Is the subreflector of the 40 m radiotelescope tilted?

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Informe Técnico IT-OAN 2010-15

Revision history

Version	Date	Author	Updates
1.0	10-08-2010	P. de Vicente	First version
1.1	10-10-2010	P. de Vicente	Second version. Update on new pointing/focus model

Contents

1 Introduction

Report OAN 2008-08 pointed for the first time, that a pointing error in elevation happens when the subreflector is shifted along the Z axis, which, in an ideal situation, should match the axis of the hyperboloid and of the main paraboloid reflector. This report investigates further this effect and tries to find an explanation and offer a solution.

2 Subreflector movements

The 40m radiotelescope subreflector is an hyperboloid with a diameter of 3.28 metres. It is supported by a structure attached to the tetrapod of the telescope. The subreflector has five degrees of freedom; it can move along the Z, X and Y axis and rotate around the X and Y axis. The movements are implemented via 6 linear drives, also known as spindles, which are depicted in Fig 1.

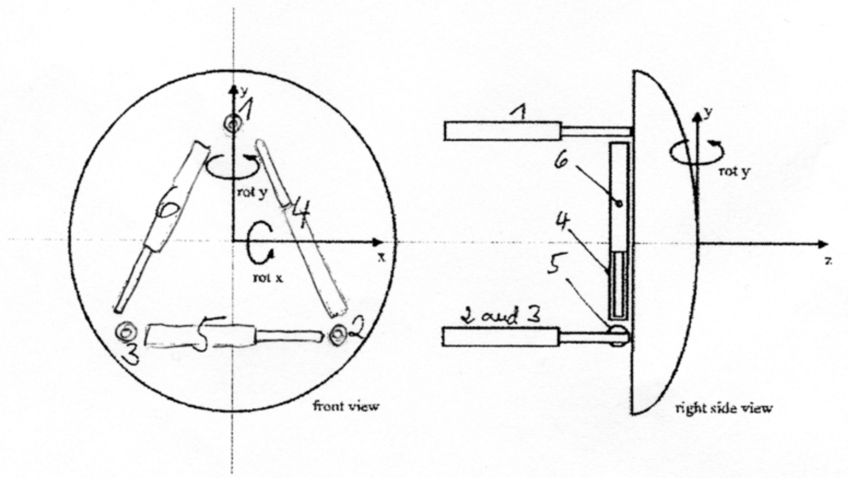

Figure 1: *Schematics of the subreflector coordinate system and the linear drives that move the subreflector.*

The reference system moves with the antenna and hence it is not fixed with respect to the ground. The X and Y axis are perpendicular to the symmetry axis of the hyperboloid (and of the paraboloid if properly aligned). The Y axis is perpendicular to the ground and the X axis is horizontal (and parallel to the ground) when the antenna looks towards the horizon. Y increases upwards and X rightwards as we look towards the subreflector from the paraboloid. Z axis is along the symmetry axis of the hyperboloid and increases towards the surface of the paraboloid. Rotation around the X axis is positive when the subreflector is tilted from a vertical position to another position in which it points towards the ground. Rotation around Y axis is positive when the subreflector turns counterclockwise as seen from the sky.

The range of the movements of the subreflector along the different axis are summarized in table 1:

Type of movement	Lower limit	Upper limit
X displacement	-65 mm	65 mm
Y displacement	-75 mm	75 mm
Z displacement	-50 mm	50 mm
Tilt around X	-2 °	2 °
Tilt around Y	-2 °	2 °

Table 1: *Range of movement for the five degrees of freedom of the subreflector.*

3 Current optimum subreflector position

The current optimum position for the subreflector in its "secondary" position was determined in 2008 (de Vicente 2008) using the 22 GHz receiver and finding the maximum efficiency. X axis remains fixed at -6 mm and Y and Z axis depend on elevation as shown in fig. 2. The position for both rotation angles was chosen to be 0 since the efficiency depends weakly on the tilt angle and measurements did have a poor resolution.

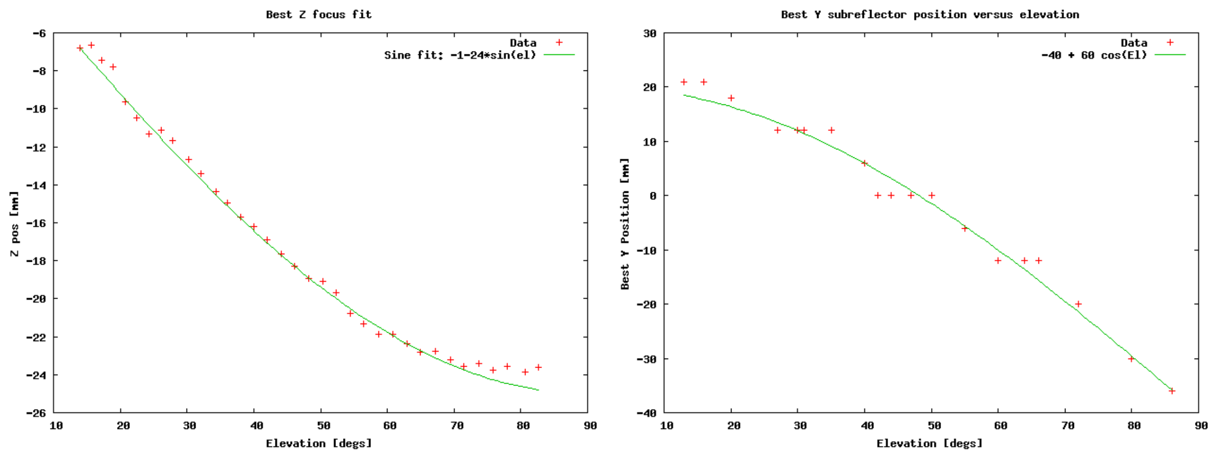

Figure 2: *Best focus in Z and Y at 22 GHz as a function of elevation. Z and Y values are in millimeters and were obtained in 2008. They have been rechecked in 2010. A sinusoid plus a constant term was used for fitting the data. The curve is used to predict the best focus as a function of elevation.*

Table 2 shows the current best focus model used at C, X band and 22 GHz, using an analytical function which depends on elevation.

Focus in Z may change 2 mm from day to night. The temperature of the environment and the illumination from the sun do have a non negligible influence at frequencies higher than 20 GHz. Figure 3 shows the normalized antenna temperature towards 3C274 and DR21 versus Z for different pointing drifts. While observing 3C274 all legs from the tetrapod were illuminated by the sun westwards and the environment temperature was 32 to 27 C. DR21 was observed during the night and at a temperature range of 29 to 26 C.

Type of movement	Current model (August 2010)
X displacement [mm]	-6
Y displacement [mm]	$-40 + 60\ \cos(el)$
Z displacement [mm]	$-1 - 24\sin(el)$
Tilt around X [°]	0
Tilt around Y [°]	0

Table 2: *Current best focus model (subreflector position) as a function of elevation. August 2010*

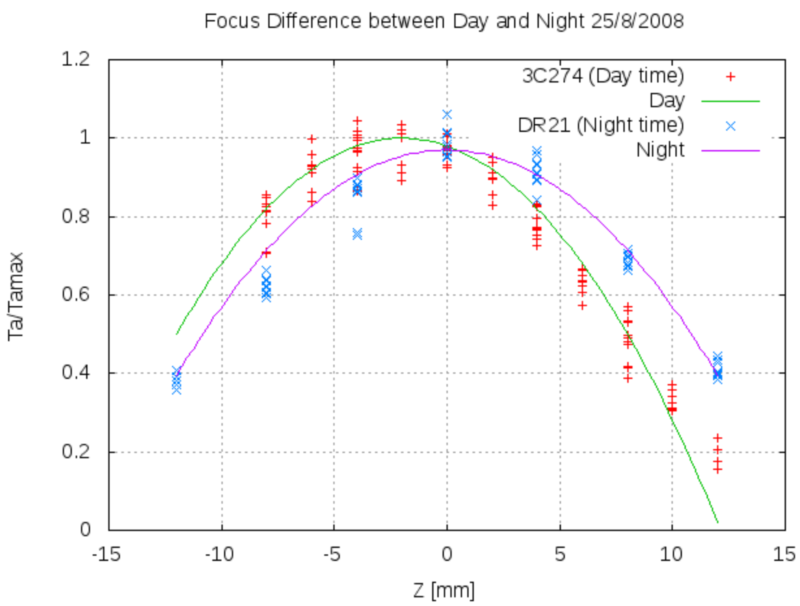

Figure 3: *Normalized antenna temperature towards 3C274 (day time) and DR21 (night time) versus Z. Several pointing drifts at elevations between 40 and 80 degrees were performed. Two polynomials of degree 2 have been fitted to show that the maximum antenna temperature happens at Z=0 mm and Z=-2 mm.*

4 Subreflector rotation around X and Y axis

Prior to investigating the problem to be addressed in this report we searched for the best tilt angle around the X and Y axis by making double pointing scans on 3C84 and DR21 along the whole elevation range while testing different tilt angles. Results are in figure 4. Since efficiency has a weak dependence on the tilt it was necessary to rotate the subreflector from $+1°$ to $-1°$ in steps of 900 arcsecs to notice the loss of efficiency. Data are scarce and noisy and hence results are not conclusive. According to them the tilt around the X axis is constant with elevation and approximately equal to 0.1 degrees (360 arcsecs). The tilt around the Y axis varies with elevation and seems to be associated to the azimuth. It varies between -0.10 and 0.15 degrees.

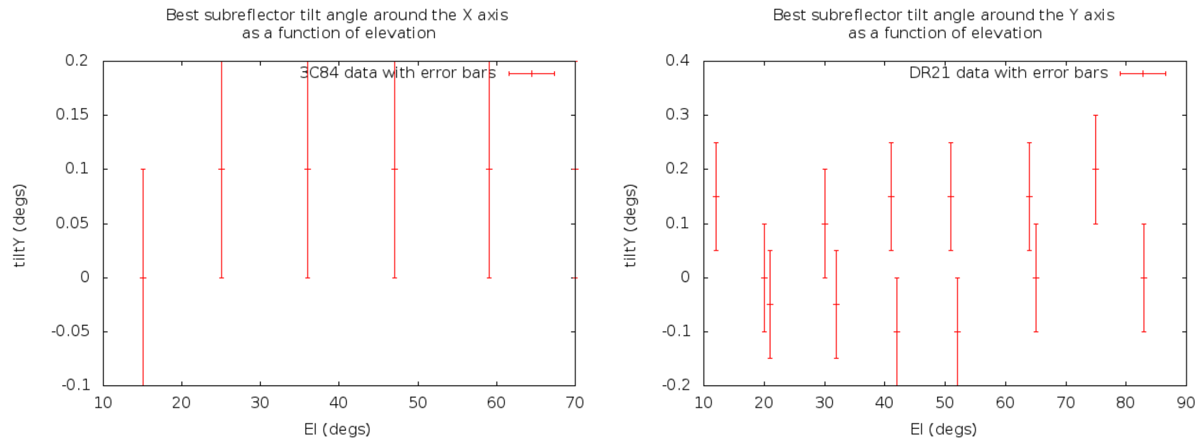

Figure 4: *Best subreflector angle around the X and Y axes. Obtained from double pointing scans and the highest signal. Data are scarce and noisy.*

5 Effects of a subreflector tilt/displacement on pointing

The shift of the subreflector along the X and Y axes and the rotation around these axes cause a pointing error. These errors can be deduced from geometry optics as explained by Barcia (1995) for a cassegrain telescope. From now on we will follow Barcia's formulae for a cassegrain. In order to estimate these errors we need to know the most important optical parameters of the antenna. We include them in table 3. The beam deviation factor has been estimated from the focus diameter ratio and the illumination in the main reflector (Baars 2007).

A displacement of the subreflector upwards causes the antenna to point downwards (see figure 5a). Similarly a displacement of the subreflector rightwards causes the antenna to point leftwards. The pointing error can be estimated as follows. Let δ_s be the linear displacement of the subreflector along the Y or X axis. The pointing error will be:

$$\theta = \left(K - \frac{K_e}{M}\right) \frac{\delta_s}{F_m}$$

Parameter	Variable	Value
Main Reflector Diameter	D_m	40 m
Primary focus	F_m	15 m
Primary focus primary diameter ratio	F_m/D_m	0.375
Primary Beam Deviation Factor	K	0.375
Subreflector Diameter	D_s	3.28 m
Excentricity	e	1.0995
Magnification	M	21.09
Distance subreflector vertex to primary focus	f_1	1.204 m
Distance subreflector vertex to secondary focus	f_2	25.396 m
Secondary focus	F_s	26.6 m
Equivalent focus	F_e	316.6 m
Ratio Focus Diameter for equivalent paraboloid	F_e/D_m	7.9
Beam Deviation Factor for equivalent paraboloid	K_e	1.0

Table 3: *Main geometric parameters for the 40 m antenna.*

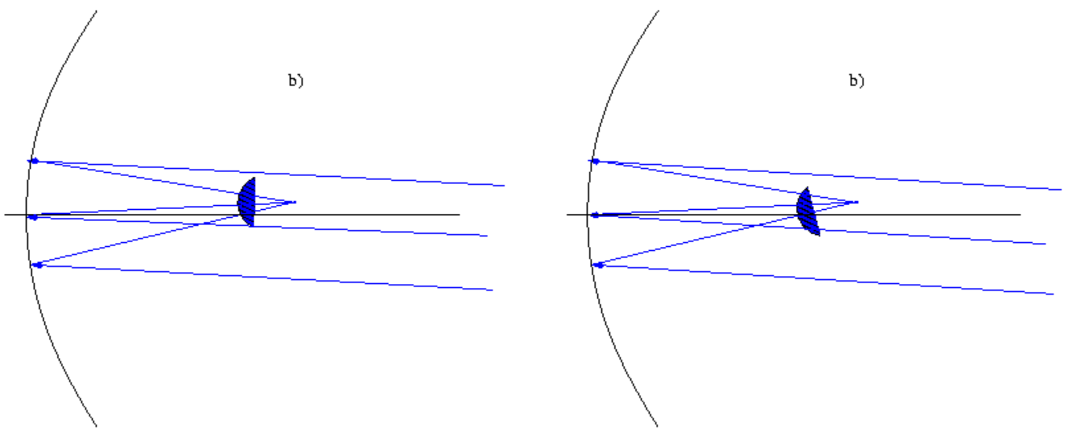

Figure 5: *Simple scheme to show the pointing error direction when the subreflector is moved upwards (a) or tilted downwards (b), according to optical geometry. In both cases the radiation coming upwards concentrates above the axis symmetry. The secondary (hyperboloid) focus has to be at the primary focus, which means that, either the subreflector is moved upwards or tilted downwards. The angle with the simmetry axis is very small and has been greatly exagerated in the plot.*

Assuming that the equivalent paraboloid is the same for all receivers and that there is no other magnification after the subreflector, we get a pointing eror of **-10.35"/mm**. However there are several mirrors which modify the focal length: M5 (an elliptical mirror) for 22 GHz, the parabola after M4 for C band, and the parabola plus the dichroic mirror for X band. Currently we do not know the magnification of any of these mirrors but they shorten the equivalent focus and hence -10.35"/mm is a lower limit to the real pointing error.

A rotation of the subreflector around the X axis downwards (looking towards the ground), being the vertex of the hyperboloid the center of rotation, causes the antenna to point downwards (see figure 5b). Similarly a rotation around the Y axis rightwards causes the antenna to point rightwards. Let α be the rotation angle. The pointing error will be:

$$\theta = \frac{\alpha f_1}{F_m}(K + K_e)$$

As in the previous case we will assume that the same equivalent paraboloid is valid for all receivers. We obtain **0.144 arcsecs/arcsec**.

Model and results from observations at 22 GHz are summarized in table 4.

Type of movement	Units	Col Az error (Estimated)	El error (Estimated)	Col Az error (Observed)	El error (Observed)
X displacement	1 mm	10.35″	0″	11″	0″
Y displacement	1 mm	0″	10.35″	0″	11″
Tilt around X	1 arcsec	0″	0.144″	0″	0.154″
Tilt around Y	1 arcsec	-0.144″	0″	-0.154″	0″

Table 4: *Estimated and measured pointing errors due to radial displacements and tilts of the subreflector.*

6 The pointing shift due to Z focusing

This problem is already known since 2008 and it is described in report OAN-2008-8. When the subreflector is shifted along the Z axis, the antenna displays a pointing error which depends linearly on the shift. Figure 6a and 7a show the antenna temperature (green) and the pointing error (red) versus elevation for 7 cycles in which the subreflector was moved along Z from -8 mm to 12 mm in steps of 4 mm. The data come from double pointing drifts at 22 GHz on 3C84 while tracking the source from zenith to horizon.

Plots from 6b and 7b represent respectively the elevation and azimuth pointing error versus Z for 7 elevation intervals. There is a big systematic pointing error along elevation for the elevation drifts while there is very small systematic pointing error along the azimuth axis. The elevation error in 6 seems to depend linearly on Z and to be approximately independent of elevation. A total displacement of 20 mm along Z causes a pointing error in elevation of approximately 30 arcsecs, which gives 1.5 arcsec per mm. The lower elevation interval has a bigger dispersion probably due to a systematic pointing error in elevation drifts associated with

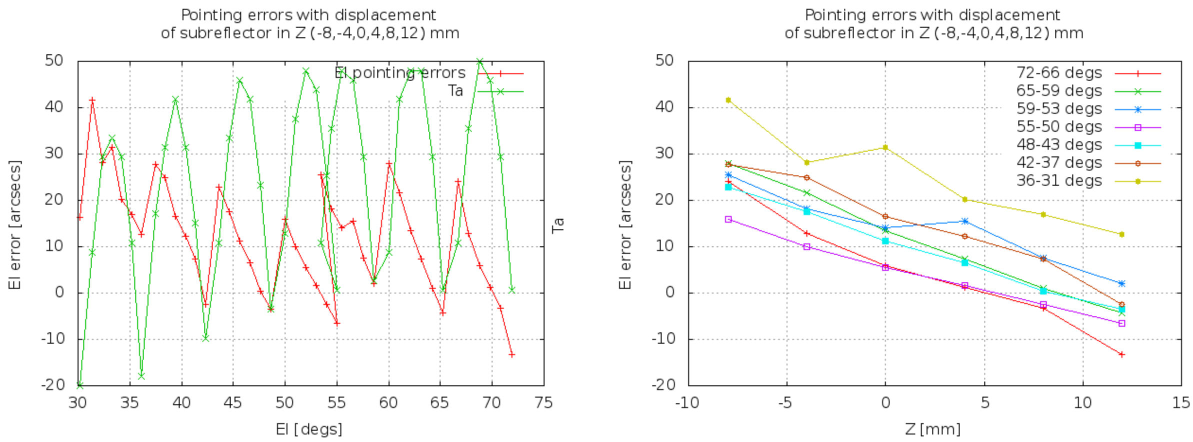

Figure 6: *Two curves are depicted. Left: In green, antenna temperature towards 3C84 at 22 GHz versus elevation; In red, elevation pointing errors for the same data. Right: elevation pointing error versus Z for 7 elevation intervals (each interval is depicted in a different color). The data were obtained averaging the subscan fits from double pointing drift in elevation while tracking the source from 70 to 30 degrees in elevation.*

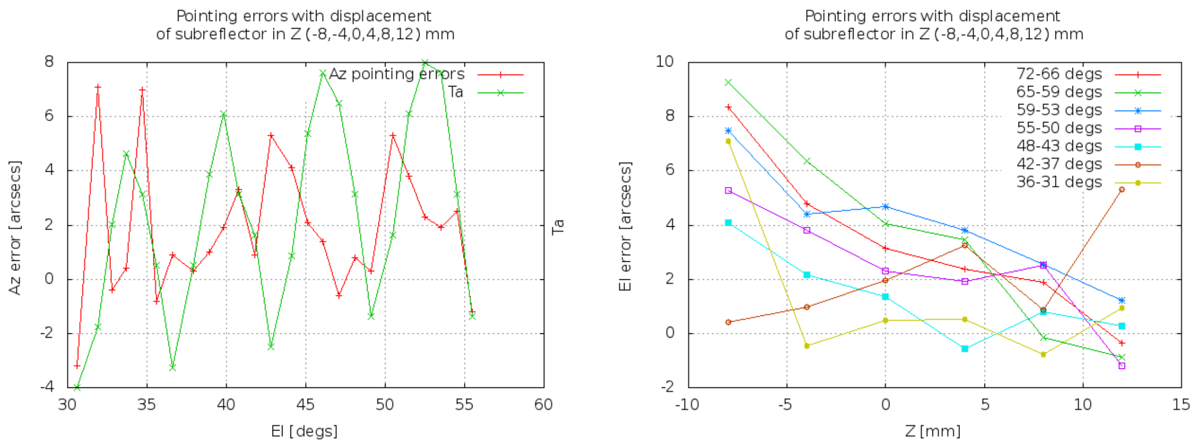

Figure 7: *Two curves are depicted. Left: In green, antenna temperature towards 3C84 at 22 GHz versus elevation; In red azimuth pointing errors for the same data. Right: elevation pointing error versus Z for 7 elevation intervals (each interval is depicted in a different color). The data were obtained averaging the subscans fits from double pointing drifts in azimuth while tracking the source from 70 to 30 degrees in elevation.*

the hysteresis of the elevation encoders. The azimuth error is very small, depends linearly on Z and also is independent of elevation. A total displacement of 20 mm along Z causes a pointing error in azimuth of approximately 5 arcsecs, which gives 0.25 arcsecs per mm (6 times less than the other axis). For the rest of the discussion in this section we will focus on the error around the X axis and leave the error around the Y axis for the end.

The dependence of the elevation error on Z may have two causes which are graphically explained in figure 8:

- The subreflector supporting structure is tilted around the X axis.
- Z movement is incorrectly implemented by the linear drives, in such a way that the subreflector is also tilted when it is moved along the Z axis.

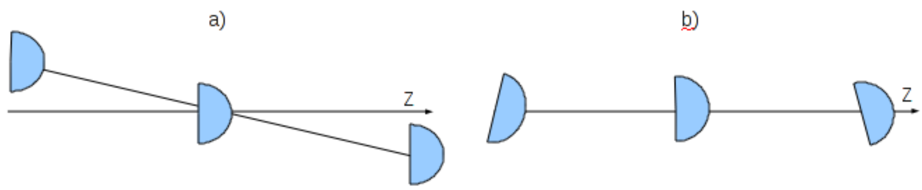

Figure 8: *Two possible explanations for the existence of an elevation error which depends linearly with Z: The subreflector structure is tilted and a movement along Z moves up or down the subreflector (a), or the subreflector tilts when moving it along the Z axis. Vertical axis is Y, and the subreflector is seen from one side.*

6.1 Permanent subreflector tilt hipothesys

If the subreflector structure were tilted we can estimate the direction and the angle of tilt. Figure 9 shows a schematics. When the subreflector is moved along the Z axis getting away from the paraboloid (Z decreases) the error pointing increases. According to table 4 a shift of 1 mm along the Y axis causes a pointing error of 11 arcsecs. This means that an error of $30''$ is caused by a shift of approximately 2.7 mm along the Y axis. Hence a movement of 20 mm along Z originates a shift of 2.7 mm along Y which can be explained if the subreflector structure is tilted 7.6° approximately. The pointing error increases when the subreflector gets away from the paraboloid, which means that the subreflector goes up.

A permanent tilt of the subreflector structure of $\sim 7°$ is too large. During the commissioning of the 40 m radiotelescope in 2006, the axial subreflector movement was checked at 45° elevation using a theodeolite. The subreflector did not move neither along X or Y axis when its was displaced $\pm$25 mm along the Z axis. Table 5 summarizes the measurements (Barcia 2007). It was also seen that a tilt around the X and Y axis did not move the subreflector center from the crosshair of the theodolite. Hence we think that it is rather improbable that the subreflector structure is tilted.

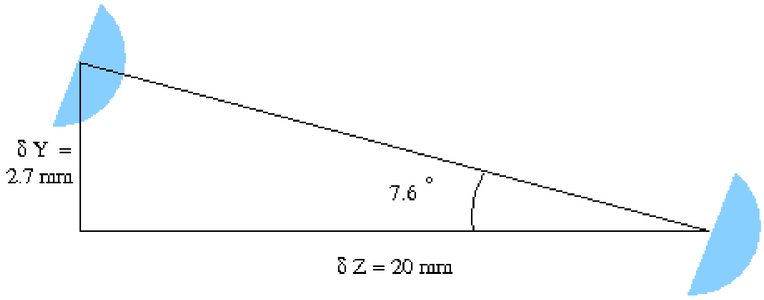

Figure 9: *If the subreflector structure were tilted, a movement along Z of 20 mm causes a shift in Y of 2.7 mm, and a pointing error of 30" in elevation.*

Focus	X (mm)	Y (mm)	Z (mm)	Transversal shift	Distance (mm)
Secondary focus	-6.94	10.93	25	0	12381
Secondary focus	-6.94	10.93	0	0	12405
Secondary focus	-6.94	10.93	-25	0	12430

Table 5: *Cross of the mirror in the subreflector with the paraboloid axis. Theodolite total station (elevation: 45.38). No transversal movements were seen when the subreflector moved along Z.*

6.2 Dynamic subreflector tilt hypothesis

If the subreflector tilts when a Z shift is applied, we can also estimate this tilt from table 4. A pointing error of $30''$ caused by a subreflector rotation around the X axis requires a tilt of 194 arcsecs ($\sim 3'$).

A tilt around the X axis associated with a displacement along the Z axis may be possible. The Z displacement is achieved by the movement of 3 linear drives at the same time. However if the linear drive on top, does not move the same ammount as the other two or the drives are not parallel to the movement, the net effect is a rotation around the X axis. In order to cause a rotation of 3 arcmin either the top spindle should have an error of 3 arcmin relative to the direction of movement or the linear drive should have an error of 870 μm. The latter value is probaby too high. The rotation is towards the ground when the subreflector is moved away from the paraboloid (Z decrease).

We have made some tests to check the last hypothesis. A shift in Z has been corrected by a rotation of the subreflector around the X axis. The rotation was positive when Z increased and negative when Z decreased and the ammount was 9.8 arcsecs per mm of shift along Z. Figure 10 shows the results of double pointing drifts while tracking 3C274 and shifting Z from -8 mm to 10 mm. We can extract two conclusions: the sign and magnitude of the rotation correction around X is correct since there is no net elevation pointing error dependent on Z and the fit in Z applied during the operation of the telescope along the whole elevation range has to be corrected by a similar rotation correction around the X axis.

Figure 11 shows the normalized antenna temperature as a function of Z at 60 degrees elevation when the rotation correction is applied and when it is not applied. There is no significative

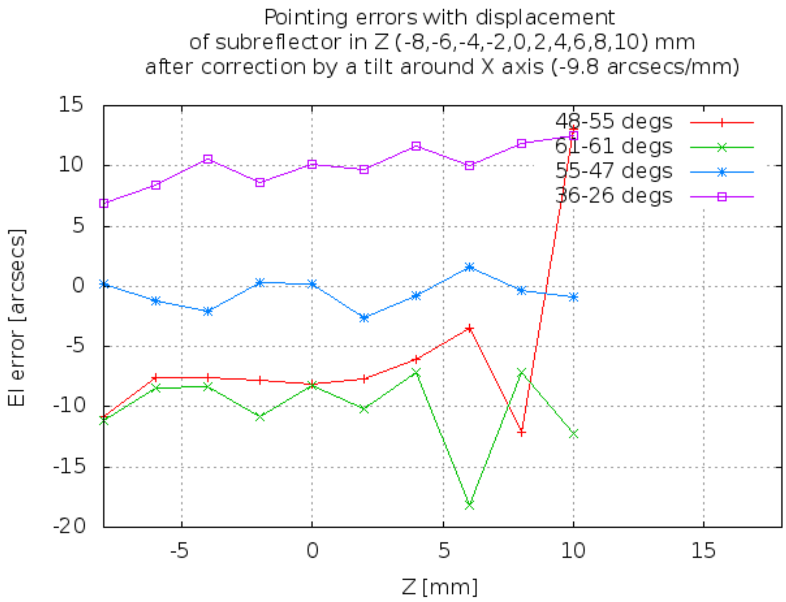

Figure 10: *Elevation pointing error versus Z for different elevation intervals having corrected each relative positive Z shift by a relative rotation of 9.8 arcsecs/mm around the X axis. Each interval is plotted in a different color.*

difference observed, which means that the pointing error due to the tilt of the subreflector was low and did not have an important effect on efficiency.

6.3 Effect on the rotation around the Y axis

After applying the dynamic correction which corrects the tilt of the subreflector around the X axis, we have also examined if a correction for the tilt around the Y axis is required. Figure 12 shows the results from double pointing drifts on 3C274 near culmination for different Z values. The figure shows several important facts:

- All values for Z=12 mm are much lower than the rest of values. This may be a real effect or a consequence of the signal to noise ratio, since which such defocussing, the signal is much weaker and broader.
- Curves which correspond to culmination are flater than the curves for the intervals: 59-55 and 54-49 degrees of elevation. This may come from the fact that Z also varies within these intervals; according to figure 2, Z varies around 2 mm at most.
- The pointing error is 7”/20 mm for the flater curves and 10”/20 mm for the steeper ones, if one discounts Z=12 mm. These ratios, according to table 4 correspond to a tilt of 48 and 69 arcsecs around the Y axis respectively. However from figure 7 we get a pointing error of 5”/20 mm which corresponds to a total tilt of 32” for a shift along Z of 20 mm.

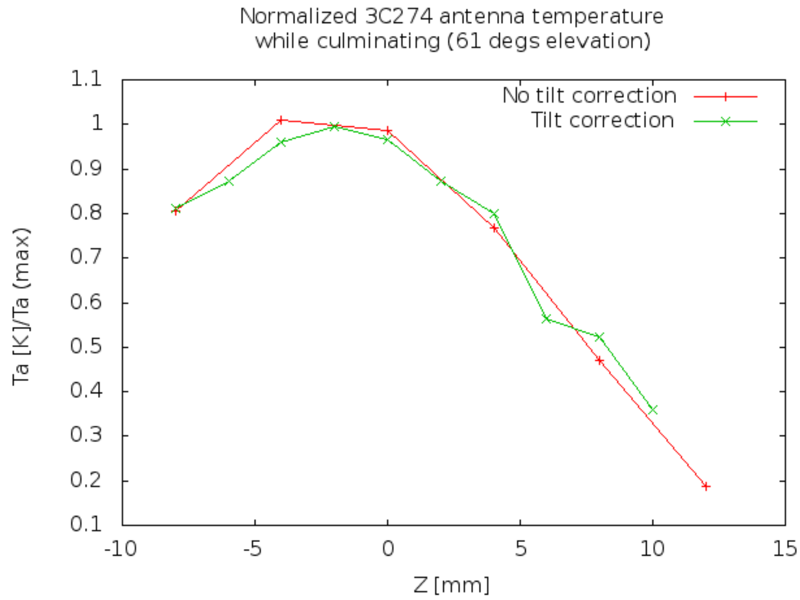

Figure 11: *Normalized antenna temperature towards 3C274 for different Z positions at 61 degrees elevation with and without a tilt correction applied. Data were obtained averaging the results from the subscans of each double pointing drift.*

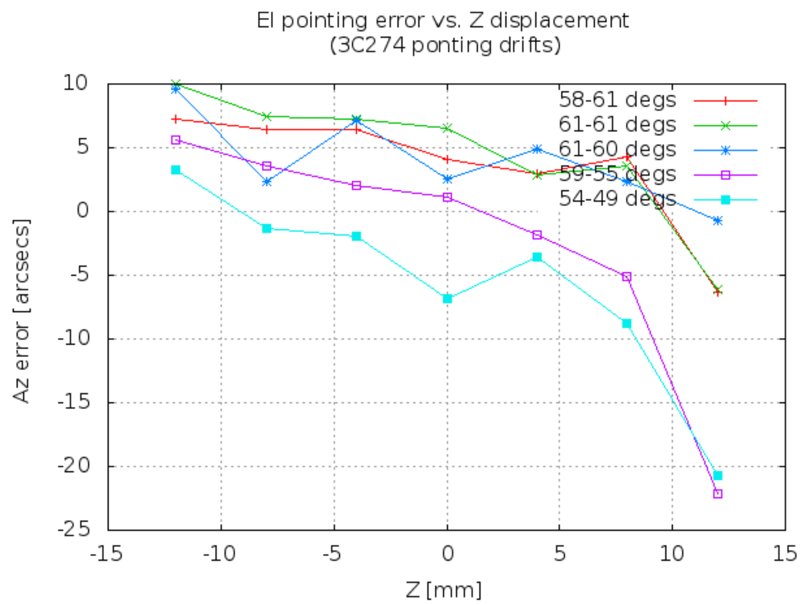

Figure 12: *Azimuth pointing error versus Z displacement after applying a subreflector tilt correction around the X axis. Data were obtained averaging the results from the subscans of each double pointing drift.*

We took a conservative approach and assumed that the proportionality between a Z displacement and a tilt of the subreflector tilt around the Y axis is 1.2”/mm. We have tested the correction. The results from pointing drifts in which both tilt corrections are applied for different Z values are shown in figure 13. In these case we also applied the tilt correction required by the dependence of the focus along Z with elevation.

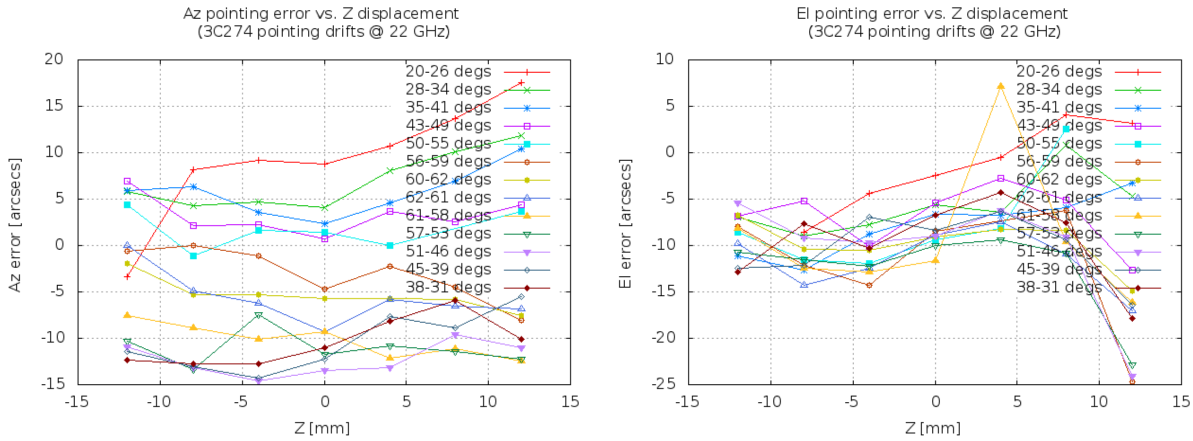

Figure 13: *Azimuth and elevation pointing error versus Z displacement after applying a subreflector tilt correction around the X and Y axes. Data were obtained averaging the results from the subscans of each double pointing drift.*

7 Conclusion, consequences and solution

The most probable cause of the pointing error due to a subreflector displacement along the Z axis is a subreflector tilt caused by one or more linear drives at the subreflector parallel to the hyperboloid symmetry axis. It may be possible that some linear drives are not placed parallel to the hyperboloid axial axis. If this is the case, the subreflector tilts towards the sky when moving it closer to the paraboloid (increasing Z), and towards the ground when moving away from the paraboloid (decreasing Z). The ammount of tilt is proportional to the displacement along Z and we estimate it to be approximately 9.8 arcsecs per mm around the X axis and 1.2 arcsecs per mm around the Y axis.

The consequences in such a scenario is that the subreflector rotates 3 arcmin around X and 24 arcsecs approximately from horizon to zenith due to its dependence on the Z axis. As we saw in a previous section the subreflector moves from -6 mm at the horizon to -24 mm at the zenith to get the best Z position that maximizes the efficiency. The tilt offset for Z = 0 mm is however unknown and would require further tests to obtain it.

In a Nasmyth telescope a tilt of the subreflector causes the signal spot to rotate on the focal plane drawing a quarter of a cycle. This means that, if this effect is not corrected, the horn is not placed in its best position at all elevations. This seems to be the case for the X band receiver as already reported in OAN-2010-10. However we have not confirmed this effect and hence it should be investigated and checked in the future.

The simplest solution to correct for the previous effects is to provide a tilt (around X and Y axes) curve which depends on elevation, with the same dependence as Z:

$$\delta tX[''] = K_{tx}\,\delta Z[mm] = K_{tx}\,(-1 - 24\,\sin(el)) = -9.8 - 235.2\,\sin(el)$$
$$\delta tY[''] = K_{ty}\,\delta Z[mm] = K_{ty}\,(-1 - 24\,\sin(el)) = 1.2 + \ 28\,\sin(el)$$

where δtX is the correction to be applied in arcsecs, el the elevation and the proportionality constants between the tilts and Z shift are: $K_{tx} = 9.8$ arcsecs/mm and $K_{ty} = -1.2$ arcsecs/mm. The previous equations assume that the tilt offsets are zero when $Z = 0$. We will apply these corrections and as a consequence a new pointing model for the antenna for all receivers is required. It is also advisable to repeat the efficiency curve as a function of elevation once the new pointing model is implemented.

Update (October 2010

Table 7 summarizes the final subreflector model when operating the telescope as a nasmyth antenna. This model has been used since Mid-October 2010.

Type of movement	Current model (August 2010)
X displacement [mm]	-6
Y displacement [mm]	$-40 + 60\,\cos(el)$
Z displacement [mm]	$-1 - 24\sin(el)$
Tilt around X [°]	$-9.8 - 235.2\,\sin(el)$
Tilt around Y [°]	$1.20 + 28\,\sin(el)$

Table 6: *Current best focus model (subreflector position) as a function of elevation. Mid-October 2010*

In October 2010 a new pointing model was applied after implementing the subreflector focus model in table . The appearence of azimuth and elevation errors as a function of a shift of the subreflector along Z mostly disappeared. Results are shown in figure 13. Some residual effects remain unexplained, like the systematic elevation error shown when Z=12 mm. We think that this new model is an improvement as compared to the previous situation. Corrections with higher resolution probably require observations at higher frequencies with stable weather conditions.

References

[Barcia 1995] A. Barcia. ”Efectos de las deformaciones de la geometría sobre la puntería de la antena ESSCO de 45 pies”. Informe Técnico OAN-1995-8.

[Barcia 2007] A. Barcia. ” ” Private communication. 2007.

[Baars 2007] J. W. M. Baars. ”The Paraboloidal Reflector Antenna in Radio Astronomy and Communication”, Springer 2007.

[de Vicente 2008] P. de Vicente. ”Preliminary characterization of the 40m radiotelescope at 22 GHz”. Informe Técnico OAN-2008-08.