WROCŁAW UNIVERSITY OF ENVIRONMENTAL AND LIFE SCIENCES

Systematic effects in SLR measurements to GNSS satellites

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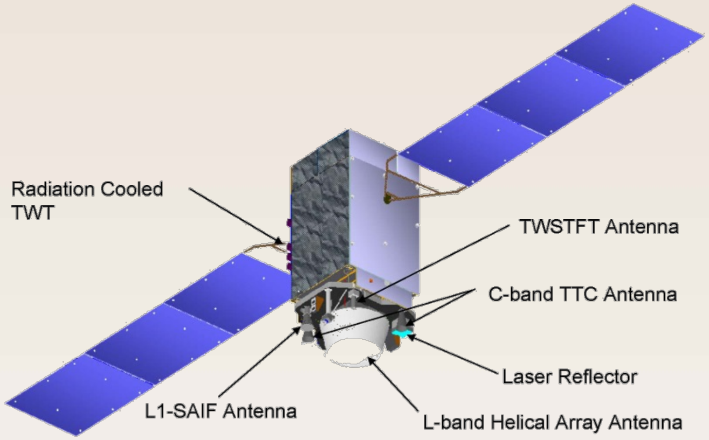
GNSS satellites

GPS Block-IIRM

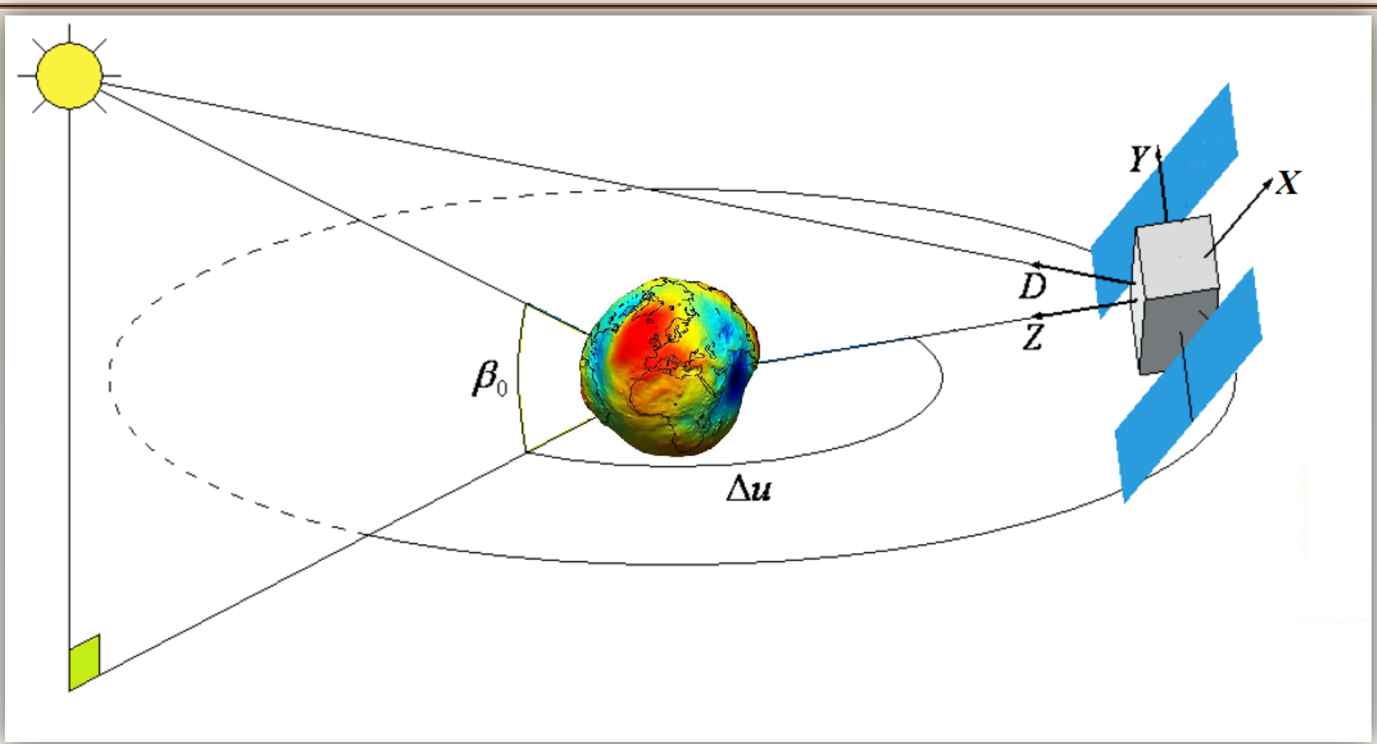
GLONASS-M



QZS-1

For many years the Empirical CODE Orbit Model (ECOM, Beutler et al., 1994; Springer et al., 1999), developed in 1994, was used for generating high-precise GNSS orbits and GNSS products due to its high efficiency in mitigating the impact of solar radiation pressure. Recently, it was found that the classical ECOM is well suited for the near cubic-shaped GPS satellites, whereas the orbit quality of the elongated cylinder-shaped GLONASS-M satellites suffers from some modeling deficiencies. This was the major motivation for developing a new Empirical CODE Orbit Model (new ECOM, Arnold et al., 2015).

GNSS orbit modeling



GNSS dynamic orbit parameters in reduced ECOM model:

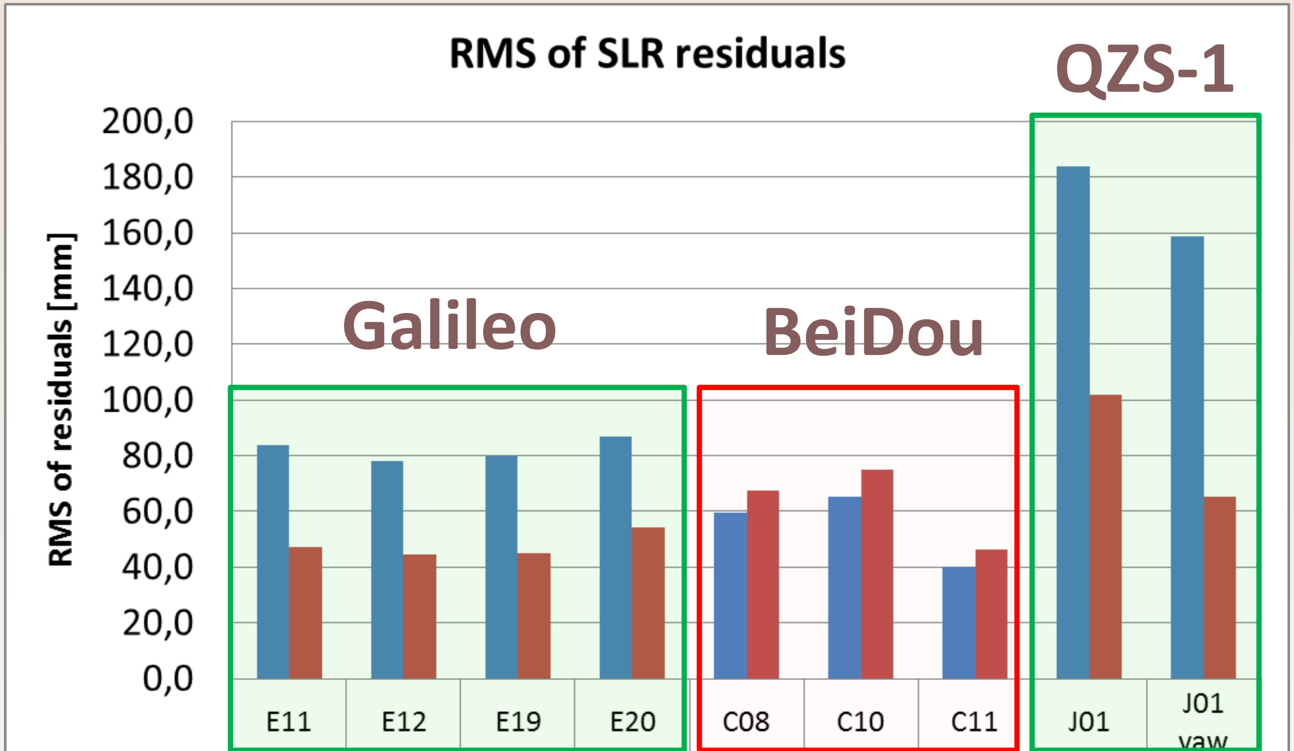
$$\begin{pmatrix} D \\ Y \\ X \end{pmatrix} = \begin{pmatrix} D_0 \\ Y_0 \\ X_0 + X_C \cos u + X_S \sin u \end{pmatrix}$$

old empirical CODE orbit model (old ECOM)

$$\begin{pmatrix} D \\ Y \\ X \end{pmatrix} = \begin{pmatrix} D_0 + D_{2C} \cos 2\Delta u + D_{2S} \sin 2\Delta u \\ +\{D_{4C} \cos 4\Delta u + D_{4S} \sin 4\Delta u\} \\ Y_0 \\ X_0 + X_C \cos \Delta u + X_S \sin \Delta u \end{pmatrix}$$

new ECOM

Validation of GNSS orbits using SLR

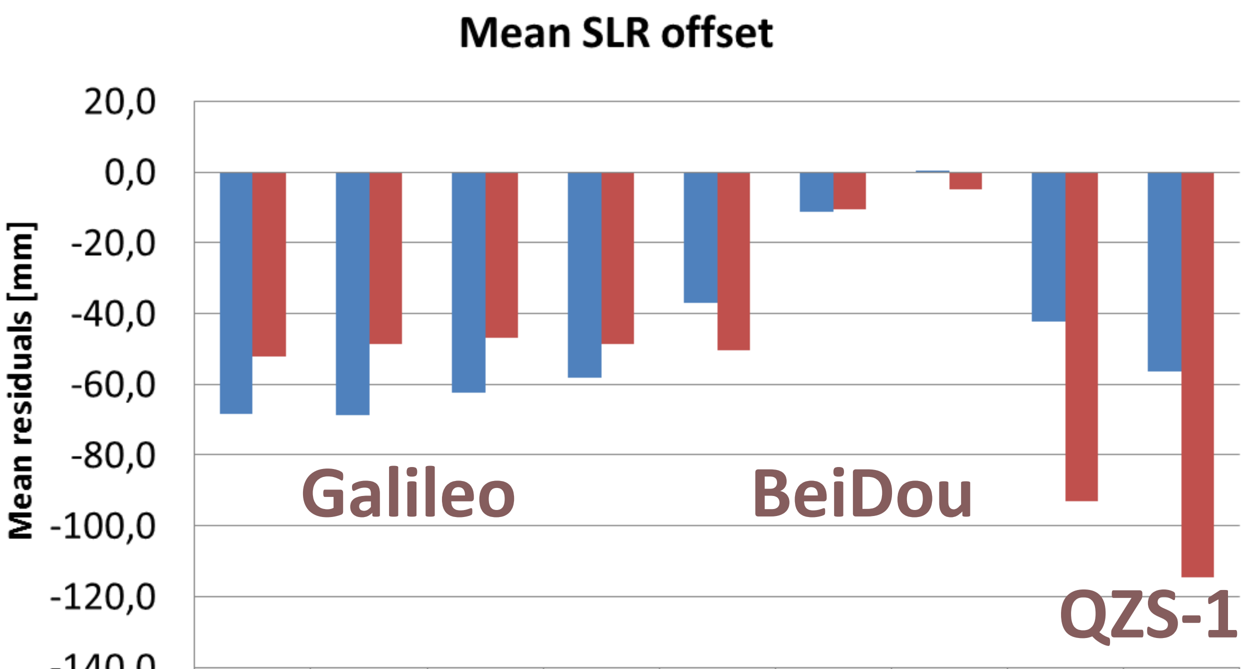


	E11	E12	E19	E20	C08	C10	C11	J01	J01 yaw
Old ECOM	83,7	78,1	79,7	86,8	59,6	65,3	40,0	183,8	158,7
New ECOM	47,0	44,4	44,9	54,4	67,6	74,8	46,5	101,9	65,4

Center for Orbit Determination in Europe (CODE) provides the 5-GNSS system solutions (GRECJ) starting from January 2014. Here orbits from 2014 are analyzed.

- **Galileo orbits are remarkably improved** when using new ECOM (**by ~44%** of SLR resid.)
- **BeiDou** orbits show a slight **degradation** in the new ECOM **(~15%)**
- **QZSS orbits are substantially improved (from RMS=160 mm to 65 mm)** when using new ECOM and excluding observations for |β|<20 deg (due to the normal orbital attitude)

Validation of GNSS orbits using SLR

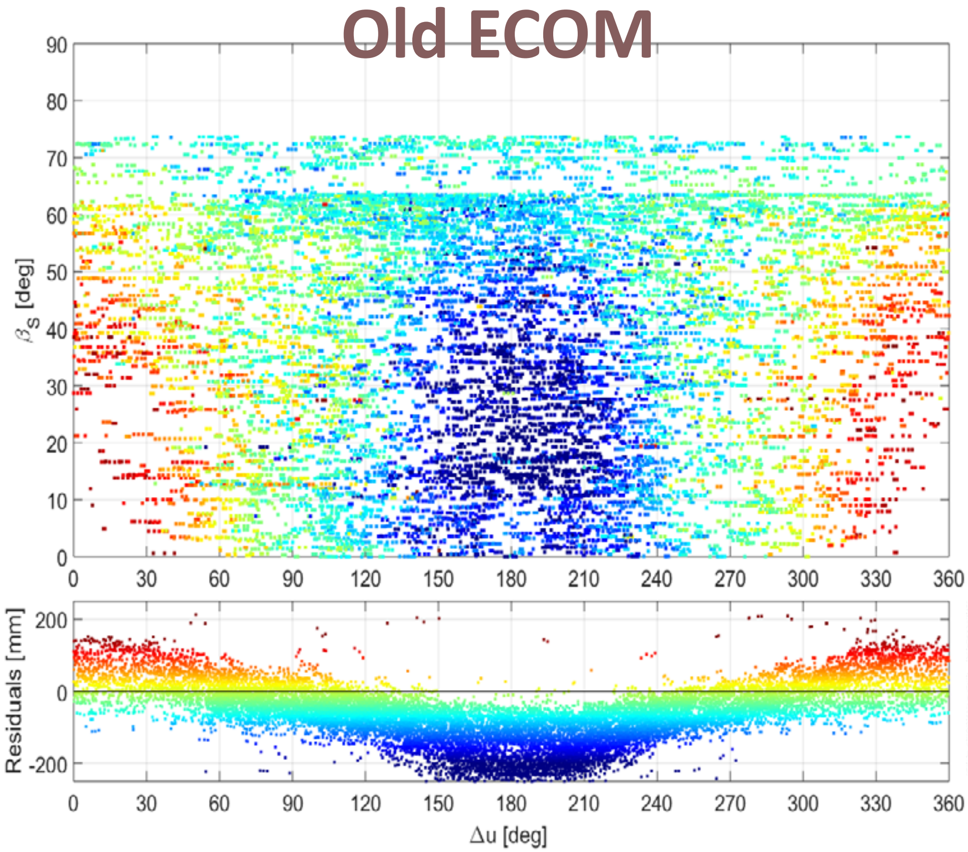


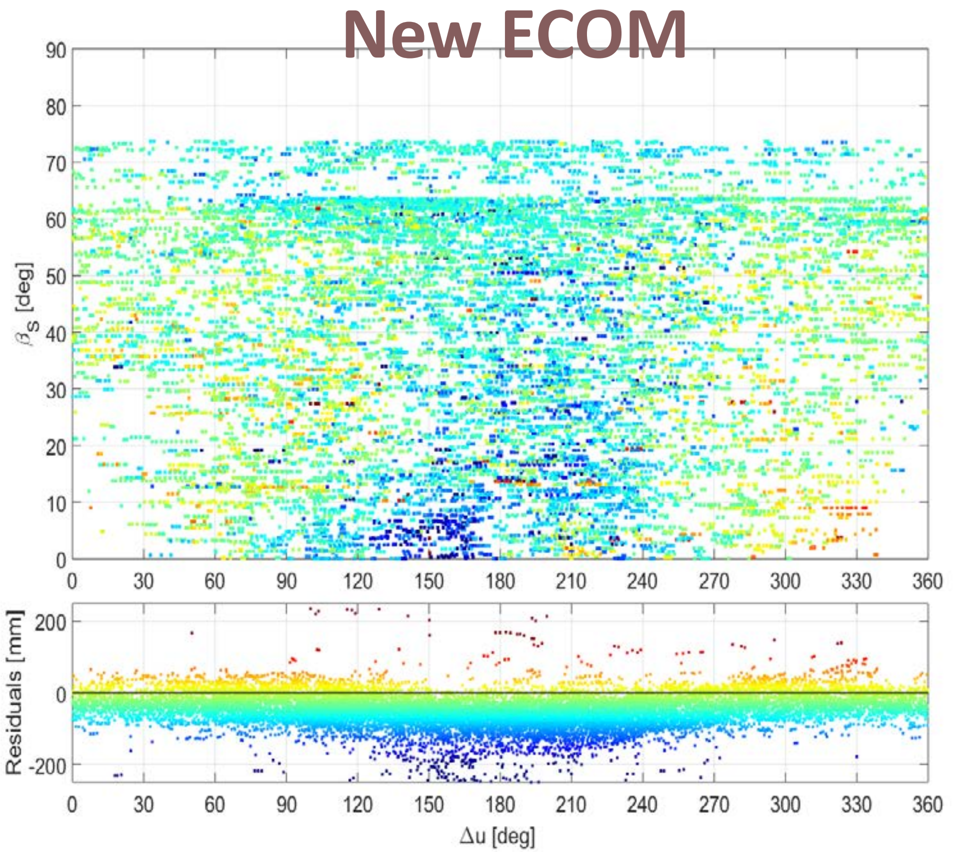
	E11	E12	E19	E20	C08	C10	C11	J01	J01 yaw
Old ECOM	-68,4	-68,7	-62,4	-58,1	-37,1	-11,2	0,2	-42,2	-56,4
New ECOM	-52,0	-48,6	-46,9	-48,6	-50,3	-10,7	-5,1	-93,1	-114,5

Center for Orbit Determination in Europe (CODE) provides the 5-GNSS system solutions (GRECJ) starting from January 2014. Here orbits from 2014 are analyzed.

- **There is an SLR-GNSS offset for Galileo orbits of about -50 mm. Unmodeled antenna thrust may correspond to an offset of about -15 mm, whereas albedo+infrared Earth radiation to about -20 mm. Remaining part can be related to the satellite signature effect, orbit modeling errors, and the Blue-Sky effect.**
- **The reason for a large offset of QZS-1 (more than -110 mm) is unknown.**

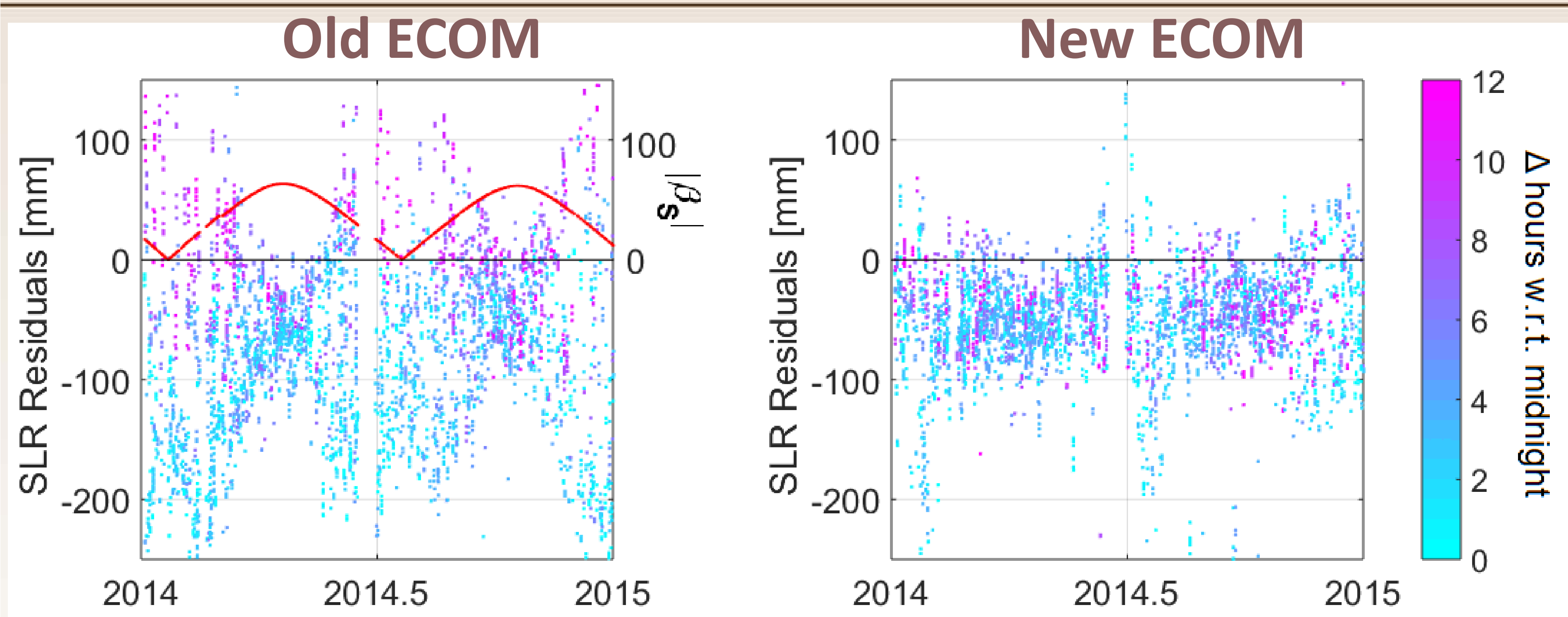
Galileo -101,102,103,104





- **Systematics related to orbit modeling deficiencies of all Galileo satellites are remarkably reduced in the new ECOM model.**

Galileo -102

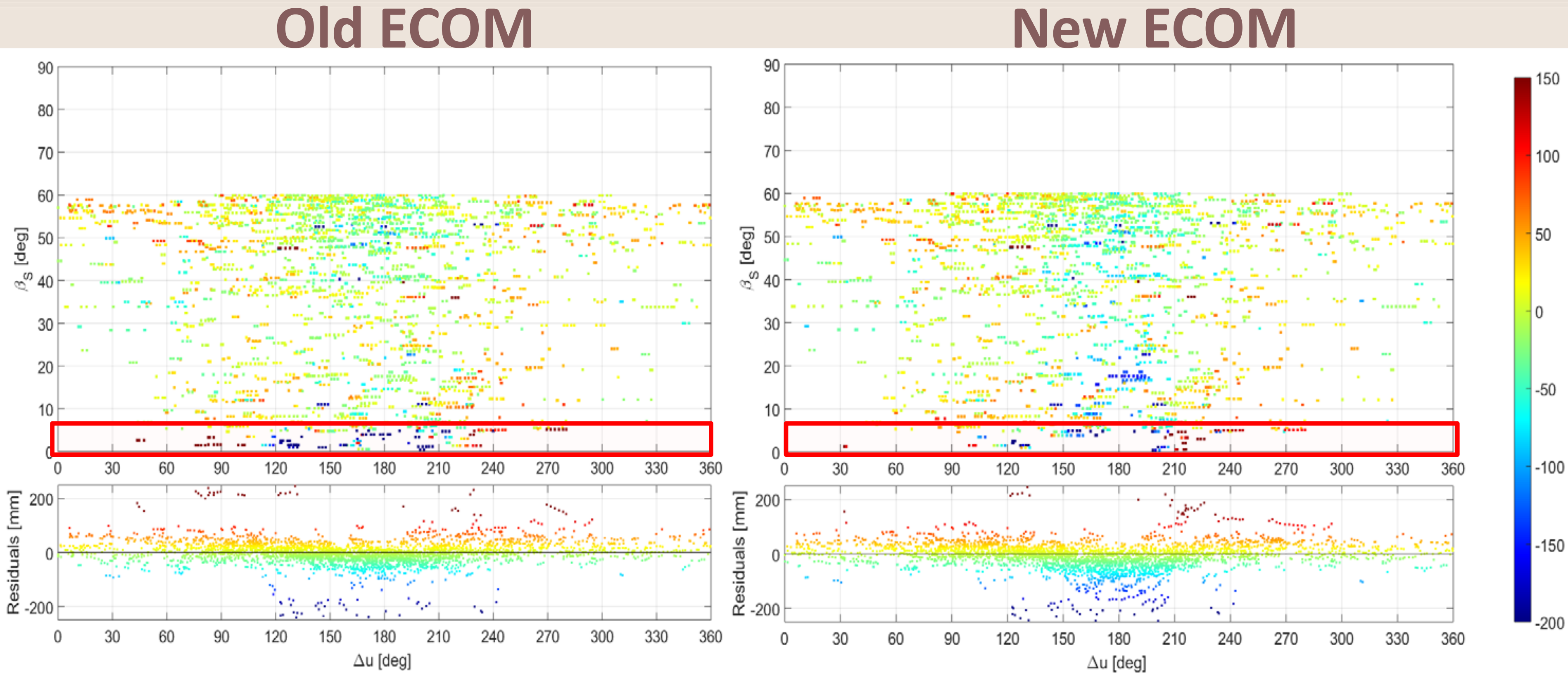


For the old ECOM model:

- Nighttime SLR observations shifted towards negative values (-150 mm)
- Daytime observations positive (+30 mm)
- Spread of residuals substantially larger for low β angles

For the new ECOM all these features disappear and the spread of residuals is reduced by a factor of two.

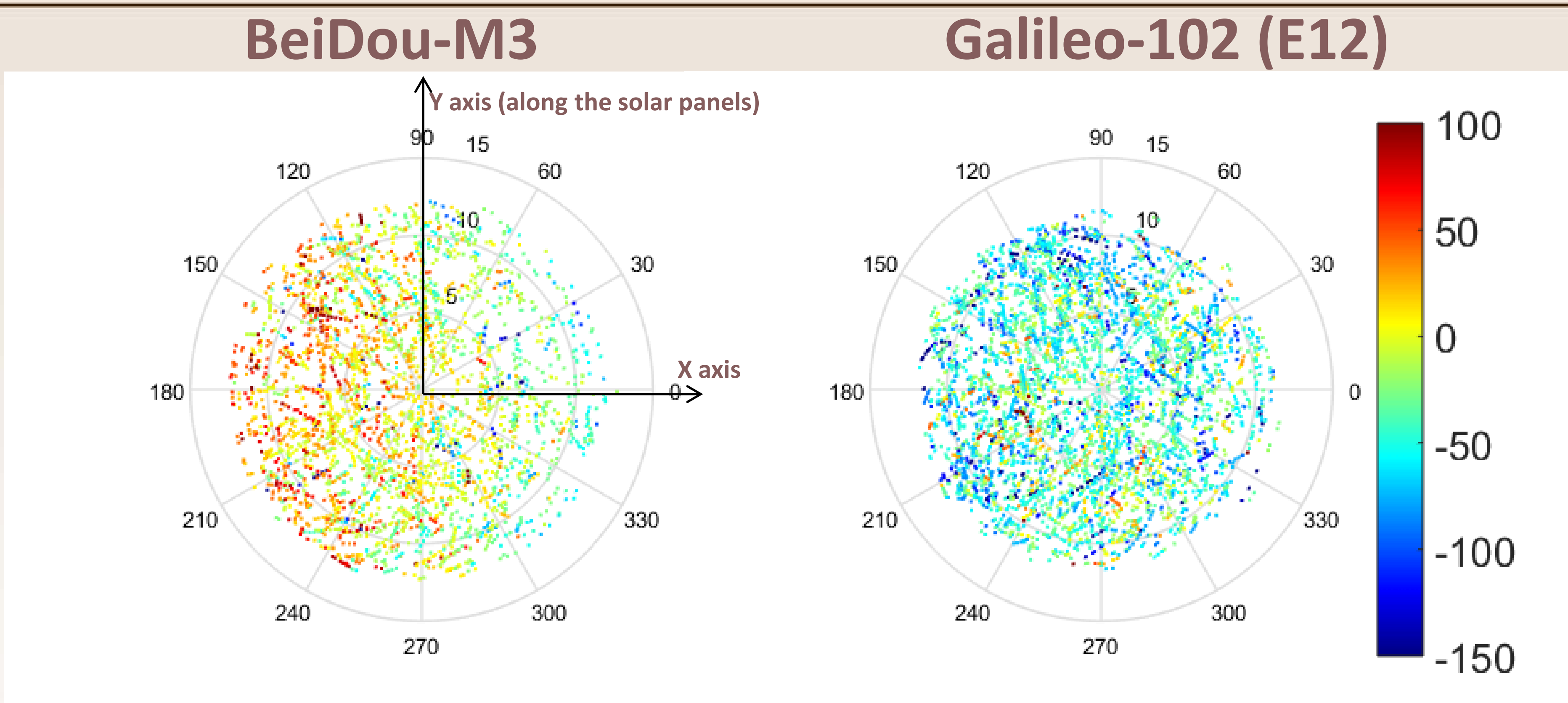
BeiDou/COMPASS-M3 (C11)



For BeiDou-M3 (MEO orbit):

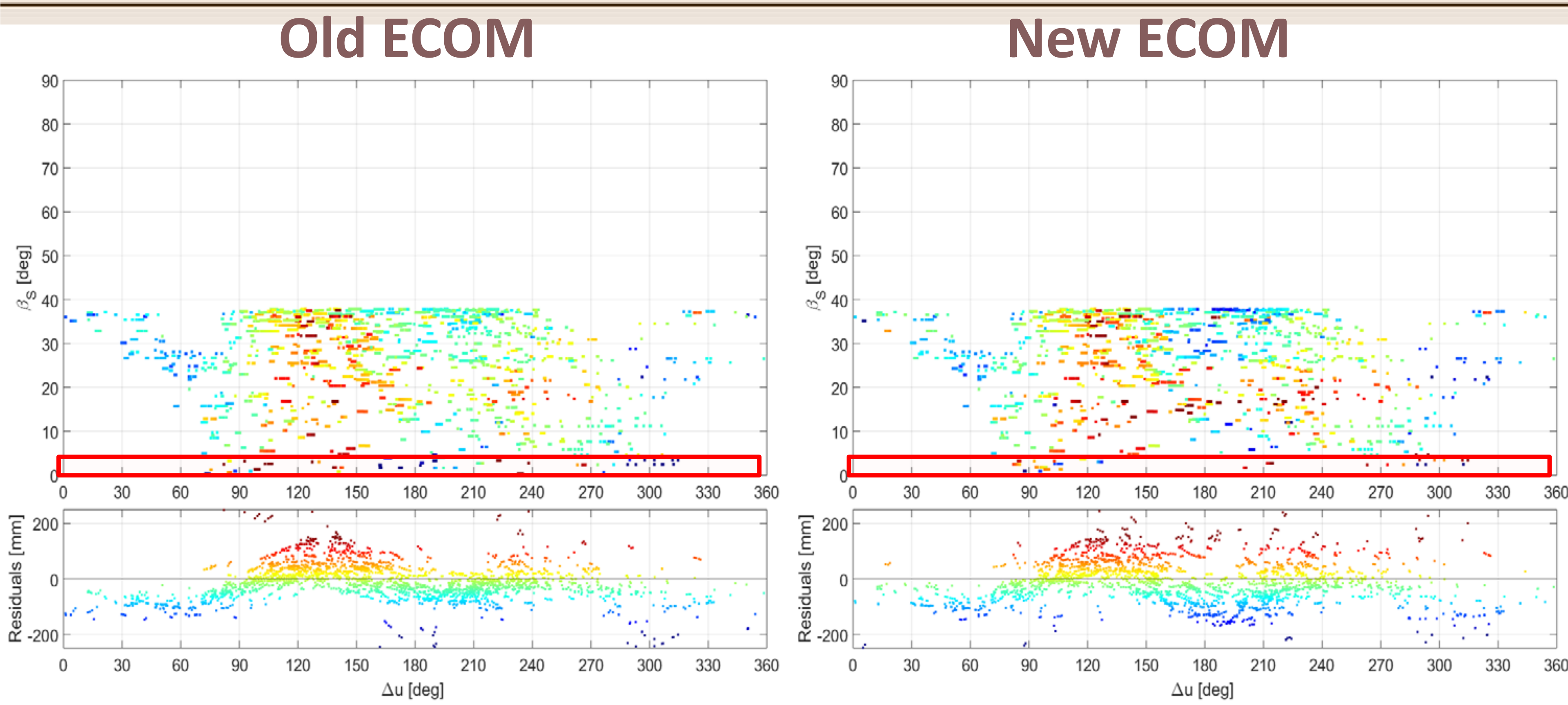
- **Very low SLR residuals ~40 mm comparable to those of GLONASS satellites despite a much worse ground network of GNSS observing stations,**
- **Old model even sligthly better than a new one (by about 15% in terms of RMS),**
- **Large residuals in both cases for |β|<4 deg (due to the normal orbital attitude).**

BeiDou/COMPASS-M3 (C11)



BeiDou-M3 shows a systemtic pattern of SLR residuals in the nadir view along the X axis (when using both the old and new ECOM). This can be explained by a wrong nominal value for CoM relative to satellite-based origin or a wrong value of location of phase center of the LRA relative to a satellite-based origin.

BeiDou/COMPASS-I5 (C10)



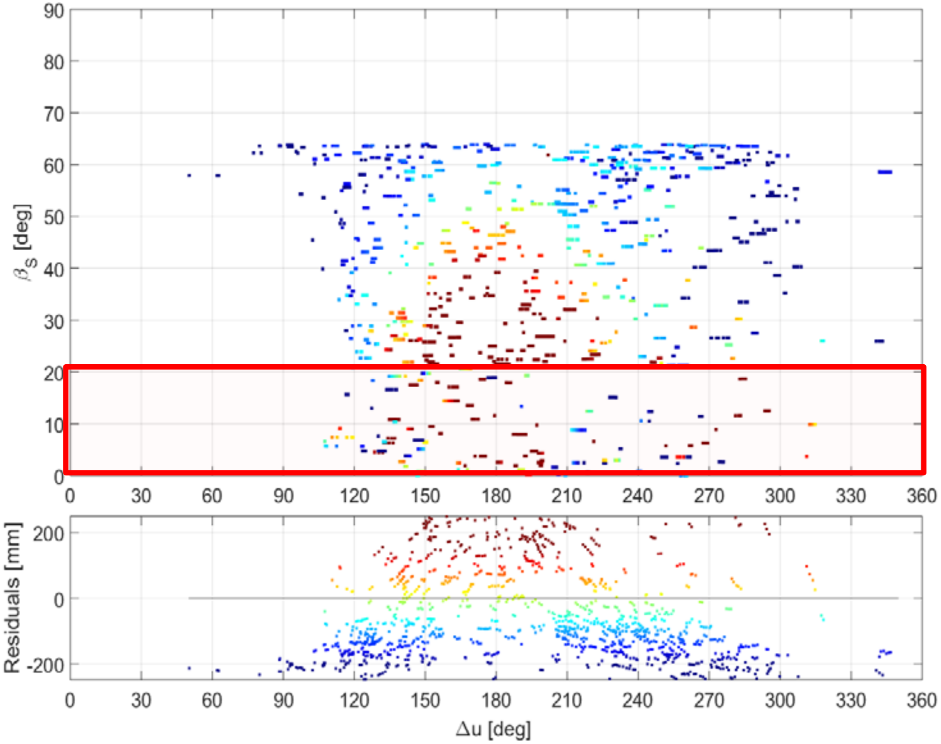
For BeiDou-I5 (geosynchronous inclined orbit):

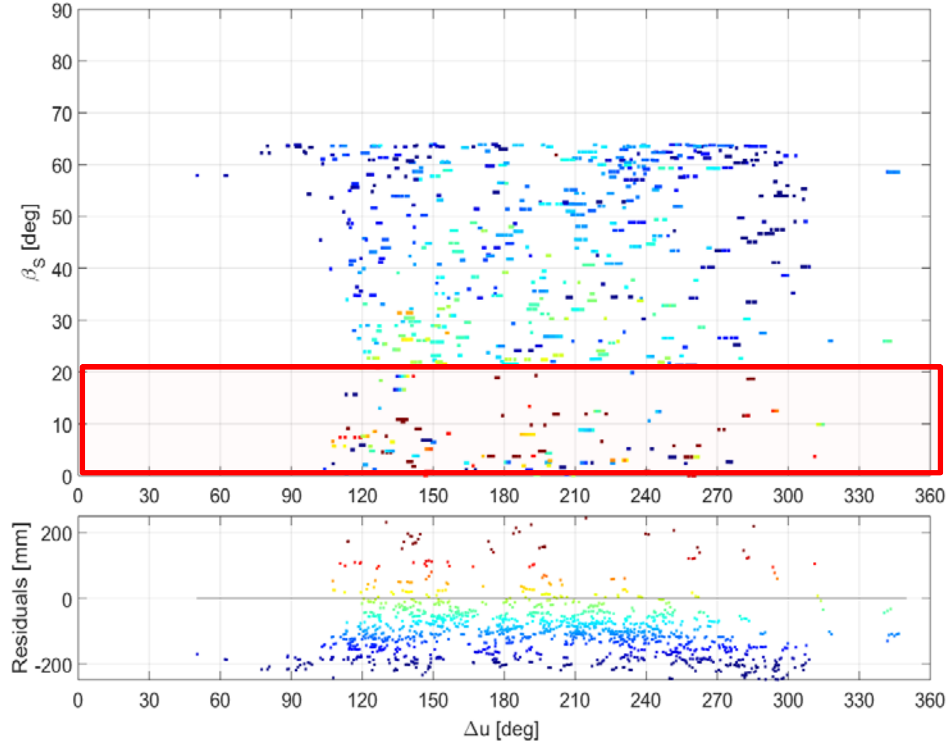
- **Large residuals for |β|<4 deg (due to the normal orbital attitude),**
- **A strange sinusoidal pattern between SLR redsiduals and Δu for both the old and the new ECOM.**

QZSS/QZS-1 (J01)

Old ECOM

New ECOM

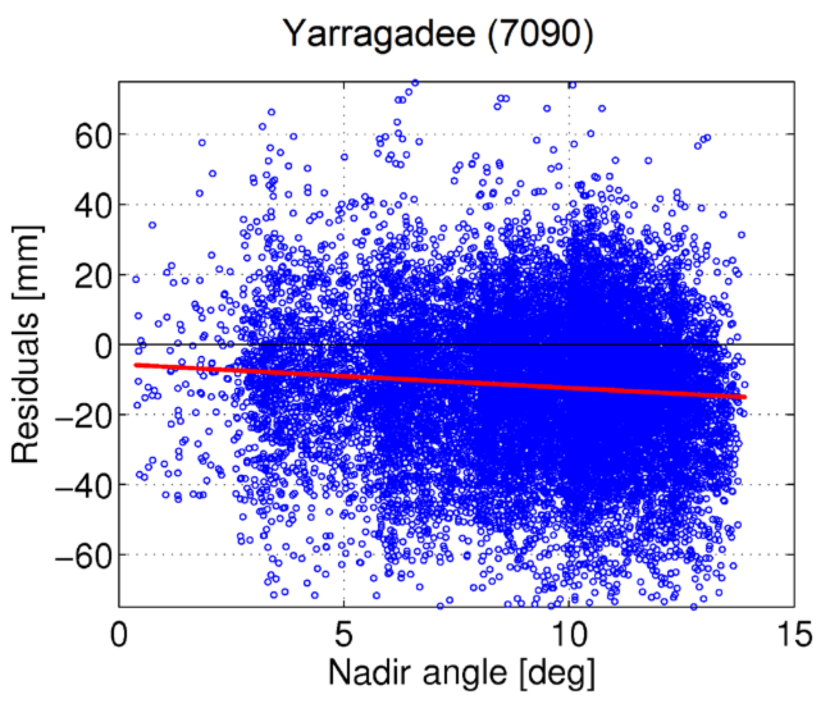




For QZS-1 (elliptical geosynchronous inclined orbit):

- **Old ECOM: huge SLR residuals (RMS=180 mm),**
- **New ECOM: RMS of SLR residuals = 65 mm for |β|>20 deg, offset=-110 mm,**
- **Large residuals for |β|<20 deg, due to the normal satellite altitude.**

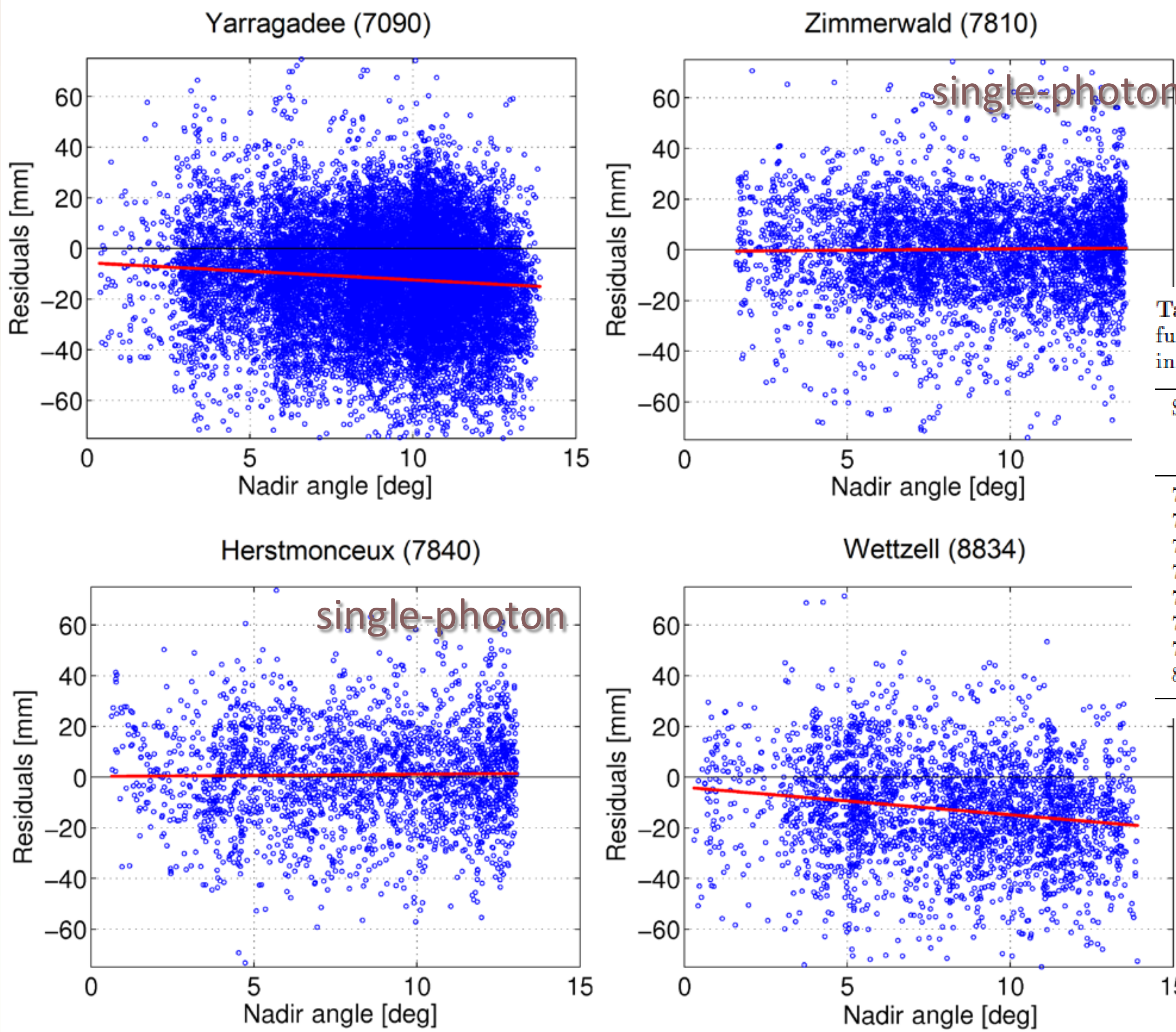
SLR Satellite Signature Effect



Satellite signature effect: a spread of optical pulse signals due to reflection from multiple reflectors.

Effect described in: Otsubo T, Appleby G, Gibbs P (2001) Glonass laser ranging accuracy with satellite signature effect. SGEO 22(5–6):509–516. doi:10.1023/A:1015676419548

SLR Satellite Signature Effect - uncoated GLONASS-M



SLR observation residuals to microwave-derived GLONASS-M orbits with uncoated CCRs for SLR stations equipped with multi-photon and single-photon detectors.

Table 5 SLR mean residuals to GLONASS-M satellites as a function of the satellite nadir angle for selected SLR stations in 2012–2013. Single-photon stations are marked by ^{S}.

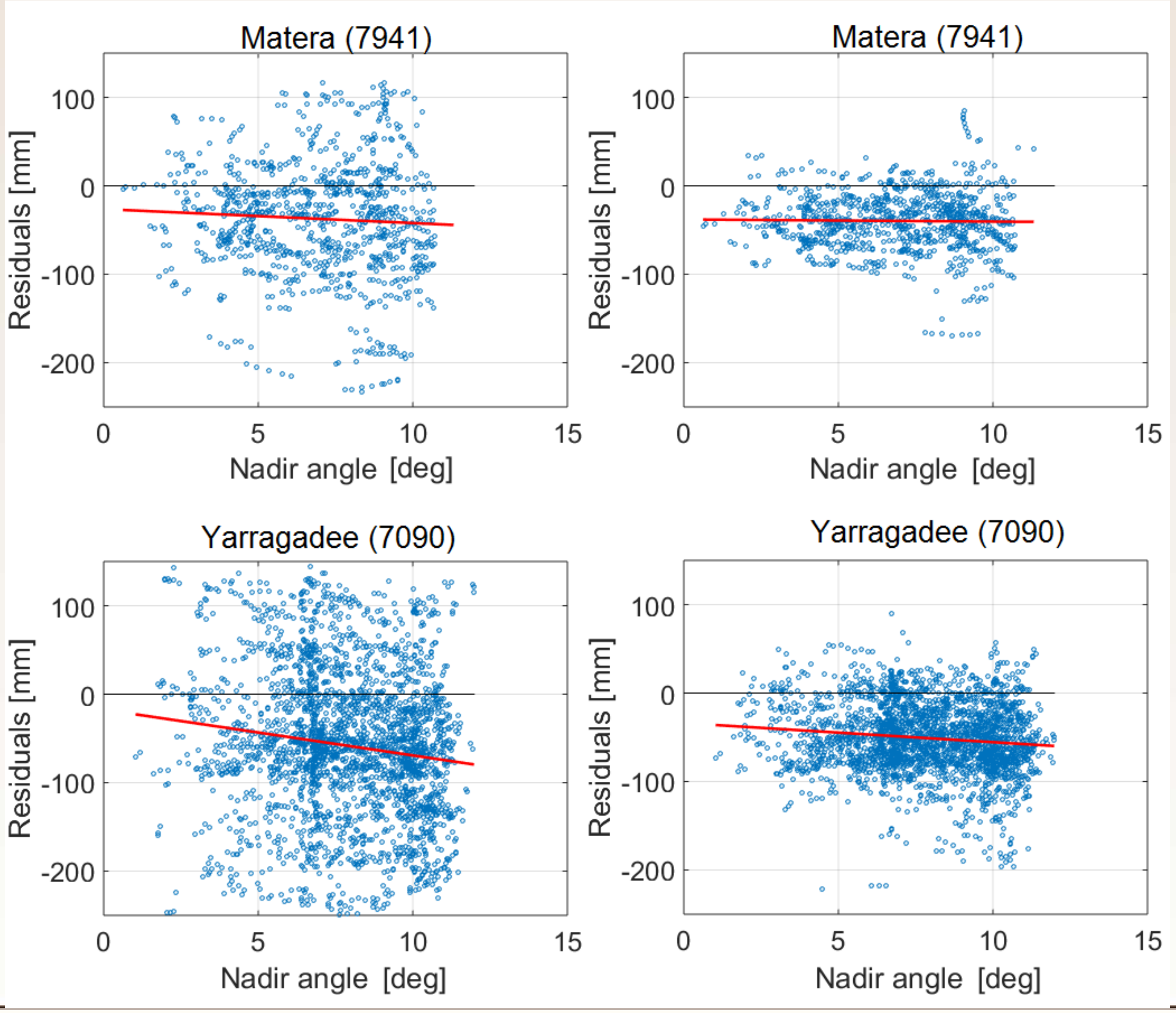
Site	uncoated nadir [mm]	uncoated drift [mm/deg]	coated nadir [mm]	coated drift [mm/deg]
7080	−15.1	−1.10	−9.6	−1.06
7090	−5.6	−0.67	−11.8	−0.46
7105	−22.0	−0.40	−5.1	−0.79
7110	−4.8	−0.64	20.7	−1.31
7810^S	−1.3	0.07	−13.7	1.08
7839^S	1.4	0.06	−5.1	0.65
7840^S	0.2	0.09	−2.8	0.61
8834	−4.0	−1.09	1.2	−0.97

Differences between the scale in the GNSS and SLR solutions are ~1mm!
(for single-photon stations)

Reference: Sośnica, K., Thaller, D., Dach, R., Steigenberger, P., Beutler, G., Arnold, D., Jäggi, A. (2015). Satellite Laser Ranging to GPS and GLONASS. **J Geod** 89(7), pp 725-743

SLR Satellite Signature Effect - Galileo

Old ECOM | New ECOM



Conclusions

1. SLR biases (and nadir-dependent slopes) are a function of:

- **CCR coating,**
- **Detectors (single photon/multi photon),**
- **Satellite orbit model for SRP.**

2. New ECOM remarkably reduces systematic effects in SLR residuals for almost all GLONASS-M, Galileo, QZSS satellites. The differences between nighttime and daytime tracking are removed when using new ECOM.

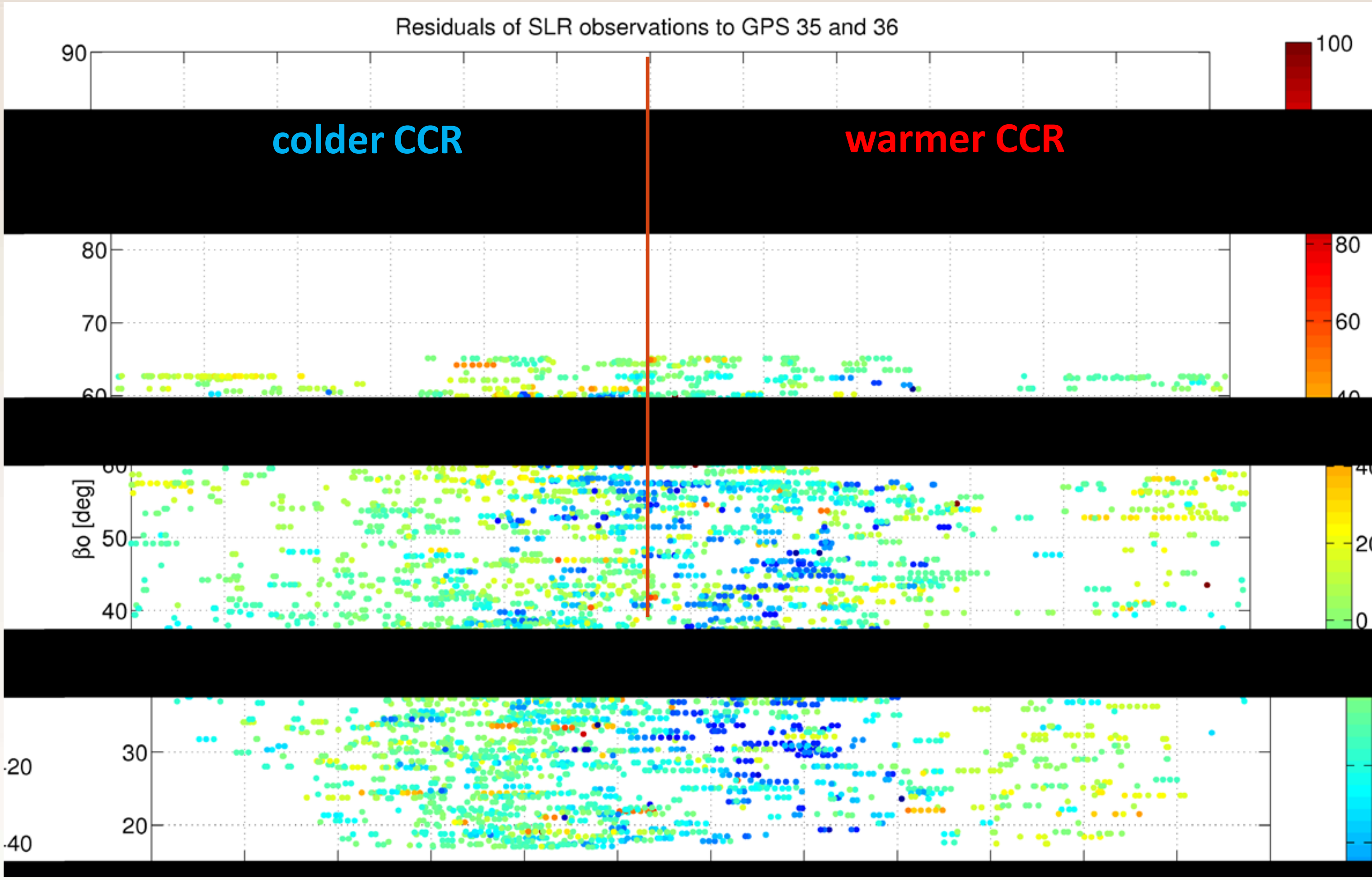
3. There is a large, unexplained SLR offset for QZS-1. SLR offsets for Galileo can be mostly explained by unmodeled antenna thrust and Earth radiation pressure.

4. The scale agreement between SLR and GNSS solutions (based on GLONASS-M satellites) is at the level of ~1mm, when using:

New ECOM + Single photon detectors + uncoated CCRs.

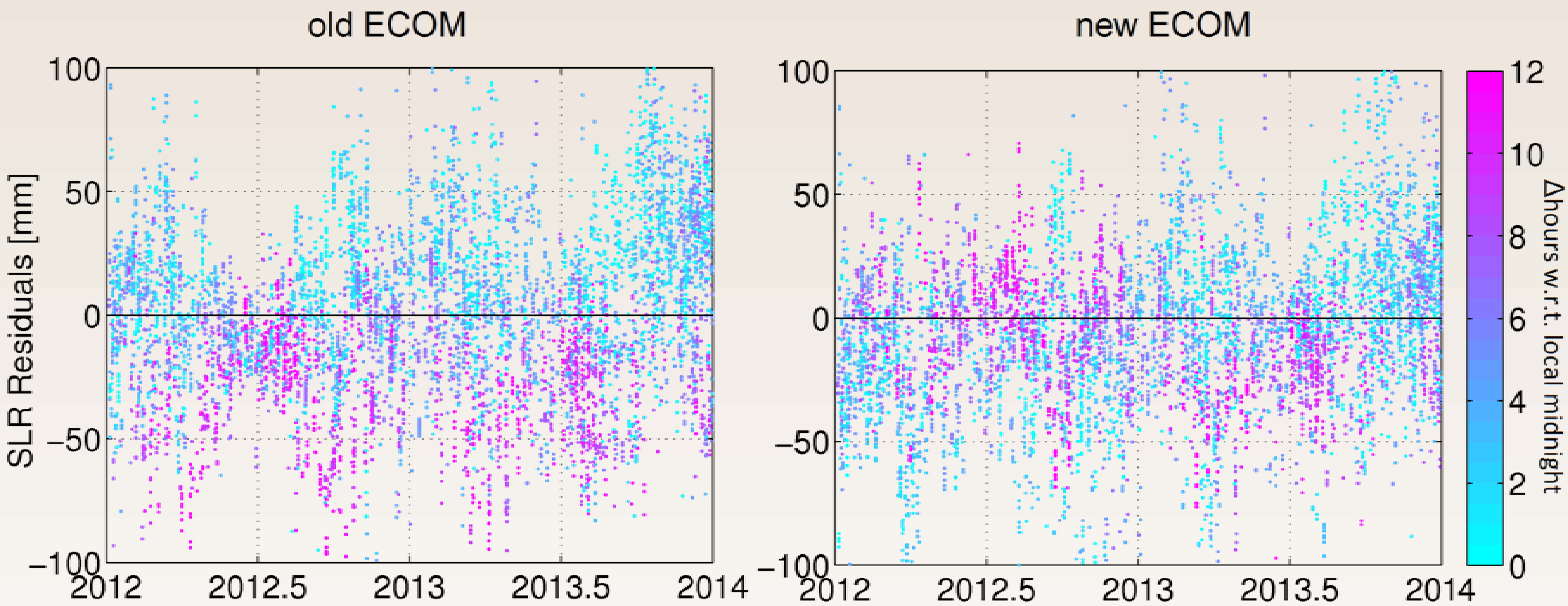
Thank you
for your attention

GPS with coated CCR LRAs



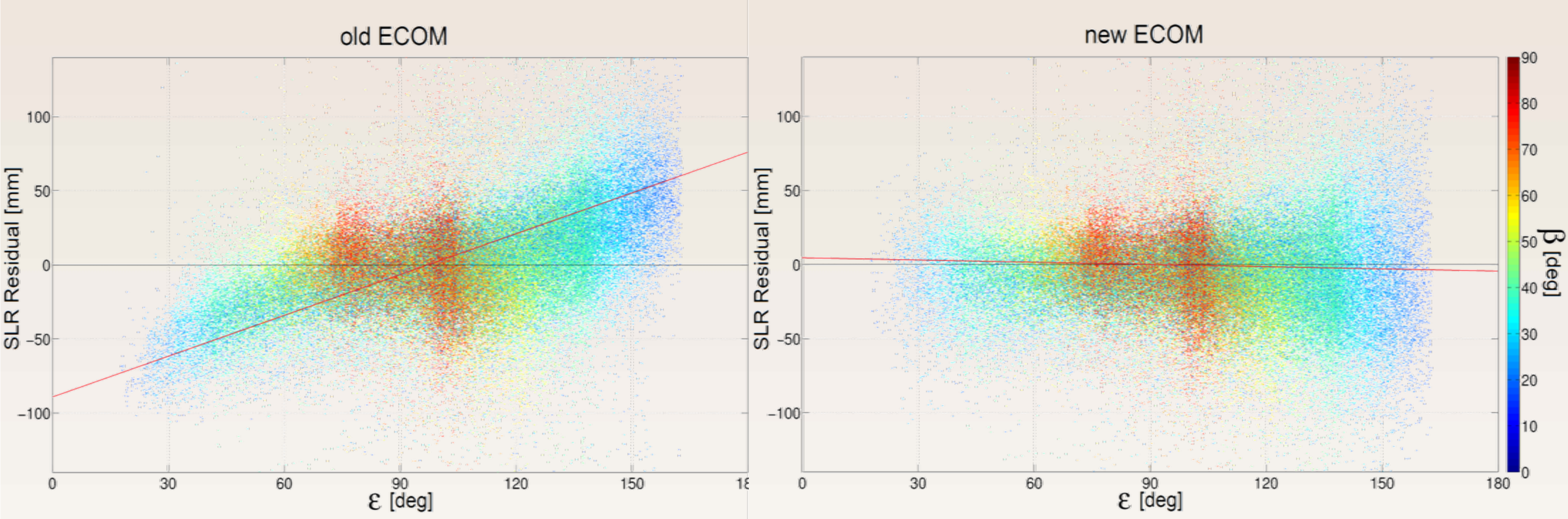
All GPS satellites equipped with coated CCR (as opposed to other GNSS). Residuals should be symmetric w.r.t. Δu. Assymetricity may be related to heating of CCR aluminum coating => needs further investigations

Validation of GLONASS orbits using SLR



SLR residuals to GLONASS-M (SVN 738) as a function of the local time of collected data at a station. Daytime observations are shown in magenta, whereas nighttime observations in cyan. Left figure is generated using classical ECOM, whereas the right Figure using extended ECOM (for the same satellite).

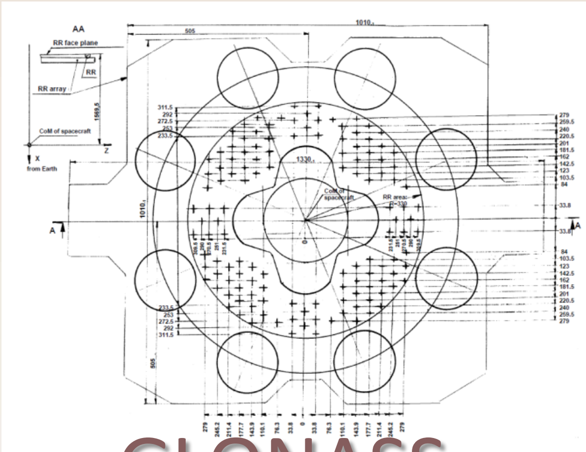
Validation of GLONASS orbits using SLR



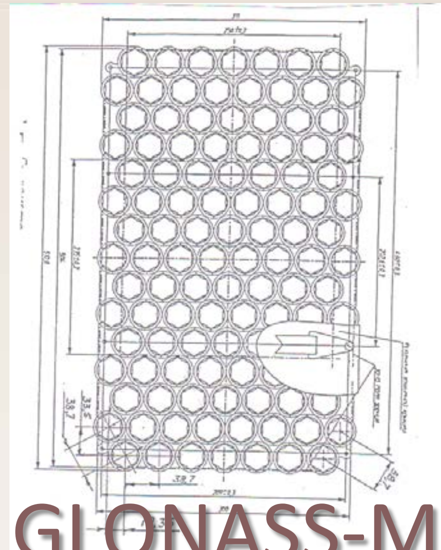
$$\cos \varepsilon = \cos \beta \cos \Delta u$$

SLR residuals to GLONASS-M as a function of the satellite elongation angle and the solar elevation angle above and below orbital plane. The SLR residuals from the classical ECOM model are shown in the left figure, whereas the right figure shows the residuals for the new extended ECOM. Beta angles are color-coded. The red line denotes the linear trend of the SLR residuals.

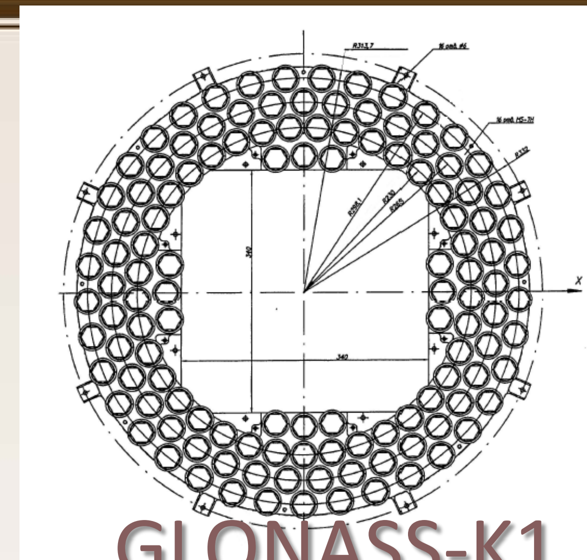
GNSS retroreflectors



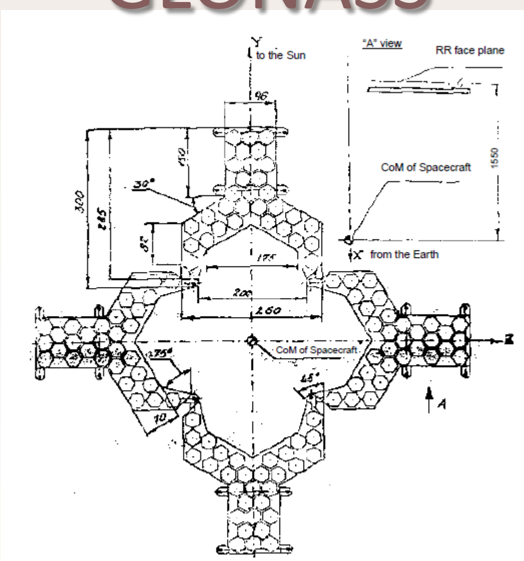
GLONASS



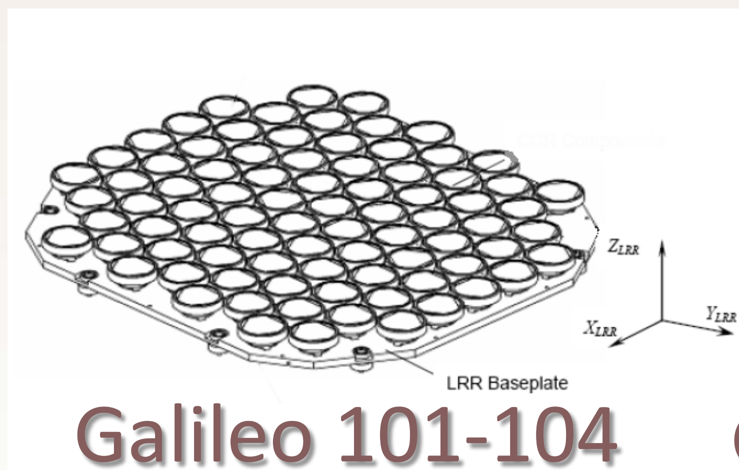
GLONASS-M



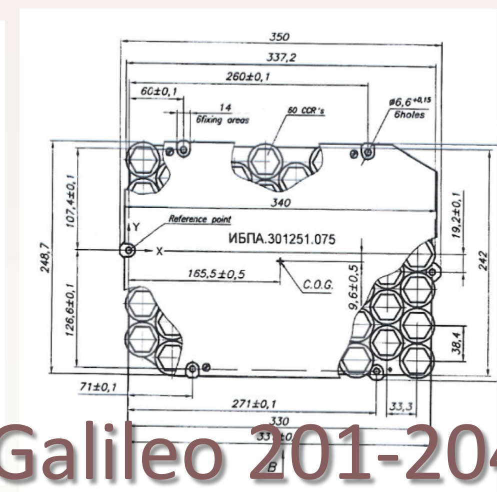
GLONASS-K1



GLONASS



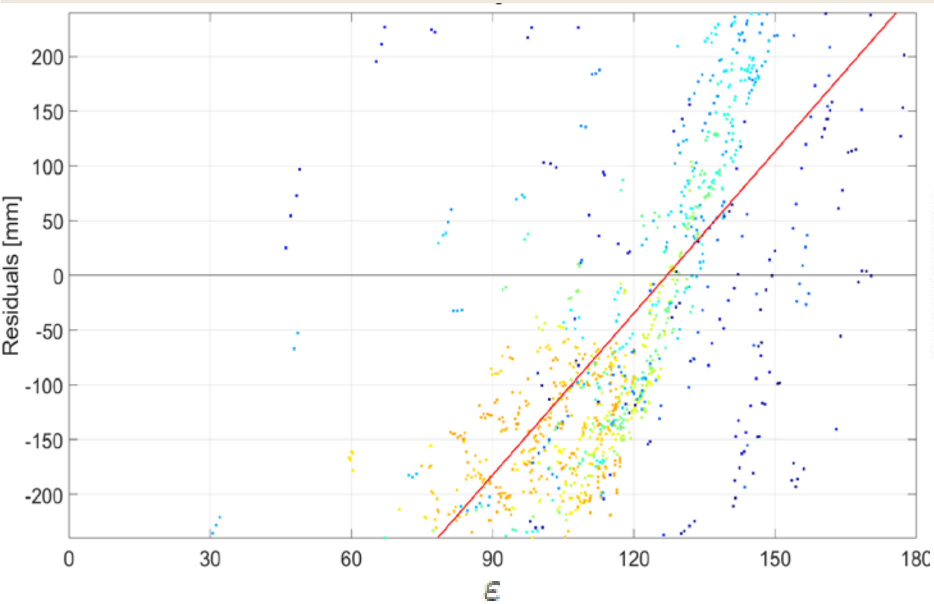
Galileo 101-104
(84 CCRs)



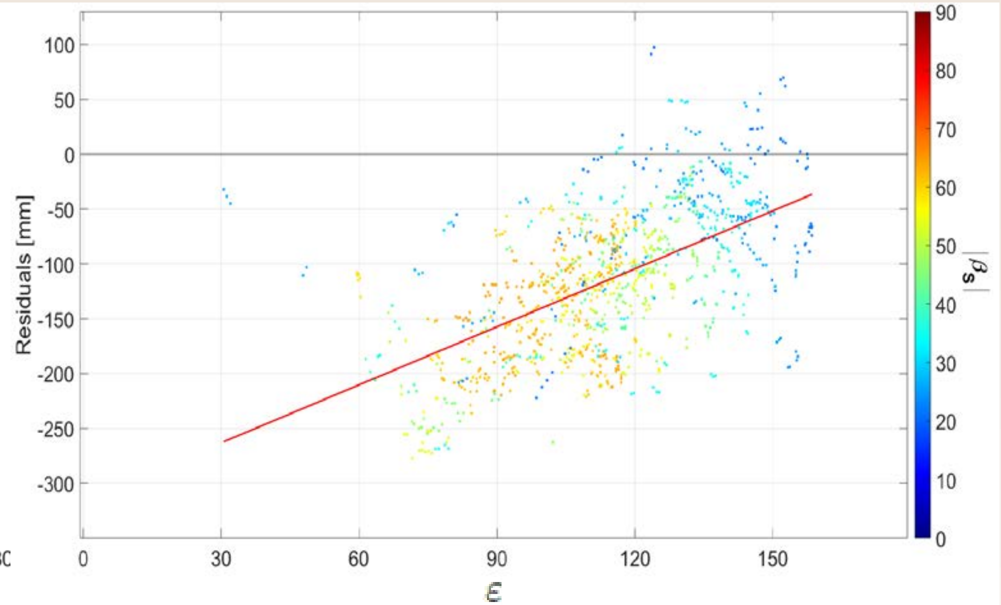
Galileo 201-204
(60 CCRs)

QZSS/QZS-1 (J01)

Old ECOM



New ECOM



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