Crustal deformation on the Chinese mainland during 1998–2014 based on GPS data

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\textbf{A B S T R A C T}

This study focuses on resolving moderate amounts of crustal motion at the continental scale based on a large volume of global positioning system (GPS) data during 1998–2014. A state-of-the-art GPS processing strategy was used to resolve position time series and velocities from carrier beat phases for all available data. Position time series were closely analyzed to estimate linear constant, coseismic displacements, postseismic motions, and other parameters. We present coseismic offsets inferred from the GPS data for the 2010 Yushu and 2014 Yutian earthquakes, and also illustrate transient postseismic motions following the 2001 Kokoxili, 2008 Wenchuan, and 2011 Tohoku-Oki earthquakes. Since not all GPS position time series dominated by postseismic motions can be modeled and corrected reasonably, we present contemporary horizontal velocities from 2009 to 2014 for campaign stations and from 1998 to 2014 for continuous stations, irrespective of postseismic deformations. Our study concludes that we need to accumulate observations over a greater duration and apply accurate postseismic modeling to correct for transient displacement in order to resolve reasonable interseismic velocity.

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1. Introduction

The first trial GPS network used to monitor crustal deformation was established in the Yunnan experimental field of earthquake monitoring and prediction in the 1988, starting a new epoch of employing GPS technology to measure crustal deformation in China. Various types of crustal deformation GPS network were established during the following decade, mainly in West China, for instance on the Tibetan Plateau in the Himalaya, at Qilian Shan. The Crustal Motion Observation Network of China (CMONOC) was established in 1998 by the

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2. Data set

The GPS data used in this study are mainly from the CMONOC [16–19] project, forming two successive phases. In the first phase, before 2009, CMONOC consisted only of a nationwide fiducial network of 27 continuous stations, about a thousand survey-mode stations, and 56 yearly occupied quasi-fiducial stations across continental China. Most of the permanent GPS stations were equipped with ASHTECH Z-XII3 receivers, excluding a few International Global Navigation Satellite System (GNSS) Service (IGS) stations. During this phase, campaign measurements in the entire network scale were undertaken regularly in 1999, 2001, 2004, and 2007, and all stations were observed continuously for at least four days in each session. In addition to wide-scale regular observation, regional observations were made on the northern Tibetan Plateau after the 2001 Mw8.0 Kokoxili earthquake [20], and in the Sichuan and Yunnan areas after the 2004 Mw9.0 Sumatra earthquake [21,22] and the 2008 Mw7.9 Wenchuan earthquake, respectively [23,24]. In addition, 56 quasi-fiducial GPS stations were observed continuously for at least eight days each year.

In the second phase, the CMONOC project extended the number of campaign GPS stations to approximately 2056 in 2009 and the number of continuous GPS stations to 260 in 2010. Trimble NetR8 GPS receivers and TRM59800.00 choke-ring antennas with SCIN domes equipped all the newly established permanent stations and mountains sites established in the first phase, apart from several IGS stations such as SHAO and URUM. From 2009, in approximately a dozen stations, the GPS receivers and antennas have been upgraded to Trimble NetR9 and TRM59000.00, respectively, mainly due to equipment failures. The continuous GPS stations used in this study all terminated in October 2014. Nationwide campaign mode GPS stations were observed regularly in 2009, 2011, and 2013. Moreover, regional observations were undertaken in Sichuan, Ordos, and North China in 2012 and in Sichuan, Yunnan, Ordos, North China, and the Tienshan area in 2014.

3. GPS data processing

3.1. Loosely constrained daily solutions

All the GPS receiver independent exchange data from CMONOC and some IGS stations were processed by a homogeneous state-of-the-art method using GAMIT/GLOBK software release 10.4 [25]. To reduce the processing burden, we divided the network into several subnetworks containing no more than 50 stations each. At least 10 common IGS reference stations were involved in each subnetwork to allow for the combination of solutions (Fig. 1).

As the first step, loosely constrained daily solutions were processed using GAMIT software [25]. At this step, satellite orbit parameters and satellite antenna offsets were adjusted during processing, starting with reprocessed orbits from MIT from 1999 to 2007 and IGS orbits from 2008 to the present day, as prior values. Previous solutions were used as priori coordinates to constrain orbital and station parameters for resolving integer phase ambiguities. We used an elevation cutoff angle of 10° for all stations and applied elevation-dependent weighting of data according to an assessment of the postfit phase residuals. Orbit positions of the satellite were numerically integrated in the initial conditions using a force model containing solar and lunar perturbations, the EGM08 gravity model, and a solar radiation pressure model named BERNE. In modeling the motion of stations, we employed solid earth tide and frequency-dependent corrections following the International Earth Rotation and Reference Systems Service (IERS) standards [26], and corrected ocean tide loading efforts using the FES2004 model [27]. We used the global mapping function (GMF) tropospheric mapping function [28], and chose a prior dry tropospheric delay value from the global pressure and temperature (GPT) model [29]. Atmospheric zenith delay and atmospheric gradients were estimated every hour and every day, respectively. Neither higher order ionospheric delay nor atmospheric loading and nontidal ocean loading deformation were considered, and their effects remained in the GPS daily time series for periods of longer than a day. Absolute antenna phase calibration models were used to correct antenna offsets of receivers.
3.2. Combination and frame determination

As the second step, the loosely constrained regional daily solutions with station coordinates, atmosphere delay, orbit parameters, and covariances were combined with global solutions produced by the Scripps Orbital and Position Analysis Center (SOPAC, http://sopac.ucsd.edu) using GLOBK software [25], then aligned into the International Terrestrial Reference Frame (ITRF) 2008 [30] through approximately fifty global distributed reference stations using seven parameter transformations of translation, rotation, and scale. This procedure is necessarily iterative, since the program will exclude bad reference stations, based on residuals, to guarantee a robust solution. Reference stations affected by major earthquakes since 2000, such as by the Chile earthquake of 2010 [31] or the Tohoku-Oki earthquake in 2011 [32,33], were not used in realizing the frame due to the absence of updated coordinates.

3.3. GPS position time series

After determining the daily station position, the mean station position, and the long-term linear trend, any offsets affected by great earthquakes, equipment changes, and postseismic displacement were estimated for each coordinate component, along with annual displacement signals for the continuous stations. The relationship between the position variations and the parameters is as follows:

\[ x(t) = C_1 + C_2 t + C_3 \sin(2\pi t) + C_4 \cos(2\pi t) + \sum_{i=1}^{N} D_i H(t - t_i) + E_i (t - T_i) \log_{10} \left( 1 + \frac{t - t_i}{T_i} \right) \]

where \( x(t) \) is the GPS position at epoch \( t \), \( C_1 \) is a constant offset, \( C_2 \) is the secular linear velocity, \( C_3 \) and \( C_4 \) are the amplitude and phase of the annual variations, respectively, \( D_i \) is the coseismic or other spurious offset occurring at time \( t_i \), \( E_i \) is the amplitude of postseismic relaxation, and \( H(t) \) is the Heaviside function (step function). \( T_i \) is a time constant, which is assumed to be same for all stations for each earthquake. This part of analysis is performed using a program named TSFIT, a most useful GAMIT/GLOBK program [25].

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**Fig. 1** – Distribution of continuous and campaign GPS stations used in this study. SRTM topography is shown in the background, and symbols are colored by the length of data span at each station. Black indicates those with a span of less than 2.5 years.

**Fig. 2** – Surface deformation following the 2010 Yushu earthquake, inferred from survey-mode GPS measurements. Displacement vectors are plotted using differently scaled arrows with a 95% confidence ellipse. The solid black lines are major faults. The fault plane solutions of the earthquake are from the GCMT project (http://globalcmt.org).
4. Coseismic and postseismic deformation

From 1998 to 2014, there were several influential earthquakes recorded by continuous or campaign GPS measurement: 2001 Kokoxili (Kunlun) [20], 2004 Sumatra-Andaman [21,22], 2008 Wenchuan [23,24], 2010 Yushu [34], 2011 Tohoku-Oki [32,35], 2013 Lushan [36,37], and 2014 Yutian earthquakes. Some of these earthquakes caused significant postseismic deformation over a wide area. In this part of the analysis, we attempt to estimate the coseismic deformation for each earthquake and also try to estimate the postseismic deformation after the Kokoxili, Wenchuan, and Tohoku-Oki earthquakes. Given that the coseismic displacements recorded by CMONOC GPS stations following the Kokoxili, Sumatra-Andaman, Wenchuan, Tohoku-Oki, and Lushan earthquakes have been well documented quantitatively [33,35-39], we present coseismic offsets caused only by the Yushu and Yutian earthquakes, for which the results are not documented publically.

4.1. Coseismic deformation

We obtained from seven survey-mode GPS stations the near-field coseismic offsets caused by the Yushu earthquake (Fig. 2). The displacement pattern agrees well with the mechanism of left-lateral strike rupture. The greatest offset, a value of 44.7 cm, was observed at JB49 moving toward the NWW. Coseismic deformations at J392, J396, J397, J399, and J386 were not well constrained because these stations were occupied for a single session before the event, and the secular motions were heavily reliant on their position after the shake. Therefore, the coseismic offsets at these stations may be slightly overestimated. Only one station, continuous station XJYT, was available within 200 km of the epicenter of the 2014 Yutian earthquake. Here, the estimated offset value was 2.4 cm.

4.2. Postseismic deformation

It is necessary to take into account the transient postseismic displacement following strong ruptures when estimating secular motion at each CMONOC GPS station. We fitted the postseismic relaxation using the logarithm part of the above equation. In general, the optimum value of the logarithm relaxation time $T_\text{r}$ is determined by the least $\chi^2$ of the postfit residuals. After extensive trials, it emerged that a value of 30 days adequately fits most postseismic displacements; therefore, this value was used to model postseismic...
deformation for both the north and east components of all stations that were analyzed.

Postseismic deformations following the Kokoxili earthquake were observed at CMONOC survey-mode GPS stations (Fig. 3). The most significant postseismic relaxation occurred at JB51 with an estimated amplitude $E_i$ of 38.9 mm. In fact, postseismic displacement was also detected and recorded at a continuous GPS site, DLHA, located approximately 590 km east of the epicenter.

As expected, postseismic displacement following the Wenchuan earthquake was detected mainly at the hanging wall of the Longmenshan Fault system on the eastern Tibetan Plateau, and the signals were much smaller at the footwall of the fault in the Sichuan Basin (Fig. 4). Although at some stations there was no routine observation during the earlier stage of the postseismic relaxation process, the resolved parameters are still reasonable.

The chief surprise to us is that detectable postseismic relaxation processes following the Tohoku-Oki earthquake were recorded by several permanent GPS stations in Northeast China, more than 1200 km distant from the epicenter. According to the position time series with secular motion removed (Fig. 5), postseismic relaxation signals are dominant in the east component, consistent with the coseismic displacement pattern. The postseismic displacement in the east component reaches 18, 22, and 27 mm over 3.3 years at JLCB, JLJY, and SUIY, respectively.

5. Error analysis

The daily station position repeatability, computed as the weighted root mean square (WRMS) of station position residuals with respect to the modeled position, is an objective approach to assessing the quality of GPS position time series. We computed daily position WRMS values for the horizontal and vertical components, all of which have a minimum length of 2.5 years. WRMS values of most stations range from 1 to 5 mm in the horizontal component and from 3 to 10 mm in the vertical component. The average WRMS values are 2.4, 2.3, and 6.4 mm for the north (N), east (E), and up components, respectively. The mean WRMS value in the vertical component is approximately three times that of the horizontal component. The large horizontal WRMS values shown in Fig. 6

Fig. 4 – Observed horizontal north (left) and east (right) time series data of campaign GPS stations near the epicenter of the 2008 Wenchuan earthquake. Note: secular motions have been removed from the original displacement caused by the earthquake. Observed points are colored to make them easy to separate visually, and model time series data using logarithmic function are shown by black dashed lines.
Fig. 5 – Observed horizontal north (left) and east (right) time series data for far-field continuous GPS stations after the 2011 Wenchuan earthquake.
are mainly attributable to the instability of the monument and bad environment.

In our solution (all with spans larger than 2.5 years), we determine the random walk to be applied using the “realistic sigma” method of Herring [40], described by Reilinger [41]. This algorithm evaluates the decrease in scatter as a function of averaging time, and compares this with the decrease to be expected for white noise. In general, the velocity uncertainties obtained using the method are approximately 10 times greater than the value achieved by taking into account only white noise.

As mentioned above, some survey-mode campaign GPS stations observed large WRMSs, most of which are attributable to bad observation conditions (i.e., sky visibility and multipath issues) and the instability of the monuments. GPS stations with very large WRMS, typically double the average value, were disregarded in the final velocity solution. Moreover, we removed velocities that were clearly incompatible with their neighbors. This procedure was aided through the inspection of the residuals between the estimated and interpolated values using the Kriging interpolation method.


As described above, many CMONOC GPS stations are strongly influenced by major earthquakes. Although the associated coseismic offset and the transient postseismic relaxation could be constrained by GPS position time series for stations occupied for several sessions before an earthquake, it is a challenging task to estimate reasonable secular motions for many sites established afterward, such as for the Wenchuan and Tohoku-Oki earthquakes. Because of these considerations, we present a contemporary horizontal velocity field for campaign mode stations from 2009 to 2014 and for continuous stations from 1998 to 2014 using the some processing methods but disregarding postseismic deformation during this period. The Euler vector [42] is used to transform velocities from ITRF 2008 to Eurasia. The data are listed in the auxiliary material (camp_velo.doc and cmnc_velo.doc for campaign and continuous stations, respectively). Fig. 7 illustrates the contemporary crustal motions between 2009 and 2014 for survey-mode sites and between 1998 and 2014 for permanent sites.

7. Conclusion

Through a unified analysis of CMONOC’s campaign mode and continuous GPS stations on the Chinese mainland from 1998 to 2014, we have attempted to estimate a spatially dense
field of secular motions for each station, along with associated errors. In the analysis procedure, we estimated coseismic displacements and transient postseismic motions due to several significant earthquakes during this period. We have presented the coseismic deformations for the 2010 Yushu and 2014 Yutian earthquakes, which are not otherwise publicly documented. In addition, we have presented the transient postseismic deformations following the 2001 Kokoxili, 2008 Wenchuan, and 2011 Tohoku-Oki earthquakes. The most interesting phenomenon we report is that transient postseismic processes can be detected at far field continuous stations, over 1200 km from the epicenter, with a relaxation displacement of more than 1.0 cm within 3.3 years. Due to the inevitable absence of necessary observations before major earthquakes at newly established survey-mode GPS stations, we cannot induce the secular motion for all stations. Therefore, for campaign stations from 2009 to 2014 and for continuous stations from 1998 to 2014, we provide the latest contemporary horizontal velocities depicting the detailed deformation pattern of East Asia, especially the Tibetan Plateau and the surrounding region. Our study also implies that we need to collect observation data from a longer span and to apply precise postseismic deformation modeling to correct transient displacement in order to resolve reasonable interseismic deformation.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.geog.2014.12.006.

References


Zhao Bin is an assistant researcher at the Institute of Seismology, China Earthquake Administration, who works primarily on processing GPS data, assessing the quality of results, and producing various types of GPS products for publication. He also studied interseismic deformation, strain accumulation, and interseismic coupling along active faults in China, especially West China.