Surveying Co-located GNSS/VLBI/SLR Stations in China

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ABSTRACT

The local tie vectors between different space geodesy instruments in co-located sites, such as Global Navigation Satellite System (GNSS), Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR), are essential for ITRF combination. This paper introduces the surveying method, data processing model for determining the tie vectors in the seven co-located sites in Shanghai, Wuhan, Kunming, Beijing, Xian, Changchun and Urumqi, and presents the values and full variance-covariance of these local ties. Our surveying methodology and data processing method are rigorously determined to guarantee the relative positional precision of Reference Points (RPs) of different instruments in each co-location site to be a few millimeters. Compare our tie vectors with that derived from ITRF2008 products to overview the discrepancies at tie epoch. Likewise, by comparing with the previous results by the Institute Géographique National (IGN) in 2003, our tie vector at Wuhan site is well consistent, but the vertical coordinate difference of the tie vector at Shanghai site is as larger as $2.24\ cm$. Therefore, the tie vector at Shanghai site may be changed about 2 cm from 2003 to 2011.

Keywords: GNSS, VLBI, SLR, Co-location Survey, Reference Point, Three Dimensional Adjustment

INTRODUCTION

The co-located site is equipped with two or more space geodesy instruments in the close locations, the tie vector between different instruments can be determined using GNSS or classical surveys. The co-located sites are essential for connecting diverse space geodetic techniques of Global Navigation Satellite System (GNSS), Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) with the tie vectors for computing the International Terrestrial Reference Frame (ITRF) (Altamimi et al. 2007; Abbondanza et al. 2009). Until now, a lot of tie vectors of co-located sites in the world have been measured and used in generating ITRF products (see e.g. http://itrf.ensg.ign.fr/local_surveys.php; Johnston et al. 2000, 2001, 2004; Richter et al. 2003; Garayt et al. 2005a, 2005b; Long and Carpenter 2008). Ray and Altamimi (2005) evaluated the 25 co-located ties relating the VLBI and GNSS reference frames using 5 years of space geodetic time series observations, they found that most of the residuals were at the level of 1-2 cm; however they identified 9 sites with the precision better than 4mm. The local tie vector is the 3D baseline vector between two reference points (RPs), which are the fixed points relative to ITRF when the telescope rotates (Sarti et al. 2004; Dawson et al. 2007). Hence RPs can be regarded as the geometric rotation centers of SLR and VLBI telescopes as well as the Antenna Reference Point (ARP) of the GNSS antennas(as shown in Fig 1). The rigorous definition of RP by Abbondanza et al. (2009) is the intersection of the primary fixed axis, with the perpendicular vector between the secondary moving axis and the primary axis. Since the RP could not be observed directly, it is usually determined via indirect approach, where the targets mounted on the telescope are measured during specific horizontal and vertical rotation sequences and the coordinates of RP are determined with the horizontal and vertical rotation centers, respectively. As to the rigorous mathematical model of determining RPs, one can refer to Sarti et al. (2004); Vittuari et al. (2005); Dawson et al. (2007), Leinen et al. (2007); Abbondanza et al. (2009) and Lösler (2009).

The Crustal Movement Observation Network of China (CMONOC) consists of more than 2000 GNSS stations (including 260 continuous tracking stations), 3 VLBI stations and 6 SLR stations. There are totally seven co-located sites occupying two or three space geodesy instruments, the sites in Shanghai and Kunming are equipped with GNSS/VLBI/SLR instruments, the sites in Beijing, Xian, Changchun and Wuhan with GNSS/SLR instruments, and the site in Urumqi is with GNSS/VLBI. The locations of these seven co-located sites are shown in Fig 2. The names of GNSS stations at Shanghai, Kunming, Beijing, Changchun, Wuhan and Urumqi sites are named as SHAO, KUMN, BJFS, CHAN, WUHN and GUAO by International GNSS Service (IGS), respectively. The GNSS station at Xian site is named as XIAA by CMONOC. The instruments and their DOMES number in these seven sites are presented in Appendix. In order to determine the precise tie vectors for these co-located sites, precise terrestrial survey, as described by Garayt et al. (2005a) and Johnston et al. (2004), had been carried out from September to November 2011 by using both GNSS and conventional terrestrial measurements, including distances, horizontal and vertical angles. We set up at least 2 and 4 control points for measuring the targets on the SLR and VLBI telescopes, respectively. Thereby, a three dimensional control network needs to be established. This paper presents the overview of field survey, data processing model and method, and then shows the related results.

The rest of the paper is arranged as follows. The methodology of field survey is presented in section 2, the data processing model and method are introduced in section 3, and the obtained results of local tie vectors are shown in section 4. Conclusions and remarks are summarized in section 5.

OVERVIEW OF FIELD SURVEY

The 4 Trimble NET R9 receivers with choke ring antennas, 2 Leica TC 2003 and 1 TS30 total stations (0.5″, 1mm+1ppm) were used in our field survey, before and after the field work, all the instruments were calibrated including the incline of total station horizontal axis and vertical axis, prism constant and antenna phase center. The methodology of field survey is referred to Garayt (2005a) and Johnston et al. (2004). Since intersecting the targets on VLBI telescope requires at least three total stations and measuring the targets of SLR requires at least 2 control points with three dimensional (3D) coordinates, a 3D control network should be established beforehand. Force centering piers were used at all 3D control points in the network established around the VLBI/SLR instruments, therefore the horizontal centering precision is about 0.1mm, the height of GNSS antennas and total stations are measured with a slide caliper with the precision of about 0.2mm. Two steps are included in the field survey: the first is to measure the control network using both GNSS and total station, and the second is to measure the targets mounted on the VLBI and SLR telescopes during specific rotational sequences.

Control network survey

Fig 3 shows the control network around the VLBI telescope in Shanghai site. The control points are measured with the instruments including GNSS and total station. The GNSS data of control points are collected spanning at least 24 hours with two sessions consisting of more than 12 hours per session. And the four round of Direct/Reverse terrestrial measurements, including slope distances, horizontal and vertical angles are observed with TCA 2003 total station. The control network surveying connects the IGS station with the control points set around the VLBI and SLR telescopes. And the GNSS measurements of IGS station at each co-located site are downloaded from the IGS website.

VLBI targets survey

The VLBI target is a red ball with the diameter of 6 mm, which is fixed on the outer edge of

VLBI telescope dish (as shown in Fig 4). Each target is observed with three total stations at the same time, each total station is operated by a surveyor. The VLBI telescope rotates around primary axis with 15 degrees at each step, the surveyor aims and records a group of measurements at each step. Both clockwise and counterclockwise finish a complete round of observation. Similarly, it rotates with step of 10 degrees around secondary axis. The measurements of the VLBI target observed by three total stations are only horizontal and vertical angles, not including distances since the target cannot reflect distance signal. Because of the limitation of rotation freedom, only 9 points around the secondary axis were observed.

SLR targets survey

The prism target, mounted on the top of SLR telescope as shown in Fig 5, is strictly fixed on the SLR telescope as the SLR telescope rotates around both primary and secondary axes. Therefore slope distance, horizontal and vertical angles can be observed with a total station nearby the telescope as the SLR telescope rotates each 15 degrees and 10 degrees around the primary and secondary axes, respectively. In some sites, the prism can only be put on the top of telescope, which can be used to achieve the observations as rotating around the primary axis. The reflection tapes pasted on the telescope are used to achieve observations of rotating around the secondary axis. The rotation procedure is similar to VLBI.

The SLR telescope in Wuhan is different from others. Firstly the IGS station WUHN is 13km apart from the SLR station. The 7 days of GNSS measurements were collected for achieving high precision baseline vector. Secondly as described in Garayt et al. (2005b), the SLR is installed in a very narrow room at the top of a rather high building, it is impossible to set up control points around it. Therefore, a GNSS antenna was set on the top of SLR telescope for data collection. After finishing one observation session of 12 hours, the SLR telescope rotated around the primary axis of 60 degrees. As shown in Fig 6, 6 points can be measured around the primary axis as the SLR telescope rotating 360 degrees. Since the SLR primary axis lies in the centre of the circle formed by 6 points, the horizontal coordinates of SLR RP can be computed with these 6 points. The vertical coordinate of SLR RP is determined by using the vertical coordinate of the GNSS antenna and the height differences between the GNSS antenna and the reflection tapes pasted on the top and bottom edges of the secondary rotation axis as shown in Fig 7. These height differences are measured with a total station. Since the two tapes are set in the same plumb line, the mean of the two height differences is just the value related to the center of secondary axis.

DATA PROCESSING AND MATHEMATICAL MODEL

The GNSS data were processed to solve for the GNSS vectors between the control points by using GAMIT v10.35 and Bernese v5.0 Software. The results derived from Bernese software were used to check the results from GAMIT v10.35, and this procedure ensured the consistent GNSS solution estimates. When processing the GNSS baseline, final satellites' orbits, clocks and Earth rotation parameters from IGS were used ,while exploiting absolute phase centre variation models(PCV) and offsets (Schmid et al. 2005) .The elevation angle of satellites was cut off to 15 degrees .For phase data, the GAMIT only use L1 frequency data. Both GAMIT and BERNESE compute an ambiguity fixed solution. Then the 3D GNSS vectors, the terrestrial observations of the control network, and the target points are solved together by using 3D least squares adjustment. The coordinates of IGS stations in ITRF2008, such as SHAO at shanghai co-located sites, are fixed as the initial values. Therefore, the 3D coordinates of all the points of targets can be derived in the 3D adjustment. Then by using the coordinates of targets, the coordinates of the RPs can be further determined. Since each target rotating around an axis can form a circle in the same plane, two constraint conditions for the points of each rotation circle can be constructed as follows (Johnston et al. 2000, 2001; Soler, 2001):

$$a\bar{x}_i + b\bar{y}_i + c\bar{z}_i + d = 0 \tag{1}$$

and

$$(\bar{x}_i - u)^2 + (\bar{y}_i - v)^2 + (\bar{z}_i - w)^2 + d = 0 \tag{2}$$

where, a, b, c, d are the plane parameters, u, v, w are the coordinates of rotation center and r is the radius of rotation circle, $\bar{x}_i, \bar{y}_i, \bar{z}_i$ are the adjusted coordinate of point i, which can be expressed as,

$$\bar{x}_i = x_i + v_{xi},\ \ \bar{y}_i = y_i + v_{yi},\ \ \bar{z}_i = z_i + v_{zi} \tag{3}$$

where x_i, y_i, z_i are the coordinates of point i, which are already derived by 3D least squares adjustment, $v_{xi},\ v_{yi},\ v_{zi}$ are the corrections. All the parameters in (1) and (2) are expressed with their approximate values plus corrections. By substituting the parameters with approximates and corrections and (3) into (1) and (2), the linear equations for all points in a circle can be derived, it is as follows,

$$\boldsymbol{Ax} + \boldsymbol{Bv} = \boldsymbol{y} \tag{4}$$

where, $\boldsymbol{x}$ is the correction vector of parameters and $\boldsymbol{A}$ is its design matrix, $\boldsymbol{v}$ denotes the correction vector of coordinates of targets and $\boldsymbol{B}$ is its design matrix, the correspondent covariance matrix is denoted by $\boldsymbol{\Sigma}$, which has already been derived in 3D adjustment. $\boldsymbol{y}$ is the misclosure vector of the constraint equations. From the law of error propagation, the covariance matrix of $\boldsymbol{y}$ can be described as,

$$\boldsymbol{\Sigma}_y = \boldsymbol{B\Sigma B}^{\mathrm{T}} \tag{5}$$

The solution of (4) based on the weighted least squares adjustment can be expressed as,

$$\boldsymbol{x} = \left(\boldsymbol{A}^{\mathrm{T}}\left(\boldsymbol{B\Sigma B}^{\mathrm{T}}\right)^{-1}\boldsymbol{A}\right)^{-1}\boldsymbol{A}^{\mathrm{T}}\left(\boldsymbol{B\Sigma B}^{\mathrm{T}}\right)^{-1}\boldsymbol{y} \tag{6}$$

Its covariance matrix $\boldsymbol{\Sigma_x}$ can be derived from (6) and (5) as,

$$\boldsymbol{\Sigma}_x = \left(\boldsymbol{A}^{\mathrm{T}} \left(\boldsymbol{B\Sigma B}^{\mathrm{T}} \right)^{-1} \boldsymbol{A} \right)^{-1} \tag{7}$$

The subset of $\boldsymbol{\Sigma}_x$ corresponding to u, v, w denote the covariance matrix of rotation center of the circle, since the IGS station is fixed in the 3D adjustment, this covariance also denotes the covariance of the vector from the IGS station to the circle rotation center. The fitting residual vector $\boldsymbol{v}$ only denotes the fitting errors, which reflects the fitting accuracy of the points in the same circle. Fig 8 shows two fitting circles with respect to the primary and secondary axes of the VLBI telescope in Shanghai.

If total m_1 and m_2 circles respectively rotating around the primary and secondary axes are observed, m_1 and m_2 numbers of solutions can be obtained. Certainly, these m_1 and m_2 circles can be solved together for getting better results. With these solutions, the coordinates of RP can be computed through the following expressions (Soler, 2001),

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{bmatrix} -sin\varphi cos\lambda & -sin\lambda & cos\varphi cos\lambda \\ -sin\varphi sin\lambda & cos\lambda & cos\varphi sin\lambda \\ cos\varphi & 0 & sin\varphi \end{bmatrix} \begin{pmatrix} N \\ E \\ U \end{pmatrix} \tag{8}$$

where, $\mathrm{X}, \mathrm{Y}, \mathrm{Z}$ are the 3D coordinates of RP in ITRF2008 system, φ, λ are the geodetic latitude and longitude of the rotation center of the primary axis, *N*, *E* and *U* are the coordinates in the terrestrial topocentric coordinate system, its *U* axis coincides with primary axis and points to upwards, *N* and *E* axes are perpendicular to the primary axis, with *N* pointing to north and *E*=*U*×*N*. The *N*, *E* and *U* coordinates are computed with,

$$\begin{pmatrix} N \\ E \end{pmatrix} = \frac{1}{m_1} \begin{pmatrix} -sin\varphi cos\lambda & -sin\varphi sin\lambda & cos\varphi \\ -sin\lambda & cos\lambda & 0 \end{pmatrix} \begin{pmatrix} \sum_{i=1}^{m_1} u_i^p & \sum_{i=1}^{m_1} v_i^p & \sum_{i=1}^{m_1} w_i^p \end{pmatrix}^{\mathrm{T}} \tag{9}$$

and
$$U = \frac{1}{m_2} \begin{pmatrix} cos\varphi cos\lambda & cos\varphi sin\lambda & sin\varphi \end{pmatrix} \begin{pmatrix} \sum_{i=1}^{m_2} u_i^s & \sum_{i=1}^{m_2} v_i^s & \sum_{i=1}^{m_2} w_i^s \end{pmatrix}^{\mathrm{T}} \tag{10}$$

where, u_i^p, v_i^p, w_i^p are the coordinates of rotation centers around the primary axis, while u_i^s, v_i^s, w_i^s are the coordinates of rotation centers around the secondary axis. Since their covariance matrices have been already derived with (7), the covariance matrix of RP can be easily derived by using (8), (9) and (10) via the law of error propagation. Note again that the derived covariance matrix is relative to the IGS station; therefore it is also the covariance of the tie vector between the RP and the IGS station.

RESULTS AND ANALYSIS

Table 1 presents our tie vectors (Δ*X*, Δ*Y*, Δ*Z*) in the ITRF2008 frame and their precision ($M_{\Delta X}$, $M_{\Delta Y}$, $M_{\Delta Z}$) between the RPs of IGS stations and the VLBI or SLR stations at co-located sites. In Table 1, BJFS, CHAN KUNM, SHAO, GUAO, WUHN and XIAA denote the GNSS stations at

Beijing, Changchun, Kunming, Shanghai, Urumqi and Xian sites, and SLR and VLBI are the SLR and VLBI stations in the same site with GNSS station.

From Table 1, it can be seen that the precision estimates of the coordinate components of all the tie vectors are is better than 5 millimeters. The full covariance matrices of the tie vectors are presented in Appendix.

Tie discrepancies with the products of ITRF 2008

In order to overview the tie discrepancies with the products of ITRF 2008, the correspondent tie vectors from ITRF2008 products at the same epochs were computed, and the results were listed in Table 2. For the description of ITRF2008 products, one can refer to Altamimi et al. (2011).Table 3 shows the differences of our tie vectors with respect to the tie vectors of ITRF2008 products, both in ITRF2008 Cartesian coordinate system X, Y, Z and local Cartesian coordinate system N, E, U in order to observe the differences in horizontal and vertical directions.

From Table 3, it can be seen that the differences of the coordinate components in most of the sites are larger than 1cm except Urumqi. That means the tie discrepancies with the products of ITRF2008 at tie epoch of November 2011 has already been very large.

Comparison with the results of IGN

In order to further evaluate the accuracy of our tie vectors, the tie vectors surveyed by IGN in 2003 were compared with our results in Table 4 and 5(Garayt et al. 2005a, 2005b).

Table 5 shows that the differences of all the three coordinate components at WUHN site are all less than $1\ cm$, although the distance between the two RP are 13km, this tie vector is consistent well with that surveyed by IGN in 2003. At Shanghai site, the differences of N, E coordinate components are less than 2 millimeters, and the difference of the vertical coordinate component U is as large as $2.24\ cm$. This vertical coordinate difference is statistically significant by using the statistical testing of Fok (2009), if the standard deviation is chosen as 5mm.

CONCLUSIONS AND REMARKS

This paper has presented the tie vectors of 7 co-location sites in China and introduced the field work and data processing method. Based on the internal accuracy of our tie vectors as well as the external comparisons with both ITRF2008 products and the co-location surveying performed by the IGN, the conclusion can be made that the precision of our tie vectors can achieve a few millimeters, or better than $5\ mm$ for each coordinate component. Moreover, the tie discrepancies with the products of ITRF2008 at tie epoch of November 2011 has already been very large. Last but not least, we find that the U coordinate component of the tie vector SHAO-VLBI has changed by about $2\ cm$ from 2003 to 2011. These results of the co-location survey may contribute the next ITRF solution and improving the accuracy of the regional reference frame.

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APPENDIX

The seven surveyed co-located stations and their techniques with DOMES number

Shanghai	GNSS, 21605M002	VLBI, 21605S009	SLR, 21605S010
Beijing	GNSS, 21601S004		SLR, 21601S004
Urumqi	GNSS, 21612M003	VLBI, 21612S001	
Changchun	GNSS, 21611M002		SLR, 21611S001
Kunming	GNSS, 21609M001	VLBI ,new	SLR, 21609S002
Wuhan	GNSS, 21602M001		SLR, 21602S004
Xian	GNSS, CMONOC		SLR, new

The covariance matrices of tie vectors (unit in meters)

BJFS-SLR

0.157556191090401 E-5		
-0.238393336132076 E-5	0.361342559020585 E-5	
0.034368132806019 E-5	-0.052065291276669 E-5	0.007603490487091 E-5

CHAN-SLR

0.012262615511410 E-5		
-0.020956798227493 E-5	0.101069069828642 E-5	
-0.004090402900230 E-5	0.012331371191173 E-5	0.002797267806378 E-5

KUNM-VLBI

0.563557451248481 E-5		
0.000335303315578 E-5	0.038661643533635 E-5	
-0.000495688599563 E-5	-0.570878225736602 E-5	0.844397707094733 E-5

KUNM-SLR

0.015234654862457 E-5		
0.000228105088039 E-5	0.051878163842341 E-5	
0.001543278126098 E-5	0.002723637519170 E-5	0.154327812609791 E-5

SHAO-SLR

0.179276905457207 E-6		
0.007053575796153 E-6	0.932716653959722 E-6	
0.002543234388231 E-6	-0.225295664406483 E-6	0.606897397382865 E-6

SHAO-VLBI

0.050125515317930 E-5		
0.001207863851628 E-5	0.205595109667600 E-5	
0.000306590355650 E-5	-0.003358129979339 E-5	0.125320573991028 E-5

GUAO-VLBI

0.04340093033510 E-5		
0.28141044855448 E-5	2.36413627346170 E-5	
-0.01609364747955 E-5	-0.12707527686516 E-5	0.02896403685292 E-5

WUHN-SLR

2.18789315632294 E-5		
0.12556366398616 E-5	0.40914926398616 E-5	
0.11548019478437 E-5	0.01518266310516 E-5	0.18733493671087 E-5

XIAA-SLR

0.411835073200029 E-5		
0.023123134418093 E-5	0.102983719362957 E-5	
0.033322732131964 E-5	0.003158231059055 E-5	0.076614379858290 E-5

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Figure Captions List

Fig 1 The definition of RP

Fig 2 Locations of seven co-located sites in China

Fig 3 Control network around the VLBI in Shanghai

Fig 4 Target fixed on VLBI telescope

Fig 5 the prism and reflection target mounted on the SLR telescope

Fig 6 the GNSS points and primary axis of the SLR survey in Wuhan

Fig 7 The vertical coordinate of SLR survey in Wuhan

Fig 8 Fitting circles around the primary (left) and secondary (right) axes of the VLBI in Shanghai

Table 1 Tie vectors estimates and standard deviations

Vector	Δ*X*/m	Δ*Y*/m	Δ*Z*/m	$M_{\Delta X}$/mm	$M_{\Delta Y}$/mm	$M_{\Delta Z}$/mm
BJFS-SLR	-16.5166	118.3174	-146.2835	1.25	1.90	0.27
CHAN-SLR	40.2996	46.0158	-13.3399	0.35	1.01	0.17
KUNM-VLBI	103.1364	118.3366	-226.3731	2.37	0.62	2.90
KUNM-SLR	-20.2160	-18.8560	45.7754	0.39	0.72	1.24
SHAO-SLR	989.0580	914.3549	-296.5724	0.42	0.96	0.77
SHAO-VLBI	46.3460	67.6428	-41.8153	0.71	1.43	1.12
GUAO-VLBI	-68.5363	-24.1483	35.5471	0.66	4.90	0.54
WUHN-SLR	-11964.9994	-4386.8925	-1496.7445	4.68	2.02	1.37
XIAA-SLR	-14.8656	14.6918	-28.0790	2.03	1.01	0.87

Table 2 Tie vectors computed from ITRF2008 products (m)

Vector	Δ*X*	Δ*Y*	Δ*Z*
BJFS –SLR	-16.512	118.310	-146.303
CHAN-SLR	40.302	45.995	-13.37
KUNM –SLR	-20.245	-18.787	45.840
WUHN –SLR	-11964.98	-4386.857	-1496.801
GUAO –VLBI	-68.542	-24.149	35.547
SHAO –SLR	989.064	914.342	-296.585
SHAO –VLBI	46.360	67.630	-41.829

Table 3 Tie discrepancies with ITRF2008 products at tie epochs(mm)

Vector	*E*	*N*	*U*	*Distance*
BJFS-SLR	-0.9	-9.5	-19.1	21.8
CHAN-SLR	10.1	-9.0	-34.1	36.7
KUNM-SLR	13.0	27.3	94.1	98.9
WUHN-SLR	-33.2	-60.8	-8.1	69.8
GUAO-VLBI	5.7	0.6	-0.7	5.8
SHAO-SLR	1.6	-3.5	-18.6	19.0
SHAO-VLBI	-5.3	-2.3	-22.7	23.7

Table 4 Ties vectors surveyed by IGN (m)

Vector	*ΔX/m*	*ΔY/m*	*ΔZ/m*	Date
SHAO-VLBI	46.3560	67.6254	-41.8255	2003.11

WUHN-SLR	-11964.9969	-4386.8836	-1496.7389	2003.12

Table 5 Differences between our tie vectors with respect to that of IGN (m)

Vector	ΔX	ΔY	ΔZ	ΔN	ΔE	ΔU
SHAO-VLBI	-0.0100	0.0174	0.0102	-0.0016	-0.0005	0.0224
WUHN-SLR	-0.0025	-0.0089	-0.0056	-0.0012	0.0059	-0.0089