Atacama
Large
Millimeter
Array

Ancillary Calibration Instruments

Specifications and Requirements

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Table of Contents

1 Description

This document outlines the requirements for the instruments needed to provide the atmospheric information necessary for effective scheduling and accurate calibration of ALMA. There is a general discussion of the problem and a list of the instruments expected to be most valuable, together with an indication of their roles. This document provides a set of requirements for the measurement of the necessary meteorological quantities (temperature, humidity, etc.) and defines both the output from the instruments and the input to the calibration software.

2 Introduction

As for many other astronomical telescopes, the ALMA calibration scheme 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. (To a lesser extent, the same applies to polarisation.) At millimetre and submillimeter wavelengths, however, the atmospheric transmission 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. Furthermore, it is 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, therefore, will be equipped with calibration devices to transfer the calibration from the known sources to the current observations. For amplitude and polarization, these "Primary" calibration devices are thermal sources ("loads") of known temperature installed in the space above the receivers. For the phase, the primary system consists of the 183 GHz 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. *WVR won't calibrate instrument phase.* (An electronic system that injects a coherent reference signal into the receiver in order to measure instrumental phase and polarisation has also been proposed, but is not currently being developed for ALMA. *Leave out?*) Antenna pointing also has a critical effect on accurate calibration. Although the pointing is mostly determined from measurements of objects of known position, accurate values of the atmospheric parameters are necessary for accurate refraction corrections.

These Primary Calibration Devices are specified elsewhere (*Reference?*). This document covers the other "Ancillary" calibration instruments needed for calibration at the desired level of accuracy. These instruments measure the atmosphere above the ALMA, 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 183 GHz 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, & Serabyn 2001). 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 modeling 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. In any case, it is clear a significant amount of data about the conditions in atmosphere above the site will be needed to guide the modeling and to provide a firm basis for calibrating the data and setting limits on the errors in the calibration.

These Ancillary instruments will 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 assess how beneficial such additional devices would be until more is known about how different the conditions can be across the site. A related topic is the prediction of atmospheric conditions in the short and medium term as an aid flexible scheduling. This has been addressed in a proposal by Otárola and Holdaway (2002), but is not a funded part of the project at present.

Finally it is noted that instrumentation will also be required to assure 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. 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.

3 Ground level conditions

High quality and robust meteorological instruments are required to measure the ground level ambient temperature (T_s), barometric pressure (P_s), humidity (RH), and wind speed (W_s) and direction (W_d). The temperature, pressure, and humidity measurements are necessary for calculation of the atmospheric refraction and for setting the values of the bottom layer in the atmospheric transmission model. Wind vector measurements are needed to:

- Assure the safe operation of the antennas and of the ALMA as a whole;
- Correlate antenna deformation and oscillation due to wind;
- Verify wind homogeneity over the terrain around each antenna station; and
- Minimize measurement corruption due to downwind turbulence from one of the other antennas.

Especially when the antennas are deployed in the extended configurations, these quantities must be measured at each individual antenna for accurate refraction calculations. In addition, ground level conditions should be measured at a central fixed location and at a few other locations across the array to provide reference data for atmospheric modeling and for array scheduling and operations. For simplicity, the same instruments should be used both on the antennas and at the fixed locations.

Mangum (2001) specified the weather instrument accuracy (Table 1) required for atmospheric refraction calculations with better than 0.2″ accuracy. (See also Mangum and Greve [2001] and Wootten, Mangum, and Butler [2003].) Although these specifications are demanding, they are achievable with commercially available instrumentation. It should be noted, however, that the critical requirement would appear to be on the errors in offset pointing (i.e. differences over a few degrees in position and up to perhaps 15 minutes in time). Satisfactory offset pointing could be achieved with considerably lower accuracy.

Table 1: Surface Weather Measurement Requirements

Parameter	Symbol	Accuracy	Range	Sampling Rate

Barometric Pressure	P_s	0.5 mb	500–1060 mb	0.017 Hz (1 min)
Ambient Temperature	T_s	0.1 °C	–30 – +40 °C	0.017 Hz (1 min)
Relative Humidity	RH	0.5%	0–100%	0.017 Hz (1 min)
Wind Speed	W_s	0.5 m s^{-1}	0–60 m s^{-1}	1–10 Hz
Wind Direction	W_d	5°	0–360°	1–10 Hz

Accuracy: 0.1 K in temperature, 0.5% in humidity, 0.5 mbar in pressure
Resolution: 0.05 K in temperature, 0.25% in humidity, 0.25 mbar in pressure

Below we describe and recommend instruments meeting these requirements, including manufacturers and prices (Table 2).

3.1 Barometric Pressure

The Buck Research Instruments model CR-4 chilled mirror hygrometer described below contains a pressure sensor with 0.1% accuracy, which nearly meets the specifications.

Alternatively, the Theodor Friedrichs model 5002 pressure sensor (1000 DM [$445]) has an accuracy of ±0.2 mb accuracy over a measurement range of 800–1060 mb at an ambient temperature of 20 ± 5 °C. Friedrichs states all of their instruments are delivered with a calibration chart and the accuracy degradation outside the specified range for a given instrument is less than a factor of 2. In order to obtain serial data output from this device, an additional data logger must be purchased.

3.2 Ambient Temperature

The Buck model CR-4 chilled mirror hygrometer also contains a temperature sensor with ±0.1 °C accuracy, which meets the specifications.

Alternatively, the Friedrichs model 2030 (250 DM [$111]) temperature sensor has ±0.1 °C accuracy. As with the Friedrichs pressure sensor, an additional data logger must be purchased in order to obtained serial data output from this instrument.

3.3 Humidity

The Buck Research model CR-4 three stage, thermoelectrically cooled chilled mirror hygrometer ($ 6000) meets the specifications. This instrument has the following basic properties:

- Dew/frost range: –65 to 100 °C (corresponds to a relative humidity of 0 to 100% at air temperatures from 0 to 30 °C)
- 90 °C dew/frost point depression
- Resolution: 0.1 °C
- Accuracy: ±0.1 °C (corresponds to <0.5% at typical air temperatures)
- Ambient temperature sensor with ±0.1 °C accuracy (option)
- Ambient pressure sensor with 0.1% accuracy (option)
- RS232 serial data output

More information on this system, including a manual, is at http://www.buck-research.com/CR4specs.htm. Note this instrument includes pressure and temperature sensors (see above). For reference, the relationship between RH, dew point (DP), and ambient temperature (T_s) is given by Buck (1981).

3.4 Wind Speed and Direction

For the low frequency wind measurements, the R. M. Young Company model 09101 ($1210) Wind Monitor SE meets the requirements. It measures wind speed over the range 0–60 m s^{-1} with ±0.3 m s^{-1} accuracy.

Alternatively, the Friedrichs model 4400 anemometer (1000 DM [$444]) has a speed accuracy of 0.3 m s^{-1} accuracy and direction indication. (Note this instrument is actually a combination of the model 4034 wind speed sensor and the model 4122 wind direction sensor). As with the other Friedrichs instruments, an additional data logger must be purchased in order to obtain serial data output.

Table 2: Recommended Weather Instruments

Parameter	Manufacturer	Model Number	Price
P_s, T_s, RH	Buck Research Instruments	CR-4	$6000[a]
W_s & W_d	R. M. Young Company	09101	$1210

a) This price includes pressure, temperature, and humidity sensors.

3.5 Instrument Mounting Requirements

On the antennas, the anemometer may either be sited on the lip of the antenna surface or in a nearby location to be determined. Ambient temperature, barometric pressure, and temperature may instead be provided by a device in the antenna's metrology package.

In addition to measurements at each antenna, meteorological measurements should be made at a few fixed locations across the site. Given the large extent of the array and the topographic variation across the site, at least four locations will be necessary: a central meteorology station near the compact configuration and a satellite station towards the end of each arm of the extended configuration. Although they are making "ground level" measurements, the instruments should be mounted on masts at least 15 m high (and significantly higher than any nearby buildings) to minimise any local disturbances. The site utilities must provide power and communication connections for these meteorology stations.

4 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: 20 GHz.
Frequency coverage: 100-900 GHz
Accuracy: 3 K of brightness temperature
Precision (i.e. noise level): 2 K 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 uncooled 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
Cost: 500 k$?

Development project? No commercial supplier?

5 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 O_2 absorption band at ~60 GHz. 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: 1 km from 5 to 8 km and 2 km from 8 to 12 km (altitude above sea level)
Precision 1 K and accuracy of 2 K from 5 km to 8 km 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. Modeling is needed to find whether this performance is adequate.)
Status: High priority(?)
Cost: 100 k$
Radiometrics

5.1 Justification

The radiometric brightness temperatures measured at 183 GHz depend both on the integrated water vapour content, and on the atmospheric temperature profile, and this introduces some degeneracy into the phase retrieval process. In a series of idealised experiments where water vapour perturbations were confined to a single layer at a given height, and the temperature of these perturbations was varied, it was found that the fractional error on the path length ranged between 0.2-0.7% per Kelvin for PWV levels at the 25th percentile (PWV < 0.7 mm). The range reflects the impact of different scale heights for the water vapour distribution (which were varied between 1-2 km), with larger errors associated with greater scale heights. In order to achieve a 2% accuracy in the path, the temperature of the fluctuating layer would therefore need to be known to within 3-10 K.

One instrument that would be able to measure the temperature profile to this accuracy is a seven-channel radiometer that measures emission from oxygen lines between 51-59 GHz.

Typically these oxygen radiometers can measure temperature profiles with an r.m.s. error of less than 1 K up to 1 km above ground level, increasing to 1.5 K at 6 km. There is some uncertainty about the vertical resolution of such an instrument, and in particular it may not resolve higher level temperature inversions, which could increase the uncertainty in temperature to about 3 K at an inversion. The dominant water vapour fluctuations, however, are expected to be concentrated at lower levels where inversions are better represented. In this case, the instrument would allow us to reduce the uncertainty in path due to temperature to about 1%.

6 Cloud monitor

The purpose is to detect the presence of clouds and if possible give an indication of their nature. For daytime a TV camera may be 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
Comment: an all-sky IR system is in use at the Apache point observatory, see http://hoggpt.apo.nmsu.edu/irsc/irsc_doc/

7 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(?)

8 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 four.
b) An indication of the height at which most of the *fluctuations* in the water content are occurring. This can be determined by using two, 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 fluctuations 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, modeling and experiment needed.

9 Phase monitor(s)

It is possible to use radio interferometers looking at 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 at 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(?)

10 Accommodation and other requirements

A suitable housing for this apparatus needs to be provided, equipped with power, communications and perhaps temperature regulation. A container similar to those used for the site evaluation may be appropriate. This should be located near the centre of the array at a location chosen for convenient access and, if possible close to one of the electrical transformers and one of the fibreoptic consolidation points. Some of the apparatus will require suitable windows for viewing the sky. Details of the accommodation requirements can only be determined when the instruments have been identified.

More detail are needed on the interfacing of the instruments to the control and software systems.

Details to be addressed in the Site Facilities ICD.

11 References

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