Volume Title
*ASP Conference Series, Vol. **Volume Number***
Author

Calibration of the Atacama Large Millimeter Array

J. G. Mangum[1]

[1]*National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903–2475*

Abstract. The Atacama Large Millimeter Array (ALMA[1]), which began early science observations in October 2011, is an array of 66 antennas designed to study the universe at millimeter and submillimeter wavelengths. Critical to the quality of the science derived from ALMA is the calibration of its measurements. In the following I describe how the ALMA telescope is calibrated.

1. The Design of ALMA

The design characteristics of ALMA were set based on the desire to meet three key science goals:

- Detect CO or CII in a normal galaxy like the Milky Way at a redshift of 3 in less than 24 hours.
- Image the gas kinematics in protostars and protoplanetary disks around young Sun-like stars in the nearest (d = 150 pc) molecular clouds.
- Provide precise high-dynamic range images at an angular resolution of 0.1 arcsec.

To meet these three key science goals, ALMA has been configured with the following capabilities:

- Continuous frequency coverage from 100 to 1000 GHz.
- Greater than 6600 m^2 of collecting area.
- Baselines ranging from 15 m to 16 km.
- The ability to process up to 16 GHz of bandwidth.

---

[1]ALMA, an international astronomy facility, is a partnership of Europe, Japan, and North America in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere; in Japan by the National Institutes of Natural Sciences in cooperation with the Academia Sinica in Taiwan; and in North America by the National Science Foundation in cooperation with the National Research Council of Canada and the National Science Council of Taiwan. ALMA construction and operations are led on behalf of Europe by the European Southern Observatory (ESO), on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ), and on behalf of North America by the National Radio Astronomy Observatory (NRAO). The NRAO is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

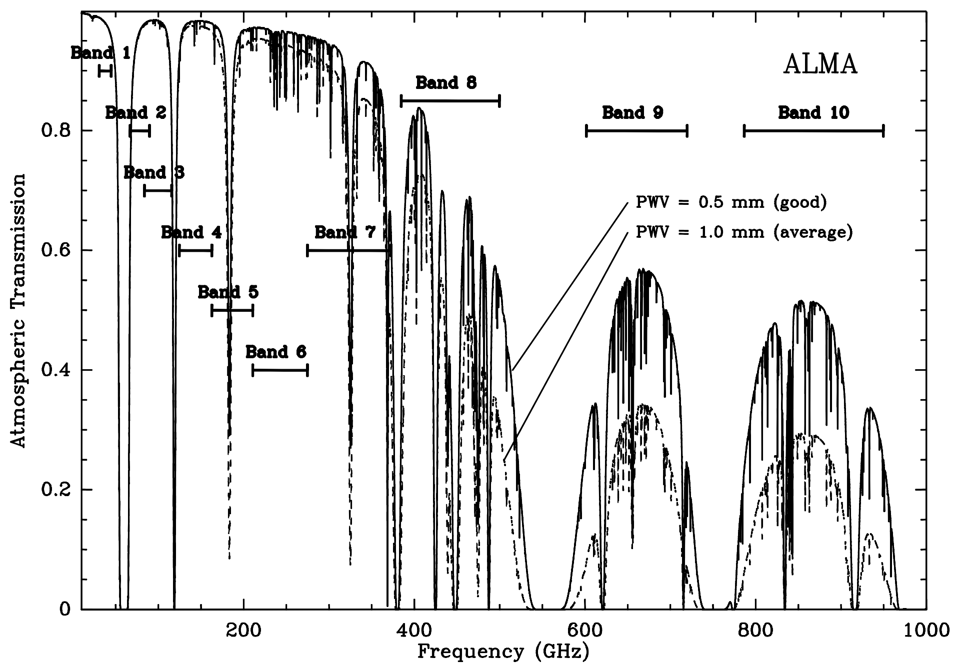

Figure 1. Atmospheric transmission at the ALMA site under good (0.5 mm precipitable water vapor (PWV); solid) and average (1.0 mm PWV; dashed) atmospheric conditions. The frequency ranges for each of the ALMA observing bands are shown.

- 24 hour operation.
- Continuum sensitivity: 0.05 to 1 mJy in 60 seconds
- Spectral line sensitivity: 7 to 62 mJy in 60 seconds for a spectral resolution of 1 km/s.

The review of the ALMA telescope by Wootten & Thompson (2009) describes the site, antenna, configuration, and detection hardware systems which comprise ALMA. In the following I summarize these systems in order to place the calibration requirements and procedures into context.

1.1. Site

The ALMA site is located in the Chilean Andes of Region II in northern Chile on a plain at the foot of three volcanic peaks: Cerro Toco, Cerro Chajnantor, and Cerro Chascon. At a mean altitude of ∼5050 m (∼16568 ft), the ALMA site location offers excellent atmospheric transparency at all operational frequencies (see Figure 1). At a longitude of 67° 45′ W and a latitude of 23° 01′ S, the ALMA site lies just north of the Tropic of Capricorn, about 50 km east of the village of San Pedro de Atacama, 130 km southeast of the mining town of Calama, and about 275 km east-northeast of the coastal port of Antofagasta. Figure 2 summarizes the geographical location of the ALMA site.

Figure 2. Geographical map of the region around the ALMA site.

1.2. Antennas

The 66 antennas that comprise the ALMA telescope are of two varieties which derive from four separate designs (see Figure 3):

- 54 12 m antennas comprised of three designs:
  - 25 antennas provided by the National Radio Astronomy Observatory (NRAO) which have been designed, assembled, and delivered by VertexRSI.
  - 25 antennas provided by the European Southern Observatory (ESO) which have been designed, assembled, and delivered by a consortium comprised of the companies Thales-Alenia Space, European Industrial Engineering (EIE), and MT Mechatronics (consortium referred to as AEM).
  - 4 antennas provided by the National Astronomical Observatory of Japan (NAOJ) which have been designed, assembled, and delivered by Mitsubishi Electric Company (MELCO).
- 12 7 m antennas provided by NAOJ which have been designed, assembled, and delivered by Mitsubishi Electric Company (MELCO).

The ALMA telescope system can be operated as two separate arrays: the array of 50 12 m antennas provided by NRAO and ESO which is referred to as the "12 m Array", and an array comprised of the MELCO antennas (4 12 m and 12 7 m) which is referred to as the "Atacama Compact Array (ACA)". The main performance requirements for the ALMA antennas, listed in Table 1, are set to allow ALMA to operate continuously during the following weather conditions:

- $T_{ambient} = -20$ to $+20$ C
- $\Delta T_{ambient} \leq 0.6/1.8$ C over 10/30 minute durations
- $V_{wind} \leq 6/9$ m/s (day/night)

1.3. Array Configuration

There are nearly 200 foundations upon which the ALMA antennas can be mounted. Transporters move antennas between the foundations according to observing demand. The maximum baselines available between antenna foundations are approximately 15 km. It is expected that antennas will be moved on a few-per-day basis along a self-similar configuration of roughly spiral geometry. All antenna configurations will provide excellent imaging characteristics. The ACA antennas occupy a special set of closely spaced foundations, which allow for limited repositioning to improve the resolution for extreme north or south source declinations.

1.4. Receiver and Correlator Systems

Each of the 12-m ALMA antennas will be equipped with a receiving system to cover the range from 31 to 950 GHz in ten bands (see Figure 1). Each receiver is packaged in the form of a cylindrical cartridge (e.g., Ediss et al. (2004) and Satou et al. (2008)) which is mounted within a circular Dewar located within each antenna. All receiver bands produce dual-linearly polarized outputs. Intermediate frequency amplification

Figure 3. ALMA antennas. VertexRSI (top-left; photo courtesy Art Symmes) and MELCO (top-right; photo courtesy ESO/José Francisco Salgado) antennas under test at the ALMA Operational Support Facility (OSF). Bottom: An AEM antenna is transported with the ALMA antenna transporter on the ALMA site (photo courtesy ESO/S. Stanghellini).

of these receiver band output signals results in an output total bandwidth of 16 GHz. The ALMA correlator (Escoffier et al. 2007) for the 12 m array is designed to process all cross-products for up to 64 antennas, with total bandwidth 16 GHz per antenna. The correlator is a development of the XF type, i.e., cross-multiplication with time lags followed by Fourier transformation to provide frequency spectra. In the ALMA correlator, these processes are preceded by digital filtering, which divides each 2-GHz-wide band into 32 subbands of width 62.5 MHz. Thus, the spectral resolution is 32 times finer than would result from the same number of lags applied to the full 2 GHz bandwidth. A further factor of two in the resolution is available by digital filtering to 32 bands of width 31.25 MHz, but with a reduction of a factor of two in the total bandwidth covered. The center frequency of each filter is independently tunable, thus providing high flexibility to the correlator system.

2. ALMA Calibration Specifications and Requirements

Performance specifications for ALMA hardware and software which relate directly to our ability to calibrate the signals ALMA acquires are listed in Table 1. The types of calibration measurement that ALMA must acquire can be separated into two categories: those calibration measurements that are performed as part of the regular operation and maintenance of the ALMA telescope:

- All-Sky Pointing
- Polarization (basic)
- Antenna Location
- Antenna and Electronic Delay
- Optics
- Primary Beam

and those calibration measurements that must be performed by ALMA observers as part of their program measurements:

- Offset (Reference) Pointing
- Amplitude
- Phase
- Bandpass
- Polarization (specific)

In the following I will describe the process used to effect the user calibration measurements listed above. I concentrate on the details of phase and amplitude calibration as these two types of calibration present the most challenges to our ability to acquire accurate millimeter and submillimeter measurements of astrophysical objects with ALMA.

Table 1. ALMA Specifications and Requirements

Specification	Requirement
Antenna Poining (All-Sky / Offset)	2.0 / 0.6 arcsec over 2 deg radius on the sky
Antenna Surface Accuracy	25μm (12 m antennas) / 20μm (7 m antennas)
Antenna Path Length Stability	15μm / 20μm RMS (non-repeatable / repeatable)
Primary Beam Characterization	6% in power out to 10% of the primary beam
Feed Setting	280 μm vertical / 3200 μm lateral
Subreflector Setting	28 μm vertical / 140 μm lateral / 1.7 arcmin rotational
Antenna Motion[a]	1.5 deg position switch in 1.5 seconds
	Settle to 3 arcsec peak pointing error after 1.5 sec
	Settle to 0.6 arcsec RMS over 2 to 4 sec time window
Antenna Location	65 μm
Geometric Delay	5 fs systematic
Atmospheric Delay	10 fs systematic / 40 $\times$ (1.25 + PWV) fs fluctuating
Antenna Delay	7 fs systematic / 50 fs fluctuating
Electronic Delay	7 fs systematic / 30 fs fluctuating
Bandpass	10000:1
Polarization	0.1% in amplitude / 6 deg in position angle
Sideband Gain Ratio	0.1%
Amplitude (Relative)	1% / 3% ($\nu < 370$ GHz / $\nu \geq 370$ GHz)
Amplitude (Absolute)	5% (all frequencies)
Corrected Visibility Phase	< 57 deg at 950 GHz for timescales < 10 seconds

[a] Applies only to 12 m antennas provided by NRAO and ESO.

3. Offset (Reference) Pointing

For those experiments that require a high level of positioning performance and stability, ALMA has been designed to point its antennas to an accuracy better than 0.6 arcsec within a 2 degree radius around a target source position. Furthermore, the ALMA antennas must maintain this positioning stability for at least 15 minutes. These measurements will normally be made by measuring the position of a bright point source, such as a quasar, in the observer's target source field.

4. Bandpass Calibration

Calibration of the ALMA detector bandpass is accomplished by measuring a bright source, such as a quasar, for a sufficient duration to obtain a high signal-to-noise measurement of the bandpass calibrator's flux. This measurement then allows for the derivation of the frequency dependence of the detector system response.

5. Polarization Calibration

For polarimetry measurements one must calibrate the inherent polarization response of the ALMA detector system. These calibration measurements assume that the basic polarization purity (*i*.e. the purity of the dual linear polarization signals from the ALMA receiver systems) has been determined. Calibration of the polarization response of an

ALMA receiving system then requires a measurement of a known source of polarized signal.

6. Phase Calibration

Calibration of the phase measured by a radio interferometer usually involves a measurement of a relatively strong phase-stable signal located outside the Earth's atmosphere. Measurements of quasars over a variety of timescales are often used as phase calibrators at radio and millimeter wavelengths. In order to meet the requirement that the system phase stability be monitored over short (few second) and long (minutes to hours) timescales within all of the ALMA frequency bands a number of measurement techniques have been devised:

- Fast position switching (see the "Antenna Motion" specification in Table 1) between science target and phase calibrator will allow for short timescale calibration of the phase.
- For the higher frequency bands ($\nu > 350$ GHz) calibrator availability might require phase referencing to measurements made at 90 GHz.
- Parallel measurements of the phase variations due to water vapour absorption in the Earth's atmosphere above each antenna are made using water vapour radiometers (WVRs) installed on each antenna (see §6.1 for further information).

One possible phase calibration measurement sequence which allows for the calibration of both low and high frequency observations is shown graphically in Figure 4. This example phase calibration sequence is composed of two sequences:

- Instrumental Sequence:
  - Required for cross-band calibration of dual-frequency fast switching measurements
  - Calibrator measured at both calibration (90 GHz) and target frequencies
- Target Sequence:
  - Measure target and phase calibrator separated by ≤ 2 deg

6.1. Water Vapour Radiometers

Each 12 m antenna is equipped with a radiometer which is tuned to the 183 GHz absorption transition of H_2O whose purpose it is to monitor the phase variations due to the water vapour above each antenna. These Water Vapour Radiometer (WVR) systems (Nikolic et al. 2011; Nikolic & Bolton 2011) have the following properties:

- Omnisys Radiometers
- 8 filters measuring 177 to 195 GHz total power centered at the 183 GHz water line
- Sensitivity: 0.08 to 0.1 K per channel.

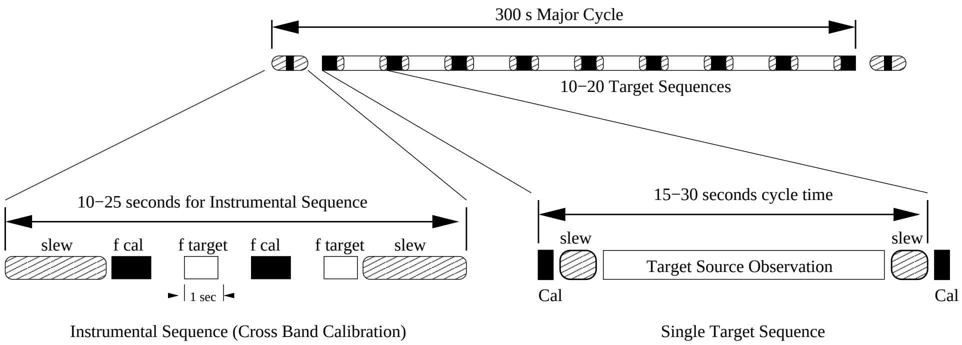

Figure 4. Schematic example of a possible phase calibration sequence for ALMA.

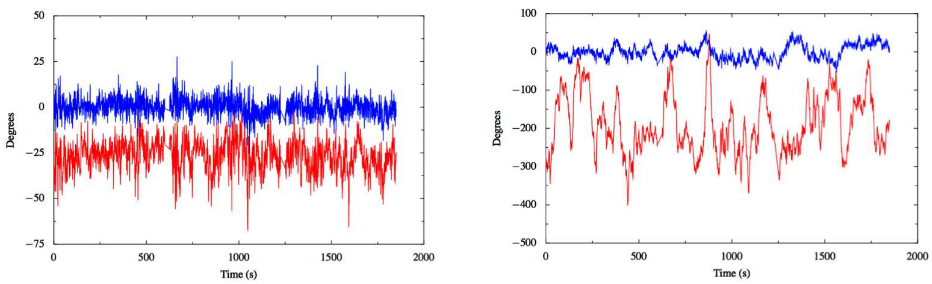

Figure 5. Uncorrected (lower spectrum) and WVR-corrected (upper spectrum) examples of the effectiveness of the WVR phase correction over a short (left; ~ 50 m) and long (right; ~ 300 m) ALMA baseline (from Nikolic & Bolton (2011)).

- Stability: 0.1 K peak-to-peak over 10 minutes.
- Absolute Accuracy: 2 K maximum error.
- All 58 systems delivered to ALMA.
- System developed by University of Cambridge (Bojan Nikolic)

Figure 5 shows example uncorrected and WVR-corrected phase measurements for a short (~ 50 m) and long (~ 300 m) baseline. As one can see, the WVR phase correction does a very good job of removing much of the residual phase scatter.

6.2. Example ALMA Phase Calibration at 660 GHz

In the following we describe an example ALMA phase calibration measurement observed at 660 GHz (Ed Fomalont, private communication). The logistics of these calibration measurements are as follows:

- Data acquired 2011-08-31.
- Four ICRF quasars were observed alternately for one minute over a 70 minute period.
- WVR corrections made virtually no difference in the phase data and were not applied.

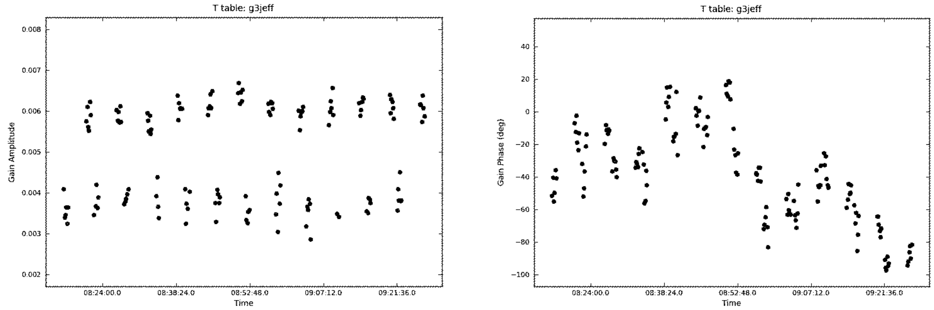

Figure 6. Raw (uncalibrated) gain amplitude (left) and phase (right) for two of the four ICRF quasars using antenna DV12. The upper points represent the gain amplitude and phase for J0522−364, while the lower points are from J0538−440. Each clump of points in time represents a one minute scan with each data point indicating a 10 second integration. Amplitudes are derived by averaging eight channels (2 polarizations over 4 spectral windows).

- Precipitable water vapor (PWV) was measured to be ~ 0.2 mm.
- The correlator configuration employed four spectral windows (spw), each with 2 polarizations and a useable bandwidth of 1.7 GHz. The spw frequencies were 687, 689, 691, and 693 GHz.
- All four Stokes parameters were measured and each spw had 64 spectral channels.
- The ALMA array used for these measurements included 5 antennas with an average baseline of ~ 150 m.

Note that, as a general rule-of-thumb regarding the correspondence between phase and amplitude errors in radio interferometry: **1 degree of phase error corresponds to approximately 2% in amplitude error** (Perley 1989).

Figure 6 shows the raw (uncalibrated) gain amplitude and phase for measurements of two of the four ICRF quasars using antenna DV12. As these measurements show, the uncalibrated amplitude and phase is quite stable, with amplitude and phase gain variations of $\sim 7\%$ and 10/25 degrees over 1 to 70 minute timescales, respectively.

Figure 7 shows the raw (uncalibrated) gain amplitude ratio (XX/YY) and phase difference (XX−YY) for the independent linearly-polarized signals measured at 660 GHz. The XX and YY ratio and difference were derived for one of the ICRF quasars using antennas DV11, DV12, PM01, and PM03. The amplitude ratio is indicative of the signal-to-noise of each 10 second integration due to differences in instrumental gain between the dual-linearly polarized signals (XX and YY). Gain variations due to tropospheric emission are removed in this calculation. Similarly, the phase difference removes tropospheric delay changes, thus reflecting the instrumental phase stability. Since both the gain amplitude ratio and phase difference are consistent with the signal-to-noise limitations of these measurements, instrumental contributions to the gain amplitude and phase stability are marginal.

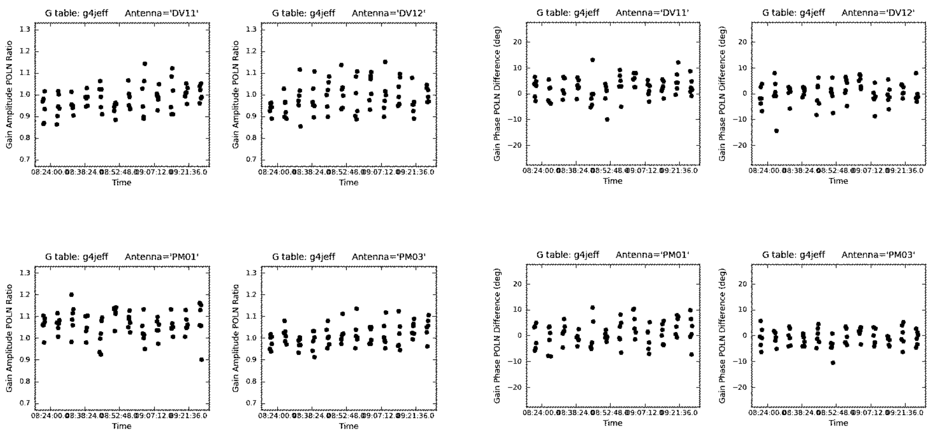

Figure 7. Raw (uncalibrated) gain amplitude polarization ratio (XX/YY; left) and phase polarization difference (XX-YY; right) for the ICRF quasar J0522−364 measured with antennas DV11, DV12, PM01, and PM03. Both of these measures remove amplitude and phase instabilities due to atmospheric (tropospheric) emission sources, thus representing a calculation of the amplitude and phase stability of the ALMA measurement system at 660 GHz.

7. Amplitude Calibration

Calibration of the amplitude, or flux, at millimeter and submillimeter wavelengths is usually separated into "steps" which comprise an amplitude calibration "ladder". A description of this amplitude calibration ladder is shown in Figure 8. Very often the two middle steps in this amplitude calibration ladder are accomplished with a load calibration device located within each antenna. ALMA has developed such a system, which is a variant of the "chopper wheel" calibration technique developed by Ulich & Haas (1976). Figure 9 shows an illustration of this dual-load amplitude calibration system.

7.1. Converting Total Power to Antenna Temperature

To convert the total power measurements derived from the ALMA receiver systems to a temperature scale two calibration loads, one at ambient and the second accurately set to a temperature of between 50 and 100 C are sequentially measured and compared to a total power measurement of the sky emission in the direction of the target source. The accuracy of these calibration loads is 0.3 (ambient load) and 0.5 (hot load) C. These temperature controlled load measurements provide a standard to which a total power to temperature scale can be determined and applied to all ALMA total power measurements. This results in an amplitude scale which is converted to a temperature and corrected for the opacity of the atmosphere above each antenna (T_A^* in Figure 8). Each ALMA receiver can be presented with both calibration loads by a robotic arm, thus allowing rapid calibration measurements for all ALMA receiver bands. A solar filter and quarter-wave plate are also included for solar and certain polarimetry measurements, respectively.

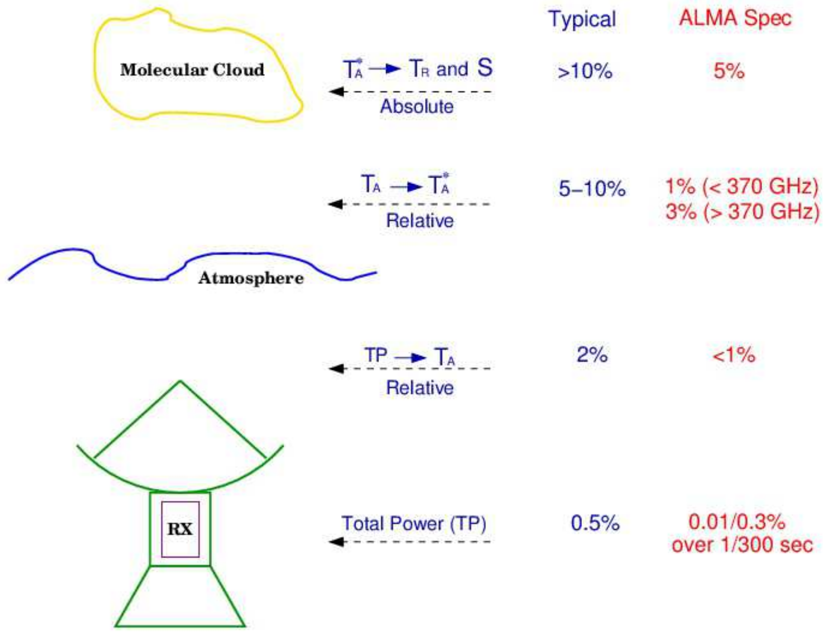

Figure 8. The millimeter and submillimeter amplitude (or flux) calibration "ladder". The typical (i.e., that available at existing millimeter and submillimeter observatories) and ALMA specification accuracies for each step in the ladder are indicated.

7.2. Absolute Amplitude Calibration

The biggest calibration challenge for ALMA is the last step in the amplitude calibration ladder shown in Figure 8: characterization of a network of absolute amplitude calibration sources. Table 2 lists several traditional and potential millimeter and submillimeter amplitude calibrators, along with advantages and disadvantages that each presents when using them as absolute amplitude calibrators. Of these historic and potential absolute amplitude calibration sources two are believed to have a large potential for meeting the absolute amplitude calibration requirements for ALMA: asteroids and cool giant stars.

Asteriods have received recent attention as flux calibration sources for Herschel (Marston 2012). Cool giant stars have proved valuable as flux standards in the mid- and far-infrared (i.e., ISO, MSX, AKARI, FIS) but have not been extensively studied for their potential as absolute amplitude calibrators in the millimeter/submillimeter. To-date, one can characterize the millimeter/submillimeter emission properties from cool giant stars as a "mixed-bag":

- Altenhoff et al. (1994) surveyed 270 stars at 1.2 mm which included 37 cool giants (15 detected). Most of these 15 stars present 1.2 mm emission which is larger than predicted, suggestive of active chromospheric emission.
- αTau and αBoo measurements at 1.4 and 2.8 mm (Cohen et al. 2005) suggest active chromospheric emission at $\lambda > 100\,\mu$m (see Figure 10).
- γCrux (closest M giant) appears to be a simple Rayleigh-Jeans radiator out to $\lambda \simeq$ 5 mm (see Figure 11). No excess emission at millimeter wavelengths is observed.

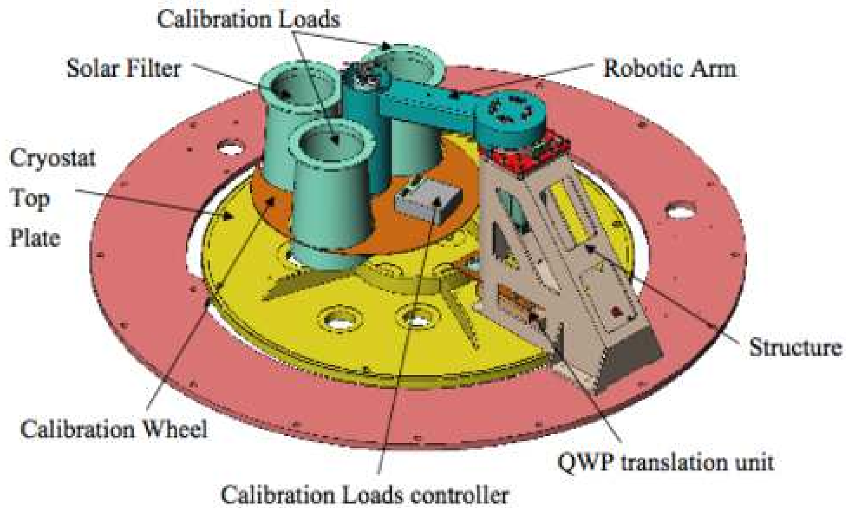

Figure 9. The ALMA dual-load amplitude calibration device. Mounted just above the dewar which houses the detectors for the ALMA receiver bands, this amplitude calibration device is a variant of the "chopper wheel" amplitude calibration technique traditionally used at millimeter and submillimeter wavelengths. A robotic arm presents each of two temperature-controlled loads to the receiver band currently being used for science measurements. These calibrated load measurements allow for the conversion of the total power signals gathered by the ALMA receivers to a temperature scale which has been corrected for the atmospheric absorption above the antenna (T^*_A in Figure 8).

- Ultraviolet/optical studies suggest that chromospheric activity declines for later spectral types (i.e., M).

Cool giant stars clearly have the potential for becoming reliable absolute amplitude calibration standards for ALMA. For this reason ALMA is currently studying the millimeter/submillimeter emission from cool giant stars to see if their emission properties allow them to be used as flux calibration standards.

8. Conclusion

The challenging ALMA calibration requirements are a direct consequence of the ALMA science goals. With many of the ALMA performance specifications verified, investigation of the calibration performance of the ALMA telescope is currently underway. With a combination of excellent instrumentation, site characteristics, and observing creativity, early ALMA calibration measurements indicate that it will meet its calibration specification goals. The biggest calibration challenge will be the derivation of a set of absolute amplitude calibration standards. The investigation into objects which are potential absolute amplitude calibration standards, including asteriods and cool giant stars, will be a focus of study for the coming years as ALMA evolves into a fully operational research facility.

Table 2. Historical and Potential Millimeter/Submillimeter Amplitude Calibrators

Source	Advantages	Disadvantages
Moon	Well modeled Bright	Too big Structure at nominal resolution
HII Regions	Well modeled Bright	Too big (with structure)
Planets and Satellites	Well studied Bright	Best (Mars) $\gtrsim$ 5% (millimeter) Too big (Jupiter, Saturn, Mars, Venus) Phases (Venus) Complex (Mars: dust storms, polar caps) Poorly modeled (most except Mars)
Quasars	Radio flux standards	Weak at millimeter/submillimeter
Asteroids	Simple (black bodies) Bright	Variable fluxes (Ceres: ±4% interday) Poorly modeled in submillimeter Poorly known physical dimensions
Cool Giant Stars	Simple (RJ emission) Point sources Multiple sources	Weak (?) Active chromospheres

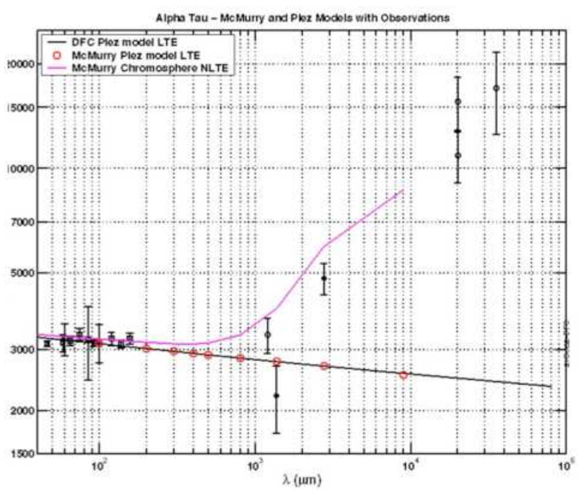

Figure 10. Infrared through radio continuum emission from the K giant star αTau from Cohen et al. (2005). Note how the measurements above 1 mm are in excess of the Rayleigh-Jeans extrapolation of the flux at infrared wavelengths. This excess emission at millimeter through radio wavelengths is suggestive of an active chromosphere.

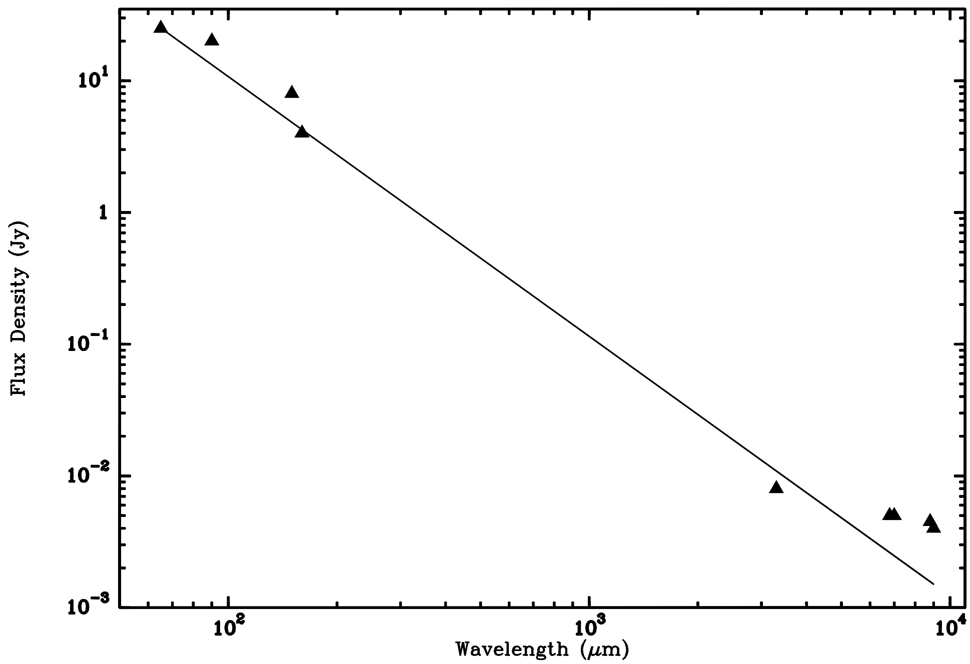

Figure 11. γCrux fluxes from 65 μm to 9 mm. The line represents a Rayleigh-Jeans blackbody fit to these fluxes (Cohen et.al., 2012, in preparation).

Acknowledgments. I would like to thank Ed Fomalont and Martin Cohen for providing the ALMA 660 GHz calibration and γCrux measurements, respectively. Without these measurements this contribution would have been much less informative.

References

Altenhoff, W., Thum, C., & Wendker, H. J. 1994, A&A, 281, 161
Cohen, M., et al. 2005, AJ, 129, 2836
Ediss, G. A., et al. 2004, ALMA Band 6 Prototype Cartridge: Design and Performance, Tech. Rep. ALMA Memo 502, National Radio Astronomy Observatory
Escoffier, R. P., et al. 2007, A&A, 462, 801
Marston, A. 2012, in this volume, vol. 0, 0
Nikolic, B., & Bolton, R. 2011, WVRGCAL and Radiometric Phase Correction at ALMA, Tech. rep., Presentation given at the Joint ALMA Observatory, Santiago, Chile
Nikolic, B., et al. 2011, in Proceedings of the 2011 General Assembly of URSI, vol. 20 of URSI General Assembly, 4
Perley, R. A. 1989, in Synthesis Imaging in Radio Astronomy, edited by R. A. Perley, F. R. Schwab, & A. H. Bridle (Astronomical Society of the Pacific), vol. 6 of ASP Conference Series, 27
Satou, N., et al. 2008, PASJ, 60, 1199
Ulich, B. L., & Haas, R. W. 1976, ApJS, 30, 247
Wootten, A., & Thompson, A. R. 2009, Proc. IEEE, 97, 1463