Report on the Correction of the Illumination Offset

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Abstract

As shown in ALMA Memo 402, offsets in the illumination of the dishes by the feeds will result in a phase gradient in the voltage patterns. If left uncorrected, this is very problematic for high dynamic range mosaicing. However, a simple correction algorithm exists which would remove essentially the entire effect of the voltage pattern phase gradient. We explore the details of how to measure the offsets and how to apply the corrections to the (u,v) coordinates.

1 The Problem

The ALMA feeds will be designed to introduce a 10 dB illumination taper on the ALMA dishes. The feeds have a specification to be aligned such that the illumination pattern is aligned with the dish center to within 0.1 dish radii, rms. It is supposed by some that a more accurate illumination alignment should be possible, but may be difficult or expensive to achieve. Of course, if the illumination alignment can be better aligned than the spec, this is good.

The effects of the illumination alignment error have been calculated via detailed numerical imaging simulations and presented in ALMA Memo 402. There are basically three effects:

- primarily, a phase gradient is introduced across each antenna's voltage pattern (this is the effect which we can correct).
- low level amplitude distortions are also introduced into the voltage pattern (we cannot correct this effect without aligning the feeds more accurately, or without detailed measurement of each voltage pattern in conjunction with the use of some pretty heavy duty software which doesn't yet exist).
- some sensitivity (a few percent) is lost as part of the inner high amplitude illumination pattern will fall off the edge of the dish, illuminating hot ground (we cannot correct this effect without aligning the feeds more accurately).

By far the most important effect is the phase gradient across the voltage pattern. This phase gradient will have little effect on observations of compact sources, but for sources which span the beam, as in mosaiced observations, the effects of the phase gradient will be more important than pointing errors for observations up to about 500 GHz. The specifications for the illumination offset are frequency independent, while pointing errors as a fraction of the beam will increase with frequency, and at high frequencies the effects of pointing errors will be more important than the effects of illumination offsets.

2 The Solution

Fortunately, there is a very simple fix to the phase gradient introduced into the voltage pattern by the feeds' illumination offsets. An offset in the illumination pattern of one antenna is equivalent to the baseline between antennas being offset by the difference between the illumination centroid on the dish and the dish center. The illumination centroid is, presumably, constant, and is fixed to the antenna frame, which means that on the sky, it will rotate with the parallactic angle. Preliminary work has indicated that the illumination offset correction applied to the baselines (ie, changing the (u,v) coordinates but not changing the visibility data) essentially eliminates this error from the resulting images. Hence, what is required is:

- calculation of the illumination centroids for each feed on each dish, to be done as an observatory service during test observations
- storage of the illumination centroids in a lookup table in the on-line system
- option for the automatic correction of the baselines by the baseline's antenna's illumination centroids, each rotated by the parallactic angle at that instant
- possibility of flagging baselines during times when the parallactic angle has changed substantially during an integration (this feature will only be invoked for long integration times on sources which transit near the zenith, at times when the sources are very close to transit).
- correction of baselines for the antenna-based illumination centroids offline. Suppose we took data on Monday, and on Tuesday, service observations determined the antenna-based illumination centroid offsets, which were substantially different from earlier values (ie, a feed has been moved). We can take good data without any knowledge of the illumination offsets, but we must know the offsets for accurate wide-field imaging.
- Since illumination offsets have never been an issue for any existing telescopes, we have no experience with the determination and application of the offset centroids to the baselines. There may be other subtle effects which we have not been able to foresee.

3 Details for the Illumination Offset Correction

3.1 Determination of Baselines

Random illumination offsets among antennas will result in a different phase gradient across each antenna's voltage pattern. Do these phase errors confuse the determination of the baselines between antennas?

If there are no pointing errors, sources used to determine the baselines or delays would lie at the center of the voltage pattern where the phase gradient will be zero, and there will be no effect.

In the presence of pointing errors, a single antenna-based phase error will be introduced by the phase gradient across the voltage pattern at the spot in the voltage pattern sampled by the calibrator source. Because baseline determinations use the pattern of the antenna-based phase errors across the sky to determine the locations of the antennas, we probably cannot solve for this special antenna-based phase error. However, for reasonable pointing errors, this phase will be less than 10 degrees in all cases, and a good distribution of parallactic angles for calibrator sources around the sky will result in these illumination offset phase errors being well randomized, and they will probably not adversely affect the determination of the traditional component of the baselines.

3.2 Determination of Illumination Centroid

One way to determine the illumination centroid would be to perform a holography observation and look at the amplitude pattern on the dish. The centroid of this amplitude pattern will give us the illumination centroid we desire. The difference between the amplitude centroid and the dish center is then the illumination offset which we need to feed into the baseline correction process.

While this calculation should be done as a check whenever we do holography, it is not necessarily the calculation we should do to determine the illumination centroid. Our primary concern is not with the illumination centroid, but with the phase gradient in the voltage pattern. If a phase gradient of

$$e^{2\pi i \mathbf{\Delta u} \cdot \mathbf{x}} \tag{1}$$

is found in the voltage pattern, this implies an effective illumination centroid offset of $\mathbf{\Delta u}$. The $\mathbf{\Delta u}$ must be de-rotated by the parallactic angle during the observations. This effective illumination centroid offset should be very similar to the illumination centroid offset calculated from the holography data, but in principle is closer to the manner in which this problem affects the data (ie, through the voltage pattern phase gradient). In addition, this effective illumination centroid offset is trivial to calculate: when performing a pointing determination, look at the phase as well as the amplitude. The phases of the 5-point (or equivalent) pointing procedure will permit us to determine the phase gradient in the voltage pattern. Common phase errors due to the mean atmospheric phase or the electronic phase during the course of the calibration will cancel out.

An accuracy of about 1 degree of phase at the half power point is desired. (Using Perley's rule of thumb that a 1% amplitude error is roughly equivalent to a 1 degree phase error, and a 1% error in the voltage pattern at the half power point is a reasonable goal. This level of accuracy may need to be adjusted when we gain more experience in correcting for this effect.)

The phase gradient must be determined for each antenna and each feed. However, we expect the illumination offsets and hence the phase gradients to be very stable with time, perhaps changing minimally over years. The software which handles the pointing determination should calculate the effective offset automatically, and when we perform the full pointing model determination observations, we should average the effective offsets (de-rotated by the parallactic angles) and look for significant changes in the offsets.

3.3 Storing the Illumination Offsets

The entire set of illumination centroid offsets needs to be stored in a table which is generally accessible to the imaging pipeline and to all data reduction programs. Illumination offsets will depend upon the observing band and the antenna number. We expect the illumination centroid offsets for a given antenna will be relatively constant in time, even after moving the antenna to a different pad. We expect the offset to change only after the feed has been manually modified, repaired, or replaced. However, if it is found that these terms are time variable, we may decide to archive and distribute the table with the raw visibility data.

3.4 Application of Illumination Offsets

The illumination offsets do not augment the visibility data in any way, but rather augment the baselines. Normally, the projected baselines rotate as a function of hour angle and source declination. The voltage patterns (or antennas) rotate simply with parallactic angle. Basically, the antenna centroid needs to be shifted by the effective illumination centroid offset, rotated by the parallactic angle. Hence, the baseline from antenna 1 to antenna 2 will need to add antenna 2's offset, rotated by the parallactic angle, and subtract antenna 1's offset, rotated by the parallactic angle.

The effect of the illumination offset on the baseline as the baseline and beam rotate with time is shown in Figure 1

3.5 Automatic Application

The on-line system knows the parallactic angle of each integration, and can get access to the stored illumination offsets. The default behavior should be for the on-line system to automatically apply the baseline corrections. There may be times when application is not desired, so the option to turn off the automatic correction should be included.

3.6 Flagging Based on Fast Parallactic Angle Change

When observing a source which transits close to the zenith, the parallactic angle can go through a large change during an integration, especially if the integrations are long. Consider an observation in the most compact array, as might be done for mosaicing. Fast switching generally does little to assist such short baseline observations, so we would rely mainly on the good graces of the atmosphere or upon radiometric correction, which could take place on time scales shorter than an integration. Since the baselines are short and we require no fast switching, we can use a very long integration time before the longest baselines start to move into the next Fourier cell. In such a situation, we would like to be able to flag any integrations for which the parallactic angle changed more than some critical angle (ie, 5 or 10 degrees) from the beginning to the end of the integration. Flagging on the parallactic angle change could be useful for polarization observations as well. This operation would typically flag no data, or occasionally a tiny amount of data.

4 Conclusions

The illumination offset correction process is very light weight. Each task which must be accomplished is very simple, but taking care of this effect ends up touching many parts of the ALMA system, so a programmer and an astronomer with a good feel for the distributed nature of much of the ALMA software should address this issue together.

Very little software needs to be added to the radio pointing procedure to calculate the offsets. The observations to determine the offsets will probably need to be performed very rarely, though the determination must be made at high signal to noise. The table which will hold the offsets will be very simple. The software which rotates the offsets by the parallactic angle and applies them to the (u,v) baseline vector is simple and very quick. A single person (or perhaps an on-line programmer and a reduction package programmer) could implement all of the software in the on-line and reduction system in a small number of weeks or less. An ALMA staff astronomer could implement the automatic measurement of the offsets as a periodic calibration task, could then check up on the measured offsets, and then determine how often the offsets needed to be measured. The astronomer will need to perform a high dynamic range mosaic at low frequency with and without the offset correction to verify the offset correction has been done correctly. So, it might take the astronomer a month or two to verify that everything was fine and to correct any problems in the implementation of the offset correction.

This is all very easy to do.

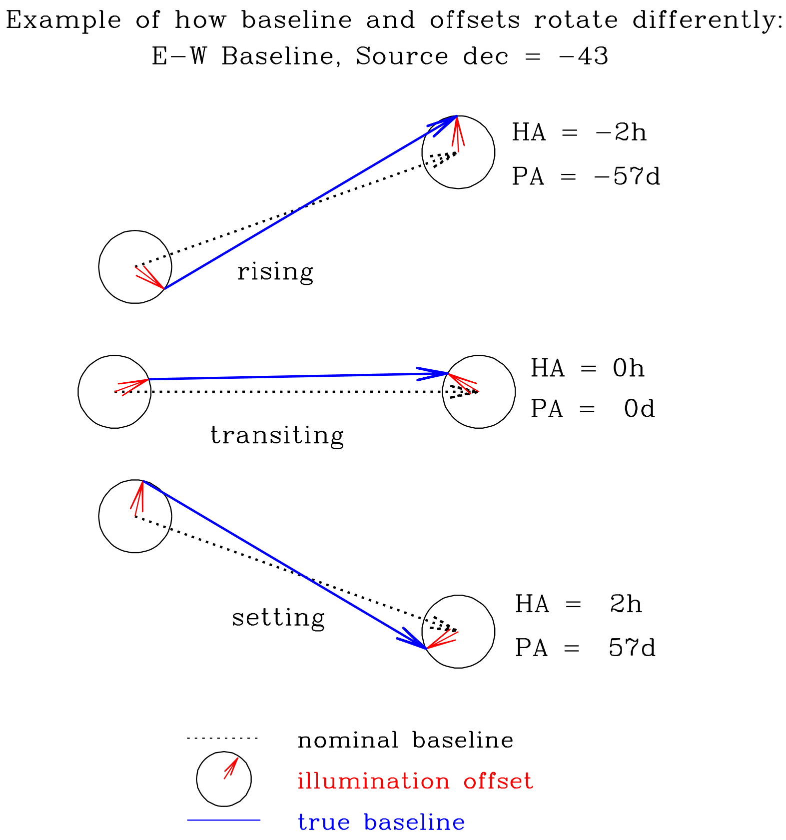

Figure 1: An example of how an E-W baseline rotates against the sky, and how the incremental baseline correction rotates with the parallactic angle.