Nontectonic Signals in Reprocessed Continuous GPS Position Time Series of CMONOC

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Abstract The nearly nine-year continuous GPS data collected since 1 March 1999 from the Crustal Motion Observation Network of China (CMONOC) were consistently analyzed. Most of the nonlinear movements in the cumulative position time series produced by CMONOC data center disappeared; and more accurate vertical terms and tectonic signals were extracted. Displacements caused by atmospheric pressure loading, nontidal ocean loading, soil moisture mass loading, and snow cover mass loading using the National Centers for Environmental Prediction (NCEP) Reanalysis I/II models and Estimation of the Circulation and Climate of the Ocean (ECCO) data can explain most of the vertical annual terms at many stations, while only parts can be explained at Lhasa and southern coastal sites, indicating that there are some deformation mechanisms that are still unknown or not modeled accurately. The remarkable differences in vertical position time series for short-baseline sites reveal that GPS stations can be greatly affected by local factors; and attention should be paid when explaining observed GPS velocity vectors.

Keywords GPS; position time series; CMONOC; mass loading; reprocessing

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Introduction

Continuous GPS (CGPS) has been widely used for geophysical studies, for example, the aseismic slow slip events¹ and displacement caused by strong quakes.² Since 1998, the Crustal Motion Observation Network of China (CMONOC) project has setup 27 continuous GPS stations, 55 annually observed (8 days each session) campaign sites, and about 1000 survey-mode GPS monuments (3 sessions during 1999-2006; 4 days each session). Those GPS observations advanced the research of crustal movements in China.³-⁵

However, CGPS positions are affected by spatial–temporal correlated noises and Earth surface mass redistribution, complicating the accurate extraction of tectonic signals. Flicker noise had been found to be the major power-law noise in the regional and global GPS networks.⁶-⁹ Langbein¹⁰ recently considered additional noise types and found that some stations could be described by first-order Gauss-Markov noise or band-pass filter noise models. The vertical annual amplitudes can be partly explained by seasonal surface

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mass variations.\cite{11-14}

As for CGPS stations in CMONOC network, Huang and Fu\cite{9} first examined power-law noises, finding that noise at most CMONOC sites could be best described by a “white noise + flicker noise” model and that some could be described by a “white noise + flicker noise + random walk noise” model. They also noted that the southern sites had larger colored noises and that random walk noise was prone to appear at southern sites. Regarding displacements caused by surface mass loads in the vertical component, Dong et al.\cite{12} analyzed three IGS sites in China (LHAS, SHAO, and XIAN); however, their estimations of vertical annual terms are different from later studies, e.g. XIAN shows inconsistent phase with adjacent sites. Zhang et al.\cite{13} and Wang et al.\cite{14} analyzed the loading effects caused by several sources for most CMONOC sites. Zhang et al.\cite{13} used GIPSY to analyze nearly three-year data for 25 sites. They took into account deformations caused by atmosphere pressure, nontidal ocean mass, snow and surface water mass variations; and they found that most of the vertical annual amplitudes could be explained, and a systematic bias could be seen between the GPS observations and the predicted load results. Wang et al.\cite{14} analyzed extended time series (1 March 1999 to 7 February 2004) for 25 sites with GAMIT/GLOBK. Besides the loading origins considered in Zhang et al.\cite{13} they also included the ocean tides loading corrections that were not applied at the observation level at that time. They finally found an average explanation of 37\% for vertical annual amplitudes.

With the accumulation of GPS data and the development of global meteorological models, the nontectonic signals in GPS position time series is now worth investigating again. The time series used in Zhang et al.\cite{13} are too short to determine annual terms accurately for some sites. For example, there are many data gaps at YONG; HLAR also shows abnormally large vertical seasonal variations in earlier years; the observations at TAIN were disturbed by water leakage into the antenna during 8 July 1999 and 2 September 2000. Compared to results given by Wang et al.\cite{14} the vertical annual terms given by Zhang et al.\cite{13} at LHAS, YONG, XIAM, and KMIN are much different. As for Wang et al.\cite{14} they used cumulative time series that contains nonlinear movements caused by upgrades of software and changes of models or parameter settings; thus, their results are somewhat biased. A rerun should be done for detecting the noise and tectonic signals more accurately. Moreover, meteorological data used in previous studies are unstable due to the climate anomaly during years around 2000. The IGS community has completed the rerun of global historical CGPS data, which makes it possible now to do a whole rerun for CMONOC data, because the final time series were usually obtained by combining CMONOC daily loosely constrained solutions with those of igs1, igs2, and igs3 subnetworks produced by Scripps Orbit and Permanent Array Center (SOPAC). In this paper, reprocessing of nearly nine-year CMONOC CGPS data and investigation of the types of colored noises and vertical annual terms origins were done. Eight more sites (CHAN, GUAO, HRBN, KC01, LHAZ, KUNM, WHJF, and ZHNZ), which had not been analyzed by Zhang et al.\cite{13} and Wang et al.\cite{14} were included. Some of these sites are seated very close to other CMONOC stations and can be used to validate the observations of the adjacent sites. Moreover, Zhang et al.\cite{13} and Wang et al.\cite{14} did not take into account the colored noises, which will get a much optimistic results of estimation errors.\cite{6-7} To get reasonable estimation of errors, a white noise plus flicker noise model was assumed.

1 Data and analysis

Data collected during 1 March 1999 and 12 November 2007 for 29 CMONOC CGPS sites and 4 IGS tracking stations in China (Fig. 1) were analyzed. Not all sites had been built in the first phase. The observations started on 4 June 2000 for CHUN, 1 January 2002 for WHJF and ZHNZ, 15 June 2002 for GUAO, 15 October 2003 for KC01, and 5 January 2003 for HRBN. Data for CHAN were missing during 2 July 2000 and 31 December 2004. To tie CMONOC network to ITRF2005\cite{15} several IGS tracking stations were included in the daily solutions.

The daily solution of CMONOC network using GAMIT (v10.32 with updates for 27 November 2007) was obtained.\cite{16} Ocean tides loading corrections were done using the FES2004 model.\cite{17} Global Mapping Function,\cite{18} IERS 2003\cite{19} solid Earth tides
model, and absolute antenna phase center models\(^\text{[20]}\) were adopted. Atmospheric delays were estimated hourly, and the cutoff angle was set to 10°. No corrections for atmosphere pressure loading were applied. IGS final orbit products (in SP3 format) were used. The daily CMONOC loosely constrained solutions were combined using GLOBK\(^\text{[21]}\) with igs1-igs6 solutions reanalyzed by SOPAC and were then aligned to ITRF2005 by a seven-parameter transformation constrained by about 158 global fiducial sites as shown in Fig. 2. The color of point in Fig. 2 represents the percentage of inclusion in defining the reference frame. The time series were then demeaned, and the outliers that deviate from the mean more than three times the IQR (Interquartile Range) values\(^\text{[22]}\) were removed.

2 Results

Compared to the cumulative time series generated at CMONOC analysis center, the rerun time series do not show any nonlinear movements caused by software upgrades, which proves the advantage from a consistent processing strategy. However, although a total of 158 fiducial sites were used to define the reference frame, it was found that only about 100 were actually available for transforming CMONOC daily coordinates into the ITRF2005 reference frame each day, due to missing observations or unstable solutions for some fiducial sites. This might cause the instability of the definition of reference frame; and certain large-scale common-mode noises can be seen in the residual time series.

2.1 Offsets and postseismic decays

Position discontinuities and postseismic relaxation displacements were found in the time series of several CMONOC CGPS sites (Table 1).

| Type                        | Time     | Affected sites                  | Cause                        |
|-----------------------------|----------|---------------------------------|------------------------------|
| Offset                      | 2000-02-24| BJSH and KMIN                   | Unknown                      |
| Offset                      | 2000-09-09| DXIN                            | Unknown                      |
| Offset                      | 2001-04-09| XNIN                            | Unknown                      |
| Coseismic offset and post-seismic decay | 2001-11-14| DLHA                            | Mw 7.8 Kokoxili earthquake, 631 km away. |
| Offset                      | 2002-01-21| WUHN                            | Monument reconstruction     |
| Coseismic offset and post-seismic decay | 2004-12-26| YONG, QION, GUAN, XIAM, KMIN, KUNM, LUZH, and IAG | Mw 9.0 Sumatra earthquake, Indonesia. |
| Coseismic offset             | 2005-10-08| TASH                            | Mw 7.6 Pakistan earthquake, 388 km away. |
| Offset                      | 2006-10-27| HLAR                            | Unknown                      |

Fig.3 shows some typical time series (vertical dashed lines indicate time of earthquakes). The 14 November 2001 M\(_{w}\) 7.8 Kokoxili earthquake caused large deformations at DHLA (Fig. 3(a)), which is 631 km away from the epicenter; the quake-induced displacements at DXIN and XNIN are also visible. Fig. 3(b) shows that QION was affected by the 26 December 2004 great Sumatra earthquake. It is difficult to detect the deformations at XIAG and YONG caused by the 28 March 2005 Sumatra earthquake, as claimed by Wang et al.\(^\text{[14]}\) Moreover, it was found that a fit for only coseismic jump cannot fully explain the deformations caused by strong earthquakes at most affected sites; and a logarithmic model fits the post-seismic relaxation process quite well.
2.2 Abnormal observations

By examining the time series, it was visually evident that there are some abnormal spans at several sites (Fig. 4). HLAR showed large vertical annual amplitude before December 2000 (Fig. 4(a)). Fig. 4(b) shows the east component of HRBN, which contains an exceptional large annual term. TAIN observations during 8 July 1999 and 2 September 2000 (Fig. 4(c)) were affected by leakage of water into the antenna. Moreover, URUM vertical component contains several successive jumps since 2006 (Fig. 4(d)).

2.3 Subsidence

The rerun time series also show that there are no obvious subsidence at CMONOC GPS fiducial stations, except at KMIN, XIAA, and KC01 (Fig. 5; upward arrows indicate uplifting; the ellipses represent the 95% confidence level). Moreover, several sites are uplifting. For example, BJFS is uplifting at a rate of about 2.91±0.71 mm/a; however, nearby site BJSH, which is about 77 km away, shows no obvious uplifting or subsidence. Thus, it may be related to local tectonic activities.
Compared to KUNM, aside from the fact that KMIN endured a subsidence trend, it is found that KMIN also moves much faster than KUNM toward east at a rate of 33.66±0.42 mm/a, while KUNM only moves by 30.46±0.37 mm/a (Fig. 6). KMIN and KUNM are both located at Yunnan Observatory, Chinese Academy of Sciences, which is seated on a small hill in the northeast of Kunming city. KMIN is on the east side of KUNM. The baseline between KMIN and KUNM is about 62 m. KMIN is supposed to experience strong local deformations that may be caused by unstable antenna monument or small landslide. In Fig.6, positions of KUNM are shifted down by 30 mm.

**2.4 Temporal correlated noise**

Previous studies show that there are remarkable random walk noises in the east component of CMONOC CGPS position time series.[9]

Beside flicker noise and random walk noise, Langbein[10] included more types in the noises analysis and found that first-order Gauss-Markov noise and band-pass filter noise were suitable for several sites in southern California and Nevada. The best noise models in CMONOC position time series was compared in the way as in Langbein.[10] It was found that only 1 of 33 east components can be best described by a “random walk noise + first-order Gauss-Markov noise” model in the rerun results. The best correlated noise types in CMONOC horizontal components are similar to that in other regional GPS networks,[10] however, the vertical components are much different. Only about half of the vertical component can be best described by single flicker noise model and contains more cases of fractional power-law noise. This may indicate that vertical component has larger noise magnitude and seasonal amplitude; thus current available length of observation may be too short to identify accurately the correlated noises.

**Table 2 Counts of best correlated noise models for the CMONOC CGPS network**

| Noise Model                      | North | East | Vertical |
|----------------------------------|-------|------|----------|
| Flicker noise                    | 27    | 27   | 16       |
| Random walk noise                | 1     | 0    | 1        |
| Power-law noise                  | 1     | 5    | 8        |
| Flicker noise + random walk noise | 0     | 0    | 0        |
| Random walk noise + first order  | 2     | 1    | 3        |
| Gauss-Markov noise               |       |      |          |
| Power-law noise + band-pass filter noise | 2 | 0 | 5 |

**2.5 Annual amplitudes and possible origins**

The amplitude and phase lag of annual term were calculated for each site in “sin and plus” convention, $A\sin(Pr+\phi)$, where $A$, $P$, and $\phi$ are amplitude, period, and phase lag, respectively. Abnormal observations spans pointed out in section 2.2 were deleted. To get reasonable estimation errors, the “white noise + flicker noise” assumption was adopted. For horizontal components (Figs. 7(a) and 7(b)), annual amplitudes at most sites (except URUM, YONG, XIAG, etc.) are less than 1 mm. HRBN has an exceptional large annual ampli-
tude of 4.92 ± 0.28 mm for the east component, which may be due to monument instability—HRBN is seated on the roof of one building at the Heilongjiang Bureau of Survey and Mapping in the central Haerbin City.

Fig. 7  Annual terms of CMONOC CGPS sites

For vertical annual term, the rerun results (Fig. 7(c)) show comparable similarity to those obtained from the cumulative time series. The annual terms reach maximum around late May and early June for most sites, while at LHAS, KMIN, and TASH, reach maximum in mid-March. However, several different conclusions could be drawn.

Compared to Zhang et al., [13] vertical annual terms at TASH, WUSH, DLHA, DXIN, HLAR, SHAO, YONG, LHAS, and KMIN are much different either in amplitudes and/or phase lags.

Compared to Wang et al., [14] sites HLAR, TASH, WUSH, YONG, CHUN, and SUXY show maximum disagreements either in amplitudes and/or phase lags for vertical annual terms.

Previous studies showed that TASH had a small vertical annual term; however, 2.47±0.55 mm annual amplitude at TASH was observed, and it reaches maximum in early January. HLAR shows nearly no obvious annual term (0.81±00.77 mm) since 2001. In previous studies, the result was overestimated because the annual terms was abnormally large (6.01±1.83...
mm) before November 2000. It was found that ZHNZ has a large east annual term of 1.74±0.22 mm; however, its other terms are consistent with adjacent sites.

Furthermore, by examining annual terms of three pairs of adjacent sites, it was found that local deformation could play an important role. The phase lag of vertical annual term at KMIN is earlier than that at KUNM for about 20 days, which may be due to local deformations, as stated in Section 2.3. The east annual term of KMIN (2.24±0.30 mm) is almost two times that of KUNM (1.16±0.27 mm). CHAN is much different from CHUN in terms of vertical annual terms. CHAN and CHUN are both located at the Changchun Observatory, Chinese Academy of Sciences. The distance between them is only about 39 m. However, the horizontal annual terms of CHAN and CHUN are more similar. URUM also has different annual terms from GUAO, which is located 50.7 km away. URUM is seated in the central Urumqi with a several meters tall concrete pillar monument, while GUAO is located far away in the mountain area. Other adjacent site groups, WHUN and WHJF (13 km apart), and LHAS and LHAZ (3.5m apart), show consistent trends. As for the four stations in the North China plain, BJFS, JIXN, BJSH (113 km away from JIXN), and KC01 (121 km away to JIXN), the first two sites show consistent results; while BJSH shows smaller vertical annual term, and KC01 is experiencing subsidence and has different north and vertical annual terms. KC01 is seated at the coast of Bohai sea where there are remarkable land subsidence caused by drilling of underground water.

To check whether the rerun annual terms can be fully explained by seasonal surface mass variations, I calculated atmospheric pressure loading, nontidal ocean loading, soil moisture mass loading, and snow cover mass loading effects. Fig. 7(d) is the vertical annual terms of the sum of atmospheric pressure loading (ATML), nontidal ocean loading (NTOL), soil moisture mass loading (SMML), and snow cover mass loading (SCML) corrections. In Fig. 7(e), blue and yellow arrows denote ATML and SMML, respectively. In Fig. 7(f), red and pink arrows represent SCML and NTOL, respectively. The arrow directions indicate phase lags in degrees that are counterclockwise from the east. The ellipses represent 95% confidence level. Daily averaged surface pressure (2.5º×2.5º), soil moisture, and snow cover (1.875×1.9º) data were acquired from NCEP Reanalysis I/II projects (http://www.cdc.noaa.gov/). Ocean bottom pressure data were obtained from the 12h (1×0.3-1.0º) Estimating the Circulation & Climate of the Ocean (ECCO) model. The calculations of loaded displacements were done by convolving mass loads with the Green’s Function over the whole Earth’s surface using QOCA software (http://gipsy.jpl.nasa.gov/qoqa/).

It is worth noticing that there is large (about 3.86 mm) vertical amplitude predicted by snow cover data at site HLAR before 2001; after then, the amplitude only reaches 1.31 mm (Fig. 8(a)). This trend is in very good agreement with the GPS observed vertical variations, which also shows abnormal large annual amplitude at HLAR before November 2000 (Fig. 8(b)). In Fig. 8, the points represent GPS observations, and solid curves are modeled data. It seems that the snow cover mass loading can partly explain the abnormal observations in earlier years at HLAR. The residual difference may be due to the inaccuracy of modeling and errors in snow observations. At other sites (e.g. URUM, TASH, and SUIY), the time series data collected before November 2000 may also be affected by heavy snow fall. However, the amplitudes are usually less than 2 mm, and the time series before November 2000 is too short to derive the annual terms accurately.

![Fig. 8 Abnormal heavy snow load caused exceptional large vertical annual term before November 2000 at HLAR](image)

Because the meteorological data were unstable before 2001, only data after November 2000 were used.
The biases caused by loads in horizontal only reach submillimeter level and cannot explain those observed by GPS. For vertical component, at WUHN, WHJF, KUNM, TAIN, and XIAG, loading effects can explain most of the annual amplitudes; while at URUM, YONG, QION, XIAM, LHAS, and LHAZ, obvious residual annual terms can be seen. KC01, CHUN, URUM, and KMIN are obviously affected by unknown error sources compared to adjacent sites. The amplitudes at LHAS, LHAX, and TASH await further investigations. Southern sites, QION, YONG, and XIAM, may be mainly affected by ocean tides, and their vertical annual amplitudes cannot be explained by existing geophysical loading factors.

3 Conclusion

The nine-year data for CMONOC CGPS sites were analyzed in a consistent way for the first time. Together with longer time series and more sites, more accurate and detailed estimations of spatial-temporal correlated noise in GPS position time series and tectonic signals in China were obtained.

(1) The temporal correlated noises in CMONOC CGPS positions are the same as those in other regions. The previously recognized prevailing random walk noises in the east component of CMONOC sites may arise from processing strategy.

(2) Large vertical annual amplitude at northern site HLAR before November 2000 was detected. This can be partly explained by heavy snow fall during 1999-2001. Snow fall might also have affected other sites (URUM, SUIY, TASH, etc.), but it is difficult to detect due to the short length of the time series and small loading displacements compared to vertical variations caused by other factors and noises in the series.

(3) With longer observation periods for meteorological data, the effects of anomalous climate changes prior to 2001 could be removed. Thus, the explanation of the geophysical origins of vertical annual terms given in this paper is more reliable than previous studies. It is found that vertical annual amplitudes can be explained as a whole by predictions from NCEP/ECCO models at most sites. Southern coastal sites (YONG, QION, and XIAM) have large annual terms that cannot be explained by surface mass loadings, and they may be caused by ocean tides.

(4) At some places, vertical components are sensitive to local effects. Three adjacent site pairs, CHAN and CHUN, KMIN and KUNM, and GUAO and URUM, show different amplitudes and/or phase lags. The multipath noises, instability of monuments, or the strong local loading masses can cause vertical annual terms with amplitudes of several millimeters. The monument designation and environments are worth investigating fully in details.

Aside from the factors considered in this paper, the thermal expansions of bedrock and monument are also candidates for vertical annual amplitudes. Yan et al. calculated the contribution from thermal expansion for 86 global CGPS stations, and their results were much larger (a few millimeters) than that by Dong et al. They found that URUM is mainly affected by a thermal effect that is larger than the mass loading contributions. This can explain the annual variations at URUM. They also found a large thermal effect on LHAS site, but the phase is not in accordance with that of vertical annual term of GPS observation. It was found that many sites exhibit residual annual amplitudes that are in the same phase caused by water loads. Thus, at some sites, the results from thermal expansion modeling must be considered with caution. More work is necessary to better explain observed abnormal position variations at HRBN, KMIN, and URUM, etc. This will surely deepen our understanding on deformations caused by local environments and will therefore be helpful in avoiding constructing problematic monuments in the future.

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