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

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Abstract

We present an update on the multi-GNSS orbit and clock solution (COM), the CODE analysis center provides to the International GNSS service (IGS) in the frame of the multi-GNSS extension (MGEX). In recent years substantial progress was achieved in the fields of orbit modelling (Earth albedo, transmit antenna thrust, thermal radiation, eclipse attitude law), receiver and transmitter antenna calibration, ground tracking network, data dissemination, completeness of satellite constellations, availability of spacecraft-related meta information, observation biases, and ambiguity resolution. This led to improvements in orbit and clock parameter estimation, which are substantial for the European GNSS Galileo and are to a large part attributed to the availability of disclosed spacecraft meta data. Orbit and clock validation of the COM results using different validation methods (SLR residuals, orbit misclosures, linear fit of clock corrections) indicate that the quality of the updated Galileo products is meanwhile on the same level as the corresponding GPS and GLONASS products. Based on these achievements CODE decided to include Galileo in its IGS Rapid and Ultra-Rapid products and to contribute to the third reprocessing effort of the IGS with a three-system solution including GPS, GLONASS, and Galileo.

Keywords: Multi-GNSS, precise orbits, integer clocks, IGS, MGEX, Galileo, Ultra-Rapid

1. Introduction

The International GNSS Service (IGS, Johnston et al. 2017) is generating precise reference products for the Global Positioning System (GPS) on an operational basis since 1994. This is achieved by the worldwide cooperation of diverse institutions acting as data and infrastructure providers, data dissemination centers, analysis centers (AC), combination and validation facilities, coordinated by a governing board, by a central bureau, and by working groups (WG) devoted to important research and development topics. "Final" products with a latency of up to 2 weeks have been provided from the beginning. "Rapid" products with a delay of about one day are delivered since 1996 (Beutler et al. 1999). Short-latency "Ultra-Rapid" orbit products including orbit predictions have been added to the IGS product portfolio in the year 2000 in order to serve the requirements of real-time and near real-time users, as well (Choi et al. 2013; Lutz et al. 2014). After running an IGS GLONASS EXperiment (IGEX, Willis et al. 2000) in the late 1990s, several IGS ACs have started to analyze the Russian Global Navigation Satellite System (GNSS) GLONASS in their operational IGS products. For the Center for Orbit Determination in Europe (CODE, Dach et al. 2019a) this is the case since 2003 (Dach et al. 2009).

One decade later, additional GNSS (e. g., Galileo, BDS3 (BeiDou Navigation Satellite System-3)), Space-Based Augumentation Systems (SBAS), and Regional Navigation Satellite Systems (RNSS), namely QZSS (Quasi-Zenith Satellite System), BDS2, and IRNSS (Indian Regional Navigation Satellite System), were deployed. The IGS launched the Multi-GNSS-EXperiment (MGEX, Montenbruck et al. 2013) in 2012 in order to gain experience and prepare the IGS for the inclusion of these systems into its legacy product lines. CODE has contributed to the MGEX with a dedicated solution including Galileo from the very beginning (Prange et al. 2016). In 2014 CODE's MGEX (COM) solution was extended to provide orbits and clocks for the five satellite systems GPS, GLONASS, Galileo, BDS2, and QZSS (Prange et al. 2017a).

The analysis of the COM products from 2014 and 2015 by Prange et al. (2017a) indicated that the orbit quality achieved for the new systems could not yet compete with that of the established GNSS. A comprehensive review of the MGEX achievements by Montenbruck et al. (2017b) confirmed that the IGS was not yet sufficiently prepared for incorporating new satellite systems in its legacy products in late 2016. Compared to 2003—when GLONASS was included into the legacy IGS products—the entry barrier for new GNSS is higher nowadays for various reasons: Firstly, the accuracy of IGS products has considerably evolved (check, e. g., the consistency of AC products in the IGS combination, Moore et al. 2019). Deficiencies, such as draconitic errors caused, e. g., by insufficient solar radiation pressure (SRP) modelling (described, e. g., by Rodriguez-Solano et al. 2014) or the GLONASS orbit errors analyzed by Dach et al. (2019b) are, therefore, better visible than in the past. Secondly, the user expectations towards the quality of IGS products have grown accordingly (consult, e. g., the GGOS goals defined by Gross et al. 2009). After all, the IGS prod-

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ucts nowadays provide the main access to the International Terrestrial Reference Frame (ITRF) for operational geodesy users around the world (Altamimi 2013).

Prange et al. (2017a) and Montenbruck et al. (2017b) listed several limitations concerning the new satellite systems in the COM- and MGEX-products in general. These included orbit errors partly attributed to a lack of satellite meta data, missing antenna calibrations, radiation pressure modelling, inhomogeneous geometry of the tracking network, lack of data from receivers tracking new constellations, and incomplete satellite constellations. Moreover many GNSS analysis software packages were not yet fully prepared to treat all the new signals in a consistent way, which—in turn—influenced the handling of observation biases, the inter-system consistency, and the phase ambiguity resolution. In the recent years, however, the multi-GNSS data analysis improved significantly—removing some of the aforementioned limitations. Subsequently, we summarize the relevant changes from the perspective of the CODE AC and reassess the possible incorporation of new satellite systems into CODE's legacy IGS products.

The current status of the satellite constellations and of the IGS infrastructure are summarized in Sect. 2. The knowledge of the new satellite types has significantly improved—partly due to the disclosure of satellite meta data and partly due to the efforts by the scientific community, including the IGS. These developments triggered significant model improvements in the COM analysis, the most important of which are summarized in Sect. 3. The impact of the above mentioned changes on the COM orbit and clock products is assessed by comparing the results from the first half of 2019 to the corresponding products from 2014 (Sect. 4). The inclusion of the new GNSS in CODE's product lines for the IGS and the possible implications and limitations are discussed in Sect. 5. The results are summarized in Sect. 6.

2. Constellations and tracking network

2.1. The satellite constellations

Apart from the established GNSS GPS and GLONASS, the IGS MGEX supports several "new" satellite systems (IGS MGEX 2019). One of these systems, Galileo, was declared ready for initial services, with the European GNSS Agency (GSA) being in charge of the operations starting from 1 January 2017 (GSA 2016). Since the commissioning of the last four satellites in February 2019, the Galileo constellation consists of 22 (3 IOV (In-Orbit Validation) and 19 FOC (Full Operational Capability)) operational satellites (GSA 2019). Two FOC spacecraft in excentric orbits are usable for post-processing analysis, in addition (Prange et al. 2017a). All 24 Galileo satellites are included in the COM solution. Malys et al. (2019) acknowledge the excellent quality of Galileo broadcast information and their high compatibility with the ITRF.

The Japanese Quasi-Zenith Satellite System (QZSS) RNSS is complete since the launch of three QZSS satellites in 2017. The QZSS services officially started on November 1, 2018 (CAO 2018). The three QZSS satellites in IGSO (Inclined Geosynchroneous Earth Orbit) are included in the COM solution, the GEO (Geostationary Earth Orbit) satellite QZS-3 is not so far.

The construction of BDS2, the RNSS component of the Chinese BeiDou system, was completed by the end of 2012 and provides services to the Asia-Pacific region since then (Government of China 2019). The currently 3 MEO (Medium Earth Orbit) and 7 IGSO spacecraft of the BDS2 constellation are included in the COM solution, whereas the satellites in GEO orbits are not. The global BDS3 service, which is currently being built up, is not yet condsidered in COM. Satellites belonging to the Indian RNSS IRNSS (also called NAVIC) and SBAS are not considered in the COM solution, as well.

We summarize that among the "new" satellite navigation systems Galileo is the only true GNSS, which is operational already. The question, how RNSS, such as QZSS and BDS2, may contribute to the determination of global TRF (terrestrial reference frame) parameters (e. g., ERPs (Earth rotation parameters), GCCs (ceocenter coordinates), ITRF station coordinates) needs further investigation.

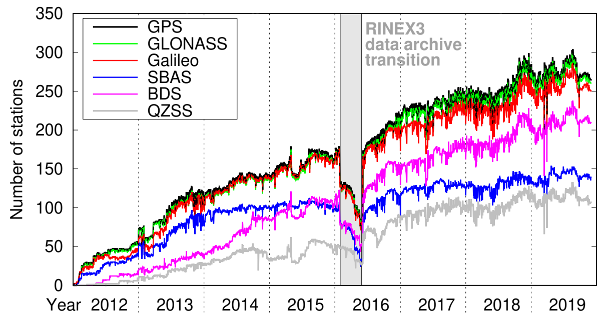

Figure 1: RINEX3 data of different satellite systems considered in CODE's data monitoring. Note that the gradual transition of the RINEX3 archives and of the file name convention at the IGS data centers in the first half of 2016 was followed by CODE with some delay (time interval marked gray).

2.2. The tracking network

Initially, the COM analysis relied on data provided by multi-GNSS-capable stations of a dedicated IGS MGEX network, complemented by stations of the legacy IGS network (Prange et al. 2017a). In the course of the year 2016 the MGEX network was fully integrated into the legacy IGS network and data archives (Noll 2017; Romero 2017). Moreover, a growing number of legacy IGS stations (including ITRF stations) changed to new receivers capable of tracking more systems and signals and are providing the data in the RINEX3 format (Receiver INdependent EXchange format, version 3, Gurtner and Estey 2018; MacLeod and Agrotis 2019)—following the IGS RINEX3 transition plan (IGS Infrastructure Committee 2014). Hence, the transition into a multi-GNSS capable IGS has been accomplished to a large extent on the network and data archive side. Thanks to these efforts the spread of RINEX3 data within the IGS data archives has significantly improved since 2014. Almost all IGS stations providing RINEX3 data are today tracking GPS, GLONASS, and Galileo (Fig. 1).

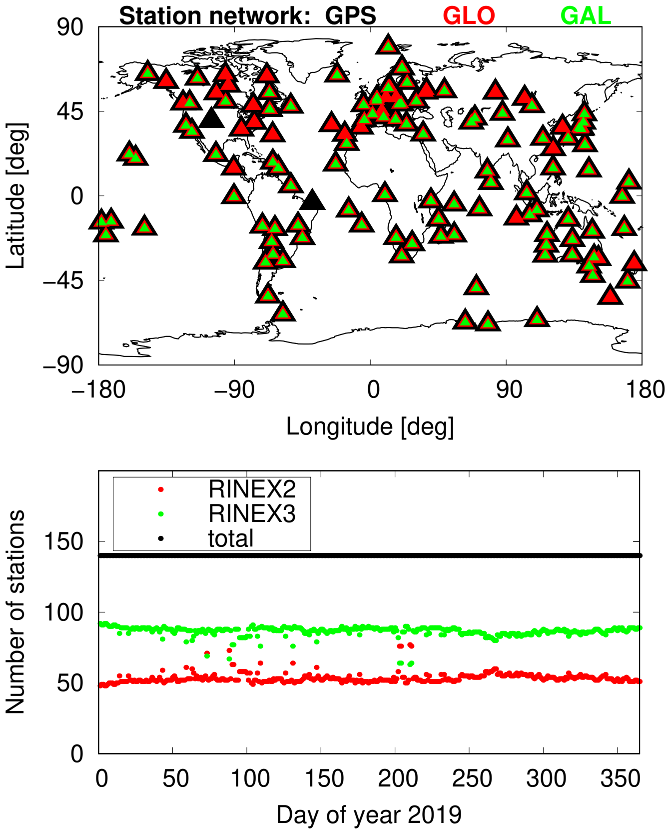

Figure 2: Top: Distribution of stations providing GPS, GLONASS (GLO), and Galileo (GAL) data to the COM solution on DOY 310/2019. Bottom: RINEX format versions and number of stations (140 in total) contributing to the COM solution in 2019.

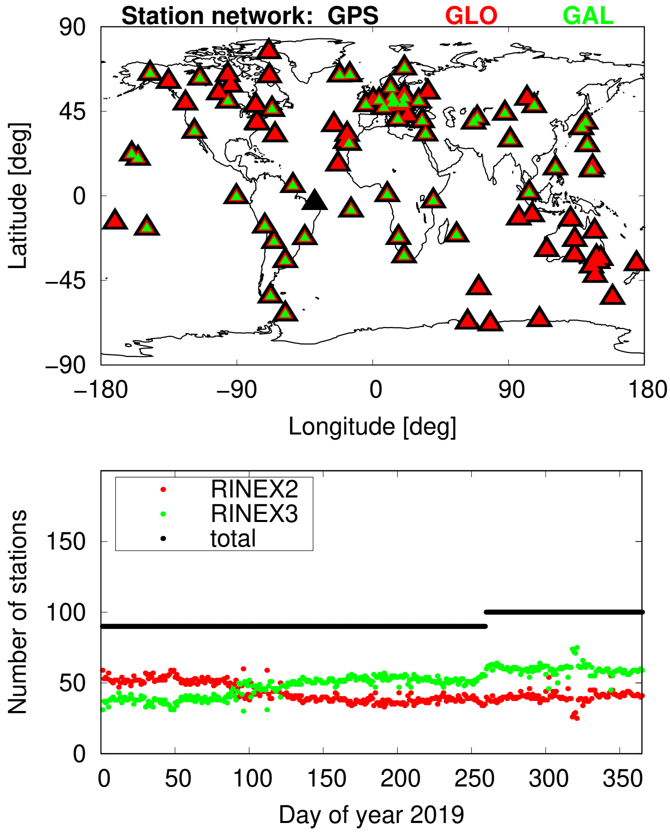

Figure 3: Top: Distribution of stations providing GPS, GLONASS (GLO), and Galileo (GAL) data in hourly RINEX files available for a typical early (first six hours of the day) CODE Ultra-Rapid solution (example from DOY 310/2019). Bottom: RINEX format versions and number of stations contributing to the early CODE Ultra-Rapid solution in 2019. Note the increased (90→100) number of stations since DOY 260/2019.

Experience with MGEX tells that this network is nowadays capable to ensure full observation coverage for all satellites included in the COM solution along their orbits in a Final-like post-processing scheme (i. e., with a latency of 1-2 weeks). Nevertheless, a significant amount of IGS stations is still providing the raw data only in the RINEX2 format (Fig. 2). Such sites are still used to ensure a close alignment of the MGEX products to the ITRF. Others serve as a clock reference.

The availability of RINEX3 data is somewhat less comfortable when only hourly RINEX3 files with latencies of a few hours are taken into account (i. e., a scenario typical for a near real-time Ultra-Rapid analysis, see Lutz et al. 2014, for details). With the station-selection scheme used at CODE for generating IGS Ultra-Rapid products, roughly half of the stations would contribute to Galileo precise orbit determination (POD)—even after the increase of the network size by about 10 % by adding data of additional RINEX3-capable stations (Fig. 3). Figure 4 shows that the extended network is just sufficient for determining gap-free Galileo orbits and satellite clocks in the Rapid and orbits in the Ultra-Rapid mode. Compared to GPS, however, the data coverage for Galileo is still poor in some regions (compare Fig. 4, left vs. right).

3. Model changes impacting the COM analysis

The most important model, software, and processing changes in the COM analysis since early 2015 are listed in Tab. 1. Apart from this the methods and background models remained the same as described by Prange et al. (2017a).

Worth of mentioning is the disclosure of meta data related to the Galileo IOV and FOC spacecraft by the GSA (GSA 2017) and to the QZSS satellites by the Cabinet Office, Government of Japan (CAO, CAO 2017). The published Galileo meta data comprises sizes and optical properties of the main satellite surfaces, eclipse attitude laws, and transmit antenna calibrations. In addition, the GSA provides center of mass and LRA (laser retro-reflector array) offset vectors in the satellite-fixed reference frame, and the mass of the Galileo spacecraft to the International Laser Ranging Service (ILRS, Pearlman et al. 2002). The CAO provides sizes and optical properties of the main surfaces, center of mass, LRA and navigation antenna offsets, transmit power, eclipse attitude law, maneuver history, and mass history of the QZSS spacecraft.

Other insights result from the research performed by the scientific GNSS community. These concern, e. g., estimated transmit antenna power of the GPS, GLONASS, Galileo, BDS2, and QZS-1 spacecraft (Steigenberger et al. 2018) and

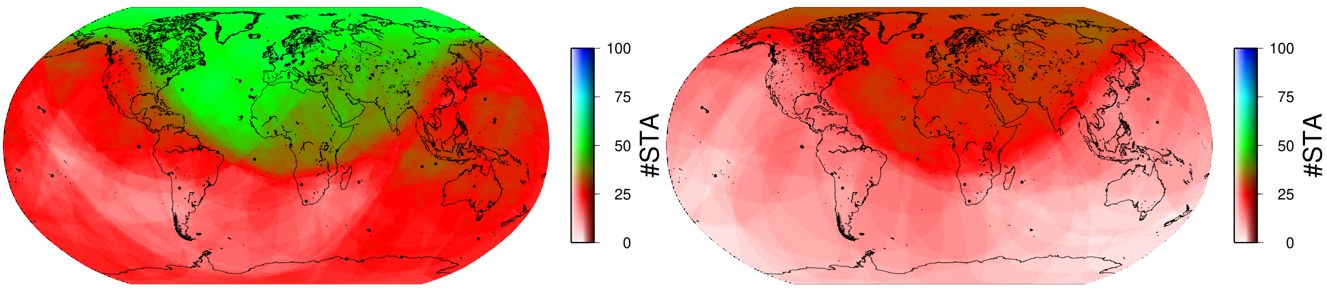

Figure 4: Theoretical tracking density with a network typical for an early Ultra-Rapid solution when assuming a 45° elevation mask. Left: GPS. Right: Galileo.

Table 1: Changes in the COM solution since 2015. The RINEX characters G,R,E,C,J abbreviate the systems GPS, GLONASS, Galileo, BDS2, QZSS, respectively.

	Early 2015 (Prange et al. 2017a)	Late 2019
# of satellites:	≈70	>90
# of stations:	G: 130, R: 110, E: 85, C: 55, J: 20	G: 140, R: 130, E: 100, C: 50 (CLK)/80 (ORB),J: 40
Reference frame:	IGb08 (before GPSWEEK 1934)	IGS14 (since GPSWEEK 1934)
Sat. antenna model:	E: PCO and PCV calibrated (GSA 2017) J: PCO from MGEX (IGS MGEX 2019)	E: PCO estimated (Steigenberger et al. 2016) J: PCO calibrated since 2017 (CAO 2017)
Earth albedo:	E,J: none	E,J: (Rodriguez-Solano et al. 2012) since 2017; Sat.-Info from GSA (2017), CAO (2017)
Transmit thrust:	E,J: none	E,J: since 2017; transmit power from Steigenberger et al. (2018), sat. masses from ILRS (2019), CAO (2017)
Ambiguity resolution: (AR)	G: DD AR E: active, but not tuned C,J: active, but not tuned	G: DD+ZD AR since 2018 (Dach et al. 2019a) E: DD since 2017; ZD since 2018 (Dach et al. 2019a) C,J: DD since 2017; ZD (WL only) since 2018 (Dach et al. 2019a)
Attitude model:	YS (Yaw-steering) always assumed	G: YS + eclipse law (Kouba 2009) since 2016 R: YS + eclipse law (Dilssner et al. 2011) since 2016 E: YS + eclipse law (GSA 2017) since 2017 J: YS + ON (QZS-1 in eclipse) since 2018 C: YS + ON eclipse law since 2018
SRP model:	always: ECOM2 (9 param.) (Arnold et al. 2015)	during YS: ECOM2; since autumn 2015: 7 param. (no D4 terms); C MEO during ON: ECOM-TBP since 2018 (Prange et al. 2020) C IGSO during ON: ECOM-TBMP since 2018 (Prange et al. 2020) QZS-1 during ON: ECOM-TB since 2018 (Prange et al. 2020)
Stochastic pulses: (Beutler et al. 1994)	G,R: every 12 h	G,R: every 12 h E: every 12 h, since 2017 C,J: every 12 h, since 2018
Thermal radiation:	partly absorbed by SRP parameters outside eclipse	E: ECOM-D1 for IOV and ECOM-YD1 for FOC with $\|\beta\| < 12°$ including a permanent a priori accel. component (also outside ecl.) since 2019 (Sidorov et al. 2019, 2020)
Orbit format:	SP3c, 900 s sampling	SP3d, 300 s sampling since 2017
Clock-RINEX:	300 s sampling	30 s sampling since 2017
Observation biases:	ISBs for multi-GNSS stations, IFBs for GPS+GLONASS stations, GPS P1-C1 DCBs in Bernese DCB- and preliminary BIAS-SINEX format	OCBs for satellites and receivers since 2017 (Villiger et al. 2019), OPBs for satellites and receivers since 2018 (Schaer et al. 2018; Schaer 2020), BIAS-SINEX 1.00 format since 2017 (Schaer 2018);
Distribution:	CDDIS (short file names)	CDDIS (long file names) and ftp://ftp.aiub.unibe.ch/CODE_MGEX/

transmit antenna phase center offsets (PCO) compatible to the ITRF2008/2014 scale, which were estimated for Galileo (Steigenberger et al. 2016) and BDS2 (e. g., Dilssner et al. 2014; Guo et al. 2016; Huang et al. 2018). Semi-analytical SRP models were determined for Galileo (Montenbruck et al. 2015), QZS-1 (Montenbruck et al. 2017a; Zhao et al. 2018), and BDS2 (Duan et al. 2019). The empirical SRP model ECOM-TB (Prange et al. 2020) and its derivatives are, in theory, applicable to all satellites applying orbit normal (ON) attitude. An empirical thermal radiation pressure model for Galileo satellites suggested by Sidorov et al. (2019, 2020) is capable of improving the Galileo orbit accuracy during eclipse seasons by up to 14 %. Updated attitude information about BDS2 and BDS3 has recently been contributed by different groups (e. g., Zhao et al. 2017; Dilssner et al. 2018; Li et al. 2018; Xia et al. 2018).

The question, whether the level of detail of the disclosed meta data (size, optical properties, sub-division of satellite surfaces, spacecraft mass) is sufficient for defining a box-wing model suited for analytical SRP modelling—stand-alone or in combination with empirical or adjusted parameters is studied by different groups (e. g., Yuan 2018; McNair et al. 2018; Sośnica et al. 2019).

Prange et al. (2017b) demonstrated with MGEX data from the first two months of 2017 that even a simple box-wing model in combination with the disclosed spacecraft mass is feasible for modelling Earth albedo—thus reducing the satellite laser ranging (SLR) offset of Galileo orbits by ≈1.8 cm. A further reduction of the SLR offset by another ≈2 cm was achieved by modelling the antenna thrust using the disclosed mass information and the transmit power provided by Steigenberger et al. (2018). By estimating pseudo-stochastic pulses (Beutler et al. 1994) every 12 h in the radial, along-track, and cross-track directions of the local orbital reference frame, the SLR offset was shifted by another 0.5 cm and the inter quartile range (IQR) of the SLR residuals was reduced from ≈4.5 to ≈3.5 cm.

Ground antenna calibrations covering all GNSS, RNSS, and all frequencies became available to the IGS recently. They have been collected and analyzed by the IGS antenna WG (Villiger

Table 2: SLR residual and 3D orbit misclosure (OMC) statistics of COM orbits. Time interval: DOYs 1-320/2019. In brackets: satellites with ON-attitude or in eclipse seasons are excluded.

SLR	**Median [cm]**		**IQR [cm]**	
GLONASS	-0.1	(0.0)	4.6	(4.6)
Galileo	0.2	(0.2)	3.6	(3.4)
BDS2	0.1	(0.3)	6.7	(6.4)
QZSS	-1.5	(-2.5)	16.2	(14.8)
OMC	**Median [cm]**		**IQR [cm]**	
GPS	0.8	(0.8)	0.6	(0.6)
GLONASS	1.2	(1.2)	1.0	(1.1)
Galileo	1.4	(1.4)	1.0	(0.9)
BDS2	3.0	(2.9)	2.0	(1.9)
QZSS	4.0	(3.6)	3.4	(2.9)

et al. 2020). This particularly important topic is discussed in Sect. 5.1.

Several developments with a technical character improved the multi-GNSS capabilities of the software packages—in the case of the COM solution the Bernese GNSS Software (BSW, Dach et al. 2015). The replacement of differential-code biases (DCB) by an undifferenced, pseudo-absolute, observable-specific signal bias (OSB) representation (OCB are OSB referring to code observations, Villiger et al. 2019) allows, e. g., a more flexible handling of the observation biases belonging to the various signal types, which are present in an analysis based on data from the heterogeneously equipped IGS network. Observable-specific phase biases (OPB, Schaer et al. 2018; Schaer 2020) allow for generating ambiguity-fixed COM clock products since 2018 (Dach et al. 2019a).

4. Validation of COM satellite orbit and clock results

The COM orbits from the first 320 days of the year (DOYs) 2019 are validated by computing SLR residuals. The quality of the corresponding satellite clock corrections is represented by the RMS of the linear fit through the epoch-wise clock corrections for each day (subsequently abbreviated as RMS-LCF; see Prange et al. 2017a, for details). Figure 5 shows the satellite-specific median offset and IQR of the SLR residuals. The system-specific statistics of the residuals are listed in Tab. 2.

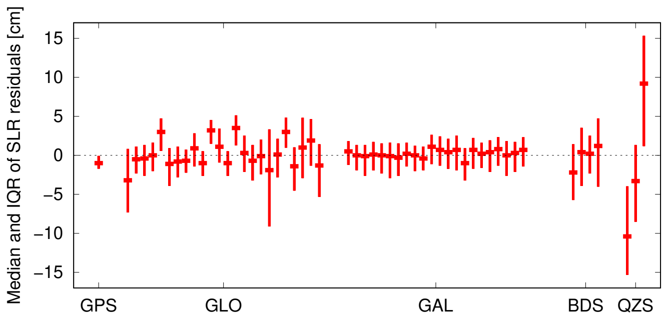

Figure 5: Median offset (horizontal bars) and IQR (vertical bars) of the SLR residuals of COM orbits. Time interval: DOYs 1-320/2019. Satellite PRNs are increasing from left to right

Compared to mid 2015 (Prange et al. 2017a) the overall IQR of GLONASS SLR residuals is slightly degraded due to issues with several aging GLONASS spacecraft, which have been analyzed in depth by Dach et al. (2019b). For BDS2 the difference between the IQR when in- or excluding orbits during eclipse-seasons is less pronounced than in 2015. This is partly attributed to the correct modelling of the ON-attitude and the use of the ECOM-TB SRP model during ON-intervals since 2018 (Prange et al. 2020). All QZSS spacecraft show significant SLR offsets in Fig. 5—either with positive or negative signs. Compared to 2015 the median offset of QZS-1 was reduced by several centimeters due to the activation of models for antenna thrust and Earth albedo in 2017. The reduction of the SLR offset is, however, less pronounced than expected from previous studies (e. g., by Prange et al. 2017b). Note that Prange et al. (2017b) assumed different spacecraft masses, dimensions, surface properties, and relied on a short data interval for their study.

The "new" GNSS performing best in Fig. 5 and Tab. 2 is Galileo. Compared to mid 2015 the absolute value of the SLR offset has dropped significantly (from -3.0 to +0.2 cm). The IQR has improved, as well (from 5.3 to 3.6 cm). Table 2 shows that the IQR is even smaller (i. e., 3.4 cm), when SLR residuals from eclipse seasons are neglected—indicating that the Galileo orbits are still slightly degraded during eclipses. Compared to GLONASS the orbit accuracy within the Galileo constellation is very homogeneous (Fig. 5). The median of the three-dimensional (3D) orbit misclosures (OMC) of the Galileo constellation is, however, slightly larger than that of GLONASS (Tab. 2). Despite these differences the orbit quality of GLONASS and Galileo is at a comparable level.

As orbit errors are mapped into the satellite clock estimates, the RMS-LCF represents not only the pure clock performance, but to some extent also orbit errors. Nevertheless, Galileo has the smallest RMS-LCF among all constellations analyzed in the COM solution (Fig. 6). This indicates not only that the performance of the Galileo satellite clocks is excellent. The estimated clock corrections are also less deteriorated by orbit errors of significant size than in the past (compare, e. g., with Prange et al. 2017a). As shown in Sect. 3 many model and processing changes contribute to the performance gain of Galileo in the COM solution. Subsequently, we address the most remarkable changes and their impact on the COM results in more detail.

4.1. Satellite meta data

The SLR time series of the Galileo IOV satellite SVN E102 (Fig. 7) illustrates that the most significant orbit improvements are related to two major upgrades: Firstly with the change of the SRP model from ECOM1 (Beutler et al. 1994) to ECOM2 (Arnold et al. 2015) in early 2015—significantly reducing orbit errors depending on the β-angle (elevation of the Sun above the orbital plane, see Prange et al. 2017a, for details); secondly with the activation of pseudo-stochastic pulses and several background models in Summer 2017, namely the models for Earth albedo, transmit antenna thrust, and Galileo eclipse attitude law (see Sect. 3). Based on the previous studies (Prange et al. 2017a, b) we assign most of the reduced variations in

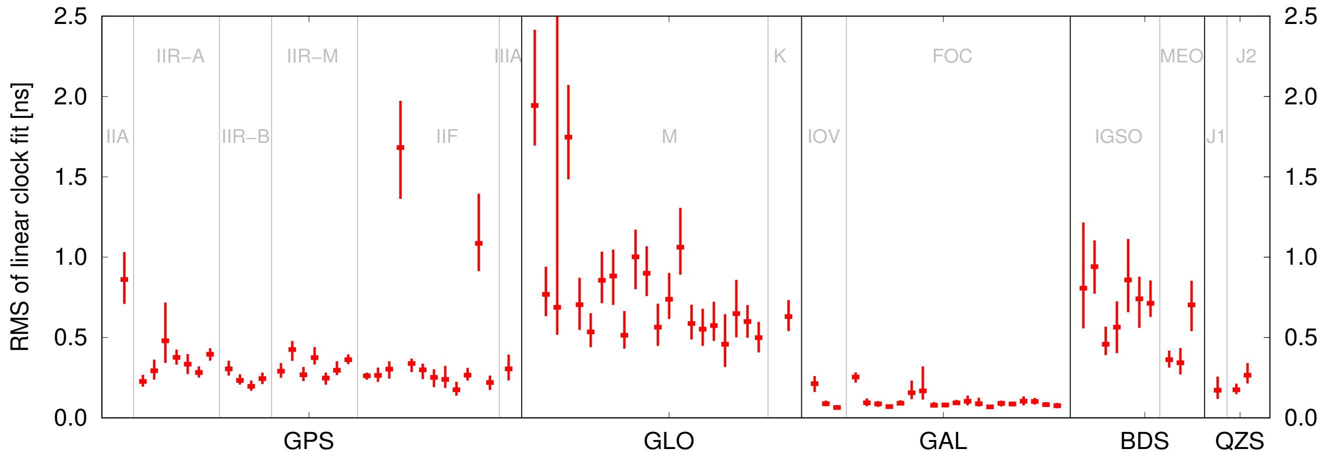

Figure 6: Median (horizontal bars) and IQR (vertical bars) of the daily RMS-LCF for COM clocks. Time interval: DOYs 1-320/2019. GNSS are separated by vertical black lines. Blocks are separated by vertical gray lines. Satellite SVNs are increasing from left to right within each block

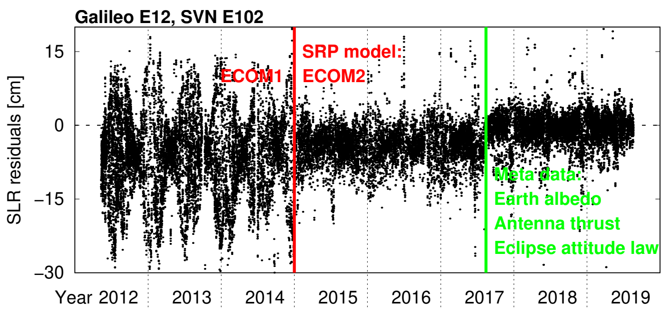

Figure 7: SLR residuals of Galileo IOV SVN E102. Vertical lines mark the activation of important model changes.

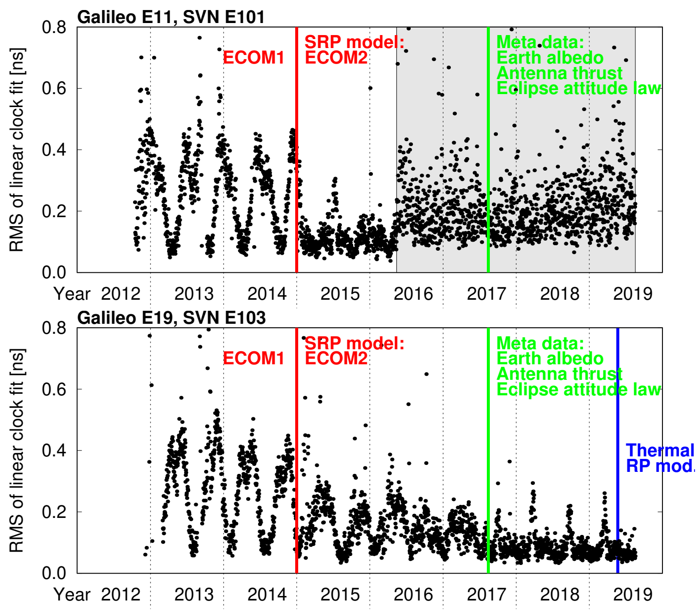

Figure 8: RMS-LCF of COM satellite clocks. Vertical lines mark the activation of certain model changes. **Top:** Galileo IOV SVN E101. **Bottom:** Galileo IOV SVN E103. **Shaded zones:** Active clock is a RAFS.

Fig. 7 to the improved SRP modelling (ECOM and pulses) and most of the SLR offset reduction to the models based on meta data (Earth albedo and transmit antenna thrust).

The update of the SRP model improved the RMS-LCF of the estimated Galileo clocks, as well (see SVN E101 in Fig. 8 top, as an example). Figure 8, top shows, however, that orbit improvements of the shown order of magnitude are only relevant for the Passive Hydrogen Maser (PHM) clocks. Rubidium Atomic Frequency Standard (RAFS) clocks, such as the one active on SVN E101 since spring 2016, cannot benefit because of their larger noise. SVN E103, on the other hand, relied on one of the PHMs all along since 2013 (Fig. 8, bottom). Nevertheless, for POD of this spacecraft the switch to the ECOM2 SRP model was slightly less benefitial as for SVNs E101 and E102. Unlike them, SVN E103 is moving in an orbital plane exhibiting larger maximum values of the β-angle (≈75-78° compared to ≈45-60° for SVN E101 and E102) within recent years. At high absolute values of β, the SRP coefficients related to one ECOM axis (E1-axis in Prange et al. 2020) are correlated with other parameters effective in Earth-Satellite direction (e. g., troposphere, pulses in radial direction) or influenced by modelling errors acting in this direction (e. g., z-PCO of transmitting and receiving antennas, antenna thrust, Earth albedo). This fundamental weakness of ECOM SRP models has previously been addressed by other authors (e. g., by Meindl 2011)—underlining the need for further improvements in SRP modelling.

Figures 8 (bottom) and 9 (top) show that reducing the radial orbit errors (see Fig. 7) by activating the meta data-driven models in 2017 had no significant impact on the RMS-LCF: The radial orbit offset caused by the unmodelled Earth albedo and antenna thrust can be absorbed by the clock offset, while a mismodelled attitude during eclipse affects only a limited number of epochs.

4.2. Thermal radiation modelling

The statistics of the SLR residuals in Tab. 2 and the time series in Fig. 7 confirm earlier reports (e. g., Prange et al. 2017a)

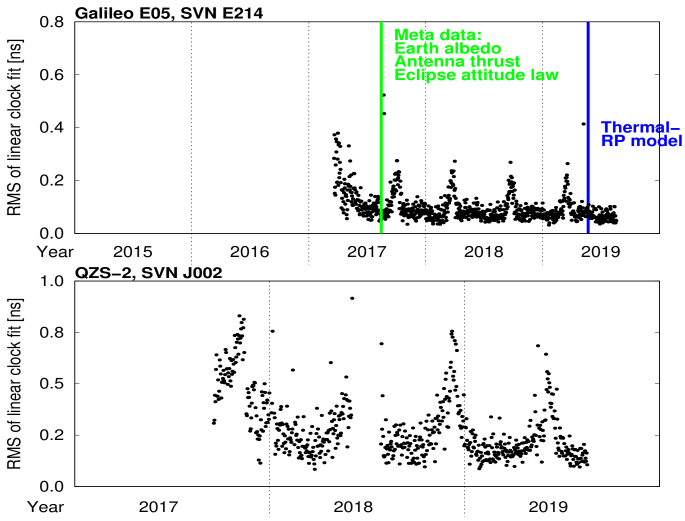

Figure 9: RMS-LCF of COM satellite clocks. Vertical lines mark the activation of certain model changes. **Top:** Galileo FOC SVN E214. **Bottom:** QZSS SVN J002.

of elevated Galileo orbit errors during eclipse seasons, showing up in the satellite clocks, as well (Figs. 8 and 9). The initial assumption that attitude errors may be the main reason for this orbit degradation, was later ruled out by Prange et al. (2017b), who reported that most of the degradation remained—even after the correct eclipse attitude law was applied.

A dedicated analysis performed by Sidorov et al. (2019, 2020) exposed thermal radiation from the spacecraft body as the cause. This analysis also showed that these orbit errors are more prominent in a POD relying on long orbit arcs. Based on realistic assumptions Sidorov et al. (2019, 2020) developed an empirical model for accelerations caused by the spacecraft's thermal radiation and achieved an improvement of Galileo orbits and clocks by about 14 % during eclipse seasons. The authors expect more significant improvements when additional meta data about the spacecraft (e. g., details on the thermal control) becomes available.

Note that the satellite clock statistics of QZSS satellites are degraded during eclipse seasons (Fig. 9, bottom) by a similar signal as the Galileo FOC spacecraft—however with a larger amplitude (≈0.8 rather than 0.2–0.3 ns).

4.3. Observation biases and ambiguity resolution

The change from DCBs to OCBs in Summer 2017 is not visible in the shown validations, because the COM analysis is based on phase measurements. The change allows, however, for a more consistent and flexible handling, estimation, application, and reporting of GNSS observation biases and thus contributes to the overall consistency and stability of the solution—especially to the clocks and to the ambiguity resolution (AR) in a multi-GNSS environment.

Making use of the OCBs the COM double-difference (DD) orbit solution incorporates narrow-lane (NL) and wide-lane (WL) AR for the new satellite systems Galileo, BDS2, and QZSS since Summer 2017 (see Dach et al. 2018, for details). The typical percentage of resolved ambiguities per system is listed in Tab. 3. The resolution rates of GPS and Galileo are at similar levels.

Table 3: Percentage of resolved ambiguities in double-difference (**DD**, elevation cutoff: 3°) and zero-difference (**ZD**, elevation cutoff: 5°) COM solutions.

GNSS	DD [%]	ZD [%]
GPS	≈60	≈80
GLONASS	20-25	n/a
Galileo	60-65	≈85
BDS2	≈45	70-75
QZSS	40-50	50-60

OPBs were introduced to the COM zero-difference (ZD) clock solution in June 2018 in parallel with CODE's legacy IGS solutions. Their determination is a pre-condition for ZD AR activated in the CODE clock analysis (including the COM clocks) at the same time (Dach et al. 2019a). While the IGS Rapid and Final clock analysis performs NL and WL AR for GPS, the COM analysis performs NL and WL AR for GPS and Galileo, while NL AR is active for BDS2 and QZSS. Note, that the AR success rates in Tab. 3 are generally better in the ZD- than in the DD-analysis, because they do not depend on baseline lenghts. For GPS the excellent performance of ambiguity-fixed satellite clocks is confirmed by the IGS clock combination (IGS ACC 2019). For MGEX products, a combination is not yet available. Schaer (2020) demonstrate, however, that phase-aligned COM Galileo clocks in combination with OPBs allow for precise point positioning (PPP) with ambiguity fixing (PPP-AR). Compared to a conventional static PPP the repeatability of the East coordinate component improves significantly (from 2.7 to 1.6 mm), which is in good agreement with the GPS results presented by Schaer et al. (2018) and Banville et al. (2020). Banville et al. (2020) emphasize that phase biases are required for generating combined IGS clock products enabling PPP-AR. They encourage the use of OSBs for this purpose. The COM clocks are, thus, already prepared to contribute to such a kind of potential IGS product.

Moreover, ZD ambiguity-fixing does also improve the day-to-day continuity of satellite clocks estimated in independent daily sessions. This may increase their value for dedicated applications, such as testing general relativity utilizing the high-performance PHM clocks onboard the Galileo spacecraft (SVNs E201 and E202) in excentric orbits (Juan et al. 2019). According to Schaer (2020), the standard deviation of integer-corrected between-satellite COM Galileo clock differences extrapolated to the midnight epochs is at a level of 12 ps. The corresponding value for CODE's Final GPS clock product (not affected by extrapolation errors) is about 8 ps (Schaer et al. 2018).

5. New satellite systems in the IGS products

Recalling the goal of the IGS MGEX effort "to prepare the IGS for inclusion of new satellite systems into IGS products" (see Sect. 1) we discuss subsequently, whether we are sufficiently prepared for such a step after seven years of MGEX operations.

Section 2.1 showed that Galileo is currently the only "new" GNSS included in the IGS MGEX, which is fully established. The other systems are either RNSS (QZSS, BDS2, IRNSS), SBAS, or GNSS that are still under deployment (BDS3). The question, whether and how SBAS and RNSS should contribute to legacy IGS products and which "side effects" (e. g., on TRF parameters) this may cause, needs further research. Therefore, we focus on fully deployed GNSS here, i. e., on Galileo. The validations in Sect. 4 confirm that Galileo performs best among the "new" satellite systems analyzed in COM. This is to a large extent attributed to significant improvements in the processing strategy (observation biases, AR) and to improved background models, which are listed in Sect. 3. With the orbit and clock accuracy similar or even superior (in the case of the satellite clocks) to GLONASS, Galileo is definitely ready for inclusion into the legacy IGS products. In Sect. 2.2 we learned that the legacy IGS network is meanwhile ready for the new satellite systems—thanks to the successful execution of the RINEX3 transition plan by the IGS.

In summary we consider Galileo as a valid candidate GNSS for legacy IGS products. There are, however, IGS-related criteria that need to be taken into account. We will discuss them subsequently.

5.1. The role of the antenna calibrations

Providing operational and scientific geodesy users access to the ITRF, including its scale, is a major task of the IGS legacy products (Altamimi 2013). A consistent ITRF access can only be ensured when the ITRF scale, ground antenna calibrations, and transmit antenna calibrations are consistent (see Villiger et al. 2020, for a detailed discussion). Absolute robot calibrations of receiver antennas for the L1 and L2 frequencies of GPS and GLONASS are used by the IGS since 2006 (Gendt 2006). Transmit antenna phase center offsets (PCO) of GNSS satellites were, however, not available so far. Therefore, the IGS uses transmit antenna PCOs of GPS and GLONASS, which were estimated maintaining the consistency to the ground antenna calibrations and to the scale introduced by the ITRF (currently ITRF2014, Altamimi et al. 2016). As the satellite PCOs depend on the ITRF scale, GNSS cannot contribute to the definition of the scale, so far (Schmid et al. 2016).

For the new GNSS included in the MGEX, IGS-compatible robot calibrations of the ground antennas were for a long time not available. Their PCO values were instead adopted from the GPS L1 and L2 frequencies. The expected coordinate inconsistency (i. e., different coordinates for different GNSS) is one of the reasons why new GNSS have not yet been included in the legacy IGS products. The satellite antenna PCOs of the new satellite systems estimated in recent years (Sect. 3) are compatible with the adopted ground antenna PCOs and with the current ITRF scale. In order to preserve this consistency the COM solution makes use of the Galileo PCOs provided by Steigenberger et al. (2016) since they became available.

A new situation emerged with the disclosure of Galileo and QZSS satellite antenna calibrations (a step that was, amongst others, encouraged by Schmid et al. 2016) and the recent availability of ground antenna calibrations incorporating all satellite systems and frequencies (Sect. 3). This offers the opportunity to independently determine the terrestrial scale with GNSS for the first time (Villiger and Rebischung 2019). Detailed analysis by the IGS antenna WG revealed that the Galileo-defined scale differs from the current IGS scale (introduced from ITRF14) by about 1 ppb, corresponding to a height difference on the ground of about 6.5 mm or a z-PCO difference at Galileo orbit height of about 15 cm (Villiger et al. 2020).

The IGS antenna WG, therefore, provides two different sets of antenna correction models: One is intended for generating operational IGS products maintaining full consistency with the ITRF2014 when analyzing GPS or GLONASS data. For Galileo it has been gradually extended with the disclosed satellite antenna calibrations once they were published. For the ground antennas the adopted Galileo calibrations continue to be used. When this file is applied to Galileo data analysis, biases w. r. t. to the ITRF14 coordinates have to be expected because of the above mentioned scale inconsistencies.

Another set of antenna correction models is intended for use in the third IGS reprocessing campaign, which will contribute to the next ITRF release (Moore et al. 2018). It contains all disclosed satellite antenna calibrations, estimated satellite antenna offsets (for those satellites without disclosed calibration information), as well as an updated, complete (all systems, all frequencies), and self-consistent set of ground antenna calibrations. As the receiver antenna calibrations of GPS and GLONASS are updated in this file, as well, it is not compatible with the ITRF2014 scale.

5.2. Galileo in CODE's IGS products

Acknowledging the progress achieved for Galileo data analysis in recent years, the IGS decided to open its third reprocessing campaign for Galileo (Moore 2019)—utilizing the dedicated antenna correction model described in Sect. 5.1. Villiger et al. (2020) demonstrated that the Galileo satellite and ground antenna calibrations can be used to define an independent scale and re-determine the transmit antenna offsets of GPS and GLONASS consistent with this scale. As the station coordinates do usually change between different TRF releases anyway, the reprocessing is an excellent opportunity to apply significant (model) changes or to introduce additional satellite systems without affecting the time series of operational GNSS products. CODE and other ACs therefore decided to contribute to the third IGS reprocessing campaign with an orbit and clock solution that includes not only GPS and GLONASS, but also Galileo.

The IGS Final products aim at providing users access to the latest ITRF (currently ITRF2014) with highest accuracy and consistency in a post-processing mode. It may also serve as a "ground truth" and reference for own developments or implementations. In order to keep the time series of Final products fully consistent with the current ITRF and to avoid additional jumps in the coordinate time series, CODE's Final analysis will continue to rely on GPS and GLONASS only—until the release of a new ITRF (Dach 2019).

The circumstance that MGEX products are meanwhile used by operational services (e. g., by Brockmann et al. 2019) does,

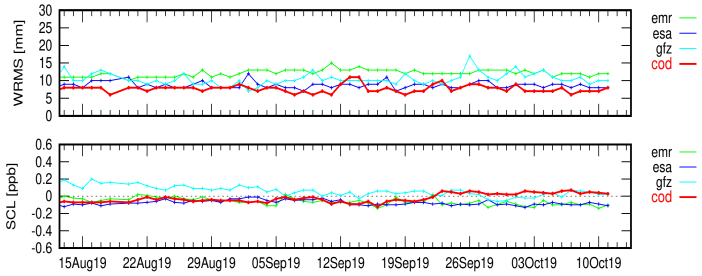

Figure 10: Rapid GPS orbits from selected ACs vs. IGS combination (**cod** stands for CODE Rapid here). Top: Weighted RMS of difference. Bottom: Scale.

however, indicate a demand for reference products supporting the new satellite systems already now. Brockmann et al. (2019) point out that one of the main benefits of additional GNSS is an improved availability of kinematic positioning under difficult visibility conditions (e. g., with high elevation masks in alpine areas or urban areas). This argument fosters the recommendations by the IGS MGEX WG (Montenbruck 2018) suggesting that the demand for multi-GNSS capability is most urgent for Ultra-Rapid and Rapid reference products. These products typically aim at providing operational (often institutional, administrative, or commercial) users with near real-time (estimated part) or real-time (predicted part) reference products. For this user group latency, availability, and reliability requirements often outweight the need for highest accuracy. Since the integrated IGS network is meanwhile able to provide sufficient Galileo tracking data with short latency (Sect. 2.2), CODE decided to activate Galileo in its Ultra-Rapid and Rapid chains using the ITRF2014-compatible antenna correction model (Sect. 5.1) on September 23, 2019 (Dach 2019). Inter-system coordinate biases as reported by Villiger et al. (2020), which are likely to occur until the new release of the ITRF becomes available, are deemed acceptable for these products. A first assessment of the IGS Rapid GPS orbit combination confirms that the inclusion of Galileo had no negative impact on the quality of the GPS orbits (Fig. 10, top). As expected, the scale of the GPS orbits has, however, slightly changed (Fig. 10, bottom).

CODE will continue to use MGEX as a test-bed for further developments mainly related to new satellite systems. Since RNSS and SBAS are not (yet) included in any legacy IGS product, MGEX remains important in particular for these systems.

6. Conclusions

We reviewed the COM orbit and clock solution, emphasizing the main developments w. r. t. the previous assessment by Prange et al. (2017a) representing the status in early 2015. Section 3 shows that many of the challenges identified by Prange et al. (2017a), which were so far hampering the inclusion of new satellite systems in legacy IGS products, have been addressed in the meantime. Hereby, the disclosure of satellite-related information by the system operators of Galileo and QZSS marks a milestone. In combination with recent research the disclosed meta data allows for modelling Earth albedo, transmit antenna thrust, and attitude during eclipse seasons. Other models, based on research at CODE (e. g., empirical models for thermal radiation and SRP for satellites under ON attitude) were introduced, as well. Substantial improvements have also been achieved in the multi-GNSS data integration—in particular concerning observable-specific signal biases (OSB) for code and phase observations and integer-ambiguity fixed clocks. In summary Galileo and QZSS benefited most from the recent developments of the COM solution (Sect. 3).

Section 2.1 shows that the GNSS Galileo and the RNSS QZSS and BDS2 are meanwhile fully established and operational (at least initially). After the successful execution of the IGS RINEX3 integration plan, the IGS infrastructure (i. e., network, data center, interfaces) is sufficiently prepared for these systems (see Sect. 2.2).

The validations in Sect. 4 confirm that the above mentioned developments result in significant improvements of the COM orbits and clocks—in particular for Galileo. Compared to Prange et al. (2017a) the median SLR offset was reduced from -3.0 to +0.2 cm and the IQR of the SLR residuals from 5.3 to 3.6 cm. With these values Galileo is not only the best performing "new" constellation in the COM solution—it performs even better than GLONASS. In summary we consider Galileo sufficiently mature for inclusion in legacy IGS products (Sect. 5). The question, whether and how RNSS and SBAS should contribute to IGS products, however, needs further research.

A background-model closely connected to the IGS task of providing GNSS users access to the current ITRF is the antenna model for transmitters and receivers. Based on latest results from Villiger et al. (2020), we conclude in Sect. 5.1 that the immediate application of the recently disclosed receiver antenna and Galileo transmit antenna calibrations in legacy IGS products would pose the risk of introducing jumps in the coordinate time series and scale incompatibilities w. r. t. the ITRF2014.

Accepting this limitation for short-latency products, CODE decided to activate Galileo in its Rapid and Ultra-Rapid solutions—making them the first legacy IGS analysis products that include three systems (namely GPS, GLONASS, and Galileo, Dach 2019). In the case of the Final products we conclude, however, that consistency with the current ITRF has highest priority (Sect. 5.2). The inclusion of Galileo in CODE's Final products is, therefore, postponed to the release of the next ITRF. The importance of the disclosed Galileo antenna calibrations is underlined by the IGS decision to include Galileo in its third reprocessing campaign with the option to define an independent IGS scale for the first time—based on the Galileo calibrations (Villiger and Rebischung 2019). CODE supports this idea by participating in this reprocessing effort with a three-system (GPS, GLONASS, Galileo) solution.

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