An Empirical SRP Model for the Orbit Normal Mode

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Introduction

The Center for Orbit Determination in Europe (**CODE**) is contributing to the IGS Multi-GNSS Extension (**MGEX**) since its start in 2012 with an orbit and clock solution. CODE`s MGEX (**COM**) product includes the satellite systems GPS, GLONASS, Galileo, BeiDou2 (BDS2), and QZSS. GEO satellites are not included, so far.
The ECOM2 solar radiation pressure (**SRP**) model, used for all satellites in the COM solution, has been designed for yaw-steering (**YS**) attitude. Consequently, the orbit quality was degraded for BDS2 and QZS-1 spacecrafts (**SC**) at times when operating under orbit-normal (**ON**) attitude, i.e., during or close to eclipse seasons.

Here we introduce a family of empirical SRP models taylored for the ON-mode, which can either be used on top of an a priori SRP model or as a stand-alone model.

SRP in YS- and ON-modes

Features of the YS attitude mode are:
- solar panel (**SP**) plane is always parallel to the terminator plane and normal to the vector Sun => satellite (**D**)
- SC`s Y-sides are never illuminated (Y=0, apart from Y-bias)
- SC body (+Z, -Z, +X panels) causes an SRP signal, which is periodic w.r.t. the argument of latitude difference betw. SC and Sun (**Δu**)
- rapid noon/midnight turns for small elevation angles (**β**) of the Sun w.r.t. the orbital plane

Features of the ON attitude mode are:
- no noon and midnight turns
- SP-normal (**SPN**) deviates from the vector D by the β-angle
- power generation is reduced compared to the YS-mode
- SRP due to SP can be absorbed by 2 SRP parameters, which are constant w.r.t. Δu, but not w.r.t. β
- all panels of SP body can be illuminated - causing periodic SRP signals w.r.t. Δu and β

Attitude Modes

Most GNSS SCs are oriented with YS attitude. Some BDS2 satellites and QZS-1 switch to ON attitude for small elevation angles β of the Sun w.r.t. the orbital plane. All GEO spacecrafts maintain the ON attitude permanently.

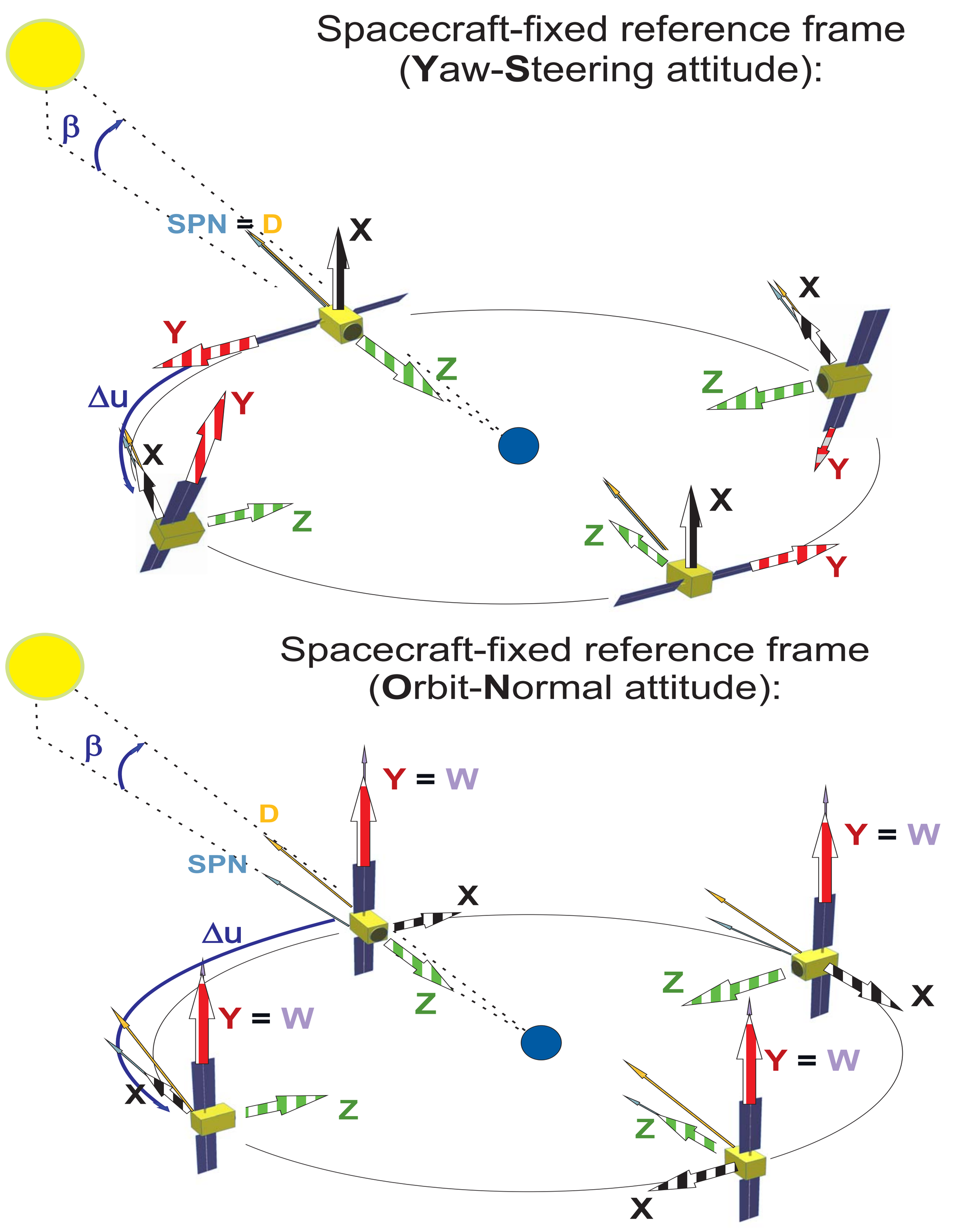


Fig. 1: Satellite-fixed ref. frames under YS- and ON-mode.

ECOM SRP Model Frames

During YS-mode the co-rotating **ECOM** decomposition is practical (SRP due to solar panels absorbed by one coeff.; Y=0). For ON-mode non-rotating frames are better suited (e.g., frames fixed to local orbit or orbital plane). We use the Terminator System Decomposition (**TERM**).

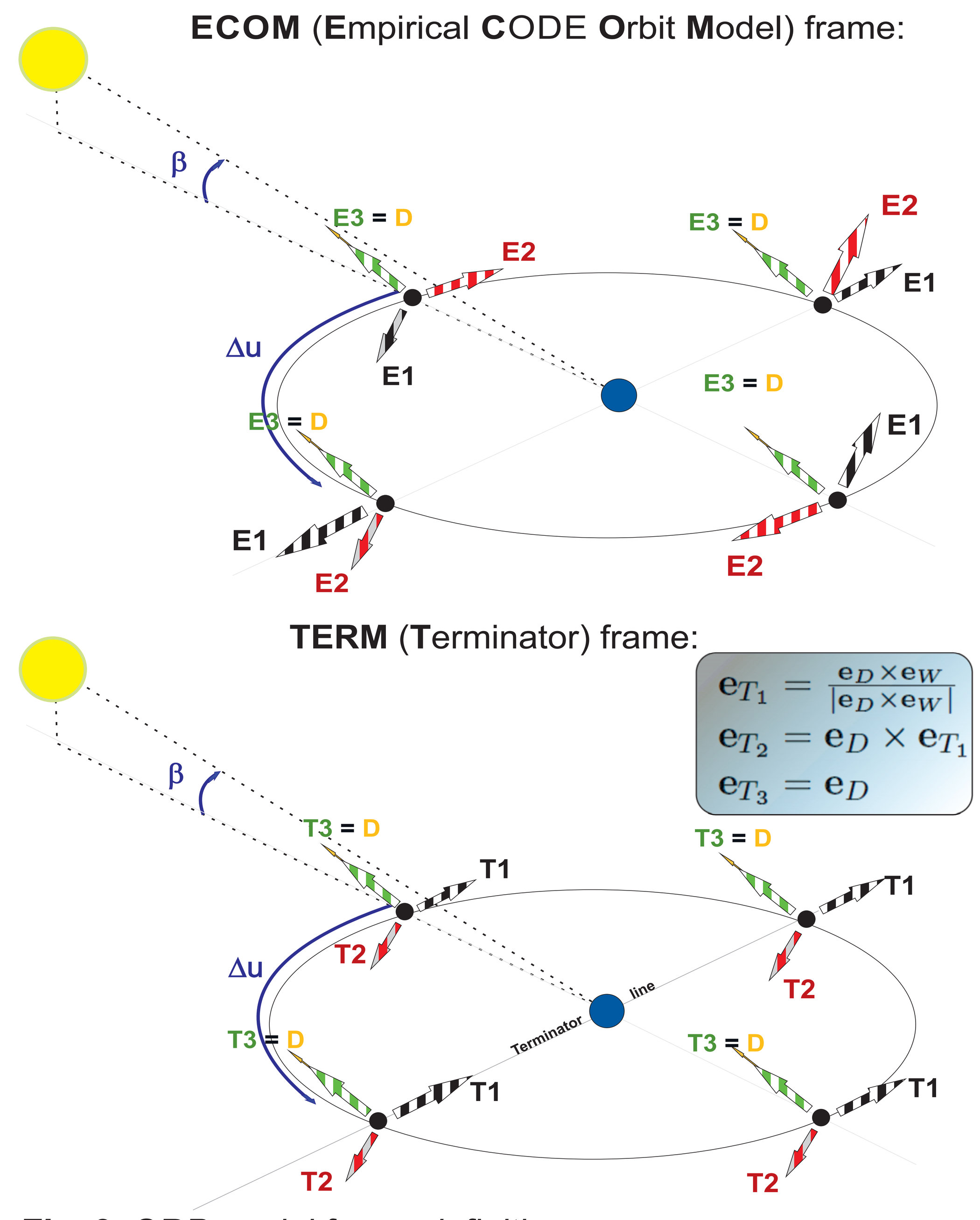


Fig. 2: SRP model frame definition.

SRP Simulation for ON

Simulations based on released meta data of QZS-1 have been performed separately for SP and SC body. Simulated SRP acceleration has been projected into the terminator reference frame (**TERM**, Fig. 2). Coefficients of significant size have been selected for **ECOM-T** (Δu) and **ECOM-TB** (Δu, β) - empirical SRP models for the ON-mode.

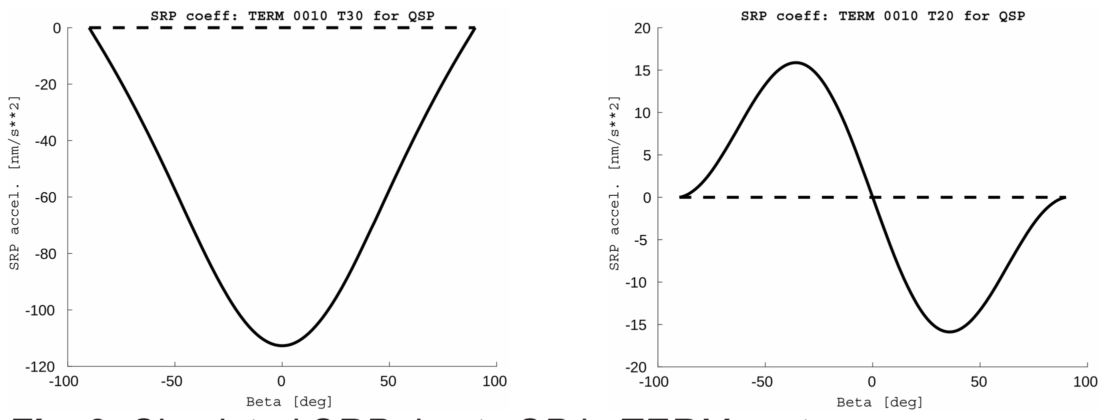


Fig. 3: Simulated SRP due to SP in TERM system.

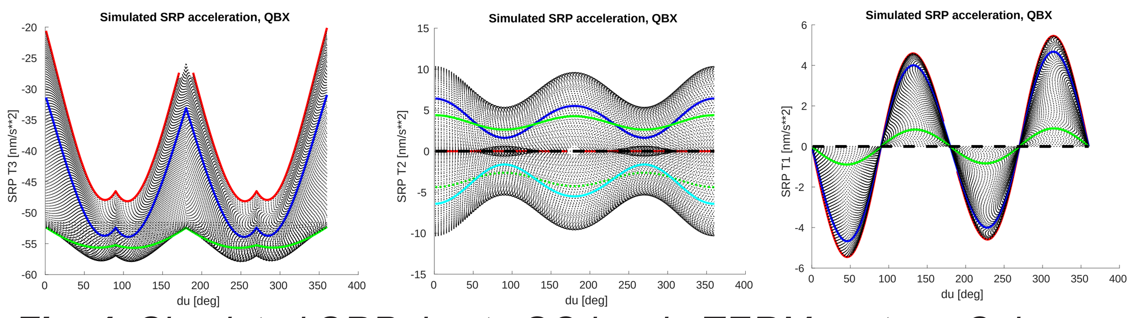


Fig. 4: Simulated SRP due to SC box in TERM system. Colors represent following β-angles: green, dotted: -80°, cyan: -30°, red: 0°, blue: +30°, green, solid:+80°.

Definition of ECOM-TBM

- version with just 2 SRP parameters covering SRP due to SP:

$$\begin{aligned} T3(\Delta u,\beta) &= \mathbf{T30C1b}\cos\beta \\ T2(\Delta u,\beta) &= \mathbf{T20S2b}\sin 2\beta \\ T1(\Delta u,\beta) &= 0 \end{aligned}$$

- β can be ignored for short-arcs => **ECOM-TM** (T20, T30)
- SRP due to sat.-body may be absorbed by stochastic orbit parameters (**ECOM-TBMP**) or by an a priori box model

Definition of ECOM-TB

- SRP acceleration during ON described in TERM system as ...

$$\mathbf{a} = \mathbf{a}_0 + T1(\Delta u,\beta)\,\mathbf{e}_{T_1} + T2(\Delta u,\beta)\,\mathbf{e}_{T_2} + T3(\Delta u,\beta)\,\mathbf{e}_{T_3}$$

- ... by 9 SRP parameters:

$$\begin{aligned} T3(\Delta u,\beta) &= \mathbf{T30C1b}\cos\beta && + \mathbf{T3C2uC1b}\cos 2\Delta u\cos\beta \\ & && + \mathbf{T3S2uC1b}\sin 2\Delta u\cos\beta \\ & && + \mathbf{T3C4uC1b}\cos 4\Delta u\cos\beta \\ & && + \mathbf{T3S4uC1b}\sin 4\Delta u\cos\beta \\ T2(\Delta u,\beta) &= \mathbf{T20S3b}\sin 3\beta && + \mathbf{T2C2uS2b}\cos 2\Delta u\sin 2\beta \\ & && + \mathbf{T2S2uS2b}\sin 2\Delta u\sin 2\beta \\ T1(\Delta u,\beta) &= && \quad\ \mathbf{T1S2uC1b}\sin 2\Delta u\cos\beta \end{aligned}$$

- β-dependency can be ignored for short-arcs => **ECOM-T**
- stochastic orbit parameters (i.e., pulses or accelerations) can be added optionally => **ECOM-TBP**

Validation of QZS-1

- Simulated and estimated SRP coefficients have comparable characteristics (apart from singularities) and show little variations from day to day:

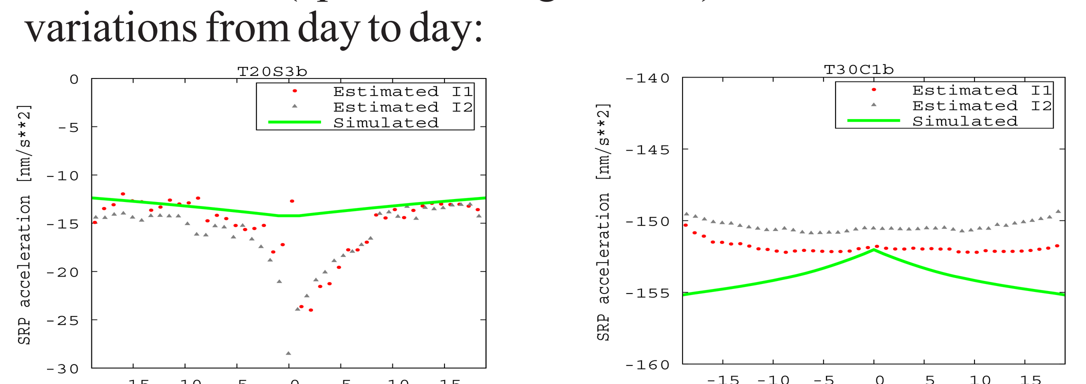


Fig. 5: Simulated vs. estimated coefficients of ECOM-TB referring to different ON-periods I1 and I2 in 2015.

- clear improvement of QZS-1 orbits and clocks:

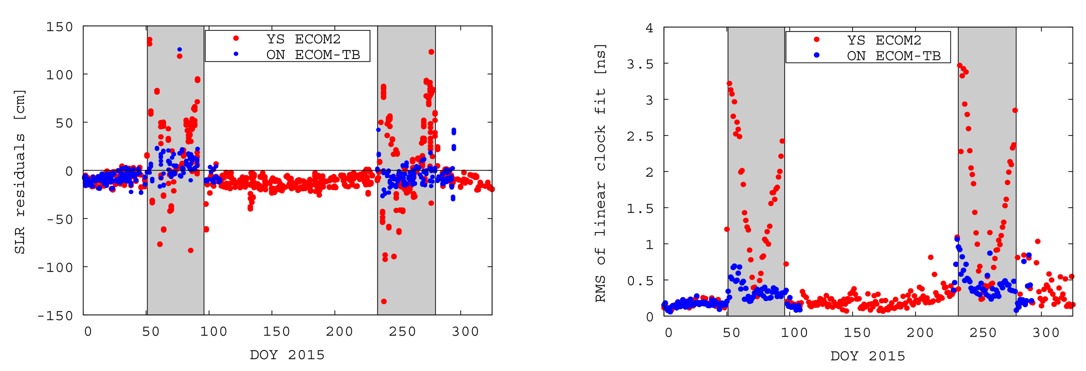


Fig. 6: Orbit and CLK-valid. of 2015 ECOM2 or ECOM-TB.

- agreement with external QZF orbit solution improves:

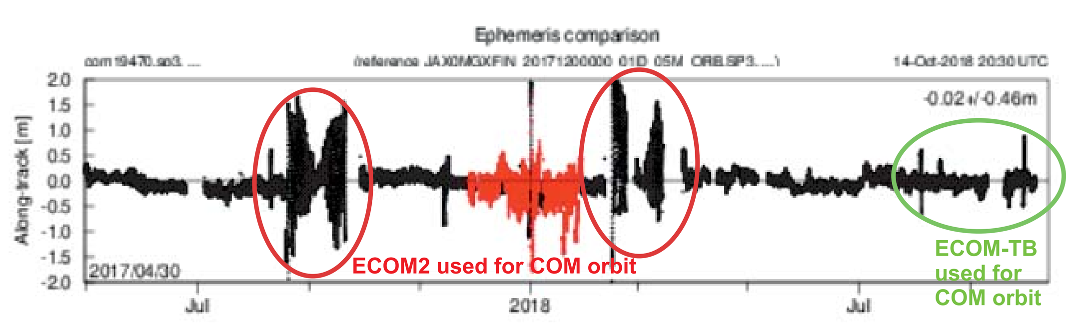


Fig. 7: QZS-1 orbit comparison betw. COM and QZF ACs (screenshot taken from http://mgex.igs.org/analysis)

Validation of BDS2

- smallest deviation of SRP coefficients from assumed values observed for MEOs, shorter orbit arcs, and ECOM-TBM(P)
- for IGSOs the periodic SRP coefficients are not well enough determined to represent the orbit over longer periods, which affects the remaining parameters:

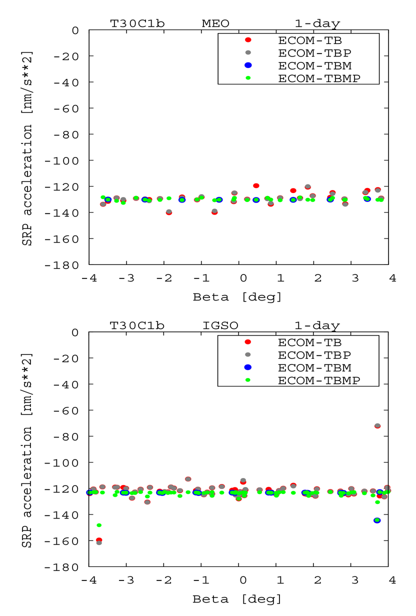
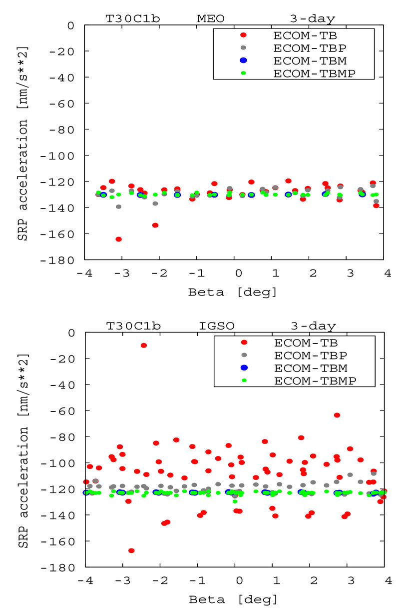


Fig. 8: SRP coefficient T30C1b of different ECOM-TB versions for BDS2 MEOs (top) and IGSOs (bottom) with 1- (left) vs. 3-day arcs



- consequently, the orbits are degraded as well in case the full ECOM-TB is used for long-arc POD of BDS2 IGSOs:

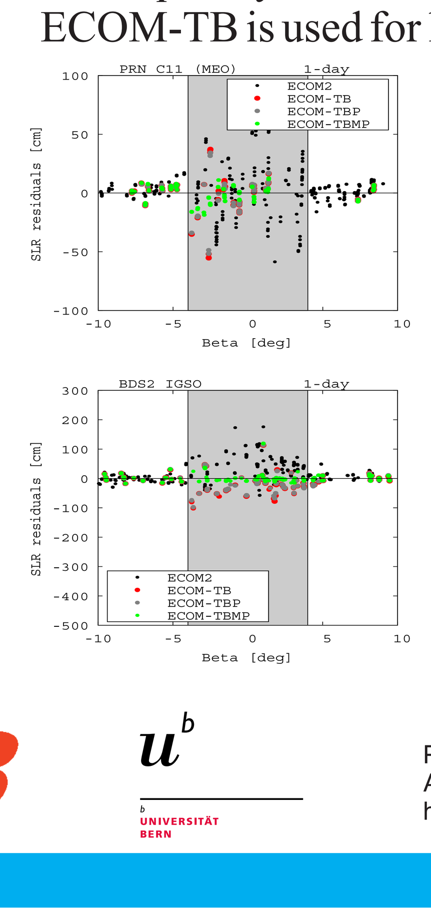
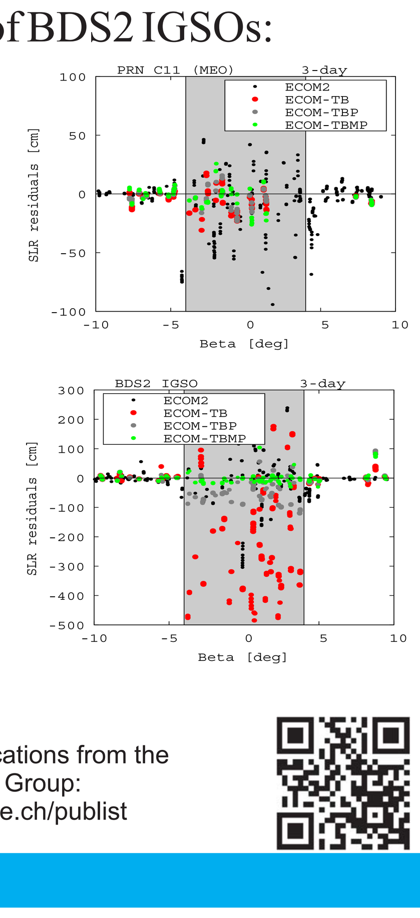


Fig. 9: SLR-validation of BDS2 MEOs (top) and IGSOs (bottom) with 1- (left) vs. 3-day arcs (right).



Validation-Summary and Conclusions

- **QZS-1: ECOM-TB** is a suitable stand-alone SRP model
- **BDS2 MEO**: addition of pulses (=>**ECOM-TBP**) or of an a priori box model is recommended
- **BDS2 IGSO**: periodic SRP coefficients cannot be estimated for long-arc orbits with current network and orbit model (=> use **ECOM-TBMP** or ECOM-TBM + an a priori box model)

*Tab. 1: Results of orbit validation with SLR residuals (**SLR**), RMS of linear sat. clock fit (**CLK**), orbit misclosures (**OMC**), and 3-day long-arc fit ( )**ORB-fit** for BDS2 IGSO (**BI**), BDS2 MEO (**BM**), and QZS-1 (**Q1**) satellites with different SRP models during ON-periods in 2014 and 2015.*

Vali.-Method	SLR, IQR [cm]			CLK-fit, median [ns]			OMC, median [cm]			ORB-fit, med. [cm]		
Sat.-System	BI	BM	Q1	BI	BM	Q1	BI	BM	Q1	BI	BM	Q1
ECOM2	20.5	21.0	62.0	1.72	1.61	1.43	55.9	29.2	42.4	23.0	10.1	14.1
ECOM-TB	-	-	15.2	-	-	0.35	-	-	14.2	-	-	5.6
ECOM-TBP	-	12.2	-	-	0.69	-	-	9.8	-	-	6.8	-
ECOM-TBMP	12.2	-	-	0.72	-	-	27.1	-	-	44.0	-	-

Possible reasons for reduced performance of ECOM-TB for BDS2:
- sampling problem for periodic SRP coefficients due to poor observation coverage over East Asia (affecting IGSOs more than globally observed MEOs; see Fig. 10)
- open questions regarding BDS orbit model (meta data!)

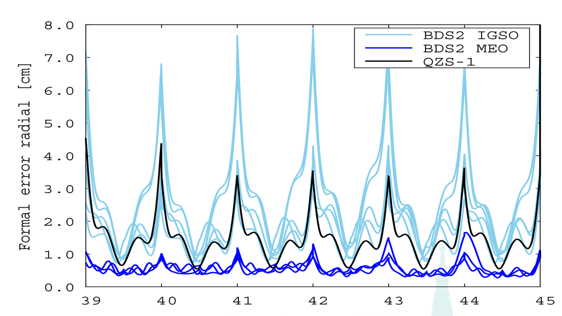


Fig. 10: Formal radial orbit error of QZS-1, BDS2 MEOs, and BDS2 IGSOs in early 2015 (YS and ECOM2 applied to all).

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Reference to COM products

Prange, L.; Arnold, D.; Dach, R.; Schaer, S.; Sidorov, D.; Stebler, P.; Villiger, A.; Jäggi, A. (2018). CODE product series for the IGS MGEX project. Published by Astronomical Institute, University of Bern.
URL: http://www.aiub.unibe.ch/download/CODE_MGEX;
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