Wrocław University of Environmental and Life Sciences

Universität Bern

bkg sehen. vermessen. verstehen.

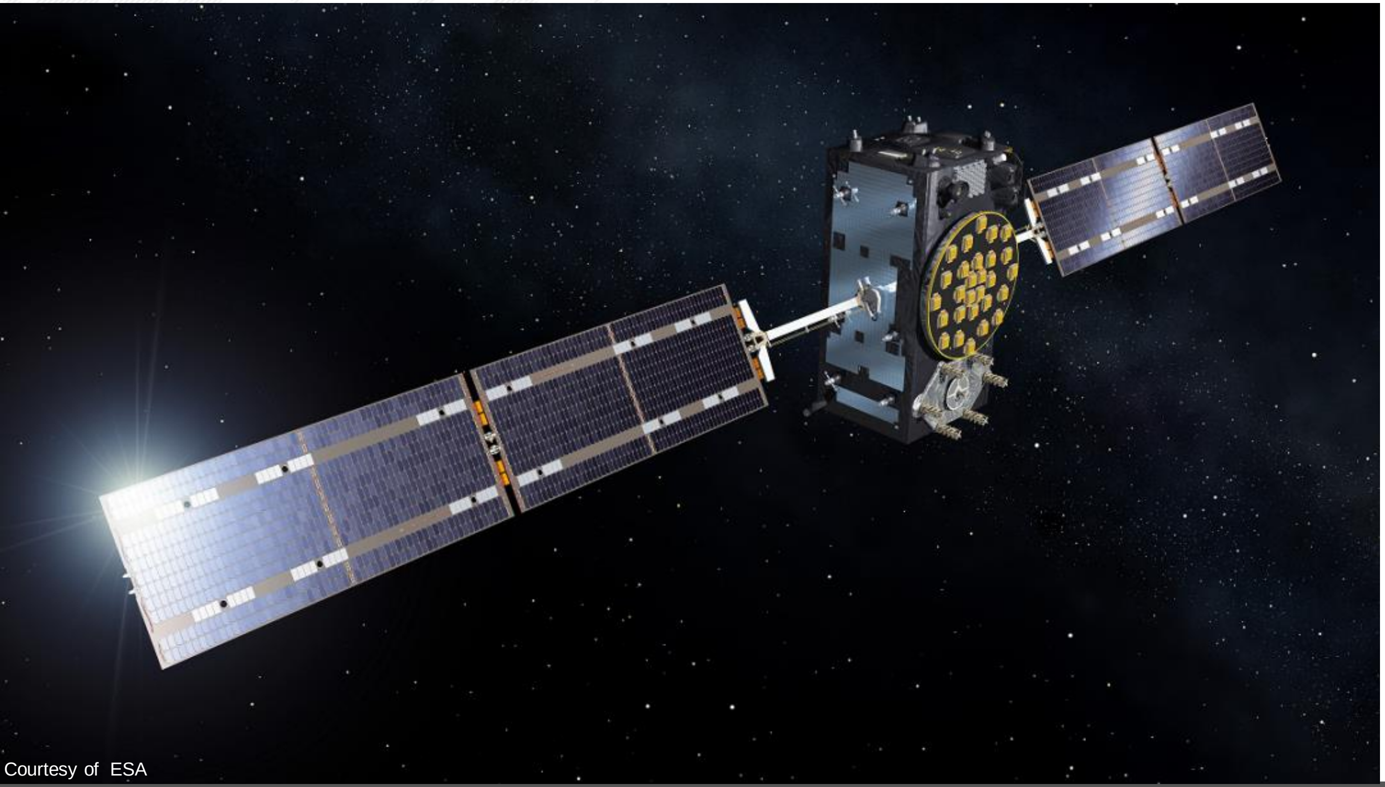
SLR signature effect for Galileo

with a focus on satellites launched into incorrect orbital planes

K. Sośnica, L. Prange, K. Kaźmierski, G. Bury,
M. Drożdżewski, H. Hadaś, D. Thaller

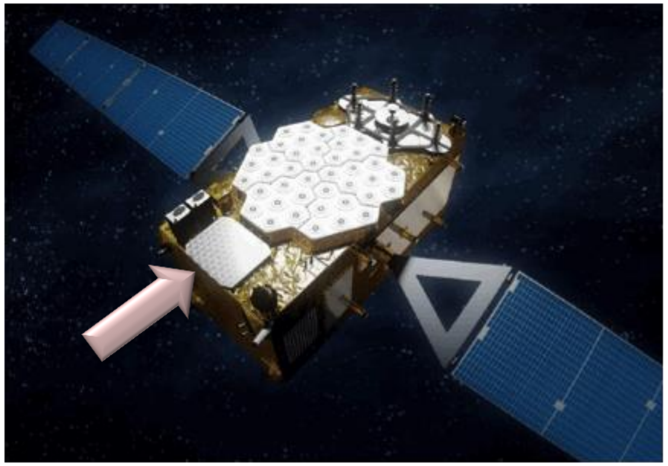
20th International Workshop on Laser Ranging
Potsdam Germany, October 09-14, 2016

Wrocław University of Environmental and Life Sciences


Courtesy of ESA

Galileo orbits – an overview

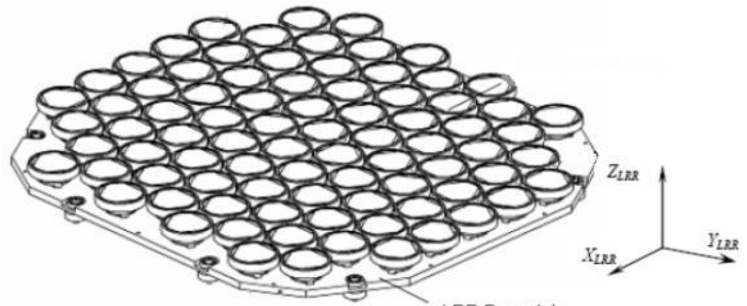
SLR retroreflectors onboard Galileo



<u>All Galileo satellites are equipped with the Laser Retroreflector Arrays (LRA)</u>, thus, the orbit validation of all Galileo orbits using SLR is possible.

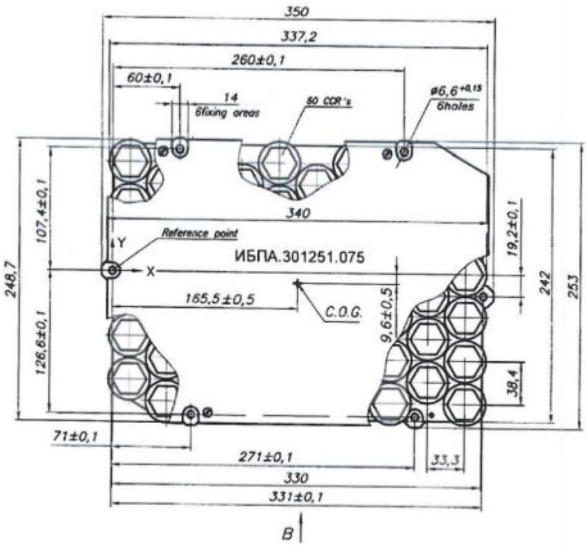
Galileo LRAs consist of 84 and 60 corner cube retroreflectors for IOV and FOC, respectively. The fused silica corner cubes are uncoated on the rear reflecting side for both IOV and FOC satellites, whereas the front side of IOV is coated by the anti-reflection indium tin oxide for 532 nm.

<u>The uncoated corner cubes are preferable</u>, as they increase the return rate signal strength so that the target is easier acquirable. The test GIOVE-A/B satellites were equipped with aluminum-coated retroreflectors, thus, their return rates were typically lower than currently for IOV and FOC satellites.



IOV LRA (84 ccr)

Courtesy of ESA/Galileo



FOC LRA (60 ccr)

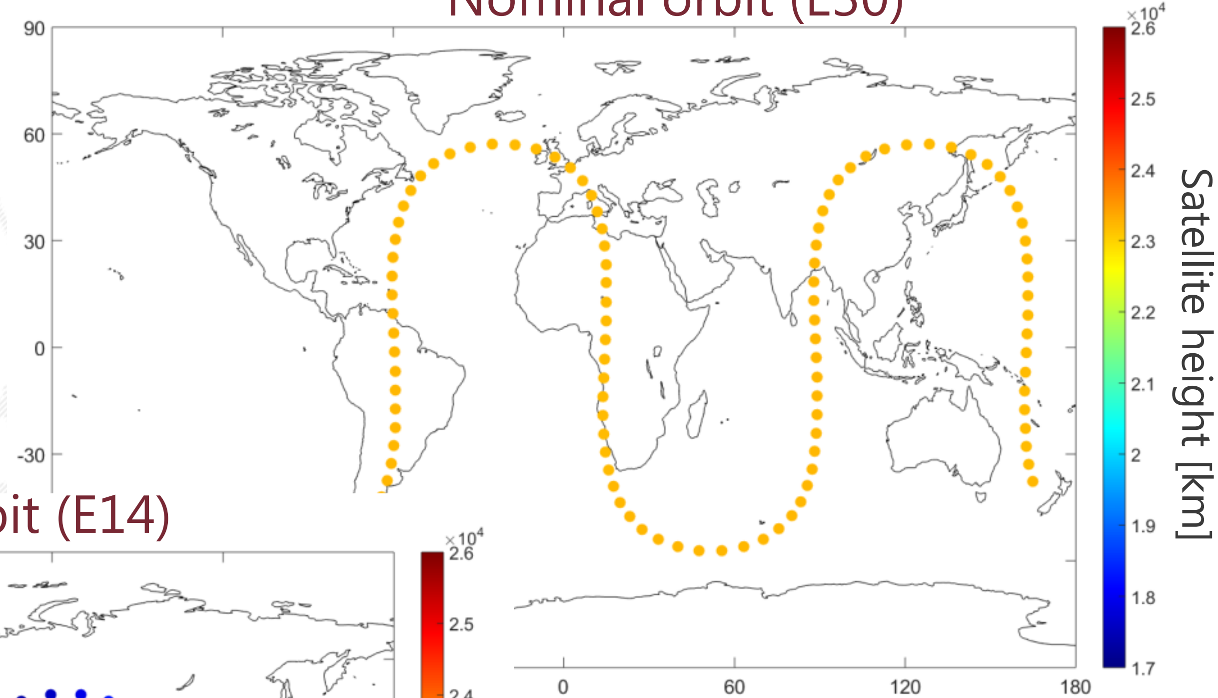
Galileo satellites in orbit

PRN Number	E11, E12	E19, E20	E18, E14	E26, E22	E24, E30	E08, E09	E01, E02
Name	Galileo-101, 102	Galileo-103, 104	**Galileo-201, 202**	Galileo-203, 204	Galileo-205, 206	Galileo-208, 209	Galileo-210, 211
Type	IOV	IOV	**FOC**	FOC	FOC	FOC	FOC
Launch date	21-Oct-2011	12-Oct-2012	**22-Aug-2014**	27-Mar-2015	11-Sep-2015	17-Dec-2015	24-May-2016
Frequencies	E1, E5a, E5b, E5, E6	E1, E5a, E5b, E5, E6, E20: only E1 since 25-Sep-2014	E1, E5a, E5b, E5, E6	E1, E5a, E5b, E5, E6	E1, E5a, E5b, E5, E6	E1, E5a, E5b, E5, E6	-
Retroreflectors (corner cubes)	84	84	60	60	60	60	60
Corner cube dimensions [mm]	33x23.3	33x23.3	28.2x19.1	28.2x19.1	28.2x19.1	28.2x19.1	28.2x19.1
Rear/front coating (Y-yes, N-no)	N/Y	N/Y	N/N	N/N	N/N	N/N	N/N
Mass [kg]	695	697	**661/662**	706	709	708	~708
Orbital plane	B	A	**incorrect**	B	C	A	C
Area-to-mass [m^2/kg]	0,019	0,019	**0,020**	0,019	0,019	0,019	~0,019
Semi-major axis [km]	29.600	29.600	**27.978**	29.602	29.601	29.600	~29.600
Altitude [km]	23.225	23.225	**17.178-26.019**	23.227	23.226	23.225	~23.225
Eccentricity	0.0001	0.0002	**0.1585/ 0.1584**	0.0003	0.0004	0.0001	~0.0002
Revolution period [h]	14.08	14.08	**12.94**	14.08	14.08	14.08	~14.08
Inclination [deg]	55.57	54.93	**50.10/ 50.16**	55.36	57.25	54.94	~56
β max[deg]	63.5	75.5	**48.0/48.5**	58.2	39.0	75.0	~40
Draconitic year [days]	355.6	355.6	**351.6**	355.6	356.1	355.6	~356
Revolution of ascending node [years]	37.5	36.9	**25.9/25.8**	37.4	39.1	36.6	~37
Revolution of perigee [years]	70.9	65.3	**31.4/31.3**	70.0	92.2	65.3	~65

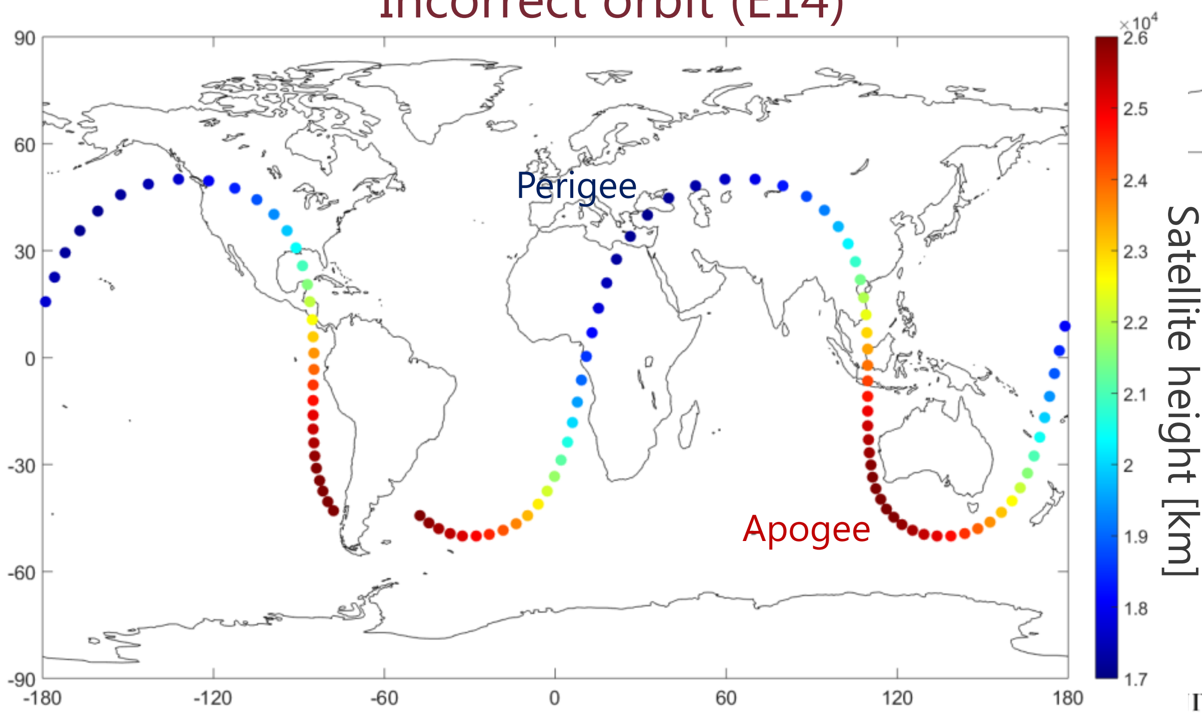
Groundtrack of Galileo satellites

Sampling: 15 min.
Data length: 26h
Starting epoch: 2016 08 30 0 0 0.00

Nominal orbit (E30)



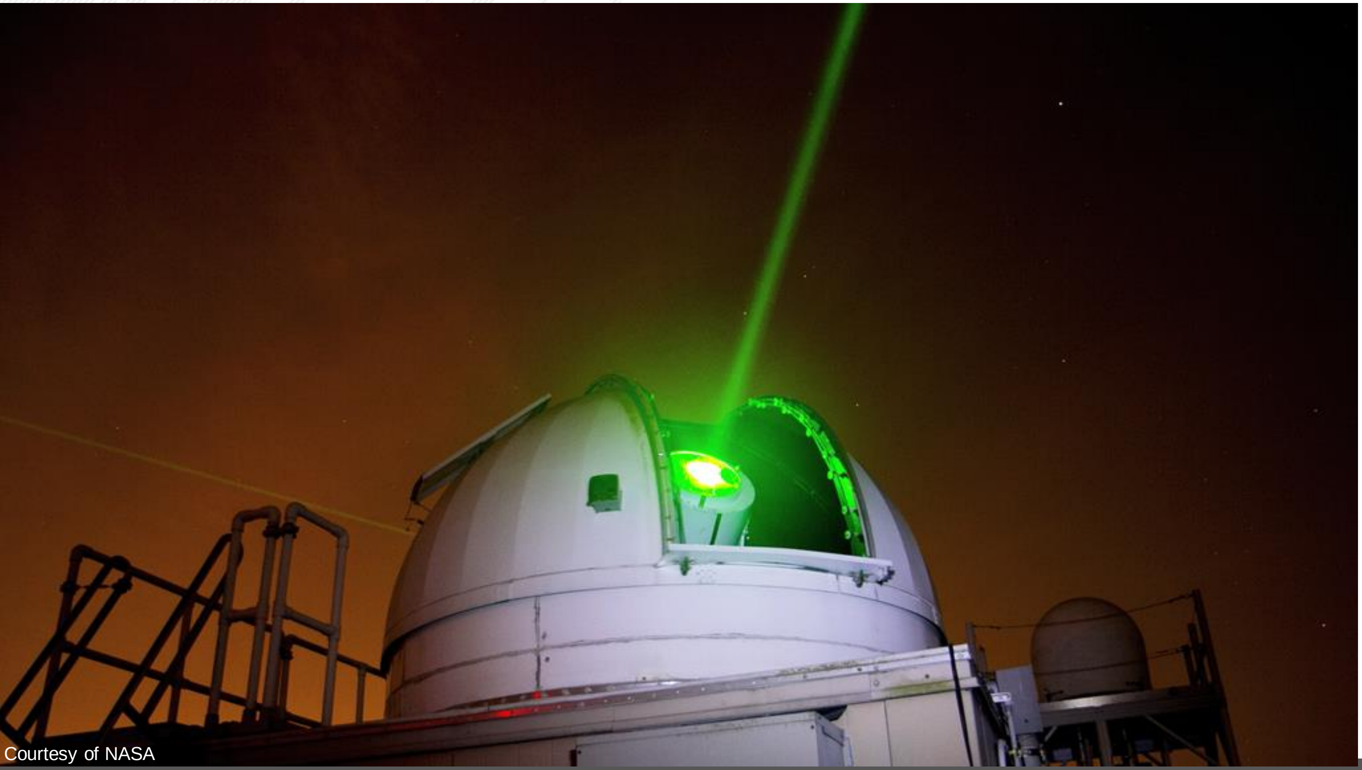
Incorrect orbit (E14)



Variable velocities:
from 1.9 km/s in the apogee
up to 3.4 km/s in the perigee

(in the Earth-fixed frame,
w.r.t. the observer)

WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES


Courtesy of NASA

SLR validation of Galileo orbits

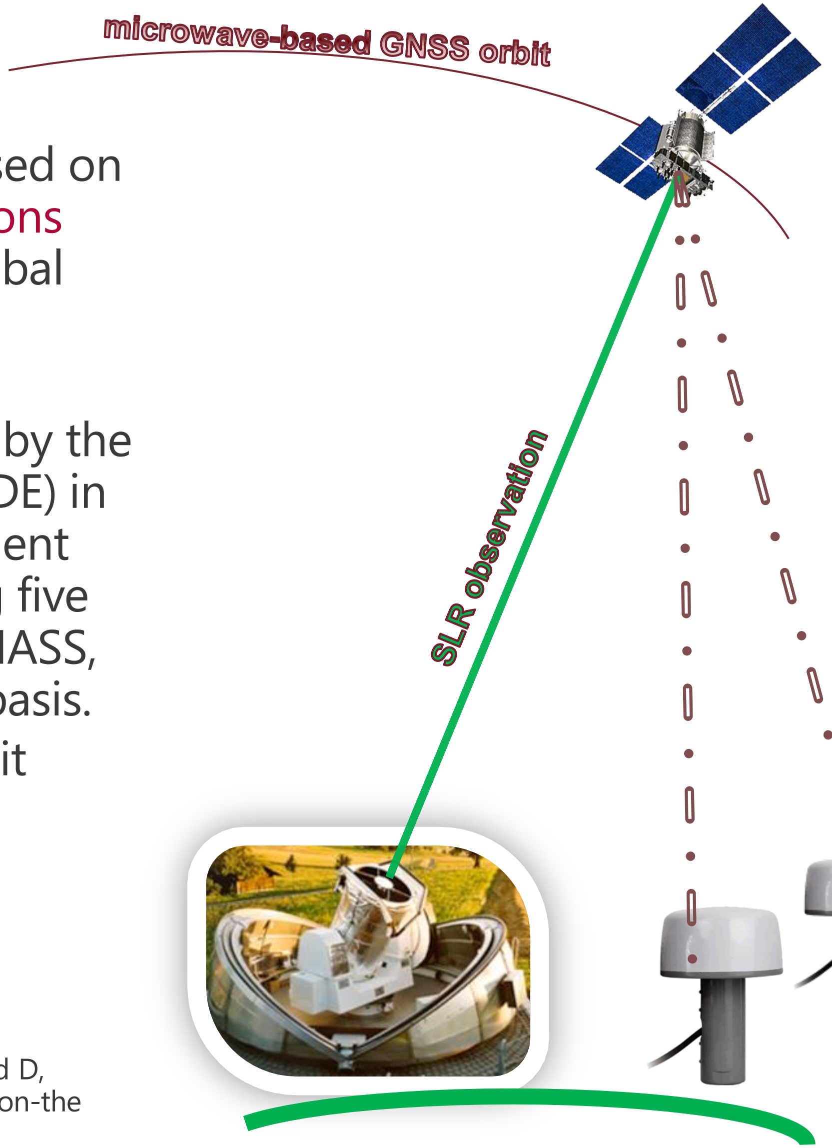
What do we analyze?

We compare the orbits of Galileo satellites based on microwave GNSS double-difference observations with the SLR observations provided by the global network of ILRS stations.

The microwave GNSS solutions are generated by the Center for Orbit Determination in Europe (CODE) in the framework of the IGS Multi-GNSS Experiment (MGEX). Since 2014, CODE has been providing five satellite system solutions based on GPS, GLONASS, Galileo, BeiDou, and QZSS on an operational basis.

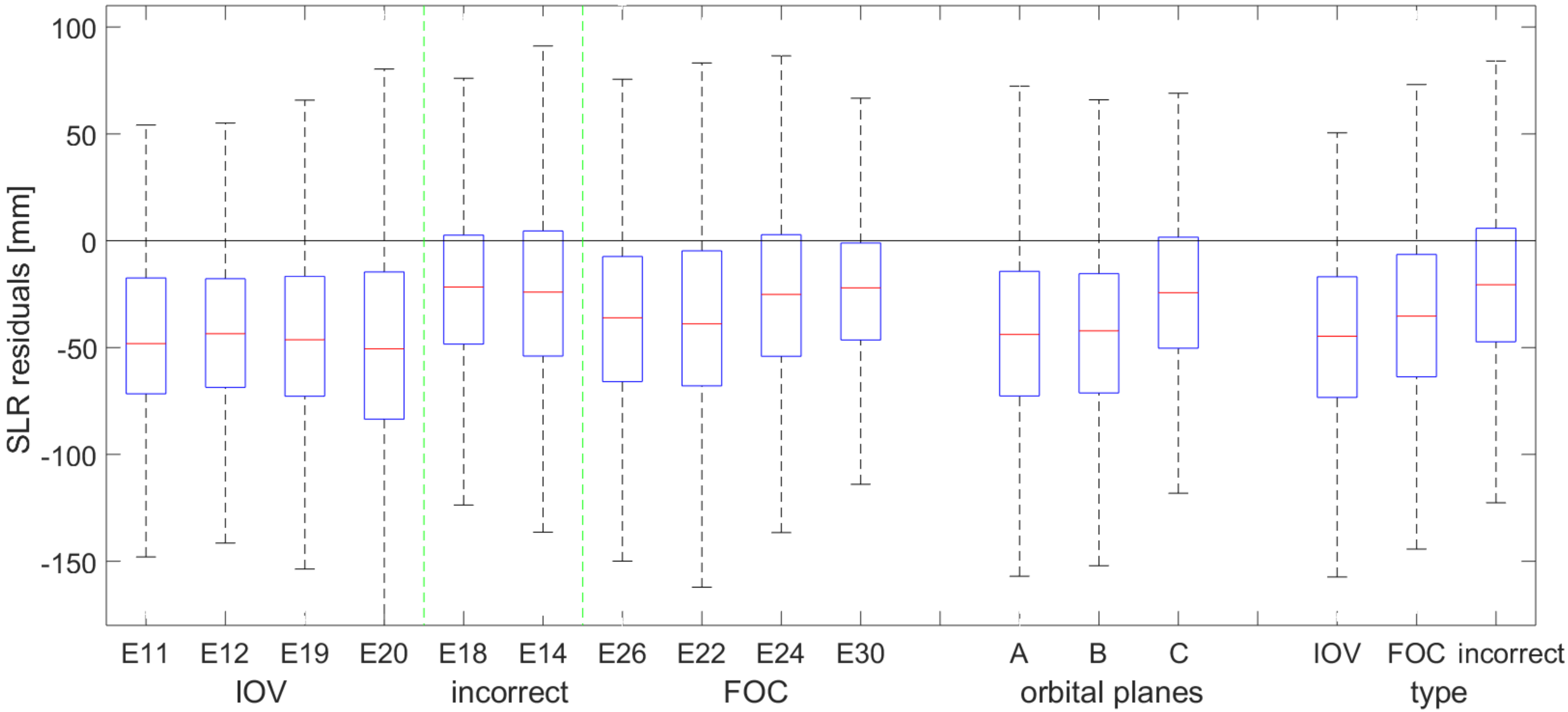
CODE uses the new ECOM2 model for the orbit generation.

Here, the comparison is done for the period: 2014.0-2016.5.



CODE 5-systems solutions are described in: Prange L, Orliac E, Dach R, Arnold D, Beutler G, Schaer S, Jäggi A (2016) CODE's five-system orbit and clock solution-the challenges of multi-GNSS data analysis. J Geod (in review), 2016.

Validation of Galileo orbits: satellite types and orbital planes



The RMS is 41, 45, 40 mm, respectively for IOV, FOC, and FOC in incorrect orbits, and the mean offset is −45, −35, −22 mm. The mean offset of SLR residuals is smallest for E18 and E14, i.e., both in incorrect orbital planes, as well as for E24 and E30, i.e., recently activated FOC satellites.

The largest offset and the largest RMS is for E20, i.e., an IOV satellite with the microwave GNSS solutions only in 2014, as it has been transmitting the signal only on one frequency since 2014.

SLR detector types

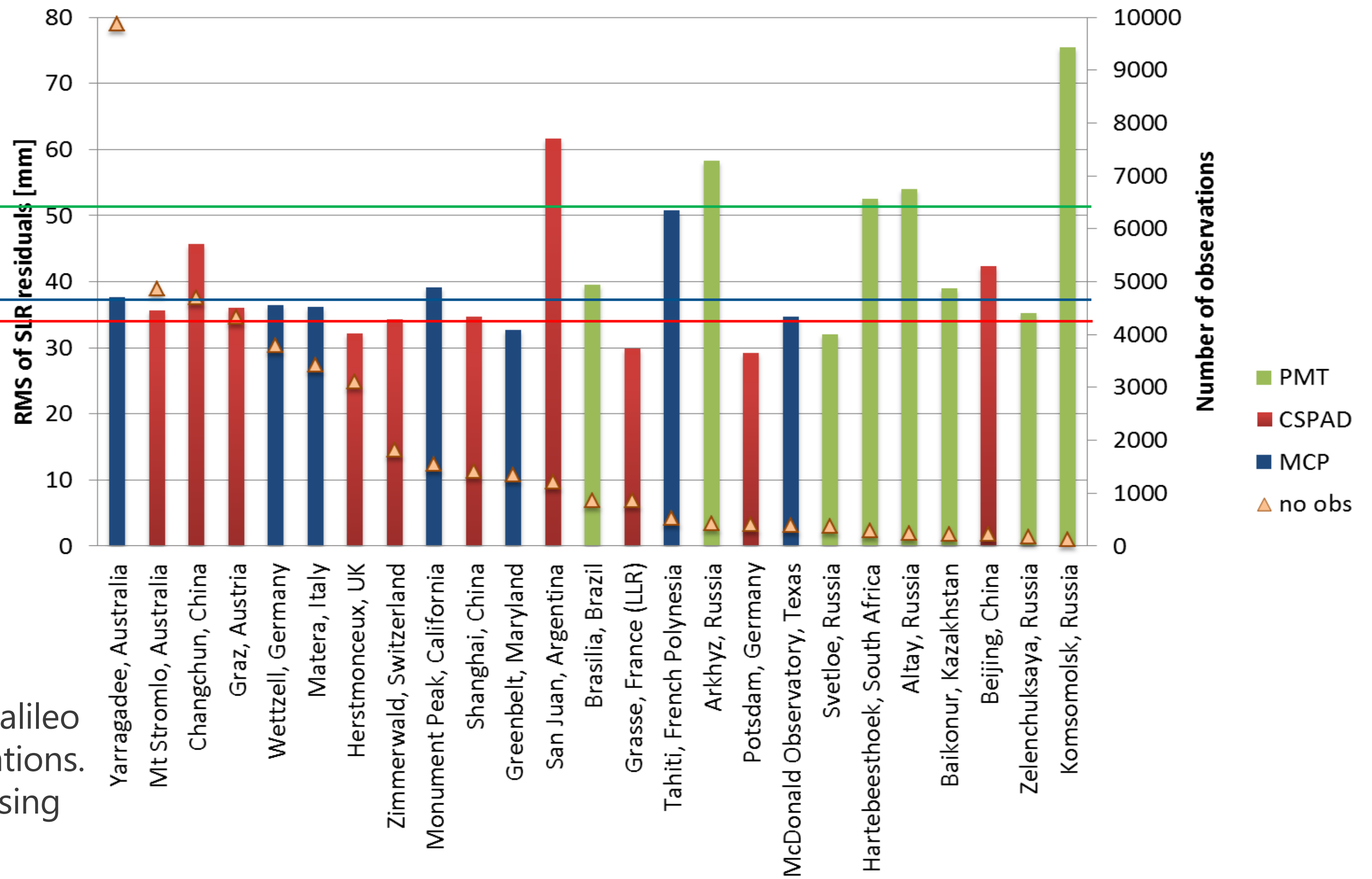
SLR stations typically employ 3 different detector types:

- Micro-Channel Plate (MCP): e.g., NASA stations+Matera+Wettzell,
- Photo-Multiplier Tube (PMT): e.g., Russian stations+Hartebeesthoek+Borówiec,
- Compensated Single-Photon Avalanche Diode (CSPAD):
  e.g., most of European stations+new Chinese stations+Mt Stromlo.

Mean PMT=51 mm

Mean MCP=38 mm

Mean CSPAD=35 mm (excluding Changchun and San Juan; 42mm when both included)



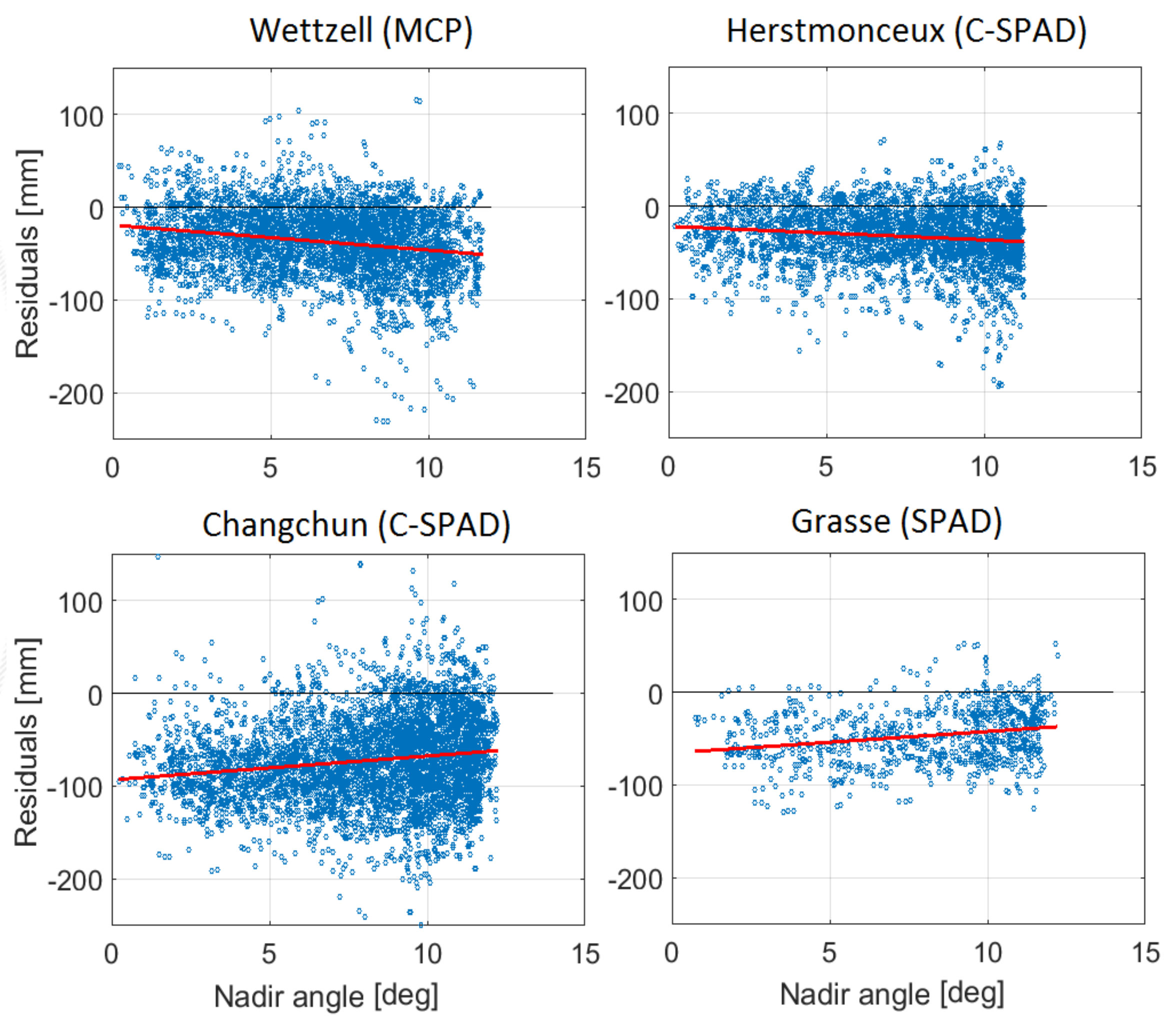
RMS of SLR residuals to all Galileo satellites for different SLR stations. Stations sorted by the increasing number of SLR observations

SLR signature effect for selected SLR stations

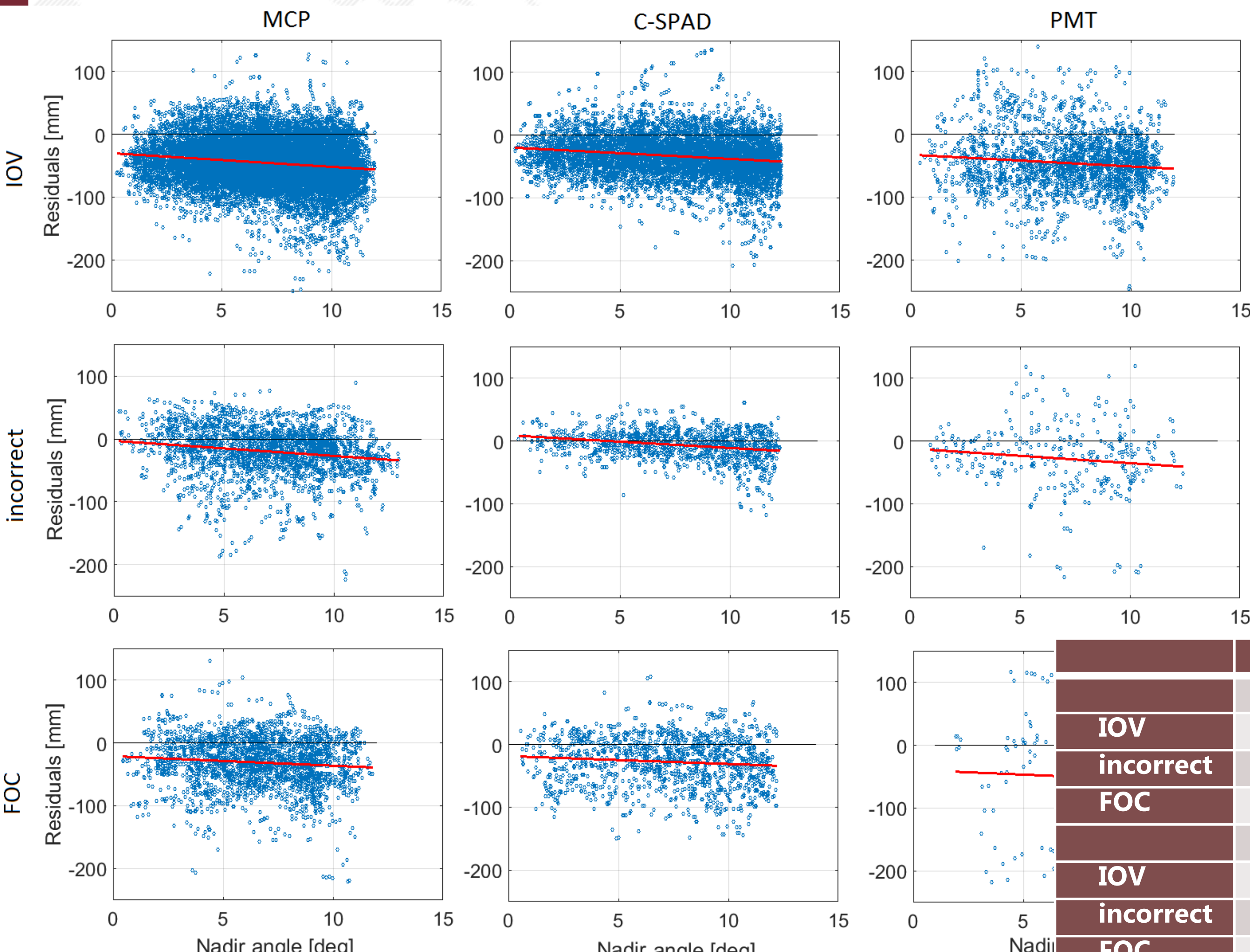
Wettzell is a good representative of all high-energy stations equipped with MCP or PMT: the offset in the nadir direction equals to about −20 mm and the slope w.r.t. nadir angle equals to about −2.0 mm/˚. The slope is a consequence of the satellite signature effect due to the first reflection of laser pulses from the nearest edge of the flat retroreflector.

Herstmonceux is one of the SLR stations operating strictly in the single-photon regime. For Herstmonceux and for most of the C-SPAD stations the nadir offset equals to about −20 mm, whereas the slope is slightly smaller than that for high-energy stations and equals to about −1.3 mm/˚.

Changchun has a large negative offset in the nadir direction of −93 mm and the slope of +2.6 mm/˚, whereas Grasse, equipped with uncompensated SPAD, has an offset of −66 mm and the slope of +2.3 mm/˚. This may indicate some issues with filters or a proper energy control (intensity-dependent bias).



SLR signature effect for different satellites and detector types



The smallest offset and RMS of SLR residuals is obtained for C-SPAD stations tracking Galileo in incorrect orbital planes.

The smallest offset cannot be explained by the change of satellite center-of-mass due to the fuel consuption during the manouvers when correcting the orbit eccentricity.

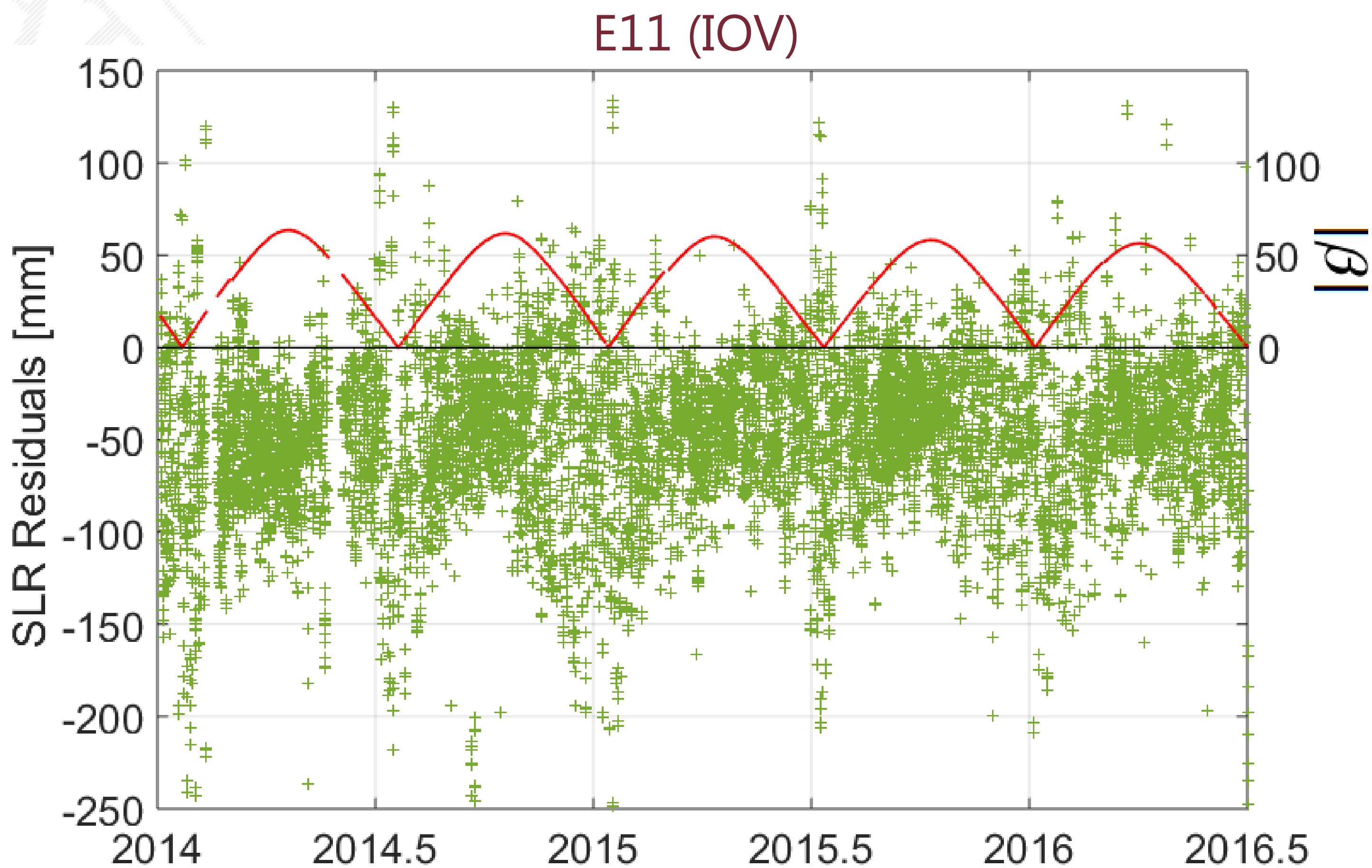
The difference of the mean offsets between C-SPAD and MCP is about. 12 mm for IOV and incorrect.

	MCP	C-SPAD	PMT
	Mean offset [mm]		
IOV	-45.8	-33.5	-46.1
incorrect	-18.6	**-6.7**	-27.0
FOC	-30.0	-27.7	-48.8
	RMS [mm]		
IOV	36.3	33.3	47.8
incorrect	35.7	**23.0**	54.3
FOC	37.3	37.2	89.1
	No. obs.		
IOV	15625	7059	2314
incorrect	2383	1238	314
FOC	2329	1361	110

Only highest-performing stations are included (European CSPAD stations, NASA stations, Wettzell, Matera, all Russian stations excluding Komsomolsk).

Modeling of solar radiation pressure

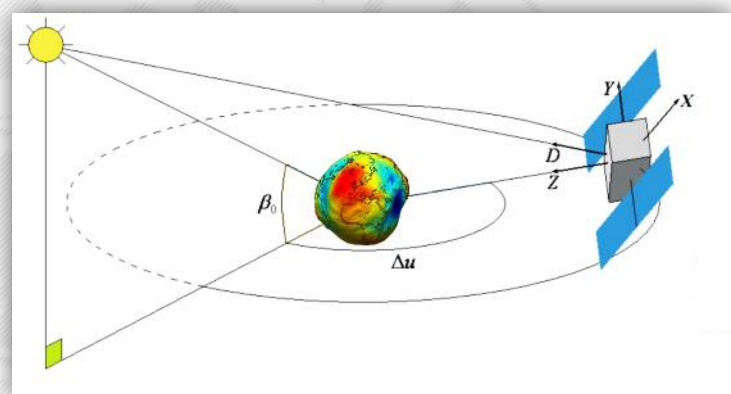
Galileo orbit modeling: impact of the solar radiation pressure



Despite using the improved model ECOM2, which substantially reduces the systematic β-dependent effects, the spread of SLR residuals is still much larger for the lowest |β| angles. This is on one hand due to the orbit modeling deficiencies and on the other hand due to the dynamic yaw steering of Galileo satellites for $|\beta|<2^\circ$.

The Sun crosses through the orbital plane every 177.8 days, whereas the passage in the same direction takes place every 355.6 days, i.e., once per draconitic year.

ECOM1 and ECOM2



The classical Empirical CODE Orbit Model (ECOM1) includes the following parameters:

$$\begin{cases} D = D_0 \\ Y = Y_0 \\ X = X_0 + X_C \cos u + X_S \sin u \end{cases}$$

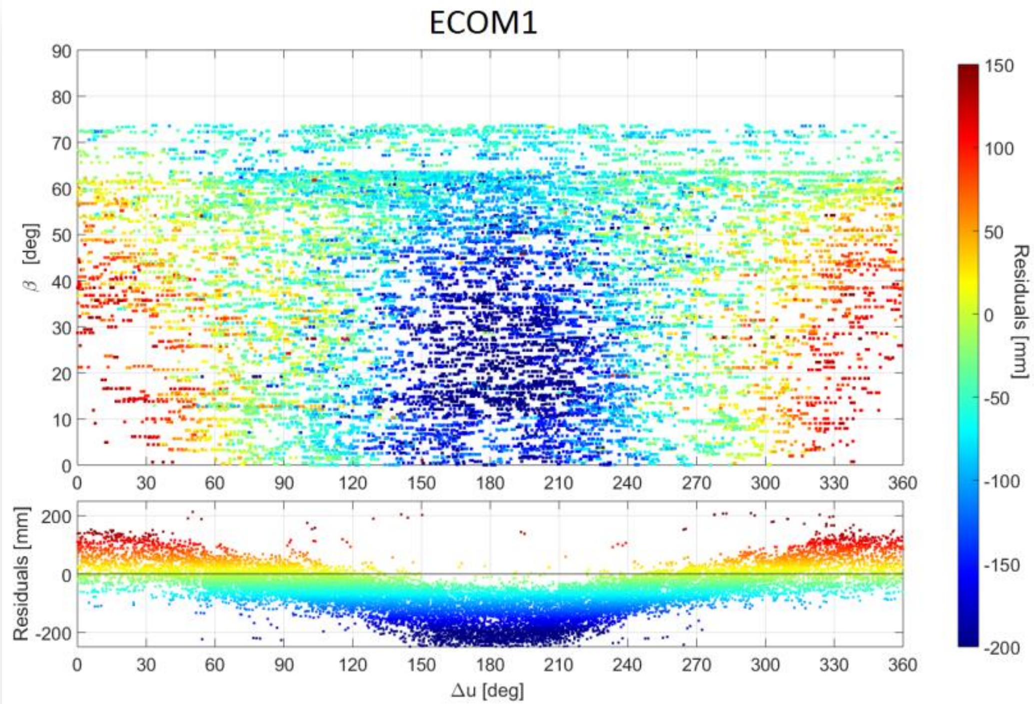
where u is the satellite argument of latitude.

ECOM2 includes following parameters:

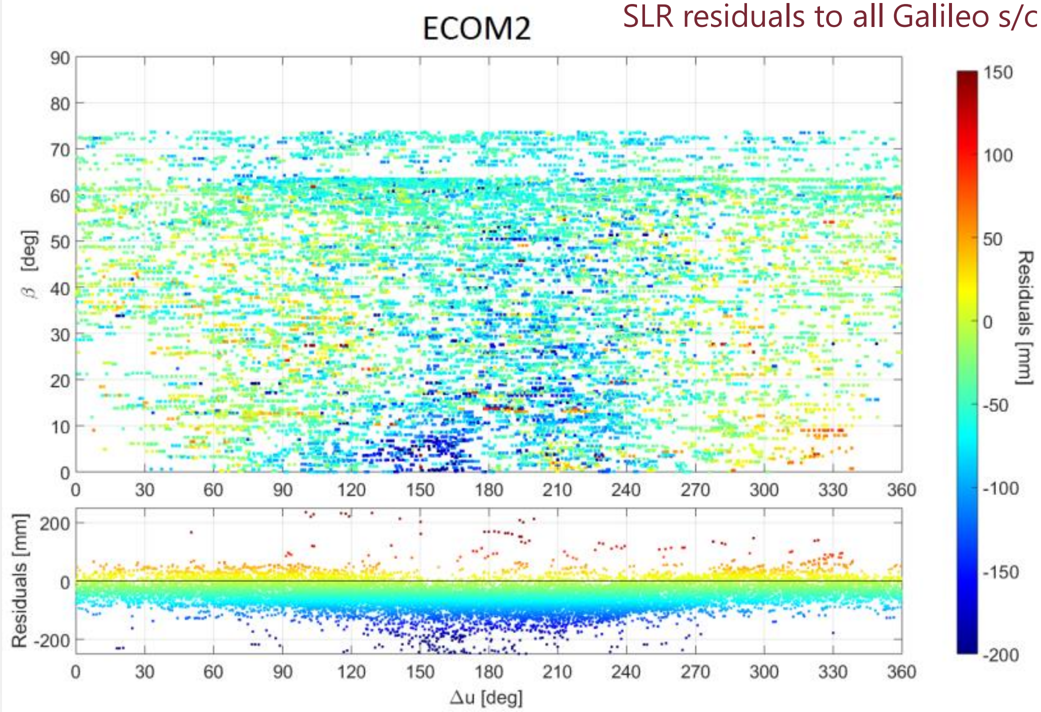
$$\begin{cases} D = D_0 + D_{C2} \cos 2\Delta u + D_{S2} \sin 2\Delta u \\ \quad + D_{C4} \cos 4\Delta u + D_{S4} \sin 4\Delta u \\ Y = Y_0 \\ X = X_0 + X_C \cos \Delta u + X_S \sin \Delta u \end{cases}$$

where Δu is the satellite argument of latitude with respect to the argument of latitude of the Sun.

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



SLR residuals to all Galileo s/c

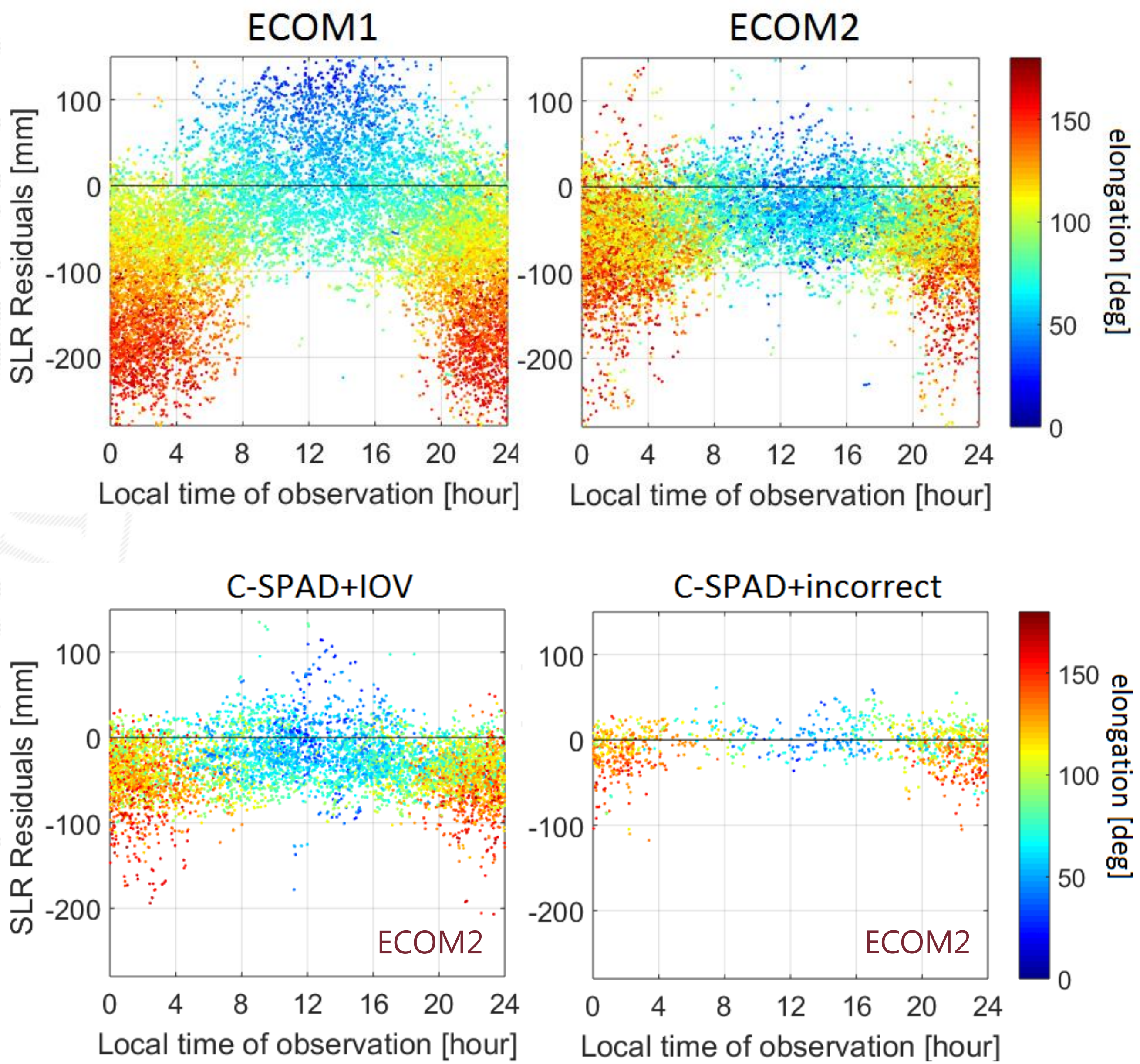


Dependency on the observation time

When using ECOM1, the daytime tracking is associated with the positive residuals of about +100 mm, whereas the nighttime tracking is associated with negative residuals of −150 mm.

Using ECOM2 reduces the night- and daytime dependency by a factor of four: the daytime residuals are reduced to about −10 mm and the nighttime residuals to −70 mm.

For single-photon stations tracking Galileo in incorrect orbits the dependency of SLR residuals on the acquisition time is smallest out of all satellites, which confirms a high quality of Galileo orbits in incorrect orbital planes.



Summary

- **The quality of Galileo satellites in incorrect orbital planes is not worse than the for those in nominal orbital planes, but even sligthly better (at least in the radial direction mostly seen by SLR).**

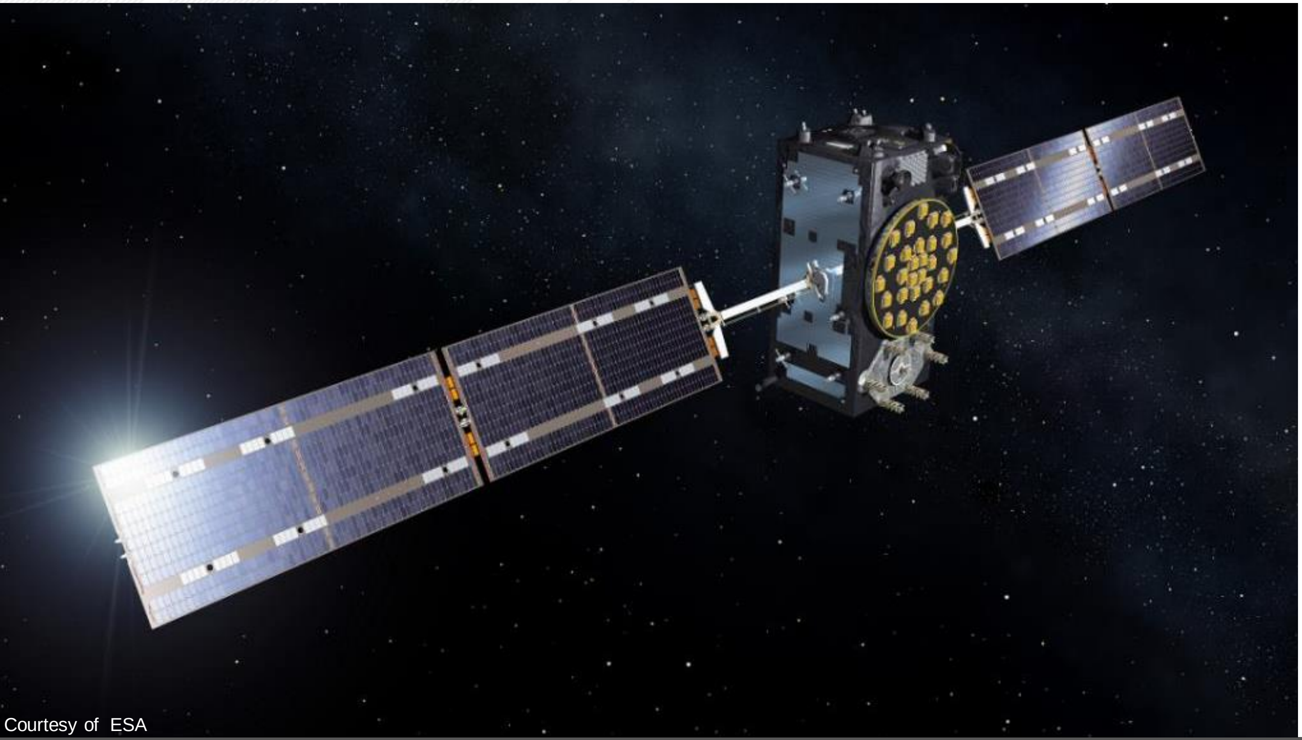
- **Galileo satellites in the incorrect orbital planes are fully useful for geodesy. Satellites have a different revolution period, different groundtrack repeatability, a different length of the draconitic year than nominal Galileo, all of which may help to decorrelate some systematics in GNSS products.**

- **The RMS of residuals is at a comparable level for CSPAD and MCP stations, but there is a systematic bias between of about 12 mm (the range registered by MCP stations is shorter by 12 mm due to the satellite signature effect).**

sehen. vermessen. verstehen.

UNIVERSITÄT BERN

WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES



Courtesy of ESA

Thank you for your attention

Dependency of SLR residuals on the Sun elongation angle

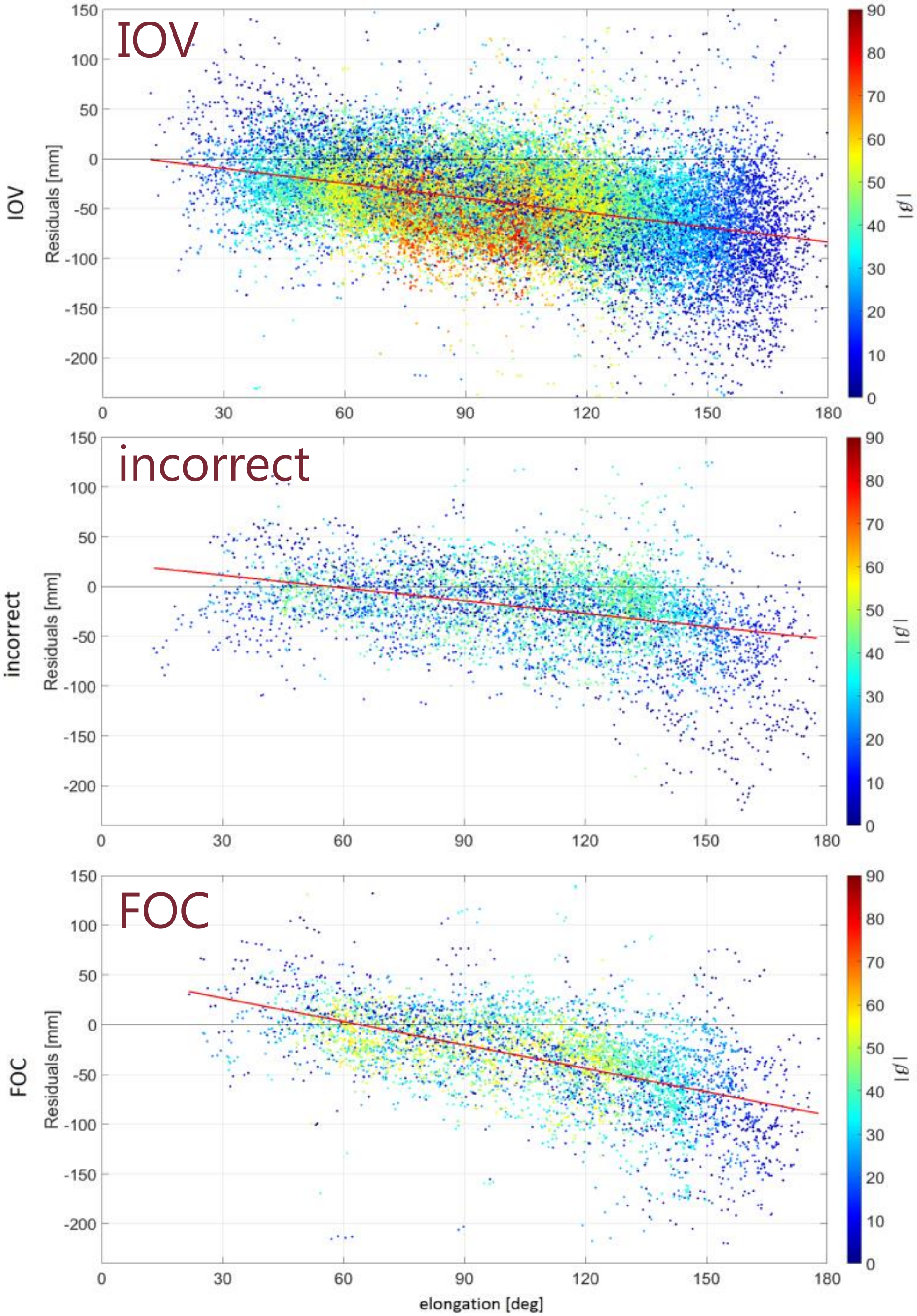
All satellite types: IOV, FOC incorrect, and FOC exhibit a residual dependency on the elongation angle. For high |β| (red and yellow dots in the figure) the elongation angle is close to 90˚ and the spread of SLR residuals becomes much smaller than for low |β| having typically a large dispersion (blue dots in the figure). When the |β| angle is high, the Sun illuminates the X surface of the satellite box for most of the time. For low |β| angles, the Sun illuminates X, +Z, and –Z sides, which results in large temporal variations of the surface area exposed to Sun for elongated satellite bodies.

The mean slope of the elongation dependency is −0.50, −0.43, and −0.80 mm/˚ for IOV, incorrect, and FOC satellites, respectively.

Thus, the smallest slope is obtained for Galileo in incorrect orbits, despite lower |β| values, which are more subject to a large residual scatter.

Satellite elongation angle is calcuted using a following formula:

$$\cos \varepsilon = \cos \Delta u \cos \beta$$



Pros and cons of GNSS and SLR observations

GNSS	SLR
• Continuous tracking	• Non-continuous observations
• Many observations, many stations	• Several (tens/hundrets) of observations
• Many frequencies	• Typically only one wavelength
• Many satellites tracked simultaneously	• 1 satellite can be tracked simultaneously
• Weather independence	• No observations if clouds
• No blue-sky effect	• Blue-sky effect
• Code, inter-frequency, inter-system biases	• (sometimes) Range biases
• Antenna offsets, phase center variations	• LRA offsets are well defined (but: the satellite signature effect)
• Ionospheric delay	• No ionospheric delay
• Dependence on troposphere	• Troposphere easy to model
• Tropospheric parameters have to estimated as additional parameters	• 70x less delayed by the wet troposphere
• Clocks as additional parameters or double-differences	• No clock estimates, no need of single or double-differences
• Multipath	• No multipath
• Phase ambiguities	• No ambiguities