

RESEARCH ON THE STABILITY OF GPS REFERENCE STATIONS IN TIANJIN CORS

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ABSTRACT:

BERNESE 5.0 Software was adopted in this paper to calculate the data observed by TJCORS of 2007-2009 in Tianjin region to obtain the reference station coordinate time series. The coordinate time series period features of TJCORS reference stations are studied. The results show that the 3 coordinate components (N, E, U) have semi-annual and annual periodicity in topocentric coordinate system, in addition, the periodicity of U direction is more obvious than that of the other two's. The time series noise features of TJCORS reference stations are analyzed using spectral index and maximum likelihood estimator methods. The results show that the spectral index of each direction of 12 reference stations distributes between -1 and 0, which means that the model of "white noise + flicker noise" is the most appropriate to explain the reference station noise. Then, the time series noise components, annual and semi-annual amplitude and phase are figured out for GPS reference stations. The composition stability of TJCORS reference stations is discussed. The result indicates that the whole TJCORS frame has the movement tendency of southeast-east direction horizontally. In the altitude direction, the annual settlement values in CH01 and SW01 are larger, but there are almost no settlement emerging in reference stations of CH02, JIXN and TJA1 that are located in the north part of Tianjin. The calculation results of TJCORS are compared with the settlement contour isograms of 2006-2007 and levelling survey velocity of 2007-2009. The settlement results gained by the TJCORS reference stations are mainly identical with those measured by levelling monitor.

1. INTRODUCTION

With the establishment in April 2004 and the accomplishment of field observation in the end of 2005, Tianjin Continuously Operating Reference System (TJCORS) came into use in June 2006. The average side length of TJCORS is between 30~40 km and there are totally 12 stations that are shown in Fig.1, whose reference station net can cover almost 10,000 km² of Tianjin.

Tianjin is located nearby the Port of Hai River. The terrain of the city belongs to alluvial plain and many regions are formed by eroding and sedimentation of Hai River and its influents during a hundred million years. The maximum settlement value of Tianjin regions has reached to 3m since 1959.

It is beneficial to analyze the reference station coordinate time series and gain the stability and reliability information of TJCORS stations to help the research of ground settlement and crust movement and the precision positioning base for the government departments such as planning or land and resources. BERNESE 5.0 Software was adopted in this paper to calculate the data observed by 12 TJCORS stations of 2007-2009 in Tianjin region to obtain the reference station coordinate time series. Then the coordinate time series are analyzed from the aspects of periodicity, noise and tendency to figure out the time series features and variation tendency, which can be referred to for similar CORS nets in other cities or provinces.

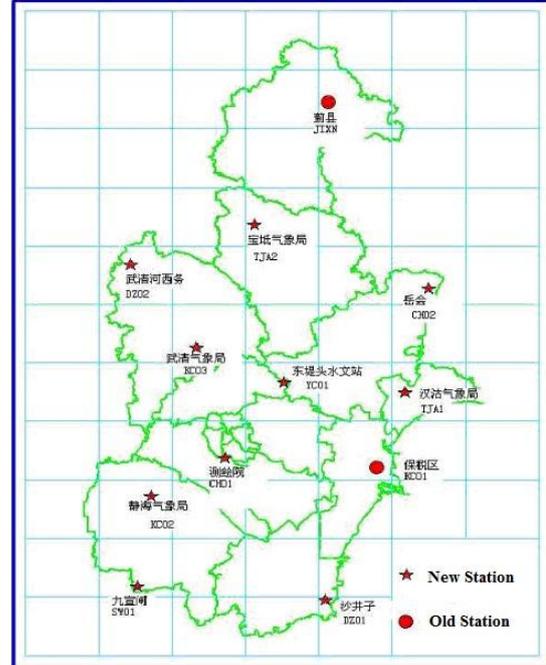


Figure 1. The distribution of CORS reference stations in Tianjin

2. CALCULATION OF TJCORS COORDINATE TIME SERIES

GPS data of 2007-2009 observed by 12 reference stations of TJCORS Net were chosen to be calculated by BERNESE 5.0

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Software and then operated the coordinate transformation to gain the everyday component time series of each station.

2.1 Data Processing

GPS accurate data processing of high quality is crucial for the analysis of CORS stability analysis. Hence, BERNESE 5.0

Software was utilized to calculate the TJCORS data of 2007-2009 and the calculation schemes are shown in Table1.

	Illustration
IGS reference station	BJFS, DAEJ, SHAO, ULAB, and WUHN
Baseline resolving type	BASELINE
Baseline selection strategy	OBS-MAX
Equivocation resolving strategy	QIF
Data sampling interval	30s
Satellite orbit	IGS precise ephemeris
Reference frame	IITRF05
Reference epoch	12 oclock everyday
Troposphere parameter estimation	piecewise linearity, interval 30min
Troposphere modified model	Saastamoinen
Satellite elevation mask angle	10°
Antenna phase position center	Relative

Table 1. Calculation schemes of TJCORS data

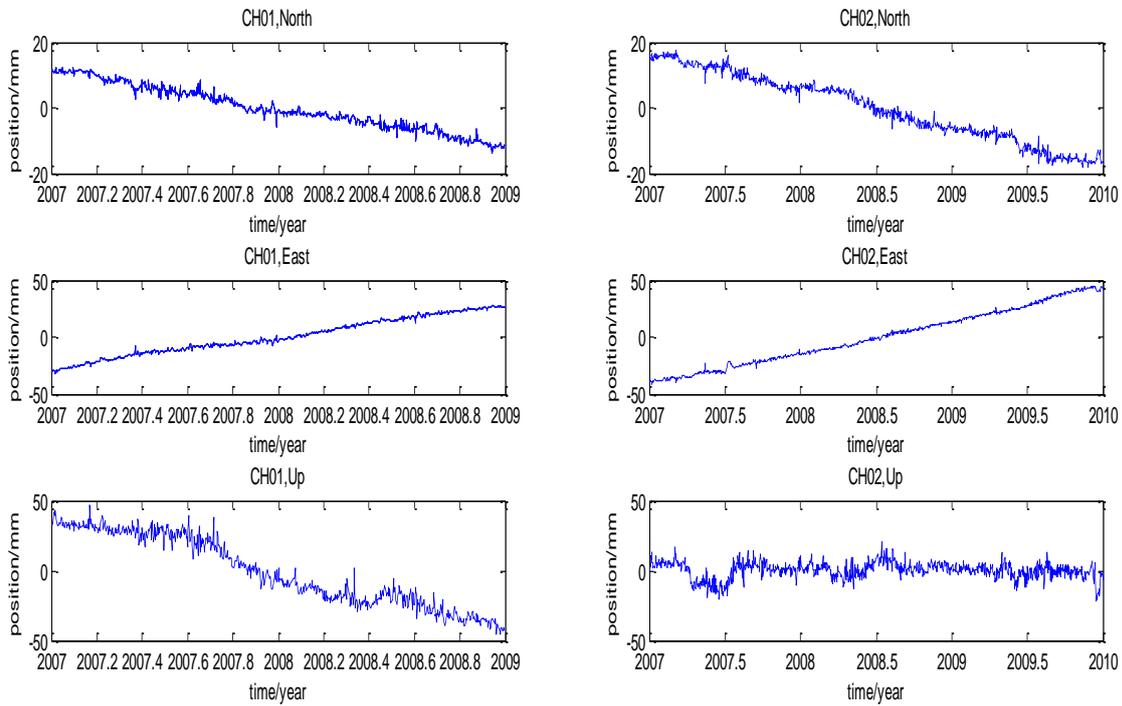


Figure 2a.

Figure 2b.

Figure 2. Coordinate component time series diagram of each reference station in TJCORS Net

(a. coordinate component time series of reference station CH01; b. coordinate component time series of reference station CH02)

2.2 The Formation of Reference Station Coordinate Time Series

After the coordinate components of TJCORS were obtained, the rectangular space coordinates of the 12 stations are transformed into the values of topocentric coordinate system. Then the few isolated values caused by such as transmission signal disturbing or electric component abrupt change are deleted and the coordinate component time series of 12 stations in the TJCORS Net are gained in the end. The time series diagrams of 2 stations can be seen in Fig.2.

3. STABILITY ANALYSIS OF TJCORS

The stability analysis of TJCORS is operated from three aspects of periodicity, noise and velocity field.

3.1 Periodicity Analysis

Many researches have been done to study if there exists linear variation tendency besides periodicity movement features in GPS reference stations(Dong, 2002; Fu, 2002; Qiao, 2003).

For examining the periodicity of TJCORS station coordinate component time series, CATS Software is used to operate the spectral analysis on the pre-processed (N, E, U) coordinate time

series of 12 reference stations. The input data that are coordinate materials of reference stations include time and (N, E, U) coordinate and the output data are psd images that will be treated by matlab. Parts of the results are shown in Fig.3 with the signal periodicity as horizontal and power spectrum (unit: m^2/yr) as vertical coordinate.

It can be seen in Fig.3 that 3 coordinate components (N, E, U) have semi-annual and annual periodicity, and the periodicity in the direction of altitude is more obvious than in the horizontal direction. As to most reference stations, the annual periodicity is more obvious than semi-annual periodicity and the features can be classified into three types as follows.

(1) The first type: All the directions (N, E, U) emerge the annual periodicity.

This type includes 7 reference stations and there are DZ01, DZ02, JIXN, KC01, KC02, KC03 and YC01. The annual periodicities of DZ02 and KC02 in E direction and KC03 in N direction are a little weaker than other stations. In addition, DZ02, JIXN, and KC02 in N direction as well as all the reference stations of the first type except YC01 in U direction appears semi-annual periodicity.

(2) The second type: One coordinate component emerges semi-annual periodicity.

This type includes 4 reference stations and there are CH01, CH02, SW01 and TJA2. Among them, CH01 presents semi-annual periodicity in N direction and others in U direction. The annual periodicity of CH02 in E direction is a little weaker than other reference stations. The annual and semi-annual periodicities of SW01 in U direction are almost the same. TJA2 appears 0.4a semi-annual and 0.8a annual periodicity in U direction.

(3) The third type: frequency spectrogram confounding.

TJA1 belongs to this type. In E and N direction, TJA1 has two spectral peaks adjacent to the one year periodicity. While in U direction, there exists annual and semi-annual periodicity at the same time.

Furthermore, it is notable that about three months seasonal variations appear in some coordinate components in parts of reference stations, such as in N direction of TJA1 and CH01, in U direction of DZ01, JIXN, KC02, SW01 and TJA2.

The main causes that result in the time series periodicity variation of GPS reference coordinate include gravity stimulation, heat effect and hydrological dynamic factors and so on.

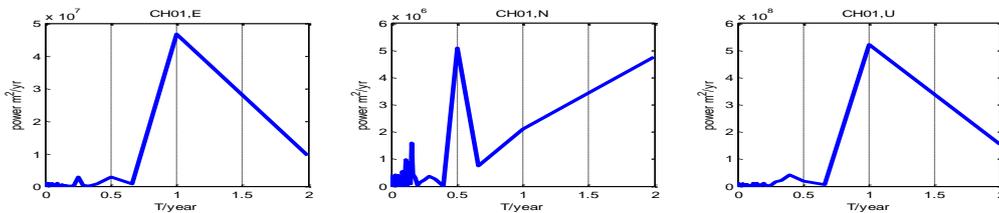


Figure 3a.

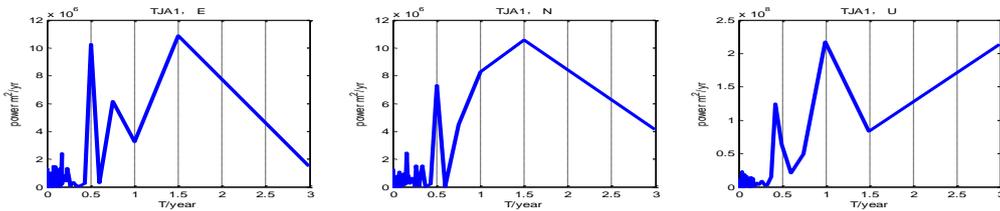


Figure 3b.

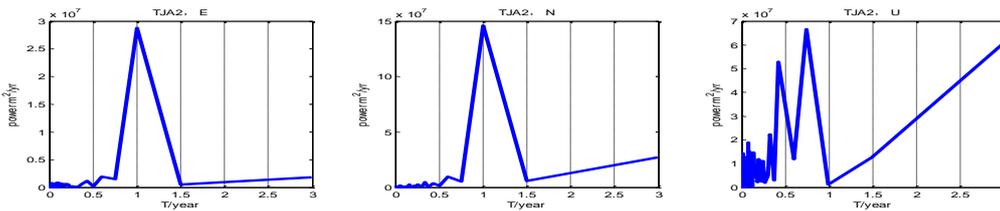


Figure 3c.

Figure 3. Periodicity in E, N, U directions of 12 reference stations in TJCORS Net

(a. power spectrum of reference station CH01 in E, N, U directions; b. power spectrum of reference station TJA1 in E, N, U directions; c. power spectrum of reference station TJA2 in E, N, U directions)

3.2 Noise Analysis

Not a few research results have indicated that there exists not only white noise in GPS reference station coordinate series but also colored noise. The time series noise features of TJCORS reference stations are analyzed using spectral index and

maximum likelihood estimator methods(Mao, 1999; Yuan, 2008).

3.2.1 Spectral Index

The spectral indexes of 12 reference stations are figured out by CATS Software. Seen in Fig.4, the noise series of 36 coordinate components of 12 GPS reference stations has distinct negative

spectral indexes and the spectral indexes of each direction in each reference station distribute between -1 and 0. The average spectral indexes in N, E, U direction are -0.7257, -0.6353 and -0.6711. Hence, there is no pure white noise (K=0) in the noise power and most coordinate component time series have coloured noise part especially flicker noise.

3.2.2 Maximum Likelihood Estimator Method

Maximum likelihood estimator method is adopted to make comparisons among white noise (WH), white noise + flicker

noise (WH + FN), white noise + random walking noise (WH + RWN), white noise + flicker noise + random walking noise (WH + FN + RWN) and white noise + first order Gaussian Markov noise (WH + GM) models, based on which the noise features of TJ CORS reference station coordinate component time series can be studied. Generally, the higher the maximum likelihood estimator values are, the more effective the noise model is.

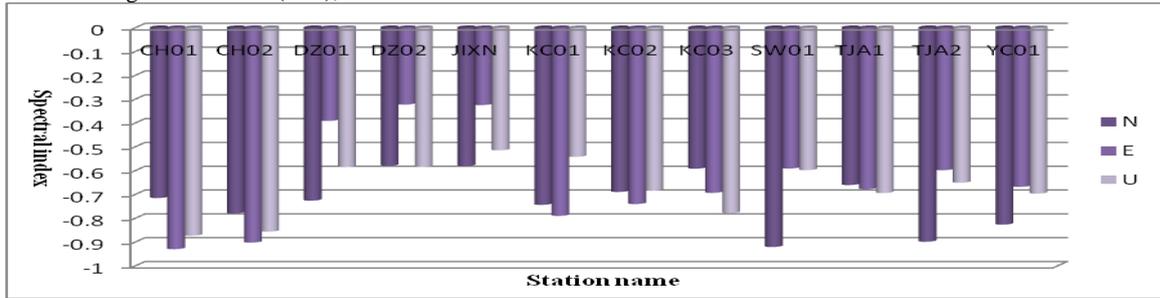


Fig.4 Spectral index histogram of TJ CORS reference station coordinate components

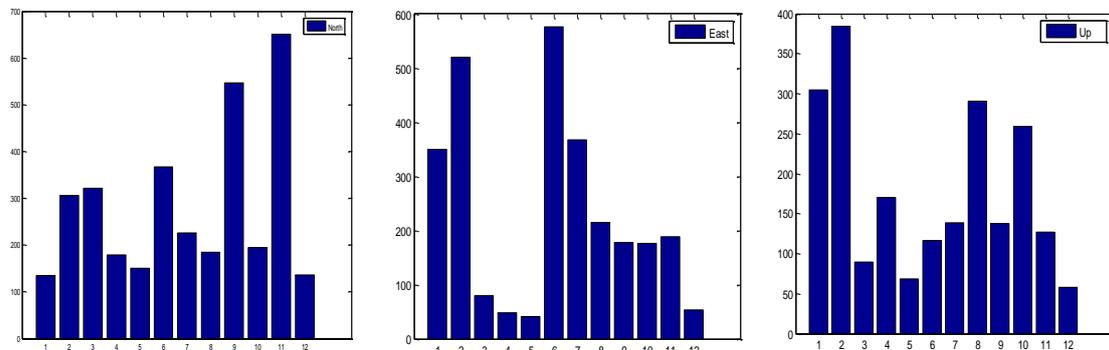


Figure 5. Maximum likelihood different values of [(WH + FN) - WH] of TJ CORS reference station coordinate component

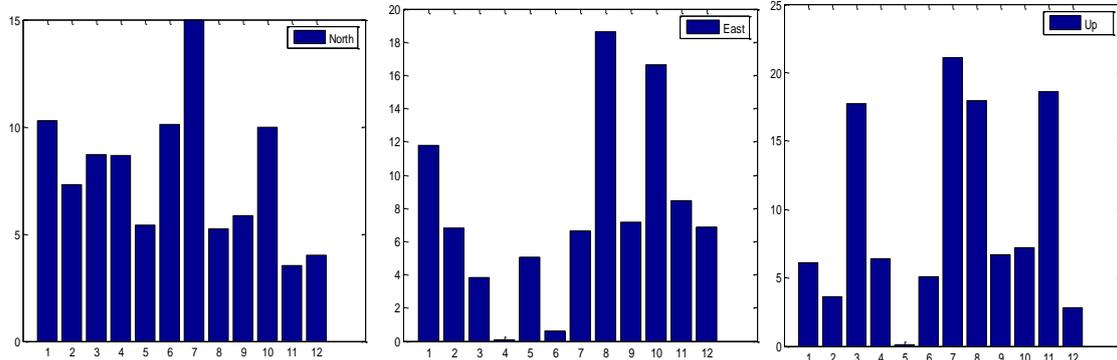


Figure 6. Maximum likelihood different values of [(WH + FN) - (WH+RWN)] of TJ CORS reference station coordinate component

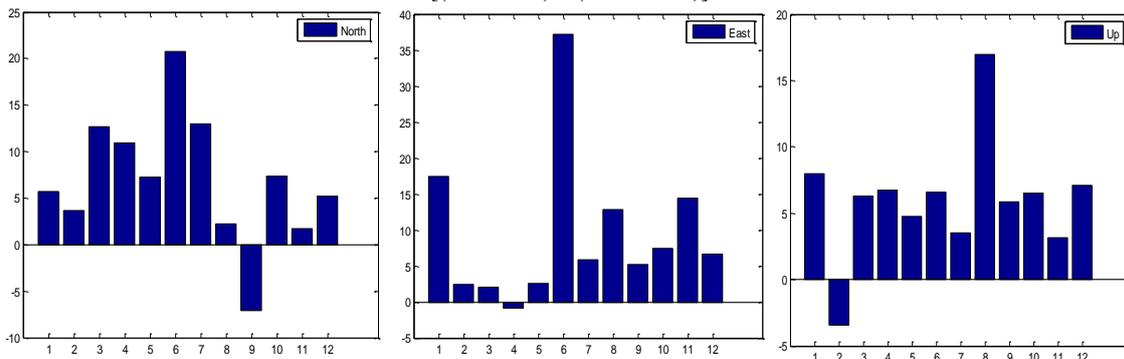


Figure 7. Maximum likelihood different values of [(WH + FN) - (WH+GM)] of TJ CORS reference station coordinate component
 In the analysis of TJ CORS reference station time series by CATS Software, the input data are the reference station coordinate and the output ones (MLE) are the maximum likelihood values of each noise group. The difference values in

the directions of north, east and up of WH + FN, WH + RWN and WH + GM are shown in Fig.5, Fig.6 and Fig.7, where the horizontal ordinate (1-12) indicates the codes of reference stations that are CH01, CH02, DZ01, DZ02, JIXN, KC01, KC02, KC03, SW01, TJA1, TJA2 and YC01, and the ordinate shows the maximum likelihood differences between two noise models.

Through analyzing the diagrams above, the conclusions can be drawn as follows.

(1) The difference values of [(WH + FN) – WH] of 12 reference stations in N, E, U directions are all positive in Fig.5, moreover, the maximum likelihood values in the model of WH + FN are much higher than those of WH and the minimum difference values are 134.483, 41.166, 58.219. The average values in N, E, U directions are 282.986, 207.323, 158.156, which means the model of WH + FN is more effective than that of WH.

(2) The difference values of [(WH + FN) – (WH+RWN)] are all positive in Fig.6, which indicates that the maximum likelihood values of WH + RWN are all less than those of WH + FN and the average difference value is about 7.658 with 7.283 in N, 6.745 in E and 8.947 in U direction. The minimum difference values are 3.549, 0.113 and 0.113 in N, E, U directions. It is clear that the model of WH + FN is more effective than that of WH + RWN.

(3) The difference values of [(WH + FN) – (WH+GM)] are mainly positive in Fig.7, which means the maximum likelihood

values of WH + FN are generally higher than those of WH + GM and the average difference value is about 6.279 with 5.868 in N, 7.911 in E and 5.057 in U direction. Hence, the model of WH + FN is more effective than that of WH + GM.

According to Monte Carlo's simulation test results (Mandelbrot,1968), it is difficult to distinguish the models of WH + FN and WH + FN + RWN. So the comparison of these two models is not operated.

It can be seen from the comparison results of maximum likelihood estimator that almost GPS reference station coordinate components have a flicker noise based colored noise part but no pure white noise. Consequently, the model of WH + FN is the best one to represent most GPS reference station coordinate components, while the ingredients of RWN can be analyzed in future research.

3.3 Stability Analysis of Reference Stations

3.3.1 Velocity Field of Reference Stations

Aimed at studying the influence of the noise model on velocity estimation and evaluated error, the velocity estimation values and evaluated error of reference stations in the model of WH + FN are listed in table2. For more visualized, Fig.8 and Fig.9 are drawn to show the horizontal and altitude movement tendencies of the reference stations in accordance with table2.

	N	E	U
CH01	-11.5242±0.3879	28.3795±0.4515	-41.2890±1.7810
CH02	-10.9216±0.3306	27.8294±0.4000	-1.6434±1.3507
DZ01	-11.1964±0.2874	28.8639±0.3298	-8.8775±1.1326
DZ02	-10.7473±0.3180	29.3931±0.3032	-17.9716±1.3133
JIXN	-9.8859±0.3117	27.8089±0.2951	-0.0522±1.1908
KC01	-9.8996±0.2660	26.8711±0.3679	-17.8742±1.2143
KC02	-10.6762±0.2464	30.1758±0.2699	-29.3066±1.2116
KC03	-9.0900±0.2770	30.7828±0.2559	-26.0900±1.1854
SW01	-3.2866±0.4845	28.1896±0.2792	-40.1999±1.1846
TJA1	-8.8764±0.3064	26.0952±0.3449	-3.6432±1.2607
TJA2	-11.9241±0.3341	29.1817±0.2199	-0.7019±1.2768
YC01	-9.2415±1.0125	30.0380±0.4951	-19.3429±3.8316

Table 2. Reference station velocity of WH + FN model (dimension in mm/yr)

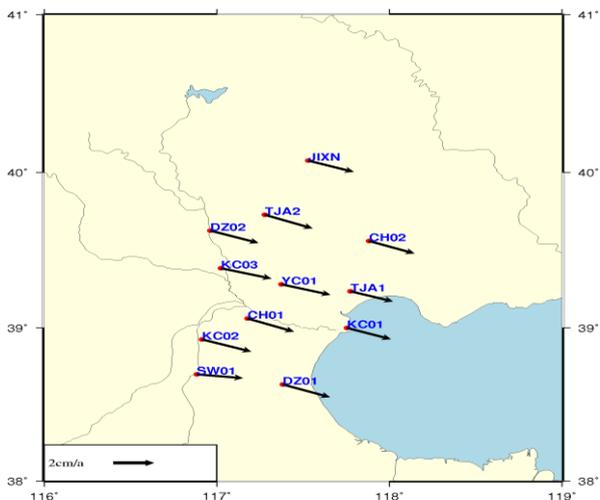


Figure 8. Horizontal movement tendency of TJCORS reference stations

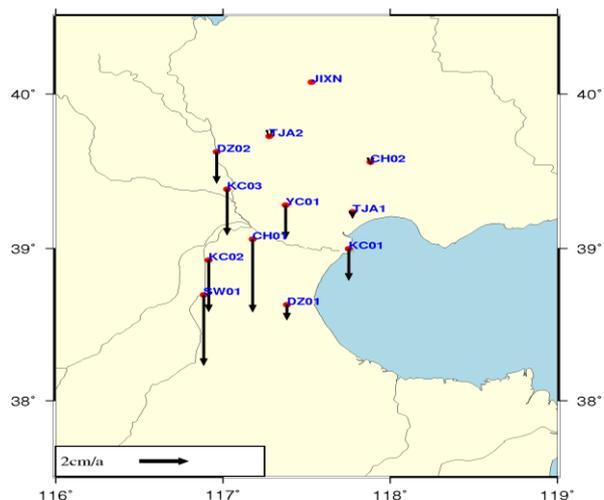


Figure 9. Altitude movement tendency of TJCORS reference stations

3.3.2 Horizontal Stability of Reference Stations

Generally, it is clear that the TJCORS Net has a horizontal movement tendency in the direction of southeast-east. The velocities towards south are from 3.29 to 11.92 mm/yr with the average value 9.77 mm/yr, while those towards east are from 26.10 to 30.78 mm/yr with the average value 28.63 mm/yr. In N direction, all 12 reference stations have the south movement trend and the most obvious two stations are TJA2 and CH01 with the corresponding velocities 11.92 mm/yr and 11.52 mm/yr, besides, SW01 has the least movement velocity that is 3.29 mm/yr. In E direction, all 12 reference stations have the east movement trend and the most obvious three stations are KC03 (30.78 mm/yr), KC02 (30.18 mm/yr) and YC01 (30.04 mm/yr), and the least one is TJA1 with the velocity 26.10 mm/yr.

3.3.3 Altitude Stability of Reference Stations

CH02, JIXN and TJA2 in the north part of Tianjin have almost no settlement in the U direction, which can be seen in Table2 and Fig.9. That is because the geological conditions in the north are better. For instance, JIXN was built on the stable bedrock and the settlement value there is less than 0.1mm, in addition, the settlement value is only -3.64mm/yr in TJA1 that is located in Hangu Weather Bureau. Conversely, the soil layer is thick in the south part of Tianjin as well as large-scale exploitation of ground water which is easy to bring about ground settlement and the total situation is much worse. For example, the settlement values in CH01 in Tianjin Institute of Surveying & Mapping and SW01 in Jiuxuan Floodgate are relatively higher,

which are -41.29mm /yr and -40.20 mm/yr. Furthermore, the settlement values even reach to from -80 mm/yr to -300 mm/yr in KC02 (in Jinghai), DZ02 and KC03 (both in Wuqing), YC01 (in Hedong), KC01 and DZ01 (both in Binhai New Area).

4. SETTLEMENT VALUE COMPARISON BETWEEN TJCORS REFERENCE STATION AND LEVELLING

In order to monitor the ground settlement, four units including Office of Controlling Ground Settlement, Tianjin Bureau of Geology and Mineral Resource, Tianjin Institute of Surveying and Mapping and No.1 Deformation Monitoring Centre of State Seismology Bureau have cooperated since 1985 and been continuing to do levelling using traditional geodesic survey methods from October to November every year. The monitoring materials gained by levelling are compared with the results obtained by TJCORS reference stations to prove that whether the latter results are of accuracy.

4.1 Comparing with the Contour Diagrams

It is shown in Table 3 that the settlement values picked up from the settlement contour diagrams of 2006-2007 supplied by Office of Controlling Ground Settlement (the 4th row in Table 3) are compared with those observed by TJCORS reference stations (the 5th row in Table3). Except Station TJA1, the results of other 11 stations generally agree with the levelling values.

Settlement sort	Station	Region	Settlement values of levelling contour	Settlement values of TJCORS reference stations
No obvious settlement	JIXN	Ji County	—	-0.05
	TJA2	Baodi Weather Bureau	<-5	-0.7
	CH02	Yuehui Town	<-5	-1.64
Settlement value >8mm	DZ01	Shajinzi	<-10	-8.88
	KC01	Baoshui Area	-10~-20	-17.87
	DZ02	Hexiwu Town	-15~-20	-17.97
	YC01	Dongditou Hydrologic Station	-20~-25	-19.34
	KC03	Wuqing Weather Bureau	-20~-25	-26.09
	TJA1	Hangu Weather Bureau	-20~-25	-3.64
	KC02	Jihai Weather Bureau	-30~-40	-29.31
Settlement value >30mm	SW01	Jiuxuan Floodgate	>-40	-40.19
	CH01	Tianjin Institute of Surveying & Mapping	>-40	-41.29

Table 3. Settlement value comparison between levelling contour and TJCORS reference stations (dimension in mm)

4.2 Comparison with the Annual Settlement Velocity of Settlement

What can be seen in Table 4 is the comparison between settlement velocities of 2007-2009 supplied by Office of Controlling Ground Settlement (the 3rd row in Table4) and those measured by TJCORS reference stations (the 4th row in Table4) that were given the consideration of flicker noise. The

2nd row in Table4 indicates the locations of connection surveying points that are all adjacent to the reference stations with the distance of dozens of meters except KC03. The difference values of the 3rd and 4th rows are listed in the 5th row for convenient comparing. The analysis of two monitoring methods is operated from two aspects of value and precision.

Station	Location of Benchmark	Levelling average value	TJCORS value	Difference value
CH01	Liqi Village	-39.59	-41.29	-1.70
CH02	Yuelong north	4.07	-1.64	-5.71
DZ01	Shajinzi north	-8.34	-8.88	-0.54
DZ02	Hexiwu Town north	-13.06	-17.97	-4.91

JIXN	Ji County southeast	0.47	-0.05	-0.52
KC01	Baoshui Area north	-18.11	-17.87	0.24
KC02	Jihai Weather Bureau north	-27.97	-29.31	-1.34
KC03	No reference station	—	-26.09	—
SW01	Jiuxuan Floodgate north	-41.41	-40.20	1.21
TJA1	Hangu Weather Bureau north	-4.42	-3.64	0.77
TJA2	Baodi north	0.01	-0.70	-0.71
YC01	Dongditou Hydrologic Station north	-19.49	-19.34	0.15
RMS				± 2.22

Table 4. Annual settlement velocity comparison between levelling monitoring and TJCORS reference stations (dimension in mm/yr)

4.2.1 Settlement Value

It is clear in the 5th row of Table 4 that the difference velocity value of YC01 is the least (0.15 mm/yr) while the ones of CH02 and DZ02 are much higher which reach to -5.71 mm/yr and -4.91 mm/yr. The absolute average difference velocity value is 1.48 mm/yr.

On the basis of monitoring materials, the vertical error of levelling points in Tianjin is 5-8mm and the coordinate error in the U direction component measured by GPS is 2-15mm. Considering the influent factors mentioned above and the two errors, the resolving results of settlement velocity by TJCORS reference stations are identical with those levelling results provided by Office of Controlling Ground Settlement.

4.2.2 Settlement Root Mean Square Error

The root mean square error of settlement different values of 11 stations is ± 2.22 as seen in Table 4. It is assumed that the levelling monitor values are accurate values and the results of TJCORS are the measured values. Hence, the root mean square error itself can be viewed as RMSE to TJCORS observed values, which is less than the vertical error (5-8mm) of bench marks in levelling monitor zones in Tianjin. In other words, the vertical accuracy of TJCORS observation is the same as the accuracy of first order levelling in the data processing.

5. CONCLUSIONS

(1) The periodicity analysis results show that there exists periodicity variation feature in the reference station coordinate time series. TJCORS reference station coordinates have semi-annual and annual periodicity in N, E, U direction and the periodicity in U direction is more distinct than the other two directions. As to U direction, the annual periodicity is more obvious than the semi-annual periodicity. In addition, it is irrational to assume only linear variation trend for reference stations. Actually, the periodicity variation should be considered as well as linear variation.

(2) The analysis of spectral index and maximum likelihood estimator indicate that it is best to use "white noise + flicker noise" (WH + FN) model to represent the TJCORS reference station coordinate time series. The vast majority of the coordinate components of GPS reference stations have a flicker noise based coloured noise part but no pure white noise feature.

(3) TJCORS Net has an integral horizontal movement tendency towards southeast-east. Due to the good geological conditions in the north part of Tianjin, there is mostly no settlement occurred in CH02, JIXN and TJA2 in U direction. And the settlement value is only -3.64mm/yr in TJA1 located in Hangu Weather Bureau. On the contrary, the settlement values in CH01 in Tianjin Institute of Surveying & Mapping and SW01 in Jiuxuan Floodgate are relatively higher, which are -41.29mm

/yr and -40.20 mm/yr. Furthermore, the settlement values even reach to from -80 mm/yr to -300 mm/yr in KC02 (in Jinghai), DZ02 and KC03 (both in Wuqing), YC01 (in Hedong), KC01 and DZ01 (both in Binhai New Area).

(4) The settlement results gained by the TJCORS reference stations are mainly identical with those measured by levelling monitor. Except KC03, the absolute average difference value of settlement velocity is 1.48 mm/yr and the root mean square error is ± 2.22 .

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