Evolution and obtained expertise in reference point determination at the GIK

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Abstract. The International Terrestrial Reference System (ITRS) is realized by geodetic space techniques, which are linked by local ties at the observation stations. Therefore, reliability and high accuracy are the main requirements for the determination of the different reference points in the corresponding local reference frame. At the Geodetic Institute of the University of Karlsruhe several scientific studies have been carried out to determine the reference point of radio telescopes at different observation stations and with different calculation models. Starting in 2002 the IVS reference point at Onsala Space Observatory was determined by 3D-circle fits with error propagation using full covariance information, which is custom procedure nowadays. In 2008 a completely new mathematical model was established able to fulfill future requirements as for example minimizing downtime of the telescope. Geodetic measurements with a tacheometer respectively a lasertracker at the Fundamentalstation Wettzell and the Onsala Space Observatory yielded a good verification of the model. This contribution shows the evolution and obtained expertise in reference point determination at the Geodetic Institute of the University of Karlsruhe by comparing the results of different campaigns at the Onsala Space Observatory.

Keywords. Reference point, VLBI, local tie, mathematical model, radio telescope, surveying

1 Introduction

The main objective of the two campaigns at the Onsala Space Observatory was the determination of the IVS reference point of the 20m radio telescope which is surrounded by a radome. But the mathematical models differ and, therefore, the strategies for the performance of the terrestrial geodetic measurements were different as well. Nevertheless the campaigns base on equal requirements. The reference point of a VLBI telescope of azimuth-elevation type is defined as the intersection of azimuth axis and elevation axis or if they do not intersect the point on the azimuth axis which is nearest to the elevation axis. This implies its independence of any orientation of the telescope and its inaccessibility. Furthermore, the 20m telescope at Onsala is surrounded by a radome, which limits the operating range for the measurement equipment. The radome wall is equipped with five steel pillars to be used as observation points for the measurements up to the telescope.

2 Campaign 2002

2.1 Measurements

The two reference points were connected by the measurement of marked points inside and outside the radome. The determination of the coordinates was separated in the horizontal and the vertical component. Therefore, the measurements included horizontal angles and horizontal distances from a Leica TCR1102 and a Leica T2002 and height differences from a Zeiss DINI10. Due to bad accessibility the height components of the steel pillars on the radome wall were calculated by trigonometric measurements. The IGS-reference point (Fig. 1) was appended from two net points.

The measurements to the telescope cabin, which result in the coordinates of the IVS-reference point, were carried out twice. In the first epoch four target markers were stuck at the two sides of the telescope cabin, in the second epoch the end points of the elevation axis itself were signalised by magnetic target markers (Fig. 2). These telescope points were observed in different telescope positions from two of the five ob-

Figure 1. IGS-reference point (right) in the IGS-monument (left).

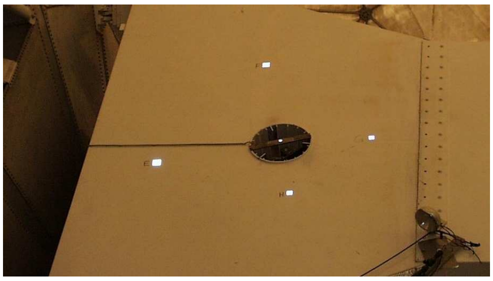

Figure 2. Target markers (2002) at the telescope cabin and at the endpoint of the elevation axis.

servation pillars without distance measurements simultaneously. The telescope was moved in discrete steps of 10° in elevation at 15 different azimuth positions.

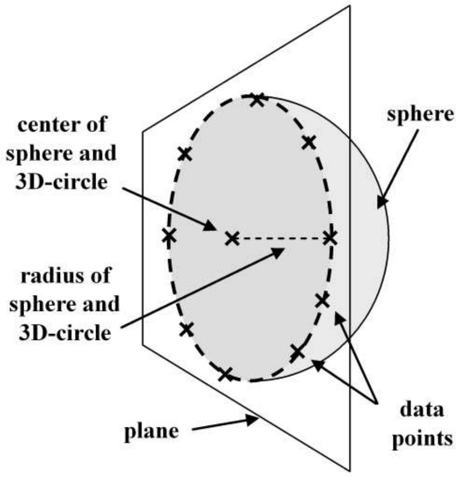

Figure 3. Schematic description of the 3D-circle fit.

Table 1. Standard deviations of the coordinates of the IVS-reference point (2002)

	X [m]	Y [m]	Z [m]
Epoch 1	0.0001	0.0001	0.0001
Epoch 2	0.0001	0.0001	0.0003

2.2 Reference point determination

The coordinates of the net points were determined by the software $Netz2D$ and $HEIDI$, programms of the Geodetic Institute (GIK) of the University of Karlsruhe (TH) (Fig 4). A free network adjustment was chosen to avoid stress in the network and still allow a transformation in superior coordinate systems. The standard deviations of the coordinates of the IGS-reference point were $\hat{\sigma}_{IGS} = [0.2\,0.2\,0.6]^T_{mm}$

The determination of the IVS-reference point based on the coordinates of the target markers at different telescope positions delivered from a 3D-network adjustment by $Netz3D$ (from the GIK). $Netz3D$ also supplies the full covariance matrix of the coordinates which was used for the following calculations. 3D-circe fits combined with restrictions deduced from the telescope structure yielded the coordinates of the endpoints of the elevation axis. The mathematical model is shown in Equation 1 and 2 and was calculated as a Gauß-Helmert-model.

$$f_i^1 = \left(\widetilde{X}_i - X_0\right)^2 + \left(\widetilde{Y}_i - Y_0\right)^2 + \left(\widetilde{Z}_i - Z_0\right)^2 \quad (1)$$

$$f_i^2 = A_0\widetilde{X}_i + B_0\widetilde{Y}_i + C_0\widetilde{Z}_i - 1 = 0 \quad (2)$$

The coordinates $\left[\widetilde{X}_i\,\widetilde{Y}_i\,\widetilde{Z}_i\right]^T$ are the observed parameters. The unknown parameters consist of the centre of the circle $[X_0\,Y_0\,Z_0]^T$, the radius R_0 and the parameters A_0, B_0 and C_0 of the plane the circle lies in (Fig. 3). The coordinates of the centres of the elevation circles again form 3D-circles which centre on the IVS-reference point. A detailed description of the model is given in (Eschelbach, 2002). The second epoch additionally provided the axis offset with $e = -0.0060\ \pm 0.0003m$. Table 1 shows the standard deviations of the IVS-reference point.

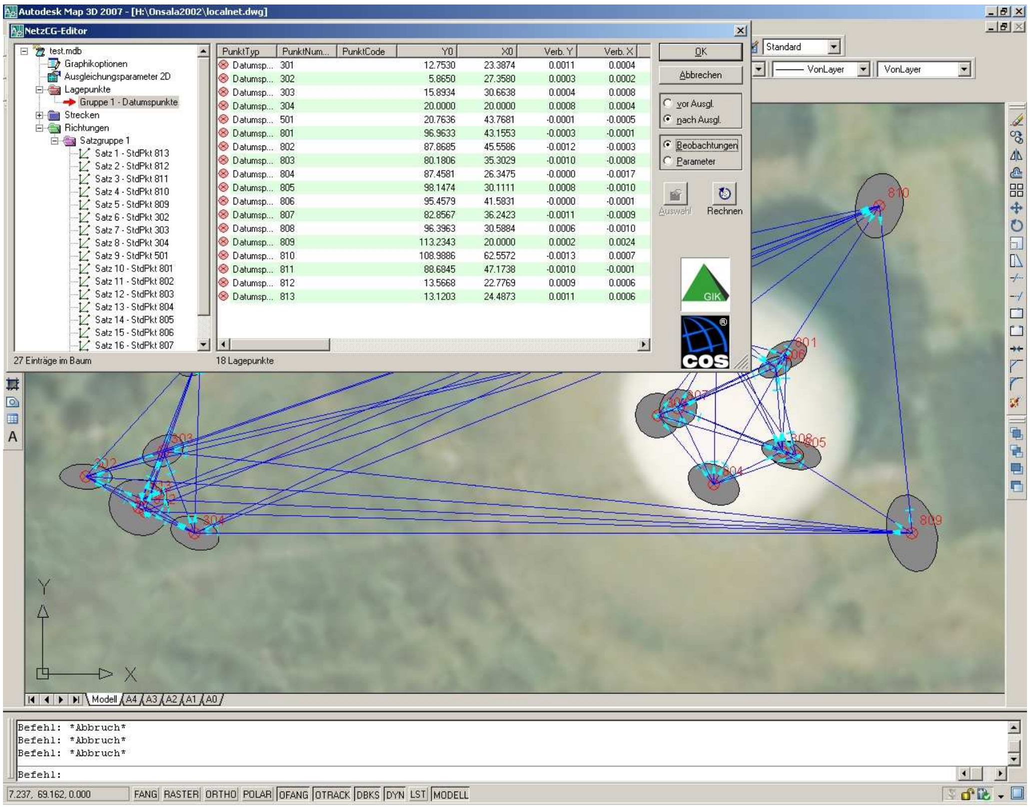

Figure 4. Observation network after net estimation (Aerial picture by Microsoft Visual Earth).

3 Campaign 2008

3.1 Measurements

In 2008 the second campaign was carried out. A Leica Lasertracker LTD840 was used instead of the two theodolites. In principle a lasertracker is similar to a tacheometer, but there are three main differences. A lasertracker operates with an interferometer, which limits its range but raises accuracy. It only works with automated target tracing and recognition and measurements do not refer to the plumb line. As a polar measuring system, furthermore, the two angles, which are necessary for 3D-coordinates, are measured with two angle encoders. The schematic description is given in Fig. 5. An emitted laser beam is deflected on a multiaxial rotatable mirror in the head of the lasertracker and is reflected at a mirrored target. The reflected laser beam is split into two signals. One leads to a position sensitive device, which controls the head to follow the target, the other one leads to the distance measurement device. For static targets the accuracy given by the manufacturer is $10ppm$ (2σ) in $40m$ range of operation, which is also limited by the opening angle of about $\pm 235°$ for the horizontal and $\pm 45°$ for the vertical angle (Leica, 2001). Moving objects are measured with an accuracy of $20 - 40ppm$ (2σ) in the same operation area.

At first the local network was measured with the LTD840. The local coordinate system of 2002 could not be used, because the lasertracker provides better accuracies than achieved in 2002 and moreover two of the five steel pillars had been replaced and have not measured yet. The measurements yielded the coordinates of the five pillars, three marked points in the radome basement, six marked points outside the radome and the IGS-reference point itself. The IVS-reference point is an immaterial point inside the telescope structure and can not be measured directly, therefore, so-called Cat-Eye-Reflectors with an opening angle of $\pm 60°$ were attached to the telescope cabin (Fig. 6). This large opening angle is necessary, so that the laser beam will not be disrupted immediately while the telescope is moved around the elevation axis. To fully utilize the cramped confines inside the radome the lasertracker was mounted on the pillars in a tilt

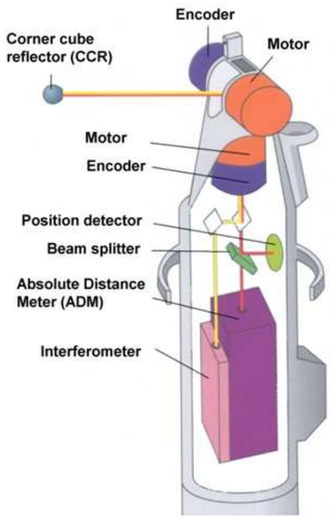

Figure 5. Schematic description of the Leica Lasertracker LTD840 (Leica, 2001).

Figure 6. Cat Eye Reflectors at the telescope cabin.

of 90° to the plumb line. This setup was possible, because the lasertracker works without referring to the plumb line anyway, and provided coordinates of 720 points resulting from 5 different azimuth positions and 18 different elevation positions (Lösler, 2009a) and (Lösler and Haas, 2009).

3.2 Reference point determination

The coordinates of the points inside and outside the radome were calculated from the lasertracker data by a free 3D-network adjustment using the author´s program. The accuracies of the coordinates resulted in $\hat{\sigma}_{IGS} = 0.3mm$ for each component and the full covarianz matrix was available after the net estimation, which provided error propagation for the subsequent determination of the IVS-reference point. The mathematical model of the determination was redeveloped and derives the coordinates of the reference point from dependencies between the local coordinate system and the coordinate system of the telescope (see Fig. 7). Equation 3 describes these dependencies between the two coordinate systems mathematically and considers the axis offset $Ecc = [0\, e\, 0]^T$ and possible inclinations of the axes by estimating the angles of rotation α, β and γ.

$$\begin{aligned} P_{Obs} = & P_R + R_x(\beta)\, R_y(\alpha)\, R_z(A + O_A) \dots \\ & R_y(\gamma)\,(Ecc + R_x(E + O_E)\, P_{Tel}) \end{aligned} \quad (3)$$

A detailed description of the derivation is given in (Lösler and Hennes, 2008), (Lösler, 2009b), in addition robust solutions for a non-linear system of equations (Gauß-Helmert-Modell) are mentioned. The model was first verified using measurement data from the Fundamentalstation Wettzell (Lösler, 2008). Unlike the traditional circle fit the new model does not require predefined telescope positions, which allows real-time measurement. Now the observation parameters are the coordinates of the points at the telescope cabin and the corresponding antenna orientation angles. The stochastical model (Equation 4) consists of the covariance matrix of the coordinates of the telescope points derived from the net estimation extended with the uncertainties of the antenna orientation angles A (azimuth) and E (elevation).

$$C_{ll} = \begin{bmatrix} \sigma^2_{X_1} & \sigma_{X_1Y_1} & \sigma_{X_1Z_1} & 0 & 0 & \sigma_{X_1X_2} & \cdots \\ \sigma_{Y_1X_1} & \sigma^2_{Y_1} & \sigma_{Y_1Z_1} & 0 & 0 & \sigma_{Y_1X_2} & \cdots \\ \sigma_{Z_1X_1} & \sigma_{Z_1Y_1} & \sigma^2_{Z_1} & 0 & 0 & \sigma_{Z_1X_2} & \cdots \\ 0 & 0 & 0 & \sigma^2_{A_1} & 0 & 0 & \cdots \\ 0 & 0 & 0 & 0 & \sigma^2_{E_1} & 0 & \cdots \\ \sigma_{X_2X_1} & \sigma_{X_2Y_1} & \sigma_{X_2Z_1} & 0 & 0 & \sigma^2_{X_2} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix} \quad (4)$$

The estimation of the IVS-reference point yielded a standard deviation of $\hat{\sigma}_{IVS} = 0.1mm$ for each coordinate. The axis offset was significantly identified with $e = -0.0062 \pm 0.0001m$.

4 Comparison of the results

The comparison of results of the two campaigns has to be exempted from any influence of the

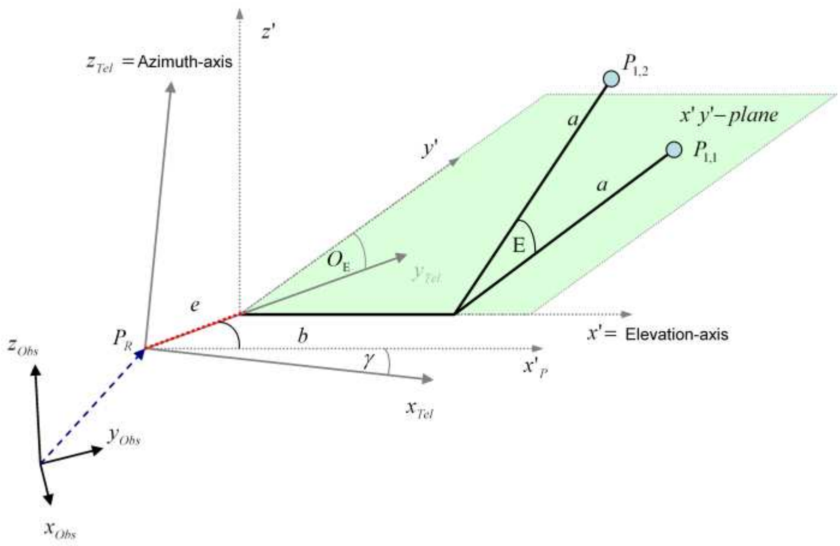

Figure 7. Dependencies between the local coordinate system and the coordinate system of the telescope.

Table 2. Comparison of the rersults

	2002 [m]	2008 [m]	Difference [m]
e	-0.0060	-0.0062	0.0002
d	79.5685	79.5678	-0.0007

geodetic data. Due to the slightly different net structure the coordinates of the reference points themselves do not reveal any conclusion about the stability of the local tie vector. Instead the length of the local tie vector and the axis offset are free from influences of the geodetic data and can be compared directly. The results in Table 2 are taken from (Haas and Eschelbach, 2003) and (Lösler, 2009a) respectively. A statistical hypothesis test detects significant deformations by choosing no deformation as the null hypothesis and the significance level to be $\alpha = 0.1\%$.

$$H_0 : T = \frac{(d_{2002} - d_{2008})^2}{\hat{\sigma}^2_{d_{2002}} + \hat{\sigma}^2_{d_{2088}}} = 5.4 \sim F_{1-\alpha,1,\infty} \quad (5)$$

If the T-value (Equation 5) exceeds the critical value $K_\alpha = 11.6$ of the *Fisher*-statistic the null hypothesis would have to be rejected and the deformation would be highly significant. The results do not show any statistically significant deformation.

5 Comparison of the strategies

The two campaigns in 2002 and 2008 achieved similar results and accuracies, but differ in a few points but basic ones. The biggest disadvantage of modelling the reference point determination by circle fits is the necessity of predefined movements of the antenna, which can only be carried out during long observation breaks of the telescope. Instead the new model can handle diffuse telescope positions but affords azimuth and elevation angles of the antenna. Furthermore, in 2002 the points at the telescope cabin were measured simultaneously from two observation pillars by two theodolites in combination with target markers without measuring distances. In 2008 the polar measurement system lasertracker with automated target tracing in combination with Cat Eye Reflectors was used, which could be replaced in the near future by a total station with the same operational opportunities but only with a slightly lower accuracy. Therefore, any disadvantages of the installation of the lasertracker can be evaded. In summary the new mathematical model in combination with modern surveying instruments is a successful evolution in IVS-reference point determination and represents an automatable measurement strategy for telescopes of azimuth-elevation type while the downtime of the telescopes is reduced or even avoided.

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