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RESEARCH ARTICLE

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Key Points:

- Individual GPS vertical crustal velocities are rigorously estimated in China
- Spatial Structure Function enabled GPS imaging provides improved estimates of the crustal deformation in China
- Combining GPS-derived velocity with GRACE-inferred deformation allows quantification of spatial patterns of tectonic block motions in China

Supporting Information:

Supporting Information may be found in the online version of this article.

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GPS Imaging of Vertical Bedrock Displacements: Quantification of Two-Dimensional Vertical Crustal Deformation in China

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Abstract The Global Positioning System (GPS) derived bedrock displacements respond to multiple geophysical effects, ranging from surface elastic loads to tectonic sources or viscoelastic uplifts stemming from Earth's viscous mantle. In this study, the GPS-inferred vertical crustal velocities are rigorously estimated in mainland China. We integrate the GPS vertical velocity field with Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GFO) data, adopting an empirical Spatial Structure Function (SSF), to image tectonic deformation in mainland China with respect to the International Terrestrial Reference Frame (ITRF) 2014. We present four profiles across China, which indicate that our new robust results are superior to kriging. Furthermore, we use the GRACE/GFO products to account for elastic deformation due to surface mass changes to isolate tectonic deformation signals at GPS sites within mainland China from 2002 to 2019. By integrating GPS and GRACE/GFO measurements, our results reveal the long-term spatial patterns of vertical tectonic motion in different blocks in mainland China. We conclude that significant steep velocity gradients occur at tectonic block boundaries that are attributable to locking and elastic strain accumulation on active block boundary faults.

1. Introduction

Global Positioning System (GPS) geodesy has been generally used as an important monitoring technique for the ground motions that are essentially associated with complicated physical processes in the Earth system (Bock & Melgar, 2016). With the refinement of geophysical models and advancements in software and hardware, the accuracy of detected changes in horizontal and vertical GPS coordinates is at the millimeter-level; such improvements make GPS a useful tool for interdisciplinary geosciences fields, such as geophysics, seismology, atmosphere, hydrology, glaciology, and natural hazards studies (Argus et al., 2017; Kreemer et al., 2014; Shen et al., 1996; Wang et al., 2001). Therefore, it is possible for us to harness the GPS data pool for interdisciplinary studies around the globe (Blewitt et al., 2018), especially in the fields of geosciences.

GPS-derived three-dimensional velocity fields have supported abundant scientific achievements, from the realizations of the early global reference frame to addressing of contemporary interdisciplinary Earth sciences problems. In mainland China, in addition to the sparse continuous GPS stations, there are many campaign-mode GPS stations with 1–3 years of observation. It is well known that GPS displacements are caused by complex and diverse geophysical sources (Blewitt et al., 2001; Ding & Chao, 2018; Ding et al., 2020), and for most of these geophysical periodic signals, the horizontal effects are much smaller than the corresponding vertical effects. Examples of these signals include the 18.6-years nodal tide effects (Agnew, 2015), pole tide (King & Watson, 2014; Wahr, 1985), and ~6-years oscillation due to mantle-inner core gravitational coupling (Ding & Chao, 2018; Ding et al., 2020). This means that for shorter-term GPS observations, the complex long periodic signals will have smaller or negligible effects on the GPS horizontal velocity fields but will heavily affect the vertical velocity fields (Ding et al., 2020). GPS-derived horizontal velocity fields

have been estimated by combining continuous and campaign-mode GPS data, and have contributed substantially to measurements of horizontal crustal motion due to seismic deformation in mainland China (Gan et al., 2007; Wang et al., 2001; Zhang et al., 2004; Zheng et al., 2017). However, GPS vertical velocity field monitoring has been greatly limited due to the sparse coverage of continuous GPS stations, which lead to insufficient spatial resolution of data representing in mainland China.

In order to study the vertical crustal deformation in mainland China based on a sparse network of continuous GPS (CGPS) stations, we use the method of GPS imaging proposed by Hammond et al. (2016), which uses a Spatial Structure Function (SSF) to represent the horizontal wavelengths of the vertical signals. The organization of this paper is summarized as follows.

We first concisely describe the GPS imaging technique; we then analyze the estimated correlations between station-to-station distances and velocities based on the statistical results to establish the strategies to image GPS-derived vertical ground motion in different areas in China. Next, we modify the offsets and outliers of 260 Chinese terrestrial network observed time series referenced to ITRF2014 (Altamimi et al., 2016), to improve the robustness of the estimates of the GPS time series, including that of linear trend determination. Then, we use the CATS (Create and Analyze Time Series) software (Williams, 2008), to estimate the velocity field and its uncertainty. Our results show that the imaged vertical velocity field in mainland China is considerably improved in terms of its spatial resolution, and the robust imaging integrating GPS and Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GFO) measurements reveals long-term spatially varying crustal tectonic deformation in mainland China.

2. Data Sets

2.1. GPS Networks

The GPS stations from the crustal deformation network in China are divided into installment I and II, with a total of 260 continuous stations (CGPS). The distribution of GPS stations is shown in Figure 1, which includes 27 GPS stations that form the Crustal Movement Observation Network of China covering the period of 1999–2019 (CMONOC I), and 233 CMONOC II stations, spanning from 2010 to 2019. We also present the distribution of the Centroid Moment Tensor (CMT) solutions of earthquakes ($M_w \geq 6$) (Figure 1) for our study of tectonic deformation along the block boundaries in mainland China (in Section 5).

The GNSS data products used in this study were released by the China Earthquake Administration (<ftp://ftp.cgps.ac.cn/products/position>), and the time series were processed by GAMIT/GLOBK software. The data processing strategy is concisely described as follows:

- (1) *GPS data and network.* The national GNSS reference stations are divided into seven subnets, and each subnet is associated with a fixed station to ensure a sufficient number of common GPS stations when merged using the software GLOBK/GLRED. The CMONOC GPS stations can be combined into a whole large network, and referenced to the ITRF through the International GNSS Service (IGS) network
- (2) *One-day relaxed solution.* A single-day relaxation solution was processed using GAMIT software (the version of 10.5) (Herring et al., 2010a). The single-day relaxation solution is mainly to obtain the parameter to be estimated and its covariance matrix. The data processing procedures involve geophysical corrections employed through forward models (e.g., the troposphere (Vienna Mapping Function), ionosphere (Ionosphere-free linear combination), and ocean tidal (FES2004 model)) and improvement via estimation of instrument and other parameters (e.g., satellite clock bias, orbit, solid Earth tides, and Earth rotation parameters) according to the IERS 2010 Conventions. An unconstrained relaxation solution is adopted throughout the processing. We imposed certain constraints on satellite orbits and station coordinates, which were constrained horizontally by 5 cm and vertically by 10 cm
- (3) *GPS time series modification.* A seven-parameter similarity transformation is performed using GLOBK, to align the solutions to ITRF2014. GPS-based velocity could be biased by transient deformation (e.g., outliers and offsets) in the time series from coseismic and postseismic displacement from earthquakes, or from GPS instrument issues (update, replacement, and failure). Figure 2 shows that there are some outliers and offsets in the raw GPS time series (the gray points), and we use a GNSS time series analysis software, named TSAlyzer (Wu et al., 2017), to further improve the solutions. This program uses an extensive L1 regularization model to correct for outliers and offsets in GPS time series (Wu et al., 2018).

Figure 1. Distribution of GPS stations in mainland China. Red triangles denote CGPS with records spanning the interval from March 1999 to December 2019 (CMONOC I), blue triangles denote CGPS with records spanning the interval from May 2010 to December 2019 (CMONOC II). White dashed lines are the tectonic boundaries of different blocks in mainland China (Pandey et al., 2014). The focal mechanism solutions are given from January 1976 to December 2019, from the Global Centroid Moment Tensor (CMT) catalog (Ekström et al., 2012). Green beach balls indicate earthquakes with $M_w \geq 7$ and gray beach balls are for earthquakes with $6 \leq M_w < 7$. CGPS, continuous Global Positioning System.

The GPS time series are substantially improved, presented by red lines in Figure 2, which in turn improved velocity estimations

2.2. CATS Vertical Velocities

The power spectrum of flicker noise or random walk noise was suggested as the background noise model in the continuous GPS (CGPS) position time series (Williams, 2003). Following this, a combination of white noise plus random walk noise models, along with seasonal signals (annual and semiannual) removal, were conducted on all CGPS time series. We use the CATS software (Williams, 2008) to estimate the GPS velocity and its corresponding uncertainty (Williams, 2003). The statistics of velocity and uncertainties of CGPS in mainland China are shown in Figure 3. Here, we present 257 GPS velocities with rates ranging from -8 to 8 mm/yr, and 3 CGPS sites show abnormal subsidence rates exceeding -20 mm/yr in the North China Plain (Figure 4, inset). The CATS-derived vertical velocity and uncertainty of GPS sites spanning 1999–2019 are supplied in the supporting information (Table S1).

In Figure 3a, the GPS velocities are mainly distributed between -3 and 3 mm/yr, and three sites with anomalous regional subsidence >20 mm/yr in the North China Plain (see in Figure 4). The uncertainties of vertical velocity are <0.9 mm/yr, and decrease systematically with the increase of data length of the time series (Figures 3b and 3c). The GPS uncertainties show significant improvement in comparison with previous studies (Pan et al., 2018, 2019) due to longer time series of continuous GPS observations.

Figure 2. The five selected raw GPS time series (blue lines) and the corresponding time series (red lines) improved with the TSAlyzer software. GPS, Global Positioning System.

2.3. GRACE and GRACE Follow-On (GFO) Data and Surface Mass Inversion

To identify the surface mass redistributions and elastic deformations around CGPS stations in mainland China, the GRACE and GFO L2 RL06 monthly solutions released by the Center for Space Research (CSR) at the University of Texas at Austin are chosen for the study, from April 2002 to December 2019. These GRACE/GFO monthly solutions are expressed in the form of spherical harmonic coefficients (SHCs) complete to degree and order 60. We replace the original C_{20} terms with those derived from satellite laser ranging (Cheng et al., 2013), and add the degree-1 terms with the estimates from Sun et al. (2016). The glacial isostatic adjustment (GIA) effect is corrected for the SHCs using a global GIA forward model, ICE-6G_D (Peltier et al., 2018). To reduce the data noise, we smooth the SHCs with a 300 km fan filter (Zhang et al., 2009). A global forward modeling method (Chen et al., 2015) performed with the intact low-degree terms (Jiao et al., 2019; Yi et al., 2017) is adopted to alleviate the signal leakage effect. Surface mass changes in the form of equivalent water height (EWH) are finally computed using the equations of Wahr et al. (1998)

$$\Delta\sigma(\phi, \theta) = \frac{a\rho_e}{3\rho_w} \sum_{l=0}^{\infty} \sum_{m=0}^l \bar{P}_l^m(\cos\theta) \left(\frac{2l+1}{1+k_l} \right) \left[\Delta S_l^m \sin(m\phi) + \Delta C_l^m \cos(m\phi) \right], \quad (1)$$

where ρ_e and ρ_w are the average density of the Earth and the density of water (1 g/cm^3), respectively; a is the equatorial radius of the Earth; θ and ϕ are the colatitude and east longitude; k_l denotes the elastic load Love number provided by Wahr et al. (1998); ΔS_l^m and ΔC_l^m are monthly spherical harmonic coefficients. $\bar{P}_l^m(\cos\theta)$ is the fully normalized Legendre function of degree l and order m .

Furthermore, we estimated the surface elastic loading displacements (i.e., hydrologic-cryospheric and other atmospheric and nontidal mass loads) using the GRACE/GFO solutions (GSM) and AOD1B dealiasing model (GAC), respectively. The surface elastic loading displacement is obtained from the GRACE/GFO spherical harmonic coefficients (van Dam et al., 2007):

$$\Delta h(\theta, \phi) = a \sum_{l=1}^{\infty} \sum_{m=0}^l \bar{P}_l^m(\cos\theta) \left(\frac{h'_l}{1+k'_l} \right) \left[\Delta S_l^m \sin(m\phi) + \Delta C_l^m \cos(m\phi) \right] \quad (2)$$

where h'_l and k'_l are the adopted load Love numbers, which are computed relative to the center of mass of the solid Earth (Fu & Freymueller, 2012); here, we referred the values given by Farrell (1972) (based on the Gutenberg-Bullen Earth model). The GIA effect is a secular trend signal that is existing in both of the GPS and GRACE/GFO observations. After subtracting the GRACE-inferred long-term of elastic loading displacement from GPS-derived velocity, the GIA effect was also removed from the final long-term trend of tectonic deformation. Therefore, we did not correct the GPS and GRACE/GFO observations for the GIA effect.

3. The GPS Imaging Method

GPS imaging is a newly designed method that has been effectively applied in the interpolation of vertical ground motion in different areas (Argus et al., 2017; Hammond et al., 2016; Kreemer et al., 2018). As a spatial filter, the main function of SSF is to eliminate the peak or outlier points throughout the whole network, which is inconsistent with the overall trend. A key difference compared to Kriging (Kriging, 1951), the more commonly used interpolation technique, is that SSF considers the weighted medians within local clusters of neighboring stations. It is constructed using a correlation-based mapping between distance and velocity of station-to-station pairs based on the statistical properties of the velocity. Here, we give a simple

Figure 3. (a) Histogram of CATS GPS vertical velocities in mainland China. (b) Histogram of CATS uncertainty in vertical GPS velocity. (c) CATS vertical rate uncertainty as a function of the length of the GPS time series. GPS, Global Positioning System; CATS, Create and Analyze Time Series.

introduction, and more detail about this method can be found in Hammond et al. (2016). The value of SSF depends on the median absolute deviation (MAD) function, as follows:

$$SSF_0(\Delta_k) = 1 / \max[MAD(\delta v_{k-1}), MAD(\delta v_k)] \quad (3)$$

which is a nonnormalized function, estimated from pairs of GPS vertical velocities with a similar signal as a function of distance Δ (in degrees). The value of δv_k is a set with each element being the absolute value of the difference between the vertical velocities of a given pair of GPS stations in the k th bin of distances. The function is normalized to set its maximum value to 1

Figure 4. The vertical GPS bedrock displacement from CATS-derived velocity with respect to ITRF2014. The inset subplot presents the three sites with anomalous subsiding rates of >20 mm/yr in the North China Plain. GPS, Global Positioning System; CATS, Create and Analyze Time Series.

$$SSF(\Delta_k) = SSF_0(\Delta_k) / \max(SSF_0(\Delta)) \quad (4)$$

It is unstable to estimate of the SSF over very short distances since that the given pair of GPS stations is with very short baselines. Moreover, the SSF could be flattened near $\Delta = 0$ due to $1/\delta v$ approaches infinity. Therefore, we set $\Delta \leq 3$ for the first two points of the SSF to flat unity. After that, median spatial filtering is applied, which is scaled by the contribution of the GPS-derived uncertainties

$$w_i = SSF(\Delta_{k(i,j)}) / \sigma_i \quad (5)$$

where w_i is the obtained weights, σ_i is the GPS-derived uncertainties of station i , and $\Delta_{k(i,j)}$ is a distance associated with bin k in Equation 4 that contains the distance between the stations in pair (i,j) . Finally, the spatially filtered velocity u_j at the evaluation point j in the triangulation is calculated by at the i th station (v_i) with median spatial filter applied

$$u_j = \text{weighted_median}(v_i, w_i) \quad (6)$$

where the weighted median is obtained by counting the sorted elements, and then incrementally summing normalized weighted values.

4. Results

4.1. CATS-Derived Vertical Velocity in Mainland China

We present the CATS-derived GPS vertical velocity in mainland China from the CMONOC I/II during period ranging from 1999 to 2020 (Figure 4). There are three GPS stations in the North China Plain (NCP) region that subside irregularly at rates exceeding 20 mm/yr (Figure 4, inset). It is generally believed that

the subsidence is related to the intensive exploitation of groundwater storage in the NCP (Feng et al., 2013). At this stage of processing, the GPS-derived vertical velocities reflect crustal deformation resulting from a combination of surface loading (hydrological) and tectonic deformation. The CATS-derived GPS vertical rates are presented in Table S1 in the Supporting Information.

4.2. The Detailed Processing Flow of GPS Imaging

The GPS-derived vertical velocity at any site reflects bedrock motion, which we assume to be the crustal response to some type of forcing, as part of the regional deformation signal. To understand this regional signal, we need to extend point-wise GPS-velocities spatially to image the pattern of crustal deformation in mainland China. First, we used the SSF as an empirically derived function to evaluate the variance of the signal that is attributable to the distance between stations, as shown in Figures 5a and 5b. The value of SSF as a function of distance (Δ) derived from the MAD-based function in Equation 4 is shown in Figure 5c.

Furthermore, a median spatial filtering (MSF) based on a Delaunay triangulation is applied to the vertical velocity rates at each station, which is accomplished by employing the weighted median of values of the nearby GPS stations (Hammond et al., 2016). This helps reduce the influence of outliers and anomalous values of the neighboring rates in the spatial distribution. We use spherical Delaunay triangulation (Renke, 1997) to identify the station neighbors for each site and apply the spatial filter. The weights for each site are computed using the SSF. The application of the spherical Delaunay triangulation of GPS sites and the distribution of weights, strengthens the spatial correlation and robust MSF-based velocities in the GPS network. We present the vertical velocity derived from GPS sites in mainland China in Figure 6a and the estimation of the velocity after adopting the preliminary median spatial filter, as shown in Figure 6b. It shows the consistency of velocity inside the given spatial domains within mainland China. The residual velocity is obtained by subtracting the filtered rate from the GPS-derived vertical velocity, as shown in Figure 6c, indicating that outlier velocities with large rates have been significantly reduced, and signals supported by multiple stations have been preserved. Filtering was performed for the MSF-based vertical velocities (Figure 6b) using the Delaunay triangulation (Figure 6d).

4.3. GPS Imaging of Vertical Velocity in Mainland China

The final step is the GPS imaging, which calculates the SSF-constrained velocity field on a 0.5° grid raster. In this study, we use a Delaunay triangulation (i.e., on the sphere) to connect each grid point to the neighboring GPS stations to image the vertical ground motion in mainland China. Meanwhile, imaging with Kriging interpolation was applied for a comparison, as shown in Figure 7. The corresponding gridded uncertainties have also been computed based on the procedure of GPS imaging. The spatial patterns of imaging velocity present differences between the three methods. A comparison with the vertical GPS velocities of all stations in Figure 6a shows that the GPS imaging constrained by Delaunay triangulation shows better results than that the kriging interpolation technique (Figure 7e). The average of GPS uncertainty in Figure 3c is ~ 0.4 mm/yr, which is consistent with the result estimated by SSF. The uncertainty of imaging constrained by kriging interpolation is much larger than the GPS-derived uncertainty rates, as shown in Figure 7f.

Furthermore, we make four profiles throughout the imaging velocity to compare the three results, as shown in Figure 8. The SSF-inferred GPS imaging provides more robust results than kriging interpolation. Therefore, SSF-based imaging seems more reliable than kriging interpolation. Moreover, adding the spherical Delaunay triangulation is significant in improving the details of the imaging velocities with irregular station spacing in mainland China.

4.4. The Elastic Deformation Induced by Surface Fluid Mass Changes

Mass changes, typically hydrological in nature, are influential geophysical phenomenon that cause elastic crustal deformation, which can be measured by geodesy techniques (Fu & Freymueller, 2012; Pan et al., 2018, 2019). In order to identify the surface mass changes and corresponding elastic deformation, we use the spherical harmonic coefficients of GRACE/GFO Level-2 gravity field products released by CSR to estimate the long-term terrestrial water storage (derived from GSM coefficients) (Figures 9a and 9b), and

Figure 5. The construction of the SSF that is a function of the distance between GPS stations and an evaluation point. (a) Histogram of the distances between pairs of GPS stations in mainland China. (b) The absolute value of the difference in vertical GPS velocity as a function of baseline distance. (c) The value of SSF as a function of distance (black line) derived from the MAD-based function (pink line). SSF, Spatial Structure Function; GPS, Global Positioning System; MAD, median absolute deviation.

atmospheric and nontidal ocean mass anomalies (derived from GAC coefficients) in mainland China (Figures 9c and 9d). Here, the GAC model is atmosphere and ocean background dealiasing model used in the standard GRACE/GFO processing. Furthermore, we use these mass change rates to calculate the long-term elastic deformation at each GPS station.

We considered the long-term mass changes and related loading displacements in two-time intervals, i.e., 2002–2019 (Figures 9a and 9c) and 2010–2019 (Figures 9b and 9d), because most of CGPS sites began collecting observations in 2010. The GRACE/GFO-derived spatial variability of TWS, and the GAC-inferred variability of the atmospheric and nontidal ocean after 2010 are mainly induced by different cycles of climate condition over mainland China (Li et al., 2020; Yao et al., 2020). Meanwhile, the long-term elastic deformation is changing, as shown in Figure 9.

Figure 6. (a) CATS vertical GPS velocities for all stations with time series duration over 4 years, in the ITRF2014 reference frame. (b) CATS velocities with the MSF applied corresponding to (a). (c) The difference values between (a) and (b). (d) The spherical Delaunay triangulation at connected stations for the rates with a median spatial filter in (b). The color scale in all plots is in mm/yr; positive (red) is upward, and negative (blue) is downward. CATS, Create and Analyze Time Series; GPS, Global Positioning System; MSF, median spatial filtering.

The GRACE-inferred mass change of TWS and the GAC modeled atmospheric and nontidal ocean during the past 18 years show significant spatial differences after the 2010 ENSO event, which may indicate accelerated atmospheric forcing (Long et al., 2015). Figure 9a presents two large-scale regions with obvious positive trends in mainland China, i.e., inner Tibetan Plateau (TP) and southern China (the yellow areas in Figure 9a). Three regions that exhibited negative trends are the southern TP, Tianshan Mountain, and North China Plain, respectively (the blue areas in Figures 9a and 9b). The surface mass changes of the TWS in mainland China can be summarized as follows:

The mass of TWS increases in the central Tibetan Plateau (inner TP) due to the presence of many endorheic glacier-fed lakes. The mass change rate shows slowdown after 2010 due to the hydrologic budget, as shown in Figure 9b. In southern China, the increasing surface TWS was induced by accelerated precipitation after 2010. ENSO events drive the positive trend of TWS in southern China, which is related to increased

Figure 7. Result of GPS imaging of the vertical velocity field in mainland China using the median spatial filter. The unit of color scale is mm/yr; positive (red) is upward, and negative (blue) is downward. (a) is the GPS imaging with spherical Delaunay triangulation and (b) corresponding uncertainty. (c) The result of GPS imaging of the vertical velocity field using Delaunay triangulation (without on the sphere) applied and (d) corresponding uncertainty. (e) is the GPS imaging with Kriging interpolation and (f) corresponding uncertainty. GPS, Global Positioning System.

Figure 8. Imaged vertical land motion in China along four profiles that cross the mainland China. (a) Same as in Figure 7a except that vertical rate is plotted over topography to illustrate the correlation between imaging and geographic features. (b)–(e) are vertical velocities along four profiles across the Chinese territory in (a).

Figure 9. GRACE/GFO-derived surface mass changes in mainland China from 2002–2019 to 2010–2019. The corresponding elastic deformation (the long-term trends without GIA correction) at the GPS site locations are shown with vectors. Note, here, the ocean area is masked out in the plots. (a) and (b) are the trend of mass changes of TWS from 2002–2019 to 2010–2019, respectively. (c) and (d) are the trend of atmosphere and nontidal ocean mass changes from 2002–2019 to 2010–2019, respectively. The vectors are corresponding surface elastic displacements induced by mass changes. GPS, Global Positioning System; GIA, glacial isostatic adjustment.

precipitation and dam construction (Huang et al., 2015; Long et al., 2015). The negative mass changes of the TWS in the southern TP and Tianshan Mountains are primarily associated with the continuing glacier melting around the Himalayas. Meanwhile, the drought vulnerability and declining precipitation induce the reduction of the surface water balance in southeastern TP (Tan et al., 2018). GRACE-derived negative mass changes in the North China Plain are mainly caused by the over-pumping of groundwater (Feng et al., 2013).

Furthermore, the mass changes of atmosphere and nontidal ocean present large-scale spatial variability after 2010 (Figures 9c and 9d), which is mainly induced by accelerated variation of land surface air temperature over mainland China (Li et al., 2020; Yao et al., 2020). All these spatial and temporal surface mass redistributions will deform the lithosphere over different time periods, so we estimate the elastic loading deformations over 2002–2019 and 2010–2019, as shown in Figure 9. In addition, a positive long-term trend of nontidal ocean mass loading would be focused along the coast, which could be a sign of leakage caused by the fact that the exploited data product stores information in the form of a spectral representation (as sets of spherical harmonic coefficients up to a certain limited degree) (Figures 9c and 9d). In addition, the GPS-derived vertical displacements are compared with the GRACE/GFO-inferred surface elastic loads

Figure 10. The comparison between detrended GPS vertical displacements (gray lines) and detrended GRACE/GFO-inferred elastic loads (red lines) at 10 stations during 2002–2019. GPS, Global Positioning System.

showing consistent variations (Figure 10). This is a strong indication that GRACE/GFO-derived hydrological, and GAC modeled atmosphere and nontidal ocean loads can support the need to correct the surface elastic deformation in the GPS observations (Fu & Freymueller, 2012; Hammond & D'Agostino, 2020; Hao et al., 2016; Pan et al., 2018).

4.5. The Application of GPS Imaging to Vertical Crustal Deformation in Mainland China

GPS-derived vertical velocity provides new significant motivation to research crustal deformation (Pan & Shen, 2017). And the GPS imaged velocity provides a higher spatial resolution for mapping crustal deformation in the Chinese territory. Vertical ground motion is a complex dynamic process of the crust that comprises the geophysical effects from surface loading to tectonic deformation from a range of depths. The GPS-based imaging of the vertical bedrock reveals the crustal motion of mainland China in response to the total process of the ground deformation during the past ~20 years, as shown in Figure 8a.

In this study, we use the GRACE/GFO-derived elastic deformation to correct for the long-term loading/unloading displacement in vertical GPS velocity, after which it reveals the extent of tectonic deformation of mainland China, as shown in Figure 11a. The imaged tectonic deformation using the SSF and Delaunay triangulation on a sphere is shown in Figure 11b, which is constrained by the velocities shown in Figure 11a. Furthermore, we extract four profiles (in Figure 11b) throughout the mainland China in order to specify the regional vertical tectonic deformation of the blocks (from Figures 11c to 11f). The spatial characteristics of tectonic uplift and the subsidence of different blocks in mainland China are described below.

4.5.1. Tibetan Plateau (TP) and Himalaya

Crustal deformation and the dynamic process of the TP and its forelands are controversial issues. Meanwhile, an estimation of the recent vertical tectonic deformation from geophysical and geodetic observations is the most effective way to constrain the evolution and mechanism of the continental orogeny in the TP and its forelands (Pan et al., 2018; Tapponnier et al., 2001). In this study, the estimated vertical tectonic deformations reveal a homogeneous uplift at a rate of ~0.7 mm/yr in the southern Tibetan Plateau and subsidence at the rate of ~−0.5 mm/yr in the central TP. The uplift of the southern TP suggests that tectonic deformation is mainly related to the elastic accumulation of strain due to the subduction of the Indian lithosphere beneath the edge of the southern Eurasian plate (Fu & Freymueller, 2012; Pan et al., 2018; Zhao et al., 2010). This is where the strongest crustal shortening in the southern TP region occurs, where the middle and lower crust shortens and thickens in the north-south direction. While crustal extension in the NW-SE direction may induce crustal subsidence in the center of TP (Ge et al., 2015), the east-west crustal extension and diverging flows along lithospheric scale strike-slip faults in the central TP lead to the formation of a north-south ridge structure in the shallow brittle crust (Ge et al., 2015). The tectonic uplift from the eastern Himalaya to the southeastern TP (Figures 11b and 11e) reveals the local alteration of the strain fields that are associated with the recent rapid exhumation of the Indian crust (Chang et al., 2015).

The subsidence throughout the Qiangtang and Songpan-Ganzi blocks is consistent with thinning amid W-E tectonic extension as reported in previous studies (Wang & Shen, 2020; Zheng et al., 2017). Vertical tectonic deformation with uplift rates ranging from ~−0.1 to ~0.3 mm/yr throughout the Qaidam Basin to Qilian fold system is mainly induced by the crustal strain accumulation in the northeastern TP (Pan et al., 2018). The tectonic subsidence throughout the northern to southern of Chuandian Block, may be the result of the crustal thickening and detachment of the lower lithosphere in southeastern TP (Bai et al., 2010; Guo et al., 2016; Pan & Shen, 2017). In Figure 11a, an anomalous uplift with a rate of ~5.8 mm/yr (GPS sites of SCML) along the Longmen Shan fault may be induced by crustal shortening as a result of postseismic deformation after 2008 Wenchuan earthquake (Wang et al., 2011).

4.5.2. Tianshan Mountains and Tarim Basin

The continent-continent collision of the Tianshan Mountains was an important orogenic event in the Mesozoic and Cenozoic (Tapponnier & Molnar, 1979). The Tianshan Mountains and their forelands are resurrected or regenerated orogenic belts in the continental interior (Avouac et al., 1993; Deng et al., 1996; Yin et al., 1998), which are surrounded by the stable Tarim Basin (Allen et al., 1999; Carroll et al., 1995), and the Junggar Basin (Carroll et al., 1990; Feng et al., 1989). The whole Tianshan range was compressed and shortened under the extrusion of stable blocks on both sides (Burchfiel et al., 1999). The tectonic environment in the eastern part of the Tianshan region is a typical compressive structure in a continental orogenic belt. The Cenozoic continental collision caused the Tianshan uplift and further subsidence of the basins on both sides, gradually forming the current landform and structural pattern. In this study, the constrained imaging of vertical tectonic deformation with GPS and GRACE/GFO measurements reveals that the tectonic uplift progresses an average rate ~0.4 mm/yr in the Tianshan Mountains which agrees well with our previous

Figure 11. (a) The point-wise vertical tectonic deformations from GPS and GRACE/GFO measurements. (b) The tectonic deformations for mainland China based on (a), which is also presented with detailed tectonic units in Figure S1 in the Supporting Information. (c)–(f) are the profiles consistent with Figure 8a and the topography along with the profiles. The blue and red dots denote the tectonic and single-point GPS velocities, respectively, throughout AA', BB', CC', DD' in Figure 11b; and the corresponding terrain heights are shown by gray shadowing. Abbreviations: Western Tibetan Plateau (WTP), Tarim Basin (TB), Tianshan (TS), Junggar Basin (JB), Tibetan Plateau (TP), Qaidam Basin (QB), Qinglian (QL), IMP, Eastern Himalaya (EH), Eastern Tibetan Plateau (ETP), Ordos Basin (OB), Inner Mongolian-Daxing'anling Fold System (IM-DH), Songliao Basin (SLB), CFB, Yangtze Craton (YZC), Southern North China Plain (SNCP), Northern North China Plain (NNCP). GPS, Global Positioning System.

study (Pan et al., 2019). The dynamic mechanism of tectonic uplift is lateral compression, which leads to the formation of contemporary mountain-building in Tianshan (Pan et al., 2019). In Figure 11a, the subsidence seen at GPS stations in the Tarim Basin is mainly related to the thrusting and exhumation around the margins of continental collision (Deng et al., 2017; Sobel & Dumitru, 1997).

4.5.3. South China block

South China is a stable block without tectonic movements or seismicity, which has been widely recognized as a separate subplate in mainland China (Bird, 2003; Holt et al., 2000). Tapponnier et al. (1982) reported that South China acts as a tectonic unit under south-southeast slippage induced by the collision and compression of the mainland. The South China block consists of two structural units, namely, the Yangtze and Cathaysia Cratons. The estimation of vertical tectonic deformations reveals uplift at a rate of ~ 0.3 mm/yr in the upper-middle Yangtze Craton, which is reduced to 0–0.1 mm/yr in the Cathaysia Craton. In the Yangtze block, the uplift rate is 0.4 mm/yr in the west, which gradually declines to 0.1 mm/yr in the east possibly due to the eastward lateral crustal extrusion of the TP (Liu et al., 2014).

4.5.4. North China block

North China is located on the eastern margin of Eurasia and is divided into two tectonic units with different geomorphologic features; the Ordos block, and the North China Plain. The GPS observations reveal a general eastward movement in northern China relative to the rest of Eurasia (Shen et al., 2000).

The Ordos block (OB) is located in the central and northern parts of China. The southwest corner of the Ordos block is compressed by the northeast edge of the Tibetan Plateau, but all the other sides are bounded by the fault basin belt. In addition, relative to the surrounding area, the internal structure of the Ordos block is weakly active, with little seismicity, and there are no large-scale active faults. In Figure 11b, the vertical tectonic deformation observed by GPS and GRACE/GFO reveal an overall uplifting interior of Ordos block. The uplift rate is ~ 1 –2 mm/yr which is consistent with the leveling result in the previous study (Hao et al., 2016). However, there is an uplifting difference of ~ 1 mm/yr at the southern border of the OB, which neighbors the northeastern boundary of the Tibetan Plateau in the Qilian Shan region.

4.5.5. Northeast China block

Northeast China is a stable block without tectonic activity. Excluding deep source earthquakes (such as the 7.9 Mw 2008 Wenchuan earthquake in the eastern TP) and volcanic activity in the Wudalianchi volcanic cluster and Changbai Mountain (on the border with Korea), there was no obvious fault activity in this area. In the northeastern area, the Inner Mongolian-Daxinganling Fold System and Songliao Basin form two tectonic units. In Figure 11b, the estimated vertical tectonic deformation shows uplift throughout the Inner Mongolian-Daxinganling Fold System, which may be related to the crustal thickening due to the collision of the amalgamated North China-Mongolia region with Siberia (Meng, 2003). The subsidence within the Songliao Basin is mainly attributed to the lithospheric thinning and crustal extension, which is characterized by early stage rifting and late-stage sagging (Meng, 2003; Royden & Keen, 1980).

5. Discussion

The interactions between the Eurasian plate and its surroundings (the Indian, Pacific, Philippine sea plates), and the geodynamics within the Eurasian plate itself result in different types of active faults in the mainland China (England & Molnar, 1990, 1997b). The inner crustal structure of continental China is complicated due to its widely distributed tectonic boundary deformation (Yin, 2010; Zhang et al., 2004). Over the past 20 years, GPS space geodesy plays an important role by providing observational constraints on the tectonic dynamic process in mainland China, which could be combined with a block model to reveal the kinematics within basement blocks (Gan et al., 2007; Wang & Shen 2020; Wang et al., 2001). Overall, the continental upper crust is characterized by brittle deformation, which is manifested as a continuous (or rigid) block movements and interblock interactions (Thatcher, 2007), while the lower crust and upper mantle are characterized by viscoplastic flow (Gan et al., 2007).

The present-day vertical tectonic deformations exhibit steep gradient variations across the different structural units of mainland China, which have been constrained by the integration of GPS and GRACE measurements (Fu & Freymueller, 2012; Hao et al., 2016; Pan et al., 2018). They also reveal that the observed vertical tectonic motions are block-like with locking on faults (Pan et al., 2019). In this study, we present a new high-resolution imaging technique for describing crustal deformation to reveal geodynamic processes of different blocks in mainland China. This suggests that the measurable tectonic uplift occurs in regions that are located in the southern and northeastern TP, and Tianshan Mountain due to crustal shortening. In

addition, the stable peripheral cratonic blocks, such as the Tarim Basin, Sichuan Basin, and Ordos block, are all characterized by tectonic uplifts that are related to an increasing crustal thickness (Bao et al., 2015). Meanwhile, spatial patterns exhibiting notable differences between neighboring blocks may be associated with the stress accumulation, which could lead to the generation and occurrence of strong earthquakes in mainland China, as shown in Figure 1.

6. Conclusions

In this study, we analyze the imaging of vertical crustal deformation in mainland China over past 20 years from 260 GPS continuous observation time series. The TSAlyzer software is used to preprocess and eliminate outliers and offsets in GPS time series, which considerably improves the reliability of vertical velocity field. We apply an empirically designed Spatial Structure Function (SSF) to image the two-dimensional vertical crustal deformation. The mass changes of land water and atmosphere/nontidal ocean and the corresponding elastic load deformation surrounding CGPS sites in the Chinese mainland from 2002–2019 to 2010–2019 were corrected for using the GRACE/GFO and GAC spherical harmonic coefficients. We found that the secular trends of surface terrestrial water storage were significantly different in spatial patterns after 2010, which may be associated with the different cycles of climate conditions in the mainland China. The imaging of vertical tectonic deformation constrained by GPS and GRACE observations reveals the geodynamic process of vertical tectonic deformation in mainland China. The obtained images present the differential movement of blocks, and the profiles show a noteworthy velocity gradient across the boundaries of different blocks, which may be dominated by lithospheric thickness. Crustal shortening may have played an important role in the tectonic uplift of terrestrial orogenic zones, such as the TP and Tianshan Mountains. The vertical tectonic deformation of the Ordos block and Yangtze Craton exhibits vertical uplift which may be related to the outward crustal deformation of the TP.

Data Availability Statement

GPS data support from “China Earthquake Networks Center, National Earthquake Data Center” (<http://data.earthquake.cn>). Position time series in this study are provided by GNSS data products of China earthquake administration, <http://www.cgps.ac.cn/index.htm>. The GRACE data products used in the study were downloaded from <http://www2.csr.utexas.edu/grace/>.

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