IOP Publishing

Measurement Science and Technology

Meas. Sci. Technol. 31 (2020) 055012 (6pp)

https://doi.org/10.1088/1361-6501/ab69d4

Impact analysis of arc length in multi-GNSS ultra-rapid orbit determination based on the one-step method

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Received 6 November 2019, revised 24 December 2019
Accepted for publication 9 January 2020
Published 5 March 2020

Abstract

With the development of near real-time and real-time high-precision global navigation satellite system (GNSS) applications, users' requirements for the accuracy and stability of ultra-rapid orbits have increased, especially for multi-constellation orbits. Generally, several factors affect the accuracy and stability of multi-GNSS ultra-rapid orbit determination; however, this study is focused only on analyzing the orbit arc length of ultra-rapid orbits of the GPS, GLONASS, BeiDou-2, and Galileo satellites based on the one-step method. To realize nearly ideal conditions in the process of analysis, one full year's rapid orbit products during 2018 provided by the GeoForschungsZentrum multi-GNSS experiment analysis center were used as fitted observed orbits and also as a reference orbit for comparison to the predicted orbit. In terms of residual analysis of orbit difference and stability analysis of Helmert transformation parameters, the numerical results showed that the optimal orbit arc lengths of quad-constellation medium earth orbit (MEO) satellites for 6 h and 3 h predicted ultra-rapid orbits based on the one-step method were in the range of 44–45 h and 41–44 h, respectively. Overall, for both 6 h and 3 h predictions, when only considering the impact of the orbit arc length on the accuracy and stability of the orbit itself, 44 h can be considered as the overlapping optimal orbit arc length of quad-constellation MEO satellites' ultra-rapid orbits generated by the one-step method. In addition, these ranges of orbit arc length can contribute to the multi-GNSS ultra-rapid orbit determination.

Keywords: multi-GNSS, one-step method, optimum arc length, prediction strategy, ultra-rapid orbit

(Some figures may appear in colour only in the online journal)

1. Introduction

Compared to real-time kinematic positioning [1, 2], satellite ultra-rapid orbit products are some of the most important products for positioning, navigation, and timing users to obtain real-time and near real-time precise services in a single point mode [3, 4]. Several research projects have been focused on improving the accuracy of satellite ultra-rapid orbit products as this has always been a difficulty in the field of global navigation satellite systems (GNSSs) [5–8]. Development over decades has led to improvements in the updating rate of GPS satellites' ultra-rapid orbit products provided by the International GNSS Service (IGS), from 12 h initially to the current 6 h. Orbit accuracy (one-dimensional mean RMS values in the three *XYZ* geocentric components) has also been reduced from dozens of cm initially to approximately 5 cm.[1] Although the

[1] www.igs.org/products.

IGS has not yet provided combined GPS/GLONASS satellite ultra-rapid orbit products, some IGS analysis centers (ACs) have developed and providedultra-rapid orbit products from a single GPS satellite to a GPS/GLONASS dual system [2] [9–11]. With the establishment and development of the multi-GNSS Experiment (MGEX), the precise orbit determination of multi-GNSS satellites based on the one-step method [12–14] has become one of the IGS's top research priorities.[3] Currently, the key methods to improve the accuracy of the GNSS satellites' ultra-rapid orbits are as follows: (1) shortening the time interval for updating the ultra-rapid orbit, such as from 6 to 3 h, or even to 1 h [5, 7, 15]; (2) improving the models and strategies for precise orbit determination (POD), such as the attitude and solar radiation pressure (SRP) model, or choosing the 'one-step method' and 'two-step method' separately [16–18]; (3) optimizing the distribution of reference stations for POD [19]; (4) improving the accuracy of short-term predictions of earth rotation parameters (ERPs) [20]; (5) choosing the optimal orbit arc length of orbit prediction [21, 22]; and so on.

In this study, only progress related to the impact of orbit arc length on orbit prediction is discussed. Although some MGEX ACs are testing ultra-rapid orbit products of additional systems to provide stable and reliable products for multi-GNSS users in the future, there are relatively few analyses determining the multi-GNSS satellites' ultra-rapid orbits based on the one-step method. In particular, there are few studies on the impact analysis of the prediction strategy and of the optimum arc length of quad-constellation (GPS, GLONASS, Galileo, and BeiDou-2 (BDS)) medium earth orbit (MEO) satellites[4] [12]. It is well known that the key to determining the ultra-rapid orbits of GNSS satellites is to use a known precise orbit arc to fit the initial state of the satellite as well as other information such as the SRP [23], or to directly calculate the initial state of the satellite and other information according to the observations of a certain arc length, and subsequently to use numerical integration to obtain the predicted orbits [12, 21]. Presently, in order to better match the corresponding ultra-rapid orbit determination algorithms and strategies, some IGS ACs are using different orbit arc lengths to provide their ultra-rapid orbit products for the GPS satellites, e.g. NASA's Jet Propulsion Laboratory uses 30h orbit arc lengths to generate ultra-rapid orbits and provide these products to users.[5] Natural Resources Canada[6], the U.S. Naval Observatory AC[7], Geodetic Observatory Pecný in the Czech Republic [7, 9, 10] and Wuhan University (WHU)[8] [24] use 48–72, 27, 72, and 24 h orbit arc lengths to provide ultra-rapid orbit products, respectively. Additionally, to develop a prediction strategy that contributes to the IGS ultra-rapid product combination, Choi *et al* [21] analyzed the impact of orbit arc length on ultra-rapid orbits based on the GPS rapid orbit products provided by the IGS, and it was concluded that the most stable and accurate ultra-rapid GPS satellite orbits can be obtained with an orbit arc length of 40–45 h [21]. For better precise point positioning ambiguity resolution (PPP AR) and positioning, Li Y *et al* [22] analyzed both the impact of orbit arc length on ultra-rapid orbits, and the impact on satellite clock estimation and PPP AR. The final analysis showed that an orbit arc length of 38–48 h can obtain satisfactory results, and 42–48 h was the recommended range for the predicted 6 h orbits of the GPS satellites [22]. Subsequently, analysis of the ultra-rapid satellite orbits and ERP products provided by the Center for Orbit Determination in Europe (CODE) [11] led to a change in the orbit arc length of GPS/GLONASS dual-system ultra-rapid orbit products provided by the CODE AC from 72 h initially to the current 54– 60– 66– 72 h [11]. Considering the GPS rapid orbit products provided by IGS, the GLONASS final orbit products provided by IGS, and the BDS/Galileo final orbit products provided by WHU, Geng *et al* [25] analyzed the impact of orbit arc length on ultra-rapid orbits of each satellite navigation system separately, and it was concluded that 40–45, 42–48, 42–48, and 42–54 h orbit arc length obtain the best ultra-rapid orbits for the GPS/GLONASS, Galileo, BDS inclined geosynchronous orbit, and BDS-MEO satellites, respectively [25]. The aforementioned studies can provide beneficial references for GPS and GPS/GLONASS ultra-rapid orbit determination, as well as provide valuable information for multi-GNSS ultra-rapid orbit determination based on the two-step method. However, these studies did not analyze and discuss quad-constellation ultra-rapid orbit determination based on the one-step method.

The current status quo exhibits limited research on the analysis of the impact of orbit arc length on the ultra-rapid orbit determinations of quad-constellation MEO satellites based on the one-step method. Considering the potential advantages of the one-step method [5, 12] and considering that the IGS MGEX encourages each AC to achieve multi-GNSS POD based on this method, our goal is to determine an optimal orbit arc length that will contribute to the quad-constellation ultra-rapid orbit determination. Therefore, in this study, the impact of orbit arc length on quad-constellation MEO satellites' ultra-rapid orbit determinations based on the one-step method was analyzed to provide a beneficial reference for the one-step method software platform and improve the accuracy and overall stability of quad-constellation MEO satellites' ultra-rapid orbit determination. The contents of this paper are as follows: the analytical approach is introduced in the second section; then, the preliminary results are shown in the third section and, finally, discussion and conclusions are presented.

2. Methods

In this study, similar to Choi *et al* [21], and unlike Geng *et al* [25], nearly ideal conditions were adopted by using GeoForschungsZentrum (GFZ) MGEX orbits and ERP products as observations, and these are the rapid products based on the

[2] ftp://cddis.gsfc.nasa.gov/gps/products/.
[3] www.igs.org/wg.
[4] ftp://cddis.gsfc.nasa.gov/gps/products/mgex/.
[5] ftp://ftp.igs.org/pub/center/analysis/jpl.acn.
[6] ftp://ftp.igs.org/pub/center/analysis/emr_Ultra_And_Rapid_V52.acn.
[7] ftp://ftp.igs.org/pub/center/analysis/usno_UltraRapid.acn.
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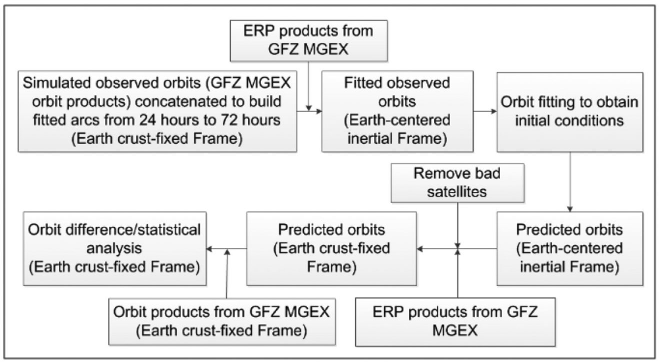

Figure 1. Basic method of analysis of orbit arc length on ultra-rapid orbits.

Table 1. Summary of the dynamic model and the orbit integration method.

Items	Description
SRP	ECOM five-parameter model
Earth gravity	EGM2008 12×12
Solid earth tide and pole tide	IERS2010
Ocean tide	FES2004
Nutation model	IAU2000
N-body gravitation	Sun, Moon, and other planets (DE405)
Integration step size	900 s
Orbit integration method	Collocation method

one-step method. The basic method of analysis and processing used in this study is shown in figure 1. The initial conditions of figure 1 represent the orbit state vectors of the satellites, including the semi-major axis of the orbit, the eccentricity of the orbit, the inclination of the orbital plane with respect to the equatorial plane, the right ascension of the ascending node, the argument of perigee, the argument of latitude, and the SRP parameters. In addition, the five-parameter CODE orbit model is adopted [23, 26]. Table 1 contains a list of the details for the dynamic model and the orbit integration method.

Two aspects were considered when analyzing the impact of orbit arc length on quad-constellation MEO satellites' ultra-rapid orbits solved by the one-step method: (1) residual analysis of the orbit difference between the simulated predicted orbits and the GFZ MGEX orbits; and (2) stability analysis of the Helmert transformation parameters of orbit difference, which are discussed below.

3. Results and discussion

In this experiment, MGEX orbits and ERP products provided by the GFZ AC based on the one-step method for the whole year from 1 January 2018, to 31 December 2018 were analyzed and discussed. In addition, the prototype software platform for orbit determination developed by the Institute of Geodesy and Geophysics was used [12].

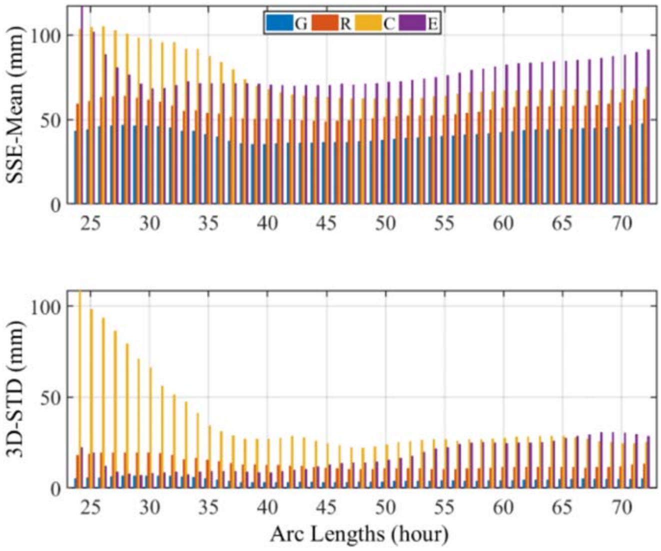

Figure 2. The 6 h predicted results for all MEO satellites of the GPS (G), GLONASS (R), BDS (C), and Galileo (E) systems.

3.1. Residual analysis of orbit difference

The spherical standard error (SSE) of each GNSS satellite orbit and the standard deviation (STD) of each GNSS satellite orbit residual in three dimensions (3D) are analyzed to evaluate the accuracy of multi-GNSS satellite ultra-rapid orbits solved by the one-step method for different orbit arc lengths. The expression for SSE_i is as follows:

$$SSE_i = \frac{\sigma_R^i + \sigma_A^i + \sigma_C^i}{3} \tag{1}$$

where i is the PRN of the satellite, and σ_R^i, σ_A^i, and σ_C^i stand for the STD of the orbit difference between the simulated predicted orbits and the GFZ MGEX orbits in the radial, along-track, and cross-track directions, respectively.

Based on the basic method discussed in section 2 and the aforementioned GFZ MGEX products, the average values of SSE for each satellite navigation system and the STD values for each GNSS satellite orbit residual in 3D can be obtained. Figures 2 and 3 show the 6h and 3h predicted results of all the MEO satellites of the GPS (G), GLONASS (R), BDS (C), and Galileo (E) systems, respectively.

For the average values of SSE of the 6 h ultra-rapid orbits predicted by the one-step method, the optimal orbit arc lengths of the GPS, GLONASS, BDS, and Galileo satellites are 37–45, 38–46, 43–52, and 29–45 h, respectively, as shown in figure 2. For the STD values of each navigation satellite system orbit residual in 3D, the optimal orbit arc lengths of the GPS, GLONASS, BDS, and Galileo satellites are 37–48, 40–52, 44–51, and 26–45 h, respectively. For the average values of SSE of the 3 h ultra-rapid orbits predicted by the one-step method, the optimal orbit arc lengths of the GPS, GLONASS, BDS, and Galileo satellites are 37–45, 36–46, 41–50, and 30–44 h, respectively, as shown in figure 3. For the STD values of each navigation satellite system orbit residual in 3D, the optimal orbit arc lengths of the GPS, GLONASS, BDS,

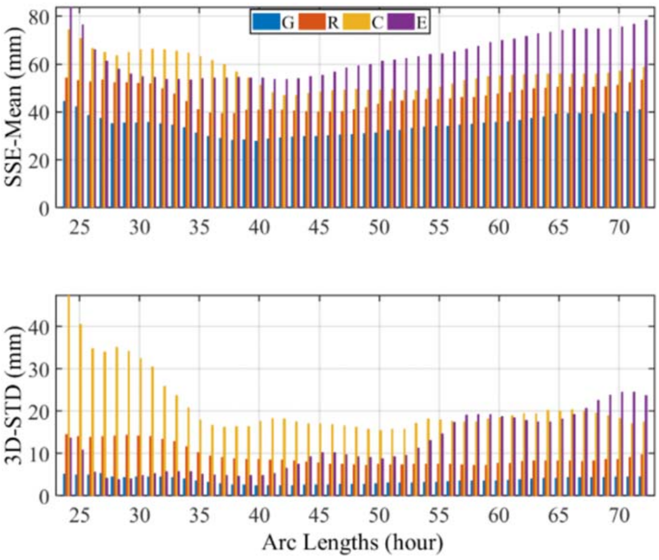

Figure 3. The 3 h predicted results for all MEO satellites of the GPS (G), GLONASS (R), BDS (C), and Galileo (E) systems.

and Galileo satellites are 37–50, 40–60, 35–53, and 26–44 h, respectively. From figures 2 and 3, it was observed that for the predicted ultra-rapid orbits of the BDS satellites, within a certain range of orbit arc length, increasing orbit arc length can significantly improve the accuracy of these ultra-rapid orbits. In conclusion, for the residual analysis of the orbit difference, the optimal orbit arc lengths of the 6 h and 3 h predicted ultra-rapid orbits of quad-constellation MEO satellites based on the one-step method are 44–45 and 41–44 h, respectively.

3.2. Stability analysis of the Helmert transformation parameters

The seven-parameter Helmert frame transformation is as follows [21]:

$$\begin{bmatrix} x_2 - x_1 \\ y_2 - y_1 \\ z_2 - z_1 \end{bmatrix} = \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} + S \cdot \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} + \begin{bmatrix} 0 & R_z & -R_y \\ -R_z & 0 & R_x \\ R_y & -R_x & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} \tag{2}$$

where S is an orbit frame scale factor, T_x, T_y, and T_z are the translational parameters of the orbits' origin, and R_x, R_y, and R_z are the rotational parameters for each geocentric axis, and their values are sufficiently insignificant here.

Calculations of the STD, median, and mean of the Helmert transformation parameters after the quad-constellation MEO satellites' simultaneous Helmert transformation, are presented in this section. Figures 4–6 represent the STD, median, and mean of the translation, rotation, and scale parameters of the Helmert transformation for the 6 h predicted results using different orbit arc lengths based on the one-step method, respectively. Figures 7–9 represent the STD, median, and mean of the translation, rotation, and scale parameters of the Helmert transformation for the 3 h predicted results using different orbit arc lengths based on the one-step method, respectively.

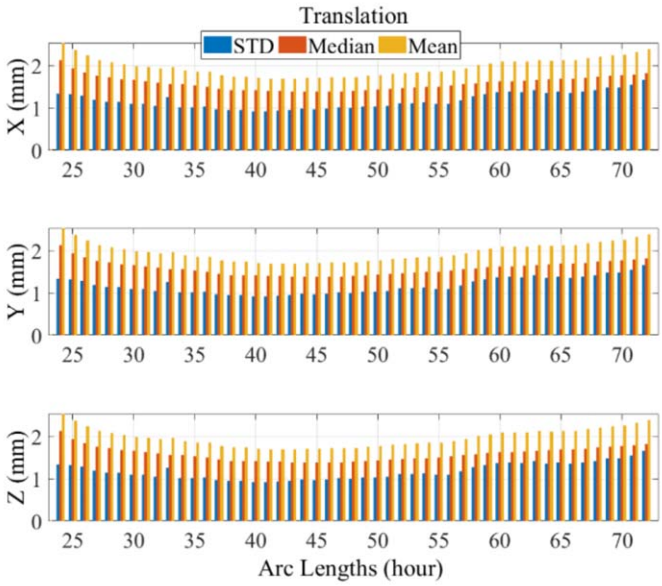

Figure 4. STD, median, and mean of the translation parameters of the Helmert transformation for the 6 h predicted results.

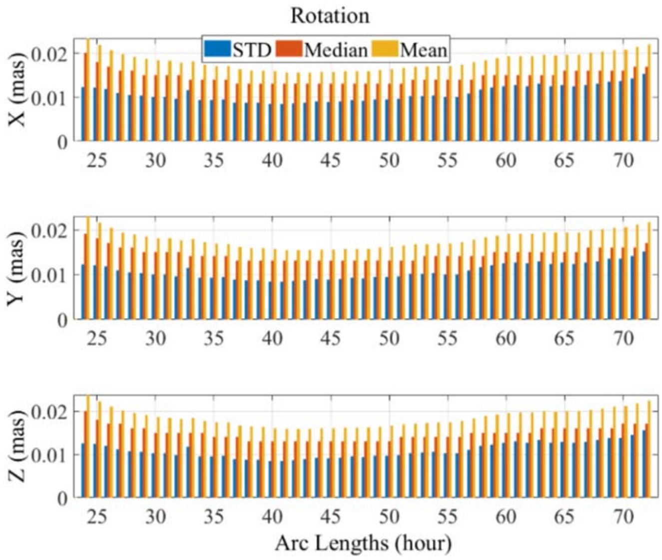

Figure 5. STD, median, and mean of the rotation parameters of the Helmert transformation for the 6 h predicted results.

From figures 4–6, it was observed that for the Helmert transformation parameters of the 6 h quad-constellation MEO satellites' ultra-rapid orbits predicted by the one-step method after simultaneous Helmert transformation, the statistical values, i.e. STD, median, and mean of the translation, rotation, and scale parameters showed that the optimal orbit arc lengths were in the range of 40–46 h. Similarly, from figures 7–9, it was observed that for the Helmert transformation parameters of the 3 h quad-constellation MEO satellites' ultra-rapid orbits, the statistical values showed that the optimal orbit arc lengths were in the range of 39–45 h.

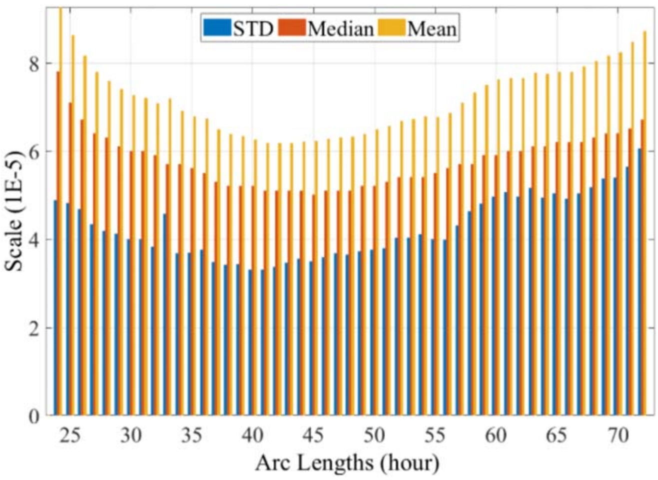

Figure 6. STD, median, and mean of the scale parameters of the Helmert transformation for the 6 h predicted results.

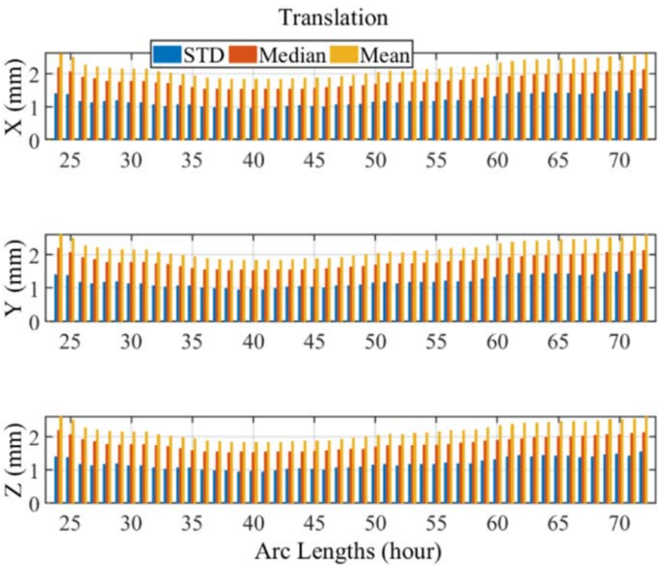

Figure 7. STD, median, and mean of the translation parameters of the Helmert transformation for the 3 h predicted results.

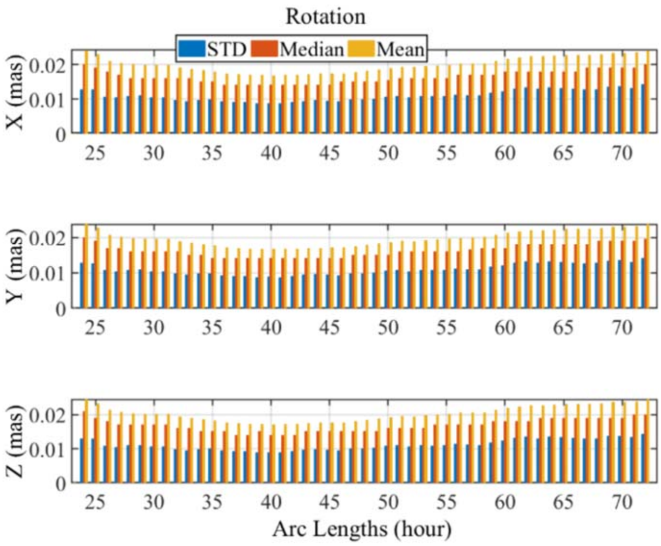

Figure 8. STD, median, and mean of the rotation parameters of the Helmert transformation for the 3 h predicted results.

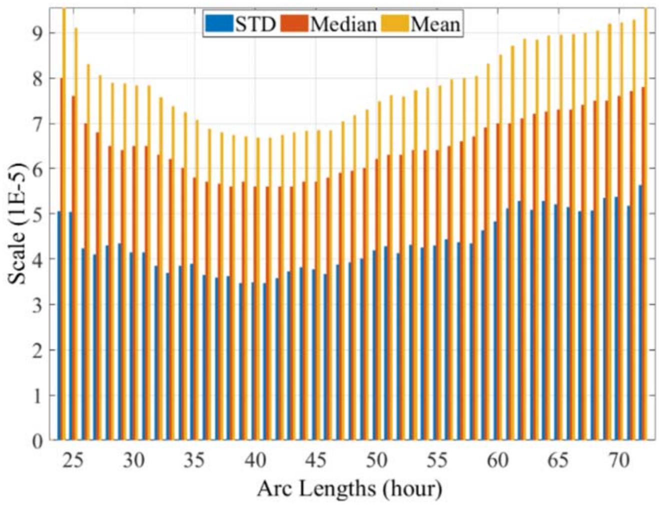

Figure 9. STD, median, and mean of the scale parameters of the Helmert transformation for the 3 h predicted results.

4. Conclusion

The impact of orbit arc length on ultra-rapid orbit determination of quad-constellation (GPS, GLONASS, BDS, and Galileo) MEO satellites based on the one-step method was analyzed in this study. To focus on the dynamic aspects of the impact, MGEX rapid orbits and ERP products provided by GFZ AC for the whole year from 1 January 2018, to 31 December 2018 are analyzed and discussed. The impact was analyzed from the orbit difference and the Helmert transformation parameters.

For the 6 h ultra-rapid orbits predicted by the one-step method, in terms of orbit difference, the optimal orbit arc lengths of the GPS, GLONASS, BDS, and Galileo satellites were in the ranges of 37–45, 40–46, 44–51, and 29–45 h, respectively. In terms of the Helmert transformation parameters, the optimal orbit arc lengths of the GPS, GLONASS, BDS, and Galileo satellites were in the range of 40–46 h. In addition, for the 3 h ultra-rapid orbits predicted by the one-step method, in terms of the orbit difference, the optimal orbit arc lengths of the GPS, GLONASS, BDS, and Galileo satellites were in the range of 37–45, 40–46, 41–50, and 30–44 h, respectively. In terms of the Helmert transformation parameters, the optimal orbit arc lengths of the GPS, GLONASS, BDS, and Galileo satellites were in the range of 39–45 h.

Furthermore, it was shown that the optimal orbit arc length of the quad-constellation was in the range of the optimal orbit arc length of the GPS [21, 22]. In addition, the range of the optimal orbit arc length of the ultra-rapid orbit determination based on the one-step method was also in the range of the optimal orbit arc length based on the multi-step method [25].

The ranges of optimal orbit arc length presented in this study can provide targeted and precise reference information for software platforms of quad-constellation MEO satellites' ultra-rapid orbit determination based on the one-step method. It was observed from the results that 44 h was the overlapping optimal orbit arc length in multi-GNSS for the 6 h and the 3 h ultra-rapid orbit determination based on the one-step method.

Acknowledgments

The authors would like to acknowledge the MGEX, the Crustal Dynamics Data Information System of the IGS, and the GFZ, for providing valuable data and products. This study was supported by the Collaborative Precision Positioning Project funded by the Ministry of Science and Technology of China (Grant No. 2016YFB0501900), China Natural Science Funds (Grant No. 41974008), and iGMAS.

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