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GPS, GLONASS, Galileo and BeiDou real-time products validation

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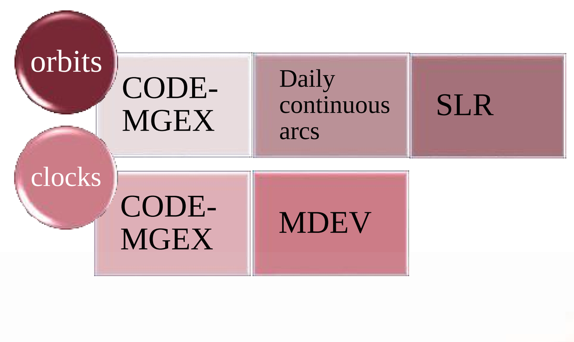
INTRODUCTION

The existing Global Navigation Satellite Systems (GNSS), GPS and GLONASS, are systematically modernized and together with systems that are constantly developed (Galileo, BeiDou and QZSS) allow for improving the accuracy and enables performing the GNSS measurements in demanding environment. Among GNSS fields of application we can distinguished: the primary application which is focused on coordinate determination, space weather monitoring and estimation of the zenith total delay. Multi-GNSS experiment (MGEX) has been established by the International GNSS Service (IGS) to provide precise products for all available systems. The most precise products ensured by IGS may be used only in post-processing mode due to the latency of these products. In order to enable calculations in real-time, a user has to take advantage of corrections which are provided in real-time and are delivered to the users e.g. via Internet. Such corrections are produced by IGS Real-Time (IGS-RT) service which provides data for GPS and GLONASS. Another analysis centre which provides corrections for all available systems is Centre National d'études Spatiales (CNES).

METHODOLOGY

QUALITY ASSESSMENT SCHEME



We check the availability and quality of real-time corrections provided by CNES for orbits and clocks. Dates from 1st to 30th of April 2016 (DoY 92-121) were selected as a test period. All computations were performed in post-processing mode using the in-house developed Wroclaw Algorithms for Real-time Positioning Software (GNSS-WARP). Additionaly, Bernese GNSS Software for SLR analysis was used. BKG Ntrip Client (BNC) was employed as a decoder of RTCM messages. Orbits were assessed in three ways: by comparing to the post-processed MGEX products, by analyzing orbit discontinuities through fitting continuous arcs, and by validating using the Satellite Laser Ranging (SLR) technique. The clocks were evaluated using the post-processed MGEX products as a reference data and by the analysis of the clock stability using Modified Allan Deviation (MDEV).

PRODUCT AVAILABILITY

Figure 1 illustrates the availability of clock and orbit corrections in the test period. The overall availability statistics are presented in Table 1. Four different groups of unavailability events are listed in Table 2.

Table 1 Percentage availability of the precise real-time orbit and clock corrections for April 1-30, 2016

	GPS	GLONASS	Galileo	BeiDou
max	94 (G15)	92 (R06)	91 (E12)	85 (C07)
min	52 (G32)	50 (R16, R17)	12 (E08)	38 (C03)
median	92	91	90	83

Table 2 Corrections unavailability events for April 1-30, 2016

Unavailability	Example	Possible reason
Permanent	G04	No corrections provided
Temporal	R01, R22	Scheduled manuveres, Short time from the satellite launching
No corrections for some systems	first half of DoY 108 for BeiDou	mismatches in the transmitted streams
No corrections for all systems	Vertical bands on Figure 1	Internet connections failure

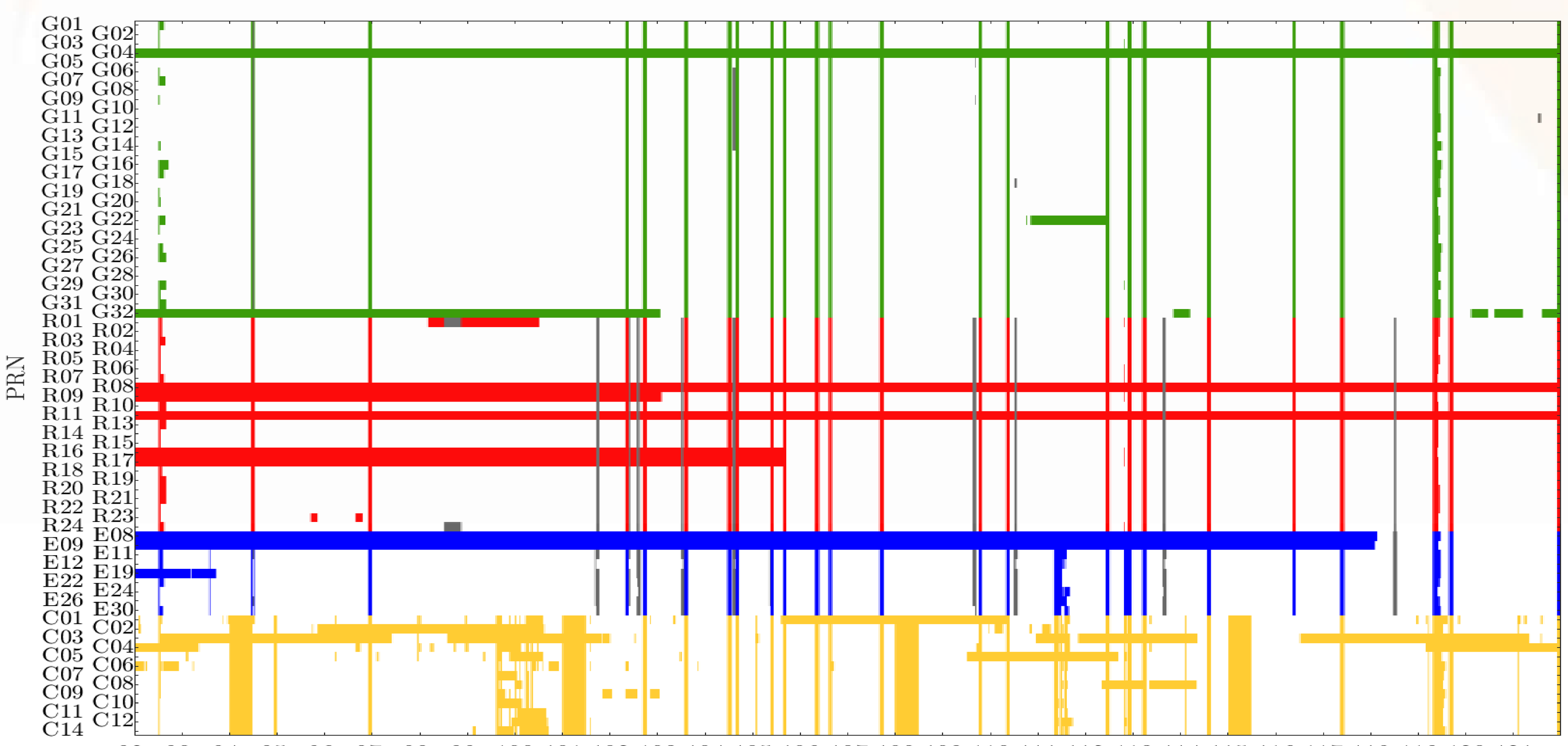


Fig. 1 Availability of precise real-time orbit and clock corrections for April 1-30, 2016 - GPS (green), GLONASS (red), Galileo (blue), BeiDou (yellow), broadcast ephemeris (grey), unavailability epochs are filled

Fitting continuous orbital arcs

For the orbit fit, ECOM2 is used with the estimation of 9 empirical parameters with no stochastic pulses. Figure 4 shows some discontinuities which for MEO orbit reach up to 6cm while for BeiDou IGSO are several times bigger than the results for MEO. The substantial discontinuities for BeiDou GEO satellites which reach up to 6m may refer to a deep 1:1 orbit resonance with the Earth's gravity field. The discontinuities interval is equal to 3h for GPS and GLONASS and 6h for Galileo and BeiDou. This may be connected with the period of orbit prediction. The standard deviation values for the residuals of the fitting procedure are listed in Table 4.

Table 4 Standard deviations from fitting a continuous 1-day orbit

	3D StdDev [cm]
GPS	4.9
GLONASS	10.6
Galileo	16.7
BeiDou MEO	18.7
BeiDou IGSO	41.7
BeiDou GEO	169.9

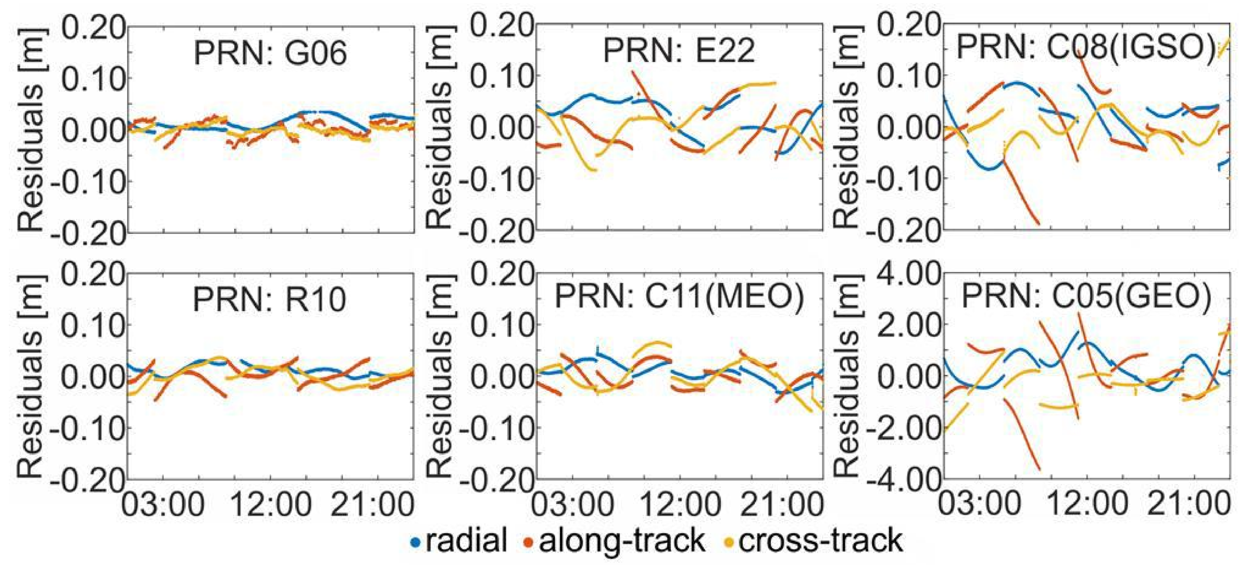


Fig. 4 Examples of radial, along-track, cross-track fitting residuals for DoY 98, 2016; note a different scale for C05

Orbit validation using SLR observations

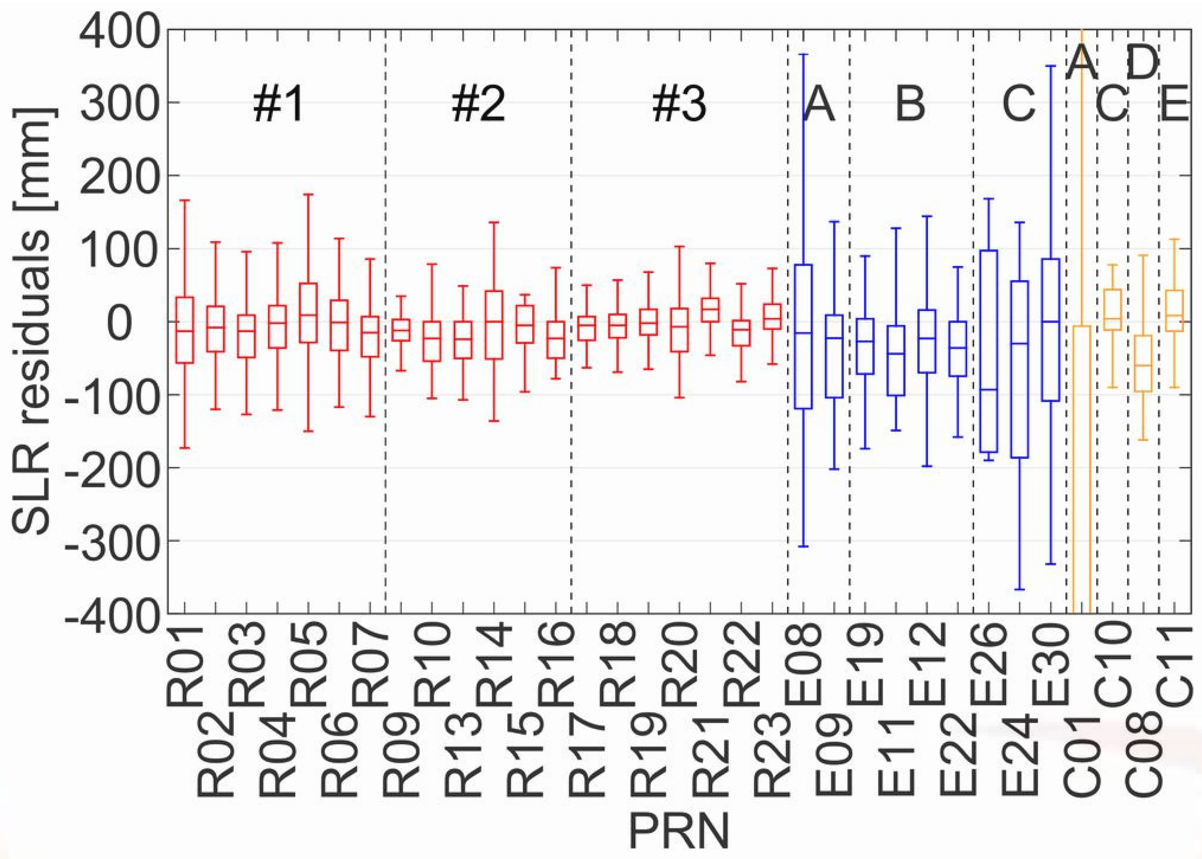


Fig. 5 Results from the validation of RT orbits using SLR observations for April 1-30, 2016 with a distinction between different orbital planes for GLONASS, Galileo and BeiDou

Table 5 Standard deviation of SLR residuals for April 1-30, 2016

	3D StdDev [cm]
GLONASS	4.1
Galileo	8.2
BeiDou MEO	4.0
BeiDou IGSO	6.3
BeiDou GEO	84.2

Active GPS satellites are not anymore equipped with retro-reflectors, thus, the orbit validation using SLR is not possible for GPS today. The results from the SLR validation show a twice lower accuracy for Galileo satellites than for fully operational GLONASS (see Fig 5 and Table 5). GLONASS satellites from the orbital plane #1 have a little worse quality than spacecraft from the orbital planes #2 and #3 which is similar to the comparison with MGEX final products. The quality of the obtained satellite positions depends on the orbital plane. This aspect is especially visible for Galileo satellites. Statistics illustrate a significantly worse quality for BeiDou GEO satellite.

Assessment of clock stability using Modified Allan Deviation

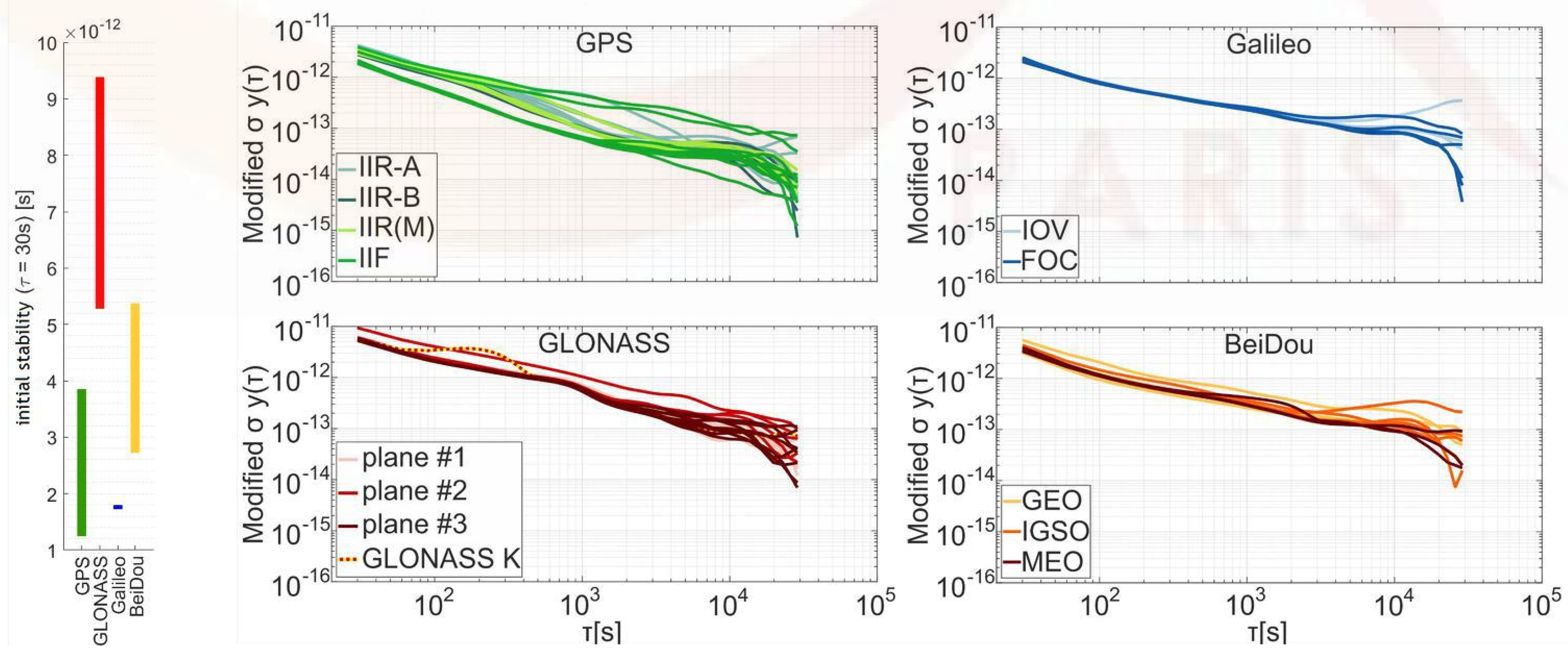


Fig. 6 Initial clocks stability (left) and RMSE of RT orbits and clocks referenced to the CODE MGEX final solution (right) for DoY 120, 2016

QUALITY ASSESSMENT

ORBIT AND CLOCK COMPARISON TO FINAL CODE PRODUCTS

Radial is the best determined component for all GNSS. For GPS satellites it is hard to find strong relations between the orbital plane or satellite block and the orbit quality. GLONASS satellites from the orbital plane #1 obtain slightly bigger residuals than GLONASS satellites from planes #2 and #3. This is probably related to low Sun elevation angle β above the orbital plane #1 (-5.0° to 25.2°) in the test period. Additionally, it is necessary to split BeiDou satellites according to the orbital type (Figure 3) because of significantly worse results for satellites that occupy IGSO planes. Residuals obtained by the FOC and IOV Galileo satellites were slightly different. Statistics are shown in Table 3.

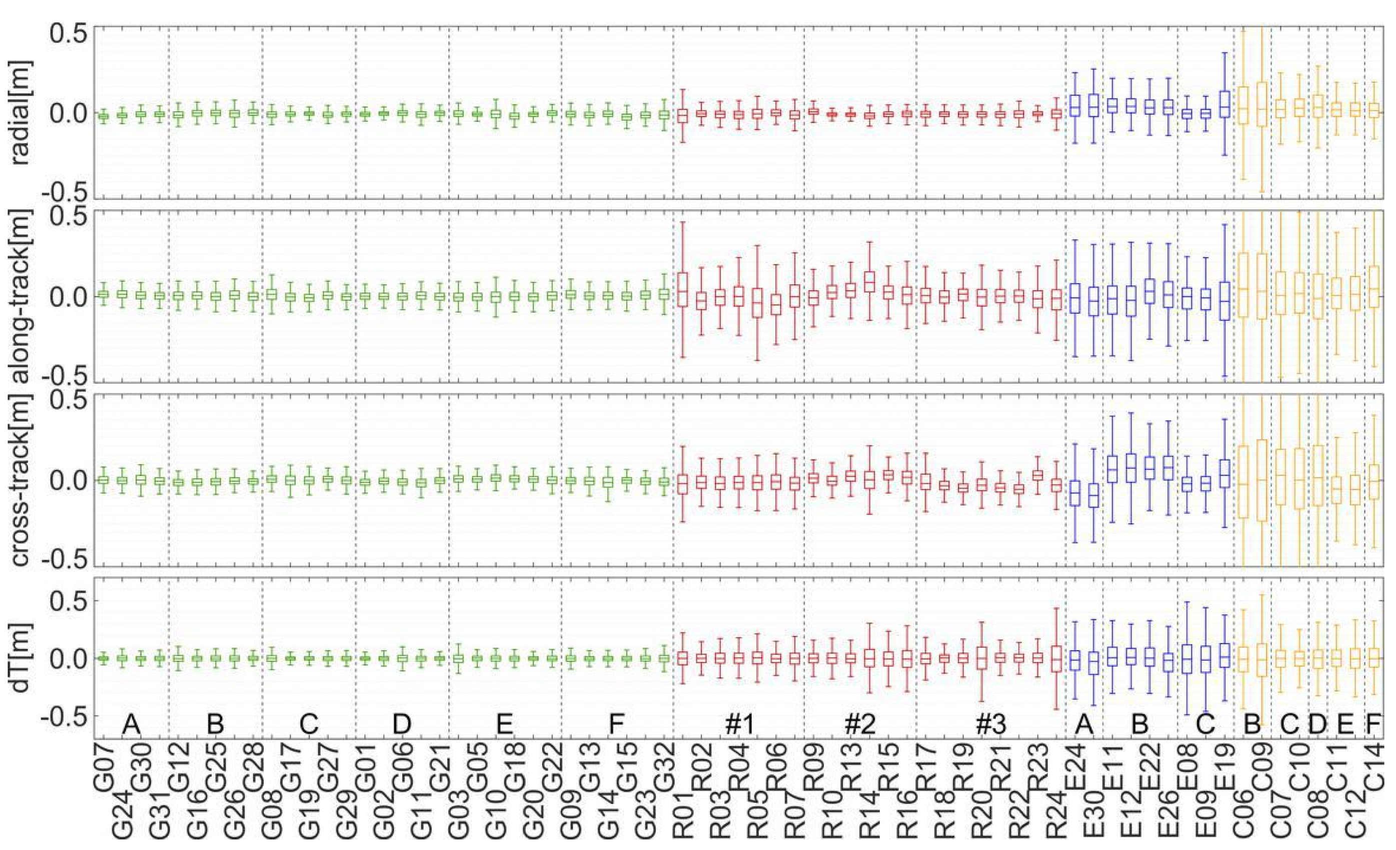


Fig. 2 Differences of orbit positions and clocks calculated on the basis of RT products with reference to CODE MGEX products for April 1-30, 2016 for GPS (green), GLONASS (red), Galileo (blue), BeiDou (orange)

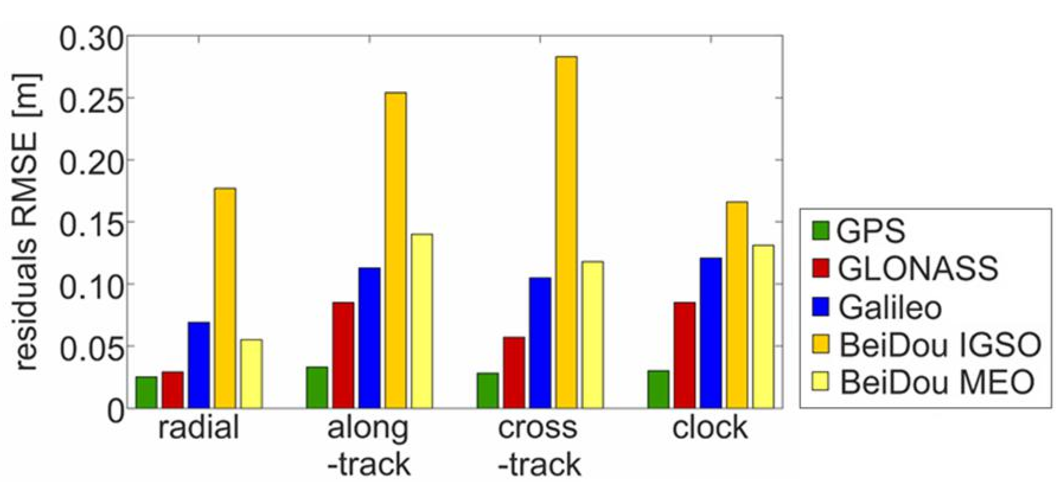


Fig. 3 RMSE of RT orbits and clocks referenced to the CODE MGEX final solution for April 1-30, 2016

Table 3 Standard deviation for orbits and clocks calculated on the basis of real-time corrections with respect to CODE MGEX orbits for April 1-30, 2016

	GPS	GLONASS	Galileo	BeiDou MEO	BeiDou IGSO
3D StdDev [cm]	4.9	10.6	16.7	18.7	41.7
Clock StdDev [cm]	3.0	8.5	12.1	13.1	16.6

Modified Allan Variance diagram in Figure 6 indicates that Galileo has the most consistent clocks. The analysis of the clock stability indicates that the stability is related to the satellite block. The large differences are especially visible in the case of the GPS system. What is more, the clock stability is not related to the orbital type which may be proven by the BeiDou system. For the GLONASS-K satellite some problems occur in the initial part of the integration period (τ=200s). The bump is hard to explain and verify because there is no other satellite of the GLONASS-K type.

SUMMARY

Satellite positions and clocks calculated on the basis of real-time corrections obtain different quality. The availability of real-time corrections in the test period is at the level of about 80% for BeiDou and about 90% for the remaining GNSS systems. All used validation methods confirm the hierarchy of the GNSS accuracy as follows: GPS, GLONASS, Galileo and BeiDou. These results may form a background for further works connected with real-time PPP (e.g. appropriate observation weighting).

ACKNOWLEDGMENTS

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