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Proof-of-Concept Studies for a Local Tie Monitoring System

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Abstract

We present preliminary results of proof-of-concept studies for an automatic monitoring system of local site ties. The system is based on the usage of robotic total stations. A set of tests were performed with a Leica TCA2003 total station on the local network of Goddard's Geophysical and Astronomical Observatory (GGAO) and the 5-m VLBI antenna at this site. Both the TCA2003 and the VLBI antenna are controlled from a Matlab-coded control program. Running specific observational programs, data were collected that indicate that the reference point of the VLBI antenna can be automatically determined with an accuracy of 1 mm or better.

1. Introduction

Monitoring the local ties between different techniques at co-located sites is an important task for the Global Geodetic Observing System (GGOS). In order to be able to combine the various space geodetic techniques, local site ties need to be known with high accuracy. Since the GGOS accuracy goal is 1 mm (and 0.1 mm/yr), the tie needs to be known at least at this level of accuracy, probably better. Hence, it is necessary to monitor the position and the stability of the invariant reference point (IVP) of the different techniques and to determine the local ties between them. To date, this task has been done by manual measurements, which are costly in terms of time and manpower. The surveys need to be repeated on a regular basis (e.g., semi-annually or annually).

In this paper we address the prospects of an automatic monitoring system to replace manual measurements. The system is based on robotic total stations. These instruments constitute a proven technology that is capable of providing the required high accuracy at a relatively low cost. A demonstration system was set up at the Goddard Geophysical and Astronomical Observatory (GGAO) for the 5-m Very Long Baseline Interferometry (VLBI) antenna there.

2. Location and Equipment

The local site at GGAO features the four geodetic techniques of VLBI, GPS, Satellite Laser Ranging (SLR), and Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS). The different sensors are connected by a local geodetic network consisting of several survey monuments. Figure 1 shows the 5-m VLBI antenna (MV-3) at GGAO and the local surveying network in its vicinity.

The survey equipment for the proof-of-concept studies were based on a robotic total station Leica TCA2003 and a Trimble 606 360°-mini-prism, which was mounted on the VLBI antenna. Unlike standard prisms, the 360°-mini-prism does not need to be oriented towards the total station. However, as the 360°-mini-prism consists of seven individual prisms arranged in a full circle, the

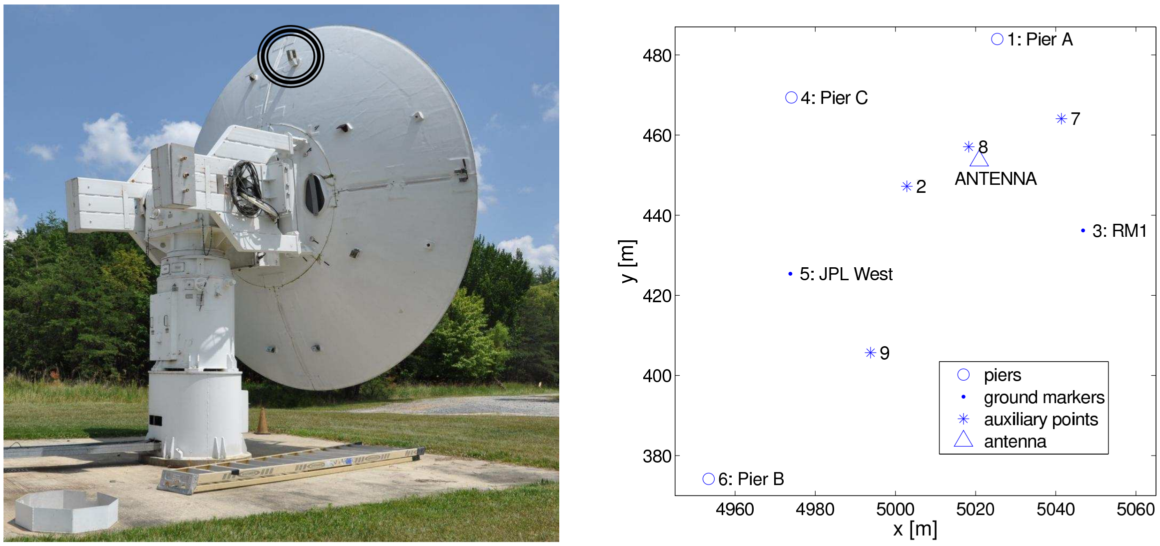

Figure 1. (left) The 5-m VLBI antenna (MV-3) at Goddard Geophysical and Astronomical Observatory (GGAO). The black circles indicate the location where the 360°-mini-prism was mounted. (right) The local surveying network around GGAO's 5-m VLBI telescope.

mini-prism's reference point may change depending on its orientation with respect to the instrument. Hence, the mini-prism requires a correction which is dependent on the angle of incidence. In a calibration survey the mini-prism was rotated around its vertical axis in small steps, and the total station measured changes in the reference point. A correction is then determined based on the orientation of the mini-prism with respect to the "zero reference direction" (marked by a white arrow). Figure 2 shows the distance variations when rotating the 360°-mini-prism. The effect of the seven individual prisms within the mini-prism is clearly discernible.

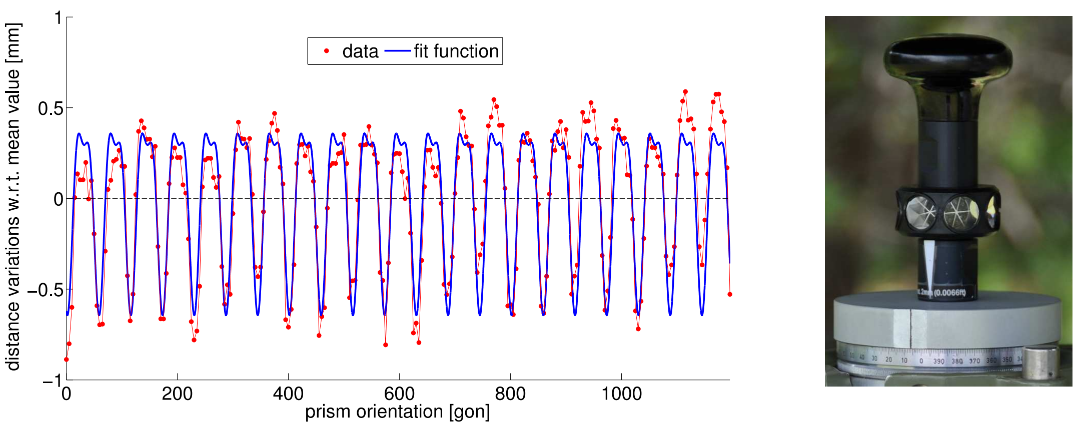

Figure 2. Results of the calibration of the 360°-mini-prism. A double *cos* base function was fitted to the real data. Depicted are three full circles (1200 gon).

Since the calibration can be done only for angles of incidence orthogonal to the vertical axis of the mini-prism, a limit is put on the degrees of freedom for the movement of the VLBI antenna for each instrument position. The VLBI antenna can only be moved such that the 360°-mini-prism mounted on the antenna describes motion paths with the line-of-sight always being orthogonal to the mini-prism's vertical axis.

3. Simulations and Preliminary Results

The literature basically describes two techniques for the determination of the invariant point (IVP) of a VLBI telescope. The conventional surveying approach involves circle fitting for the positions of markers mounted on the telescope structure as the antenna moves (e.g., Dawson et al. 2007). The survey procedure has to ensure that the markers trace a reasonable portion of a circle in space. The center points of the circles coincide with the IVP. A newer approach, suggested by Lösler (2008), moves away from the geometrical constraints towards a "transformation approach", where the transformation parameters from an antenna-fixed coordinate system to a local network coordinate system describe the antenna characteristics. This has the advantage that not only the IVP but also other VLBI antenna parameters can be estimated together with their formal errors in a combined solution strategy.

The observation equation of the transformation approach can be written as (Lösler 2008)

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x_{IVP} \\ y_{IVP} \\ z_{IVP} \end{bmatrix} + R_x(\beta) \cdot R_y(\alpha) \cdot R_z(A + O_A) \cdot R_y(\gamma) \cdot \left(\begin{bmatrix} 0 \\ ecc \\ 0 \end{bmatrix} + R_x(E + O_E) \cdot \begin{bmatrix} a \\ b \\ 0 \end{bmatrix} \right)$$

where the observations are the marker positions x, y, z in the local network system as determined by the total station and the VLBI antenna positions A, E (azimuth and elevation) as given by the VLBI Field System which controls its movements. The unknown parameters are the invariant point $x_{IVP}, y_{IVP}, z_{IVP}$ of the VLBI antenna, the axis offset ecc (eccentricity), the marker positions a, b in the telescope-fixed system, axes non-orthogonality corrections α, β, and an inclination correction γ. In addition, there are two orientation unknowns O_A, O_E. The parameters can be solved for using a least-squares adjustment.

Figure 3 shows the schematics of the planned measurement and analysis procedure. From previous measurements the coordinates and covariances of the local network are known in the local system. From one or several standpoints, measurements (horizontal and vertical angles, slant distances) are taken to orientate the total station into the local system and then to determine positions of the marker on the VLBI antenna in the same system. Using the transformation approach the antenna parameters can then be solved for.

Both the data capturing in the field and the subsequent analysis of the data in the office can be done in an automated fashion. The Leica TCA2003 and the VLBI antenna MV-3 can be controlled from a Matlab-coded control program, which can run predetermined observational sequences. An adjustment program based on the transformation approach was also coded in Matlab.

In order to test the software suite and to check if the target accuracy is attainable, simulations were done using the existing network geometry at GGAO. In a first step, the expected precision of the coordinates of the local geodetic network in the local system was determined. For the total station, an angle accuracy of 0.45 mgon ($= 1.5''$) and a distance accuracy of 1 mm ±1 ppm were assumed. Using full sets of measurements between all points of the local network, the analysis package PANDA estimated standard deviations of about 0.2–0.3 mm for the horizontal and of

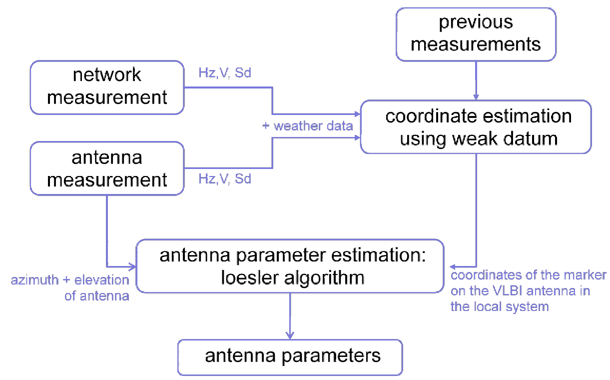

Figure 3. Data flow of the planned measurement and analysis procedure.

about 0.1–0.2 mm for the vertical components.

Using the coordinates and standard deviations previously obtained, measurements from several instrument standpoints to the marker mounted on the telescope were simulated and analyzed. Based on a chosen observation sequence, true measurement values were computed. These values were modified by adding noise based on the instrument and network point accuracies. Then the antenna parameters were estimated using the modified observations and compared to the true values. For each instrument standpoint, the simulated observing schedules had around 60 different azimuth and elevation positions for the VLBI antenna. Table 1 shows the results when using a single instrument standpoint only and when using four instrument standpoints in a combined solution. The formal errors are at the sub-mm level clearly fulfilling the 1-mm target. The line-of-sight dominance visible in the single standpoint solution (in the direction of the x_{IVP} component) vanishes in the combined solution.

Table 1. Simulation results for a single instrument standpoint (left) and for a combined solution using four instrument standpoints (right). The error estimates stem from 200 simulation runs. The true error is the difference between the known parameter value and the estimated value. Listed are the mean values from the 200 repetitions, where the true error is averaged over the absolute values.

Instrument standpoint: 4			*Instrument standpoints: 1,3,4,5*		
Parameter	**True error**	**Formal error**	**Parameter**	**True error**	**Formal error**
x_{IVP}	0.15 mm	0.18 mm	x_{IVP}	0.04 mm	0.05 mm
y_{IVP}	0.08 mm	0.10 mm	y_{IVP}	0.04 mm	0.05 mm
z_{IVP}	0.14 mm	0.17 mm	z_{IVP}	0.06 mm	0.08 mm
axis offset	0.13 mm	0.16 mm	axis offset	0.06 mm	0.08 mm

Following the successful simulation results, a local network measurement campaign was observed on 13 August 2009 and a first set of VLBI antenna observations from four standpoints on 2 September 2009. The analysis of the local network campaign, however, revealed anomalies in the measured data. A comparison of direction measurements between faces I and II showed differences in the range of −25 to 15 mgon, which is significantly higher than the instrument accuracy. We have been unable to identify the reason. Further, a network analysis with PANDA only yielded consistent results after deleting about 15% of the observations. Such a high outlier rate is not expected given the quality of the total station. These inconsistencies need to be investigated further.

For a preliminary check of the VLBI antenna observations, only approximate coordinates were used for the network points, and each instrument standpoint was considered independently. Thus, we determined four different sets of antenna parameters in slightly different reference frames. It is, however, possible to compare reference frame independent parameters such as the axis offset. Table 2 compiles the four results for the axis offset and its standard deviation.

Table 2. Axis offset parameter and its standard deviation as obtained from four independent determinations.

Standpoint	ecc	σ_{ecc}
#1	0.19 mm	0.23 mm
#3	0.20 mm	0.18 mm
#4	0.15 mm	0.18 mm
#5	0.12 mm	0.18 mm

The independent determinations of the axis offset are consistent within their error estimates. The formal errors are only slightly worse than in the simulation. The formal errors for the IVP coordinates are worse by a factor of 2–3 but can still be considered satisfactory.

4. Conclusions and Future Work

As a first step towards an automatic monitoring system for local site ties using robotic total stations, an automatic measurement procedure was developed. Both the total station and the VLBI antenna can be controlled from a Matlab-coded control program. Running specific observational programs, data was collected that indicate that the reference point of the VLBI antenna can be automatically determined with an accuracy of 1 mm or better. However, anomalies in the combination of the results from different standpoints of the total station require further investigation.

In addition to finding the reason for the data inconsistencies, future work will include the verification of results (e.g., repetition of measurements), improvement of the marker and mounting (e.g., replacement of 360° prism with a reflective target sphere, mounting the marker at different positions on the VLBI antenna structure), and applying the approach to the SLR systems at GGAO.

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