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Research on Key Issues of Refining GNSS-based Terrestrial Reference Frame

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ABSTRACT

Space geodetic techniques play a crucial role in constructing and maintaining modern reference frames, with the Global Navigation Satellite System (GNSS) providing essential data through high-precision coordinate time series. Advances in GNSS technology have significantly enhanced observational precision and spatiotemporal resolution, enabling the precision and stability improvement of the GNSS-based terrestrial reference frame. This study focuses on refining the reference frame based on GNSS data and introduces three key methods for its maintenance and densification: common-mode error (CME) filtering, long-term Precise Point Positioning with Ambiguity Resolution (PPP-AR), and the integration of Low Earth orbit (LEO) satellites with GNSS for PPP-based long-term coordinate solutions. The specific research objectives and findings are as follows:

(1) The refinement of the global reference frame through regional CME correction was validated. Using weekly coordinate solutions from globally distributed stations over a 21-year period, principal component analysis was applied to estimate regionally correlated CMEs in GNSS solutions. The CME filtered coordinate solutions were then obtained, the refinement of the global reference frame through regional CME correction was verified from three aspects: coordinate solutions, velocity fields, and Helmert transformation parameters. Specifically, after CME correction, the RMS of the residual time series for the east, north, and vertical components decreased by 28.9%, 22.1%, and 29.5%, respectively. The velocity uncertainty of almost all stations was reduced, with a maximum difference of 0.13 mm/yr. The standard deviation of the Helmert transformation parameters between ITRF2020 and IGS solutions with/without CME filtering was reduced by more than 30%.

(2) The feasibility of using BDS PPP-AR to solve long-term coordinates, extract long-term velocity fields, and seasonal signals for maintaining and densifying the terrestrial reference frame was verified. Firstly, PPP-AR solutions were obtained based on GPS + Galileo dual-system data, yielding long-term coordinate solutions and station velocity with precision comparable to IGS solutions. Subsequently, PPP-AR solutions with five years data were derived using BDS data to derive coordinate

and velocity time series. The results show that the average RMS of BDS solutions is less than 5 mm and 8 mm in the horizontal and vertical direction, respectively. Applying the Helmert transformation, the average RMS difference between IGS and BDS solutions is less than 4 mm in the horizontal direction and less than 7 mm in the vertical direction, demonstrating millimeter-level accuracy of the BDS solutions. Regarding velocity field fitting, the velocity uncertainty of BDS solutions is less than 1 mm/yr in all three directions, and the absolute mean difference between IGS and BDS velocity solutions is less than 1 mm/yr in the horizontal direction and less than 3 mm/yr in the vertical direction, indicating that the velocity field accuracy of BDS solutions has reached the millimeter level. In terms of seasonal signal fitting, the mean amplitude difference of the annual cycle between IGS and BDS solutions is less than 1 mm in all three directions, and that of the semi-annual cycle is less than 0.5 mm.

(3) The improvement of the convergence of PPP and the accuracy of long-term PPP coordinate solutions of the BDS by LEO was verified. PPP was performed using both GPS+BDS multi-system observations combined with simulated LEO constellation, and BDS-only observations combined with LEO constellation, to assess the impact of LEO satellites on the construction of terrestrial reference frames. The evaluation focuses on convergence time, coordinate accuracy, velocity accuracy, and Helmert transformation parameters accuracy. These analyses demonstrate the potential of LEO constellations to enhance GNSS positioning performance, providing support for establishing a high-precision BDS reference frame augmented by LEO satellites. Results show that incorporating LEO satellites with BDS reduced the average convergence time across all stations from 26 minutes to 3 minutes—a decrease of 87%—and improved the coordinate accuracy by 20%, 13%, and 14% in the east, north, and up components, respectively. Moreover, the inclusion of LEO satellites significantly improved the accuracy of the velocity field and the reliability of the reference frame constructed based on the PPP solutions.

Key words: Terrestrial Reference Frame, Global Navigation Satellite System, Common-Mode Error, Precise Point Positioning, LEO navigation constellation enhanced BDS PPP