The Calibration of ALMA using Radio Sources

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For ALMA to produce high quality images of astronomical objects with sub-arcsecond resolution at frequencies above 85 GHz, the radio signals must be combined from up to 66 antennas spread over 15 km with a maximum path length delay difference of about 0.025 mm. This accuracy requires precise antenna structures, stable electronics, compensation for many temporal changes in the system and the measurement of the path-changing water vapour emission in the line of sight. The final stage of path length calibration is provided by frequent observations of relatively strong, point-like distant radio sources, quasars, that lie within a few degrees of the astronomical object. The ALMA Quasar Catalogue was implemented to provide a database that contains the essential parameters for hundreds of quasars and their brightness variations at several frequencies as a function of time. This paper describes the filling of the catalogue and the use of these quasar test signals to provide the path length accuracy needed for the imaging of radio sources.

The Atacama Large Millimeter/submillimeter Array (ALMA) is an array of up to 66 antennas, placed in configurations with baselines (antenna-to-antenna vectors) up to 16 kilometres, and located in the Atacama Desert in Northern Chile. Each of the antennas receives the electromagnetic waves from a celestial source in the submillimetre (submm) to millimetre (mm) wavelength range. These faint signals (sensitivity of tens of μJy; 1 Jansky = 10^{-26} W m^{-2} Hz^{-1}) are transported to a central point where they are combined at a virtual focus. The complex digital processing device that focuses the signals is the correlator. In order to produce a high quality image, the signals from each antenna must be combined with a phase difference that is less than about 0.5 radian. At a frequency of 950 GHz with a wavelength of 0.3 mm, this phase difference corresponds a path delay accuracy of about 0.025 mm or 0.08 picosecond in relative time delay.

There are several relevant time scales associated with the delay changes. The short-term path length noise (less than one second) depends on the coherence properties of the ALMA electronics which meet the needed tolerance. The longer-term change of path delay, caused by the slowly changing properties of many ALMA components, is in excess of the tolerance, although some aspects can be monitored and their effects removed. Finally, the variable path delay associated with the propagation of the radio waves in the atmosphere above each antenna is one of the major contributors to the defocusing of the signal at the correlator, from time scales of one second to several hours.

In order to monitor the changes in path length during an observation, test signals with known properties can be propagated through the entire ALMA system — from above each antenna to the correlator — and the variable delay from each antenna can be suitably adjusted (both online and offline) before the image is formed.

Accurate and convenient test signals are provided by point-like radio sources in the sky, most of them distant quasars, typically brighter than about 0.1 Jy, with accurately known positions. A short observation of a quasar for a few minutes with ALMA provides the test data needed to determine the path length adjustments to improve the array imaging. The optimum coupling of the quasar calibrator and science target observations to produce high fidelity images are discussed below.

The filling of the ALMA Quasar Catalogue

Quasar emission is produced near the nucleus of an associated massive galaxy which may contain a black hole. The emission is variable because of the interaction of material with magnetic fields near the black hole, and often leads to the ejection of material in narrow radio jets. The changes in the emission from these objects have been widely studied (e.g., Antonucci, 1993), especially with very long baseline interferometric techniques. But, their significant variability in intensity is a complication in their use as amplitude (gain) calibrators. However, these quasars are sufficiently far away that most of their emission is contained in a region that is less than 0.01 arcseconds in projected size, so that their variability has little effect on their use to monitor path length changes.

In order to compile and store the information for hundreds of quasars, a source catalogue for ALMA was implemented in 2010. The initial content of the catalogue was taken from several low frequency catalogues from other observatories which used them for similar calibration purposes[1,2,3]. However, the strength of these quasars at the ALMA frequency range of 85 to 900 GHz was unknown except for those monitored at these high frequencies by the Submillimeter Array[4], the Wilkinson Microwave Anisotropy Probe[5] and the Herschel Space Observatory[6]. On account of the great sensitivity of ALMA, a much larger calibrator database would be needed. With the ability of ALMA to determine radio positions at the milliarcsecond level, the quasar positions were obtained from several Very Long Baseline Catalogues[7,8,9].

The special ALMA calibration observations began in early 2011 when many hundreds of sources were checked for their intensities. From these observations and other observatory monitoring at or above 85 GHz, about forty strong and relatively stable sources, well-distributed over the sky, were chosen to be observed

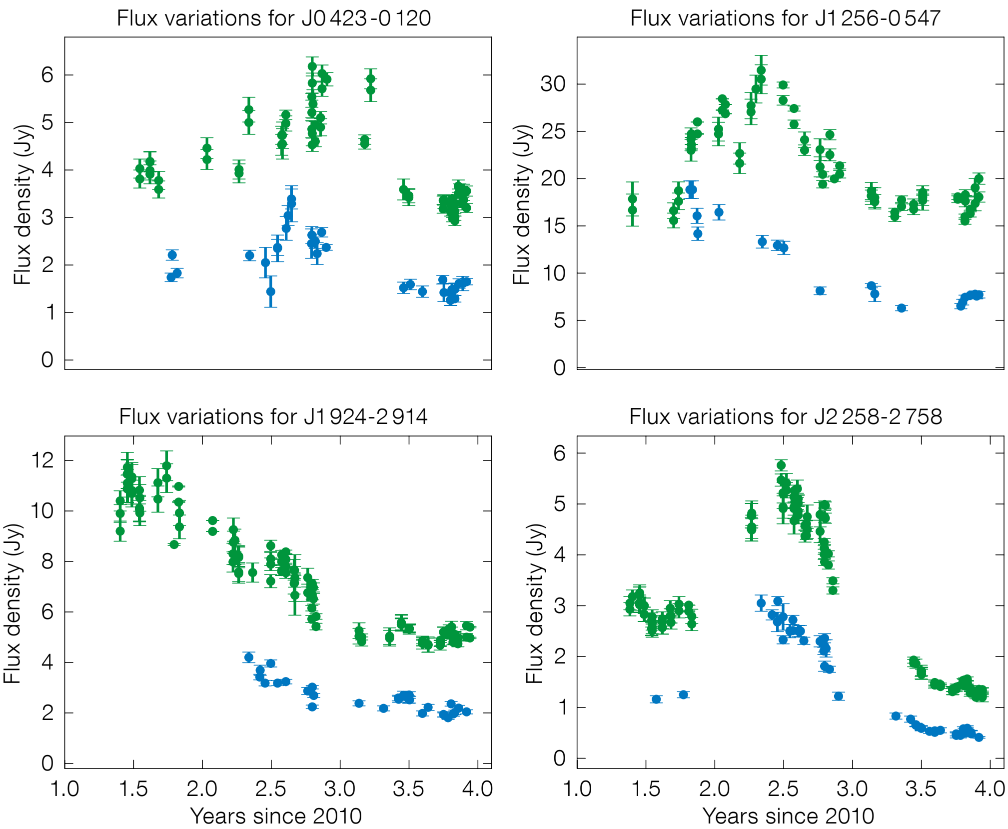

Figure 1. The flux variations of selected quasars are shown. The flux densities for J0423-0120, J1256-0547 (3C279), J1924-2914, J2258-2758 at Band 3 (100 GHz) in green and Band 7 (350 GHz) in blue are shown in the four panels. The observations cover the period from January 2011 to January 2014. The estimated uncertainties are shown by the error bars from each observation. The gaps in monitoring occur when the sources are near the Sun and not monitored regularly during the daytime.

by ALMA at 90 GHz and 350 GHz periodically. This sample is called the grid sample because at least one of them is visible at any time in the sky from ALMA and is usually within 30 degrees of any science target. These sources are sufficiently strong that the calibration across all narrowband frequency channels can be determined to a few percent accuracy.

Each ALMA grid session takes about 40 minutes and consists of one scan of about eight sources. In order to determine the flux density scale of the observations, a scan of a Solar System object is included. These objects have been well studied by many groups over the years, so that their strength is accurately known to about 5 % in the ALMA frequency range. But, because of the high resolution of ALMA and the wandering of these bodies around the sky, they are not always available for use as flux density standards. The objects with sufficiently accurate models, but not larger than about 5 arcseconds in angular size are Mars, Uranus, Neptune, and the moons Titan, Ganymede and Callisto (Europa and Io are often too close to Jupiter), the asteroids Pallas, Juno and Vesta and the dwarf planet Ceres.

Examples of the variability at 100 and 350 GHz of four selected quasars are shown in Figure 1. These plots display the range of variability properties and were chosen because they have the most extensive monitoring history so far. The data histories for these and others show that their emission generally changes smoothly with a typical variation of 10 % per month. Hence, a flux density measurement every two or three weeks, tied to a Solar System object, should provide a flux density estimate accurate to < 10 % at any time. This accuracy is sufficient for the goals of most ALMA projects. But occasional outliers, which vary strongly over less than one month (e.g., J0423-0120 and J1256-0547), do occur. Changes in a factor of two over yearly periods are common, and the content of the grid source list will be modified accordingly.

The relatively constant ratio between the 100 and 350 GHz flux densities reflects the small range of quasar spectral slope around $\nu^{-0.7}$, although flares occur at somewhat different times at the two frequencies. Thus, the interpolation of a quasar flux density between 100 and 350 GHz is accurate to about 10 %, if the two flux density measurements were made within two weeks. Extrapolation to 500 and 900 GHz is somewhat more uncertain, at the 15 % level. Occasional simultaneous observations at three frequencies of these quasars show that many have a spectral curvature between 100 and 400 GHz that is sufficiently small not to impact significantly on the simple linear spectral index extrapolation to higher frequencies. Since the good observing conditions necessary for > 600 GHz observations are at a premium, calibrator measurements have lower priority than science observations. However, flux density estimates obtained from science projects are entered into the ALMA catalogue and provide some check of the extrapolation accuracy[10].

Finally, catalogue data-filling observations of weaker sources are also continuing in

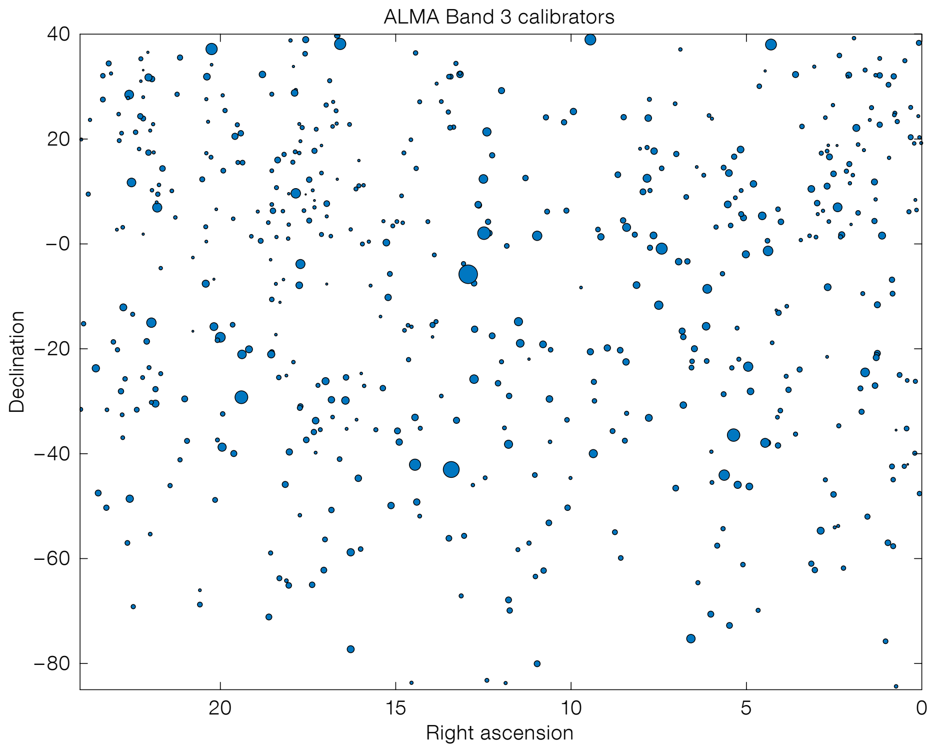

Figure 2. The distribution of ALMA Band 3 (100 GHz) calibrators are shown. Each circle represents a quasar with an ALMA-measured flux density at Band 3. The largest points are in the 10–20 Jy range; the smallest are near 0.1 Jy.

order to find quasars that are sufficiently strong for use as phase calibrators. At present there are 600 sources that are satisfactory calibrators, but several thousand are needed for future ALMA observations at baselines > 10 km, when target–calibrator separations of two degrees are needed to remove the large delay changes.

The ALMA quasar calibration methods

The observing schedule for an ALMA project is produced dynamically in order to accommodate optimally the requirements of the project with the variable conditions. Thus, the choice of calibrators is often made at run time. The relevant parameters of the scientific target are its position in the sky, the desired resolution (required size of the ALMA array) and the range of frequencies at which to observe. The latter depends on the molecule(s) the astronomer wishes to study. The amount of observing time requested depends on the image sensitivity that must be reached in order to achieve the proposed scientific results.

To accommodate the above scheme, just before the start of an observation a software-based calibrator query algorithm searches the ALMA Quasar Catalogue in order to find suitable quasar test sources that are needed to produce good quality images of the target. There are generally three kinds of test sources (calibrators) needed. If available, one of the Solar System objects is observed for about ten minutes in order to determine the flux density scale of the observation. Next, in order to determine the path length and gain changes across the range of frequencies relevant to the astronomical observations, one of the bright grid sources is observed for up to 15 minutes when narrowband channels are used. Both of the above test observations need only be done once per project execution and that can last up to several hours. If the grid source flux density has recently been measured and a Solar System object is not available, the grid source can be used for the flux density scale.

The final calibration type, called the phase referencing, removes path length variations that occur in the atmosphere above each of the antennas in the switching time between the calibrator and target, generally from 20 seconds to 5 minutes. The calibrator query for the most optimum phase calibrator has several criteria that must be balanced. First, the closer the quasar is to the science target in the sky, the more accurately it will remove the path length fluctuations in the target source. On the other hand, the calibrator must have sufficient signal in order to measure these fluctuations precisely and this depends on the intensity of the calibrator and its scan length. As shown in Figure 1, quasars often vary in flux density by more than a factor of two over a year. Since most of these fainter quasar calibrators have limited observations, it is possible that one or more may be too weak for use. Thus, a quick check of the flux density of such quasar candidates before the selection is recommended, especially for those quasars that are just above the sensitivity limit needed for sufficiently accurate measurements.

The switching time between calibrator and target also depends on the wind speed, the water vapour content, the observing frequency and the size of the array. Typically, a phase calibrator is observed for a scan length 10 to 120 seconds with a repetition rate that is about five times the scan length. Thus, the additional observations of calibrator sources can use up to 30 % of the total project observing time.

The distribution of the nearly 600 quasars measured with ALMA at Band 3 is given in Figure 2. The probability of finding one of these calibrators within a specified distance from a random target location is given in Figure 3. At the higher frequencies, the number of available calibrators decreases because of the poorer ALMA sensitivity and the lower flux density of most quasars. Although still at the experimental stage, it may be possible to observe a quasar calibrator at, for example, 100 GHz, to calibrate a science target at 350 or 650 GHz. This band-to-band calibration scheme will be successful if: (1) the phase change measured by the quasar at 100 GHz can be scaled with frequency precisely (i.e., it represents a true path length change); and (2) the instrumental phase differences between the low and high frequencies are smoothly changing over several hours and can be measured by occasionally grid calibrator observations, not necessarily close to the target.

Even though the ALMA site is extremely dry, delay variations of 0.1 mm on time scales as short as a few seconds are produced by small "clouds" of water vapour moving across the beam of each antenna. Such changes on timescales of between about one second to twenty seconds cannot be removed by phase referencing with quasars near the target. However, a group at the University of Cambridge has developed a 183 GHz water vapour radiometer (WVR) system that has been placed on the ALMA antennas in order to measure the water vapour emission along the line of sight to the radio source (Nikolic et al., 2008; 2013). The amount of emission is well-correlated with the path length changes toward the source, and the application of these corrections often decreases the short-term phase variations by more than 50%.

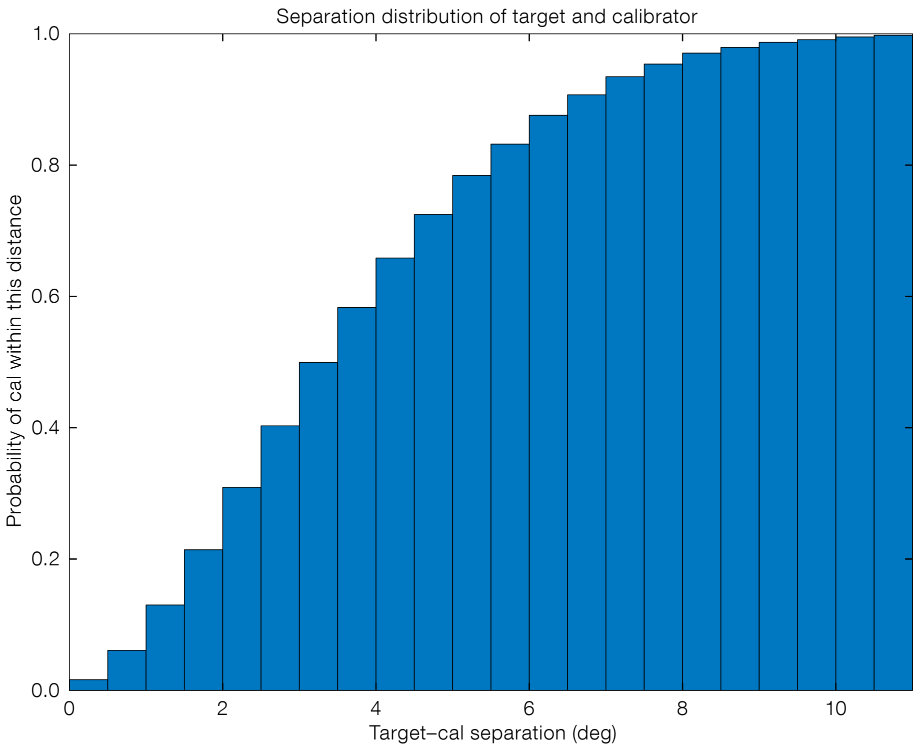

Figure 3. The histogram of the target–calibrator separation from the ALMA catalogue on 1 January 2014. The probability distribution for the minimum separation of a random position in the sky from the nearest Band 3 calibrator is shown. The median separation is 3.5° and there is a 90% probability of finding a calibrator within 7° of a random target.

Future ALMA calibrator developments

ALMA observation and development will continue over at least the next five years to improve the quasar calibration methods, at the level of about 5% of the total observing time. The detailed monitoring of the brightest 50 quasars at several frequencies will continue since these sources are secondary flux density calibrators for many ALMA observations. The need to have closer quasar and target pairs will increase for higher resolution, longer baseline projects, and will require the finding of more than one thousand additional calibrators. It is probably more efficient to search in a small area around likely targets for suitable quasars, rather than perform more global searches around the sky. Techniques to remove the dry-air component of the path delay changes (the WVR system only aids in the delay estimate from the wet component) will become more important for the longer baselines. Many ground weather and sounding devices would be needed, and multi-quasar calibrations can remove some of the longer temporal and angular changes. Finally, the experimental development of band-to-band phase quasar calibration is now in progress.

The uniqueness of the observing conditions in the high Atacama Desert, the quality of the ALMA antennas, the sensitivity of the receivers and electronics, and the infrastructure developed for array operation, have provided an array that can produce high quality images of a wide variety of astronomical objects at millimetre and submillimetre wavelengths. This image fidelity is significantly increased by interleaving relevant observations of a quasar calibrator with the target source, in order to remove the fast changing delay in the troposphere.

References

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Links

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[2] AT20G 20 GHz catalogue: http://heasarc.gsfc.nasa.gov/W3Browse/all/at20g.html
[3] VLA Calibrator Manual: http://www.vla.nrao.edu/astro/calib/manual/csource.html
[4] SMA calibrator list: http://sma1.sma.hawaii.edu/callist/callist.html
[5] WMAP catalogue: http://lambda.gsfc.nasa.gov/product/map/dr3/ptsrc_catalog_get.cfm
[6] Planck compact source catalogue: http://www.sciops.esa.int/wikiSI/planckpla/index.php?title=Compact_Source_catalogues&instance=Planck_Public
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