Determination of the Telescope Invariant Point and the Local Tie Vector at Onsala using GPS Measurements

Tong Ning, Rüdiger Haas, Gunnar Elgered

Abstract At Onsala Space Observatory, two gimbal-mounted GPS antennas were installed on each side of the 20-m VLBI radio telescope. The coordinates of the GPS antennas estimated for different VLBI telescope angle readings, at different epochs, were used to calculate the invariant point (IVP) of the telescope. The GPS data, with 1-s sampling rate, were recorded for five semi-kinematic observing campaigns. Two different methods, Precise Point Positioning (PPP) and single difference analysis, were used to estimate the GPS coordinates. The results show that the local tie vector between the Onsala IVS and the IGS reference points can be determined with an accuracy of a few millimeters. The single difference data processing gives a better accuracy ($\sim$1 mm) in determining the axis offset of the telescope.

Keywords GPS, invariant point, local tie vector, axis offset

1 Introduction

In order to measure the local tie vector between a GPS and a VLBI reference point, we need to determine the invariant point (IVP) of the VLBI telescope. The IVP is the intersection of the primary axis with the shortest vector between the primary, rotated by azimuth, and secondary axis, rotated by elevation [1]. For the VLBI telescope at the Onsala Space Observatory (OSO), the primary and secondary axes do not intersect, and the IVP is thus the projection of the secondary axis onto the primary axis. Therefore, the IVP can only be measured by indirect surveying methods [2]. In the years of 2002 and 2008, two classical geodetic measurement campaigns were performed at OSO where the local tie vector was determined with very high accuracy on the sub-mm level for both campaigns. The difference of the estimated local tie between the two campaigns is 0.7 mm [3]. However, the whole working time consumed for the classical measurements was also significant.

Based on a model first presented by [4, 5] proposed a modified model in which the telescope axes can be presented in the same three-dimensional Cartesian system as the observed coordinates. This is well suited to measurements obtained by GPS antennas that are attached to the telescope structure. Following this approach, in the summer of 2013 two gimbal-mounted GPS antennas were installed on each side of the 20-m VLBI radio telescope at OSO. GPS data were acquired, with a sampling rate of 1 s, for five semi-kinematic observing campaigns. The data were analyzed using two different processing methods, Precise Point Positioning (PPP) and single difference analysis. Both the local tie vector between the IGS and the IVS reference points and the axis offset of the telescope were determined.

2 Methodology

We used a model developed for the Metsähovi telescope in order to calculate the IVP of the VLBI telescope from the time series of estimated GPS coordinates [5].

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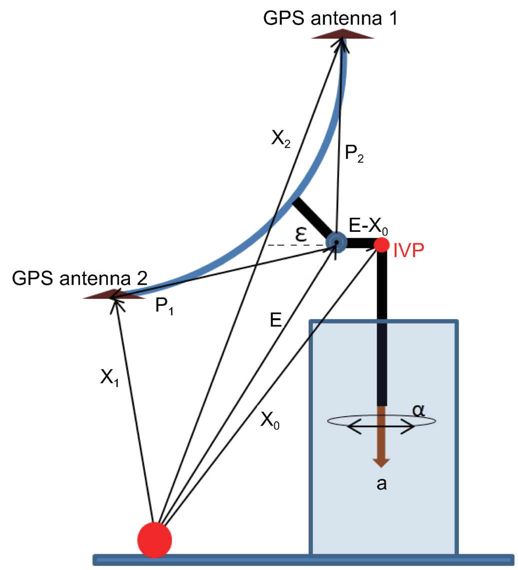

Fig. 1 The schematic diagram of the model parameters in a local reference frame. Note that the actual positions of the GPS antennas are on the sides of the telescope (see Figure 2).

$$X_n = X_0 + R_{\alpha,a}(E - X_0) + R_{\alpha,a} R_{\varepsilon,e} P_n \quad (1)$$

where the coordinate vector of the GPS antenna X_n (n=1, 2) in an arbitrary reference frame is determined by the sum of three vectors (see Figure 1): the coordinate vector of the IVP of the telescope X_0, the horizontal axis offset vector $E - X_0$ rotated by the angle α about the azimuth axis a, and the vector from the eccentric point E to the antenna point P_n (n=1, 2) rotated about the elevation axis e by the angle ε and about the azimuth axis by the angle α.

The input data to Equation 1 are the estimated coordinates of the two GPS antennas, together with the azimuth and the elevation angles of the VLBI telescope for each time epoch.

Since the axes are unit vectors, we have two condition equations for the azimuth axis and the elevation axis.

$$a_x \cdot a_x + a_y \cdot a_y + a_z \cdot a_z = 1 \quad (2)$$

$$e_x \cdot e_x + e_y \cdot e_y + e_z \cdot e_z = 1 \quad (3)$$

Meanwhile the offset vector $E - X_0$ is perpendicular to both the azimuth and elevation axes, so we have two more condition equations:

$$(E - X_0)_x \cdot a_x + (E - X_0)_y \cdot a_y + (E - X_0)_z \cdot a_z = 0 \quad (4)$$

$$(E - X_0)_x \cdot e_x + (E - X_0)_y \cdot e_y + (E - X_0)_z \cdot e_z = 0 \quad (5)$$

All unknown parameters in Equation 1 were estimated as corrections to their approximate values starting from a priori values by solving a least squares mixed model including all condition equations and the main function. The solution is reached by iterations until convergence is found, i.e., the correction of the IVP coordinates to the previous estimates are less than 0.1 mm.

3 GPS Observations and Data Processing

We first mounted two Leica AS10 multi-GNSS antennas on both sides of the telescope dish using two rotating holders. Both holders have counterweights in order to make the two antennas point to the zenith regardless of the position of the VLBI telescope (see Figure 2). Then we conducted five observing sessions in which the movement of the VLBI telescope was scheduled for different azimuth and elevation angles. The duration of each session was 24 hours. For the first two sessions (July 9 and 10, 2013), the telescope was positioned at elevation angles 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 55°, 65°, 75°, and 85°. For each elevation angle, the telescope was positioned at four different azimuth angles with an interval of 90°. In total, we had 48 telescope positions. After every 30 minutes, the telescope moved to a new position. For the later three sessions (September 21–23, 2013), the telescope moved through the same elevation angles as for the first two sessions, but with four more azimuth angles for each elevation angle with an interval of 45°, which gave us a total of 96 telescope positions.

The sampling rate of GPS measurements was 1 Hz. We first processed the GPS data using GIPSY/OASIS II v.6.2 where the Precise Point Positioning (PPP) strategy was implemented for a kinematic solution. The GPS orbit and clock products were provided from a reprocessing of existing archives. In a kinematic solution, it is difficult to estimate tropospheric delay with a high accuracy. Considering the short distance (∼78 m) between the IGS station (ONSA) and the VLBI telescope, the Zenith Wet Delay (ZWD) and its horizontal gradients estimated from ONSA should be approximately the same as the ones estimated from the two GPS antennas on the telescope. Therefore, we first estimated ZWD and gradients from the data obtained at

(a) (b)

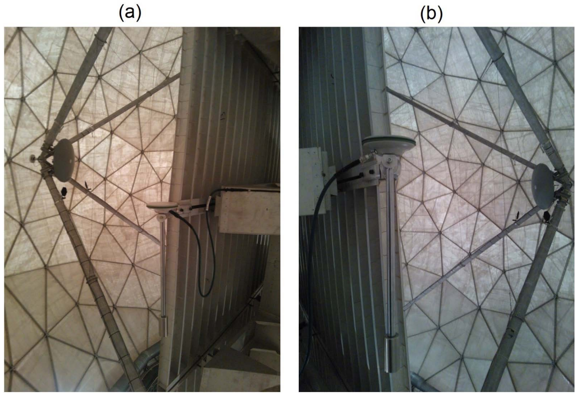

Fig. 2 The installation of the GPS antennas on (a) the left side and (b) the right side of the 20-m radio telescope.

ONSA using a static solution. Thereafter, the ONSA-estimated ZWD and gradients were input to the data processing for the two GPS antennas, while the hydrostatic delay was modeled with a scale height parameter given by the nominal position without adjustments.

Besides PPP, we also processed differenced GPS data considering that the two GPS antennas on the telescope and the IGS station ONSA have a common ionospheric delay and the common delay of the neutral atmosphere. We took advantage of this feature in our data processing by forming two baselines (GPS1–ONSA and GPS2–ONSA) in order to avoid the estimation of those common parameters. As a start, we used single differenced observations from only the L1 frequency in order to achieve a low level of noise where the baseline coordinates were solved after the ambiguities were fixed as floats.

For both processing methods, PPP and single difference analysis, the absolute calibration of the Phase Center Variations (PCV) of the GPS antennas is necessary. However, it is complicated to implement in our case, because the orientation of the GPS antenna on the radio telescope varies while the telescope is rotating. The true azimuth angle of the satellite seen from the GPS antenna changes with the VLBI telescope azimuth. If we would apply the standard absolute PCV calibration directly, it would cause systematic errors in the estimated GPS coordinates and the resulting IVP. In order to solve this problem, we calculated the orientation of the two GPS antennas based on the position of the telescope for each epoch. Then the true azimuth angle seen in the direction of the GPS satellite was calculated, and the corresponding PCV correction reading from the standard IGS table was applied in the RINEX files. Eventually, the corrected RINEX files were used in the GPS data processing.

Finally, the estimated GPS coordinates and the telescope angle reading (azimuth and elevation) for each epoch were input to the linearized least squares mixed model with condition equations (see Equations 1 to 5). After the first two iterations, residuals larger than 50 cm were removed, and after another two iterations, the threshold value was set to 25 cm. Then, after two more iterations, the data points with residuals larger than three times the standard deviation were removed. Thereafter, we let the model run for another two iterations in order to reach convergence. On average, about 50% of the input data points were removed as outliers.

4 Results

Figure 3 depicts the estimated baseline between the two GPS antennas mounted on the VLBI telescope for two different sessions in which the telescope moved to 48 positions (July 9) and to 96 positions (September 23), respectively. The mean value and standard deviation given by PPP are 20.7778 m and 2.7460 m, and 20.7590 m and 2.8292 m for the two sessions, respectively. The corresponding values for the single difference data processing are 20.7465 m and 0.0384 m, and 20.7450 m and 0.0496 m. It is clear that the baseline estimated by single difference analysis has a much smaller variability. Figure 3 also gives the number of satellites, with an elevation cutoff of 15°, included in the data processing for each epoch. It indicates that the variations for both methods are correlated to the number of observed satellites.

The estimated local tie vector between the IGS and the IVS reference points together with the estimated axis offset of the VLBI telescope are shown in Figure 4. For comparison, we also calculated the local tie vector in ITRF2008 coordinates referring to the epoch of July 1, 2013, while for the axis offset we used values given by two local surveys as references [3]. The results for the estimated east and north components of the local tie vector show no significant differences between the two processing methods in terms of the mean value and the standard deviation over five sessions. For the vertical component, the single difference data processing gives

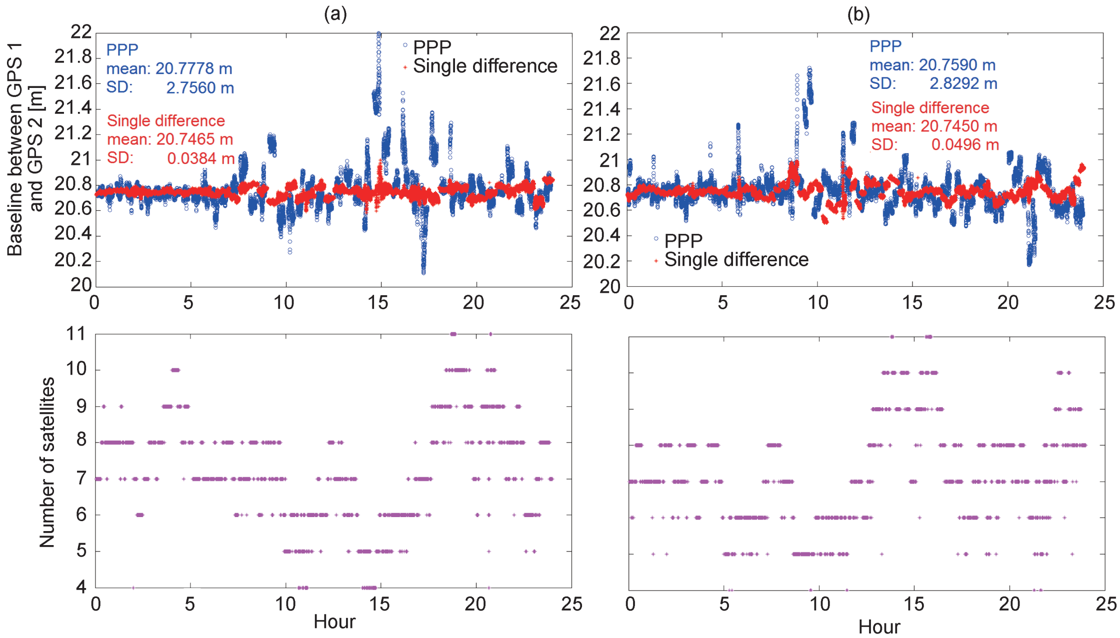

Fig. 3 The baseline between the two GPS antennas on the sides of the telescope, estimated from both PPP (blue circles) and single difference analysis (red stars), for two sessions in which (a) the telescope moved for 48 positions and (b) the telescope moved for 96 positions.

a smaller standard deviation (0.0027 m) than the one derived by PPP (0.0079 m). The differences between our estimated and the ITRF local tie vector are within 0.007 m. The comparison of the axis offset (see Figure 4d) shows a much better result for the single difference data processing, which gives a mean axis offset of −0.005 m with a standard deviation of 0.0021 m over five sessions. A difference of about 0.001 m is seen with respect to the two local surveys (−0.0060 m for 2002 and −0.0062 m for 2008). The result from the PPP data processing shows a significant difference, the mean axis offset of −0.0224 m with a standard deviation of 0.0077 m, from the reference values.

5 Conclusions and Future Work

We carried out five semi-kinematic observing sessions in which the coordinates estimated for two GPS antennas mounted on the rim of the main reflector of the Onsala 20-m radio telescope for different telescope angle readings, at different epochs, were used to calculate the local tie vector between the Onsala IGS and the IVS reference points. Two different methods, PPP and single difference analysis, were used for the GPS data processing. The result shows no significant differences in the estimated local tie vector using the two different processing methods, while the mean difference between the estimated local tie vector and the ITRF calculated local tie vector is within 0.007 m. We also estimated the axis offset of the VLBI telescope, where the single difference data processing gives a better result with a difference of 0.001 m from the reference axis offset given by two local surveys, while the difference seen from the PPP result is at the centimeter level.

As shown in Figure 3, larger variations in the estimated baseline, seen for both processing methods, are correlated with the number of satellites. For future work, in order to increase the number of observables, measurements from other GNSS, e.g., GLONASS, will be included.

Due to the blockage by the telescope, a significant number of cycle slips occurred in the GPS phase measurements, and this introduces more ambiguity parameters. Therefore, a higher sampling rate of GPS measurements, e.g., 10 Hz or 20 Hz, would be good in order to have more data available for the ambiguity estimation.

The final goal of the work is to use only GPS measurements obtained during standard geodetic VLBI sessions, in which no extra telescope time will be re-

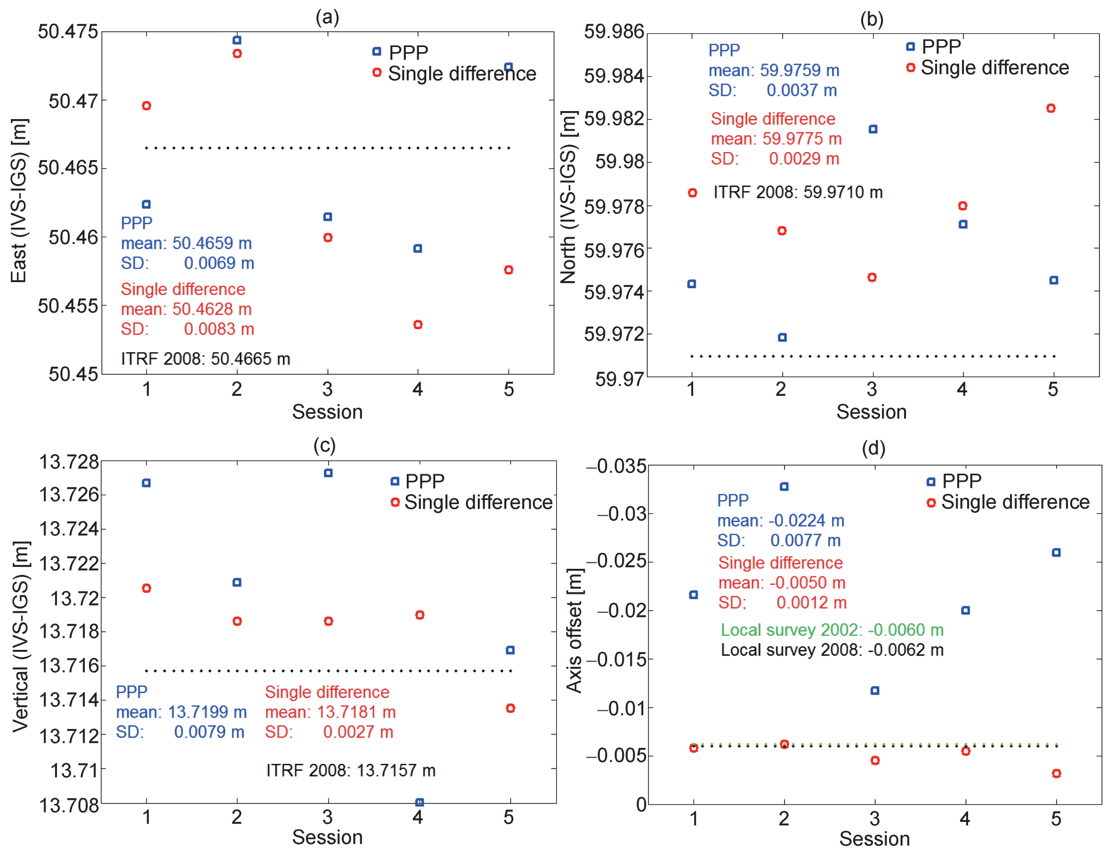

Fig. 4 The estimated local tie vector between the IGS and IVS reference points shown for (a) East, (b) North, (c) Vertical components, and (d) the axis offset of the telescope, given by both PPP (blue squares) and single difference data analysis (red circles). The calculated ITRF local tie vectors are given by black dotted lines, while the axis offsets obtained from two local surveys are given by black and green dotted lines.

quired. In that case, the GPS antenna will only be static for very short observational time spans, in which the ambiguities, when estimated as floats, become poorly separable from the baseline coordinates. This will result in a poor accuracy of the estimated GPS coordinates. In order to solve this problem, a double difference data processing with ambiguity fixing to integer values will be used.

References

1. J. Dawson, P. Sarti, G.M. Johnston, and L. Vittuari. Indirect approach to invariant point determination for SLR and VLBI systems: an assessment, *J. Geod.*, 81(6–8), doi:10.1007/s00190-006-0125-x, 433–441, 2007.
2. C. Eschelbach and R. Haas. The 2002 Local Tie Survey at the Onsala Space Observatory, In: Proc. IERS Workshop on site co-location, edited by B. Richter, W. Schwegmann, and W.R. Dick, IERS Technical Note, 33, Verlag des Bundesamts für Kartographie und Geodäsie, 55–63, 2005.
3. M. Lösler. New mathematical model for reference point determination of an azimuth-elevation type radio telescope. *J. Surv. Eng.*, 135(4): 131–135, 2009.
4. M. Lösler and R. Haas. The 2008 Local-tie Survey at the Onsala Space Observatory, In Charlot P., A. Collioud, and G. Bourda, (Ed.) Proceedings of the 19th European VLBI for Geodesy and Astrometry Working Meeting, March 24–25, 2009, Bordeaux, France, p. 97–101, 2009.
5. U. Kallio and M. Poutanen. Simulation of Local Tie Accuracy on VLBI Antennas, In IVS 2010 General Meeting Proceedings, (Eds. Dirk Behrend and Karen Baver), NASA/CP-2010-215864, p. 360–364, 2010.
6. G. Blewitt. Carrier phase ambiguity resolution for the Global Positioning System applied to geodetic baselines up to 2000 km, *J. Geophys. Res.*, 9j, (B8), 10,187–10,203, 1989.