Atacama
Large
Millimeter /
submillimeter
Array

The Effect of the Differential Antenna Height Term in the Delay Model

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THE EFFECT OF THE DIFFERENTIAL ANTENNA HEIGHT TERM IN DELAY MODEL

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SUMMARY: This memo describes the systematic residual phase offsets versus elevation for ALMA data that are now occurring for configurations larger than about 400 m. It is shown that the systematics are caused by the lack of the height difference delay term and the Earth-curvature term that are not included in the Calc model used to obtain the correlator delay model. The effects will produce very large phase offsets between even close calibrators and targets during the long-baseline campaign if not compensated for. The algorithms needed are described, and it is hoped that these can be added to the ALMA correlator model before the campaign begins in early September.

1 Systematic Phase Residuals after Baseline Corrections:

The positions of the ALMA antennas are determined with observations of quasars consisting of approximately 100 20-sec scans of 30 quasars distributed over the sky. These are called *baseline runs*. From these data, the position of the antennas (Bx, By, Bz) can be determine to < 0.1 mm accuracy, using software in telcal that operates on the ASDM, or by a python script (written by M Sugimoto and E Fomalont), that operates on the measurement set. The solutions can be obtained with no or with wvr-delay corrections. This position accuracy is needed to decrease the systematic phase difference between a calibrator and target from a typical science experiment. Often, the limit of the target image quality is not from the short term phase fluctuations, but from the systematic phase differences between calibrator and target. Pad position errors are the largest, but not the only contribution, to this systematic phase difference.

As the array has expanded out beyond the 0.4 km size, the results of the baseline runs (both with and without the wvr correction) show that there is a clear systematic phase residual with source elevation that persists even after accurate antenna positions have been derived in good weather conditions. This systematic error is proportional to the pad height difference between the antenna and a reference antenna that is taken within 100 m of the center of the array which is flat to about 2.0 meters.

Fig. 1 (top) shows the residual phase for two antenna pads that have been occupied for two months and are on pads with the maximum height difference from the array center, about 9 m up and down. All ten baseline runs show the same residual trend, although the phase noise from general atmospheric conditions change the rms noise level. The systematic phase error is almost completely removed. **The phase residual shown is for 100 GHz. It scales with frequency and should already be a concern at bands 7 and 9 for the present configurations.**

The expected additional delay term caused by the height difference among the antennas was added to the data off-line, and then the antenna positions were determined. As shown in the bottom of Fig. 1, the systematic phase error is almost completely removed, indicating that the delay term associated with the antenna height difference should be included. The rms of the phase scatter with time (this plot is not shown, only the elevation dependence) decreases significantly when the height term is included.

The difference between the baseline parameters with and without the height term can differ by over 4 mm, as shown in the table below. The differences indicate that the baseline parameters can 'mimic' some, but not all of the height difference phase effects. [As an aside, the differences for runs with and without wvr correction are about 1mm.] The most accurate and stable baseline parameters will be those obtained with the wvr correction and the additional delay model terms.

BASELINE CORRECTIONS BEFORE AND AFTER HEIGHT CORRECTION

ANTENNA	BX	BY	Bz	rms
		(millimeters)		(deg)
DA60 before	0.66	-1.04	-0.29	24.6
DA60 after	-0.71	2.24	0.98	10.7
DV15 before	0.24	-0.39	-0.38	18.8
DV15 after	1.59	-3.88	-1.57	9.3

2 The Effect on the Long Baselines:

The systematic phase introduced between a calibrator and target, separated by five degrees for the two antennas, illustrated above, range from about $+10^\circ$ to -20°, depending on their relative positions in the sky. This is not serious problem for the 10-m height differences. **But,** these residuals are for 100 GHz and scale with frequency.

The following table shows the height differences for some of the long baseline pads that will be occupied in September, and range from -16m to +255m. Since the effect scales linearly with height difference, the residual systematic phase error between the antennas on pad S301 and S305, for example, will increase systematic phase errors by about 25-fold, to well over 100° for calibrator target separations of 5° in the sky at 100 GHz. Multi-calibrator techniques can remove some of this, but will not be the main mode of phase referencing observations unless this is absolutely necessary which would be the case if this known delay term is not removed.

HEIGHT DIFFERENCES FOR SELECTED PADS

ANT	PAD	HEIGHT (m)
DA60	A090	-9.1
DV15	A089	9.1
	P403	-140
	S301	-16
	S305	-255
	W204	-191
	W210	17

3 The Dry Height Term

Calc was written mainly for VLBI arrays in which each antenna is at a different location and the accurate delay above the antennas are calculated based on local conditions. For small diameters arrays such as the EVLA and ALMA, the conditions at each antenna are assumed the same and this is a good approximation. However, two delay terms associated with small-diameter arrays are not included in Calc (although they could be): The differential delay between two antennas that are at different heights above the mean site level. This delay is also proportional to the refractivity of air. The other term is associated with the curvature of the earth across the array; i.e. that antennas observe a source at slightly different zenith angles. Both of these terms are added to the Calc delay model used at the EVLA. A full description of the history of the height effect and comments from various people is given in ALMA JIRA ICT-272.

The delay associated D with the height term is:

$$D = N * DH * \mathrm{sec(z)} \tag{1}$$

where DH is the height difference, z is the zenith angle and N is the refractive index on the ground (anywhere in the array to first order). The units of D are those of DH. $N \approx 77.6 * P/T * 10^{-6}$ with P in mbars and T in K.

For the ALMA site, nominal values of P=555, T=270, giving N=0.159mm. Hence, for a 10 meter height difference at 100 GHz, the phase is about $190° *$ sec(z). This large phase is not as serious as it appears, since it is the phase difference for two close sources (say separated 5° in elevation) which is in the order of 10° at 100 GHz.

The wet component of the delay associated with the height difference between antennas is taken out directly with the application of the wvr correction; hence application of the wvr correction, besides removing short-term fluctuations, also removes the systematic phase difference from the ambient water vapor density near ground level.

4 Earth Curvature Term:

The other delay term that is *probably* not included in the Calc model is that caused by the earth curvature between antenna elements, which means that each antenna observes any source at a slightly different zenith angle. This term is

$$E = (c * \tau)/r_e * L * sec(z)^2 \tag{2}$$

where E = path length difference due to earth curvature, $c * \tau$ is the geometric delay in meters, r_e is the earth radius = 6370000 meters, z is the zenith angle, and L = total atmospheric path delay at the zenith. L (in cm) $\approx 0.228 * P$(millibars)

For the ALMA site P=555 mbar; for 1000 m baselines $c * \tau / r_e = 1.57 \times 10^{-4}$. At 100 GHz this produces a curvature phase difference between two antennas up to 24° $\sec^2$(z).

5 Testing the Additions:

When these additional delay models are added to the current Calc model that is used by the ALMA correlator, a 30-min baseline run can check whether the residual elevation-dependent phase has been largely removed.

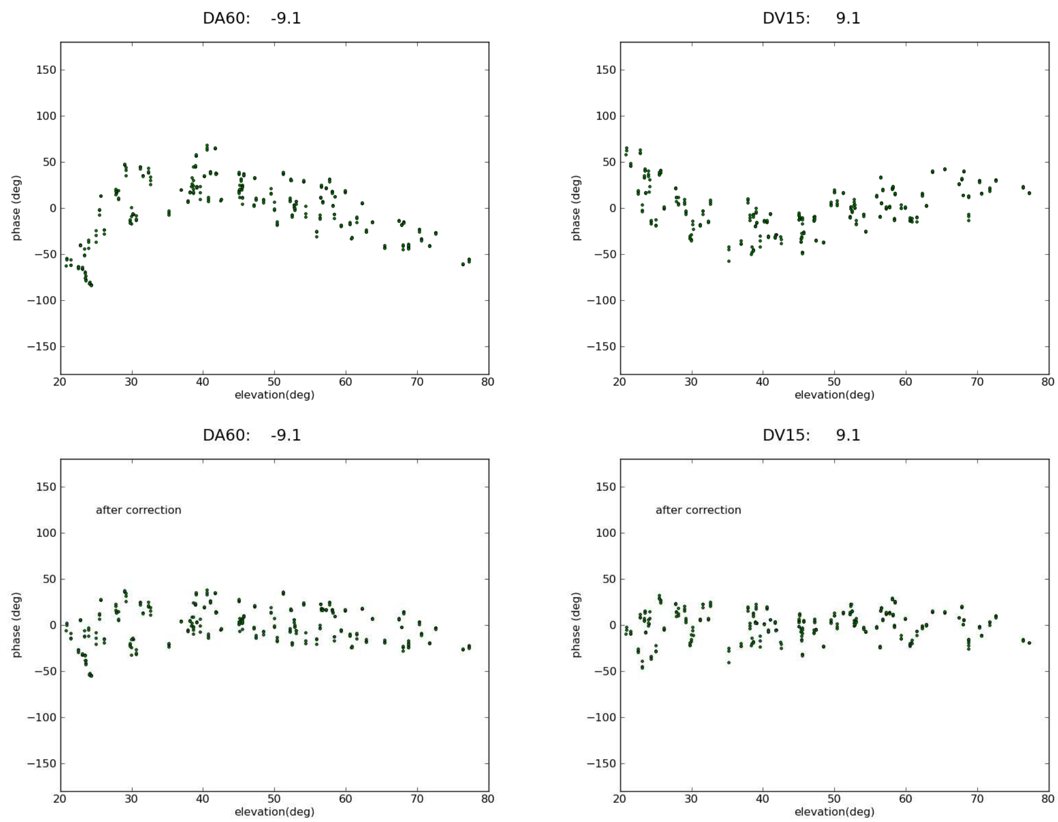

Figure 1: **Top Row:** The residual phase versus elevation for the two antennas, DA60 on A090 and DV15 on A089, with the maximum height difference in configuration C32-5. Each point represents the phase residual for a 20-sec scan, after removing the best baseline parameters for the antenna. **Bottom Row:** shows the residual phase versus elevation after correcting the phase for the delay associated with the antenna height difference.. The elevation dependence is largely removed.