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Validation of GNSS-based reference point monitoring of the VGOS VLBI telescope at Metsähovi

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ABSTRACT

VLBI telescope reference point, the closest point in the telescope primary axis from the secondary axis, is typically determined indirectly by observation of points co-rotating with the telescope. We have previously measured telescope reference point indirectly with two GPS-antennas attached on the edge of the dish of the Aalto University Metsähovi radio telescope in 2008-2015. Now we have applied the same technique to the new VGOS-telescope of the FGI Metsähovi geodetic research station. The reference point of the VGOS antenna was estimated using post-processed trajectory coordinates of two GNSS antennas. The antennas are attached on the edge of the radio telescope dish with gimbals where a counterweight with shock absorber act as compensators to ensure zenith pointing at all telescope elevation angles. In addition, spherical prisms are attached to the structure of the telescope for tachymetric reference point determination. One purpose of this study is to evaluate the limit values and uncertainties of the compensator assembly by simulations and precise tachymeter measurements. To ensure that the compensation error is nearly constant or can be modelled, we have measured the residual tilt of the GNSS antennas with different VLBI antenna elevations. The results indicate a need to apply the corrections or to improve the compensator design. We aim to improve the counterweight and dampening so that no extra model corrections to trajectory coordinates are needed. For final assurance of our GNSS-based reference point monitoring performance, we have compared the reference point coordinates determined by simultaneous tachymetric and GNSS data. Our results and simulations showed that, with a small compensation error, the influence on reference point coordinates is marginal but the axis offset will be compromised, provided that the compensating angle bias is nearly constant. Preliminary reference point estimates show a rather good agreement of simultaneous GNSS-based and tachymetric reference points. The final results will be achieved as part of the 18SIB01 EMPIR GeoMetre project, funded from the EMPIR programme and co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

I. INTRODUCTION

The first published work using a GPS antenna on the structure of the VLBI telescope for the determination of local ties or axis offset was done by (Combrinck and Merry, 1997). At the Hartebeesthoek Radio Astronomy Observatory, the GPS antenna was attached to the apex of the radio telescope quadripod with a gimbal having the axis aligned to the antenna's nominal phase centre.

Promising results for GPS-based local ties were achieved at the observatory of Medicina in 2001-2006. Two GPS antennas with compensators were attached on the left and right sides of the telescope dish. The quality assessment, results, and comparison with tachymeter measurements were reported in Abbondanza *et al.*, (2009a; 2009b). The coordinates of rotating points were based on Bernese 5.0 processing and the local GPS network was combined with a larger one. The reference point estimation was based on 3D circle fittings. The effect of the orientation of vectors to the combination of Terrestrial Reference Frames was also studied.

At Metsähovi, Southern Finland, the first experiments with corresponding, locally designed compensators and GPS antennas on the Aalto University radio telescope were performed in 2008 (Kallio and Poutanen, 2012). In contrast to the static method in Medicina, at Metsähovi the GPS points were measured, for the first time, simultaneously with the VLBI campaign (Kallio and Poutanen, 2012). The effective detection of outliers of trajectory points was developed and a new model for reference point estimation was introduced.

Two Ashtech Dorne Margolin choke ring antennas were used in the first GPS-based local tie campaigns but they were later changed to Leica AX2012 antennas which were lighter and more suitable for the purpose. In both cases, the antennas were individually calibrated and the phase centre offset (PCO) and variation (PCV) were taken into account. In spring 2009 also the static GPS was tested with Bernese processing. The results showed that the kinematic approach was more suitable and even more precise than the static one in the Metsähovi case (Kallio and Poutanen, 2013).

The GPS-based local tie measurements were continued regularly at Metsähovi simultaneously with geodetic VLBI campaigns in 2009-2015 (Jokela *et al.*, 2016). In this case, the trajectories of GPS antennas were processed with commercial software and the PCO and PCV corrections were included in the RINEX file. The first Metsähovi system was validated in 2015 in the EMPR SIB60 campaign with simultaneous tachymeter monitoring, GPS-based monitoring, and the VLBI campaign (Kallio *et al.*, 2016) and (Jokela *et al.*, 2016).

A similar type GNSS local tie system was used at Onsala Space Observatory 20m telescope in 2013. In-house software was used, and in addition, the hydrostatic part of the tropospheric time-delay differences between the permanent GNSS station and the rotating GPS antennas with varying heights were corrected for. The mathematical model for estimating the reference point was the same as in (Kallio and Poutanen, 2012). Both static and kinematic strategies were tested and results of local tie vectors were reported (Ning *et al.*, 2015).

The new VLBI Global Observing System (VGOS) compliant telescope at Metsähovi, constructed in 2018, was equipped with two NovAtel NOV850 GNSS antennas in March 2020. Both antennas were individually calibrated. The new design of compensators includes stabilisation. The rotating points were processed with RTKlib (Takasu, 2013), and the final processing after troposphere and PCC corrections were applied in the RINEX file.

One of the activities in the 18SIB01 EMPIR GeoMetre project (GeoMetre, 2019), funded from the EMPIR programme and co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme, was to investigate the influence of the compensator as this was not studied in the previous work. The functional or installation error of the compensation system and its influence on the reference point coordinates are discussed in Section IV. The principles of GPS processing are presented in Section V B, and validation of the GPS-based local ties is shown in Section VII.

In this paper, the acronym "GNSS" was used when discussing generally the method or if the receiver and antenna have been capable to observe GNSS. In our experiments, we used GPS-only observations and the acronym "GPS" is used.

II. Principle of compensator

The gimbal or compensator corrects the GNSS antenna to normal position with a counterweight and bearings (Figure 1) and thus compensates for the rotation of the radio telescope dish around the elevation axis. The counterweight keeps the GNSS antenna axis perpendicular to the gimbal axis and horizontal line, which is perpendicular to the gimbal axis. If the gimbal axis is collinear with the elevation axis of the telescope and the elevation axis is on the horizontal plane (perpendicular to the plumb line), then the gimbal compensates for the elevation angle.

Figure 1. GNSS antenna on the left side of the VLBI-antenna with the compensator. The black Thorlabs plate was installed by the manufacturer of the VLBI telescope.

The rotation of the telescope around the azimuth axis changes GNSS antenna orientation and it is taken into account by applying the phase centre offsets (PCO) and phase centre variations (PCV) from the calibration tables of the GNSS antenna.

The compensator should be reliable, react quickly, and be stable. Because the angular velocity of the VGOS-telescope is rather high, maximum speed 12°/s in azimuth and 6°/s in elevation, we decided to install a damping system to stabilise the counterweight. We use a shock absorber, originally designed for snowmobiles.

A question arises, whether it would be better to let the GNSS antenna rotate with the telescope without any active compensation. If we have the GNSS antenna in a normal position when the telescope elevation is at zero, then when the telescope points to the zenith the attitude of the GNSS antenna will be rather bad for tracking signals from satellites, and probably a good quality position solution cannot be achieved.

III. Methods

Two methods were used to investigate the influence of compensation error on the reference point coordinates of the VLBI telescope and the uncertainties of the GNSS-based local tie vectors. The limit values of installation and functional errors of the compensator were obtained by simulation. On the other hand, real GPS observations were used for estimating the reference point and to compare the results with the simultaneous tachymeter determination.

A. *Simulation*

In the simulation, the errors due to the installation and compensation are added to the "perfect" GNSS antenna coordinates. The antenna parameters are then estimated using these erroneous coordinates and compared with the results of the perfect antenna. In addition, the random effect of compensation is included. The simulated cases are:

- Case 1: Extreme case.
- Case 2: No compensation angle basis error.
- Case 3: No installation error.
- Case 4: Basis compensation error compared to real case.
- Case 5: Only random part of compensation angle error.

The simulation parameters for installation, compensation, and random errors are listed in Table 1.

Table 1. Parameters in simulation cases. eRight is compensation angle error in the right side, eLeft the compensation angle error in the left side, ±eRand the random part of compensation, eInst error angle in installation

	eRight rad	eLeft rad	eRand rad	eInst rad
Case 1	0.175	0.175	0.035	0.050
Case 2	0	0	0.035	0.087
Case 3	0.175	0.175	0.035	0
Case 4	0.087	0.122	0.035	0.170
Case 5	0	0	0.035	0.170

B. *Comparing the GPS local tie with the tachymeter local tie*

The actual measurements were used to validate the functionality of the current installation of the compensation system. With the real GNSS trajectories, it is hard or nearly impossible to separate the contribution of error sources of GNSS measurement and processing from the contribution of compensation errors. The local tie vector based on the precise tachymeter measurements can be used as a reference for the GNSS local tie vector, especially if the measurements are performed simultaneously.

In our experiment, simultaneous measurements with GPS and tachymeter were performed on the rotating part of the telescope (Figure 2). The telescope was stopped for 40 s in each position for the tachymeter measurements. The GPS measurements were processed to the coordinates at each telescope position. The coordinates of the prisms in the tachymeter measurements were calculated in a 3D-network adjustment as a part of the local network. The reference point estimation was performed independently for both GPS and tachymeter data sets.

IV. Error Sources in Simulation

The errors of the compensation system can be handled as an error of the functionality of the system and as installation errors of the system. Even if we had a perfect calibration table for GNSS antennas and we used it for correcting the phase observation to the antenna reference points (ARP) of the antenna, the correction would be inaccurate due to the errors in the compensator axis direction or actual angle of the compensation. That is why we need to handle the PCC in connection with the compensation.

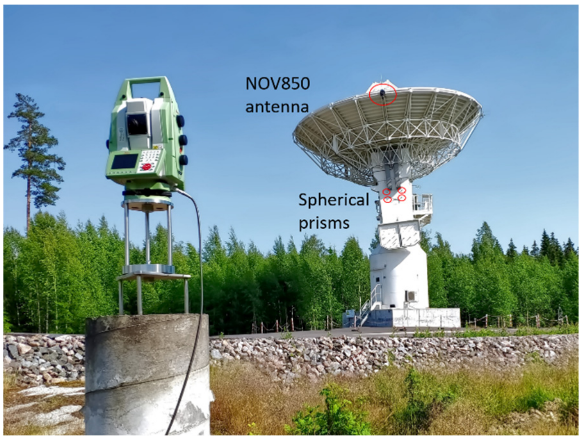

Figure 2. Simultaneous tachymeter and GPS local tie monitoring.

A. *Perfect errorless case*

In our perfect errorless telescope, we have two axes that are perpendicular to each other. In an az-el-type telescope, they are the azimuth axis and elevation axis. The azimuth axis is the primary axis around which the elevation axis rotates. In a perfect telescope, the axes intersect; there is no axis offset. The azimuth axis is perfectly vertical. The ARP of the GNSS antennas are attached to the compensator axis which is collinear with the elevation axis. The counterweight of the compensator turns the GNSS antenna axis to align it with the plumb line. We have a perfect model for GNSS antenna phase centre corrections (PCC) and we correct GNSS observations to the ARP without errors.

The errorless coordinates at antenna position azimuth α and elevation β are calculated as (Kallio and Poutanen, 2012), Eq. (1).

$$X_{\alpha,\beta} = X_0 + R_{\alpha,a}(E - X_0) + R_{\alpha,a}R_{\beta,e}p \qquad (1)$$

where $X_{\alpha,\beta}$= (3x1) coordinates of the point in antenna position α, β
X_0= (3x1) coordinates of the reference point
$R_{\alpha,a}$ = Rotation matrix around azimuth axis a by angle α
E = (3x1) Coordinates of the eccentric point in elevation axis in zero position
$R_{\beta,e}$= Rotation matrix around elevation axis e in zero position by angle β
p = Vector form eccentric point to the prism or ARP in zero position

B. *The direction of the compensator axis*

The direction of the compensator should be collinear with the elevation axis. Inaccuracies in the installation of the compensator may cause an error in the direction of the GNSS antenna supporting axis. The misalignment of the compensator axis and thus the direction of the GNSS antenna axis change in rotation around the elevation axis (Figure 3) even with a perfect compensator. Also the angle of the incoming signal in the GNSS antenna coordinate system changes.

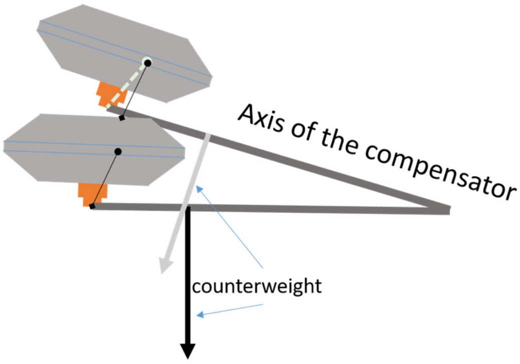

Figure 3. The misalignment of the compensator affects the elevation-dependent change in the direction of the compensator axis.

The PCC of the GNSS antenna is applied with the assumption that the antenna axis points to the zenith. The errors propagate to the estimated reference point coordinates, axis offset, and the other parameters in estimation. The direction error is systematic by nature and modelled in simulation as limit values (Table 1).

C. *Compensation angle*

The compensation angle is opposite to the elevation angle. If the shock absorber or bearings work improp¬erly, they generate an angular error (Figure 4). The GNSS antenna remains in the wrong attitude if there is a compensation angle error. Overcompensation might also occur. In the simulation example, the limit values (Table 1) for a basic constant compensation angle error are used. The possible changes to that are modelled by a random angle with uniform distribution.

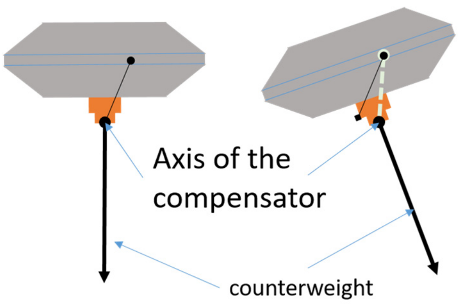

Figure 4. The GNSS antenna remains in the wrong attitude if there is a compensation angle error.

D. *PCC correction*

The phase centre of the GNSS antenna changes every epoch due to the change of the elevation and azimuth of the satellites. PCC also depends on the attitude of the GNSS antenna. In our case, the VLBI telescope rotates moving the GNSS antennas with it, thus the attitude of them changes with the telescope elevation and azimuth positions. With real observations, we correct phase observations according to the antenna orientation and the calibration table for every epoch, every frequency, and every satellite during the GNSS data processing. We do it before estimating the trajectories and generate a new RINEX-file with corrected observations. When the correction is applied it is assumed that the compensation is perfect due to rotation around the elevation axis.

We do not simulate the phase observations of GNSS but start from perfect trajectories. Thus, we need to proceed differently with PCC than in the case of real observations. We generate an error by applying the perfect correction to the incorrectly compensated case. In simulations we rotated the right and left antenna PCO vectors for L1 [0.0002, 0.00048, 0.05192] m and [0.00024, -0.00012, 0.05147] m. Before the compensation (situation if no compensator is available) the GNSS antenna rotates around the elevation axis with the telescope. In compensation, it turns around the compensator axis which has an axis direction error. Moreover, the full compensation does not occur due to the shock absorber errors. Thus the GNSS antenna does not stop at the position of the perfect case. In the simulation, we calculate trajectory points with these axis directions and compensation angle errors and still apply the PCO corrections of the perfect case. After that, the generated point coordinates are the observations for reference point (RP) estimation in simulation.

V. Actual Measurements

A. *Tachymeter measurements*

Monitoring measurements of the reference point of the VLBI telescope were performed with a robot tachymeter TS50 from two concrete pillars and a 3 m steel mast near the telescope. Four prisms on the counterweight of the VLBI telescope were measured in several telescope angle positions. The timetable of tachymeter measurements was calculated before the measurement to synchronise the observations with the movement of the telescope. An in-house software controlled the automated measurements. Telescope movements were predefined in a schedule covering the antenna positions that allow visibility to the prisms. The movement of the telescope was controlled with another in-house software. The angle and distance measurements to the prisms were the observations in the 3D adjustment and their coordinates were estimated as a part of the local network in the global frame. The orientation of the network comes from the GPS network around the area. The coordinates were then used as observations in RP estimation.

The behaviour of the counterweights during the movement of the telescope was visually inspected and the directions of the counterweights of the GNSS antenna compensators were also measured with the tachymeter using prisms positioned on the counterweight.

B. *GPS measurements*

The same VLBI antenna positions were simultaneously tracked with GPS and tachymeter measurements. In-house software was used to control the data logging of GNSS receivers and the movement of the telescope. In our experiment, we collected only GPS observations. GPS-only data was used since it was sufficient for this purpose and simplified the analysis. The coordinates of GNSS antennas were estimated and used as observations in RP estimation. The local tie vector was compared with the tachymetric RP.

The procedure for processing the GPS observations is as follows:

1. Processing trajectories with RTKlib (Takasu, 2013) using basic settings.
2. Calculating corrections using troposphere model GMT3 (Landskron and Böhm, 2018) for every single observation by using preliminary coordinates calculated in step 1.
3. Calculating corrections using PCO and PCV of the calibration tables and VLBI-telescope antenna positions.
4. Applying corrections to the observations.
5. Writing RINEX with corrected observations.
6. Processing trajectories with RTKlib without tropospheric corrections and PCC corrections.
7. Compiling trajectory coordinates and related VLBI antenna positions to the input files for RP estimation.
8. Estimating the RP and other related parameters.

To see the effect of the corrections on the RP coordinates, the RP estimation was performed after steps 1, 2, and 7.

VI. Results of simulation

A final simulation was performed with the extreme value 0.050 rad for the directions of the compensation axes and 0.175 rad (10°) for the basic compensation error with uniform distribution from –0.035 rad to 0.035 rad. The direction error was applied in four directions for both compensators to obtain 16 different directions in each VLBI antenna position.

The error in compensation or compensator axis direction propagates mainly in the axis offset parameter: In the extreme case, a -1 cm axis offset was obtained (Case 1 in Table 1). The height of the RP is affected in the extreme case about -1 mm. In the horizontal components, the effect was less than 0.1 mm. The numerical values of the input parameters in simulations are listed in Table 1 and the results in Table 2.

VII. Results of real measurements

The comparison of tachymetric-based local tie and GPS-based local tie is presented in Table 3.

Table 2. Influence of compensator errors on RP

	dN mm	dE mm	dU mm
Case 1	0.00	0.00	-0.86
Case 2	-0.01	-0.01	-0.08
Case 3	0.02	0.01	-0.88
Case 4	0.00	0.01	-0.36
Case 5	0.01	0.02	0.00

Table 3. Difference between GPS local tie and tachymeter local tie (GPS minus tachymeter)

	dX [mm]	dY [mm]	dZ [mm]	dN [mm]	dE [mm]	dU [mm]
Step 1	-2.69	-0.63	-3.28	+0.72	+0.53	-4.19
Step 2	-1.64	-0.24	-0.92	+0.92	+0.46	-1.59
Step 7	-0.80	-0.02	+0.56	+0.92	+0.31	+0.12

The varying height due to the change of the elevation angle of the telescope causes the difference in troposphere corrections influencing 2.6 mm in height of the RP. The full PCO and PCV corrections at the permanent GNSS point and the rover points cause a 1.6 mm change in height of the RP. The RTKlib software can read antenna calibration tables but apply only the elevation-dependent corrections. In steps 1 and 2, RTKlib was allowed to do the PCC, and for rover antennas the North and East offsets were changed to zeros in the calibration tables. In step 7 full PCC was applied with an in-house OCTAVE function before the RTKlib processing.

VIII. Comparison of simulation and real data cases

The compensator counterweight directions were determined with tachymeter measurements. The results showed that the left side counterweight was stuck to the position differing about 0.12 rad from the plumb line and at the right side almost the same. A visual inspection confirmed this. The shock absorber inhibited the free movement of the counterweight. There is a trade-off between the dampening power of the shock absorber and the counterweight being able to settle at the plumb line quickly enough to follow the antenna movement.

Simulations and the real case observations showed equally well that the uncertainties in the compensator axis direction and compensation angle influence the axis offset parameter but not significantly the RP coordinates. The simulation was repeated with the inspected compensation error values with 0.017 rad for installation error. The result agrees with the real data case. However, the influence of the errors on the axis offset in the simulated case was more than the difference between the real case tachymeter-based and GPS-based axis offset.

IX. Discussion and conclusion

The study of the compensator system shows that sufficient installation accuracy of the compensator axis direction is rather easy to achieve. The antenna support with bearings forms the basis of the compensation system. In addition to the compensator bearings, some kind of dampening is needed. New fast-moving VGOS telescopes and the future geodetic VLBI campaigns with short tracking times may otherwise cause undesirable swinging of the GNSS antennas.

The GNSS-based local ties give an alternative for the rather time-consuming tachymeter measurements. The concept has been confirmed first in Medicina, then at Metsähovi and Onsala, and now again at Metsähovi with the new VGOS telescope. The GPS-based local tie as a system is described comprehensively in (Abbondanza *et al.*, 2009a), (Kallio and Poutanen, 2012), and (Ning *et al.*, 2015), thus it is possible to install a similar system to new VGOS telescopes and apply necessary corrections to the GNSS observations before or during the processing.

The new compensator with the shock absorber at Metsähovi needs further development. Visual inspection and tachymeter measurements of the prisms on the counterweights show that the counterweights of the compensators remain in the tilted position due to the damping. However, the comparison of the local tie vector to the tachymeter-based local ties shows that the system otherwise works and agreement is good enough if only the reference point is considered. Further development to stabilise the quick movements of the compensator will continue.

The orientation of the GNSS-based vector depends on the satellite orbits and other uncertainty sources, affecting mainly in the vertical direction (like errors in antenna calibration tables, multipath, and errors in tropospheric corrections). Individual calibrations of GNSS antennas are necessary. The changes in the height difference between permanent and rotating antenna due to the VLBI antenna elevation positions should be taken into account when correcting for the effect of the troposphere.

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References

Abbondanza, C., M. Negusini, P. Sarti, and L. Vittuari,(2009a). VLBI–GPS eccentricity vectors at Medicina’s observatory via GPS surveys: reproducibility, reliability and quality assessment of the results. Edited by H. Drewes. *International IAG symposium, Geodetic reference frames*, Munich, 9–14 O.

Abbondanza, C., Z. Altamimi, P. Sarti, M. Negusini, and L. Vittuari, (2009b). Local effects of redundant terrestrial and GPS-based tie vectors in ITRF-like combinations. *Journal of Geodesy*, 83, 1031.

Combrinck, W. L., and C. L. Merry, (1997). Very long baseline interferometry antenna axis offset and intersection determination using GPS. Journal of Geophysical Research 102.

GeoMetre, (2019). Available in: https://www.ptb.de/empir2018/geometre/home, (accessed 13. 01. 2022).

Jokela, J., U. Kallio, H. Koivula, S. Lahtinen, and M. Poutanen, (2016). FGI’s contribution in the JRP SIB60 ''Metrology for Long Distance Surveying''. Proceedings of the 3rd Joint International Symposium on Deformation Monitoring (JISDM) 30.3-1.4, 2016, Vienna.

Kallio, U., M. Lösler, S. Bergstrand, R. Haas, and C. Eschelbach, (2016). Automated Simultaneous Local Ties With GNSS and Robot Tachymeter. IVS2016 proceeding.

Kallio, U., and M. Poutanen, (2012). Can We Really Promise a mm-Accuracy for the Local Ties on a Geo-VLBI Antenna. In Geodesy for Planet Earth, 35–42. Springer Science Business Media.

Kallio, U., and M. Poutanen, (2013). Local Ties at Fundamental Stations. In Reference Frames for Applications in Geosciences, 147–152. Springer Science Business Media.

Landskron, D., and J. Böhm, (2018). VMF3/GPT3: refined discrete and empirical troposphere mapping functions. Journal of Geodesy 92, pp. 349–360.

Ning, T., R. Haas, and G. Elgered, (2015). Determination of the local tie vector between VLBI and GNSS reference points at Onsala using GPS measurements. Journal of Geodesy 89, pp. 711-723.

Takasu, T., (2013). RTKLIB ver. 2.4.2 Manual.