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Dynamic Maintenance of the Elevation Reference Frame Based on Continuous Operation Reference Stations

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In areas where urban land subsidence is frequent and significant, there are problems with heavy workload, high cost, long observation period, and difficult technical maintenance of the regional elevation reference frame in leveling measurement. In this paper, we propose a method of using continuous operation reference stations (CORSs) as nodes to perform dynamic maintenance of regional elevation reference frames. Using continuous years of Global Navigation Satellite System (GNSS) observation data and surface mass load data (land hydrology, atmospheric pressure, and sea level elevation), we calculate the normal height variation of CORSs, dynamically correct the normal height of CORSs, and verify the accuracy of the calculated CORS normal height variation results using multiperiod leveling observation data. The results showed that the average difference between the normal height variation determined using CORSs data and surface mass load data and the normal height variation of the station obtained by two-stage leveling measurement is 4.37 mm, and the calculated average accuracy of the normal height variation of CORSs is about 5.42 mm. CORSs demonstrating long-term stable continuous observation can be selected as nodes of the elevation control network to achieve the dynamic maintenance of the regional elevation reference framework using CORS data. The research results can provide exploratory experience for future elevation benchmark maintenance work in Beijing.

1. Introduction

Modern data of surveying and mapping are important infrastructure that serve the national economy, social development, ecological civilization, and national defense construction. The construction of modern surveying and mapping data infrastructure refers to the establishment of a high-precision, three-dimensional, geocentric, dynamic, and information-based surveying and mapping data framework system.[(1)] The construction of a modern fundamental system of surveying and mapping is one of the key tasks of new fundamental surveying and mapping

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during the 14th Five-Year Plan Period, and optimizing the modern surveying and mapping data system is one of the main tasks of modern surveying and mapping datum construction.(2,3) At present, China's elevation reference framework mainly relies on leveling networks of various levels to maintain and achieve elevation transmission. Another important elevation measurement mode is the use of global navigation satellite systems combined with high-precision geoid models to determine the normal height of the target point. The Beijing elevation reference frame is dynamically maintained through the remeasurement of the leveling network, with the Yuyuantan leveling origin as the reference point of the remeasurement network. The remeasurement workload is large, the cost is high, and the observation period is long, especially in areas with frequent and significant ground subsidence, making it difficult to maintain the regional elevation reference frame.

Continuous operation reference station (CORS) based on the global satellite navigation system is currently the most advanced, practical, and convenient technology for achieving and maintaining national and regional dynamic coordinate frameworks. It is the most important component of the "space data infrastructure" and an essential technical means in the information society and knowledge economy era.(4,5) The CORS station can continuously monitor the three-dimensional position variations of surface points with millimeter-level accuracy and analyze the time series to obtain accurate movement trends of the station.(6) In the context of intelligent surveying and mapping, we study the feasibility of using CORSs as nodes to dynamically maintain regional elevation reference frames, thereby shortening the distance of leveling joint measurement, reducing the cycle of leveling network remeasurement, and reducing the workload and cost of maintaining regional elevation reference frames. This is of great significance for optimizing modern fundamental systems of surveying and mapping.

2. Technical Principles

Using years of continuous observation data from CORSs in Beijing, combined with surrounding International Global Navigation Satellite System (GNSS) Service (IGS) stations, CORS network data processing is carried out to obtain the accurate three-dimensional coordinates of CORSs, and time series analysis is performed on the elevation direction of CORSs to obtain accurate time series of CORS geodetic height variations. By comprehensively utilizing surface mass load data such as land hydrology, sea level elevation, and atmospheric pressure, the height anomaly variations of CORSs can be calculated. Combining the geodetic elevation variations and height anomaly variations of CORSs, we obtain their normal elevation variations. Dynamic correction is performed using the normal height change information of CORSs to achieve the goal of dynamically maintaining the elevation reference frame with CORSs as nodes of the regional elevation control network. The technical method for maintaining the regional elevation reference framework is shown in Fig. 1.

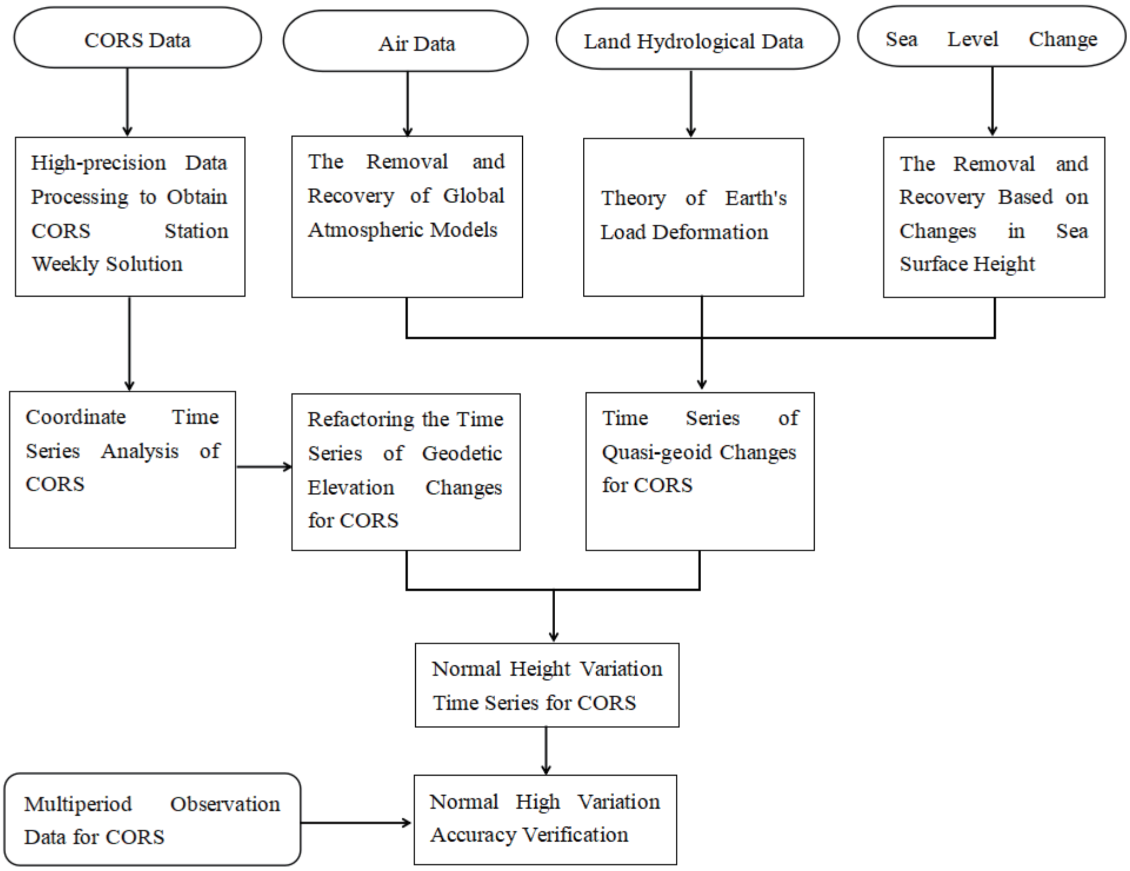


Fig. 1. Method of maintaining the regional elevation reference framework.

3. Data Processing of CORS Network

3.1 Data collection

We collect observation data from CORSs and surrounding IGS stations in Beijing from 2012 to 2021, with a sampling interval of 30 s. Beijing CORSs include DSQI, XIJI, NLSH, and CHAO stations. Twelve surrounding IGS stations are used as control points for joint calculation. The 12 IGS stations are AIRA, BADG, BJFS, PIMO, DAEJ, POL2, SHAO, TCMS, HYDE, TIXI, URUM, and YSSK. Because of data quality issues (severe cycle jumps), only data from the CHAO station from 2016 to 2021 and DSQI station from 2017 to 2021 will be processed.

3.2 Baseline processing

The baseline processing software adopts the high-precision GNSS data processing software GAMIT/GLOBK, which was jointly developed by the Massachusetts Institute of Technology (MIT) and the Scripps Institution of Oceanography (SIO) and is one of the best GNSS data processing software in the world.[7] We utilize GAMIT version 10.70 and GLOBK version 5.12

software, with appropriate constraints, to process data from CORSs in Beijing. The data processing parameter settings are shown in Table 1.

3.3 Time series calculation of geodetic height

Using GAMIT/GLOBK software to calculate the GNSS observations of each station on a daily basis, including various parameters such as station position, receiver clock bias, and satellite clock bias, the daily relaxation solution (h-file) of each CORS is obtained. Multiple daily solution files (seven consecutive days) obtained from the above calculations are summarized. The Kalman filtering method is used to merge them into a comprehensive solution (weekly solution) based on the high-precision coordinates of the IGS station ITRF2014 framework. Using the weekly solution values from the first week as a reference, we calculate the original coordinate time series of four CORSs in Beijing under the ITRF2014 framework. Taking the NLSH station as an example, its three-dimensional coordinate time series in the NEU direction is as shown in Fig. 2.

3.4 Analysis and reconstruction of CORS geodetic height–time series

The purpose of conducting time series analysis on CORS geodetic height is to obtain fitting parameters that characterize the characteristics of geodetic height variations, reconstruct and calculate a "clean" geodetic height–time series based on the fitting parameters, and then determine geodetic height variations. The CORS geodetic time series is described using the following function model:(8–10)

$$h(t_i) = a + bt_i + \sum_{m=1}^{M} A_m \sin(2\pi f_m t_i + \phi_m) + \sum_{j=1}^{J} O_j H(t_i - \tau_j) + v_i, \quad (1)$$

where t_i is the epoch time of the weekly solution of the coordinate sequence, $h(t_i)$ is geodetic

Table 1
Baseline solution strategy of GAMIT.

Parameter name	Method model
Baseline treatment type	Baseline solution
Reference frame	ITRF2014
Satellite orbit	IGS precise ephemeris
Satellite cut-off altitude angle	10°
Data sampling interval	30 s
Zenith delay correction model	VMF1
Correction of receiver antenna phase center	Absolute correction
Number of zenith delay correction parameters	13
Light pressure model	BERNE
Solid tide model	IERS2010
Ocean tide model	FES2004
Coordinate constraint	IGS station: N: 0.05 m E: 0.05 m U: 0.05 m CORS: N: 100.0 m E: 100.0m U: 100.0 m

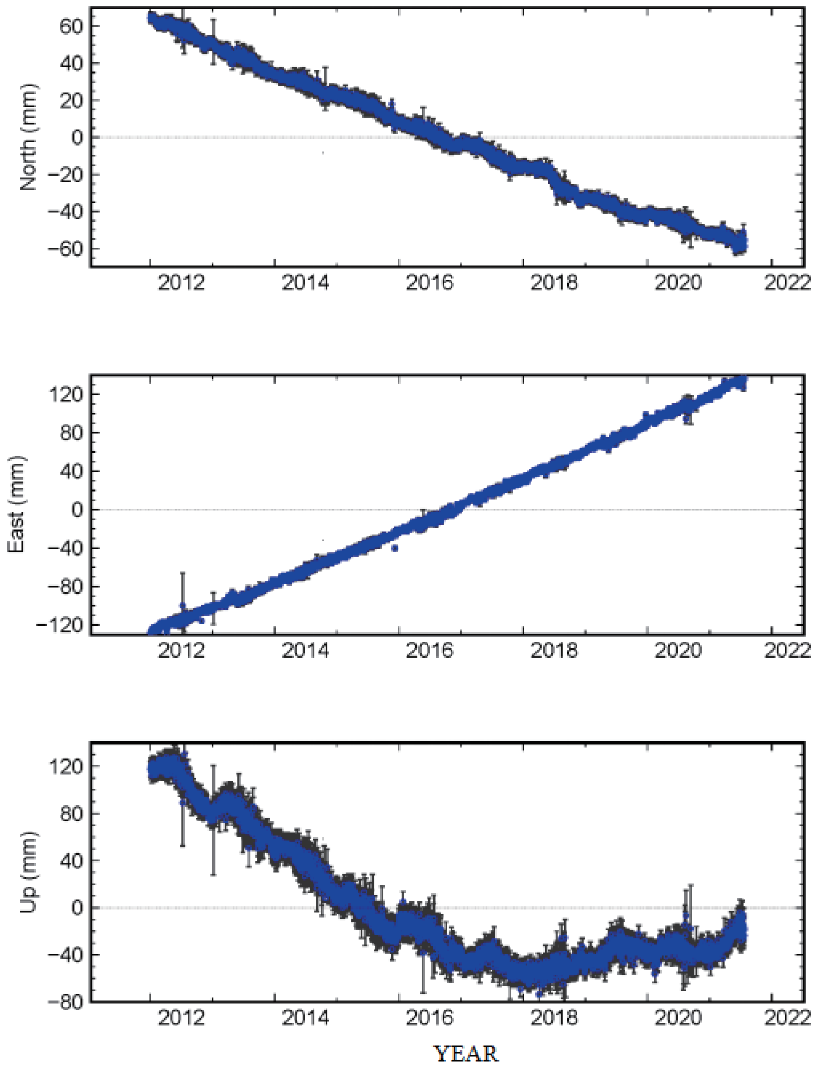


Fig. 2. (Color online) NEU direction 3D coordinate time series for NLSH station.

height, a is a constant term, b is a linear velocity term, A_m and ϕ_m are the amplitude and phase of a periodic signal with frequency f_m, O_j is the geodetic height mutation caused by various reasons, τ_j is the epoch when the geodetic height mutation occurs, H is the Heaviside step function, and v_i is residual error.

The above fitting model is used to perform time series analysis on the geodetic height of CORSs to obtain fitting parameters such as constant, linear, and periodic terms. The basic steps are as follows.

(1) Use the least squares method to estimate the parameters of the geodetic solution time series of CORSs, and determine the fitting parameters such as the constant term, linear term, and periodic term.

(2) Reconstruct the geodetic elevation time series using fitting parameters as reference values for gross error detection. Detect and eliminate gross errors in the original time series using three

times the residual standard deviation, and carry out detection iteratively until a clean original geodetic elevation time series is obtained.

(3) Fit and estimate the clean original geodetic time series, obtain constant, linear, and periodic parameters, and reconstruct and calculate the geodetic time series without gross errors and with the majority of high-frequency noise removed by combining time information.

According to the fitting parameters of the CORS geodetic height time series related to time, the geodetic height variations at two given time points can be interpolated or extrapolated. The analysis and reconstruction results of the geodetic height time series using XIJI station as an example are shown in Fig. 3.

4. Estimation of Height Anomaly Variations for CORSs

4.1 Collection of surface quality load data

(1) Land Water Data: The Global Land Data Assimilation System (GLDAS) data from NASA's Goddard Space Center and the National Environmental Forecasting Center is used. This data uses land surface modeling and data assimilation techniques to output various hydrological parameters of the land surface. The data utilizes rainfall observations and solar radiation as input parameters, with a spatial resolution of 0.25° × 0.25°, one value per month, for the time period from January to May 2021.

(2) Atmospheric pressure data: The European Centre for Medium Range Weather Forecasts (ECMWF) global atmospheric pressure model is used, with a spatial resolution of 0.25° × 0.25°, one value per month, for the time period from January to May 2021.

(3) Sea level change data: The sea level anomaly data used is the grid fusion data of Maps of Sea Level Anomaly (MSLA) provided by the Satellite Oceanography Archive Data Center of the

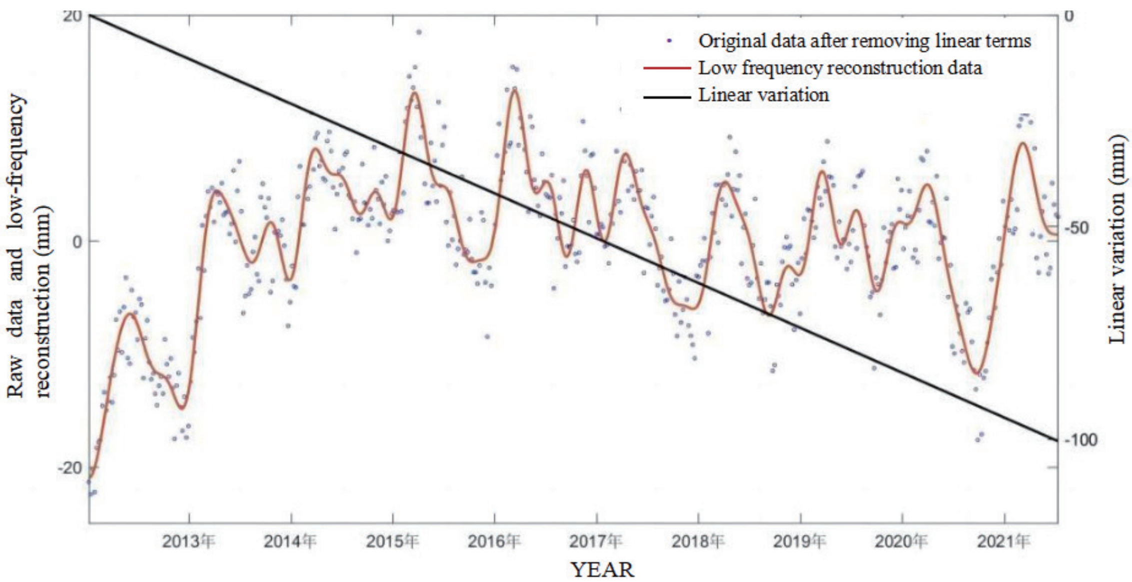


Fig. 3. (Color online) Analysis and reconstruction results of geodetic height–time series for XIJI station.

French National Centre for Space Research (CNES). This data is generated from the monthly average sea surface height anomalies measured by multiple satellites worldwide, with a resolution of 0.25°×0.25°, and covers the period from January to May 2021.

4.2 Principle of calculating height anomaly variations

The solid Earth's surface will produce significant load responses to variations in the mass of surface fluids (atmosphere, ocean, land water, cryosphere, etc.), including displacement variations on the surface, as well as variations in the gravity and stress fields on the surface. Therefore, both surface and internal mass migration of the Earth can cause varying degrees and ranges of variations in the geoid, mainly as a result of land water storage, glacier and sea level variations, glacial equilibrium adjustment (GIA), tectonic uplift and subsidence, and seismic and other geodynamic processes. For most regions of our country, the contribution of variations in the geoid mainly includes variations in land water storage, sea level variations, and atmospheric pressure variations.[11–13]

The details of the calculation procedure are shown in Fig. 4.

(1) Firstly, convert the global low-resolution and regional high-resolution land water storage, sea level height, and atmospheric pressure data into corresponding equivalent water level grid

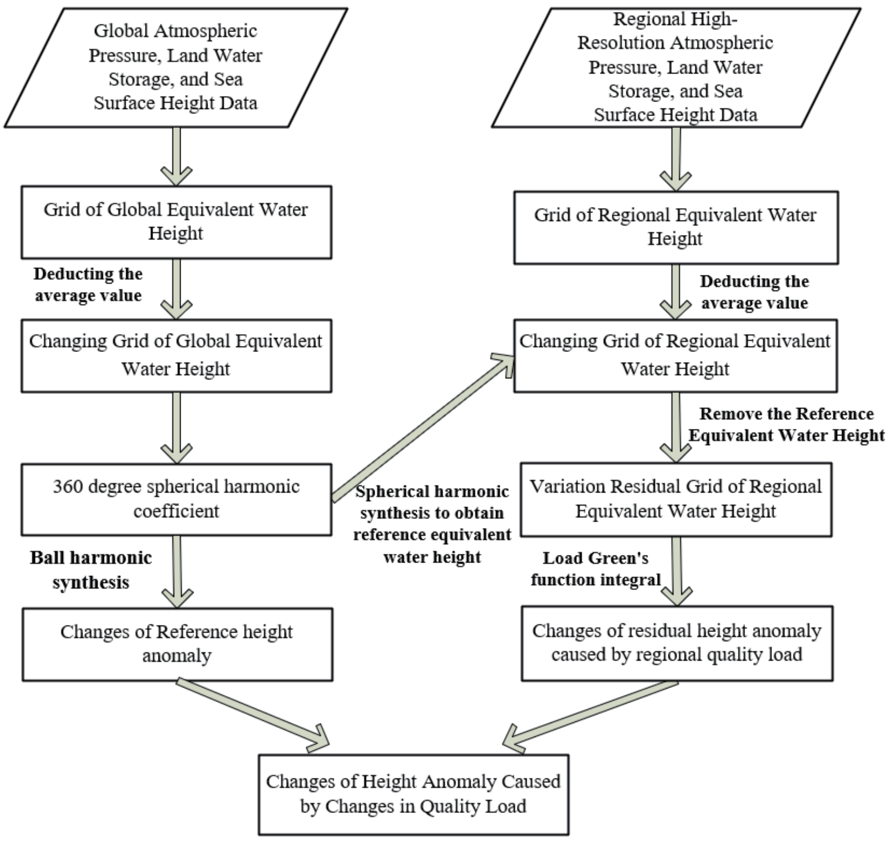


Fig. 4. (Color online) Procedure of calculating height anomaly variations

data. The average equivalent water level of the previous three months is used as the benchmark data to calculate the surface mass load change relative to this benchmark value for each month (global equivalent water level change grid and regional equivalent water level change grid data).

(2) Perform spherical harmonic analysis on the global equivalent water level change grid data for each month to obtain a 360-order load change spherical harmonic coefficient model and calculate the abnormal variations in CORS reference elevation caused by the reference equivalent water level and load variations through spherical harmonic synthesis.

(3) Then, the removal calculation recovery method is adopted to remove the reference equivalent water level from the grid of regional equivalent water level variations, obtaining residual grid data of regional equivalent water level variations. Then, use the load Green's function integration theory to calculate the residual elevation abnormal variations caused by regional mass loads.

(4) Finally, combine the abnormal variations in the reference elevation of CORSs with the residual elevation anomalies caused by regional mass load to restore the abnormal variations in CORS elevation.

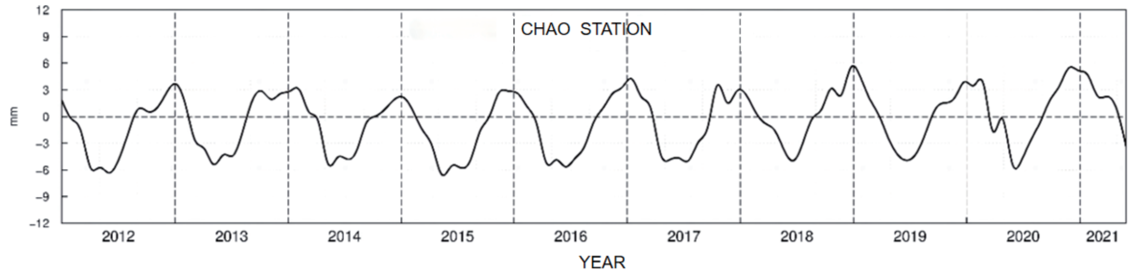
4.3 Height anomaly variations caused by total load

By summing the height anomalies caused by land water load, atmospheric pressure load, and sea level variations, height anomalies caused by the total load can be obtained. The final calculation yields the height anomaly time series of four CORSs for the time period from January to May 2021 with a time resolution of one month. The statistics and time series of height anomaly variations in the total load of each CORS are shown in Fig. 5 and Table 2.

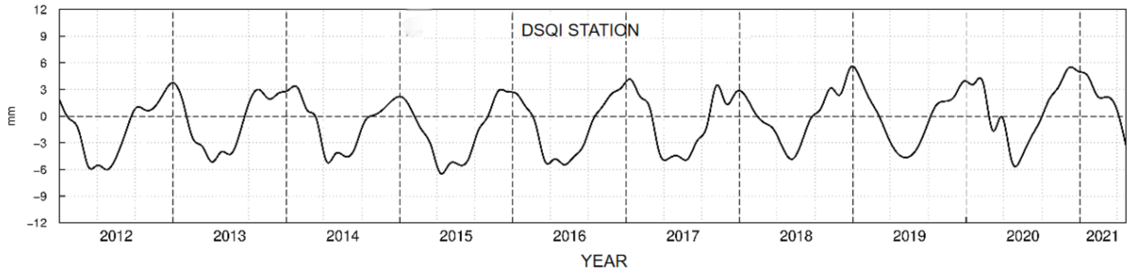
According to the analysis results in Fig. 5 and Table 2, the height anomaly caused by the total surface mass load in the Beijing area shows a significant seasonal periodic variation, with the variation of height anomaly ranging from −7 to 6 mm. The fluctuation of height anomaly values within one year can reach about 13 mm. Since the beginning of 2012, the value of height anomaly variations gradually decreased over time. From April to May, the value reached its minimum, and then gradually increased over time, reaching its maximum value from November to December. The absolute value of abnormal elevation variations in April and May is the highest. The absolute value of height anomaly variations in February and September is the smallest. It is necessary to introduce a correction of height anomalies for high-precision CORS calculations.

Table 2
Statistical information on height anomaly variations in the total load of CORSs. Unit: mm

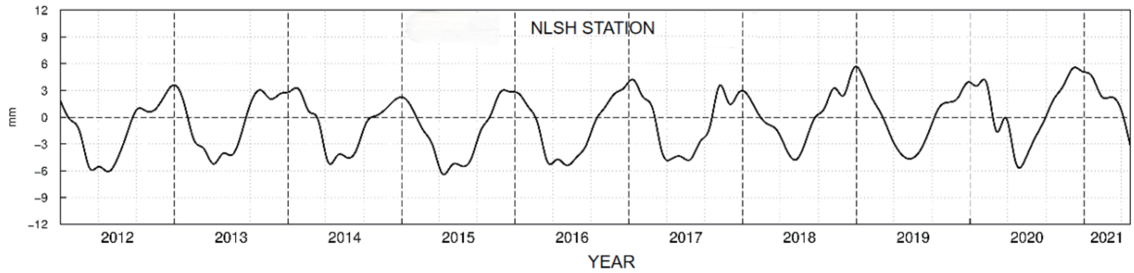
Number	Station name	Maximum value (mm)	Minimum value (mm)	Average value (mm)	Standard deviation (mm)
1	CHAO	5.3070	−6.6243	−0.7579	3.3221
2	DSQI	5.4387	−6.4078	−0.5211	3.2152
3	NLSH	5.4934	−6.3452	−0.4878	3.2216
4	XIJI	5.1903	−6.9182	−0.9722	3.4094



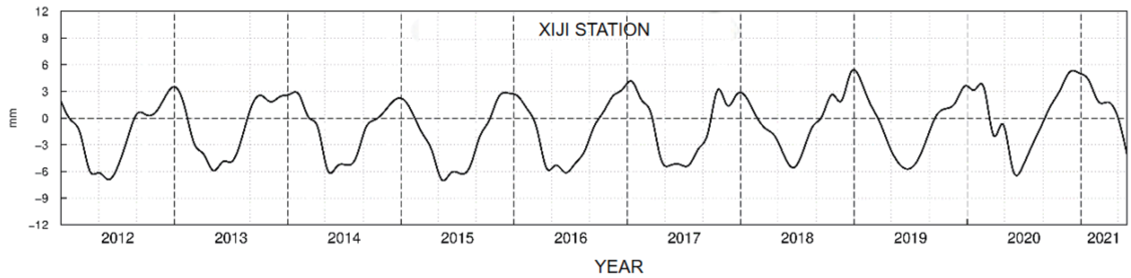
(a)



(b)



(c)



(d)

Fig. 5. Time series of height anomaly variations in total load of example CORSs.

5. Determination and Verification of Height Anomaly Variations at CORSs

5.1 Determination of normal high variation of CORS

The high-precision data processing can yield the time series of geodetic height variations at CORSs. By using data such as land water storage, sea level, and atmospheric pressure variations, the time series of height anomaly variations can be calculated. Subtracting the values of the two time series can give the normal high-change time series of CORSs.

$$\Delta H(t) = \Delta h(t) - \Delta\zeta(t) \tag{2}$$

Here, $\Delta H(t)$ is the normal height variation at time t, $\Delta h(t)$ is the geodetic height variation at time t, $\Delta\zeta(t)$ is the height anomaly variation at time t, and t is the leveling joint measurement time of the selected CORS station.

5.2 Accuracy verification of CORS with normal high variation

Using the observation time t of two or more leveling measurements, normal height variation is calculated referring to GNSS observations and load data during the corresponding time period. The verification of the external accuracy of normal height changes is achieved by comparing them with the normal height difference measured by leveling. The normal height of CORSs in different years is based on the leveling measurement results of the Beijing settlement area over many years.

CORS and surface mass load data are used to calculate the normal height variation at the time of leveling joint measurement, which is then compared with the normal height variation of leveling measurement to obtain the mean square error of CORS normal height variation $m_{\Delta H}$ and the mean square error of leveling measurement normal height variation $m_{\Delta Hs}$. Among them, the values for NLSH station, XIJI station, and CHPN station are all based on the normal height in 2012 as a reference. For CHAO station, the normal height in 2016 was used as a reference, and for DSQI station, the normal height in 2017 was used as a reference. The results are shown in Tables 3 to 6.

The statistical analysis results are as follows.

(1) In the results for CHAO, DSQI, and NLSH stations, the difference between the normal height variation of CORS+surface mass load data and the normal high variation of leveling measurement is less than 10 mm, indicating good consistency with the error in the normal high variation of leveling measurement. Among them, the NLSH results are in the best agreement, with differences of less than 5 mm in all results.

Table 3
Normal high variation accuracy verification results for NLSH station. Unit: mm

Time (Year)	CORS+Surface mass load		Leveling observation	Difference	Mean square error	
	geodetic height variation Δh	normal height variation ΔH	normal height variation ΔHs	$\Delta H - \Delta Hs$	$m_{\Delta Hs}$	$m_{\Delta H}$
2016	−134.4	−135.4	−138.0	2.6	5.5	5.1
2017	−163.3	−164.8	−162.0	−2.8	5.7	3.9
2018	−175.1	−179.2	−177.0	−2.2	5.1	4.0
2019	−161.5	−164.7	−164.0	−0.7	5.1	4.0
2020	−151.0	−151.8	−156.0	4.2	5.0	4.7
2021	−146.3	−152.8	−153.0	0.2	5.5	4.2

Table 4
Normal high variation accuracy verification results for XIJI station. Unit: mm

Time (Year)	CORS+Surface mass load		Leveling observation	Difference	Mean square error	
	geodetic height variation Δh	normal height variation ΔH	normal height variation ΔHs	$\Delta H - \Delta Hs$	$m_{\Delta Hs}$	$m_{\Delta H}$
2016	−31.3	−33.1	−44.0	10.9	6.5	7.2
2017	−40.2	−41.8	−53.0	11.2	7.3	6.0
2018	−54.3	−56.9	−67.0	10.1	7.2	6.5
2019	−67.6	−69.4	−74.0	4.6	7.4	7.3
2020	−84.8	−88.6	−85.0	−3.6	6.5	8.6
2021	−79.6	−86.8	−97.0	10.2	6.6	7.1

Table 5
Normal high variation accuracy verification results for CHAO station. Unit: mm

Time (Year)	CORS+Surface mass load		Leveling observation	Difference	Mean square error	
	geodetic height variation Δh	normal height variation ΔH	normal height variation ΔHs	$\Delta H - \Delta Hs$	$m_{\Delta Hs}$	$m_{\Delta H}$
2017	−31.2	−32.0	−32.0	0.0	6.8	5.1
2018	−64.2	−65.2	−63.0	−2.2	6.8	5.4
2019	−86.7	−87.0	−87.0	0.0	6.0	5.1
2020	−108.6	−110.8	−104.0	−6.8	6.0	5.4
2021	−110.4	−111.7	−114.0	2.3	6.6	5.1

Table 6
Normal high variation accuracy verification results for DSQI station. Unit: mm

Time (Year)	CORS+Surface mass load		Leveling observation	Difference	Mean square error	
	geodetic height variation Δh	normal height variation ΔH	normal height variation ΔHs	$\Delta H - \Delta Hs$	$m_{\Delta Hs}$	$m_{\Delta H}$
2018	−59.4	−59.9	−61.0	1.1	5.3	4.2
2019	−102.2	−101.6	−100.0	−1.6	5.3	5.0
2020	−121.4	−120.8	−130.0	9.2	5.0	5.5
2021	−134.5	−140.7	−146.0	5.3	5.1	4.4

(2) For the normal height variation of CORS+surface mass load data at XIJI station compared with the normal high variation results of leveling measurement, the differences in 2018, 2019, 2020, and 2021 are less than 10 mm, and the differences in 2016 and 2017 are 11 mm. According to the analysis results in Table 4, the leveling height accuracy of XIJI station is slightly worse than those of other stations, with an annual height mean square error greater than 6.5 mm. The reason for the slightly larger difference in normal height variations obtained by the two techniques is mainly the contribution of leveling measurement errors.

(3) The average accuracy of the normal height variation of CORSs calculated using GNSS observation data and surface mass load data is about 5.42 mm, which can be equivalent to the first-order leveling accuracy of loop lines with a length of less than 7.34 km, and the second-order leveling accuracy of coincident or closed loop lines with a distance of less than 1.83 km.

6. Conclusions

We used continuous years of GNSS observation data and surface mass load data to calculate the normal height variations of CORSs as elevation maintenance results, verifying the feasibility of using CORSs as nodes to achieve the dynamic maintenance of regional elevation reference frameworks. The dynamic maintenance of elevation reference frameworks based on CORSs is an exploration of optimizing a modern surveying and mapping data framework system. As an important infrastructure, elevation data can provide reference and inspiration for the maintenance of elevation data in Beijing in the future as well as be applied in the urban intelligent surveying and mapping industry.

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