

Automated Simultaneous Local Ties with GNSS and Robot Tacheometer

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Abstract We have used GPS-based local-tie measurements simultaneously with geo-VLBI observations since 2008 during every geodetic VLBI session at Metsähovi. This system uses gimbal-mounted GNSS antennas that are mounted on the reflector of the Metsähovi 14-m radio telescope. A similar system was installed in 2013 at the Onsala 20-m radio telescope and has been used for a large number of VLBI sessions, including, e.g., the 15-day-long CONT14 campaign. In order to verify the results of the two systems, we performed a dedicated measurement campaign in the framework of the SIB60 project, involving both Metsähovi and Onsala. During this campaign the local ties at the two stations were measured simultaneously during two VLBI sessions in August and September 2015 where both stations participated. The robot tacheometer monitoring system HEIMDALL was used for the automated classical monitoring of the telescopes at both stations. Moreover, additional local terrestrial measurements were performed several times to derive the full IVS–IGS local ties at both sites. The kinematic GPS measurements at the two stations were analyzed with two independently developed analysis programs. We present here the preparations of the campaign, the measurement process, and preliminary results.

Keywords Local ties, robot tacheometer, GNSS, IVS, IGS, reference frame

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1 GNSS Local Tie

For a GNSS local tie, two GPS antennas are attached permanently at both sides of the radio telescope dish. They are on a gimbal which keeps them pointed upwards independent of the position of the radio telescope. The reference point of the radio telescope, antenna structure elements, axis orientation, and offset are estimated using the post-processed coordinates of the GNSS antennas and the telescope antenna position angle readings. Synchronizing the telescope position angles and trajectory coordinates is performed using time stamps of trajectory coordinates and telescope angles.

Like with terrestrial local ties, calibrated instruments are needed. The GNSS antennas should be absolute calibrated individually with a robot or in an anechoic chamber. Because the GNSS antennas rotate with the telescope, the orientation of the GNSS antenna should be taken into account when applying the PCC of the antenna. The orientation of the local tie vector comes from the satellite orbits. It is necessary to use precise orbits in ITRF in kinematic post-processing.

Despite massive multipath and blockage of the visibility by the radio telescope antenna, we are able to retrieve enough data for a reliable solution. The multi-stage outlier detection, together with a robust mathematical model, enables the use of kinematic GNSS solution to determine the coordinates of the VLBI antenna reference point. GNSS-based local tie systems have been successfully used at Metsähovi since 2008 and at Onsala since 2013 (e.g., [Kallio and Poutanen (2012)], [Ning et al. (2015)]).

The software development at FGI (Metsähovi) concentrated mainly on the antenna model parts and recently also on the uncertainty in the modeling and com-

mercial or open source software packages used in kinematic post-processing. At Onsala the GNSS local tie system development includes also the kinematic post-processing software [Ning et al. (2015)].

GNSS local ties are well suited for real-time continuous local tie measurements. Once the system is installed, it can be used at any time during the normal use of the radio telescope. A local area network is not needed. The measurements are fully automated and the local tie is achieved directly in the ITRF.

2 Terrestrial Local Tie with Automated Monitoring

Local ties are mainly derived by terrestrial measurements using total stations and levelling instruments, because they cover the high accuracy requirements. The GGOS specifies an accuracy level below 1 mm for the local tie vector and 0.1 mm/yr for its variation. Because the local tie should be provided in a global reference frame, additional GNSS observations are needed. To fulfill these requirements, some preconditions must be met, for instance:

- Usage of calibrated or even certified equipment and instruments,
- Configuration of the local site network, e.g., the construction of the pillars,
- Consideration of new scientific evidence, e.g., applying [Ciddor (2002)] first velocity correction, or
- Thermal expansion corrections for the radio telescope structure.

At Metsähovi as well as at Onsala the radio telescope is enclosed by a protection radome. Thus, the combination of the observations inside and outside the radome is an additional challenge and requires special equipment and an adapted observation concept. E.g., at the Onsala Space Observatory, a special reflector support was mounted at the radome wall to combine both network parts at the local site. While the IVS reference point can be observed in an automated way, the other part of the network as well as the IGS reference point must be measured in a classical way. To avoid the influence of refraction and to minimize local temperature differences during the observation process, the measurement campaigns are preformed in the evening or at night. For this purpose, a second total station (TS30

Leica) was involved. Thus, both network parts as well as both reference points could be observed in parallel.

The big advantages of an automated reference point determination are saving time and manpower. Conventional reference point determinations need maintenance of the radio telescope, whereas an automated monitoring can be done at any time especially during normal operations. Through the automated reference point determination, the portability of conventional measurement methods and their related uncertainties propagations must be validated, reviewed, and adjusted, because additional parameters influence the dynamic measurement process, e.g., synchronization errors or effects caused by misaligned reflectors. On the other hand, an automated monitoring provides long time series and proofs the stability of the geodetic space techniques.

3 HEIMDALL – Milestones of Development

The first version of the monitoring system HEIMDALL had been developed at Karlsruhe Institute of Technology (KIT) in 2010. The developed system was able to monitor quasi-fixed positions at an object, e.g., the non-rotatable tower of a radio telescope was deployed at the Geodetic Observatory Wettzell (GOW) (cf. [Lösler et al. (2010)]). The VGOS agenda as well as the Global Geodetic Observing System (GGOS) call for an automated and continuous monitoring of the reference points of space geodetic techniques. To meet this goal an advanced version of the HEIMDALL system was developed at the Laboratory for Industrial Metrology of the Frankfurt University of Applied Sciences (FRA-UAS). Whereas the first version was able to observe only quasi-fixed positions, the new version allows for a monitoring of movable reflectors that are mounted at the turnable part of a radio telescope (e.g., [Lossin et al. (2014)]).

In general, manually operated terrestrial measurement campaigns depend on, e.g., the available time and personnel resources for maintenance of the radio telescope or weather conditions (cf. [Kallio and Poutanen (2013)]). As shown by [Kallio and Poutanen (2013)] an optimal observation strategy becomes unworkable because of the small timeframe. For example, [Kallio and Poutanen (2013)] attached six reflective tape targets at the turnable part

of the Metsähovi radio telescope and planned to observe the targets in 108 different telescope orientations (12 azimuth and nine elevation positions). Due to the small timeframe, only 18 telescope positions and 68 out of theoretical 648 points were observed. This is a 75% mismatch between the planned and the realized observation strategy. At Metsähovi, the kinematic GPS instead proved to be the best strategy for the local tie measurements ([Kallio and Poutanen (2013)]), and since 2008 this approach has been successfully applied during every geo-VLBI campaign in which Metsähovi has participated. The time frame problem was overcome in 2015 when the HEIMDALL system was installed and used at Metsähovi during two geo-VLBI sessions.

Thus, we can specify the GGOS intended automated and continuous monitoring requirement in more detail by the additional specification during normal operations of the radio telescope. The first fully automated terrestrial monitoring campaign during normal VLBI operations was carried out successfully at the Onsala Space Observatory (OSO) using the HEIMDALL system in 2013 ([Lösler et al. (2013)]). The influence of systematic errors caused by the angle of incidence on the measured reflector positions was studied and corrected analytically for the first time in the framework of reference point determination. In contrast to static stop and go campaigns, when the telescope stops at pre-defined azimuth and elevation positions, an in-process monitoring requires an extended parameterization of limiting factors. Following the *Guide to the Expression of Uncertainty in Measurement* (GUM) a comprehensive uncertainty budgeting was suggested by [Lösler et al. (2016)] and applied during CONT14 at OSO. The success rate between the planned and the realized observation strategy was about 95%.

Based on a VLBI schedule, HEIMDALL predicts the positions of the mounted reflectors and checks the measurability by the angle of incidence. For sensor communication several interfaces are provided, e.g., serial communication or socket connection. The data management is completely realized by an embedded SQL database. The results of external sensors, which are not connected to the system, can be imported to the database and synchronized by the recorded timestamp. In general, the post-processed data analysis starts with a network adjustment to connect the recorded data of several stations and

to provide the estimated Cartesian coordinates and the related uncertainties. The whole network can be defined as a local topocentric coordinate system (cf. [Lösler et al. (2013)]) or as a global geocentric coordinate system (cf. [Lösler et al. (2016)]). The network definition should be aligned to the project goals. For continually proving the stability of the network and the reference point a local topocentric coordinate system is sufficient and descriptive. For deriving local tie vectors a global geocentric coordinate system is preferred, because a final global transformation becomes dispensable.

Beside the network adjustment module, HEIMDALL contains an analysis component for the IVS reference point determination. The implemented mathematical model is based on a rotating model of a radio telescope considering the irregularities in the construction of the radio telescope. This model, presented in 2008, is the first one that allows for continued IVS reference point determination during normal operations and is a major step forward in the research of automated monitoring of local ties (e.g., [Lösler (2009)]). The prototype software HEIMDALL allows an independent, economical, time-effective, and continued monitoring of the IVS reference point.

4 Preliminary Results

In August and September 2015, automated local tie measurements were carried out at the co-location sites Metsähovi and Onsala. The geo-VLBI sessions T2105 (2015-08-25) and EUR137 (2015-09-07) were selected because both stations were participating. The local tie vectors at each site were observed and derived by classical terrestrial measurements involving the monitoring system HEIMDALL and by GNSS observations. Thus, two independent observation methods are used and can be compared to each other. Moreover, at the Onsala site, another representation of the mathematical model of the IVS reference point determination is available and allows for an independent validation.

4.1 Preliminary Results at Onsala

At Onsala, four local measurement campaigns were performed close to the dates of the VLBI sessions to derive the IGS reference point as well as control points that were partially equipped by GNSS antennas and to connect both network parts using a Leica total station TS30. The IVS reference point as well as the radome network were observed automatically by an additional total station MS50 (Leica). To get a homogeneous point distribution, 14 reflectors were mounted at the turnable part of the Onsala 20-m radio telescope. Currently, the GNSS observations are still under investigation and only the local terrestrial observations have been analyzed. Thus, a local topocentric coordinate system was used instead of a global geocentric one. Table 1 summarizes the results of the local tie determination at the Onsala Space Observatory. During the 15-day-long CONT14 campaign, the local tie vector was derived to respond to the IERS call for the ITRF2014. The length of the local tie vector given in SINEX is 79.5709 m and the estimated axis offset is -5.9 mm. The new estimated values confirm the results of the CONT14 measurement campaign very well.

Table 1 Preliminary results of the local tie estimation at the Onsala Space Observatory based on terrestrial observations. The total number of observations is NOO and the number of observed telescope points is denoted by OTP. LEN and AO are the length of the local tie vector and the axis offset with related uncertainties, respectively.

Session	T2105	EUR137
NOO	4761	4686
OTP	1022	1016
LEN	79.5708 m ± 0.5 mm	79.5707 m ± 0.5 mm
AO	-5.9 mm ± 0.2 mm	-6.0 mm ± 0.2 mm

4.2 Preliminary Results at Metsähovi

The local area pillar network was measured in 2014 and in 2015 first with a 40-day GPS campaign and then terrestrially using T2003 tacheometer and TS50 robot tacheometer. A special campaign for the height differences from the pillars to the GPS masts was per-

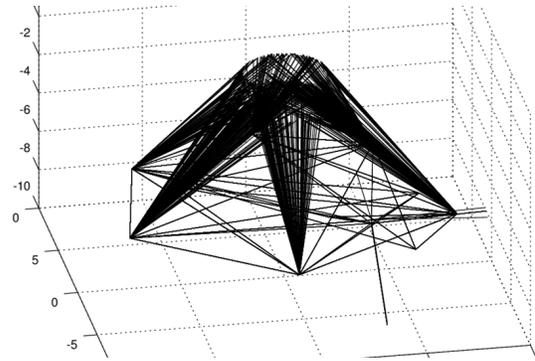


Fig. 1 Geometry of the measurements in automated monitoring at Metsähovi.

formed. The connection of the radome network and the local area network was measured soon after the SIB60 VLBI campaign. The height differences of the pillar points and some points under the radome were levelled. The monitoring observations and the measurements in radome network and the local area network were computed in one combined free network adjustment in ITRF. The orientation and positions of the network are based on the coordinates of 16 GPS points of combined solution of the 40-day campaign. Eight Leica GPR121 prisms were mounted at the rotating part of the 14-m radio telescope and used as targets in automated monitoring (Figure 1). GPS local tie measurements were performed simultaneously (Figure 2). The results reveal small systematic differences in coordinates which is best seen in the time series (Table 2).

Table 2 Preliminary results of the local tie estimation at Metsähovi. The total number of observations is NOO and the number of observed telescope points is denoted by OTP. LEN and AO are the length of the local tie vector and the axis offset with related uncertainties, respectively.

Session Technique	T2105 GPS	EUR137 GPS	T2105 & EUR137 Terrestrial
NOO			4023
OTP	1574	1898	834
LEN	128.8833 m ± 0.8 mm	128.8836 m ± 0.8 mm	128.8818 m ± 0.4 mm
AO	-4.4 mm ± 1.2 mm	-3.3 mm ± 1.2 mm	-1.8 mm ± 0.3 mm

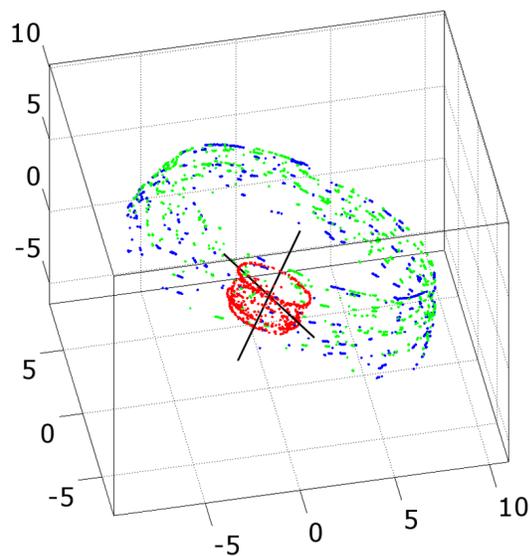


Fig. 2 Geometry of the measured points in GPS local tie (green and blue) and in terrestrial monitoring (red) at Metsähovi.

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