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Scientific note

The determination of the reference point of the VLBI antenna in Ny-Ålesund

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Abstract: We present here, the results of a campaign of measures carried on between August 25th and September 8th, 1999, in Ny-Ålesund, to tie the reference point of the VLBI antenna on the ground marks.

A number of Leica retro-targets has been attached (glued) all over the structure of the antenna, and their positions determined (horizontal and vertical angles, along with distance whenever it was possible) with respect to a local reference network. The positions of two points at opposite edges of the elevation axis have also been pinpointed and measured (only horizontal and vertical angles, in this case), to determine the vertical component of the reference point and to measure the offset between the elevation and azimuth axes. The local reference network has been measured using direct and inverse intersection depending on different position and mutual visibility of pillars. Occasionally some pillars have been measured using both methodologies. Furthermore, trigonometric levelling has been performed for connecting the levelling bolts of the six closest pillars to the 3-D network adjustment results and therefore obtain an univocal determination of the height of the VLBI reference point tight to the altimetric control network.

The positions of several markers on the antenna have been measured for 8 antenna azimuth angles, uniformly spread along 360 degrees, in steps of 45 degrees, with the VLBI antenna at the same elevation angle, nearly at the zenith direction. In order to test the position of the elevation axis, we did similar measures on a selected number of markers at different antenna elevation angles, in the range from 90 to 45 degrees, in steps of 15 degrees, for a fixed azimuth angle.

The analysis of these measures provide both coordinates for the position of the reference point of the VLBI antenna, and an estimate of the offset between the elevation and azimuth axes in the antenna of Ny-Ålesund. The offset vector from the reference pillar selected (marker 91) is $X=21.830\pm0.001$ m and $Y=18.787 \pm0.001$ m, while the height referred to the levelling bolt of the same pillar (marker 91b) is $Z=10.269\pm0.001$ m.

In the last section we list some suggestions for modifications of the local reference network around the VLBI antenna in order to simplify similar future campaigns of measurements.

1. Introduction

Very Long Baseline Interferometry (VLBI) technique applied to geodesy provides estimates of baseline lengths and their temporal variations on scales of thousands of kilometres, with sub-centimetre accuracy. However, the measurements with this technique correspond to a precise point on the antennas, the reference point of the VLBI antenna. Sometimes this point is called "invariant point", since its position is not variable in space at different pointing angles of the VLBI antenna and it remains in a fixed position during VLBI observations. For antennas with azimuth-elevation mounting, as generally is the case for single dish radio telescope, this point is located along the azimuth axis of the antenna. It coincides with the intersection of the elevation and azimuth axis if the two axes intersect. If the two axes do not intersect it is the projection of the elevation axis onto the azimuth

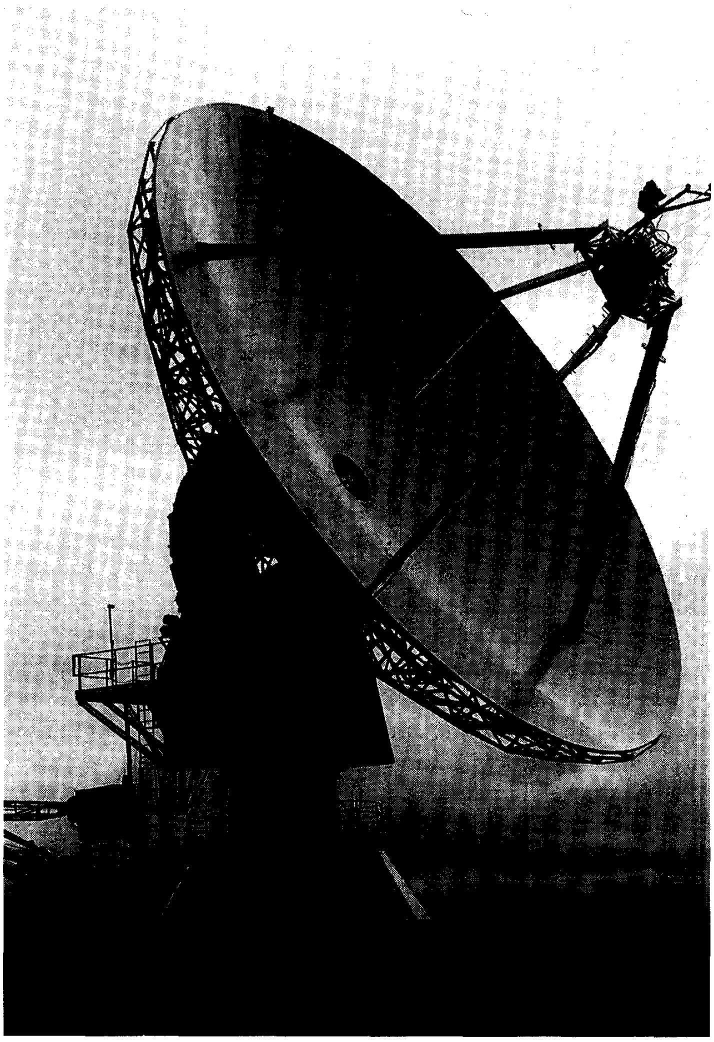

Fig. 1. The Ny-Ålesund VLBI antenna. A 20 m diameter dish with the S/X receiver in the primary focus.

axis. The second is the case for the VLBI antenna in Ny-Ålesund, with a diameter of 20 m and an axis offset around half a meter (Fig. 1).

The importance of linking the invariant point of a VLBI antenna to a local reference network is well known as a way to disentangle the possible (even unlikely) local movements of the antenna in respect to the ground, and the crust movements. In absence of that measurement we cannot be sure that local movements of the antenna and/or its basement do not affect the VLBI geodetic measurements.

In particular, for Ny-Ålesund, there is an unexpected and incomprehensible result that makes this measurement even more necessary: the significant discrepancy between the vertical velocities measured with GPS and VLBI techniques at this site. This suggests that some problems are present locally with one of the techniques (or even with both). For example, there are recent suspects of local motion at the GPS pillar. But also the VLBI antenna, even with its basement deeply dug into bedrock and permafrost could experience some local motion that should be detected, if present. Otherwise any interpretation of vertical motion detected up there in terms of crust motion would make no sense.

There are different ways of determining the position of the reference point of a VLBI antenna, depending on the antenna characteristics, *i.e.* whether the reference point is visible and physically identified, or whether this point is not visible or not physically identified. In the first case, this point can be used as a target for a total station (a theodolite equipped with a diastimeter), and any local motion will be easily detected and directly measured with a proper monitoring. If this is not the case, as it is for Ny-Ålesund, the reference point must be determined using the positions of some targets on the structure of the antenna, using a theodolite or a total station, at different pointing angles of the antenna. The strategy we have used to measure the positions of the markers was based on fundamental principle of direct intersection.

The motion of a generic point on the antenna structure during the motion of the antenna itself is contained in a surface with toric shape (Fig. 2). If the two axes intercept this surface becomes a sphere. A single point on the antenna, with a rotation only around

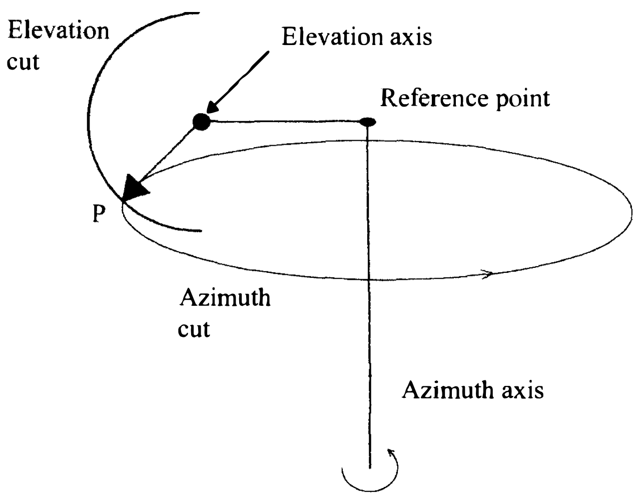

Fig. 2. A scheme of the motion of a generic point on the antenna during a rotation in azimuth and in elevation.

the azimuth axis, will move along a circumference, lying in a plane parallel to the horizontal plane. This is true under the assumption that structural deformations of the antenna, due to different effects (in general gravity and thermal deformation) are negligible. Hence, a sufficiently large set of measurements of the positions of a generic point on the antenna allows determination of the invariant point and the axis offset. That means motions around the vertical and the elevation axes. This second kind of motions (and measures) can be avoided, if it is possible to identify the elevation axis itself placing two targets at the opposite edges. In this case the position of the elevation axis can be determined and its distance from the vertical axis can be measured with indirect methods.

2. The measurements

We used standard Leica prisms for linking different pillars around the VLBI antenna and measure the local reference network while Leica tape targets were used for the antenna itself. The elevation axis of the antenna has been visualized, using two pins at the opposite ends of that axis (Fig. 3). A way to test that the two pins really represent the elevation axis would be to verify they are not moving during a run in elevation of the antenna. For the

Fig. 3. Particular of the elevation axis of the VLBI antenna in Ny-Ålesund where the pin (marker 50) has been set up. One of the Leica tape target used for testing the marker 50, is also visible. At the symmetric opposite side the marker 51 has been set up in the same way.

Ny-Ålesund antenna this easy test cannot be used, due to the fact that the pins are not turning with the antenna, while it is moving in elevation. Instead, we verified with a wooden meter, that two fixed points on the other sides of the rotating part of the antenna, at distances of about 50 cm from the pins, kept their distance to the pins constant during an elevation run within half a millimetre. Afterwards, another more precise test was done measuring the positions of one pin, and four targets on the structure of the antenna, at different elevation angles. This has been done, from two pillars at one fixed azimuth angle.

As described above we used several Leica tape targets on the antenna structure and two pins for identification of the elevation axis. In particular we used 26 Leica tape targets regularly distributed on the back of structure holding the VLBI dish. With the antenna pointing nearly to the zenith, ten targets were placed on the upper part; eight on the lower part; four near the elevation axis; four on the structure that support the gear of the elevation movements (see Fig. 4 for a detail of one marker on the lower part of the antenna). One of the reasons for using a large number of targets on the antenna is that this kind of measurement has never been tried before, hence it was difficult to define a priori how many points are needed to identify the rotation centre of the antenna, with the required precision. However, the main reason to use a large number of targets was the shape of the control network around the antenna. See Fig. 5 for the positions of the pillars and the VLBI antenna, as results of the measures presented here. Most of the pillars are so nearby that it is nearly impossible from these to target any point on the upper part of the antenna, while the ones on the lower part are reachable only with small zenith angles. The targets on the

Fig. 4. One of the Leica tape target placed on the lower part of the structure supporting the VLBI dish.

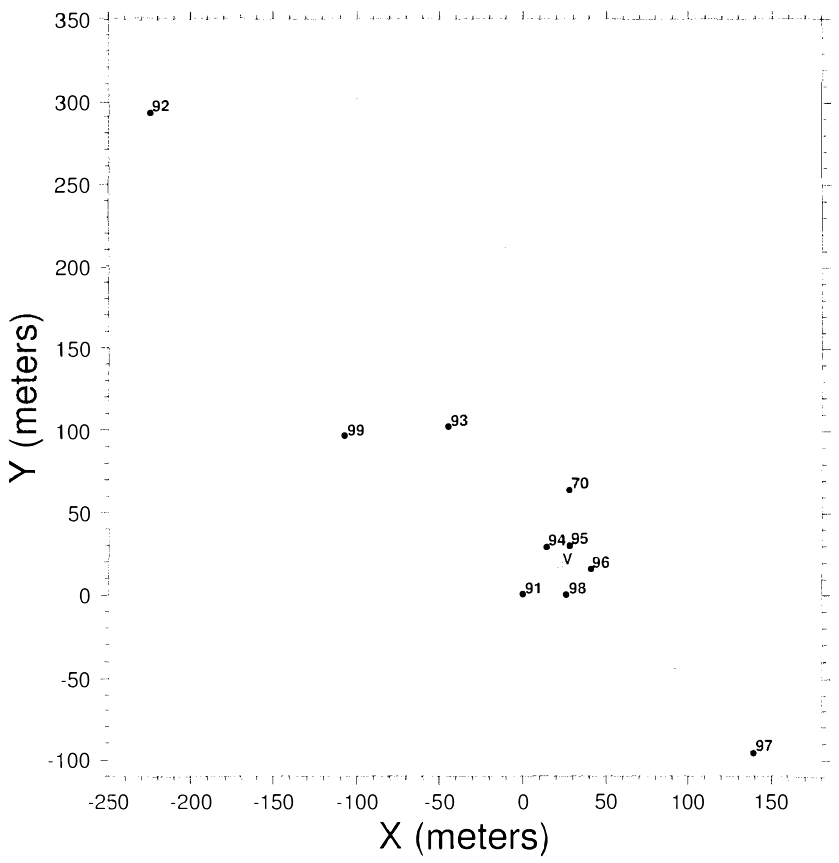

Fig. 5. The local control network around the Ny-Ålesund VLBI antenna. The VLBI antenna position (its azimuth axis) is marked by an open circle and a letter V. The pillars are marked with filled circle and the reference number used also in Table 1. The origin of the axis is pillar 91. The pillars 99 and 70 are not permanent and have been added using a tripod.

upper part are very useful when observing from distant pillars because in most cases the ones on the lower part were not visible.

The existing local control network and the targets on the VLBI antenna have been measured using two Wild total stations: TC2000 and TC2002. The eight pillars that constitute the original control network are made of concrete, deeply dug into bed rock, with a central Wild top screw for horizontal reference and an ex-centric levelling bolt for height reference (Fig. 6) and they constitute the planimetric and altimetric control network respectively. Thermal insulation layers protect all the pillars in order to reduce the effect of the sun. More details on the control network can be found in a paper by Hernes and Rekkedal (1997).

Due to the presence of buildings not all the pillars are mutually visible. In order to measure the network and the VLBI antenna, using forward intersection and inverse resection methods, two control points have been added using tripods: point 99 and point 70 on Fig. 5. This was particularly important to connect pillar 92 to the network, making the measurements made from there usable, and at the same time, enlarge the dimension of

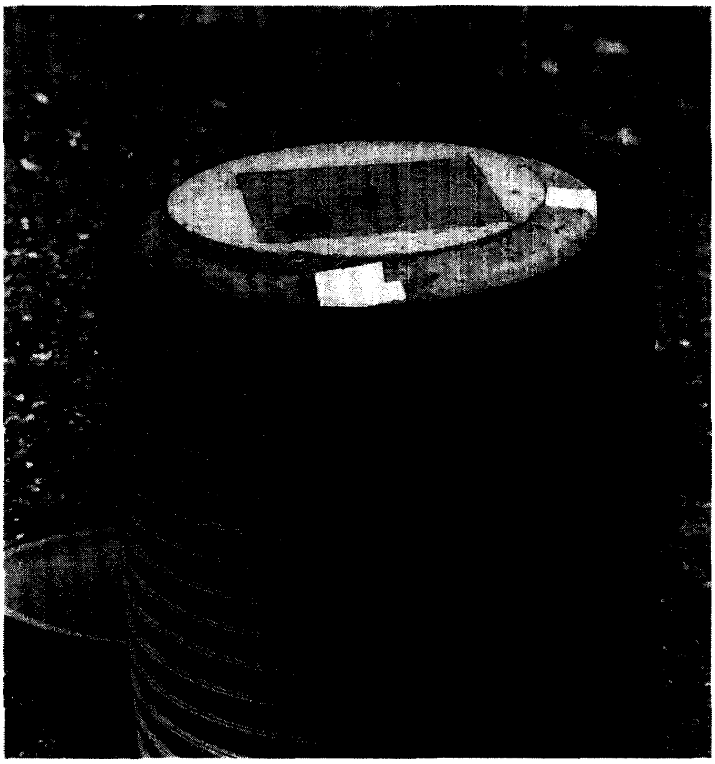

Fig. 6. One of the pillars of the control network around the VLBI antenna of Ny-Ålesund. It is visible the metal plate on the top of the pillar with the Wild central screw for horizontal reference and the ex-centric levelling bolt for height reference. All the pillars are equipped in the same way.

the network towards north-west and south-east direction. In fact, mostly for local topography reasons the pillars of the network are aligned in the opposite direction, as clearly visible on Fig. 5. For technical reasons the point 91 has been moved and substituted by point 61, with a possible difference in the vertical component of the position of the two points. It should be noted that, as clearly shown in Table 1, after the data analysis, this vertical difference turned out to be zero. Along with usual triangulation, some trigonometric levelling has been performed, in order to tight the measurements to the levelling bolts and therefore allow a unique height reference.

It should be noted that, as mentioned in the previous section, moving the antenna only around the vertical axis, all the targets on the antenna draw an arc of circumference. These arcs have different radii for every target and different heights, but all centres are aligned along the vertical rotation axis. Measuring the position of a target at least in three different azimuth positions, allows us to determine the radius and the centre of the corresponding circumference. We have then completed the coverage of antenna positions in the range of azimuth angles between 0 and 360 degrees, with a span of 45 degrees, with eight different azimuth positions. We added yet another position (ninth) (with different interval in azimuth) in order to make measurable one of the points that identify the elevation axis (point 51). At the end we proceeded with a new set of measurements, now fixing the azimuth position of the antenna, and varying the elevation angle. The fixed azimuth position (about 74 degrees) was selected to guarantee a good visibility of four targets on the antenna from pillars 61 and 98, at different elevation angles. In this case we measured the positions of the point 50 (one of the pins at the edge of the elevation axis) and other four targets around it. This has been done at different antenna elevation angles in a range of 45 degrees, in steps of 15 degrees. This procedure has been used to verify the precision of point 50 as indication of the position of the elevation axis.

3. Data analysis

The data acquired during the observation campaign have been combined in different files that have been edited and reviewed several times in order to correct the errors resulted from an incorrect measurement coding or other coarse mistakes. Merging these files, two worksheets have been created, one for each total station, totally containing more then 4500 rows. Each row of the worksheets corresponds to a collimation to a point of the general network (pillars and targets on the VLBI antenna). Therefore, each row contains at least two angles (one azimuth and one zenith) and, if measured, one distance. The data of each stratum have been combined applying Bessel's rule, thus obtaining one determination of the angle for each couple of direct and inverse observation (theodolite with vertical circle on the left and on the right respectively). The determinations originating from different strata and different total stations have been averaged obtaining one value for each angle. The distances measured at targets on VLBI antenna have been corrected applying an additive constant of 34.4 mm since no correction was imposed on the theodolite and the Leica retro-reflecting prisms that were used on pillars need no correction. In order to calculate the effect of the refractive index of the atmosphere the meteorological data collected at Ny-Ålesund weather station were used. It was the closest operating meteorological station while the measurements where taken and it is located at approximately 800 m from the VLBI antenna. The data recorded by the sensors located at 10 m above the sea level were used. Temperature and pressure have been inserted into Barrel and Sears' formula and a ppm correction of the distance has been calculated. As expected, the maximum correction value obtained by considering all the days of measurements was negligible, when applied to the distances involved in the survey. In hotter days the temperature rose up to 7–8°C (usually being only a few degrees above zero) and it was sufficiently low to remain the ruling parameter for calculating the correction that resulted in a maximum value of 9 ppm. Only a small number of pillars have reciprocal distances that exceed a couple of hundreds metres resulting in a few tens of measurements. Applying the atmospheric effect to those measurements the corrections resulted well within the precision of the diastimeter. Therefore no corrections for refractivity were introduced. The same reasons apply to the measured vertical angles. All the data have been analysed using STAR*NET V.4, a 2-D or 3-D least squares adjustment program for networks measured using angles and/or distances, produced by STARPLUS SOFTWARE INC. A total number of 1163 observations were used to estimate 475 parameters (3-D co-ordinates of points belonging to the general network); 368 measures of distances, 413 azimuth angles, 381 zenith angles and one fixed bearing. The a priori standard errors we have introduced for the adjustment are quite strict and are as follow:

— 0.0003 gon for Leica prisms on pillars and 0.0004 gon for Leica retro tapes located on

VLBI antenna for azimuth angles measured by both total stations

— 1 mm for distances to Leica prisms and 4 mm to Leica retro tapes when measured with TC2002; 2 mm to prisms and 4 mm to retro tapes when measured with TC2000. With both instruments, when observing at Leica retro-tapes, a different a priori standard error should be introduced depending on the diastimeter's signal incidence angle (Russo and Stumpo, 1993). In this particular case (retro-tape targets on the structure of the antenna having an unpredictable orientation) there hasn't been any possibility to account for this effect. However it should be mentioned that no response was obtained if the incident angle was larger than 40–50 gon from the vertical of the Leica tape target.

— 0.0006 gon and 0.0008 gon for both instruments for zenith angles for prisms and retro tapes respectively.

In order to determine the differences in elevation of the altimetric control network we have performed trigonometric levelling, using a 44 cm INVAR rod, on the levelling bolts of pillars 91, 93, 94, 95, 96 and 98. These altimetric points are named adding a "b" to the pillar number. Distances between the theodolite and the levelling bolts have been determined using the variable parallactic method. According to the formulae that characterise the methods, a proper propagation of the errors affecting the distances and the elevations has been performed and, for the latter, these errors have been used as a priori standard errors in the adjustment procedure. To perform the adjustment we have used STAR*LEV V.1.1, a least squares level network adjustment package from STARPLUS SOFTWARE INC.

4. Results

Both adjustments passed the chi-square test at 5% level giving the results showed in Tables 1 and 2. As mentioned before the pillar 91 has the same horizontal position as pillar 61, but a vertical displacement was allowed during adjustment process. No difference has been found in the vertical direction, as shown in Table 1. The coordinates in Table 1 are expressed in a local orthogonal reference frame arbitrarily centred at pillar 91 (or 61) with X-axis directed to pillar 98. The three components of the targets on the VLBI antenna, at different azimuth angles, have been also determined, with errors on the three components similar or sometimes larger then those obtained for the pillars.

In order to determine the position of the projection of the VLBI antenna's azimuth axis on the $Z=0$ plane, all the x and y coordinates of the 25 points where used to determine an equal number of circle's centres. We have used a program that performs this calculation using a least squares approach. All these estimated centres should coincide and identify the azimuth axis on $Z=0$. Nevertheless some small differences are evident and therefore the mean x-y position, its r.m.s. and the r.m.s. of the population were calculated. The results are $\boldsymbol{X=21.830\pm0.001}$ m and $\boldsymbol{Y=18.787\pm0.001}$ m, in the previous defined local reference system, and these components represent the planimetric position of the reference point of the VLBI antenna, *i.e.* the location of the azimuth axis of the antenna.

Analysing the values of the z coordinates of each rotating point, in some cases a difference was found. The circle described by each rotating point should have a unique height, being exactly the z values of the rotating point. Thermal deformations and/or inclination of the azimuth axis in respect to the local vertical can cause such effect. In order to analyse the characteristic of these differences, further investigation has been done. Using

Table 1. Results obtained from forward intersection measurements 3-D adjustment.

Pillar name	X(m)	Y(m)	Z(m)
61	0.000±0.000	0.000±0.000	0.000±0.000
91	0.000±0.000	0.000±0.000	0.000±0.000
92	−224.117±0.001	293.503±0.000	−2.668±0.001
93	−44.397±0.000	102.319±0.000	1.232±0.000
94	14.233±0.000	29.269±0.000	0.561±0.000
95	28.182±0.000	29.934±0.000	−0.337±0.000
96	41.190±0.000	15.247±0.000	−0.640±0.000
97	138.434±0.000	−95.235±0.000	−2.623±0.000
98	26.116±0.000	0.000±0.000	0.077±0.000
99	−107.309±0.001	96.849±0.001	−0.030±0.001
70	28.197±0.000	63.727±0.000	−5.249±0.000

Table 2. Rsults obtained from trigonometric levelling adjustment.

Point name	Elevation (m)	Std. dev (m)
91b	0.000	0.000
93b	1.233	0.003
94b	0.564	0.002
95b	−0.334	0.001
96b	−0.641	0.001
98b	0.074	0.001
91	0.217	0.001
93	1.449	0.001
94	0.778	0.001
95	−0.119	0.001
96	−0.422	0.001
98	0.294	0.001

a least square approach, the equations of the different planes univocally determined by the rotating points have been computed. Then the normal vectors to these planes have been determined, and the direction of the mean vector has been computed. This latter vector should represent the best 3-D determination of the VLBI azimuth rotation axis. Its deviation from the local vertical is 0.02±0.04 deg, well within the errors and the pointing precision of the VLBI antenna.

Using the total stations (TC2000 and TC2002) the measure of the distance of the two markers (50 and 51) that define the elevation axis of the VLBI antenna was not possible. In this case only horizontal and vertical angles have been measured and therefore a full 3-dimensional best fit using STAR*NET was impossible for the lack of the needed redundancy. On the contrary the same program has been used in two dimensions for computing the positions of the two markers at the different azimuth angles. Then all the azimuth angles measured from the different pillars have been used to compute the vertical component (Z) of these points. The mean of these vertical components has been computed with its standard deviation.

The result is $Z=10.052\pm0.001$ m and this is the vertical component of the reference point of the VLBI antenna, obtained using the loosely defined height reference system having origin in the intersection point of the axes of the theodolite on pillar 91. A univocal determination has been obtained using the data acquired with the trigonometric levelling. The differences in elevation between the levelling bolts and the heights of the axes intersection point of the theodolite on each pillar are shown in Table 2 and are a comprehensive solution that allows the tight of the planimetric local network (obtained using a 3-D adjustment) to the altimetric local network.

Considering the results shown in Table 2 the height of the VLBI antenna reference point referred to the 91b bolt is $\boldsymbol{Z = 10.269 \pm 0.001}$ m. The same point's height is connected to the other five bolts of the altimetric control network presented in Table 2, using results shown in this table.

The distance between the elevation axis, as defined by the position of marker 50 and 51, at six different azimuth angles (other 3 azimuth angles cannot be used for this purpose) and the invariant point has been also computed and the resultant axis offset is $\mathbf{0.524 \pm 0.003}$ m.

A final computation was needed for verifying the stability of the marker number 50, that identifies the elevation axis. In order to do that the distances from four different markers to the marker 50 have been computed, using the results of the markers positions during the elevation run, at fixed azimuth angle. The distances of the markers to the pin (marker 50), varied from 3.8 m to 0.34 m and their errors have been estimated to be 0.001 m. Then we can conclude that the elevation axis is defined by marker 50 within a circle with radium equal to 0.5 mm. Similar measures can not be performed for marker 51. However the results of the preliminary test, with the same results as the ones for marker 50, suggest that the marker 51 has the same behaviour as marker 50.

5. Final remarks

We have planned to measure the reference point of the VLBI antenna at Ny-Ålesund in the Spitzbergen Island. The task was completed successfully, with the determination of the three coordinates of the reference point with an error of 0.001 m in each coordinate. Also the antenna offset (the distance between elevation and azimuth axes) has been determined with an error of 0.003 m.

The use of Leica tape targets, instead of other kind of retro reflectors has been quite useful even if the work, due to the control network shape and weather conditions, was quite hard and time consuming.

It is well known that a single measure of the reference point, never measured before for this antenna, is only the starting point for a subsequent series of regular measures. In this respect we are suggesting here also some technical development that could make the following measures a bit easier and shorter.

First of all for this particular antenna is not difficult to materialize the reference point. On the VLBI antenna, not far from the elevation axis, there is a platform that can be modified and used to place a target at the reference point position. As soon as the point is materialized, even if it is not visible from all the present pillars, it can be measured quite easily in a short time (less then one day).

As a second item we point to the shape of the control network. Many limitations are related to the topography of the area. These are the presence of the airport on one side and steep slope on the other, and a number of buildings that put a severe limitation on mutual visibility of the reference pillars. However some of the pillars are too nearby the antenna itself, and that makes measures to the antenna difficult and sometime impossible. In some cases it is possible to move the pillar (or build a new one) a bit farther from the VLBI antenna. In particular this should be possible for pillar 98 and 96. Moreover pillars 94 and 95 are almost unusable and there is not much space left on this side of the VLBI antenna. It might be possible to build a new pillar at the position of our point 70 (made available using a tripod).

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