FGI's contribution in the JRP SIB60 "Metrology for Long Distance Surveying"

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Abstract. Within the European Metrology Research Programme (EMRP) joint research project "Metrology for long distance surveying" the Finnish Geospatial Research Institute (FGI) is advancing the work for new measurement methods, uniform scale and improved metrological traceability.

The FGI measured its Nummela Standard Baseline using the Väisälä Interference Comparator in 2013. The measurement continues the time series of nearly 70 years, during which the variation of the 864 123 mm total length has remained smaller than 0.7 mm. The result is traceable to the SI unit metre, and the expanded uncertainty is 0.2 mm. The new results provide comparison data for validation of novel surveying instruments within EMRP, and the scale from Nummela also has been transferred to a network of pillars at Metsähovi fundamental station and for comparisons to other European geodetic baselines.

A metrologically optimum processing strategy for short GPS baselines has been studied. Different antenna calibrations, namely anechoic chamber (University of Bonn), robot (University of Hannover) and type (IGS) calibrations, were verified at a pillar network "Revolver" at Metsähovi with a method developed for the purpose.

Kinematic GPS with two antennas attached on the VLBI radio telescope dish has been used for the local ties at Metsähovi since 2008. The observations have been recomputed with the new antenna calibration tables and the uncertainty model for local ties is under development. The VLBI radio telescope has been monitored at Onsala and at Metsähovi with GPS and with robot tachymeter during two VLBI sessions.

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Keywords. Length metrology, traceability, EDM, GNSS, EMRP JRP SIB60 Surveying.

1 Introduction

Precise and stable reference frames are prerequisite for reliable measurements in geosciences. Earth-exploring and navigation satellites, orbit determination and usage of ever-increasing precision applications of these satellites require a well-defined stable global reference frame. Global change related to the melting of glaciers with adjacent sea level rise and gravity changes are examples of phenomena which need precise long-term geodetic observations and time series.

Maintenance of global reference frames requires multi-technique space geodetic observations, including GNSS (Global Navigation Satellite Systems); SLR (Satellite Laser Ranging) and geodetic VLBI (Very Long Baseline Interferometry). Especially important are the geodetic Fundamental stations where all the major instruments are at the same site. Global network of fundamental stations form the core of the geodetic network. FGI participation in the JRP SIB60 aims to use the Metsähovi fundamental station for developing, testing and usage of novel techniques and new measurement methods.

Metrological traceability is achieved via Nummela Standard Baseline, the most precise outdoor geodetic baseline in the world. The scale from Nummela has been transferred to a network of pillars at Metsähovi and to many European geodetic baselines. This will also serve for comparison of baselines using different calibration methods and developing novel techniques, one of the tasks in JRP SIB60.

Development of the GNSS antenna test field at Metsähovi has improved our capabilities in local tie measurements and verifying and testing GNSS antenna calibrations. In this project we compare the GNSS solutions to the calibrated reference distances in the antenna test field to find the metrologically optimum observing strategy. We are also able to

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verify the differences between different antenna calibrations on the sub-millimetre level.

Kinematic GPS on the VLBI radio telescope was developed in the FGI and used for the local ties at Metsähovi since 2008. Obtaining the local tie vectors also with traditional tachymetric measurements within the SIB60 project enables direct comparison of different techniques and improves the uncertainty estimation of the tie vectors.

In the following we describe measurements and results achieved under the EMRP JRP SIB60 project.

2 Nummela Standard Baseline

The basis for the reference data and metrological traceability is FGI's Nummela Standard Baseline in Finland. This world-class measurement standard for geodetic length measurements is regularly measured using the Väisälä (white-light) interference comparator and a quartz gauge system, which brings the traceability.

The variation in the total length of 864 m has been smaller than 0.7 mm in the 16 measurements during years 1947–2013 (Jokela 2014). Expanded total uncertainties usually vary between 0.04 mm and 0.18 mm for the baseline sections between 24 m and 864 m. The latest remeasurement in 2013 resulted in larger uncertainty values, up to 0.23 mm, caused by unexpectedly freezing conditions before the completion of the measurements. However, the resulting distances differ only 0.1 mm at maximum from the previous measurements of 2005 and 2007, thus providing a reliable basis for calibrations at the baseline.

In 2015 the FGI prepared the Nummela Standard Baseline to be used for the project by three sets of projection measurements between the underground markers and observation pillars. This produced reference distances, which are derived from the interference measurements and thereby traceable to the definition of the metre with 0.3 mm expanded uncertainty.

2.1 Reference data for the validation of the novel optical standards

The 8-pillar 600-m geodetic baseline of the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, is one facility used for outdoor validation of the developed distance measurement systems, the German PTB's TeleYAG and the French CNAM's Telediode. The unique sensor system for acquiring weather data makes the baseline especially suited for the purpose (Pollinger et al. 2012). The FGI provided reference data by calibrating the PTB baseline for the first time in June 2011 and again in July 2014.

Another geodetic baseline closely related to the project is the one of the Austrian metrology and surveying institute (Bundesamt für Eich- und Vermessungswesen, BEV) in Innsbruck, Austria. The FGI calibrated the baseline for the first time in September 2008 and again in October 2015. The first calibration was a part of a previous EMRP long-distance surveying project and the latter for maintenance for national needs.

To transfer the traceable scale to other geodetic baselines the FGI calibrated a transfer standard, a Kern Mekometer ME5000 no. 357094 EDM equipment, at Nummela three times in June 2014 and three times in August 2014. Scale corrections of –0.06 mm/km ±0.33 mm/km and +0.03 mm/km ±0.24 mm/km and additive constants of +0.03 mm ±0.01 mm and +0.04 mm ±0.01 mm were determined, respectively. Calibrations were continued for the scale transfers in 2015.

A device based on laser spectroscopy for the measurement of temperature over long distances, developed by VTT-MIKES, was one more novel equipment successfully tested at Nummela in autumn 2015 (Tomberg et al. 2016). The innovation is expected to be applicable in obtaining accurate and reliable temperature data for refraction correction of geodetic distance measurements.

Fig. 1 Calibration facilities at FGI's Nummela Standard Baseline.

2.2 Comparison of baselines using different calibration methods

FGI's aforementioned calibration of the PTB baseline and validation of novel instruments also serve for another task of the project, comparison of baselines using different calibration methods. The participants' distance observations were compiled in uniform datasets. Concerted processing of these deliverables and reporting of results are about to be completed.

FGI's dataset from the PTB baseline in July 2014 includes 126 observed distances ranging from 50 m to 600 m. Weather data are available from both FGI's traditional instruments (psychrometers, aneroids) and from PTB's modern sensor system.

In October 2014 the scale of Nummela was transferred to the new 8-pillar 1 100-m geodetic baseline of the Universität der Bundeswehr München (UniBW). This baseline was the venue of an international intercomparison already in 2009–2011, when the nominal distances were determined using various tachymeters, Mekometers, absolute laser trackers and GNNS measurements (Heunecke 2012). FGI's dataset from the UniBW baseline includes 122 observed distances ranging from 51 m to 1 100 m. Utilizing a unique traceability chain it is a remarkable supplement to the existing comparison data.

Fig. 2 Scale transfer to the UniBW geodetic baseline.

2.3 Scale transfer to Metsähovi

The FGI calibrated the reference vectors of the novel test field at Metsähovi. The scale traceable to the SI unit metre definition was transferred from the Nummela Standard Baseline using a Kern Mekometer ME5000 no. 357094 high-precision EDM equipment as the transfer standard. The calibration certificates were written for three distances 191 m, 131 m and 63 m (yellow lines in figure 3). In addition, three more reference distances shorter than 20 m were computed from the network adjustment (chapter 3.1).

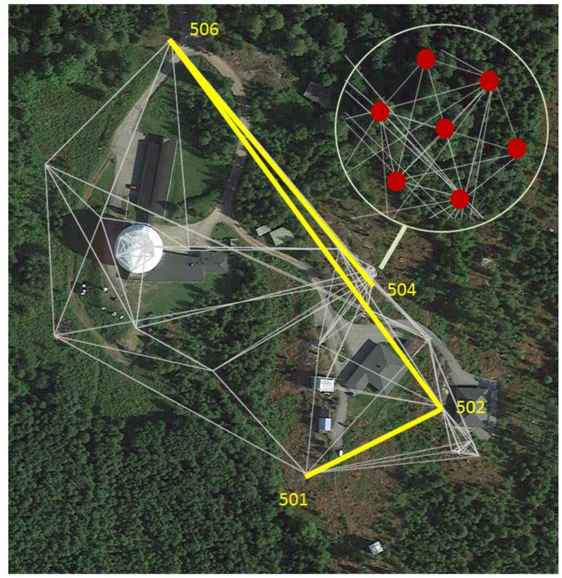

Fig. 3 The pillar network (left) and the revolver test field (inset at right) at Metsähovi. Calibrated baselines are the yellow lines. (Background photo Google Earth 2014.07.26, 60º 13' 04", 24º 23' 38").

3 GNSS metrology at Metsähovi

There are a total of 15 concrete pillars at Metsähovi which are designed for high-precision applications. The pillar network forms the reference frame for local tie measurements between space geodetic instruments like VLBI, SLR and GNSS. The network has a traceable scale through the scale transfer from Nummela. Part of the network, called "Revolver", is used for validating GNSS antenna calibration values.

3.1 Metsähovi Terrestrial Network

The Metsähovi terrestrial network includes two GNSS mast points, 14 GNSS pillar points, one terrestrial pillar point, 12 reference points inside the VLBI radome, two points inside the SLR radome, five points related to SAR, seven temporal points and 834 points on the rotating part of the VLBI telescope during two VLBI sessions. Figure 3 shows the pillar points and the revolver test field that is designed for GNSS antenna tests.

Approximate coordinates of the terrestrial network adjustment are based on the 16 GPS point network solution of the 40 days campaign measured in summer 2014. The GNSS solution was processed with Bernese 5.2 using the proposed best processing strategy of GNSS vectors less than 200 m (see chapter 3.3). The GNSS vectors were not used as observations in terrestrial network adjustment. The terrestrial solution is based on the angle and distance measurements and levelled height differences corrected with geoid model to ellipsoidal height differences.

Scale of the terrestrial network is based on the calibrated distances of the three pillar pairs. A scale factor unknown is included to the observation equations of the other distance observations. Orientation and positions of the network are based on the 16 GNSS points. The normal equations of the adjustment have constraints with three inner constraint equations (one rotation and three translations) with respect of the 16 GNSS points.

The GNSS coordinates of the MET3 were constraint to the coordinates of the weekly solution in IGb08 processed by FGI's GNSS analysis centre. The ellipsoidal height difference observations in adjustment were deduced from levelling network solution and geoid height differences from Finnish geoid model FIN2005N00.

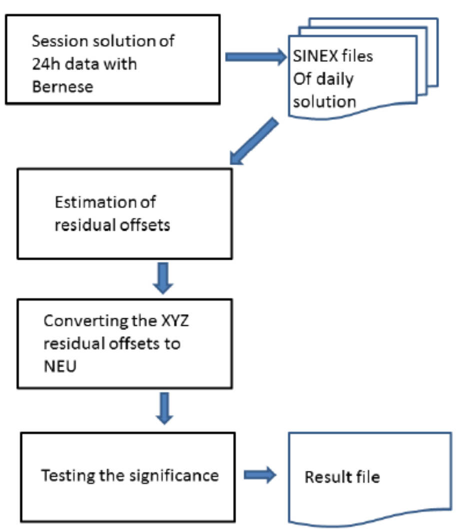

Fig. 4 A procedure to analyze residual offsets.

3.2 Validation of antenna calibration tables

The procedure for validation of antenna calibration tables is based on the circulating the antennas on the pillars. Daily solutions computed with Bernese 5.2 (Dach et al 2015) are combined to the final solution with full covariance matrix in ITRF. The design matrix of the antenna network is different than the pillar coordinate network and the residual offsets can be solved for as additional parameters during combination. In order to get absolute residual offsets for North and East components the antennas are directed to the south in some pillars instead of the North. The method is based on the Bányai (2005) and further developed in FGI (Kallio et al 2012). The procedure is shown in Figure 4.

We have estimated the residual offsets related to all calibration tables of all the antennas used in the next chapter. Our analysis show that we are able to solve for the residual offsets on 0.1 mm level.

3.3 Metrologically optimum processing strategy

We selected seven baselines from the Metsähovi terrestrial network for studying the metrologically optimum GNSS processing strategy. Dual frequency GPS data of minimum 72 hours were collected in 2014 and 2015 using Ashtech choke ring antennas which have type calibration values as well as individual calibrations made in anechoic chamber at Bonn (Institute of Geodesy and Geoinformation, University of Bonn) and with robot at Hannover (IfE, Leibniz Universität Hannover). Baseline lengths varied between 2 and 191 meters.

The GPS processing was carried out using the Bernese GNSS Software version 5.2 (Dach et. al. 2015). All the processing was based on the double difference approach. Our apriori processing strategy was to use L1, 10 degree cut off, 5s sampling, precise orbits, GMF troposphere, CODE ionosphere model, and DD phase residual screening. The outcome of the processing was the distance between antennas, and that was compared to the traceable reference distance.

The effect of ionosphere was studied using Global ionosphere model by CODE (the Center for Orbit Determination in Europe) and without any ionosphere model, and with all three antenna calibrations (Bonn, Hannover and type). In most cases the difference between solutions was 0.1 mm or less confirming the negligible role of ionosphere modelling in the distances shorter than 200 m.

In the next step different troposphere modelling options where tested using L1 and L3 frequencies and all three antenna calibrations. The results showed very small differences between the troposphere solutions independent of antenna calibration or frequency. The GMF and VMF solutions were identical as well as the GMF with gradients and VMF with site specific gradients. The mean differences between solutions were close to 0.0 mm.

The solutions with different antenna calibrations and frequencies were compared to the reference distances to find the metrologically optimum processing strategy. The comparisons were made only for the GMF troposphere model because of very small differences between the troposphere models. The standard deviations of the daily solutions within a session (3–11 days) were 0.2 mm at maximum for L1 and 0.3 mm for L3. The L1 solution with individual calibration (Bonn or Hannover) performed mostly closest to the reference. All the solutions were within ±1.0 mm from the reference.

The same antennas have been used in the Revolver test field and the residual offsets were estimated for the antennas. The effect of the residual offsets for the baselines were very small (max 0.15 mm) in the case of individual calibrations but more significant for the type calibration (up to 1.5 mm). The L1 daily offsets were corrected using the residual offsets. The residual offsets corrected solutions were within ±0.1 mm from each other (Bonn, Hannover and type calibration). Especially the type calibration solution improved significantly of the use of the residual offsets.

4 Local tie at Metsähovi

4.1 Local tie time series measured with GPS

We started kinematic GPS local tie measurements between IGS point METS and IVS point Metsähovi in 2008 with two Ashtech choke ring antennas attached at the edge of the VLBI telescope dish using Geo++ calibration tables for PCC. The results of the early measurements are reported in Kallio and Poutanen 2012 and 2013.

The choke ring antennas were needed in other GPS campaigns and we changed the antennas in May 2010 to two Leica AX2012 antennas which were better suited to the kinematic measurements than the heavy choke ring antennas. In order to be able to apply individual PCC corrections the antennas need to be calibrated. The Leica antennas were taken down for calibration in 2013 during the SIB60 ERMP. The antennas were calibrated with two different calibration methods, in anechoic chamber at Bonn and with robot at Hannover. We recalculated time series with both new calibrations.

The METS IGS antenna (AOAD/M_B NONE) broke down in July 2010 and was changed in August 2010 (AOAD/M_T NONE519). The ARP of the new METS antenna is 0.0226m lower position than the ARP of the old one. The new METS antenna has individual calibration tables by Geo++.

The METS antenna was changed again in summer 2013 because of its unstable behaviour. Also the new antenna (ASH700936C_M NONE11761) has individual calibration tables by Geo++. The ARPs of the second and the third antennas have the same position which has been verified with tachymetric measurements. The first VLBI session after the first METS antenna change was in doy 264 2010. We chose this as the starting epoch of the time series of our recalculated local ties including 25 sessions from 2010.7 to 2015.7.

With few exceptions we have measured the local tie with kinematic GPS during every geodetic VLBI session where Metsähovi has participated.

The phase observations of each session were corrected applying the both calibration tables to the RINEX files separately. The trajectories were processed using TTC (Trimble Total Control) software with OTF (on the fly) strategy in ambiguity resolution. The thermal expansion of the telescope was taken into account by correcting the trajectory coordinates of GPS antennas three dimensionally to the reference temperature 6.8 ºC using different expansion factors for aluminum and steel parts of the telescope.

The recorded VLBI antenna positions and the trajectory coordinates with time stamp were combined in iterative linearized least squares mixed model with conditions between the parameters (Kallio and Poutanen, 2012). The weight matrix of the observations was the inverse of their covariance matrix.

The scattering of the IVS reference point in time series was similar for both calibration tables. The systematic difference of the solutions is mainly in Up direction. The standard deviation of the mean from 25 sessions was 0.72 mm, 0.96 mm, 1.69 mm in topocentric North, East and Up respectively.

4.2 Terrestrial Local tie vector

We measured the local tie vector terrestrially during two VLBI sessions simultaneously with GPS and robot tachymeter in Metsähovi and in Onsala. The terrestrial monitoring was performed with HEIMDAL monitoring system (Lösler et al 2013). The HEIMDAL system was installed at Metsähovi in August 2015 with the help of Michael Lösler of Frankfurt University of Applied Sciences. During the two dedicated 24 hour VLBI sessions we measured in Metsähovi in total of 834 points from six station points. (Figure 5)

The monitoring part of the HEIMDAL system was used in the measurements. We adjusted the coordinates of the prism points in the network adjustment using an in-house network adjustment software. The monitoring system software fixed the errors due to the incident angle of the prism.

HEIMDAL is capable to apply the first velocity correction to the distance measurement in real time, too, but in Metsähovi case we did not have weather sensors connected to the system. Corrections were computed using the temperature values from the weather observations of the temperature sensors inside the radome and the Vaisala weather station outside of the radome.

The deflection of the vertical correction was applied to the angle measurements before the adjustment. The angle and distance observations were included in our Metsähovi network and adjusted in ITRF. The scale of the network is traceable to the Nummela standard baseline (chapter 3.1).

The coordinates and the covariance matrices of the prism points were used as observations in reference point estimation which were performed with the same model than in the case of GPS local tie. All angle, distance and weather observations had a time stamp. The laptop computer which controlled the robot tachymeter through the geoCOM link and recorded the observations to the data base was synchronized with the time server at Metsähovi. The VLBI antenna position angles were recorded like in the case of the GPS local tie.

The agreement of the terrestrial and GPS local tie vectors was good. The differences between the terrestrial and the GPS local tie vectors in the topocentric system during EMRP SIB60 are within two millimeters in all components.

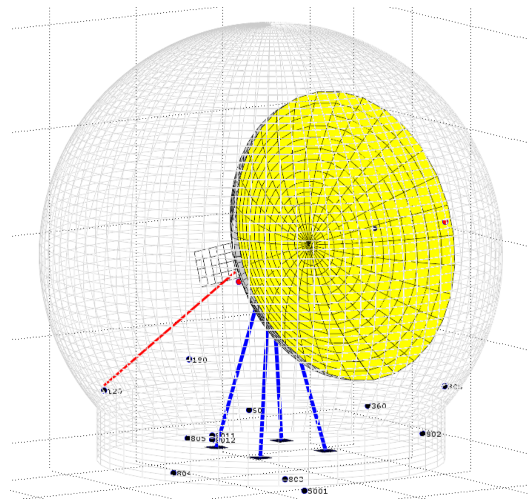

Fig. 5 Geometry of the monitoring observations.

4.3 Uncertainty of the local tie vector

The variances and covariances of the observations (i.e. the trajectory or prism coordinates) propagates to the variances and covariances of the estimated parameters in the reference point estimation process. The covariance matrix of reference point coordinates and the other parameters is an inverse of the normal equation matrix in least squares estimation and it is a function of point geometry and precision of observations. The standard deviations of the reference point coordinates are the square roots of the diagonal elements of the covariance matrix.

We studied the influence of the geometry and number of the measured points on the precision of the reference point coordinates in (Kallio and Poutanen 2010). There are still uncertainty sources the influences of which are not visible in the covariance matrix. The comparisons of the results in time series (standard deviation from the time series in the chapter 4.1) and comparison of different methods (chapter 4.3) give a more reliable estimate for uncertainty of the local tie vector than standard deviations from the adjustment.

The sensitivity of the antenna calibration to the reference point coordinates can be seen if we compare the results computed from the trajectories with two different calibration tables. The precision of the PCC depends on the satellite geometry, the frequency and the antenna itself. The near field effect due to the installation of the antenna on the radio telescope dish can change the antenna properties so that calibration values may not be valid. We handle the near field effect as a part of the antenna calibration table uncertainty. By calculating the zero base line between the tables with real observations we get the distribution of the differences in the trajectory points.

It is difficult to separate different uncertainty sources from each other because the correlations are not known. We are working on the uncertainty model of the GPS local tie. In the first trials of Monte Carlo simulation we concentrated to the GPS antenna PCC corrections.

We calculated the covariance matrix for each trajectory point by using the covariance matrices from kinematic post processing software and the covariance matrix derived from zero baseline distribution. We had different covariance matrix for each trajectory point. We generated 1000 trajectories for both antennas using the pseudo random numbers of (0,1) normal distribution and eigenvectors and values of the derived covariance matrix. Then we applied the reference point estimation to the 1000 sets of the coordinates. The distribution of solutions should then represent the uncertainty of the reference point coordinates and the other parameters in adjustment (Figure 6). We continued the study by adding the influence of other uncertainty sources in the model.

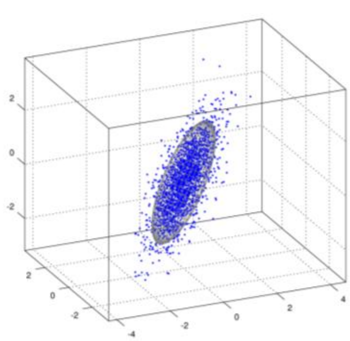

Fig. 6 Distribution of the reference point coordinates in the global frame. Scale is in [mm].

5 Discussion and conclusions

Nummela Standard Baseline is the key resource on validation of novel optical standards and comparison of baselines in the JRP SIB60. We have used the Nummela Standard Baseline to obtain the metrologically traceable scale also in the Metsähovi GNSS test field.

Metsähovi Fundamental station is a part of the global geodetic network to maintain global reference frames and compute the precise orbits of GNSS satellites. Local ties between various space geodetic instruments and their metrological traceability at fundamental stations are one of the main issues when improving accuracy and reliability of global network.

In this research we have developed novel methods to verify calibration of GNSS antenna which is one of the source of uncertainty in high-precision GNSS observations. The test field at Metsähovi has successfully used for this purpose, with a verified uncertainty chain down to the definition of meter.

Our results showed that one millimeter accuracy for a baseline length is achievable from 24-hour data using proposed strategy. More data would be needed to separate signals from environmental effects and antenna calibrations when aiming to the half-millimetre level.

A new Satellite Laser Ranging telescope will be completed in 2016, and a new radio telescope, dedicated for geodetic VLBI is anticipated in 2018 at Metsähovi. Both will be added in the local network, and we will apply methods developed under this project also for the new instruments.

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References

Bányai (2005): Investigation of GPS antenna mean phase center offsets using a full roving observation strategy. Journal of Geodesy 79:222-230. DOI 10.1007/s00190-005-0462-1.

Dach, R., F. Andritsch, D. Arnold, S. Bertone, P. Fridez, A. Jäggi, Y. Jean, A. Maier, L. Mervart, U. Meyer, E. Orliac, E. Ortiz–Geist, L. Prange, S. Scaramuzza, S. Schaer, D. Sidorov, A. Sušnik, A. Villiger, P. Walser, C. Baumann, G. Beutler, H. Bock, A. Gäde, S. Lutz, M. Meindl, L. Ostini, K. Sośnica, A. Steinbach, D. Thaller (2015): Bernese GNSS Software Version 5.2. Astronomical Instituete, Unisversity of Bern, Nov 2015. 854 pages.

Dach, R., U. Hugentobler, P. Fridez and M. Meindl (2007): Bernese GPS Software Version 5.0. Astronomical Institute, University of Bern, Jan 2007. 612 pages.

Heunecke, O. (2012). Auswertung des Ringversuchs auf der neuen Kalibrierbasis der UniBW München zur Bestimmung der Sollstrecken. *Allgemeine Vermessungs-Nachrichten* 119, 380–385.

Jokela, J. (2014). Length in Geodesy – On Metrological Traceability of a Geospatial Measurand. *Publ. Finn. Geod. Inst.* no. 154. 240 p.

Kallio U., H. Koivula, S. Nyberg., P. Häkli., P. Rouhiainen, V. Saaranen, Z. Cirule, D. Dobelis., D. Golovka (2012): GNSS antenna offset field test in Metsähovi, In *Proceedings FIG Working Week 2012, Rome Italy 6.-10.5.2012*

Kallio, U and M. Poutanen (2010): Simulation of Local Tie Accuracy on VLBI Antennas. In *IVS 2010 General Meeting Proceedings, p.360–364,* http://ivscc.gsfc.nasa.gov/publications/gm2010/kallio.pdf

Kallio, U. and M. Poutanen (2012): Can We Really Promise a mm-Accuracy for the Local Ties on a Geo-VLBI Antenna. In *S. Kenyon et al. (eds.), Geodesy for Planet Earth, International Association of Geodesy Symposia 136*, ©Springer-Verlag Berlin Heidelberg 2012

Kallio, U. and M. Poutanen (2013): Local Ties at Fundamental Stations.In *Z. Altamimi and X. Collilieux (eds.), Reference Frames for Applications in Geosciences*, *International Association of Geodesy Symposia 138*, © Springer-Verlag Berlin Heidelberg 2013

Lösler, M., R. Haas, C. Eschelbach (2013): Automated and continual determination of radio telescope reference points with sub-mm accuracy: results from campaign at the Onsala Space Observatory*, Journal of Geodesy 87, pp 791–804, © Springer-Verlag Berlin Heidelberg 2013*

Pollinger, F., T. Meyer, J. Beyer, N. R. Doloca, W. Schellin, W. Niemeier, J. Jokela, P. Häkli, A. Abou-Zeid and K. Meiners-Hagen (2012). The upgraded PTB 600 m baseline: a high-accuracy reference for the calibration and the development of long distance measurement devices. *Meas. Sci. Technol.* 23, 094018.

Tomberg, T., T. Hieta, T. Fordell and M. Merimaa (2016). Spectroscopic inline thermometry. JISDM 2016, in preparation.