EXTRACTION OF MULTIPATH AND OCEAN TIDE FROM GPS RTK DATA IN DONGHAI BRIDGE HEALTHY MONITORING

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ABSTRACT

The bridge healthy monitoring has been extensively investigated in the past decade and GPS RTK technique is used to collect the real time monitoring data due to its benefits of all weather conditions, high resolution and high precision. In the bridge deformation monitoring, the collected GPS observation series in time domain is essentially the combined multiple periodical signals, and their corresponding amplitudes and initial phases can be individually resolved by the spectrum analysis processing. In this paper, we will mainly investigate two low frequency signals with diurnal and semidiurnal periods, and analyze their attributions as well as their effects to the bridge's healthy status. In general, the diurnal signal attributes definitely to the thermal expansion and cold contraction of bridge structure due to the diurnal temperature. However, the semidiurnal signal is attributed to the combination of two semidiurnal signals caused respectively by the ocean tide and multipath. Therefore a new model is proposed to distinguish the contributions of the ocean tide and multipath to the combined semidiurnal signal, where the amplitudes of semidiurnal signals with respect to the ocean tide and multipath are estimated by using least squares adjustment. Finally, the GPS RTK observables collected in the Donghai bridge are analyzed based on the Fourier transform and the proposed model in the paper. The results show that: i) the diurnal signal can be definitely attributed to the thermal expansion and cold contraction of both the bridge structure itself with composite stuff and the long cable, and the amplitudes are about 3.5 cm for the middle point of the span and 0.35 cm for the tower peak at the end of span; ii) in the normal days without spring tide, the multipath is the key contribution to the semidiurnal signal with the amplitude of about 1.5 cm; but when the spring tide is approaching, the contribution of the ocean tide to semidiurnal signal is dramatically enhanced and the amplitude becomes larger till the largest value of about 1cm on the day of spring tide; iii) it is also observed that the amplitude of semidiurnal signal caused by the multipath becomes larger while the spring tide is approaching due to the enhanced reflection of ocean surface.

KEYWORDS

GPS, spectrum analysis, healthy monitoring, multipath, ocean tide.

INTRODUCTION

The safety and integrity of the civil engineering structures, such as long cable-stayed bridges, skyscrapers, large dams and so on, are crucial and have been extensively concerned for a long time, and the structural deformation is a key parameter to assess them. Thus man-made large structures must be monitored at a suitably given period even real time to ensure their safety and integrity in the whole process of design, construction and operation. In general, the purpose of monitoring is to measure the deformation, namely, the difference between two consecutive surveying epochs at the same point. However, it is more important that we can reasonably predict the deformation and then detect the abnormal variation by analyzing the existent measurement series, providing the scientific service for making decisions.

In tradition, the monitoring campaign for a large civil structure is implemented mainly by two strategies. One is to use the inertial sensors (such as, accelerometers) deployed on the structure for detecting the high frequency vibration response, but it is insensitive to the low frequency acceleration changes. The reason is that the velocity and displacement integrated from the uncompensated acceleration signals will drift over time due to unknown integration constants, and a high-pass filter should be used to cope with low-frequency drift introduced during the integration process. In addition, the accelerometer is so expensive that it cannot be extensively used to cover the whole structure of a large structure(Chan *et al.* 2006). The other one is to use the traditional optical instruments, for instance, theodolite, water level and total station, to measure the difference of two consecutive epochs at a given period which is reasonably determined according to the progress of the construction, normally, one day for the constructing, and half to one year for the operation. The problem is that it is rather inconvenient to deploy the optical instruments for each surveying campaign and it is impossible to achieve the high frequency data due to its long period. In the most recent years, the GPS RTK technique has been applied in the large civil structures, such as long span bridges, tall buildings and dams, to collect the real time monitoring data due to its benefits of all weather conditions, high resolution and high precision (Guo *et al.* 2007; Wang *et al.* 2008). Once we have achieved so plentiful data, our work is how to extract the useful information from this data series as much as possible, which is also the challenge for the utilization of GPS RTK technique to the monitoring campaign of large structures.

In the past two decades, many bridges with long span have been built. The safety and healthy monitoring is very important in the operation and, therefore the GPS RTK monitoring system has been completed almost for every bridge, for instance, Qingma bridge in Hongkong (Guo *et al.* 2007) and Donghai bridge in the mainland of China. In this paper, we will address the data processing methodology of Donghai bridge healthy monitoring. The GPS RTK data is collected in the Donghai bridge which is a cable-stayed one with long span of about 420 m, connecting the Yangshan and Nanhui harbors (Wang *et al.* 2008). The collected GPS RTK observation series in time domain is essentially the combined multiple frequency periodical signals, and these periodical signals can be successively extracted by the spectrum analysis processing. We are concerned mainly about two periodical signals respectively with diurnal and semidiurnal periods, and investigate their attributions as well as their effects on the bridge's healthy status. Importantly, we will propose a new method to distinguish the contributions of the ocean tide and multipath to the semidiurnal signals, where the amplitudes of semidiurnal signals caused by the ocean tide and multipath are estimated by using the least squares adjustment. In general conclusions, the diurnal signals can be definitely attributed to the thermal expansion and cold contraction of both the bridge structure itself with composite stuff and the long cable. The diurnal signals are affected by both the multipath and the ocean tide where the multipath is the key factor in the normal days but the effect of ocean tide will be enhanced with the spring tide approaching.

The rest of paper is organized as follows. In section 2, the fundamental mathematical model of Fourier transform are presented to extract the diurnal and semidiurnal periodical signals. The section 3 is the key of the paper, where the model for extraction of the ocean tide and multipath from the semidiurnal signal is described. The contributions of the multipath and ocean tide to the semidiurnal signal are distinguished by estimating the amplitudes of the semidiurnal signals introduced by them. In section 4, we will analyze the GPS RTK data for healthy monitoring of Donghai bridge based on the developed models in this paper. Finally, the research findings are summarized to conclude the paper.

FOURIER TRANSFORM FOR EXTRACTION OF THE DIURNAL AND SEMIDIURNAL PERIODICAL SIGNALS

The spectrum analysis as an important mathematical tool has been extensively used in the different fields, such as signal processing, image processing and deformation analysis, to extract the periodical signals from the data series in temporal and spatial domains. Its theoretical essence is the Fourier Transform (FT). Any one continuous signal $f(t)$ in time domain can be transformed into a new continuous function $F(\omega)$ in frequency domain. This transformation is described as (Bracewell 2005)

$$F(\omega)=\int_{-\infty}^{\infty} f(t)e^{i\omega t}dt \tag{1}$$

with the amplitude spectrum of $|F(\omega)|$, here $|\bullet|$ is a product for computing the norm of a vector. Noticing the equation of $\omega=2\pi f$ with f being the analogue signal frequency, we have

$$F(f)=\int_{-\infty}^{\infty} f(t)e^{-2i\pi ft}dt \tag{2}$$

Obviously, $F(f)$ is the complex function of frequency f, and $|F(t)|$ is the amplitude spectrum of function $f(t)$.
In real applications, we can only collect the discrete observables with a given interval and thus we can never achieve the continuous function $f(t)$, but discrete one. However, the spectrum information of the continuous function $f(t)$ is still involved in its discrete series if the sample is enough. Apparently, we cannot carry out the FT on the discrete series also by the Eqs. (1) and (2). Therefore, the Discrete Fourier Transform (DFT) is introduced to extract the spectrum information from this discrete series in temporal and spatial domains (Bracewell 2005). The time span of the whole observation is equally divided into N with step length Δt, and $T_k=k\Delta t$ is the kth sampling epoch with k=0,1,…,N-1. Noting the observation at the sampling epoch T_k as $f(k)$, the DFT reads

$$F(v)=\sum_{k=0}^{N-1} f(k)e^{-2i\pi vk/N}, \quad v\in[0,N-1] \tag{3}$$

To improve the computation speed, we often adopt the FDFT(Fast DFT) to efficiently decrease the computation burden. For more information, one can refer to Liu and Tao (e.g., Liu and Tao 2000).
By use of the FDFT, we can extract the spectrum elements from a discrete series, including the amplitude A_0 and initial phase φ_0 with respect to a given frequency f_0. Therefore we can easily recover the periodical signals at frequency f_0 as

$$s=A_0\cos(2\pi f_0 t+\varphi_0) \tag{4}$$

In the procedure of spectrum analysis, we extract the periodical signals with successively decreased amplitudes. In other words, the periodical signals with respect to the larger energy are firstly extracted and removed from the original observation series. In this paper, we will firstly extract the diurnal periodical signal due to its larger energy and then the semidiurnal one.

EXTRACTION OF MULTIPATH AND OCEAN TIDE FROM THE SEMIDIURNAL PERIODICAL SIGNALS

In the spectrum analysis, we can extract the periodical signals by the model in section 2 at any given frequency from the observation series. The problem is that the extracted periodical signal could be attributed to the different factors. In other words, this signal is the combination of multiple periodical signals with the same frequency. Therefore, we must distinguish the contribution of each factor to the extracted periodical signal in order to reasonably construct the regressive model and then correctly predict the deformation at the given epoch.
In the healthy monitoring of Donghai bridge, the semidiurnal periodical signal can be attributed to the combination of the multipath and ocean tide based on the analysis of many data. However what we are concerned much more about is the deformation affected by the ocean tide, which will really affect the bridge health. The deformation affected by the multipath is essentially the systematic errors in observations themselves, which does not affect the bridge health at all and thus should be removed from the extracted periodical deformation signal. In this section we will propose a new method to distinguish the contributions of the ocean tide and multipath to the extracted semidiurnal periodical signals, where the amplitudes of semidiurnal periodical signals introduced by the ocean tide and multipath are estimated by using the least squares adjustment.
In principle, the periods of the satellite's operation and the ocean tide are 11 hours and 58 minutes and 12 hours and 25 minutes (Zheng 2000), respectively. Therefore, the same periodical signals will be repeated on the second consecutive day except 4 minute advance for the multipath and 50 minute delay for the ocean tide. In practice, we suppose the same period of 12 hours for the multipath and the ocean tide.
We note the amplitudes and initial phases of the semidiurnal signals introduced by the multipath and ocean tide as A_m, A_t, φ_m and φ_t, respectively, and the amplitudes and initial phases of the extracted semidiurnal signals from the observation series as A and φ. Under the assumption that the extracted semidiurnal periodical signal is the combination of the semidiurnal signals introduced by the multipath and ocean tide, the equation is constructed as

$$A\cos(\alpha+\varphi)=A_m\cos(\alpha+\varphi_m)+A_t\cos(\alpha+\varphi_t) \tag{5}$$

where $\alpha=2\pi f_s t$ and f_s is the frequency of semidiurnal periodical signal. The expansion of (5) is

$$A\cos\varphi\cos\alpha-A\sin\varphi\sin\alpha=(A_m\cos\varphi_m+A_t\cos\varphi_t)\cos\alpha-(A_m\sin\varphi_m+A_t\sin\varphi_t)\sin\alpha \tag{6}$$

Because the equation (6) holds true for any α, we obtain the following two equations

$$\begin{cases} A\cos\varphi = A_m \cos\varphi_m + A_t \cos\varphi_t \\ A\sin\varphi = A_m \sin\varphi_m + A_t \sin\varphi_t \end{cases} \tag{7}$$

Thus the error equations can be derived as

$$\begin{pmatrix} \cos\varphi_m^0 & \cos\varphi_t^0 & -A_m^0 \sin\varphi_m^0 & -A_t^0 \sin\varphi_t^0 \\ \sin\varphi_m^0 & \sin\varphi_t^0 & A_m^0 \cos\varphi_m^0 & A_t^0 \cos\varphi_t^0 \end{pmatrix} \hat{x} = \begin{pmatrix} A\cos\varphi - A_m^0 \cos\varphi_m^0 - A_t^0 \cos\varphi_t^0 \\ A\sin\varphi - A_m^0 \sin\varphi_m^0 - A_t^0 \sin\varphi_t^0 \end{pmatrix} \tag{8}$$

where the estimated vector $\hat{x} = \left(dA_m \quad dA_t \quad d\varphi_m \quad d\varphi_t\right)^T$; A_m^0 , A_t^0 , φ_m^0 and φ_t^0 are the approximate amplitudes and initial phases of the semidiurnal periodical signals caused by the multipath and ocean tide respectively. If we use the data of total n days simultaneously and consider the theoretical time differences of 4 minute advance and 50 minute delay respectively for the multipath and ocean tide, the error equations can be symbolized as

$$\boldsymbol{v} = \boldsymbol{A}\hat{\boldsymbol{x}} - \boldsymbol{l} \tag{9}$$

where $A = \begin{pmatrix} \cos\varphi_m^1 & \cos\varphi_t^1 & -A_m^0 \sin\varphi_m^1 & -A_t^0 \sin\varphi_t^1 \\ \sin\varphi_m^1 & \sin\varphi_t^1 & A_m^0 \cos\varphi_m^1 & A_t^0 \cos\varphi_t^1 \\ \vdots & \vdots & \vdots & \vdots \\ \cos\varphi_m^n & \cos\varphi_t^n & -A_m^0 \sin\varphi_m^n & -A_t^0 \sin\varphi_t^n \\ \sin\varphi_m^n & \sin\varphi_t^n & A_m^0 \cos\varphi_m^n & A_t^0 \cos\varphi_t^n \end{pmatrix}$ and $\boldsymbol{l} = \begin{pmatrix} A_1 \cos\varphi_1 - A_m^0 \cos\varphi_m^1 - A_t^0 \cos\varphi_t^1 \\ A_1 \sin\varphi_1 - A_m^0 \sin\varphi_m^1 - A_t^0 \sin\varphi_t^1 \\ \vdots \\ A_n \cos\varphi_n - A_m^0 \cos\varphi_m^n - A_t^0 \cos\varphi_t^n \\ A_n \sin\varphi_n - A_m^0 \sin\varphi_m^n - A_t^0 \sin\varphi_t^n \end{pmatrix}$. It is important to notice that the amplitudes of the semidiurnal periodical signals introduced by the multipath are same for all n days, and the same case for the ocean tide. However, the initial phases are different for both multipath and ocean tide on the different day, and $\varphi_m^i = \varphi_m^1 + (i-1)\theta_m$ and $\varphi_t^i = \varphi_t^1 - (i-1)\theta_t$ are their approximate values with corresponding to the multipath and ocean tide on the ith day with φ_m^1 and φ_t^1 being the ones on the first day. Here, the constant values $\theta_m = \frac{4}{60\times 24} \times 2\pi = \frac{\pi}{180}$ and $\theta_t = \frac{50}{60\times 24} \times 2\pi = \frac{5\pi}{72}$ are the radians of 4 minutes and 50 minutes with respect to the multipath and ocean tide. The parameters can be iteratively estimated based on the least squares adjustment as

$$\hat{\boldsymbol{x}} = \left(\boldsymbol{A}^T \boldsymbol{A}\right)^{-1} \boldsymbol{A}^T \boldsymbol{l} \tag{10}$$

EXPERIMENT AND ANALYSIS

In this section, we will compute the GPS RTK data collected in the Donghai bridge according to the method developed in this paper, mainly to extract two low frequency periodical signals, diurnal and semidiurnal periodical signals, and analyze their attributions considering the bridge's structure and its stuff. Donghai bridge has a composite girder cable-stayed span and is of single cable plane. The span length is 420m and the span clearance about 40m, connecting the Yangshan and Nanhui harbors. Fig. 1 illustrates the deployment of three GPS rover receivers whose data will be used in this paper, where one receiver is placed at the middle of the span, and the others at the tower peak of the span end. The GPS reference station is deployed near the Nanhui harbor. All data are sampled in 0.1 s interval for extracting high frequency vibration response. In this paper, we just confine our scope to the low frequency periodical signals, and thus the data newly sampled at 1 minute are used in the next analysis.

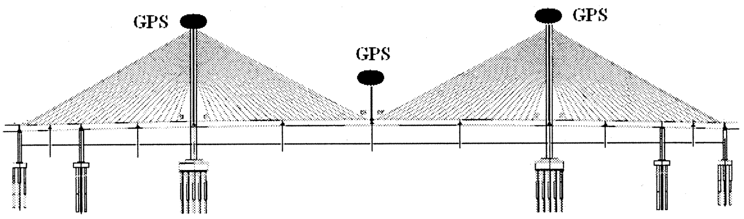

Fig. 1: The monitoring points in the Donghai bridge

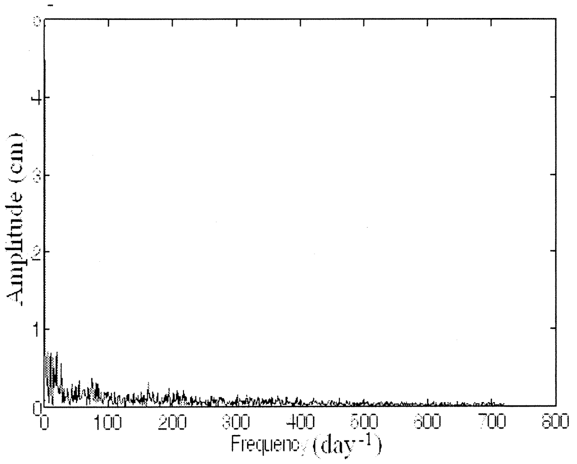

Fig. 2. Spectrums of GPS data on June 21th

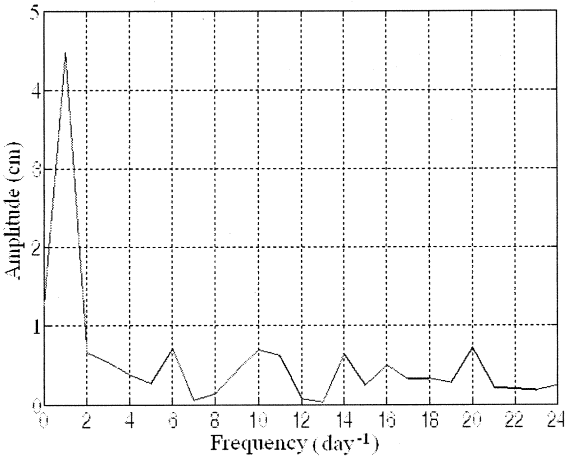

Fig. 3. Low frequency spectrums in Fig. 2

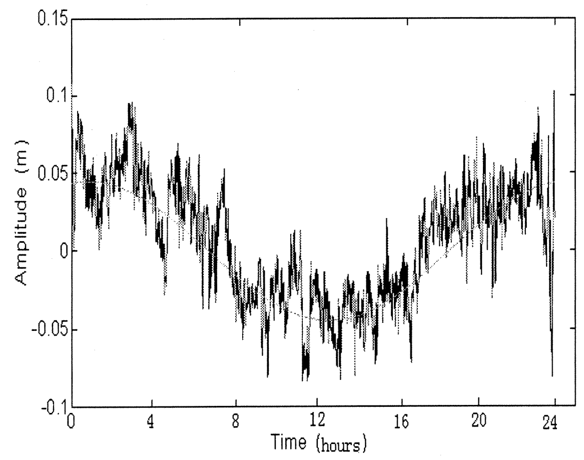

Fig.4. Comparison of the recovered signal and observables

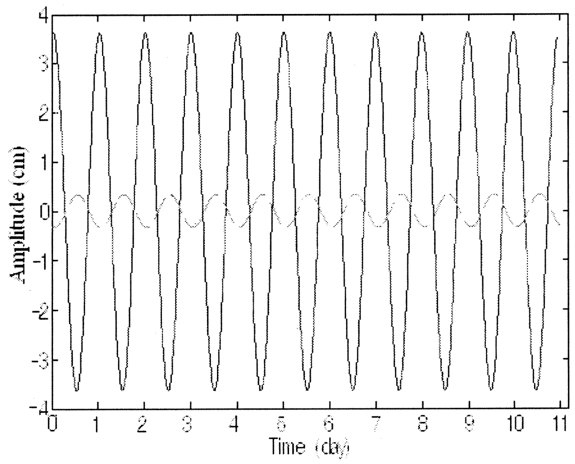

Fig.5. Deformation at the middle point and tower peak

The GPS RTK data in the middle point on June 21st 2006 is computed by the FDFT to achieve the multiple frequency spectrums and their corresponding amplitudes (see e.g. Fig. 2). It is noticed that the unit of frequency is the reciprocal of day. Fig. 3 illustrates the amplitudes at the low frequencies from 0 to 24 day-1. Obviously, the largest amplitude (4.5 cm) is corresponding to the frequency of 1 day-1 with the initial phase of -0.2205 rad. Therefore this diurnal periodical signal can be recovered by Eq.(4) as

$$s_1 = 0.045 \times \cos(2\pi \cdot 1 \cdot t - 0.2205) \tag{11}$$

It is important to notice that the unit of time t in Eq. (11) is day according to the unit of frequency. Fig. 4 presents the recovered diurnal periodical signals (dash line) and the observables (solid line), and they are so consistent, which indicates that the most deformation is introduced by this diurnal periodical signal. Analogically, we analyze the data at the tower peak and also recover its corresponding diurnal periodical signal. In Fig. 5, the recovered diurnal periodical signals at middle point and tower peak for 11 days from June 19th to July 1st 2006 are demonstrated. The variation of diurnal signals at tower peak is opposite to that of middle point and is with the smaller amplitudes.

Now, we examine the attribution of these achieved diurnal periodical signals at both middle point and tower peak. As illustrated in Fig. 4, we can see that the negative deformation is from about 8:00 AM to 20:00 PM and the largest deformation happens at about 13:00 PM. In the rest of time, the deformation is positive and the largest deformation at 1:00 AM. This variation matches the diurnal temperature variation very well. Therefore we can generally conclude that the diurnal periodical signal is caused by the thermal expansion and cold contraction of both the long cables and the composite stuff of bridge structure due to the temperature variation. In the daytime, the cables extend and the bridge girders expand with the temperature increasing, so that the middle point goes down and thus the deformation is negative, vice versa. Similarly, the tower expands and rises when the temperature rises and then the deformation of tower peak is positive. It is important to notice that the amplitudes at the tower peak (about 3.5 mm) is smaller than that of middle point (3.5 cm). This is because the deformation of middle point is introduced by not only the extension of cables but also the expansion of the composite main girders of bridge structure itself, and all these deformation can lead to the displacement in the height. However, the deformation at the tower peak is caused only by the expansion of the concrete stuff of tower (Gu and Fan 2000).

After the extraction of diurnal periodical signal, we continue to extract the all periodical signals with amplitudes larger than 5 mm. We compute the data of 4 days, i.e., 21st, 23rd, 24th and 27th of June. The extracted frequencies and their corresponding amplitudes are presented in Table 1. We can see that two periodical signals with amplitudes of 1 and 2 day^{-1} are existent in all days, which indicates the existence of the semidiurnal periodical signal for all days. Therefore we can recover the semidiurnal periodical signal of the 21st June by (4) as

$$s_2 = 0.007\cos(2\pi \cdot 2 \cdot t - 3.054) \tag{12}$$

where the amplitude and initial phase are 7 mm and -3.054 rad, respectively. The recovered function is illustrated in Fig. 6. The Donghai bridge is near the Luchao harbor, and the period of the ocean tide is about half day. Therefore, the extracted semidiurnal signal above could be caused by the ocean tide of the Luchao harbor. Referring to the material of ocean tide (see e.g., *The information center of Chinese Ocean*), we know that the two tide time of Luchao harbor on one day are 7:03 AM and 20:02 PM, respectively, and the low tide time are 1:28 AM and 13:54 PM, which are consistent with the results in Fig. 6. In addition, as we know, the period of GPS satellite operation is 11 hours and 58 minutes. In other words, the same environment are repeated and thus the variation of systematic errors of the observed measurements should be periodical with two cycles for one day. Moreover, the reflection of ocean surface can enhance the effects of multipath. In conclusion, the multipath is confirmed as another key factor to contribute to the semidiurnal signal. In the following experiments, we will distinguish the effects of multipath and ocean tide to the semidiurnal signal according to the model developed in section 3. In order to analyze the contribution variation of multipath and ocean tide in the different scenarios, the GPS data were collected at the middle point of span with sampling interval of 1 minute from the 19th September to the 15th November, where the spring tide happened on 10th October. As mentioned above, we first extract and remove the diurnal periodical signals from all observables. Then the amplitudes and initial phases of the semidiurnal periodical signals for all days are computed. Table 2 presents the results of the estimated amplitudes and initial phases from the 19th to 24th September and from the 6th to 12th October. As Table 2 shown, the largest amplitude, 5.74 cm, is assigned to the day of spring tide, which means that the ocean tide is really a factor to cause the semidiurnal periodical signal. On the other days, the amplitudes of semidiurnal signals are comparative in value, around 1 cm. Once we have obtained the amplitudes and initial phases of the semidiurnal signals for all data, we can further distinguish the contributions of the multipath and ocean tide to these achieved semidiurnal signals by estimating their amplitudes and initial phases according to the Eqs. (5-10) outlined in section 3. The results are presented in Figs. 7 and 8 for multipath and ocean tide, respectively. As illustrated in Fig. 7, we can conclude that the solved amplitudes of the semidiurnal signals caused by multipath are generally comparative in value except the slightly larger on the day of spring tide, which is because of the enhanced reflection of ocean surface on that day. In Fig. 8, some solved amplitudes are negative and they are certainly not of physical meaning. But in the period of spring tide, the solved amplitudes for ocean tide are positive and the value is apparently largest on the day of spring tide. Therefore, the negative amplitudes could be attributed to the weaker model strength because the semidiurnal signal introduced by the ocean tide is so feeble that the model (5) is somewhat not suitable. Comparing the results in Figs. 7 and 8, the conclusions are summarized as follows: i) in the normal days without spring tide, the multipath is the key contribution to the semidiurnal signal with the amplitude of about 1.5cm; ii) when the spring tide is approaching, the contribution of the ocean tide to semidiurnal periodical signal is dramatically enhanced and the amplitude increases till the largest value of about 1cm on the day of spring tide; iii) it is also observed that the amplitude of the semidiurnal signal caused by the multipath becomes larger while the spring tide is approaching due to the enhanced reflection of ocean surface.

Table 1: Frequencies and their amplitudes for 4 day data (units: f: day^{-1}; A: cm)

6.21		6.23		6.24		6.27	
f	A	f	A	f	A	f	A
1	**4.5**	**1**	**5.6**	**1**	**4.8**	**2**	**2.2**
2	**0.7**	**2**	**1.6**	3	1.7	**1**	**1.5**
6	0.7	45	0.9	**2**	**1.3**	9	1.5
10	0.7	51	0.8	15	1.2	8	1.4
20	0.7	46	0.8	12	1.0	3	1.3

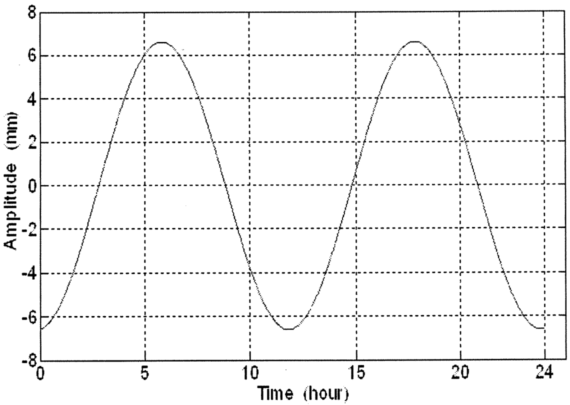

Fig. 6. Recovered periodical semidiurnal signal of 21st June

Table 2: Amplitudes and initial phases of the semidiurnal signals for 12 day data

Date	9.19	9.20	9.21	9.22	9.23	9.24	10.6	10.7	10.8	10.9	10.10	10.11
A(cm)	1.39	0.98	0.95	1.61	0.49	1.19	0.98	1.23	1.36	1.12	**5.74**	1.34
φ_0(rad)	2.93	3.35	3.11	3.4	3.2	2.25	2.97	2.64	2.54	2.79	**1.84**	2.92

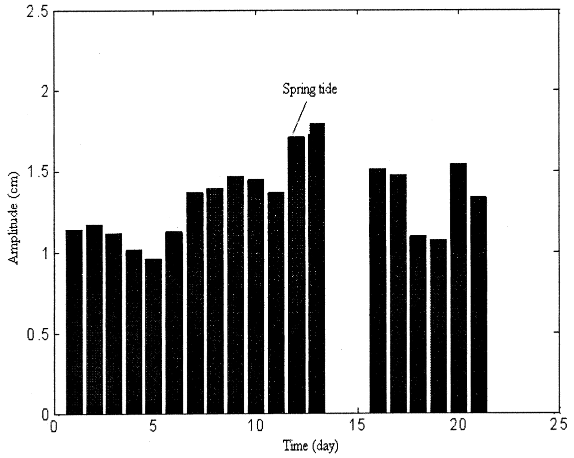

Fig.7. Amplitudes of semidiurnal signals of multipath

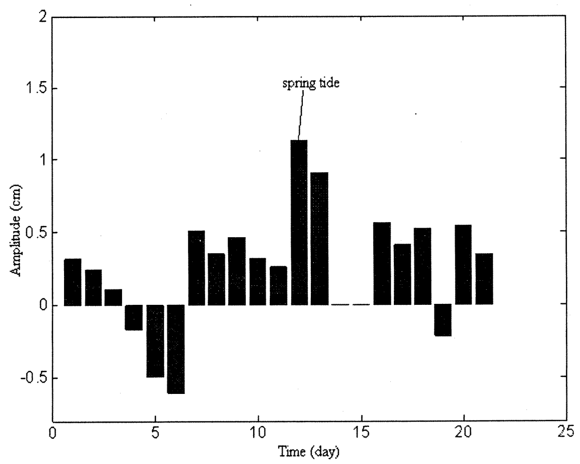

Fig.8. Amplitudes of semidiurnal signals of ocean tide

CONCLUDING REMARKS

In this paper, we have extracted two low frequency periodical signals, diurnal and semidiurnal periodical signals, from the GPS RTK observables collected in the Donghai bridge. Furthermore, we have also distinguished the contributions of the multipath and ocean tide to the extracted semidiurnal periodical signals by estimating the amplitudes in semidiurnal signals. In addition, the attributions of these periodical signals have been investigated and the conclusions are summarized as: i) the diurnal signals can be definitely attributed to the thermal expansion and cold contraction of both the bridge structure itself with composite stuff and the long cable, and their amplitudes are about 3.5 cm for the middle point of span and 0.35 cm for the tower peak at the end of span; ii) in the normal days without spring tide, the multipath is the key contribution to the semidiurnal signals with the amplitude of about 1.5 cm; but when the spring tide is approaching, the contribution of the ocean tide to semidiurnal signals is dramatically enhanced and the amplitude increases, till the largest value of about 1 cm on the day of spring tide; iii) it is also observed that the amplitude of semidiurnal signals introduced by the multipath is also increasing when the spring tide approaching due to the enhanced reflection of ocean surface. The research findings are very useful for constructing the reasonable regressive model and predicting the deformation, thus benefiting the detection of the abnormal variation and providing the scientific alarm.

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