ALMA: Specification of Ancillary Calibration Devices

Second Draft

Introduction

As with other many other astronomical telescopes, the calibration of ALMA is founded on observations of known objects: sources of known flux provide the basis of the amplitude calibration and sources with accurately known positions provide the phase calibration. (The same applies to a lesser extent to polarisation.) At millimetre wavelengths however the transmission of the atmosphere is a strong function of frequency, zenith angle and atmospheric conditions. The instrumental parameters, such as antenna and receiver gain also vary strongly with frequency and to some extent with time. It is however important to keep the amount of telescope time spent measuring calibration objects to a reasonably small fraction of the total observing time. The ALMA antennas will therefore be equipped with calibration devices whose essential purpose is to transfer the calibration from the known sources to the current observations. These are the "Primary" calibration devices: in the case of are amplitude and polarization these consist of thermal sources ("loads") of known temperature, which are installed in the space above the receivers. For the phase, the primary system consists of the 183GHz radiometers that measure the emission from water vapour in the atmosphere along the line of sight to the source, from which the atmospheric phase changes can be estimated. (An electronic system that injects a coherent reference signal into the front-end in order to measure instrumental phase and polarisation has also been proposed, but is not currently being developed for ALMA.)

The specifications of these Primary Calibration Devices are dealt with elsewhere. This document covers the other instruments (the "Ancillary Calibration Devices") that will be needed to enable the calibration to be carried out to the desired level of accuracy. These are focussed on describing the atmosphere above the ALMA site, both statistically and in real time. They are needed because the quantities measured by the primary devices – essentially the brightness temperature of the atmosphere at both the astronomical observing frequency and near the 183GHz water line – do not give directly the quantities required, namely the atmospheric transmission and phase at the observing frequency, with sufficient accuracy. The point here is that although, in both cases, the quantity required is to first order directly proportional to the quantity measured, significant corrections to this relationship are required if we are to achieve the ALMA goals. These are due to the temperature- and (to a lesser extent) pressure-dependence of the processes involved. These corrections can be evaluated by using a model of the atmosphere. The intention is to use the ATM model for this purpose (Pardo, Cernicharo and Serabyn, 2001: J. Quant. Spectr. and Radiat. Transfer 68//4, 419). The information required as input to this model includes temperature and water vapour content as a function of altitude as well as parameters describing any water or ice particles present. It is worth noting that, while the modelling of gaseous components in the atmosphere is well developed, much less is know about how best to represent the effects of particles in the atmosphere (i.e. clouds) above the ALMA site.

It should also be pointed out that, although a detailed description of the atmospheric profile is needed in order to carry out the model calculation, the actual relationship we need between measured sky brightness temperatures and atmospheric transmission and phase is a relatively simple one, which should only require a few parameters, such as the mean temperature of each molecular species contributing to the absorption, to describe it. The models will therefore be constructed using a library of profiles, chosen to be suitable for the site and the season, with a modest numbers of parameters adjusted to provide a good fit to the data from the primary and ancillary devices. It is expected that this model-fitting approach will be used during the early operation of ALMA and perhaps long-term. As more information about the atmosphere and the instruments are obtained, however, it may be possible to devise a simplified empirical procedure to relate the observed quantities to the required calibration factors without going through a full model. It is in any case clear that a significant amount of data about the conditions in atmosphere above the site will be needed to guide the modelling and to provide a firm basis for calibrating the data and setting limits on the errors in the calibration.

At present it is assumed that these Ancillary Devices be housed in a single location near the centre of the array. Since conditions may vary across the site it is possible that, when observations on the longest baselines are fully implemented, it will be worthwhile installing a number of additional devices (presumably a subset of those in the central location) at a few additional locations near the extremities of the array. It will be difficult to asses how beneficial such additional devices would be until more is known about how different conditions can be across the site. A related topic is the prediction of atmospheric conditions in the short and medium term that might aid flexible scheduling. This is addressed in the proposal of Otarola and Holdaway, but is not a funded part of the project at present (http://www.cv.nrao.edu/~awootten/mmaimcal/holdawayotarolaproposal.pdf).

Finally it is noted that instrumentation will also be required relating to the safe operation of the antennas and of the site as a whole – principally anemometers to warn of high wind speeds and probably some device to indicate the build-up of ice and snow. These are not covered here as it is assumed that the provision of these lies within the budget for the antennas. It is however possible that data from these devices might be of some use in the calibration procedure. Certainly an indication of the presence of water on the surfaces of the reflectors would be a useful as a warning that data should not be trusted.

Instruments Proposed

1) Conditions at ground level

A set of high-quality, robust, meteorological instruments to measure air temperature, pressure and humidity are required. It would be appropriate to monitor wind speed and direction as well although there is no clear application for these in the present calibration plan. These are required to set the values at the bottom layer of the atmospheric model. Although they are described as “ground level” they should be on a mast which is a least 15m high and significantly higher than any nearby buildings, to minimise any local disturbances.

Accuracy: 0.3K in temperature, 3% in humidity, 10mbar in pressure
Resolution: 0.1K in temperature, 1% in humidity, 2mbar in pressure
All figures To Be Confirmed (TBC).
Status: Essential

2) Broad-band atmospheric emission monitor

The purpose is to measure the atmospheric emission spectrum over as wide a frequency range as possible to get parameters for any water droplets and ice particles that are present, and also to measure the strength of the “pseudo-continuum” of emission due to water vapour. For this purpose, the requirements would appear to be:

Frequency resolution: 20GHz.
Frequency coverage: 100-900 GHz

Accuracy: 3K of brightness temperature
Precision (i.e. noise level): 2K of brightness level
Time for measurement – 10 minutes.
Beam: the optics should produce a beam no more that 2 degrees wide (FWHM) and have an arrangement that allow the beam to be scanned in elevation (and in azimuth as well if possible).
All figures TBC.

Comment: If this is done with an FTS using a cryogenic detector, then much more resolution and probably more sensitivity will be available than is indicated above. The possibility of using an un-cooled detector (or one cooled with a low-maintenance closed-cycle system) should also be investigated. Given the relatively low spectral resolution actually required this may provide a cheaper option, especially in operational costs and manpower.
Status: High priority

3) Temperature profiler

The purpose of this device is to measure the temperature profile in the atmosphere as a function of altitude. It is assumed that this will be done using a multi-channel radiometer operating on the side of the O2 absorption band at ~60GHz. Semi-commercial systems exist but will probably require modification (e.g. different channel frequencies) to give optimum performance on the ALMA site. It may be that this device is not sufficiently accurate to provide a full profile for the model, but it may nevertheless play a key role in showing when an inversion layer is present and at approximately what altitude. There is a question about the effect of clouds on such a device.

Probably a single device pointing straight up will be adequate. The requirements are:
Height resolution: 1km from 5 to 8km and 2km from 8 to 12km (altitude above sea level)
Precision 1K and accuracy of 2K from 5km to 8km and twice these figures from 8 to 12 km.
Time for measurement – 10 minutes.
(*Numbers are based on estimates of accuracy that can be achieved on existing systems. We need modelling to find whether this performance is adequate*.)
Status: High priority(?)

4) Cloud monitor

The purpose is to detect the presence of clouds and if possible give an indication of their nature. For daytimes a TV camera is sufficient but at night an IR camera is presumably required. The direct application to calibration of ALMA data is unclear, but it is likely that such a monitor would provide a useful indication of which data should be very good (i.e. completely clear conditions) compared to the data which may be effected by low levels of variable absorption due to thin cloud. (The presence of heavy cloud will be clear from other measurements.) Note that multiple wide angle cameras would in principle make it possible to estimate the height of the clouds.
Specs: Day and night operation. Optics to give as near as is practical full sky cover – certainly down to 20 degrees elevation.
Sensitivity: Sufficient to see cloud that produces significant emission or absorption in the ALMA observing bands.
Status: Medium Priority

5) Ozone line monitor

The Ozone lines have considerable optical depth, especially at the shorter wavelengths. It should be possible to model them with reasonably high accuracy, but values are needed for total ozone in the line of sight and its effective temperature and pressure. There are known to be seasonal and diurnal variations in these. The line strengths could be provided by a high resolution FTS or perhaps a single dedicated mm-wave radiometer tuned to a suitable line or group of lines. Alternatively it may be possible to make observations of appropriate lines sufficiently often (probably every 4 – 6 hours) using one of the ALMA receiver systems.
More information is needed on the variability of these lines and the numbers of parameters needed to describe them.
Status: Medium Priority(?)

6) Additional water vapour measurement devices

The radiometers mounted on the antennas will provide a great deal of information about the amount of water in the atmosphere and its distribution across the array, and they will give at least an indication of the distribution in altitude. There are a number of possible applications for additional water vapour measuring devices. These are:

a) Better information on height distribution of the water. It may be possible to obtain this from a radiometer equipped with more frequency channels than the standard 4.
b) An indication of the height at which most of the fluctuations in the water content are occurring. This can be determined by using 2, or possibly more, radiometers spaced a few hundred meters apart and equipped with steering mirrors. The height is obtained by finding the angular correlation function between the fluctuation in emission.

(*Experiments have been proposed, and may even be underway, with the existing radiometers on the site to test the feasibility of this.)*

Status: more consideration, modelling and experiment needed.

7) Phase monitor(s)

It is possible to use radio interferometers looking a satellites to monitor the path length fluctuations. This would provide a useful direct indication of the current atmospheric stability but not be used directly in the calibration process. We have a number of such devices on the site a present which would, however, need refurbishment as a minimum if they are to be used in the operations phase. If this continues to be done at 11GHz, as at present, then there is a contamination of the data from ionospheric effects for some fraction of the time. Satellites with beacons at higher frequencies may be available by the time ALMA comes into operation. Using these higher frequencies would reduce the ionospheric contamination but require a more extensive refurbishment / replacement of the instrumentation.

Status: Medium Priority(?)

Accommodation and other requirements

Probably need to say something about the building need to house this stuff. Obviously it needs a certain amount of space, weather protection, power, communications, etc. I am under the impression that this is already in the plans. Could someone (Simon?) please provide a summary?

Should we say something more specific about the needs for software development?