Local Survey at the Shanghai Tianma 65-m Antenna

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Abstract A local survey was implemented at the newly constructed Shanghai Tianma 65-m radio telescope in June and July of 2013. The survey implementation and data analysis are described in this report. The outcome provides an important reference for the subsequent activities of antenna maintenance and scientific applications. It is also important archive data for monitoring possible subsidence and lateral displacement of the antenna foundation as well as deformation of the antenna tracking-rail and structure.

Keywords VLBI, radio telescope, reference point, axis offset, local survey

1 Introduction

In October of 2012, the Shanghai Tianma 65-m radio antenna was equipped with S/X-band reception facilities and initially applied to deep space tracking of Chang'E-2, a lunar satellite of China, during its extended exploration mission to fly by the asteroid 4179 Toutatis. The L, C, K, and Ka-band reception devices were equipped and tested successively. The antenna also tracked the Chang'E-3 lunar satellite at the end of 2013. Based on the need for the establishment of a precise antenna orientation model, antenna orientation guidance, the extraction of VLBI observations, scientific applications, and analysis studies of the observations, a local survey to this telescope was conducted in June and July of 2013. This report describes the LCN (Local Control Network) layout, survey implementation, data analysis, and final results.

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2 Local Control Network, Observation Instrument, and Survey Implementation

Figure 1 shows a satellite map of the yard of the 65-m antenna. Figure 2 shows the horizontal projection of the LCN. A1 to A4 are the control pillars with forced-centering devices on top. G5 indicates a permanent GPS antenna, which is used for the delay correction of the transmission medium in the lunar exploration project of China. 65m indicates the horizontal projection of the vertical axis of the 65-m antenna, and the circle around it represents the antenna dish.

Fig. 1 Satellite map of the Shanghai Tianma 65-m antenna yard.

Pillar A1 is on the northwest corner of the control building and near to the western fencing wall. Pillar A2 is at the northwest corner of the fencing wall and is very near to the 65-m antenna. If targets connected

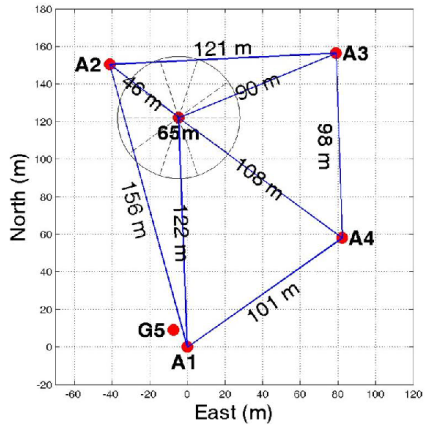

Fig. 2 Horizontal projection of the Local Control Network.

to the antenna are observed from this point, the elevation angle will be very high, and the visible dynamic range will be very limited. So A2 is inconvenient for instrument operation. But it can be a reference direction when observing targets on the antenna from other control pillars. Pillar A3 is on the right side of the entrance of the yard (near to the northeast corner of the yard). A4 is located near the turning corner of the southern fencing wall. Due to blocking by the antenna base pillars, A2 and A4 are not directly visible to each other, but every other pair of pillars is mutually visible.

The main optical instruments in the survey were the Leica Total Station TM30 and TS30, with an observation uncertainty in direction of 0.5 as (arc second) and in range of 0.6 mm + 1 ppm. The GPS receivers were dual-band geodetic type ASHTECH UZ-12 and Trimble 5700. Other auxiliary devices were cooperation targets, data transfer cable, batteries, calipers, and so on.

On 23 June 2013, an optical survey of the LCN was conducted. GPS observations of the LCN were carried out from 23 June to 7 July 2013. On 7 July, surveys to the vertical axis were also done at azimuths 30, 60, 90, and 120°. On 8 July, surveys to the vertical axis were continued at azimuths 150, 180, 240, 270, 300, 330, and 0°. On 9 July, surveys to the horizontal axis were done at an azimuth of 150° and elevations of 7, 10, 20, 30, 40, 50, 60, 70, 80, and 88°. On 13 July, surveys were also done to the horizontal axis at azimuths 120 and 188°. For the 120° azimuth, the elevations were sequentially 15, 30, 40, 50, 60, 70, 80, and 88°. For the 188° azimuth the elevations were 8, 18, 28, 38, 48, 58, 68, 78, and 88°.

3 Data Reduction

Data reduction includes the reduction of LCN observations and the reduction of spatial intersection survey observations of targets. The reduction of LCN observations is firstly to determine the relative local coordinates of pillars from optical observations, secondly to determine the geocentric 3D coordinates of pillars from GPS measurements of the LCN, and thirdly to determine the coordinate transformation relationship from the local to the geocentric 3D coordinates. In the data reduction of the spatial intersection survey of targets, there are multiple steps, including those to determine the local coordinates of targets at various antenna orientations, the local coordinates of the centers of the circular loci of targets, the location and orientation of the vertical and horizontal axes in the LCN, the plane holding the horizontal axis, the coordinates of the intersection point of this plane with the vertical axis, and the length of axis offset. Finally the local coordinates of the reference point are transformed into geocentric 3D coordinates.

3.1 The LCN Observations

Optical measurement of the LCN involved setting up the optical instrument on the pillars on A1 and A4 in turn and performing a spatial survey to all the other pillars in the LCN. The observations are the horizontal and vertical directions and the radial distance. In the data reduction, pillar A1 is taken as the origin of the local coordinate frame, the horizontal direction from A1 to A2 as the x-axis, the zenith direction of A1 as the z-axis, and xyz as constituting a right-handed frame. Table 1 shows the local coordinates of pillars resulting from weighted least squares adjustment of the optical observations, in which σ_x etc. denote the formal errors of coordinate components and "/" indicates parameters that were not adjusted. The weighted mean post-fit residuals of the horizontal and vertical directions and the radial distance are respectively -0.7 as, -1.9 as, and -0.01 mm.

Although G5 in Figure 2 is a permanent GPS station, due to some equipment failure, only some of the observations were available during the GPS survey of the LCN, and the precise coordinates of this point are still unavailable. Therefore in the GPS data anal-

Table 1 Adjustment results of the LCN optical observations.

Pillar	x/m	y/m	z/m	σ_x/mm	σ_y/mm	σ_z/mm
A1	0.0000	0.0000	0.0000	/	/	/
A2	155.9572	0.0000	−0.0066	0.02	/	0.07
A3	129.8441	−117.6418	0.0044	0.02	0.02	0.07
A4	34.2157	−94.7139	0.0004	0.03	0.02	0.07

ysis, SHAO, an IGS permanent station in the yard of the Shanghai Sheshan 25-m antenna which is about 6 km from the 65-m antenna, is taken as the reference station. The GPS data analysis software GAMIT was adopted, and through spatial adjustment of the baseline length solution, the geocentric 3D coordinates of the LCN pillars in the frame of ITRF2008 were obtained as shown in Table 2, in which σ_X etc. denote the formal errors of coordinate components. The middle epoch of the GPS survey of the LCN was UTC 0h 29 June 2013, when (−2831733.7669, 4675665.8529, 3275369.3294) m was adopted as the geocentric 3D coordinates of SHAO in ITRF2008.

Table 2 Adjustment results of the LCN GPS survey data.

Pillar	X/m	Y/m	Z/m
	σ_X/mm	σ_Y/mm	σ_Z/mm
A1	−2826729.534	4679262.767	3274544.855
	0.4	0.4	0.4
A2	−2826653.989	4679217.667	3274673.627
	0.4	0.4	0.4
A3	−2826755.409	4679152.789	3274678.772
	0.4	0.4	0.4
A4	−2826784.426	4679194.559	3274594.605
	0.4	0.4	0.4

By comparison of the LCN local and geocentric 3D coordinates as shown in Table 1 and 2, it is clear that there are large translations (on the magnitude of the Earth radius) and relative rotations between them. During the data analysis of the local survey of Shanghai Sheshan 25-m antenna in July 2008, theoretical analysis and numerical tests showed that, for the different dimensions and different magnitudes of the seven parameters in the transformation of two sets of 3D Cartesian coordinates, to adjust the parameters by multiplying different factors and so to let the resulting formal errors be basically close to each other, the condition of the normal equation could be effectively improved when the parameters are small in magnitude, and the solution stability of the parameters could be improved when the parameters are large in magnitude. In the case of large rotations, via simple and effective iterative solution mode, programming could be facilitated, and the solution would be characterized by fast convergence and by a wide dynamic range of initial parameters. Finally, in the case of large translations, applying a coordinate transformation to partly deduct the translation beforehand would benefit the stable and precise solution of the parameters. Here, all of the above strategies are directly adopted to get the transformation relationship from the LCN local coordinates xyz to the geocentric 3D coordinates XYZ. Specifically, the data in Table 2 are transformed from geocentric 3D coordinates into topocentric coordinates at pillar A1, and the coordinate origin is translated from the geocenter to pillar A1, i.e., to deduct the geocentric distance U_0 of pillar A1 from the transformed dataset. The transformation relationship from xyz to XYZ is expressed as:

$$\mathbf{X} = \mathbf{R}_{TOP}[\mathbf{T} + (1+D)\mathbf{R}_x(R_1)\mathbf{R}_y(R_2)\mathbf{R}_z(R_3)\mathbf{x} + \mathbf{U_0}] \tag{1}$$

where $\mathbf{X} = [X,Y,Z]^T$, $\mathbf{x} = [x,y,z]^T$, $\mathbf{U_0} = [0,0,U_0]^T$, and $\mathbf{T} = [T_1,T_2,T_3]^T$ are the 3D translation parameters. Superscript T indicates the transpose matrix. D is the scale factor. $\mathbf{R}_x(R_1)$ is the rotational matrix around the first coordinate axis by a counterclockwise rotation R_1, and $\mathbf{R}_y(R_2)$ and $\mathbf{R}_z(R_3)$ are analogous. $\mathbf{R}_{TOP}$ is the transformation matrix from the topocentric coordinate frame (TF) at pillar A1 to the geocentric 3D coordinates, which is related to the specific definition of the TF orientation.

The upper ends of the four pillars in the LCN are almost co-planar, which leads to exceptional solutions to the parameters in *Equation (1)* as mathematically right but physically wrong. By application of a simple identification criterion to solutions, the transformation parameters from the LCN local frame to geocentric 3D coordinates are finally determined as follows:

$$\begin{aligned}
&\mathbf{T} = [-0.53, 2.48, 0.77]^T \pm [0.30, 0.30, 0.36]^T \text{ mm},\\
&D = (0.5 \pm 2.4) \times 10^{-6},\\
&\begin{bmatrix} R_1 \\ R_2 \\ R_3 \end{bmatrix} = \begin{bmatrix} 0.0000100 \\ -0.0029992 \\ -0.2682713 \end{bmatrix} \pm \begin{bmatrix} 0.0000038 \\ 0.0000031 \\ 0.0000024 \end{bmatrix} \text{ rad},\\
&U_0 = 6372483.33920 \text{ m},\\
&\mathbf{R}_{TOP} =\\
&\begin{bmatrix} 0.2657010819 & 0.8559418582 & -0.4435836680 \\ -0.4398316729 & 0.5170720796 & 0.7342918793 \\ 0.8578758853 & 0.0000000000 & 0.5138569504 \end{bmatrix}.
\end{aligned} \tag{2}$$

Table 3 shows that the post-fit residual is less than 3 mm in magnitude for all coordinate components, which is in accordance with the expectations of the survey.

Table 3 Post-fit residuals from local to geocentric 3D coordinates.

Pillar	X/m	Y/m	Z/m
	σ_X/mm	σ_Y/mm	σ_Z/mm
A1	0.0005	−0.0025	−0.0008
A2	0.0016	0.0009	0.0005
A3	−0.0003	0.0002	−0.0010
A4	−0.0019	0.0014	0.0012

3.2 Target Intersection Survey

Taking the local coordinates of A1 through A4 as known in order to determine the directions and radial distance of a target connected onto the 65-m antenna, an intersection survey is used to determine the local coordinates of the target. Taking the survey of the vertical axis as an example, the elevation of the antenna is kept unchanged while the azimuth is changed by steps, and an intersection survey of the target is performed at every azimuth. Multiple position determinations of a target describe a circle in space, centered at a point on the vertical axis. With an intersection survey of multiple targets, the position and orientation of the vertical axis can be determined relative to the LCN. The survey of the horizontal axis can be done similarly. The plane holding the horizontal axis could be determined in the LCN by surveying the horizontal axis at more than one azimuth, and by combination with the survey of the vertical axis, the local coordinates of the reference point can be determined.

Intersection surveys of four targets at 11 antenna azimuths were performed on 7 and 8 July 2013 (denoted as v_130707). Surveys of the horizontal axis at azimuths 120, 150, and 188° were performed on 9 and 13 July, denoted respectively as h_130713_120, h_130709_150, and h_130713_188. The local coordinates of the targets were obtained through weighted least squares adjustment of the observations, and the weighted mean of the post-fit residuals are given in Table 4. It is shown that the residuals for the horizontal and vertical direction (H.r. and V.r.) are less than 0.5 as in magnitude. The corresponding positioning uncertainty for targets within 0.2 km (the LCN's geometric scale) would be less than 0.5 mm. The radial distance residual (R.r.) is less than 0.1 mm in magnitude.

Table 4 Weighted mean of the post-fit residuals in the data reduction of the intersection survey of targets.

Session	H.r./as	V.r./as	R.r./mm	Orient.	Azimuth
V_130707	0.40	0.18	−0.05	11	
h_130713_120	0.28	−0.15	0.00	8	120°
h_130709_150	−0.30	−0.02	−0.04	10	150°
h_130713_188	−0.19	0.27	−0.05	9	188°

The usual method of spatial circle fitting is to project the spatial sample points onto the coordinate plane. Data simulations and tests show that the sample points should be as dense as possible and should uniformly cover the spatial circle. Otherwise, a very low noise level would lead to divergence of parameter solutions. In the local survey of the radio antenna, especially in the survey of the horizontal axis, due to the limitations in the structure design and physical dimensions of the working site, the sample points could only cover at most one fourth of a spatial circle. Therefore, the usual method of projecting onto the coordinate plane would not be applicable. In order to get the coordinates of the locus center of a target in the antenna survey, the method that firstly gets the normal direction of the plane holding the spatial circular arc and secondly gets the coordinates of the locus center is adopted in order to suppress the detrimental effects of observation noise and uneven spatial coverage of sample points, and to improve the stability and precision of parameter solutions. Specifically, for some given 3D vectors $\mathbf{r}_1$, $\mathbf{r}_2$, and $\mathbf{r}_3$, suppose all begin at the coordinate origin and end at a spatial circle. Then the unit vectors of the vector products $(\mathbf{r}_2-\mathbf{r}_1)\times(\mathbf{r}_3-\mathbf{r}_1)$ and $(\mathbf{r}_3-\mathbf{r}_2)\times(\mathbf{r}_1-\mathbf{r}_3)$ should be in the direction of the normal vector of the plane holding the circle. In real data analysis due to the observation errors the weighted mean is taken as the normal direction of the plane. Take all the locus points of each target in the survey as vector ends, and then the plane normal direction is deduced. Via coordinate transformation, two-dimensional (2D) circle fitting and the corresponding inverse coordinate transformation, the local coordinates of locus centers (x_c, y_c, z_c) and formal errors $\sigma_{(x_c,y_c,z_c)}$ as well as the plane normal direction vector $\mathbf{n}(n_x, n_y, n_z)$ are deduced.

The post-fit residuals of the spatial circle fit are important indicators of the completeness and quality of the antenna survey. Results show that the distance of the target position to the plane holding the spatial circle and the distance to the fitted circle in the plane are less than 1 mm in magnitude, indicating that the implementation of the survey and the data analysis are reliable.

In order to determine the position and orientation of the spatial line (the vertical or horizontal axis), it is again the intuitive way to project the points onto the coordinate plane and then to perform a 2D line fit. But data simulation and tests show that the parameter solution is not stable and is low in precision in the case of the local survey. Therefore the coordinate transformation method is applied again. That is, taking the average of the normal direction as the temporary z-axis, after the coordinate transformation the resulting ideal coordinates x, y of points should be zero. Taking into account the observation noise, the weighted average is adopted. After the inverse coordinate transformation the coordinates of the ends of the measured segment on the vertical and horizontal axes are deduced. It is then easy to get the coordinates of the foot of the common perpendicular on the vertical axis and the axis offset.

Take the reference point as the intersection of the vertical axis and the plane holding the horizontal axis. The solution procedure of parameters is designed as the following steps.

a Three times, measure vector segments in a survey of the horizontal axis. The vector product of every pair of vectors will be in the direction of the normal of the plane holding the horizontal axis. After normalization, the normal direction is taken as the weighted mean of the three vector products.

b Take the normal direction as the temporary z-axis. After a coordinate transformation, the weighted mean of the resulting z-coordinate component of the end points of the measured segments on the horizontal axis is taken as the z-coordinate of the reference point, denoted as z_w.

c In the temporary coordinate frame, on the vertical axis, the x- and y-components corresponding to z_w are the planar coordinates of the reference point, denoted as x_w and y_w.

d By applying the inverse coordinate transformation to (x_w, y_w, z_w), then the local coordinates of the reference point are determined.

The solutions of the local coordinates of the reference point are as follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 118.8666 \\ -27.8894 \\ 35.2401 \end{bmatrix} \text{m} \pm \begin{bmatrix} 0.03 \\ 0.03 \\ 0.00 \end{bmatrix} \text{mm} \quad (3)$$

By using Equations (1) and (2) the geocentric 3D coordinates of the reference point in ITRF2008 are:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} -2826708.6045 \\ 4679237.0542 \\ 3274667.5314 \end{bmatrix} \text{m} \pm \begin{bmatrix} 0.42 \\ 0.45 \\ 0.43 \end{bmatrix} \text{mm} \quad (4)$$

The reference epoch is the middle epoch of the GPS observations in this survey, UTC 0h 29 June 2013.

The weighted average of the axis offset determined by the length of the common perpendicular of the vertical and horizontal axes at azimuths 120, 150, and 188°, $\bar{f}$, is as follows:

$$\bar{f} = 2.95 \text{ mm} \pm 3.26 \text{ mm} \quad (5)$$

It is shown that at the precision level of 3 mm, the axis offset is not significant, indicating that the framework rigidity of the antenna reaches a very high level.

4 Discussion

This survey lasted only about 20 days, and so the determination precision is limited. However, the precision is absolutely adequate for the establishment of an antenna orientation model and the guidance of antenna orientation, and the survey can act as a historical data archive to study factors affecting the stability of the antenna reference point.

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