# Control of Antenna Focus and Related Topics

This is a discussion of the approach to be adopted in the control of the secondary mirror and, in particular, how to adjust it to allow for gravitational and thermal deformations in the dish and the apex support structure. The main issue is whether or not the subreflector should always be placed in the position that gives the optimum antenna performance, which is assumed here to be the maximum on-axis gain. The obvious answer is that it should be, but the complication is that any change in the subreflector position will change the signal path and hence the phase, so one may prefer not to make subreflector movements either during integrations or when moving between a source and a calibrator. There is therefore a conflict that needs resolution.

## Specifications

The antenna specifications call for a range of movement of +/- 5mm in X and Y and +/-10 mm in Z. The maximum step size (effectively the resolution) is 20 microns in all three coordinates but the "differential accuracy" is set at 10 microns in X and Y and 5 microns in Z. The required speeds for the motion are quite high: 0.5 mm/sec in X and Y and 2 mm/sec in Z. This means that the motion from one end of the range to the other takes 20 seconds in X and Y and only 10 seconds in Z. By contrast the antenna takes 30 seconds to cover the full range of elevation at the nominal maximum speed of 3 degrees/second. Nothing is said in the antenna specification about acceleration and deceleration of the subreflector movements, or about settling times. We should check on what those are in the real implementations. On the basis of the numbers that are given, however, it is clear that the intention was to make it safe to assume that the subreflector will always get to the correct position as fast as the antenna can. So long as we are dealing with the elevation-dependent gravitational errors is concerned, and assuming that the command to move the subreflector to a new position is sent at the same time as the command to move the antenna, the subreflector should in fact always get there first. A possible problem is that the requirement only calls for 20 million steps of adjustment in the lifetime of the device. I estimate that we might well do that in one year.

## Tolerances – 1) amplitude effects

In order to work out how frequently we need to update the position of the subreflector, we should first ask how accurately we need to control it. We look first at the effect on the amplitude of the signal. There is an ALMA memo – number 479, by Bryan Butler – that discusses the loss in signal due to focus errors. I have run some Zemax and GRASP simulations and get similar (although not quite identical) results. The conclusions in the memo are that for a loss of 1% the axial focus should be held correct to 0.09 wavelengths and the lateral focus to 0.45 wavelengths. Now since we are trying to get 1% overall calibration accuracy we obviously cannot allow the errors due to each axis of the subreflector positioning to be as large as 1%. For example if the gain changes by 1% just due to the change in focus when we move from a source to a calibrator we are obviously in trouble. The 1% goal does however only apply at the longer wavelengths – frequencies of up to 370GHz. The following table gives the loss for some important frequencies for a particular set of assumed errors.

| | | X | Y | Z | |
|---|---|---|---|---|---|
| | Move for 1% | 0.45 | 0.45 | 0.09 | waves |
| | Assumed errors | 120 | 120 | 40 | microns |
| Freq | Wavelength | Loss | | | Sum |
| GHz | Microns | percent | | | percent |
| 300 | 1000 | 0.07 | 0.07 | 0.20 | 0.34 |
| 370 | 811 | 0.11 | 0.11 | 0.30 | 0.52 |
| 650 | 462 | 0.33 | 0.33 | 0.93 | 1.59 |
| 920 | 326 | 0.67 | 0.67 | 1.86 | 3.20 |

Since the adjustment in X and Y are less critical than in Z, I have set the values so that most of the loss is associated with the error in Z. It can be seen that these values give a total loss of just over half a percent at 370 GHz and over 3% at 920 GHz. It could well be argued that these losses are still too high but I suggest we take them as working numbers for now.

The general formula for estimating the loss due to an error in positioning the subreflector is

$$\text{Loss (\%)} = (F/300)^2 \times [ (\Delta X/450)^2 + (\Delta Y/450)^2 + (\Delta Z/90)^2 ]$$

where F is the frequency in GHz and ΔX, ΔY and ΔZ are the errors in microns.

Now the movements required to correct for gravitational deflections are of the form:

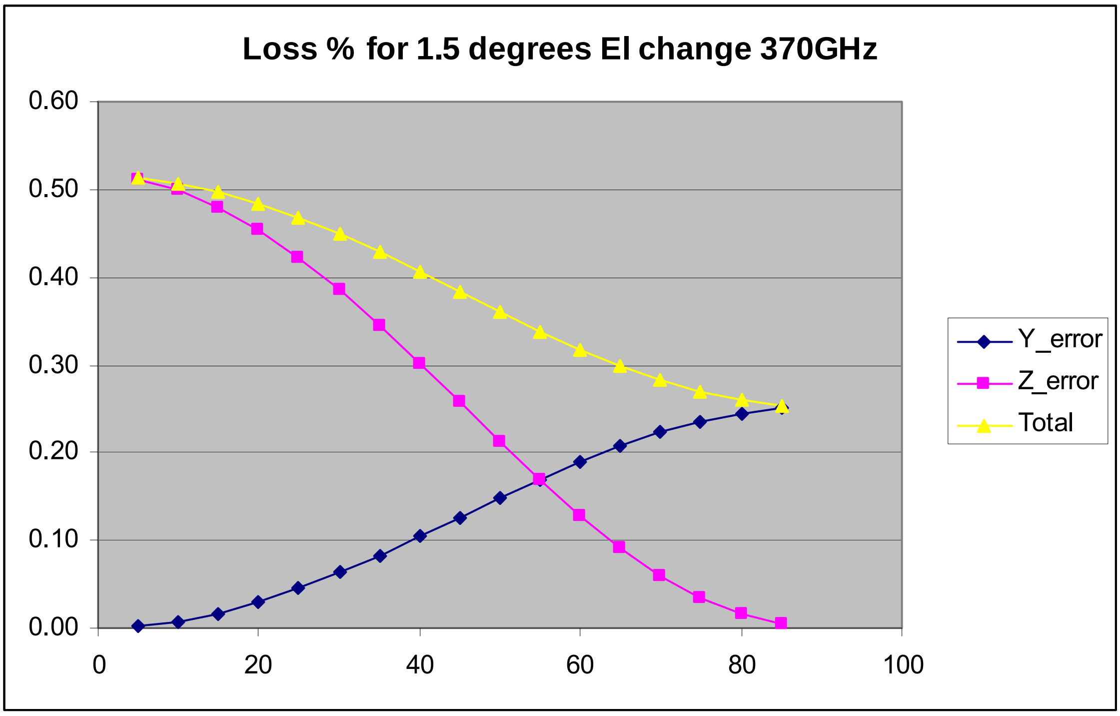
X = X_0

Y = Y_0 + Y_c × cos(Elevation)

Z = Z_0 + Z_s × sin(Elevation)

where the coefficents are Y_s ≈ –3.5 mm and –7 mm for the Vertex and Melco antennas respectively and Z_s ≈ +2 mm in both cases. From the prototype measurements, we expect the AEM design to have smaller values.

By differentiating the above expressions one can immediately find the maximum change in elevation that can be made without adjusting the position of the secondary. We see that the Z focus is changing most rapidly at low elevations while the Y focus changes most quickly near the zenith. If we restrict ourselves to the elevation range 20 to 80 degrees we see that in both cases the tolerance limits are already reached with changes of elevation of about 1 degree. This is however not quite the right thing to do since the tolerances were set assuming that errors were present in all three axes simulataneously. Here is a plot of the actual situation:



This uses the Melco numbers but the situation, except at high elevations, is not much different with the Vertex ones. This is for a 1.5 degree change in elevation and one can see that this is about as much as we can tolerate – remember that we also have to allow for thermal effects on the focus as well as these gravitational ones. This is for 370 GHz – the losses scale with the square of frequency.

Since most amplitude calibration sources will be more that 1.5 degrees in elevation away from our astronomical target, the implication is that at high frequencies we should always update the focus position when we move the antenna to do an amplitude calibration. If for other reasons we wish to limit the number of times the subreflector is moved we could use a frequency dependent threshold on whether or not we update the subreflector position when moving to an amplitude calibrator. A suitable expression for the threshold on the change of elevation would be (0.7 + 300 / F) degrees, where F is the observing frequency in GHz. (I have fiddled the numbers here to give the 1.5 degrees found above at 370 GHz and to provide somewhat smaller errors at lower frequencies and greater at high frequencies.)

So as far as the amplitude is concerned this gives us a possible strategy: the focus would be set to the correct position at the start of an observing block and the control system would record the antenna elevation at which this update was made. It would then keep watch on the commanded elevation and update the subreflector position whenever the difference exceeds the threshold. Note that, if we are tracking a single source, the 1.5 degrees of change in elevation quoted above corresponds to times of from ~6 to perhaps 15 minutes. These times are comparable to or longer than the time between calibrations, so in most cases it would be the move to the calibrator that would trigger a re-focus.

In addition to the gravitational deflections we have to deal with thermal deformations. We think that (at least on the Vertex dish) these will be of order 30 or 40 microns of change in Z focus for each degree of change in the ambient air temperature. According to the numbers above this means that for high frequencies we will need to update the focus if the temperature changes by more than about 1K. Clearly it would be possible to incorporate this into the strategy suggested above by recording the temperatures (probably one recorded on the dish rather than the air temperature) and testing the change in this relative to a second threshold. It would however be more direct and complete to calculate the required secondary position, allowing for both temperature and gravity, compare it to the current position, estimate the losses according to the expression above and issue the command if the loss is greater than some value, which could for example be (0.3 + F/1000)% with F again be the frequency in GHz.

There is no simple theory to predict the changes in the X and Y focus as a function of temperature (in fact the FEA does not predict the Z shift correctly either!). Since the structure is symmetrical we do not expect any change with the ambient temperature, but we may find significant shifts due to asymmetric heating and if so we can try to correct for them by using the measured differences between the temperature sensor readings. Clearly this is a likely future development which should be allowed for in the software design.

## Tolerances – 2) phase effects

Now let us look at the path length errors that result from these focus changes. It is clear that the most important effect is due to the movement of the subreflector in Z. On axis the change of path is of course twice the movement (because of the reflection) but when one integrates over the range of incident angles (taking account of the aperture weighting) one finds that the mean path change is 1.74 times the Z movement. To first order there is no effect due to X and Y movements for a completely symmetrical system, but because our feeds are off-axis there will in fact be a small change in path. I estimate this at only about 0.05 (TBC) times the X or Y movement, which is small but unfortunately not negligible.

It is important to appreciate that there are two components to the corrections that we have to apply to the position of the subreflector: 1) the movement of the subreflector with respect to the some reference frame (say the elevation axis) and 2) the change in the position of the prime focus – i.e. the location of the focus of the best-fitting paraboloid. This implies that the path length will change as a function of elevation whether or not we actively change the focus. In the case of the Vertex design, the Finite Element Analysis (FEA) shows that turning on gravity in the zenith position causes the subreflector to move down by about 1.25 mm while the prime focus moves up by about 0.65 mm – which gives the prediction correction in Z of ~1.9mm. The changes in path length, however, include the movements of the primary and the receiver as well as the subreflector. It turns out that there is a good deal of compensation here: the numbers I have from the Vertex FEA indicate that if we do not move the subreflector to the optimum Z focus the change in path due resulting from turning on gravity in the zenith pointing case is about -0.3 mm whereas if we do move the subreflector it is +3.0 mm.

As far as I know there is no separate item in the phase error budget for the subreflector positioning. The relevant numbers in the systems specifications on the total delay associated with the antenna movements are as follows:

> Systematic, for (az,el) change of 2.0deg, < 8 fsec
> Random, for (az,el) change of 2.0deg: < 15 fsec
> Systematic, az ± 180 º rms < 100 fsec, el ± 40 º rms < 50 fsec
> Random, for full range of permitted az,el : < 32 fsec

Light travels 0.3 microns in 1 fsec so these numbers correspond to path length changes of only 2.4(!), 4.5, 30, 15 and 9.6 microns respectively.

In the antenna specifications we find:

> The repeatable residual delay for an antenna shall not change by more than 20 microns when the antenna moves between any two points 2 degrees apart in the sky.

and

> The non-repeatable residual delay under Primary Operating Conditions (section 4.4.3) must be less than 15 micrometers RSS when tracking an astronomical source at sidereal rate.

It is not at all clear to me that these numbers are consistent, but let us see what values we can expect.

First of all the Z motion has a specified accuracy of 5 microns. This corresponds to a path length error of 8.7 microns. It is not clear whether this is intended as a peak or an rms value.

The step size of 20 microns corresponds to 35 microns of path. If we regard this as an error and if there are many steps during and observations, so that any systematic offset is smoothed out, then the effect on the phase coherence is just an rms error of 10 microns. Unfortunately we will not be tracking the calibrators for long so we must allow for the full effect of the resolution on the accuracy of the phase measured on the calibrator. Assuming that the resolution of the Z motion is really limited in this way, it is clear that we cannot simply go to the nearest step and ignore the error. Instead we will have to calculate the phase error due to the difference between the actual position and where we want it to be and apply that as a correction.

Taking the values quoted above from the Vertex FEA we see that the change in going from say elevation 30 to elevation 32 degrees if we do not update the Z-position is -9 microns, compared to +90 microns if we do update it. (The change is largest at low elevation.) The effects due to the Y movements are likely to be smaller, but this needs to be checked. As expected the conclusion from this is that the safest thing to do is NOT to change the focus position when going between the source and the phase calibrator. Assuming that we will normally use a calibrator for phase that is no more than 2 degrees away in the sky and that the FEA is correct, this will limit the error to ~9 microns. Note, however, that this does not actually meet the 2.4 microns required in the system spec. In principle therefore we should still be applying a correction to the phase for these effects, which since they are gravitational are in principle completely repeatable. We can certainly do this by using the FEA for the three different dish designs and calculating the correction. Whether we will be able to measure the changes to confirm the model is much less clear – a term that varies as sin(El) will be very hard to separate from many other effects such as baseline errors, LO changes and atmospheric refraction. Conversely, if there is a significant effect that differs from the prediction, that will lead to errors in the baseline determination, etc.

The thermal effects on path are likely to be quite large but of course this is one of the reasons why we plan to do frequent observations of phase calibrators: so long as we do this fast enough the thermal effects should get removed rather well. Thermal drifts will however complicate the process of baseline determination. To achieve high accuracy it will probably be necessary to do this at night.

## Tilting of the subreflector

In all our antenna designs the subreflector has 5 degrees of freedom: i.e. three displacements and two tilts. The intention of the specification is that the tilts take place around the location of the near focus of the hyperboloidal secondary mirror. This de-couples the effects of the displacements and the tilts. In the following it is assumed that this has been achieved exactly[1]. The requirement to tilt the subreflector was not in the original antenna specification but was added later when it was realized that, because the receivers are off-axis there is a significant advantage in sensitivity to be gained by tilting it (ALMA memo 545 – see also the change request at **http://edm.alma.cl/tiny/9m64d.html** for further discussion). In fact the optimum tilt is such that that axis of the subreflector lies half-way between the axis of the primary and the line from the feed to the prime focus. The plan is therefore to command the tilts of the subreflector according to the band being used for the astronomical observations. The tilts required are in the range 0.5 to 1 degree. Note that tilting the subreflector will produce a significant shift in the pointing, but so long as the tilt is about the correct position it should not be necessary to alter the focus. When we are doing fast-switching using a different band as the phase calibrator, we will NOT change the tilt. This would in any case be undesirable because it is likely to introduce phase changes, but in fact the drives would not be able to make these large changes in tilt quickly enough. The fact that there is a loss of a few, or at most ten, percent in sensitivity on the phase calibrator is not very critical.

## Proposed Strategies

### A) The Conservative case

In the following I assume that we are doing a "standard" interferometric observation with an amplitude calibration source being observed rarely and phase calibrators being observed frequently.

Normally the sequence will start with an amplitude calibrator and the subreflector should be set to the correct position for that elevation.

The next object will normally be a phase calibrator. If this is far enough away from this to require a change in position an update should be done when the antenna there.

The subreflector should then not be moved for the subsequent observations of the astronomical source and calibrator until it is found that the change in focus due to gravitational and thermal effects exceeds the threshold. At that point a final phase calibration should be made.

The subreflector position should then be updated and the sequence restarted, i.e. calibrator, source, calibrator…etc., ending on the phase calibrator again.

Note that in this case we will be able to check from the change in phase, whether the subreflector has actually moved by the correct amount.

The problem with this is that, according to the estimates above, the accuracy of the resolution of the positioning is not good enough to make the resulting errors negligible. This means that we will have to keep track of the phase errors produced and apply a correction based on the difference between the nominal position and the actual one. This is all getting rather complicated so we should at least look at the alternative.

### B) The Optimistic case

Here we simply adjust the subreflector all the time, either by sending frequent commands, say once a second and certainly every time we move to a calibrator, or simply by letting the ACU in the antenna take care of it. (I think this is called "autonomous mode".) We would then apply a correction to the phase for the resulting path difference relative to some nominal position for the subreflector. This correction would be calculated from the position actually read back – i.e.

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[1] If the point of rotation is not at the focus, then a tilt also produces a lateral displacement. As far as I can see errors of a few millimeters here will not have any significant effect on performance so long as the tilts are used in the way described here – i.e. fixed positions for different bands.

taking account of the limited resolution of the hexapod. If we just used a fixed position, say (0,0,0), for this reference, then the resulting phase will still contain an elevation dependent term due to the gravity as explained above. To the extent that we understand the gravity deformations we can in fact work out the correction that ought to result in a constant phase independent of elevation. Similarly if we apply refocusing for thermal changes we can allow for the movements we have made by correcting the phase.

### Discussion

As far as I can see, since the limitations in both cases are set by out lack of knowledge of the true deflections, as opposed to what the models say, the two methods should give the same answers. The second one is apparently rather simpler to implement and slightly more efficient. Note however that we might find that we are wearing out the drives if we tell them to move on every cycle of the fast switching.

The other practical difference is that in the second option we rely completely on the subreflector position drive to do exactly what it is asked to do. By contrast in the first we tell it to stay fixed while we make the critical move from source to reference.

In the end we may want to try both these, so the immediate question is, “Which should be try to implement first?”

## Zero-spacing (Single Dish) Observations

Here the considerations are somewhat different. Phase is not important so one would again think that continuous updating is the way to go. On the other hand for some cases the baseline ripple due to standing waves between the feed and the subreflector may be important, despite the fact that we have done our best to suppress them in the subreflector design. This means that the strategy of only updating when necessary is probably best here. In this case one would complete a cycle of On and Off observations before doing the update.

Richard Hills 19th May 2009