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NChina16: A stable geodetic reference frame for geological hazard studies in North China

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ABSTRACT

We have developed a stable North China Reference Frame 2016 (NChina16) using five years of continuous GPS observations (2011.8–2016.8) from 12 continuously operating reference stations (CORS) fixed to the North China Craton. Applications of NChina16 in landslide and subsidence studies are illustrated in this article. A method for realizing a regional geodetic reference frame is introduced. The primary result of this study is the seven parameters for transforming Cartesian ECEF (Earth-Centered, Earth-Fixed) coordinates X, Y, and Z from the International GNSS Service Reference Frame 2008 (IGS08) to NChina16. The seven parameters include the epoch that is used to align the regional reference frame to IGS08 and the time derivatives of three translations and three rotations. The GIPSY-OASIS (V6.4) software package was used to obtain the precise point positioning (PPP) daily solutions with respect to IGS08. The frame stability of NChina16 is approximately 0.5 mm/year in both horizontal and vertical directions. This study also developed a regional model for correcting seasonal motions superimposed into the vertical component of the GPS-derived displacement time series. Long-term GPS observations (1999–2016) from five CORS in North China were used to develop the seasonal model. According to this study, the PPP daily solutions with respect to NChina16 could achieve 2–3 mm horizontal accuracy and 4–5 mm vertical accuracy after being modified by the regional model. NChina16 will be critical to study geodynamic problems in North China, such as earthquakes, faulting, subsidence, and landslides. The regional reference frame will be periodically updated every few years to mitigate degradation of the frame with time and be synchronized with the update of IGS reference frame.

1. Introduction

Numerous studies have demonstrated that Global Positioning System (GPS) technologies are a powerful tool for geological hazard and structural health monitoring. Large GPS networks have been established in many countries, such as the Plate Boundary Observatory (PBO) GPS network and the Continuously Operating Reference Station (CORS) network in the U.S., the GPS Earth Observation Network (GEONET) in Japan, the Regional GNSS Network (ARGN) and the AuScope Network in Australia, and the Crustal Movement Observation Network in China (CMONOC). The Chinese geodesy community started to build permanent GPS stations as early as the 1990s (e.g., Ma et al., 2001). CMONOC is a nationwide permanent GPS network with over 260 CORS. The CORS network was designed primarily for earthquake and tectonic studies and for providing stable references for nationwide land surveying (Gan et al., 2012; Wang et al., 2014b). The majority of the CMONOC CORS had over five years of data accumulated towards the end of 2016. Precise site velocities associated with crustal motions are expected to be derived from the long-term GPS observations.

The GPS units used for geodetic studies do not directly provide positional accuracies at the level of a few centimeters. A complex process is required to derive precise and accurate positional measurements with respect to a specific reference frame. The ultimate product from CORS is often the site velocities rather than the direct positional measurements. The GPS data from a single station is insufficient by itself for providing accurate site velocity estimations. The raw GPS data must be carefully processed with supplementary information in order to identify minor site displacements or structural deformation over time.

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Such additional information includes precise satellite orbits and clock corrections, ocean tide loading, troposphere delay modeling, atmospheric pressure loading, a well-established reference frame, and others. A complex aspect of GPS is that it initially provides positional coordinates with respect to a global reference frame that defines the dynamic positions of the satellites. In general, a global reference frame, such as the International Terrestrial Reference Frame 2008 (ITRF08), is realized with an approach of minimizing the overall horizontal movements of a group of selected frame stations distributed worldwide (Altamimi et al., 2011). As a result, the positional coordinates for most of the GPS stations change over time with respect to a global reference. The site movements with respect to a global reference frame are often dominated by the long-term drift and rotations of the tectonic plates. Localized ground deformation, such as fault creeping, landslides and subsidence, could be obscured or biased by plate motions. A stable regional reference frame, also called a plate-fixed reference frame, indicates that regional "common" movements have been removed or minimized. The regional common movements may include a combination of secular plate motions, glacial isostatic adjustment (GIA), surface mass loading, and other minor secular effects (Booker et al., 2014). Thus, a stable regional reference frame is needed for precisely delineating localized ground displacements or structural deformation over time and space.

Groundwater has been extracted for industrial and civilian use for several decades in North China. Excessive groundwater pumping has caused serious land subsidence problems (e.g., Xue et al., 2005, 2008; Hu et al., 2004; Zhang et al., 2014). Infrastructure damages associated with subsidence have been frequently reported in North China, particularly in the Beijing-Tianjin-Hebei region. The spreading subsidence make it more difficult to identify long-term stable benchmarks for conventional geodetic surveys. A consistent and stable geodetic reference frame is needed to conduct high-accuracy geodetic survey in North China. Recently, the threat of land subsidence on the safety of the high-speed railway network in North China has become a great concern for the railway administration, the local governments, and the public. The high-speed railway uses the non-ballasted track, which is very sensitive to the uneven settlement of the railroad foundation. The ongoing land subsidence in the Beijing-Tianjin-Hebei region will cause uneven settlement for the long-span railway tracks and therefore threaten the safe operation of the railway network if the track deformation cannot be adjusted in time. Thus, highly accurate and continuous monitoring of the ground deformation under the railway tracks is critical to ensure safe operation of the railway network. Numerous GPS stations have been recently installed in North China by various government agencies and academic institutions for multiple research and engineering applications. To integrate the GPS datasets previously collected by different agencies over different regions during different time periods and to conduct near-real-time structural health monitoring in the future, a consistent stable regional reference frame is required. This study aims to establish a stable geodetic reference frame in North China using available GPS data as the end of 2016. The reference frame is called the North China Reference Frame 2016 (NChina16).

2. GPS data processing

GPS data processing algorithms generally implement two approaches to achieve high-precision positioning measurements, relative positioning and absolute positioning. The accuracy of GPS measurements (positions or displacements) does not solely rely on GPS equipment (antenna and receiver) but largely depends on how the data are collected in the field and how the data are processed in the lab (e.g., Wang, 2011; Geng et al., 2010). The relative positioning approach uses simultaneous observations from two or more GPS units. One GPS unit is considered a fixed station, also called a reference station or a base station. The relative positions of other GPS stations (rover stations) are calculated using a differential method, which inherits high accuracy from the fact that the closely-spaced base and rover GPS units share common errors and biases. The alternative approach, absolute positioning, determines the position of a single GPS station without using any simultaneous observations from other ground GPS stations. Conventionally, absolute positioning techniques use un-differenced dual-frequency pseudo-range and carrier-phase observations, precise satellite orbits and clock information, high-fidelity error modeling, and other information to determine the position of a stand-alone GPS antenna. Precise point positioning (PPP) is a typical absolute positioning method (Zumberge et al., 1997).

This study applied the single-receiver phase ambiguity-fixed PPP method employed by the GIPSY-OASIS (V6.4) software package, simplified as GIPSY, for calculating daily positions. The GIPSY software package was developed by the Jet Propulsion Laboratory (JPL). GIPSY employs the single-receiver phase ambiguity fixed PPP method that incorporates the wide-lane and phase-bias (WLPB) estimates from a global network of ground GPS stations to fix phase ambiguities (Bertiger et al., 2010). The final satellite orbits and clocks and the WLPB estimates provided by JPL were used for GIPSY processing. The other major parameters and key correction models applied during the GIPSY processing are the same as those reported in our recent publication Soler and Wang (2016). An outlier-detection-and-removal algorithm was applied to the positional time series derived from the PPP solutions. The details of the outlier rejection method were addressed in Firuzabadi and King (2011) and Wang (2011). Approximately five to seven percent of the total measurements were removed as outliers in this study. The precision of PPP solutions has been dramatically improved over the last decade. The PPP method has attracted broad interests in ground displacements and structural deformation monitoring because of its operational simplicity and high accuracy (e.g., Wang, 2013; Geng et al., 2013; Yu and Wang, 2016; Geng et al., 2017; Bao et al., 2017). It is worth noting, however, that a global GPS network and numerous redundant regional GPS networks are used to calculate precise GPS orbit and clock corrections, as well as WLPB estimates that are used by GIPSY during PPP processing, specifically, for fixing phase ambiguities. Accordingly, the PPP method essentially relies on observations from a huge number of ground GPS stations, although the end users do not need to include any data from other ground stations in their PPP processing.

The PPP solutions are defined in an Earth-Centered-Earth-Fixed (ECEF) Cartesian coordinate system that represents a position as a pair of X, Y, and Z coordinates. To study ground deformation at the Earth's surface, the geocentric XYZ coordinates were converted to a geodetic orthogonal curvilinear coordinate system (longitude, latitude, and ellipsoid height) referencing the GRS80 ellipsoid. The geodetic coordinates with respect to NChina16 were then projected to a two-dimensional (2D) local horizon plane. This enabled us to track superficial ground deformation in the north-south (NS) and east-west (EW) directions at each site. The ellipsoid height change over time is used to depict the vertical displacement (subsidence) in this study. The vertical displacements derived from the ellipsoid heights would have the same measurements as those derived from orthometric heights according to the investigation of Wang and Soler (2014).

3. Realization of North China reference frame 2016 (NChina16)

The China Geodetic Coordinate System 2000 (CGCS2000) has been the official national geodetic reference frame in China since July 2008 (Chen, 2008). CGCS2000 is a geocentric coordinate system that is referred to the International Terrestrial Reference Frame 1997 (ITRF97) at the epoch of 2000.0. The International Global Navigation Satellite Systems (NGSS) Reference Frame 2008 (IGS08) is a geocentric coordinate system that is referred to the International Terrestrial Reference Frame 2008 (ITRF2008) (Rebischung et al., 2012). Both CGCS2000 and IGS08 are global-scale reference frames and have drawbacks for precisely deriving localized ground or structural