Empirical SRP model for the orbit normal attitude mode

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Introduction

- CODE MGEX (COM) orbit and clock solution since 2012 (see doi: 10.1007/s00190-016-0968-8 for description; changes from 2015 on summarized in next IUGG report); SRP model: ECOM2
- BeiDou2 (BDS2) MEO+IGSO since late 2013; QZSS since early 2014
- BDS2 and QZS-1: Orbit-Normal (ON) attitude during eclipses
- ECOM models designed for Yaw-steering (YS); not suitable for ON-mode (⇒ very poor orbit quality during ON periods)
- Other groups: ECOM plus box-wing a priori model (Montenbruck et al. 2017, Zhao et al. 2018) for individual satellites or additional along-track acceleration parameters (e.g., Guo et al. 2017)
- Our goal: definition of an ECOM suitable for the ON-mode (to be used stand-alone or together with an a priori model)

Attitude modes of GNSS satellites

GNSS	YS	Ecl. law (small β)	ON	Other
GPS	X	x		
GLONASS	X	x		
Galileo	X	x		
BDS2 MEO, IGSO	X	x	x ($\lvert\beta\rvert < 4°$)	
BDS3 MEO, IGSO	X	x		
QZSS IGSO	X	x	x ($\lvert\beta\rvert < 17°$)	
IRNSS				X
GEO (SBAS, BDS, QZSS, non GNSS)			X	

(see doi 10.1016/j.asr.2015.06.019 for detailed information)

- MEO and IGSO satellites (BDS2, QZS-1): ON-mode is a special case of an eclipse attitude law (applied to avoid rapid noon and midnight turns at small β-angles)
- GEO satellites keep ON permanently ($\lvert\beta\rvert < (23.5° + i)$)

Solar Radiation Pressure (SRP) - definitions

SRP acceleration due to illumination of a surface (without re-radiation) according to Milani (1987):

$$a_{tot} = \boldsymbol{a}_{\alpha} + \boldsymbol{a}_{\rho} + \boldsymbol{a}_{\delta}$$

$\boldsymbol{a}_{\alpha} = -PF \cos\theta \, \alpha \boldsymbol{e}_D$	absorption (coeff. α)
$\boldsymbol{a}_{\rho} = -PF \, 2\cos^2\theta \, \rho \boldsymbol{e}_{SN}$	specular reflection (coeff. ρ)
$\boldsymbol{a}_{\delta} = -PF \cos\theta \, (\delta \boldsymbol{e}_D + \frac{2}{3}\delta \boldsymbol{e}_{SN})$	diffuse reflection (coeff. δ)

with

PF:	Pre-factor; function of solar flux, speed of light, AMR
$\boldsymbol{e}_D$:	Unit vector in Sat.-Sun direction
$\boldsymbol{e}_W$:	Unit vector normal to orbital plane
$\boldsymbol{e}_{SN}, \boldsymbol{e}_{SPN}$:	Unit vectors normal to surface i and to solar panel
θ:	Angle enclosed by $\boldsymbol{e}_D$ and $\boldsymbol{e}_{SN}$
β:	Elevation of the Sun above the orbital plane
Δu:	Difference between arguments of latitude of SC and Sun

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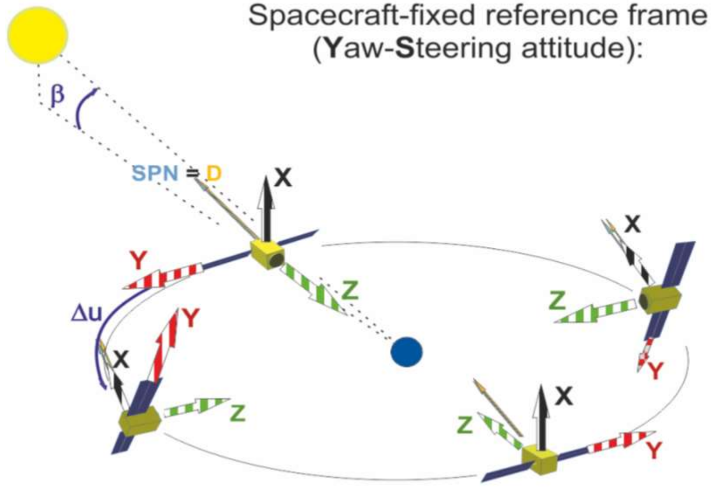
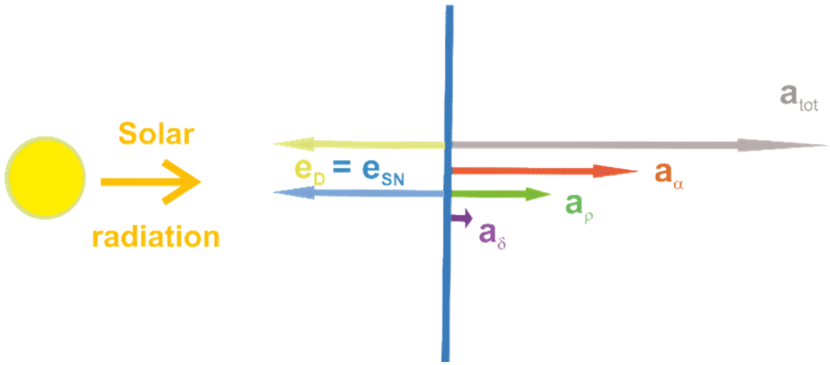
SRP during YS mode

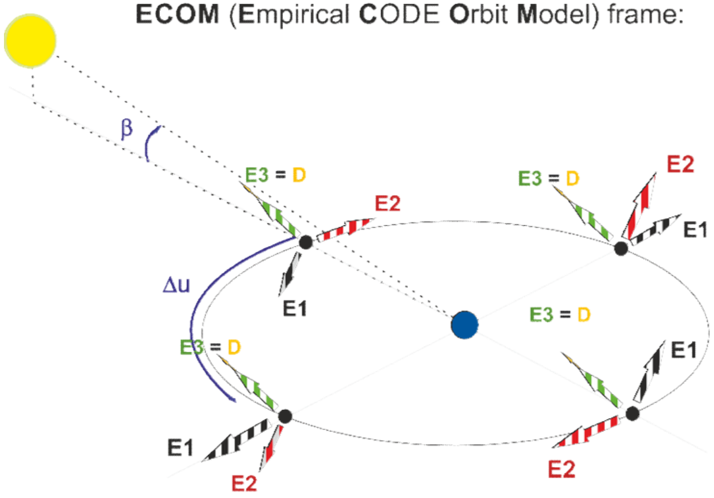
Spacecraft-fixed reference frame (**Y**aw-**S**teering attitude):



Acceleration due to solar radiation (Yaw-Steering attitude):



ECOM (**E**mpirical **CODE** **O**rbit **M**odel) frame:



- Solar panel (SP) plane is always parallel to the terminator plane and normal to the vector Satellite-Sun (D) (⇒ θ = 0)
- SRP due to SP: covered by one parameter in D
- SC`s Y-sides: are never illuminated (⇒ E2=0; exception: Y-bias)
- SC body (+Z, -Z, +X panels): causes additional SRP signal, periodic w.r.t. Δu in D and E1

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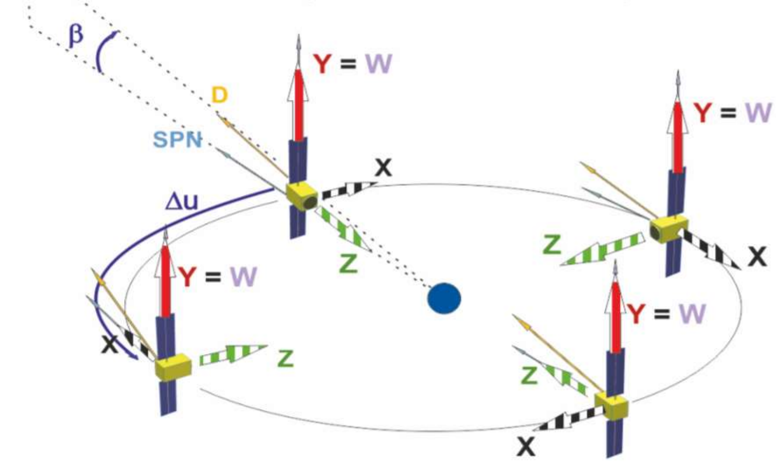
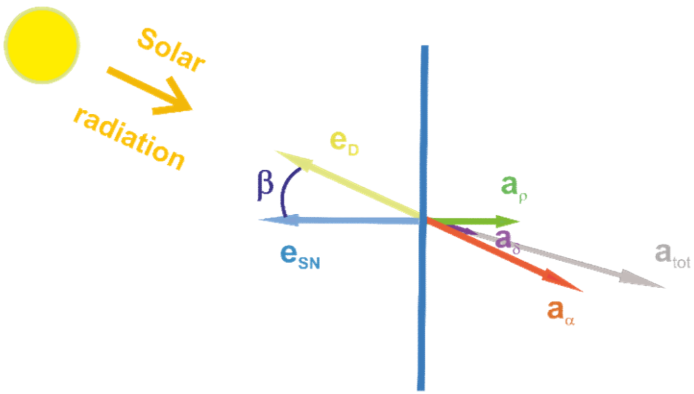
SRP during ON mode

Spacecraft-fixed reference frame (Orbit-Normal attitude):



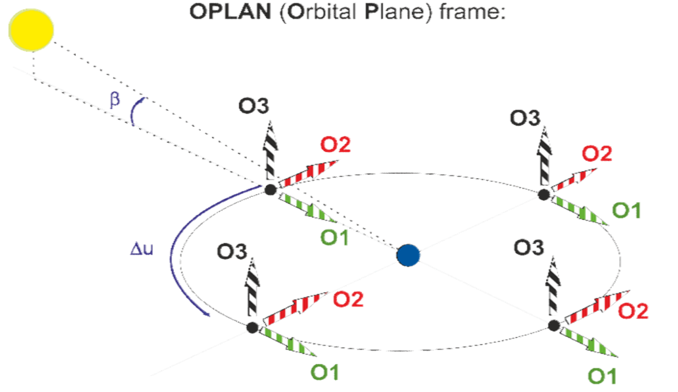
Acceleration due to solar radiation (Orbit-Normal attitude):



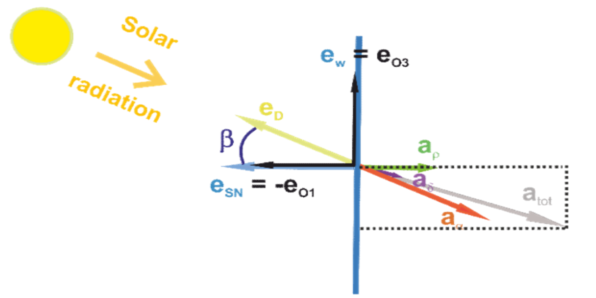
- SP-normal (SPN) deviates from the vector D (⇒ θ ≈ β)
- Power generation and SRP (a_{tot}) reduced - compared to the YS-mode
- SRP force vector due to SP is in the plane spanned by D, Y, and SPN (if all energy would be absorbed, the vector would point in -D direction)
- SRP due to SC body causes additional SRP signal, which is periodic w.r.t. Δu and β

Coordinate systems for modelling SRP

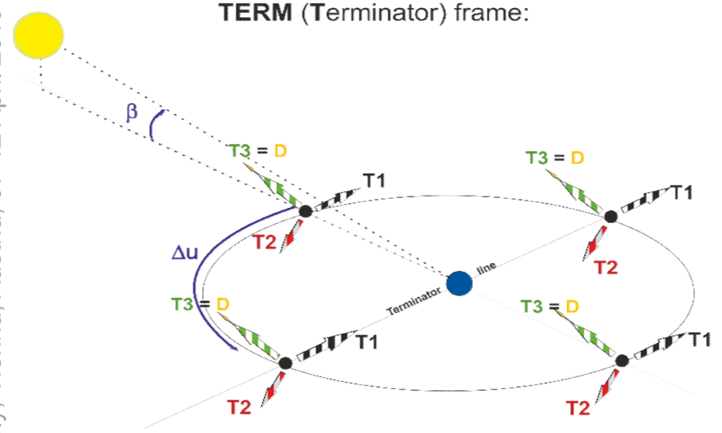
OPLAN (**O**rbital **Plan**e) frame:



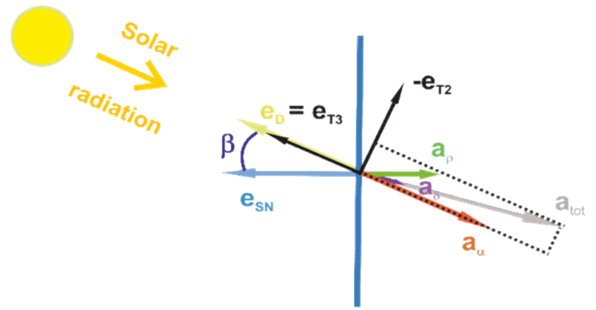
Acceleration due to solar radiation (Orbit-Normal attitude), and its projection into an Orbital Plane Fixed Reference Frame (OPLAN)



TERM (**T**erminator) frame:



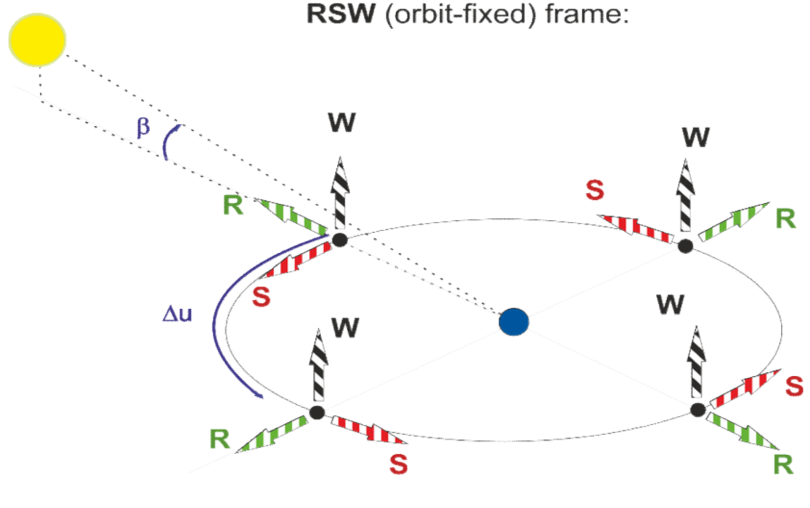
Acceleration due to solar radiation (Orbit-Normal attitude), and its projection into the Terminator Reference Frame (TERM)

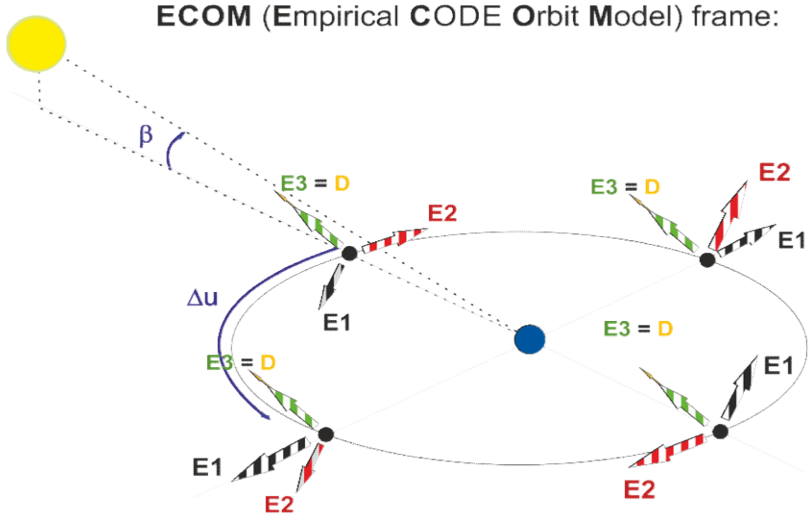


$$\mathbf{e}_{T_1} = \frac{\mathbf{e}_D \times \mathbf{e}_W}{|\mathbf{e}_D \times \mathbf{e}_W|}$$
$$\mathbf{e}_{T_2} = \mathbf{e}_D \times \mathbf{e}_{T_1}$$
$$\mathbf{e}_{T_3} = \mathbf{e}_D$$

- SRP due to SP can be absorbed by 2 parameters, which are constant w.r.t. Δu, but not w.r.t. β ⇒ both frames are suitable in practice
- TERM better suited for physical interpretation (T2 component depends solely on reflected solar radiation)

Coordinate systems for modelling SRP





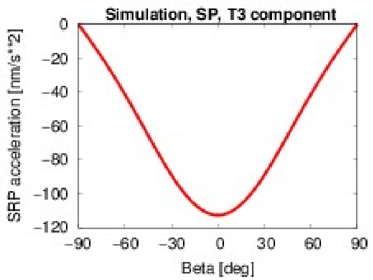
- OPLAN is special case of RSW
- TERM is special case of ECOM
- Difference: frame rotation ⇒ in RSW and ECOM one of the constant components is split up into two components, which are periodic w.r.t. β and Δu, respectively
  ⇒ more complex
- SRP due to SC bus is adding to it
- ECOM-frame offers at least operational advantages: the same basic ECOM model could be used for YS and ON modes ⇒ model switch by adding/removing constraints on the additional E2-parameters; physical interpretation of periodic E2-coeff. would be same as for T2

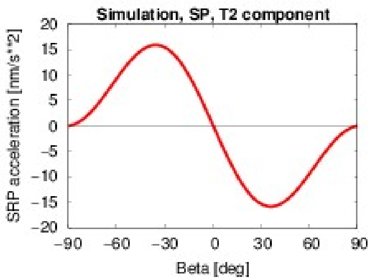
SRP simulation

- Simulation of SRP (based on Milani, 1987) for SP and SC body separately with varying Δu and β angles
- Data basis: QZS-1 meta data released by Cabinet Office, Government of Japan (2017) and by Montenbruck (2017)
- Projection into different possible SRP model frames (RSW, ECOM, TERM, OPLAN); final decision in favor of TERM
- Fit of simulated accelerations with truncated Fourier series and selection of significant coefficients

ECOM-TM:
- Minimal parameterization for SP only
- β slowly changing in time ⇒ param. not constant ⇒ not suited for long arcs

T3(Δu) = **T30**
T2(Δu) = **T20**
T1(Δu) = 0



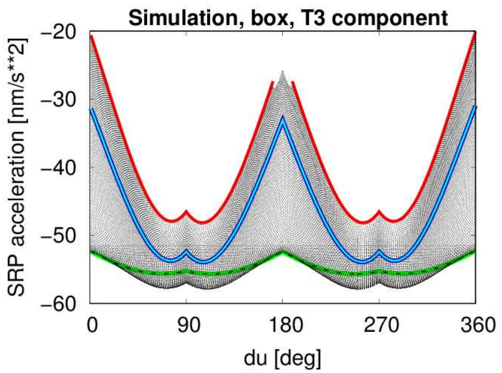


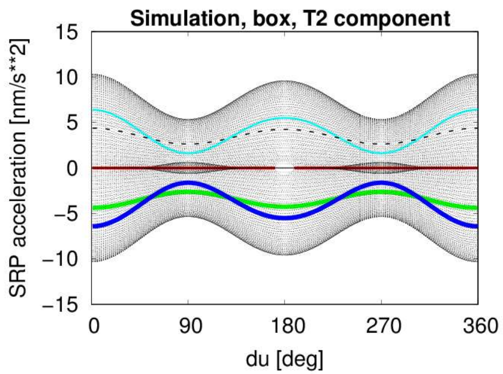
$$T3(\Delta u, \beta) = \mathbf{T30C1b} \cos\beta$$
$$T2(\Delta u, \beta) = \mathbf{T20S2b} \sin 2\beta$$
$$T1(\Delta u, \beta) = 0$$

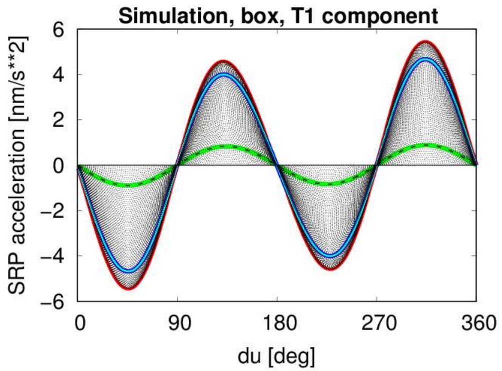
ECOM-TBM:
- ECOM-TM considerung β-dependency ⇒ suitable for long arcs

SRP model definition

SRP acceleration due to the surfaces of the SC body causes more complex signal:







(Colors highlight β-angles: green: -80°, blue: -30°, red: 0°, cyan: +30°, gray, dotted:+80°)

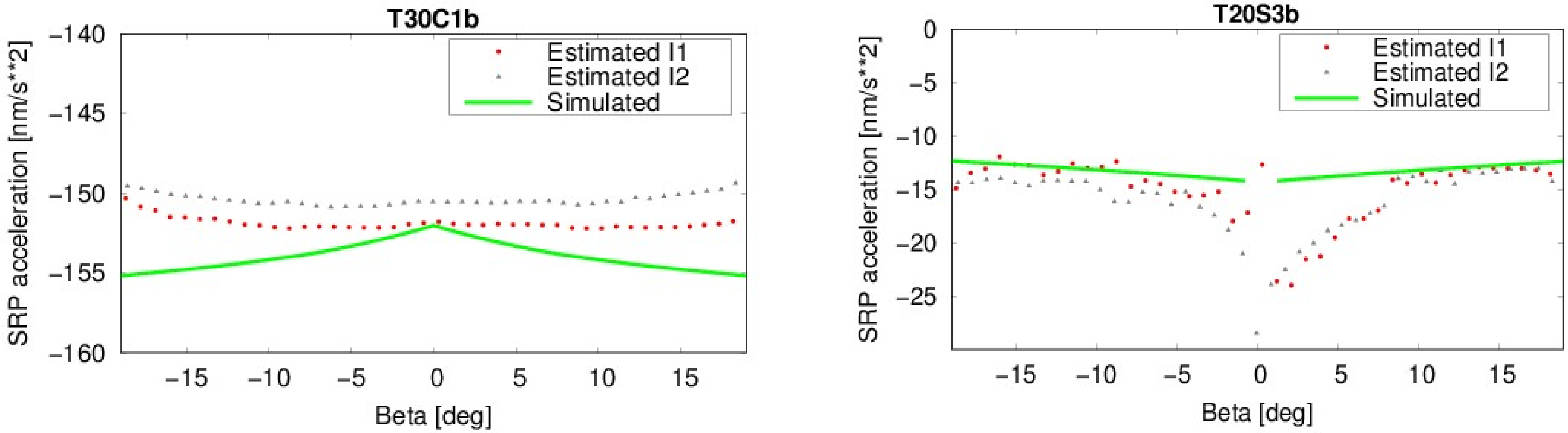
ECOM-TB:

- Full model (covering SP + SC body) with 9 SRP parameters
- Stochastic pulses/accelerations (⇒ ECOM-TBP) or an a priori model may be added

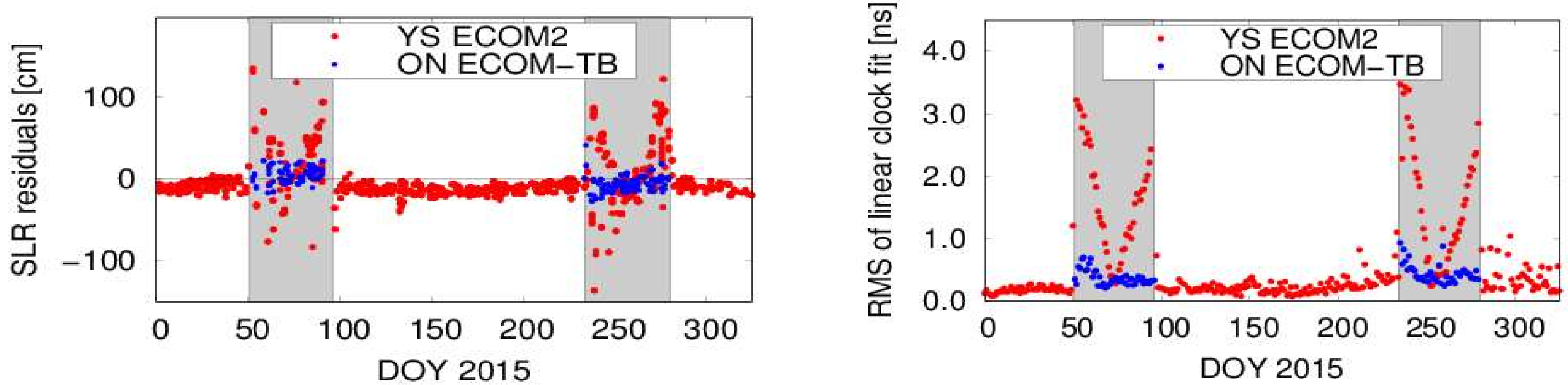
$$
\begin{aligned}
T3(\Delta u, \beta) &= \mathbf{T30C1b}\cos\beta && + \mathbf{T3C2uC1b}\cos 2\Delta u \cos\beta \\
& && + \mathbf{T3S2uC1b}\sin 2\Delta u \cos\beta \\
& && + \mathbf{T3C4uC1b}\cos 4\Delta u \cos\beta \\
& && + \mathbf{T3S4uC1b}\sin 4\Delta u \cos\beta \\
T2(\Delta u, \beta) &= \mathbf{T20S3b}\sin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

Application to POD of QZS-1

Agreement between simulated and estimated (QZS-1) ECOM-TB coefficients:



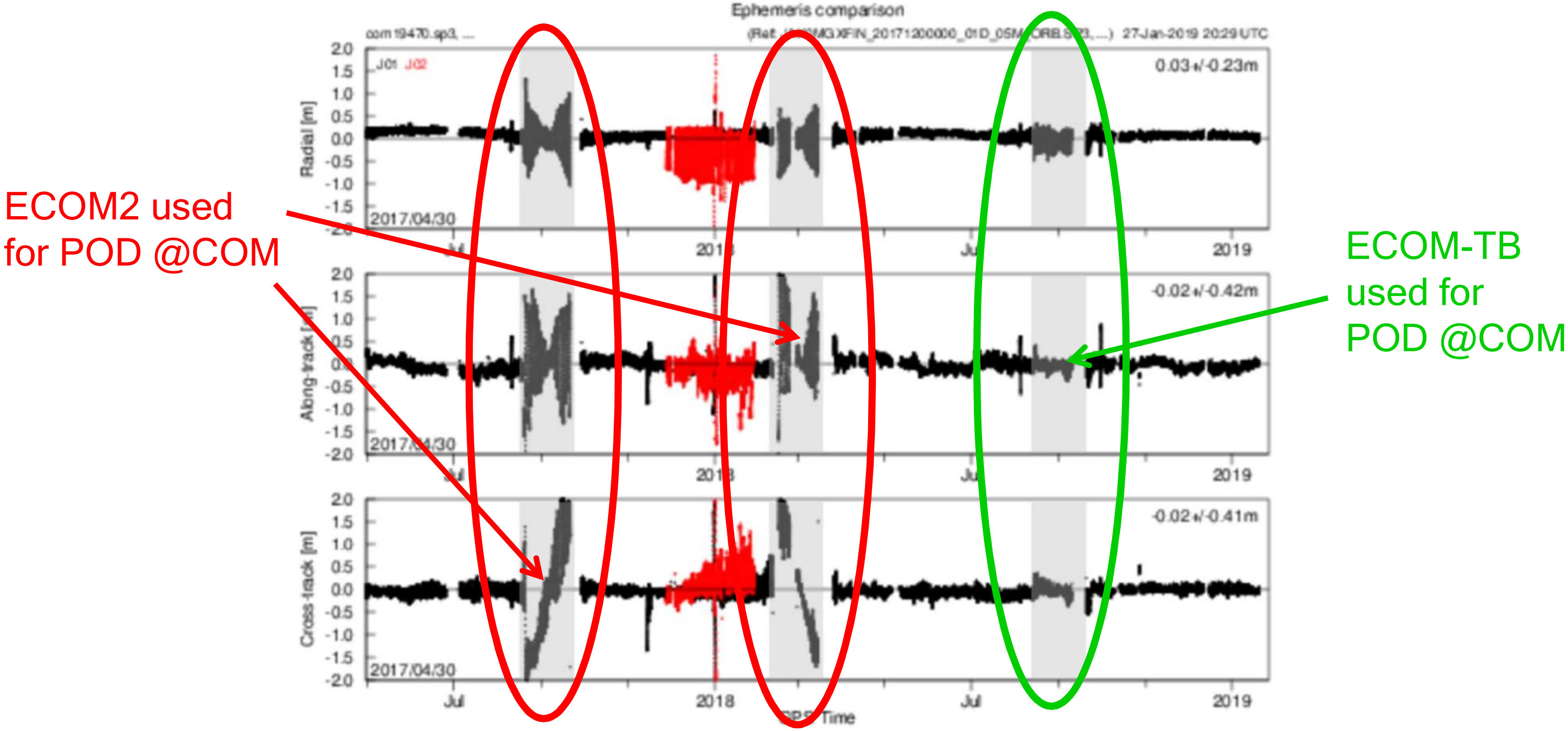
(Time intervals: I1: DOY 357/2014 to 108/2015; I2: DOY 230 - 294/2015)



Significant reduction of SLR residuals and CLK-fit RMS during ON-periods (QZS-1, 3-day long arc solution)

External Validation

Comparison between QZSS orbits (QZS-1 in black) from the MGEX solutions "JAXA" and "COM". Time windows with ON mode are shaded in gray (screenshot taken from http://mgex.igs.org/analysis/):



⇒ Significantly better agreement, since COM replacemed ECOM2 by ECOM-TB

Internal Validation

Orbit validation with SLR residuals (SLR), linear fit of satellite clock corrections (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 late 2014 to late 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	-	-

- QZS-1: improvement by factor of 3 – 4 (ECOM-TB vs. ECOM2)
- BDS2 MEO: improvement by factor 2 with ECOM-TBP (pulses in R,S,W every 12h added)
- BDS2 IGSO: minimal model (2 SRP param., no periodic terms) plus pulses (ECOM-TBMP); improvement by factor 2 over ECOM2 for most validation methods; poor long-arc fit, because model is highly un-physical; difficulties to determine full ECOM-TB in a long arc POD

Summary

- Terminator reference frame (TERM) defined as a suitable coordinate system for empirical modelling of SRP accelerations during ON-mode
- Definition of the ECOM-TB (i.e., an ECOM using the TERM frame and considering the β-angle) model ‘family’
- ECOM-TB performs well for POD of QZS-1
- Problems with POD of BDS2 IGSOs – especially for long-arcs (pulses needed)
- Activated for COM since Summer 2018
- Paper containing model details: submitted to ASR
- Combination with a priori models not yet tested

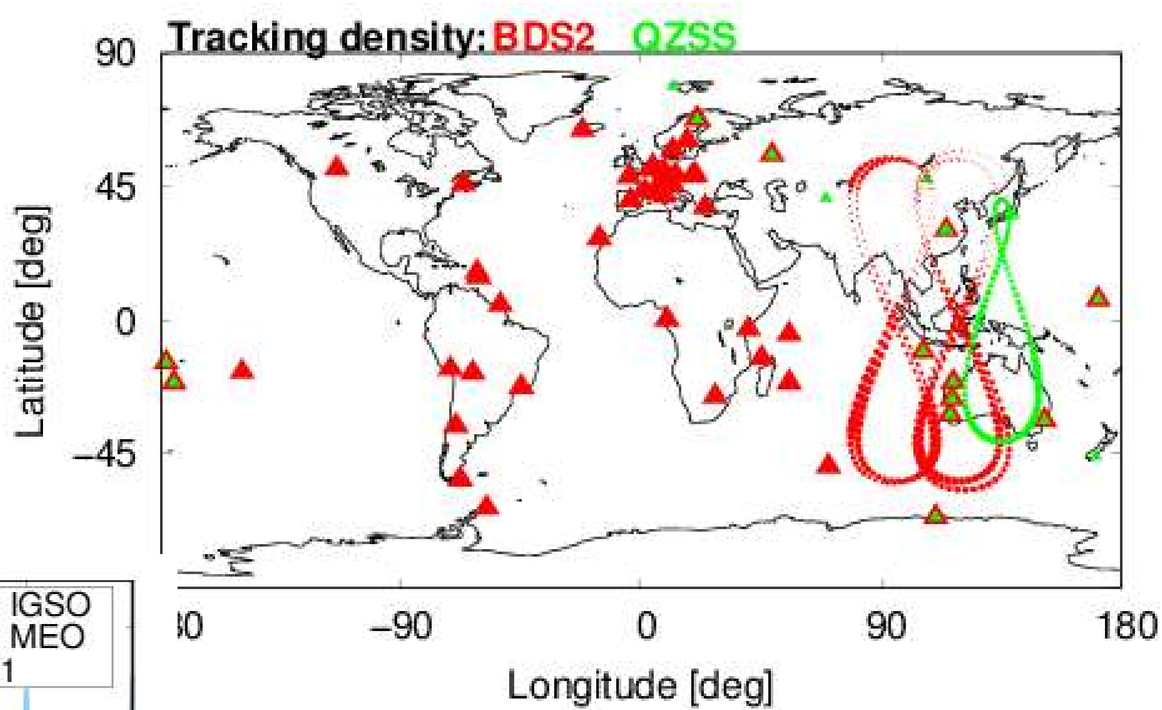
Thank you

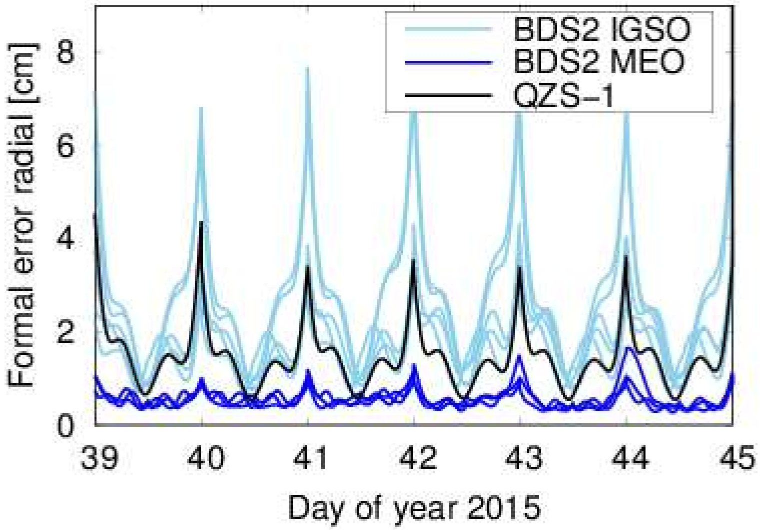
for

your interest!

Orbit errors

Ground stations contributing to and ground-tracks of BDS2 (IGSO) and QZS-1 orbits. The width of the lines corresponds with the number of ground stations with view to the satellite at the given location (elevation cutoff 45°; early 2015).





Formal error of radial orbit component (in cm) of QZS-1, BDS2 MEO, and BDS2 IGSO orbits (YS and ECOM2 applied to all satellites)