Atacama
Large
Millimeter
Array

Pointing Calibration Steps

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Specification Document

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Change Record

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7	2007-08-02	Jeff Mangum	All	Added sequencing diagram and update

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Contents

1 Goals

Establish the antenna-based pointing offsets at several levels:

1. **Global Pointing Model Parameters** for all ALMA antennas. This will generally be done with a linear least-squares fitting algorithm applied to a sequential series of randomly-distributed radiometric pointing measurements of $\sim$ 100 or more radiometric point sources. This global pointing model characterization should be necessary not more than once per month.
2. **Reference Pointing Offsets** for each antenna and receiver band. This pointing measurement tracks shorter timescale variations in the pointing performance of each antenna. These pointing variations can be tracked with either single (Az,El) offset measurements or derivation of a "local pointing model" in the region around a target source.
3. **Relative Receiver Band Pointing Offsets** for each antenna and receiver band. Necessary to monitor longer (several month) timescale variations in the relative pointing between receiver bands for each antenna.

2 Introduction

The ALMA antenna pointing specifications of $0.''6$ reference (within a 2 degree radius on the sky) and $2''$ all-sky places strict requirements on the ALMA pointing model formalism. In [1], [2], and [3], analysis of the requirements and performance capabilities of single antenna and interferometric pointing procedures have been investigated. The conclusions of these analyzes were:

— The pointing model formalism described in [1] and [2] coupled with the refraction calculation described in [1], which relies upon the weather instrumentation described in [1] will allow a characterization of the ALMA antenna pointing behavior with a basic uncertainty of at most $0.''3$ under most meteorological conditions.

— A full atmospheric model, such as that given by [4] and [5] (ATM) should be used to calculate the refractivity at the antenna, N_0^{rad}. This will insure a more accurate calculation of the refraction at the antenna.

— May want to do full refraction correction calculation within ATM.

— The suggested structure for the pointing coefficient information described in [1] will allow for a great deal of flexibility in implementation of the ALMA pointing model. Ultimately, these data should be incorporated into a general observatory database to allow detailed tracking of the pointing characteristics of the ALMA antennas.

— Short-term (hourly) time variations of antenna pointing properties can be accurately calibrated by reference pointing, while losing an affordable fraction of the available observing time (1-4 minutes per hour).

Initial pointing studies will be done with optical pointing telescopes (OPT). The OPT systems used on the ALMA prototype antennas have proven to be invaluable to the characterization of the pointing performance of these antennas.

3 Description of the Techniques and Steps

Note that in the following:

— All of the radiometric pointing measurements described in this document will use a "channel average" measurement of the total power. This "channel average" may be the whole band (continuum) or just a selected number of spectral channels (spectral line).

— Radiometric pointing measurements for a given science band are made with the subreflector positioned for optimum science band sensitivity, but measured with a lower-frequency (*i.e.* Band 3) band.

3.1 Single Radio Pointing Measurement

All radio pointing calibrations described here are made of combinations of individual radio pointing measurements. A single measurement determines the collimations CA and IE (see [1]) in the observed direction at the measurement time. Quasars are the best sources, and given the spectral index distribution, 90 GHz is the best observing frequency (while the loss of sensitivity in the lower 2mm band is affordable if one wishes to avoid shifting receiver bands for pointing only; see [3]).

Traditional five point maps can be made (to optimize sensitivity several antennas are observing on-source at any given time). Sources of $\sim$ 100 mJy are usable at 90 GHz for the 64 antenna array, in order to get the desired measurement accuracy ($0.3''$, so that the measurement error is not significantly contributing to the pointing accuracy budget). If less than 64 antennas are used (e.g. only a few antennas need to be calibrated), the on-source integration time scales like $64/N$, and the minimum flux for a given integration time scales like $\sqrt{64/N}$. However for sources stronger than $\sim$ 500 mJy, the slewing time dominates the required integration times.

1. Set up (autocorrelation). One needs to set the programmable attenuators to be sure the correlator is working at optimum sensitivity. This is done by optimizing the value of the unscaled channel zero count for each baseband, or by using the sampler statistics.
2. Observe using one of the two pointing scan types:
   (a) *5-Point*: Observe each of the 4 half-power points of the primary beam plus the boresight position for $\sim$ 1 second per point.
   (b) *3-Point*: A variant of the 5-Point where one measures 3 half-power positions of the primary beam which lie on an equilateral triangle.
   (c) *Cross*: Make a series of two or more (Az,El) cross scan slew measurements.
3. On-line fit to the pointing measurement derives the current $(\Delta Az, \Delta El)$ for each antenna.
4. Store antenna-based results in the Monitor and Control database.

Figure 1 shows a "timing diagram" which describes the three variants of a single radio pointing measurement. Summarizing the supplementary (laboratory or otherwise) measurements needed for proper pointing calibration calculation:

— Programable attenuator spectral response. Should have an initial (laboratory) measurement that is supplemented with regular (once per month) measurements of the spectral response using a strong source (*e.g.* Moon).

— Sideband gain ratio (measured interferometrically). Part of bandpass calibration.

3.2 Global Pointing Model

A global pointing model is derived by observing approximately 100 (or more) radio point sources well distributed over the observable sky. The typical distance between sources is then 16 degrees, and their typical flux is 0.5

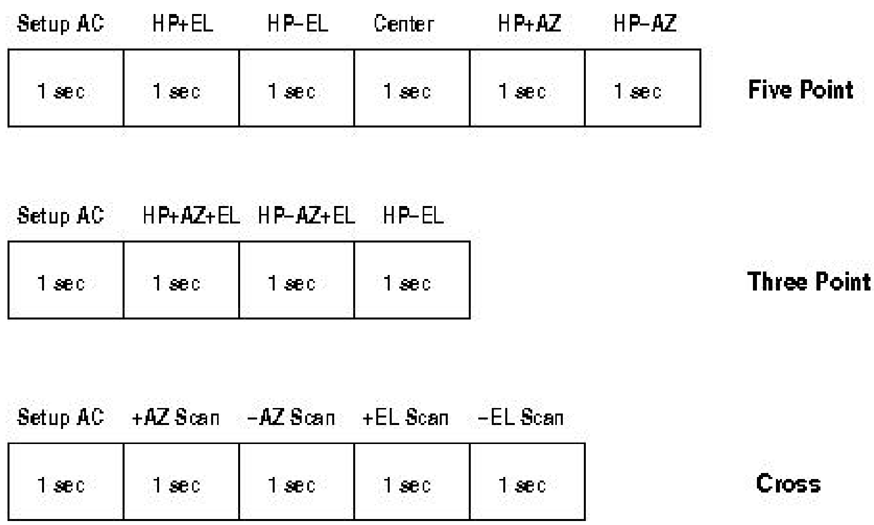

Figure 1: Three variants of a single radio pointing calibration measurement timing diagram. Note that one possible order in which each half-power measurement is shown and that the actual positioning sequence should be chosen for maximum time efficiency. For the global pointing model measurements the chosen radio pointing variant (Five Point, Three Point, or Cross) is repeated for each of the 100 or more measurements.

Jy. Each pointing measurement needs 10s (mostly switching between half-power points). Slewing between sources adds 5 s per source. The total time is then about 1500s. For *e.g.* a 4 antenna subarray, the duration of each measurement goes up to 45s. The total time to get a full model is then 5000s. Determining the pointing parameters after a move should however require fewer sources as measuring only a few parameters (AZ offset and axes inclination) should be needed.

The individual pointing results are used, after eliminating possible erroneous measurements, to constrain a set of linear equations using a linear least square fitting program such as TPOINT (see [1]).

The sequence of measurements for the global pointing model is as follows:

1. Set up array for observations at 90 GHz.
2. Select approximately 100 (or more) radiometric point sources from the ALMA catalog.
3. Randomize the selected source list in (Az,El) while ensuring good all-sky (Az,El) coverage.
4. Sequentially measure each source using the "Single Radio Pointing Measurement" described in §3.1 and shown in Figure 1.
5. After all sources have been measured derive the pointing model solution using TPOINT.

The global pointing determination is needed (conservatively) for each antenna after it has been relocated. A sufficient number of antennas should be measured simultaneously to improve sensitivity. If some additional antennas are included only for this purpose, they do not need to be scanned.

One should also make a global pointing determination at regular intervals (monthly?) to check the global pointing performance and monitor the pointing model coefficients.

3.3 Reference Pointing

The simple (and commonly used) reference pointing scheme was described in [2]. At regular intervals, a point source is observed in interferometry mode. The measured collimations (CA, IE) are used to observe the target source until a new pointing measurement is done.

An improvement of this scheme is described in [3]. Single-source pointing measurements are replaced by local pointing model determinations, using a few (~ 5) pointing sources, typically 4-7 degrees from the target source. The local pointing model should guarantee more accurate pointing as the changes in azimuth and elevation of the target source between two successive pointing calibrations is appreciable (several degrees). To the two local coefficients (CA, IE), one would add for instance the local partial derivatives of the collimations with respect to Azimuth and Elevation (4 additional terms).

For reference pointing, in order to get the best accuracy, the observing time per individual measurement on 100 mJy sources is about 90s (see [2]). If the pointing accuracy is relaxed, *e.g.* according to the needs of long wavelength programmes, or if low dynamic range programmes, then shorted measurements can be used; this is also possible if a nearby strong calibrator is available.

The integration time is not directly a function of frequency, as we should normally use a low frequency for the measurements; however the desired accuracy varies (approximately linearly) with the wavelength of the science programme.

In the local pointing model scheme, the integration times are smaller and the measurement time is dominated by slewing times between the pointing sources. One needs about one minute to observe a local pointing model of 5 sources.

The sequence of measurements for the reference pointing measurement is as follows:

1. Set up array for observations at the target observing band.
2. Select 1 (for a simple pointing offset) or ~ 5 (for a local pointing model measurement) radiometric point sources near the target source from the ALMA catalog.
3. Sequentially measure each source using the "Single Radio Pointing Measurement" described in §3.1.
4. Derive $(\Delta Az, \Delta El)$ for each pointing measurement. If a local pointing model measurement has been made, use TPOINT to derive the local pointing corrections to the global pointing model.

We basically do not know how often the reference pointing will be needed. If the antennas are stable enough (*i.e.*as specified) once every 15 minutes should be enough ([2]). If the pointing requirements are relaxed (this depends on the observing projects, which will have to require a pointing accuracy as one of the stringency factors involved in dynamic scheduling) then the time between measurements can be increased, and observing time saved.

In the local pointing model scheme, one could use less frequent pointing measurements to obtain the same operational pointing accuracy.

3.4 Relative Pointing Calibration of the Receiver Bands

The same technique is used for individual measurements, but the results should be stable unless a receiver dewar is taken off the antenna and/or taken apart. Measurements are thus considerably less frequent (several months?) for each given antenna. The accuracy should be better than $0.3''$, using much stronger sources (~ 10 Jy).

4 Archiving Needs

The following pointing information needs to be archived:

- — The results of the global pointing model determination, which includes all pointing model term and refraction term coefficients and their uncertainties.
- — We need to archive for each reference pointing measurement the measured collimations and their associated uncertainties. The total size is 1.26 kB for a 64-antenna measurement. In the local pointing model scheme this is multiplied by 3, but the rate may be smaller if the measurements are less frequent.
- — The results must be accessed by the Control Subsystem as soon as possible.

5 Further Studies

Other measurement techniques can be more time efficient, *e.g.* if stronger sources and thus shorter integration times (smaller than 2 seconds) are used. Observing a circle at the half-power point avoids the slew time between discrete integrations at half-power points. These refinements will need some tests (*e.g.* at the ATF) before they are actually implemented.

The local pointing model scheme will need some validation (can be integrated at the ATF). As sensitivity is a key factor which will determine the ultimate utility of this technique, its real efficiency can only be tested on the full ALMA array. Tests on actual telescopes are quite valuable as the main uncertainties here are the actual telescope thermal and mechanical properties.

References

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[5] Pardo, J. R., Cernicharo, J. & Serabyn E. 2001, "Atmospheric Transmission at Microwaves (ATM): An Improved Model for mm/submm applications", IEEE Trans. on Antennas and Propagation, 49/12, 1683-1694