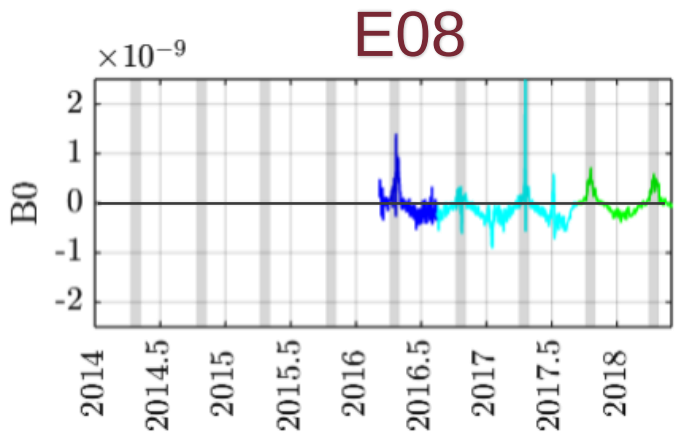
Do Galileo have any problems with the B-bias?

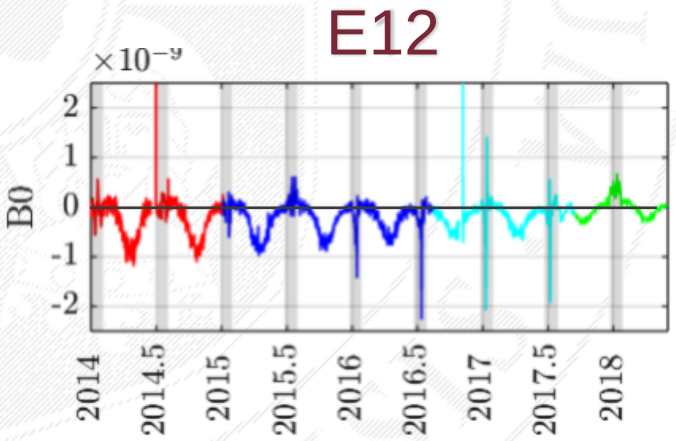


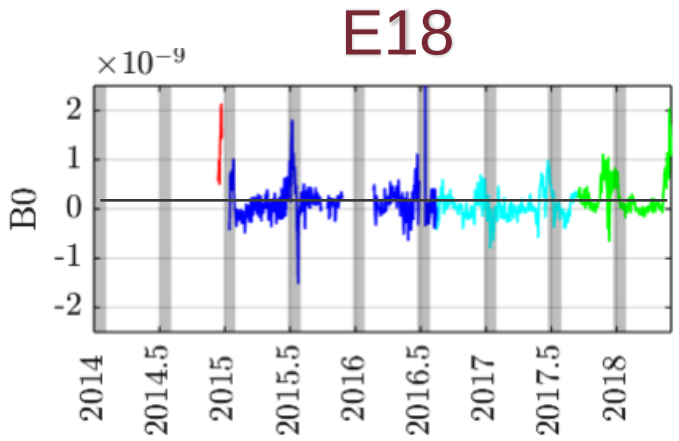
Based on CODE MGEX orbits

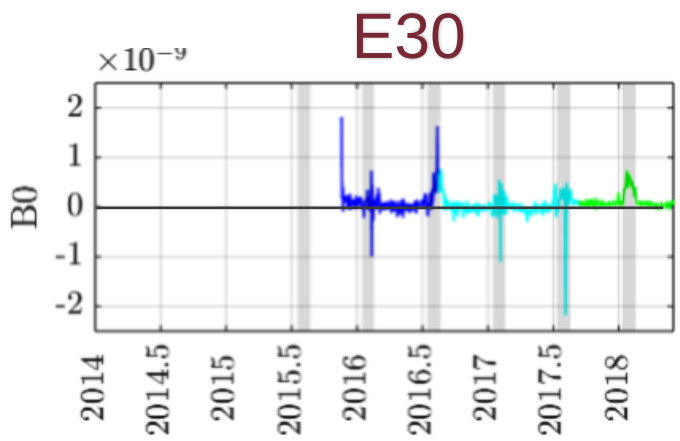






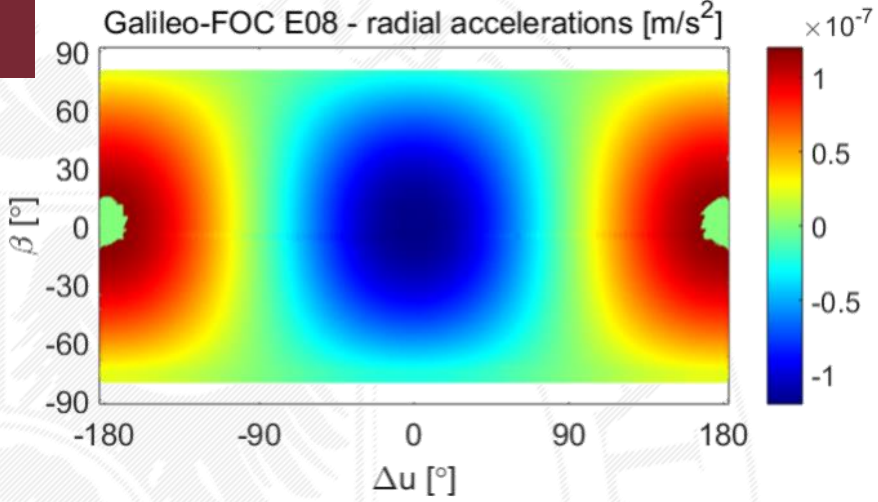


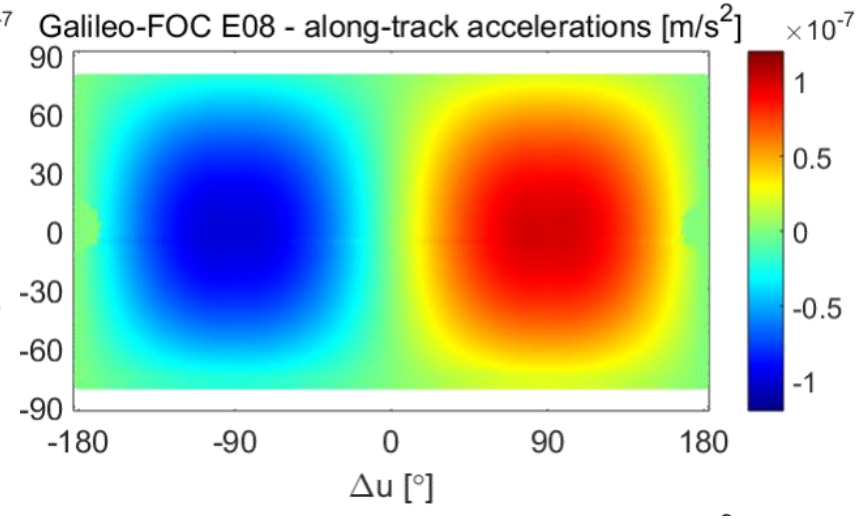


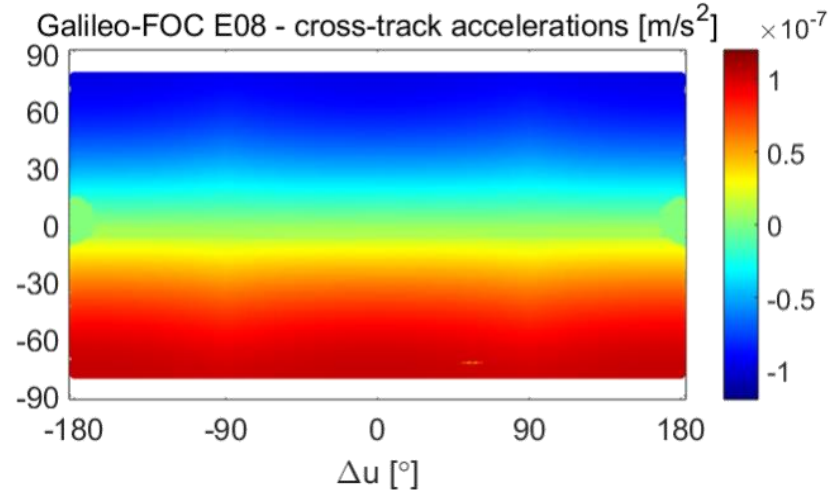


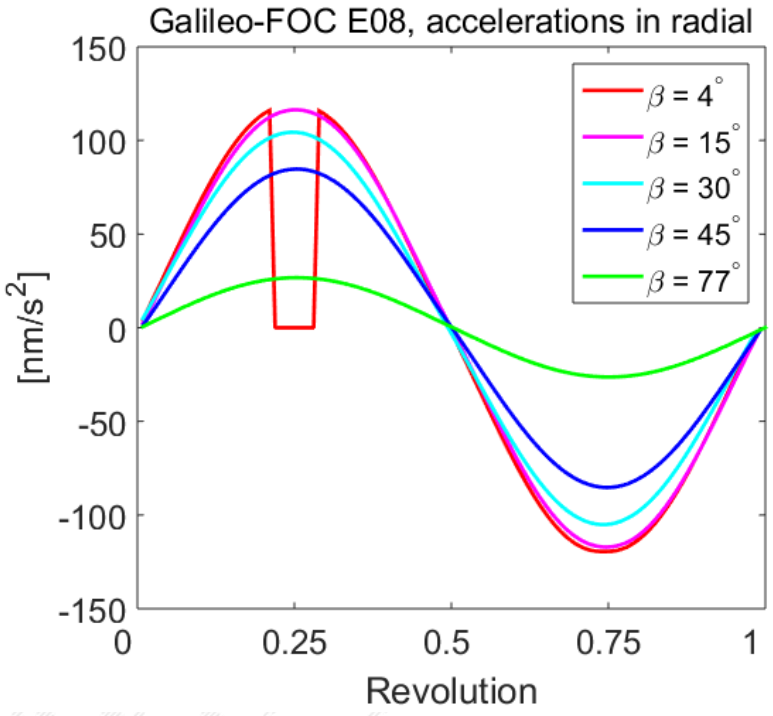
Galileo IOV show some periodic variations of the B-bias (max when beta->max)

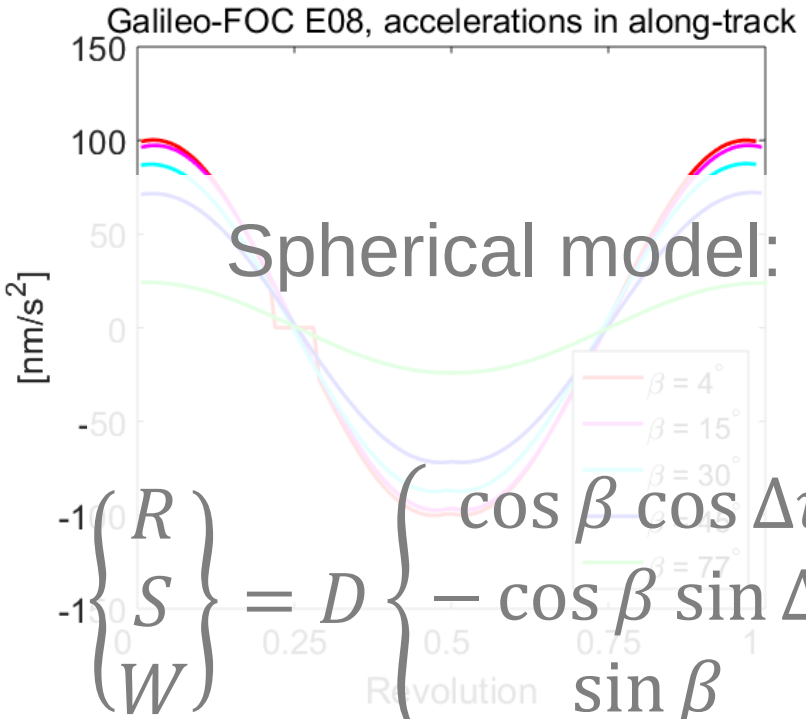
Radial, along-track, cross-track decomposition

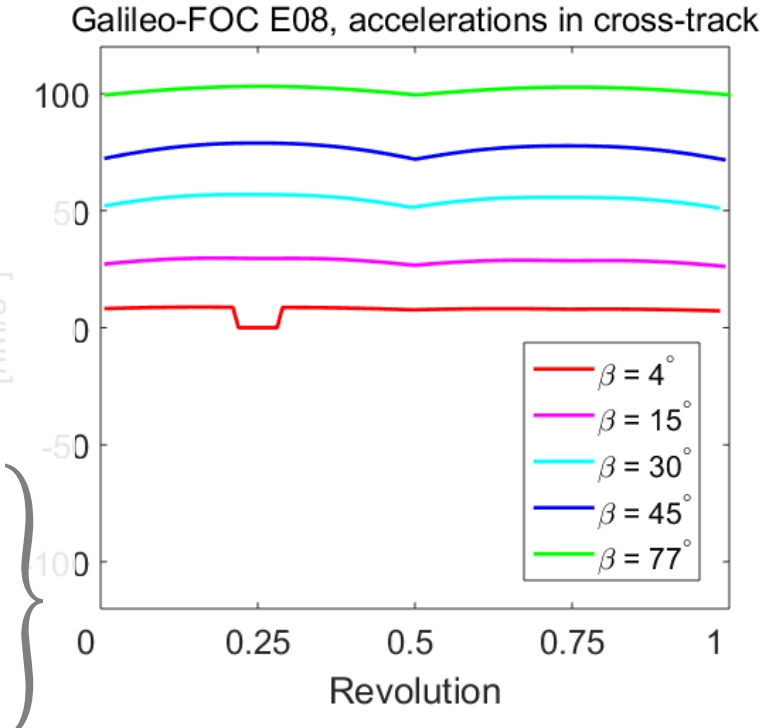








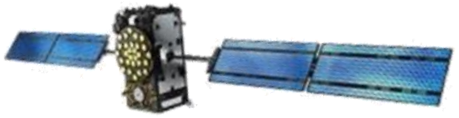




Spherical model:

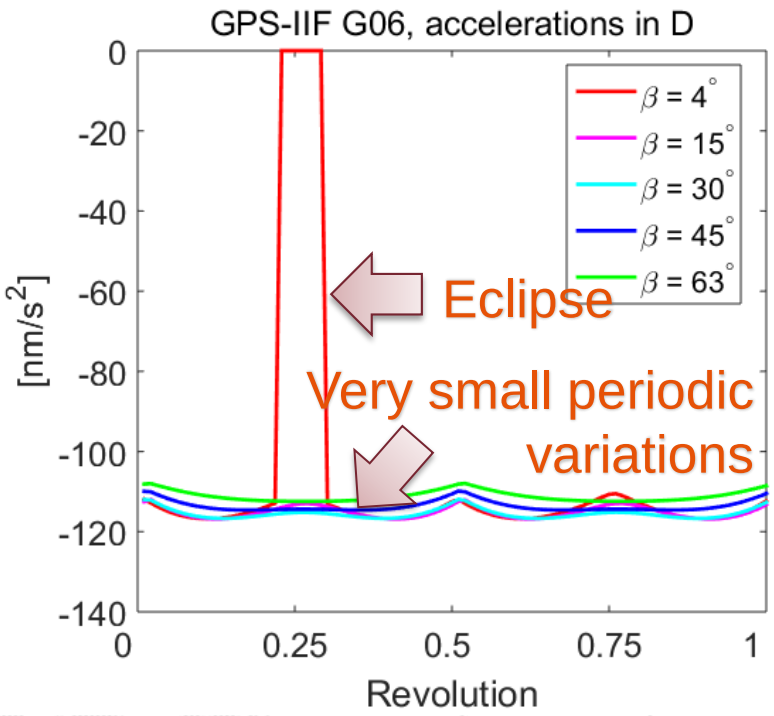
$$\begin{Bmatrix} R \\ S \\ W \end{Bmatrix} = D \begin{Bmatrix} \cos\beta \cos\Delta u \\ -\cos\beta \sin\Delta u \\ \sin\beta \end{Bmatrix}$$

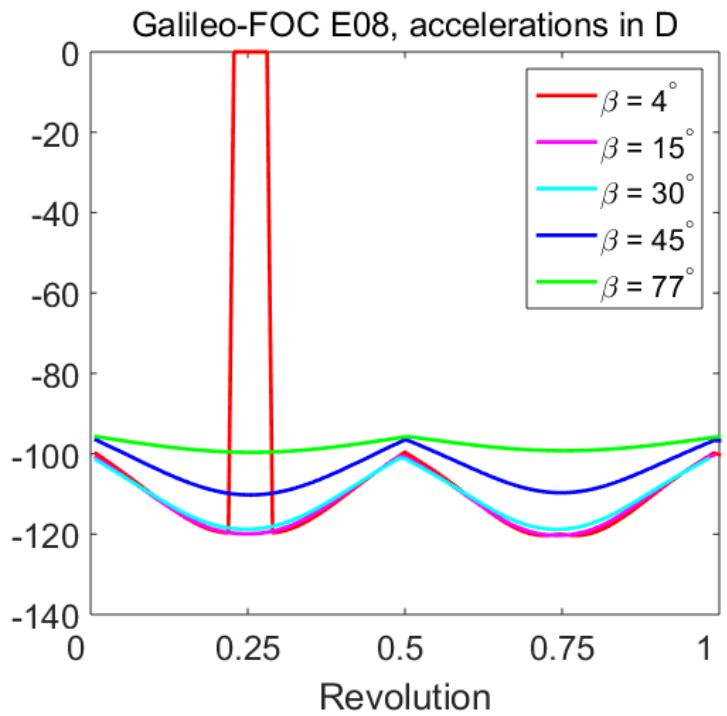
Galileo/GNSS orbit perturbation forces:

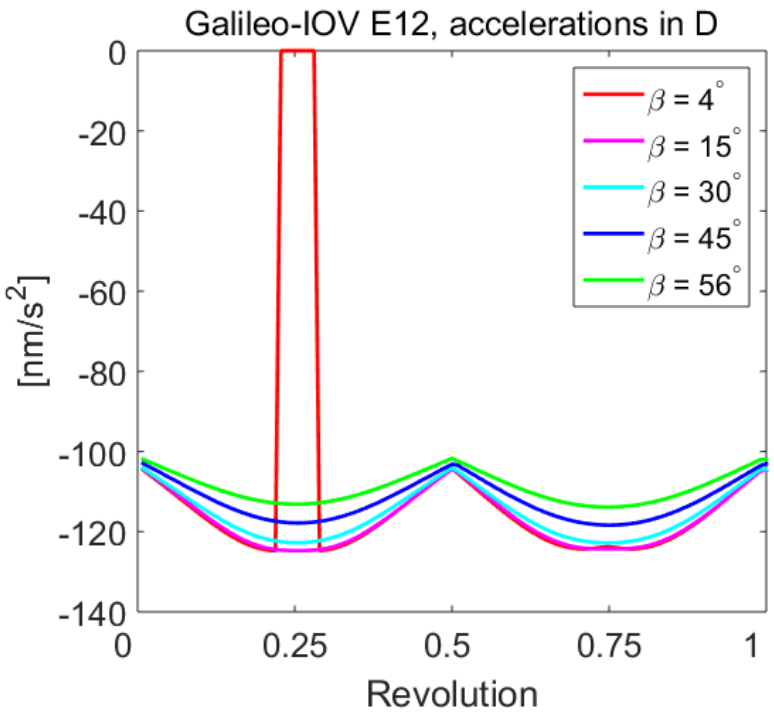


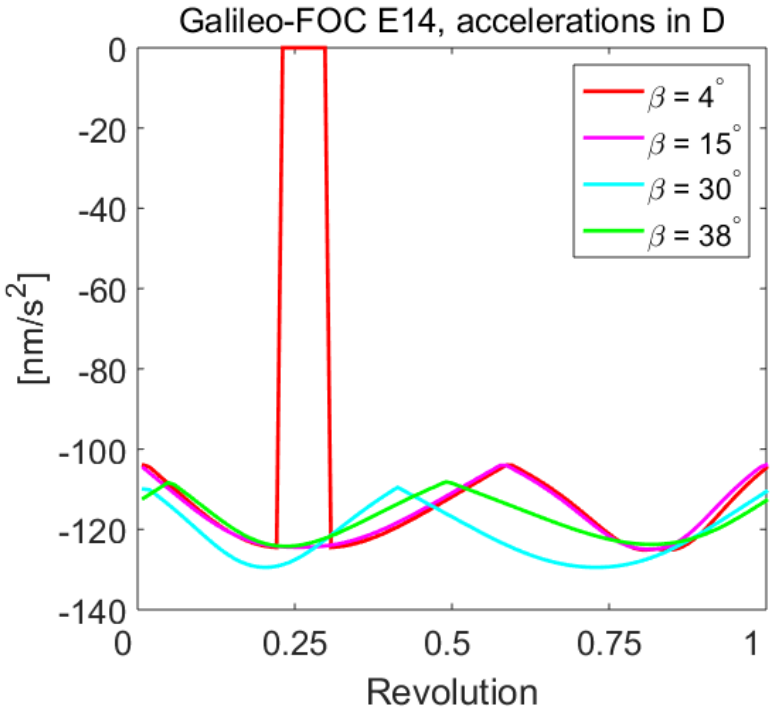
- **Gravitational & General relativity**
  - **C_{20} & time variability** — $4 \cdot 10^{-5}\ \mathrm{m/s^2}$
  - **Earth's gravity field** — $2 \cdot 10^{-7}\ \mathrm{m/s^2}$
  - **Third celestial bodies** — $6 \cdot 10^{-6}\ \mathrm{m/s^2}$
  - **Solid Earth, Ocean, Pole, Ocean Pole, Atmospheric tides** — $1 \cdot 10^{-9}\ \mathrm{m/s^2}$
  - **Non-tidal ocean, hydrology, atmosphere mass variations** — $8 \cdot 10^{-11}\ \mathrm{m/s^2}$
  - **Schwarzschild, Lense-Thirring, deSitter effects** — $5 \cdot 10^{-10}\ \mathrm{m/s^2}$
- **Non-gravitational**
  - **Direct Solar Radiation Pressure** — $1.1 \cdot 10^{-7}\ \mathrm{m/s^2}$
  - **Albedo & Infrared Radiation** — $3 \cdot 10^{-9}\ \mathrm{m/s^2}$
  - **Antenna Thrust** — $1 \cdot 10^{-9}\ \mathrm{m/s^2}$
  - **Thermal effects** — $\sim 6 \cdot 10^{-10}\ \mathrm{m/s^2}$
  - **Y-bias** — $7 \cdot 10^{-10}\ \mathrm{m/s^2}$
  - **Solar wind** — $\sim 5 \cdot 10^{-10}\ \mathrm{m/s^2}$

Direct SRP – „Box wing" model – accelerations in D

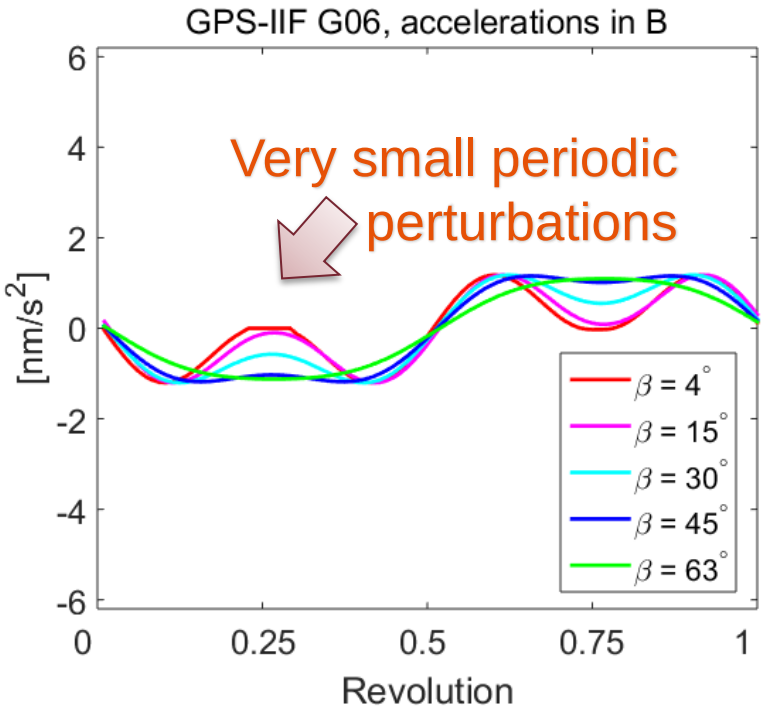


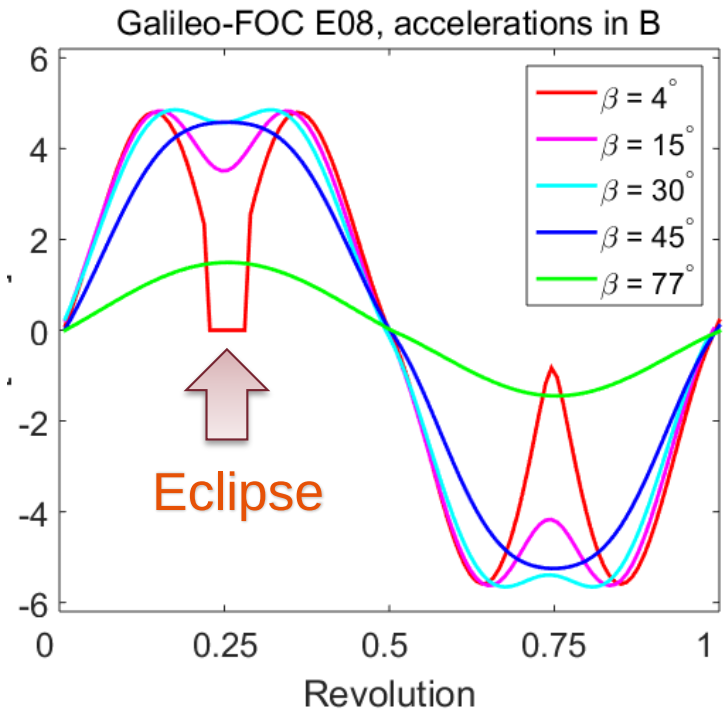


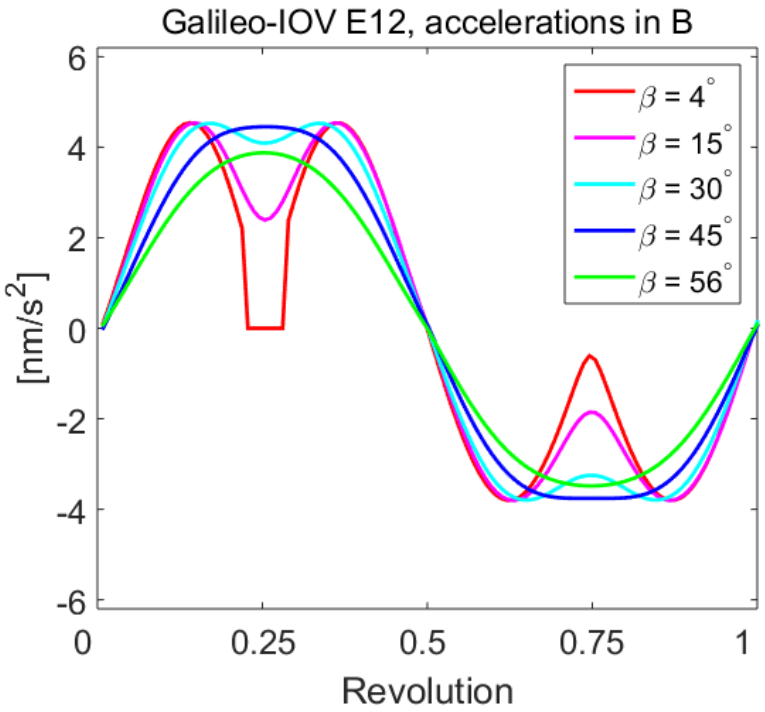


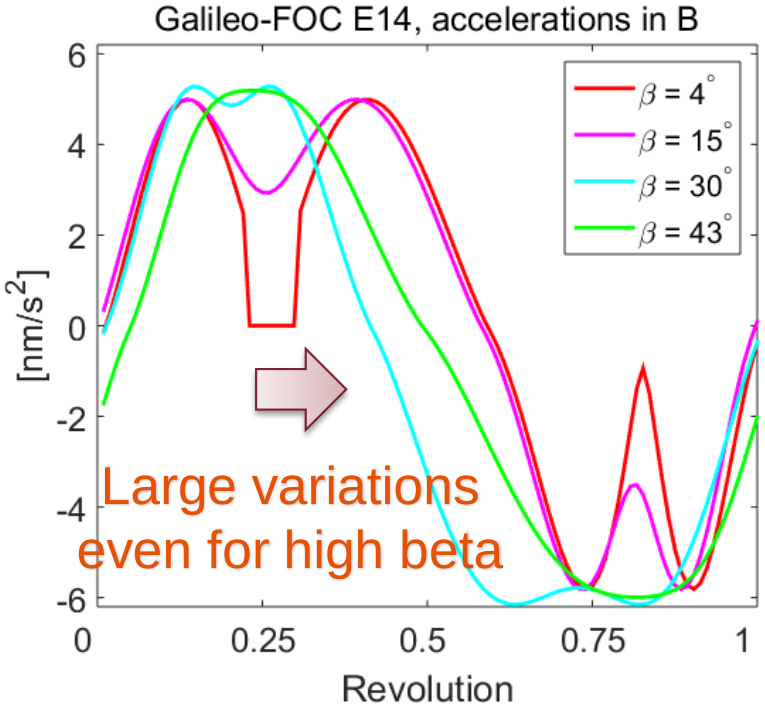


Direct SRP – „Box wing" model – accelerations in B



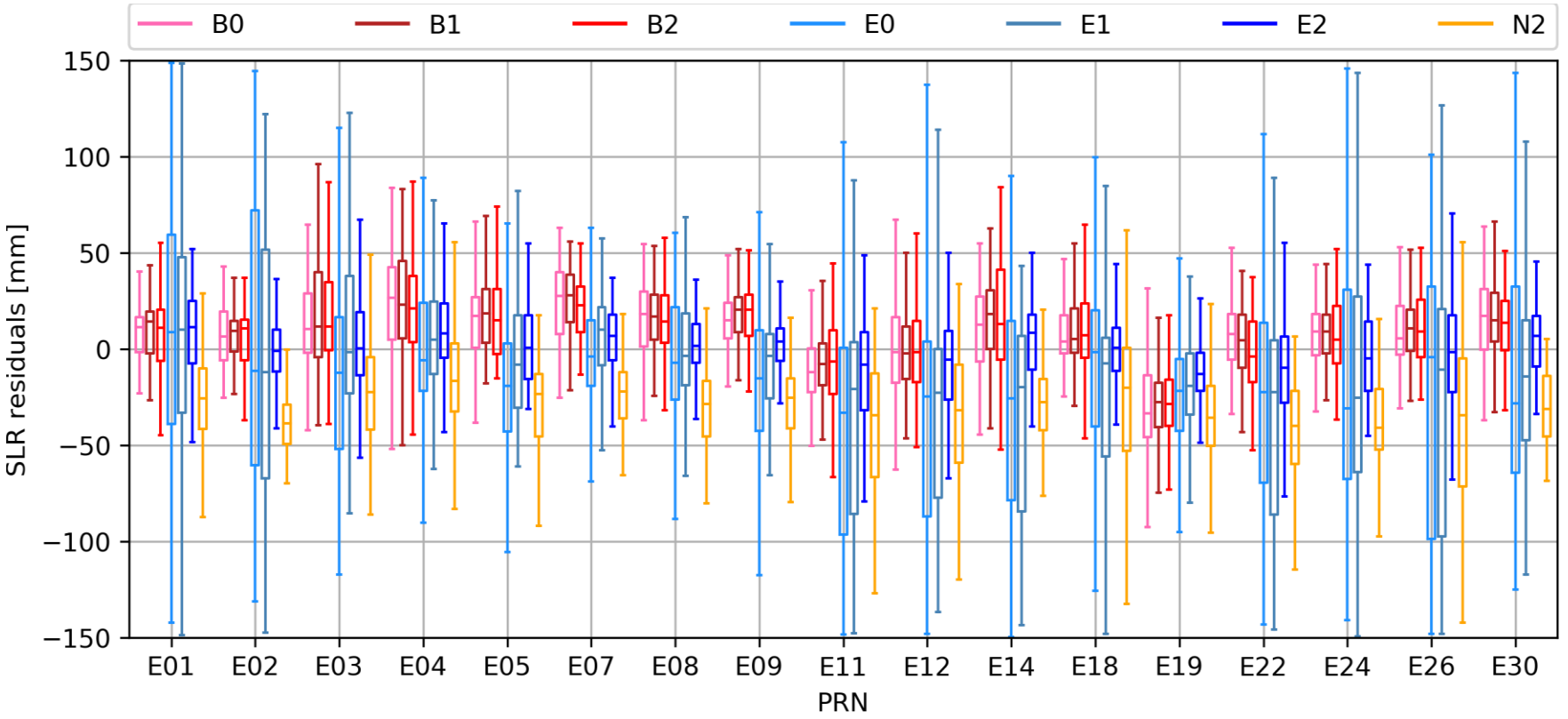






SLR validation of GNSS orbits (14 x 1-day solutions)

Solution	Box-wing	Empirical Orbit Parameters	Albedo + Antenna thrust
B0	**YES**	D0,Y0,B0	**YES**
B1	**YES**	D0,Y0,B0, B1S,B1C	**YES**
B2	**YES**	D0,Y0,B0, B1S,B1C,D2C, D2S	**YES**
E0	NO	D0,Y0,B0	**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



Very low quality for E0, E1, and N1 solutions -> inacceptable for Galileo POD

Similar quality for B0, B1, B2, E2, which means that when using a priori box-wing model, the periodic empirical orbit parameters do not have to be estimated.

B1 is sometimes even more stable than B2 (twice-per-rev parameters are not needed).