Overview of CODE's MGEX solution (with the focus on Galileo)

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- Recent changes of the COM solution
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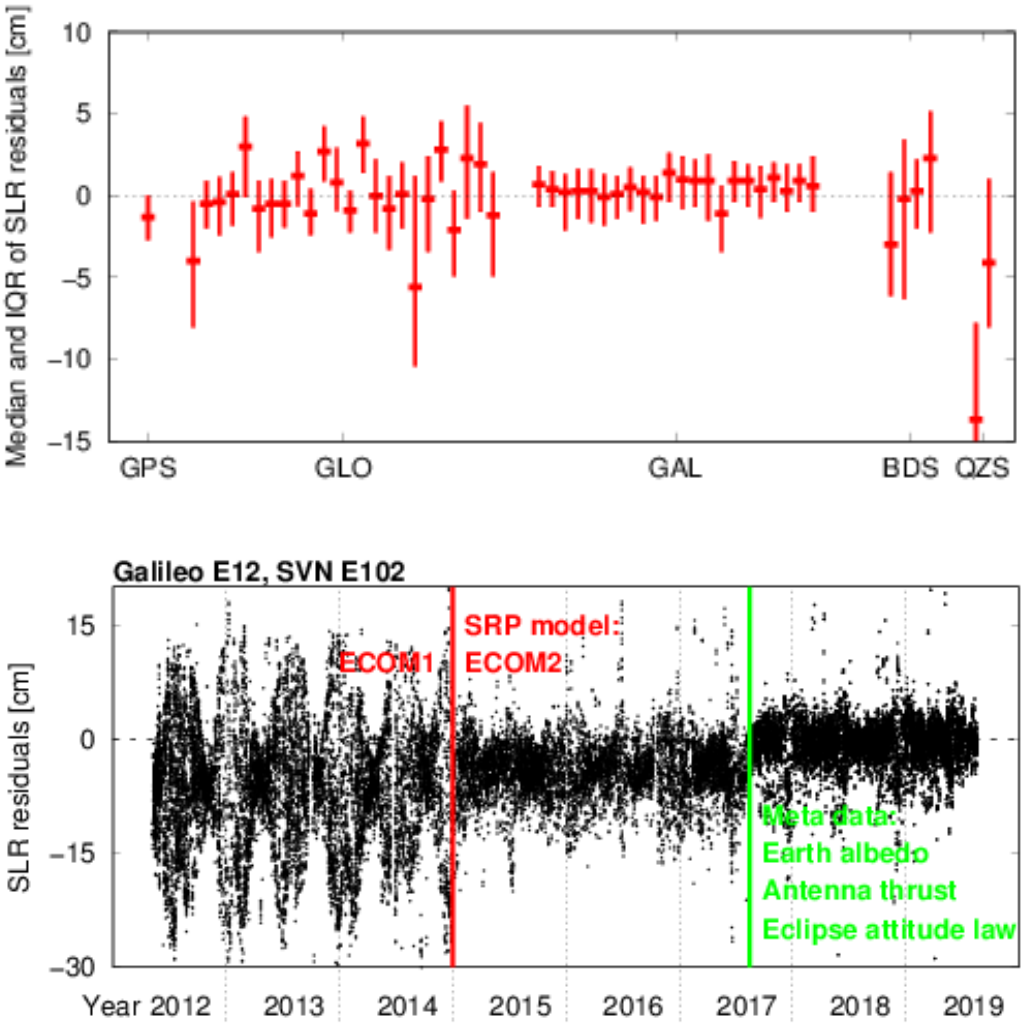
CODE MGEX (COM) orbit solution

GNSS considered:	**GPS + GLONASS + Galileo + BDS2** (MEO+IGSO) + **QZSS** (>90 SV)
Processing mode:	Post-processing (≈2 weeks latency)
Timespan covered:	GPS-weeks 1689 - today
Number of stations:	140 (GPS), 130 (GLONASS), 100 (Galileo); 80 (BDS2); 40 - 50 (QZSS)
Processing scheme:	**Double-difference** network processing (observable: phase double differences; ambiguity-fixed)
Signal frequencies:	L1+ L2 (GPS + GLO+ QZSS); E1 (L1) + E5a (L5) Galileo; B1 (L2) + B2 (L7) BDS2
Orbit characteristic:	3-day long arcs; SRP: ECOM2, ECOM-TB (during ON)
Reference frame:	IGS14
IERS conventions:	IERS2010
Product list:	Daily orbits (SP3; 300s) and ERPs
Distribution:	ftp://cddis.gsfc.nasa.gov/gnss/products/mgex/ and ftp://ftp.aiub.unibe.ch/CODE_MGEX/
Designation:	COD0MGXFIN_YYYYDDD...gz

CODE MGEX (COM) clock solution

GNSS considered:	**GPS + GLONASS + Galileo + BDS2 + QZSS** (>90 SV)
Processing mode:	Post-processing (≈2 weeks latency)
Timespan covered:	GPS-weeks 1710 - today
Number of stations:	140 (GPS), 130 (GLO), 100 (Galileo); 50 (BDS2); 40 (QZSS)
Processing scheme:	**Zero-difference** processing (code+phase undifferenced; ambiguity-fixed for G,E,C,J)
Signal frequencies:	L1+ L2 (GPS + GLO+ QZSS); E1 (L1) + E5a (L5) Galileo; B1 (L2) + B2 (L7) BDS2
A priori information:	Orbits, ERPs, coordinates, and troposphere from CODE MGEX orbit solution introduced as known
Reference frame:	IGS14
IERS conventions:	IERS2010
Product list:	Epoch-wise (30s) clock corrections for satellites and stations in daily CLK-RINEX files; daily observable-specific (OSB) code biases for satellites and stations in BIAS-SINEX-format
Distribution:	ftp://cddis.gsfc.nasa.gov/gnss/products/mgex/ and ftp://ftp.aiub.unibe.ch/CODE_MGEX/

COM orbit validation: SLR residuals

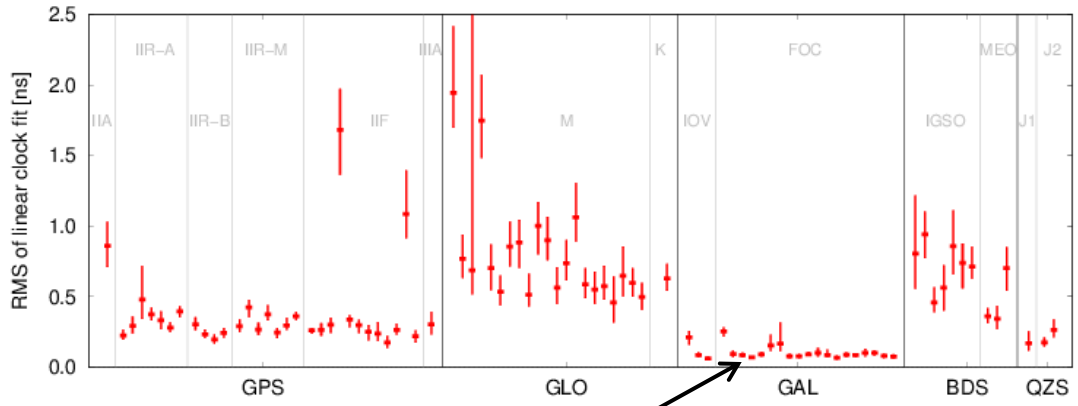


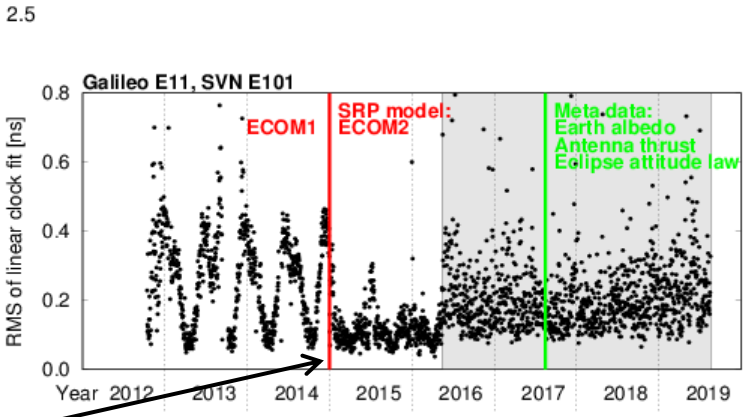
⇒ Galileo POD improved within recent years - thanks to model changes and better tracking

⇒ Disclosure of meta data contributes to orbit improvements (e.g., reduction of SLR offset)

⇒ Galileo meanwhile (2019) best performing «new» GNSS in the COM solution

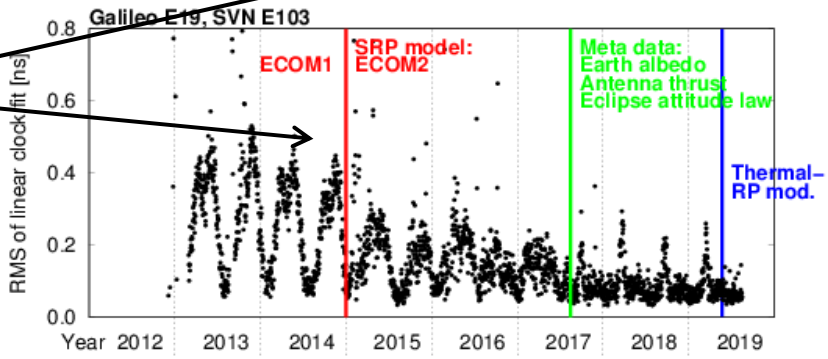
COM clock validation: daily linear fit

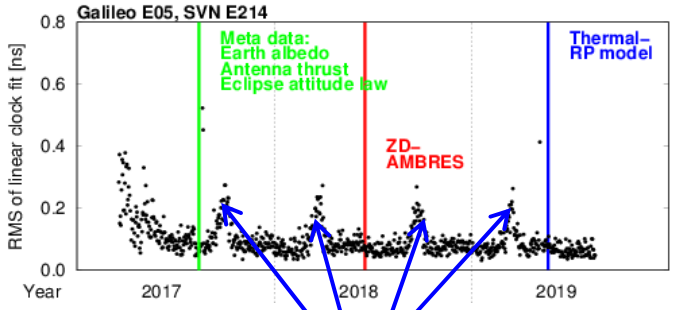




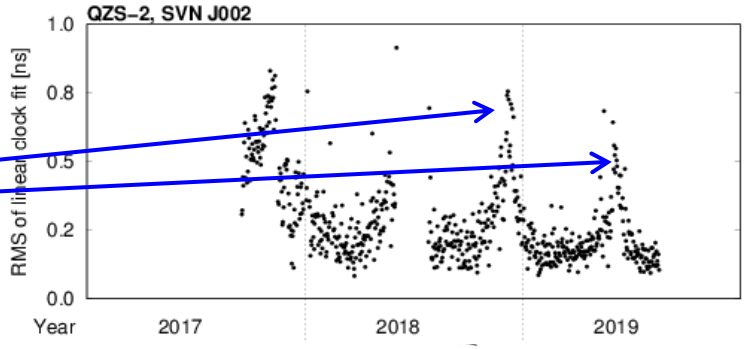
⇒ Excellent performance of Galileo PHM clocks

⇒ allows for orbit validation





⇒ Clock degradation during eclipse seasons shows similar pattern for Galileo FOC and QZSS (thermal radiation?)



Recent changes in the COM solution

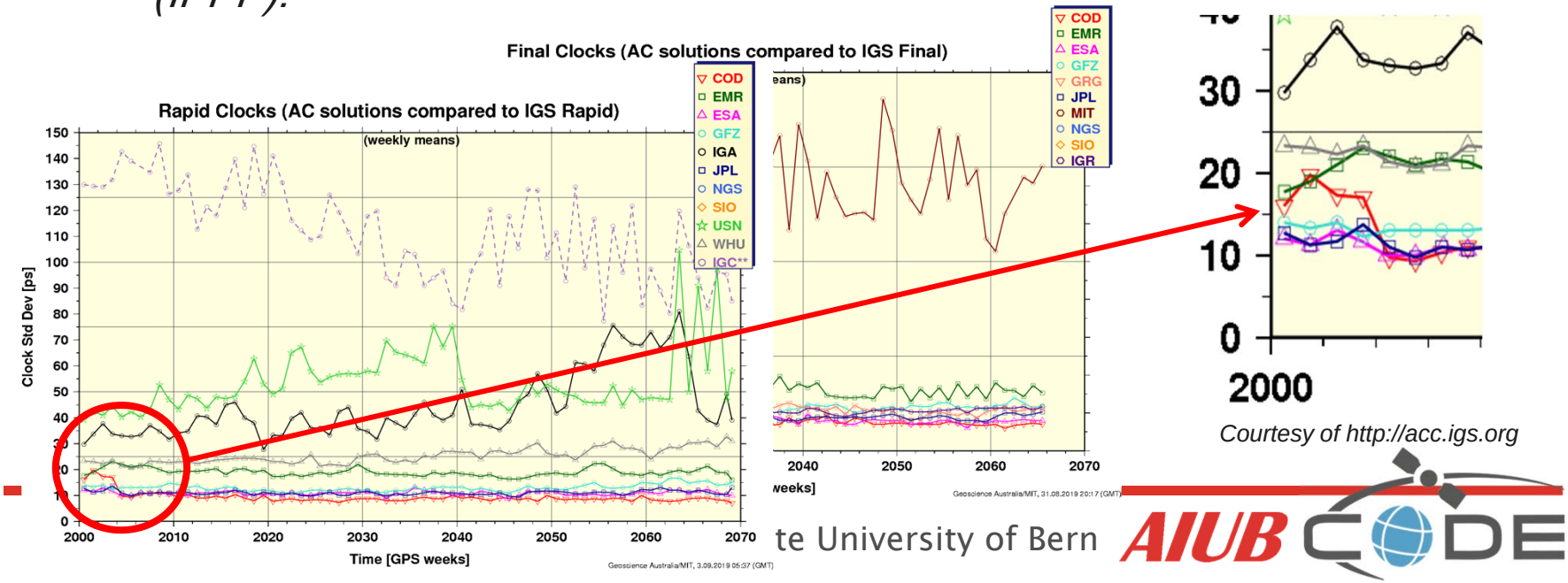
- Observation biases:
  - Observable-specific biases (OSB) ⇒ see Villiger et. al. (2019, doi 10.1007/s00190-019-01262-w)
- Phase ambiguity resolution:
  - DD orbit solution: GPS, Galileo, QZSS, BDS2 (Summer 2017) ⇒ see Schaer et al. (IGS Technical Report 2017)
  - Ambiguity-fixed clocks: GPS, Galileo (2018)
- (Antenna calibrations:
  - Satellite antenna phase center offsets (PCO) of Galileo and QZSS are known ⇒ values are included in IGS14-ANTEX file
  - Ground antenna calibrations available since 2019
  - Switch to new antenna calibrations under investigation)

Recent changes in the COM solution

- Orbit modelling:
  - Eclipse attitude laws for GPS, GLONASS, Galileo (Summer 2017)
  - Earth albedo and transmit antenna thrust applied for GPS, GLONASS, Galileo, QZSS (Summer 2017)
    ⇒ see Prange et al. (IGS Technical Report 2017)
  - Correct consideration of orbit normal (ON) attitude mode for QZS-1 and BDS2 (Summer 2018)
  - Use of ECOM-TB SRP model for satellites with ON attitude (Summer 2018)
  - Empirical thermal radiation model for Galileo satellites (Summer 2019)

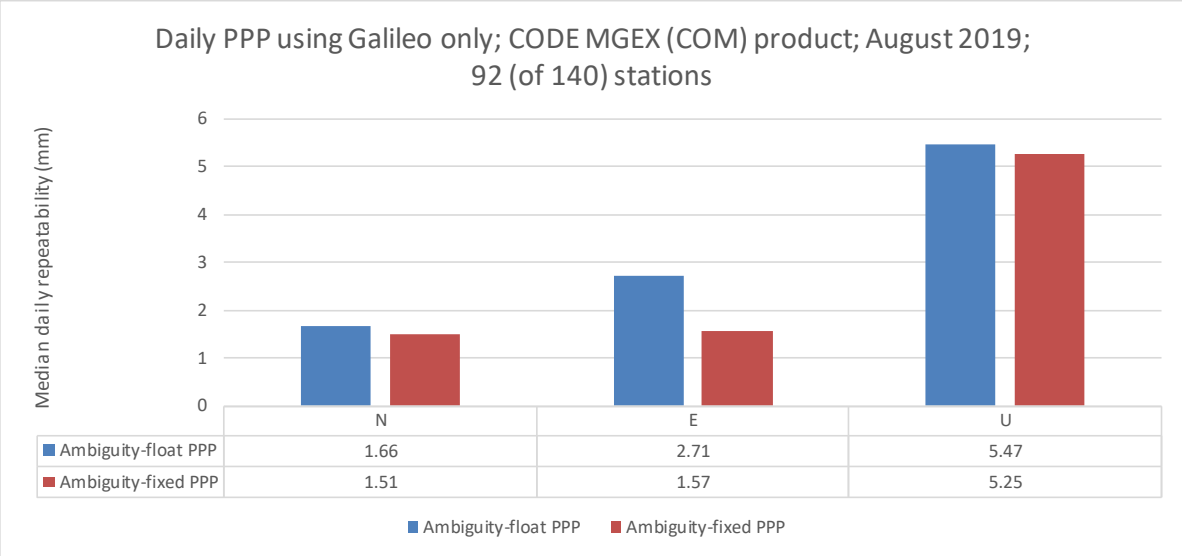
Ambiguity-fixed clock and phase bias products

- June 2018: *signal-specific phase bias (OSB)* product (internal) and a fully consistent *ambiguity-fixed clock* product for:
  - CODE rapid, GR, 30s clocks, 5° min.el., 120 stations
  - CODE final, GR, 5s clocks, 5° min.el., >300 stations
  - **CODE MGEX**, GRECJ, 30s clocks, 5° min.el., 140 stations
- The new CODE clock products reveal a notably improved quality and allow for *single-receiver ambiguity resolution*, thus enabling *integer-PPP (IPPP).*



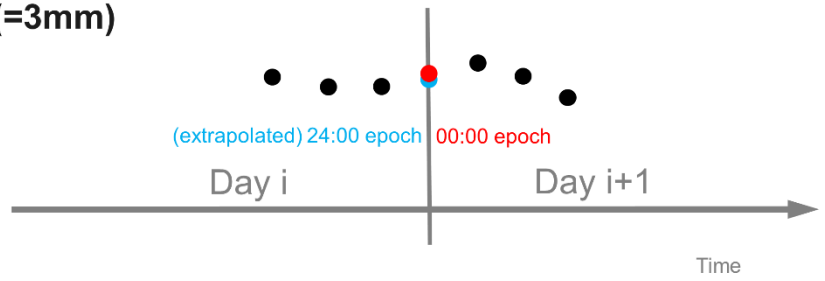
Ambiguity-fixed clock and phase bias products

Daily PPP vs. daily IPPP using Galileo only:



Galileo clock differences at day boundaries:

Standard deviation of (NLC-)integer-corrected between-satellite Galileo clock differences at midnight epochs (24:00/00:00) is at a level of **12ps (=3mm)**



References:

Schaer et al. (2018): Presentation at IGS-WS 2018.

Schaer et al. (2019): The CODE ambiguity-fixed clock and phase bias analysis products and their properties and performance. Manuscript in preparation.

Antenna calibrations

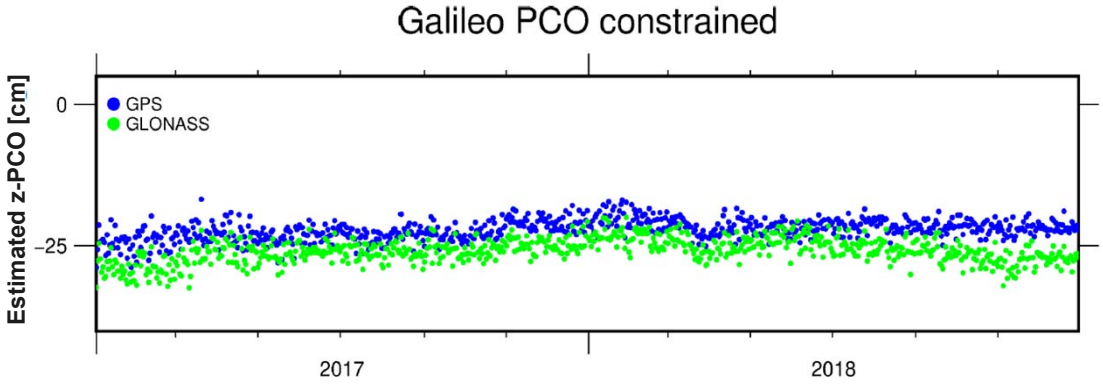
Available receiver and satellite antenna pattern:

System	Receiver		Satellite
	IGS 14	REPRO3	
GPS	L1 / L2	L1 / L2	Estimated
GLONASS	L1 / L2	L1 / L2	Estimated
Galileo	L1 / L2	L1 / L5	Calibrated
Beidou	L1 / L2	L1 / L7	Estimated
QZSS	L1 / L2	L1 / L2	Calibrated

→ Calibrated receiver and satellite antenna pattern allow to estimate a **GNSS scale**

Estimated GPS and Galileo PCO (z-component) are not compatible.

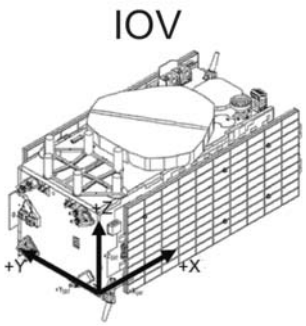
- Possible solution: adaptation of GPS and GLONASS z-PCOs to Galileo by introducing a system-wise offset
- Study related to IGS REPRO3

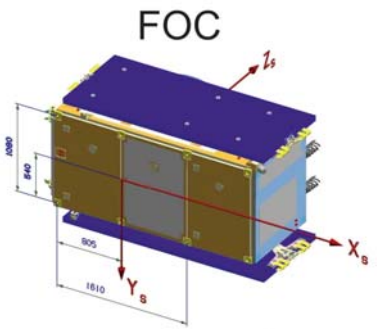


⇒ see poster by Villiger et al. in poster session for details

Orbit modelling – thermal radiation

- Galileo spacecraft have a large AMR and are equipped with thermal radiators (known from the publicly available Galileo satellite metadata – thanks to GSA)

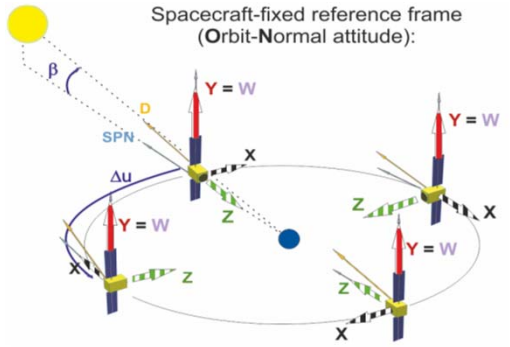




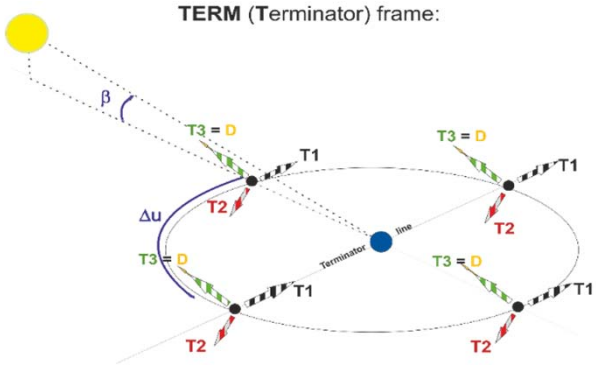
- Thermal radiators produce non-negligible forces (particularly important during eclipse seasons)
- Neglecting thermal effects may produce modelling artifacts (visible in MGEX products; magnitude depends on the employed orbital arc length)
- The ECOM2 SRP model was modified to account for these effects leading to improvements in satellite orbits and clock corrections during eclipse seasons.

⇒ see poster by Sidorov et al. in poster session PS01 for details

Orbit modelling – orbit normal (ON) attitude



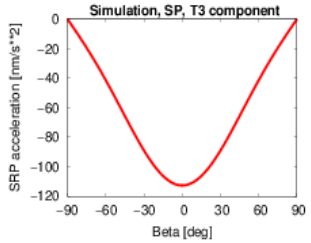
$$\mathbf{e}_{T_1} = \frac{\mathbf{e}_D \times \mathbf{e}_W}{|\mathbf{e}_D \times \mathbf{e}_W|}$$
$$\mathbf{e}_{T_2} = \mathbf{e}_D \times \mathbf{e}_{T_1}$$
$$\mathbf{e}_{T_3} = \mathbf{e}_D$$

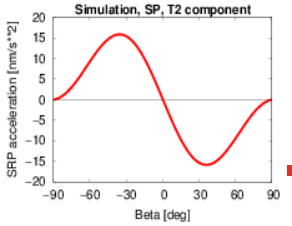


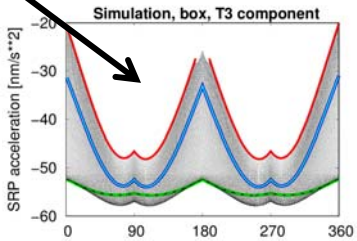
- Definition of a reference frame suited for SRP modelling during ON-mode
- Simulation of SRP due to solar panels and spacecraft body
- Definition of a suitable parameter set for SRP-model as a function of the Beta angle

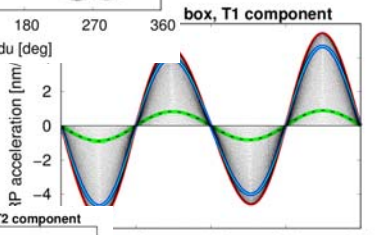
ECOM-TB:

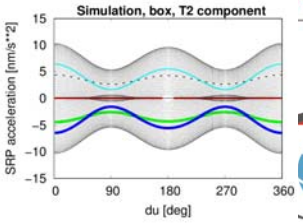
$$\begin{aligned}
T3(\Delta u,\beta) = {} & \mathbf{T30C1b}\cos\beta \\
& + \mathbf{T3C2uC1b}\cos 2\Delta u\cos\beta \\
& + \mathbf{T3S2uC1b}\sin 2\Delta u\cos\beta \\
& + \mathbf{T3C4uC1b}\cos 4\Delta u\cos\beta \\
& + \mathbf{T3S4uC1b}\sin 4\Delta u\cos\beta \\
T2(\Delta u,\beta) = {} & \mathbf{T20S3b}\sin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





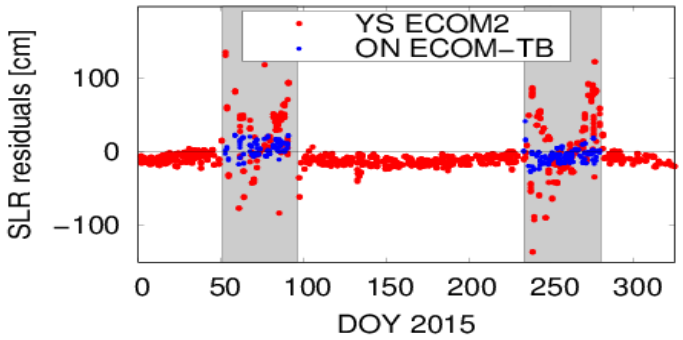




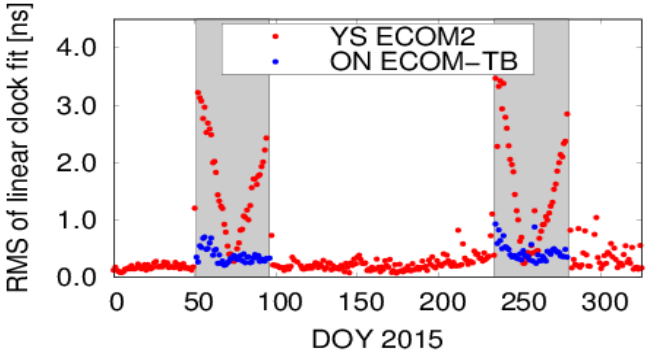


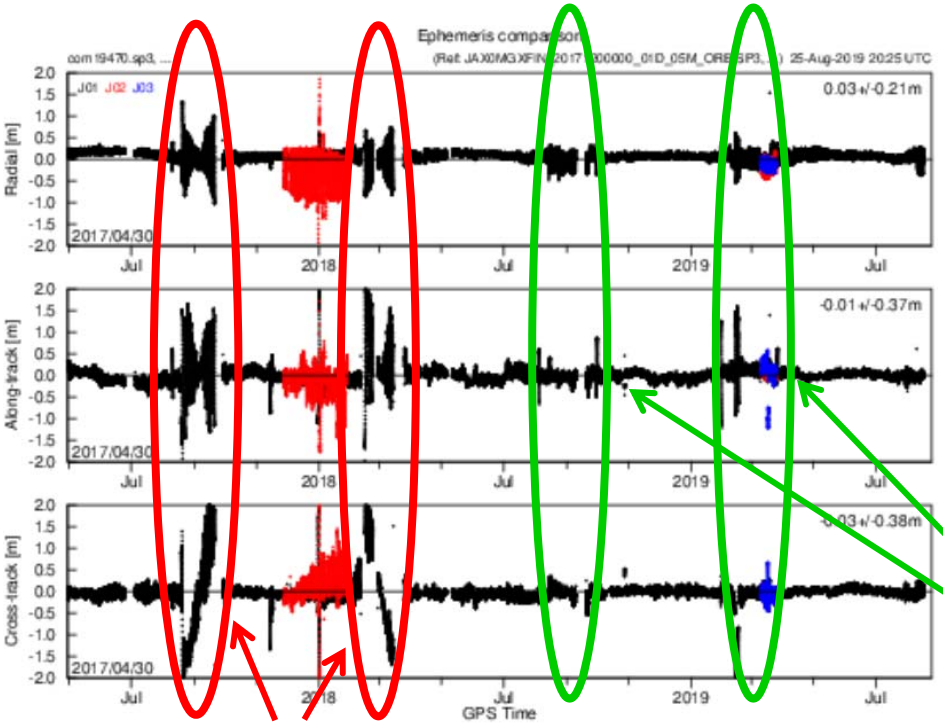
⇒ read Prange et al. (2019, doi 10.1016/j.asr.2019.07.031) for more details

Orbit modelling – orbit normal (ON) attitude



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





ECOM2 used for POD @COM

ECOM-TB used for POD @COM

External validation:

Improved **QZS-1** (**black**) orbit differences between MGEX solutions “JAXA” and “COM” during ON-mode since activation of ECOM-TB on COM side. (screenshot taken from http://mgex.igs.org/analysis/)

Reference:

Prange et al. (2019), doi 10.1016/j.asr.2019.07.031

Summary

- CODE's point of view:

  Galileo is ready for IGS legacy products

- IGS decision is expected soon:

  Galileo to be potentially included in IGS REPRO3

Outlook for COM

- Further improvement of radiation pressure modelling ((semi-) analytical SRP models, thermal radiation models, …)
- Attitude (models for Asian systems, ORBEX format, quaternions?)
- MGEX SINEX files
- MGEX ionosphere and bias product (containing phase biases and considering all signals)
- New systems and satellites (BDS3, IRNSS, GEOs)?
- Further improvements of clock products (sampling, midnight epoch, …)

Thank you

for

your attention!