Atacama
Large
Millimeter
Array

Primary Beam Calibration Steps

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Specification Document

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1 Goals

The single goal of a calibration measurement of the primary beam response is to determine the antenna power pattern of each of the ALMA antennas. The specification for determination of this antenna power pattern response is as follows:

The antenna power pattern response of each ALMA antenna must be determined to a measurable and repeatable precision of better than 1% ($\nu \leq 400$ GHz) and 2% ($\nu > 400$ GHz) of the boresight power response at all points within the -10 dB contour of the beam pattern, for each polarization. This means that at the -10 dB point the precision of that measurement is 10%/20%, respectively.

Note that this requirement is designed to allow for a better determination of the response over the inner portions (half-power point inward) of the primary beam than that over the outer portions of the primary beam. This satisfies a fundamental requirement of the mosaicing process, whereby each pointing's dirty map is multiplied by the primary beam as a weighting function before combining all pointings. The dirty map is approximately equal to the true sky brightness times the primary beam and then convolved with the point spread function. So, the primary beam is factored into the imaging twice, once by the physics of observing, and once in mathematics in processing. Hence, bumps and wiggles in the outer parts of the primary beam are down weighted a great deal, and we don't need to know them very exactly, but bumps and wiggles in the central part of the beam must be well modeled or it will lead to significant imaging errors.

2 Primary Beam Calibration Observations

Note that:

— Primary beam calibration measurements will likely be done by ALMA staff, not observers. In this sense, they are "service observations".

— As experience is gained with the characterization of the primary beams for the ALMA antennas it is anticipated that deeper levels of modelling sophistication will be developed. These modelling improvements should include subtle differences in beam characteristics as functions of elevation, frequency band, symmetry, and antenna.

— Guidelines for the application of these primary beam measurements in the imaging process need to be developed.

2.1 Measuring the Beam with Interferometric Holography

Primary beam models of each antenna will be constructed using measurements of each antenna's voltage pattern. Regarding the necessity of ancillary calibration measurements:

— *Absolute Ampltude or Flux Calibration*: Not a necessary measurement for mapping or modelling the primary beam as the beam map will be normalized to the peak value. On the other hand, a precise understanding of the noise level will benefit from knowing how bright the source is. Therefore, absolute flux calibration is of secondary importance.

— *Relative Amplitude Calibration*: It will be important to track relative amplitude fluctuations, as they could otherwise limit the accuracy of the beam's measurement.

— *Phase Calibration*: It will be important to track phase fluctuations: phase errors will lead to errors in the voltage pattern's phase, and phase fluctuations and decorrelation will lead to low amplitudes in the voltage pattern.

— *Pointing Calibration*: Pointing errors will translate into amplitude errors in the beam measurement, so we need to make our beam measurement during conditions with good pointing.

— *Bandpass Calibration*: There will be significant beam variation over the 8 GHz bandwidth, necessitating a bandpass calibration measurement.

Taking into consideration the necessary predecessor calibration measurements listed above, the measurement sequence for a primary beam calibration will proceed as follows:

1. Observations should be performed at night to take advantage of conditions which result in the lowest phase fluctuations and smallest pointing errors.
2. Optionally observe an astronomical source for flux calibration.
3. Perform bandpass calibration on a bright source.
4. Choose a bright continuum source in the sky as the target source that happens to be at the elevation angle of interest for the beam measurement (this measurement will take place at several different elevation angles). This source should be a bright point-like quasar such as 3C273. Planets could be used for holography, but they could not be easily used for phase calibration.
5. Perform a pointing observation on the target source.
6. Observe the target source for several seconds to get an accurate amplitude and phase.
7. Interferometric holography is usually accomplished by leaving one of the antennas on source while the other antennas slew over the holography raster[1]. At 90 GHz where the brightest quasars are still in the 5-10 Jy range, we will be abundant SNR in less than 1 s of observation. With 1 s on source and 1.5 s to move to the next raster point, each row of a 16 x 16 pixel raster will then take about 40 s.
8. To track changes in phase and amplitude fluctuation over the course of the raster scans boresight observations of the target source should be made every few rows (approximately every 10 seconds).
9. The total time to observe the 16 x 16 raster should be under 15 minutes.

2.2 Primary Beam Measurement Analysis

A suggested scheme for analysis of the primary beam observations is as follows:

1. Perform flux calibration if a flux calibrator was observed.
2. Solve for the bandpass on the bandpass calibrator.
3. Treat the holography observations as fast switching observations. For primary beam measurements at the higher frequency bands it may be necessary to incorporate WVR measurements to correct the phases. At 90 GHz fast switching with a cycle time of 50 s will generally have excellent results during most atmospheric conditions, obviating the need for WVR correction. Use all on-axis observations of the target source to accurately solve for the amplitude and phase gains on each antenna, and interpolate these solutions across the holography raster points.
4. Construct a complex average of all visibilities between all the fixed antennas and the i^{th} rastered antenna. That average will be the amplitude and phase of the i^{th} antenna's voltage pattern at that particular pixel. The voltage pattern model is built by gridding each of the averaged visibilities to the i^{th} antenna observed in the raster.

[1] At the higher frequency bands it may be necessary to increase the reference signal-to-noise by using more than one reference antenna.

5. Once we get the voltage patterns for all of the antennas, we will do some statistical processing. At 90 GHz, the voltage pattern phases, the phase errors, and the pointing errors will all be small, so we might be able to simply average the amplitudes of all the voltage patterns and square that to get a reasonable primary beam model. A more sophisticated approach would be to cross multiply all the voltage patterns and average all of them to form a primary beam image. These processing steps would also give us an idea of the error level across the beam.

3 Issues

It might be useful to do interferometric holography measurements of strong spectral line sources (*i.e.* SiO masers) in spectral line mode In general masers do not have as high SNR as continuum emission from strong quasars, but the narrow spectral signal could simplify processing and interpretation.