CODE IGS reference products including Galileo

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Astronomical Institute University of Bern

Contents

- Evolution of CODE's MGEX (COM) solution
- Dedicated model changes
- Galileo orbit and clock performance in the COM solution
- IGS perspective
- First experience with Galileo in (Ultra-)Rapid products
- Summary

Evolution of 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 (since Summer 2017)

  ⇒ *Prange et al. (presentation at 6th Galileo/GNSS Colloquium 2017), Dach et al. (CODE: IGS Technical Report 2017, doi 10.7892/boris.116377)*

  - Correct consideration of orbit normal (ON) attitude mode for QZS-1 and BDS2 (since Summer 2018)
  - Use of **ECOM-TB** SRP model for satellites with ON attitude (since Summer 2018)

  ⇒ *Prange et al. (doi 10.1016/j.asr.2019.07.031)*

  - Empirical thermal radiation model for Galileo satellites (since Summer 2019)

  ⇒ *Sidorov et al. (poster at 7th Galileo/GNSS Colloquium 2019; paper doi 10.1016/j.asr.2020.05.028)*

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Evolution of the COM solution

- Observation biases:
  - Observable-specific code biases (**OCB**) (Summer 2017)
    ⇒ *Villiger et. al. (2019, doi 10.1007/s00190-019-01262-w)*
  - Observable-specific phase biases (**OPB**) (Summer 2018)
    ⇒ *Schaer et. al. (presentation at IGS Workshop 2018; paper in preparation)*

- Phase ambiguity resolution:
  - DD orbit solution: GPS, Galileo, QZSS, BDS2 (Summer 2017)
  - Ambiguity-fixed clocks: GPS, Galileo (WL+NL), QZSS, BDS2 (WL only) (Summer 2018)
    ⇒ *Dach et al. (CODE: IGS Technical Report 2018; doi 10.7892/boris.130408); paper by Schaer et. al. under preparation*

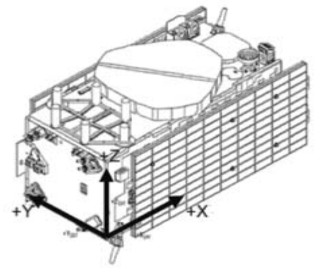
- Antenna calibrations:
  - Satellite antenna phase center offsets (PCO) of Galileo and QZSS published by system provider (values are included in IGS-MGEX-ANTEX)
  - Ground antenna calibrations considering all GNSS available since 2019
  - Switch to new antenna calibrations to be coordinated with IGS REPRO3

  ⇒ *see diverse presentations and poster by Villiger et. al. (2019), paper under review*

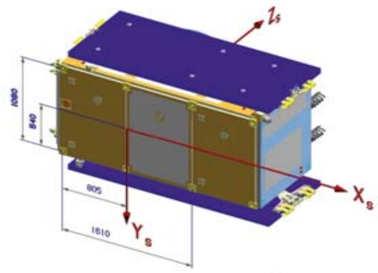
Galileo thermal radiation model

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

IOV



FOC



- 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)

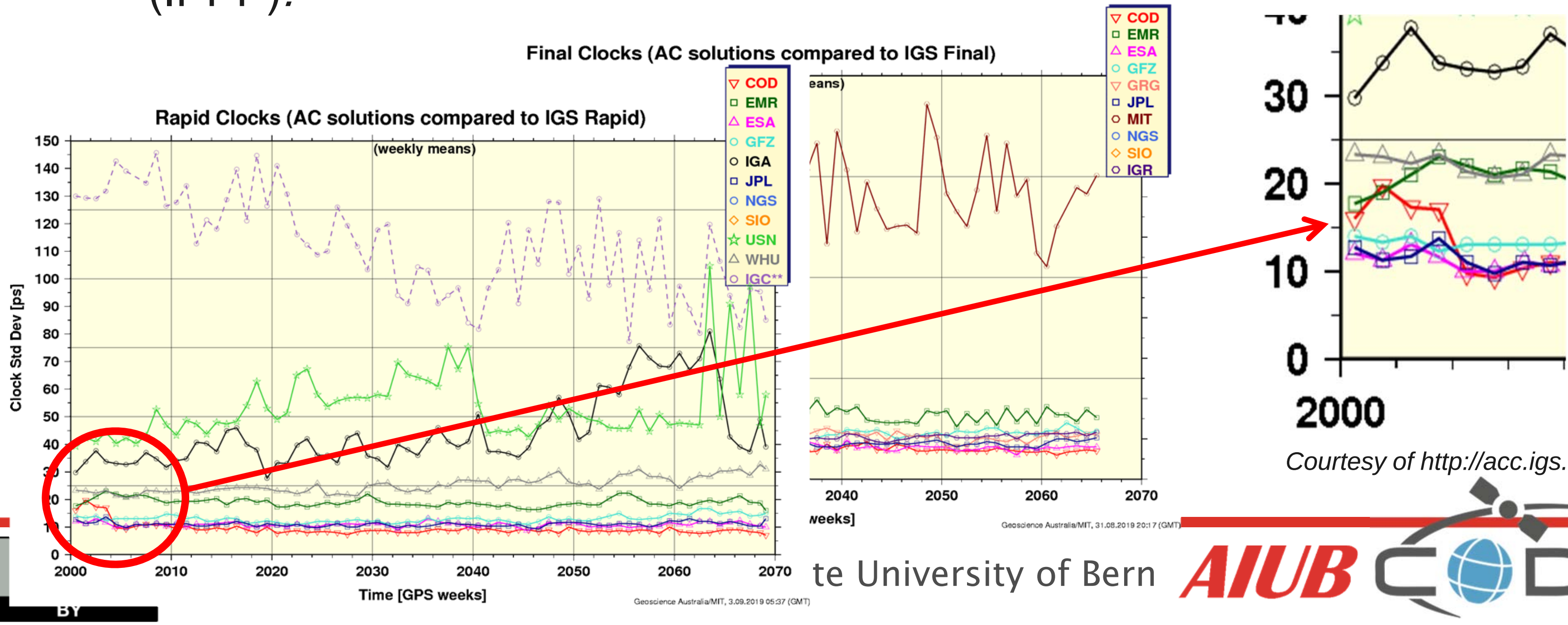
- The ECOM2 SRP model was modified to account for these effects leading to improvements in satellite orbits and clock corrections during eclipse seasons.

  ⇒ *Sidorov et al. (2020): Adopting the Empirical CODE Orbit Model to Galileo satellites. doi 10.1016/j.asr.2020.05.028*

Ambiguity-fixed clock and phase bias products

- June 2018: signal-specific phase bias (OPB) 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).



Courtesy of http://acc.igs.org

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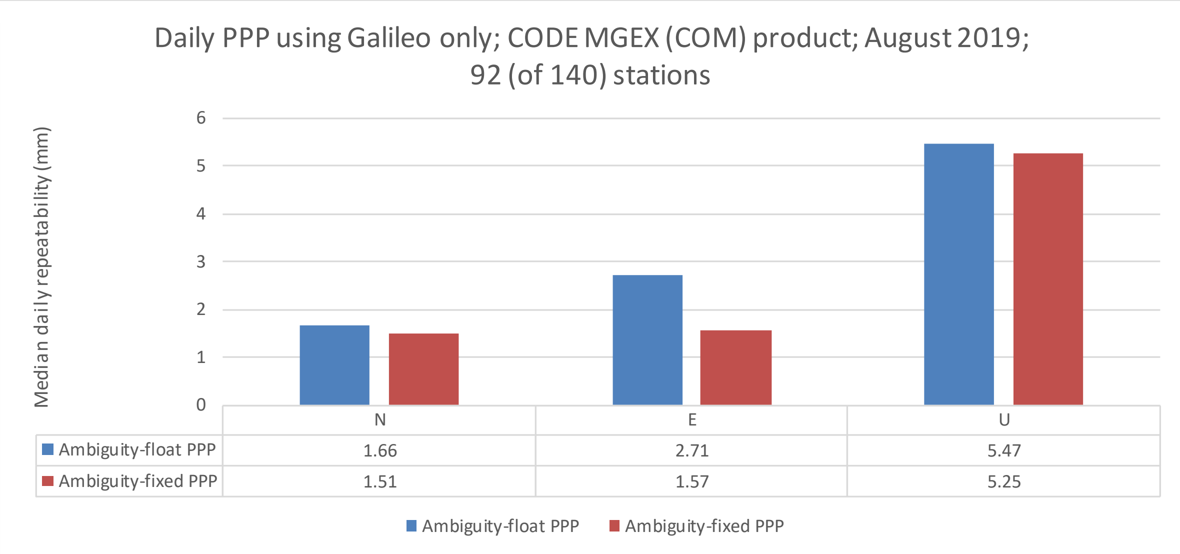
Ambiguity-fixed clock and phase bias products

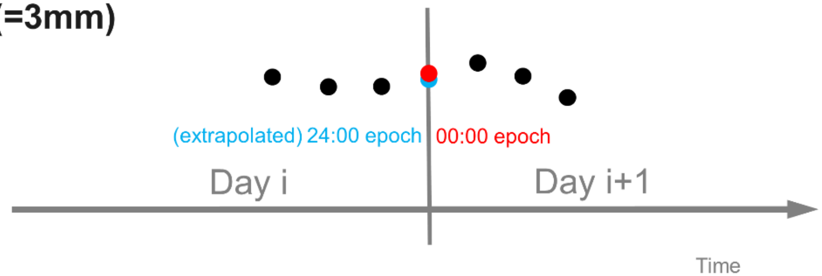
Daily PPP vs. daily IPPP using Galileo only:



	N	E	U
Ambiguity-float PPP	1.66	2.71	5.47
Ambiguity-fixed PPP	1.51	1.57	5.25

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. (2020): The CODE ambiguity-fixed clock and phase bias analysis products and their properties and performance. Manuscript in preparation.

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Antenna calibrations

Available receiver and satellite antenna patterns:

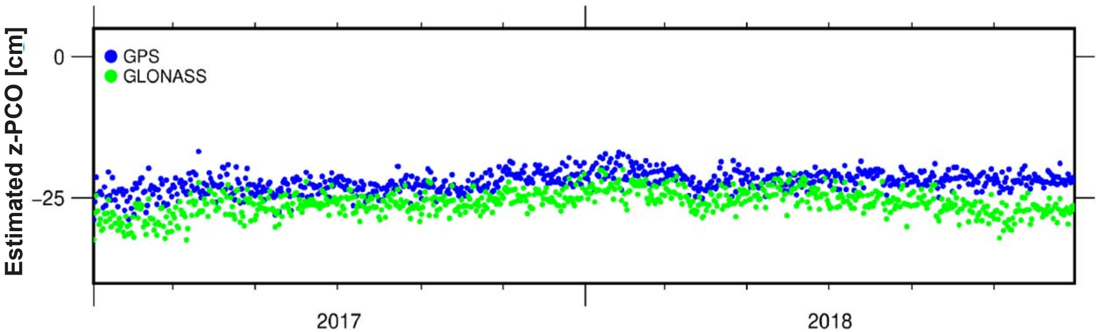
System	Receiver		Satellite
	IGS 14	REPRO3	
GPS	L1 / L2	L1 / L2	Estimated
GLONASS	L1 / L2	L1 / L2	Estimated
Galileo	L1 / L2	L1 / L5	Calibrated
Beidou	L1 / L2	L1 / L7	Estimated
QZSS	L1 / L2	L1 / L2	Calibrated

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

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

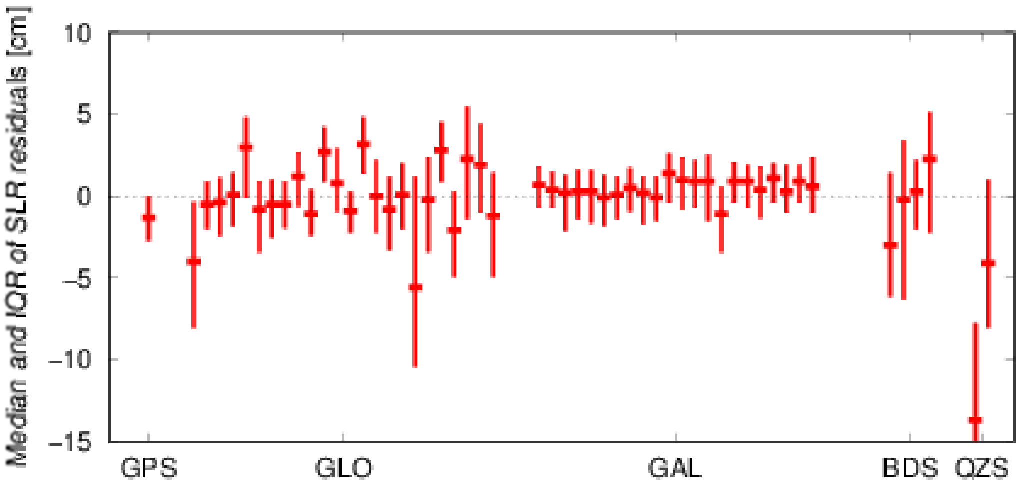
- ➢ Possible solution: adaptation of GPS and GLONASS z-PCOs to Galileo by intro-ducing a system-wise offset
- ➢ Study related to IGS REPRO3

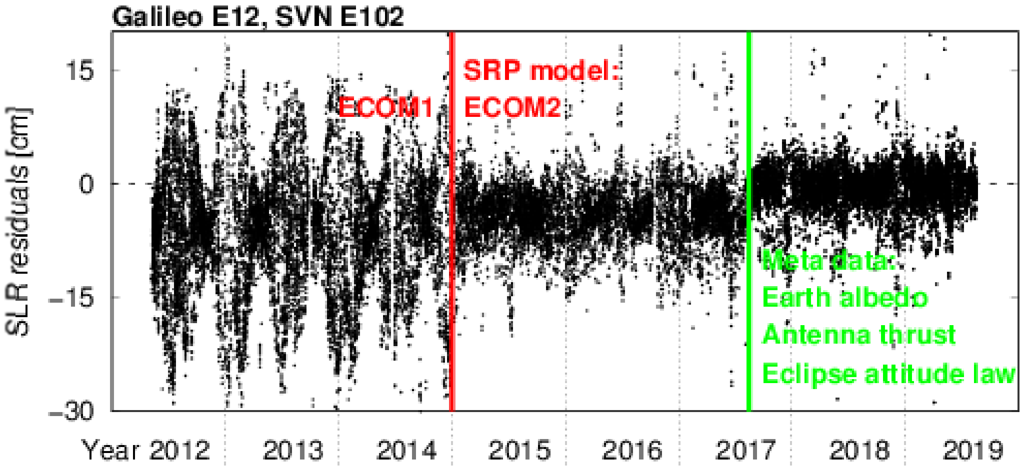
Galileo PCO constrained



⇒ *Villiger et al. (2020): GNSS scale determination using calibrated receiver and Galileo satellite antenna patterns. Paper under review*

COM orbit validation: SLR residuals





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

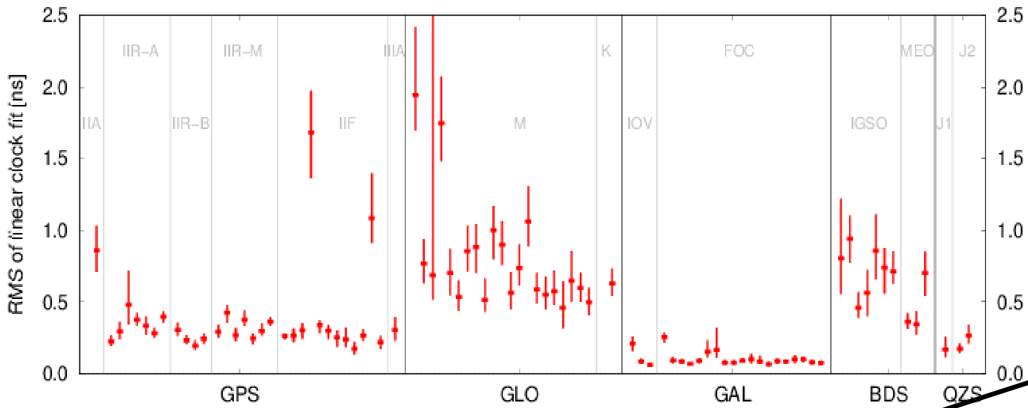
⇒ Disclosure of meta data contributes to orbit improvements (e.g., reduction of SLR offset)

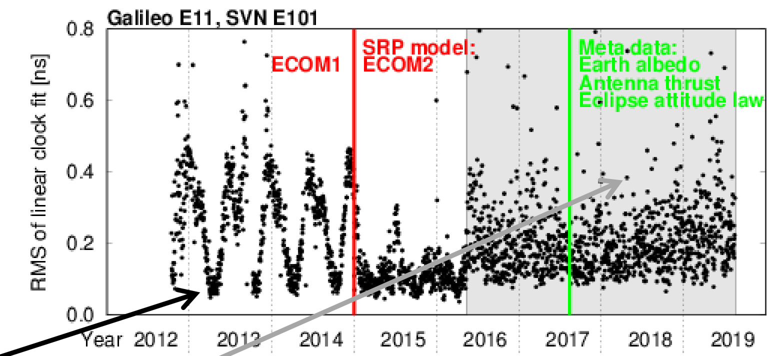
COM orbit validation DOYs 1-320/2019:

SLR	Median [cm]	IQR [cm]
GLONASS	−0.1	4.6
Galileo	0.2	3.6
3D orbit misclosures		
GPS	0.8	0.6
GLONASS	1.2	1.0
Galileo	1.4	1.0

⇒ Nowadays: Galileo orbit quality is not worse than that of GLONASS

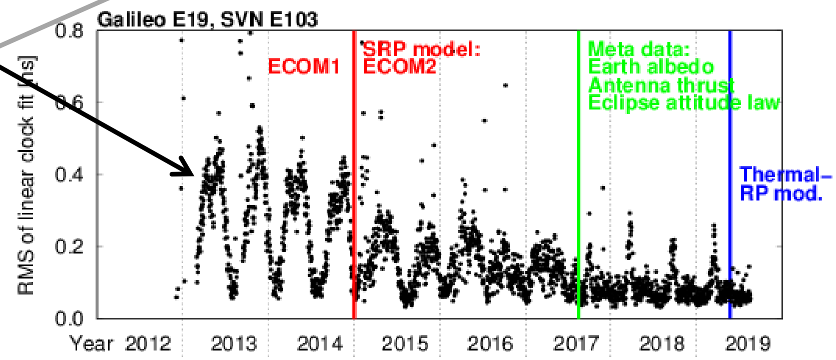
COM clock validation: daily linear fit

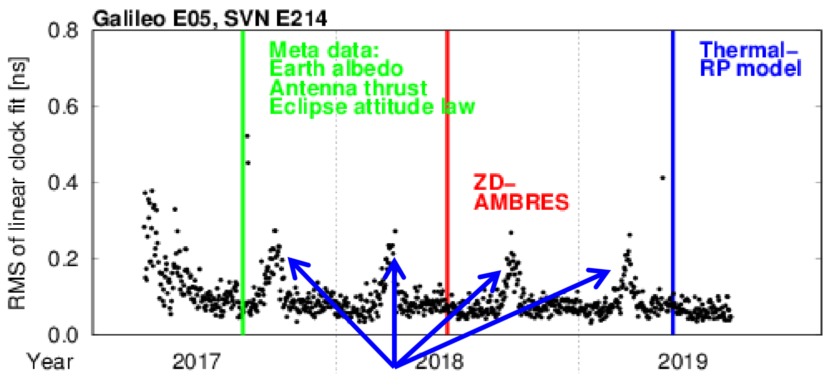




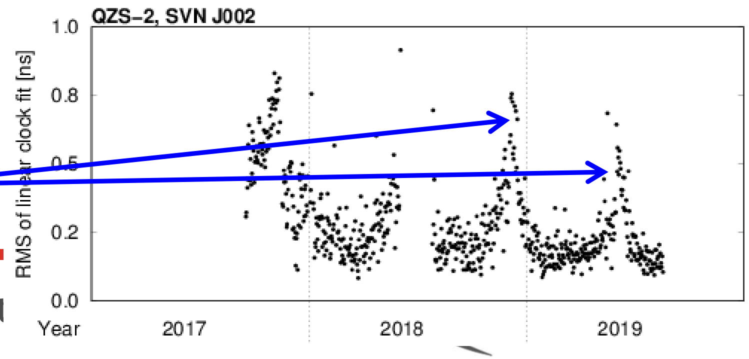
⇒ Excellent performance of Galileo **PHM** clocks enables them for orbit validation

⇒ **RAFS** clocks too noisy for orbit validation





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



IGS perspective

- Operational IGS processing chains:
  - Demand for additional systems is higher for (near-)real time applications (# of satellites in view and observation geometry matters) → (Ultra-)Rapid

Product line	Applications	Latency Req.	Accuracy Req.	Systems
Ultra-Rapid (including orbit predictions)	Real time (predictions), near real time	Very short (few hours)	Low	GR
Rapid	Reference	Short (1 day)	Medium	GR
Final	High accuracy reference (including scale); contribution to ITRF	Long (2 weeks)	High	GR

Color code: requirement or factor is…

Very important

Moderately important

Less important

System:

GPS:	G
GLONASS:	R
Galileo:	E
BeiDou:	C
QZSS:	J
SBAS:	S
IRNSS:	I

IGS perspective

- IGS processing chains (recent years):
  - MGEX: testing of new systems (other than GPS and GLONASS) and RINEX3 raw observation data format; preparation of software, processing chains, modelling

Product line	Applications	Latency Req.	Accuracy Req.	Systems
MGEX	Experimental: new GNSS and RNSS; RINEX3 data	Diverse	Diverse	GRECJ
Ultra-Rapid (including orbit predictions)	Real time (predictions), near real time	Very short (few hours)	Low	GR
Rapid	Reference	Short (1 day)	Medium	GR
Final	High accuracy reference (including scale); contribution to ITRF	Long (2 weeks)	High	GR

  - Demand for new GNSS is less urgent in Final products (scale consistency and avoiding contamination of EOP and TRF parameters by orbit modelling artifacts matter more)

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IGS perspective

- IGS processing chains (around 2020):
  - RINEX3 is gradually replacing RINEX2 data in all processing chains according to the IGS RINEX 3 Transition Plan

Product line	Applications	Latency Req.	Accuracy Req.	Systems
MGEX	Experimental: new GNSS and RNSS; **RINEX3 data**	Diverse	Diverse	GRECJ
Ultra-Rapid (including orbit predictions)	Real time (predictions), near real time	Very short (few hours)	Low	GRE
Rapid	Reference	Short (1 day)	Medium	GRE
Final	High accuracy reference (including scale)	Long (2 weeks)	High	GR
REPRO3	Preparation of new **ITRF** including definition of **GNSS scale**	On demand	Very high	GRE

  - As first AC, CODE started to include Galileo in Ultra- and Rapid products in September 2019 (accepting scale inconsistencies between Galileo and GPS/GLONASS/ITRF2014) *(see Dach (2019): IGSMAIL-7832)*

IGS perspective

- IGS processing chains (near future, 2021?):
  - REPRO3: possible definition of a GNSS scale based on Galileo satellite and new ground antenna calibrations, re-estimation of GPS and GLONASS PCO and ITRF-contribution; several ACs (incl. CODE) thus include Galileo in their contribution

Product line	Applications	Latency Req.	Accuracy Req.	Systems
MGEX	Experimental: new GNSS and RNSS	Diverse	Diverse	GRECJSI
Ultra-Rapid (including orbit predictions)	Real time (predictions), near real time	Very short (few hours)	Low	GRE
Rapid	Reference	Short (1 day)	Medium	GRE
Final	High accuracy reference (including scale); contribution to new **ITRF**	Long (2 weeks)	High	GR
REPRO3	Preparation of new **ITRF** including definition of **GNSS scale**	On demand	Very high	GRE

  - New ITRF (with new scale) to be introduced in all IGS routines

IGS perspective

- **IGS processing chains (future, 2021+):**
  - With the new ITRF Galileo can potentially contribute to Final products without causing a scale inconsistency

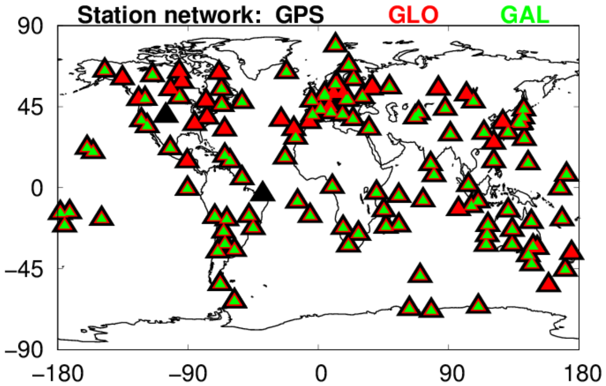
Product line	Applications	Latency Req.	Accuracy Req.	Systems
MGEX	Experimental: new GNSS and RNSS	Diverse	Diverse	GRE**CJSI**
Ultra-Rapid (including orbit predictions)	Real time (predictions), near real time	Very short (few hours)	Low	GRE
Rapid	Reference	Short (1 day)	Medium	GRE
Final	High accuracy reference (including new scale); contribution to next ITRF	Long (2 weeks)	High	GRE

  - MGEX: could address open technical (e.g., GEO POD, improving orbit models) and scientific questions (e.g., how can GEO and IGSO satellites contribute to TRF parameters and other reference products?)

Galileo in CODE (Ultra-)Rapid – first experiences

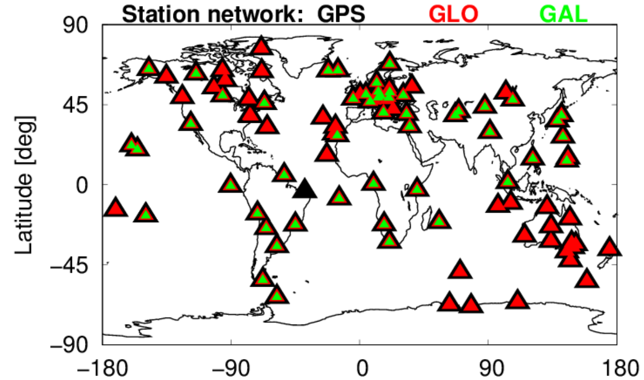
- **Galileo included in CODE (Ultra-)Rapid since September 2019:**
  - Smaller network for faster processing than with MGEX
  - Number of stations providing RINEX3 data with short latency is an issue for Ultra

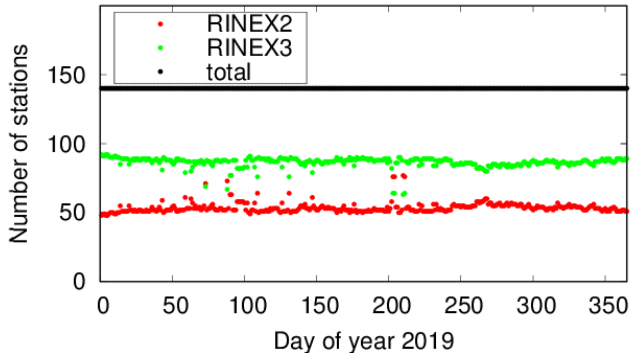
CODE MGEX vs. **CODE Ultra (early)**



Fewer stations with Ultra →

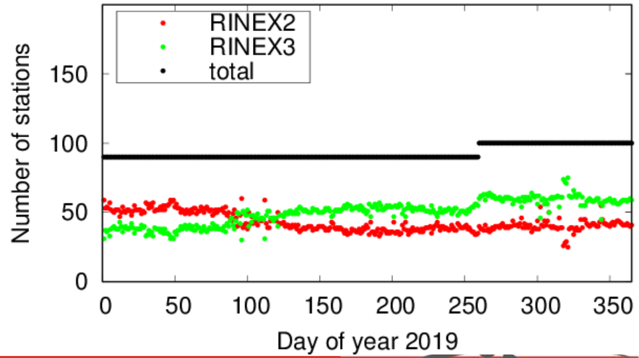
Gaps in Galileo tracking coverage – especially for early Ultra (DOY 310/2019)





Ratio of stations providing RINEX3 data is smaller when relying on short latency data →

→ Disadvantage for Galileo



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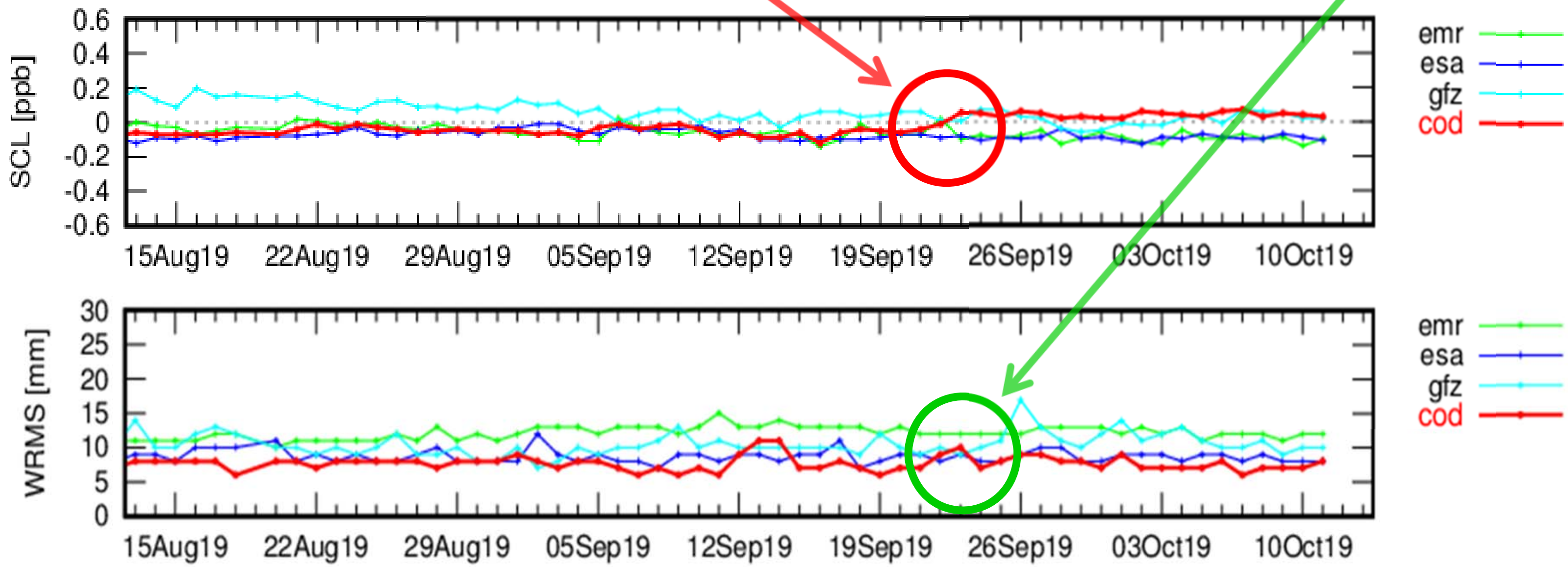
Galileo in CODE (Ultra-)Rapid – first experiences

- **IGS Rapid combination validates impact of Galileo on GPS orbits:**
  - No issues concerning data processing or reliability
  - Jump in GPS scale (as expected from *Villiger and Rebischung (2019))*
  - No degradation of GPS orbits (Helmert transformation parameters and WRMS of comparison with combined IGS Rapid orbit do not change)

Rapid GPS orbits from selected ACs vs. IGS combination (**cod** == CODE Rapid):



Summary

- Galileo data analysis has significantly improved in recent years (e.g., ambiguity-fixed clocks)
- Galileo nowadays is a fully established GNSS constellation, which is sufficiently supported by the IGS infrastructure, and is mature enough to contribute to legacy IGS products
- Availability of metadata lets Galileo appear even appropriate to determine a GNSS scale in the frame of the IGS REPRO3 campaign
- GNSS community expressed interest in Galileo short latency products
- CODE AC started to include Galileo in Ultra-Rapid, Rapid and in its REPRO3 effort
- Inclusion of Galileo in CODE`s (Ultra-)Rapid analysis has so far not indicated negative side-effects – apart from a scale difference w.r.t. GPS and GLONASS, which was expected (and is likely to disappear when a new ITRF will be introduced)

Thank you

for

your attention!

Note: For more information on this topic we refer to Prange et al. (2020): Overview of CODE's MGEX solution with the focus on Galileo. ASR. doi: 10.1016/j.asr.2020.04.038

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- *Schaer et al. (2020). The CODE ambiguity-fixed clock and phase bias analysis products and their properties and performance. Paper in preparation.*
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- *Villiger et al. (2020). GNSS scale determination using calibrated receiver and Galileo satellite antenna patterns. Paper submitted to Journal of Geodesy.*

Bonus: 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

Bonus: 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/

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