ALMA Weather Instrumentation Specification

ALMA-90.03.00.00-00x-A-SPE

2006–12–01

Specification Document

Jeff Mangum

Change Record

Revision	Date	Author	Section/ Page affected	Remarks
1	2005-08-12	Jeff Mangum	All	Initial Draft
2	2006-08-30	Jeff Mangum	All	Updated suggested vendors/devices listings
3	2006-10-20	Jeff Mangum	All	Updated tower spec and added suggested locations
4	2006-12-01	Jeff Mangum	All	Added site and ambient condition specs

`$Id: ALMAWeatherInst.tex,v 1.5 2006/12/01 14:46:28 jmangum Exp $`

Contents

1 ALMA Project Overview

The Atacama Large Millimeter Array (ALMA) is an international astronomy facility constructed and operated through scientific organizations and institutes located in North America, Europe, Japan and Taiwan. In North America, ALMA development and construction activities are led by the National Radio Astronomy Observatory (NRAO) which is managed by Associated Universities, Inc. (AUI) for the National Science Foundation.

The ALMA astronomical observatory will be a synthesis radio telescope operating in an interferometric mode and in a single dish total power observation mode. ALMA is being constructed at a median elevation of 5000 meters above sea level on the Chajnantor plateau in the Atacama Desert in northern Chile.

2 Specifications and Requirements

In the following we describe the weather measurement instrumentation required for ALMA. The choice of these instruments is based on requirements for measurement of the barometric pressure (P_s), ambient temperature (T_s), relative humidity (RH), wind speed (W_s), and wind direction (W_d) described in [1]. In this document also contains a specification for the 5 instrument towers upon which a variety of devices, including these instruments, can be installed.

2.1 Environmental Requirements

The ALMA Weather Instrumentation shall operate with no degradation when experiencing any combination of the following environmental conditions.

— Ambient Temperature: -20°C $\leq$ T $\leq$ 30°C.
— Ambient Temperature Gradients: ±0.6°C in 10 minutes, ±1.8°C in 30 minutes.
— Wind: Speeds up to 20 m/s.
— Solar Flux: Full solar loading from any direction, with solar flux up to 1290 W/m^2.
— Dust: fine particles 1 micrometer in diameter or greater.

The general operational environment will be an outdoor location on the ALMA site at 5000m elevation.

2.2 Instrument Requirements

Table 1 lists the required accuracy for the ALMA weather instrumentation derived from [1] and [2]. The requirements on P, T, and RH are driven by the need to calculate the atmospheric refraction to better than $0.''2$. The requirements on the wind vector measurement are driven by:

— The need to correlate antenna deformation and oscillation due to wind;
— Verify wind homogeneity over the terrain around the antennas;
— Minimize measurement corruption due to downwind turbulence from adjacent antennas.

3 Suggested Vendors and Devices

In the following we list suggested vendors. In some cases, we also list devices produced by these vendors which appear to meet the ALMA specifications.

— **Barometric Pressure:**

Table 1: Surface Weather Measurement Requirements

Parameter	Symbol	Required Accuracy and Range	Sampling Rate
Barometric Pressure	P_s	0.5 mb, 500–1060 mb	0.017 Hz (1 minute)
Ambient Temperature	T_s	0.1 C, −30–+40 C	0.017 Hz (1 minute)
Relative Humidity	RH	1.0%, 0-100%	0.017 Hz (1 minute)
Wind Speed	W_s	0.5 m/s, 0–60 m/s	1-10 Hz
Wind Direction	W_d	5 deg, 0–360 deg	1-10 Hz

NOTE: Require 5 of each instrument.

1. *Buck Research Instruments*: The chilled mirror hygrometer described below contains a Druck PMP4000 series pressure sensor with 0.1% stability and 0.04% accuracy, which meets our specifications. Buck will also install a more accurate pressure sensor for an extra \$500–\$1000 or so.
2. *Theodor Friedrichs & Company*: See http://www.th-friedrichs.com. Sell a pressure sensor with ±0.2 mb accuracy over a measurement range of 800–1060 mb and at ambient temperature 20 ± 5 C. Friedrichs states that all of their instruments are delivered with a calibration chart, and that the degradation of the accuracy outside the specified range for a given instrument is less than a factor of 2. It is model number 5002 in their catalog. The price for this device is ∼\$500. Unfortunately, an additional datalogger must be purchased in order to produce serial output from this device.
3. *Setra*: Model 270 (see http://www.setra.com/tra/pro/p_ba_270.htm) used at VLA/VLBA. Accuracy 0.05% over 600–1100 mb.

— **Ambient Temperature:**

1. Buck Research Instruments. The chilled mirror hygrometer described below contains a (Logan?) temperature sensor with ±0.1 C accuracy, which meets our specifications. Buck will also install a more accurate temperature sensor for an extra \$500 or so.
2. Theodor Friedrichs & Company http://www.th-friedrichs.com. Sell a temperature sensor with ±0.1 C accuracy. It is model number 2030 in their catalog. The price for this device is 250 DM (\$111). Unfortunately, like the Theodor Friedrichs pressure sensor, an additional datalogger must be purchased in order to produce serial output from this device.
3. *Yankee Environmental Systems, Inc.*: See listing under relative humidity. Accuracy 0.05 C over ±50 C range.

— **Relative Humidity:** For reference, the relationship between RH, dew point (DP), and ambient temperature (T_s) is described in §B.

1. Buck Research Instruments. Chilled mirror hygrometer which meets our specifications. Their model CR-4 3-stage TE cooled chilled mirror hygrometer has the following basic properties:
   — Dew/frost range: −65 to 100 C (this corresponds to about 0 to 100% at air temperatures in the range from 0 to 30 C)
   — 90 C depression
   — Resolution: 0.1 C
   — Accuracy: ±0.1 C (this corresponds to <0.5% at most typical air temperatures)
   — Ambient temperature sensor with ±0.1 C accuracy
   — Ambient pressure sensor with 0.1% accuracy (an option we asked for in the bid)
   — RS232 serial I/O

Figure 1 shows a picture of the Buck Instruments CR-4. For more information on this system, including a manual, see http://www.buck-research.com/CR4specs.htm. Note that this bid includes pressure and temperature sensors which nearly meet and meet our requirements of ±0.5 mb and ±0.1 C, respectively. The bid price for this ensemble is $6000.

Figure 1: Buck Research CR-4 chilled-mirror hygrometer.

2. *EdgeTech*: See http://www.edgetech.com/mh_instrumentation.htm.
   — "DewMaster" chilled mirror dew point hygrometer with D, S, or A series sensor.
   — RS232 output.
   — T_{dp} accuracy ±0.15 C (RH < 0.8%) with T_{dp} repeatability ±0.05 C over −75–100 ambient temperature range.
3. *Yankee Environmental Systems, Inc.*: See http://www.yesinc.com/products/met-hyg.html.
   — Rouged instruments.
   — Model MET-2010 Precision Meteorological Thermo-Hygrometer (Figure 2) precision ambient temperature and dew/frost point measurement devices.

Figure 2: Yankee Environmental Systems MET-2010 Precision Meteorological Thermo-Hygrometer.

  - Dew point temperatures above 0 C are determined to an accuracy of ±0.2 C (RH < 1%), while frost point temperatures down to −70 C have an accuracy of ±0.5 C (RH < 2.5%).
4. *General Eastern*: See http://www.gesensing.com/generaleasternproducts/.
  - The "Optica Hygrometer" appears to meet our specifications (T_{dp} accuracy 0.2 C).
  - "Ethernet ready".
  - Includes pressure and temperature sensors.
  - Operating range does not meet specification (0–50 C).
  - Very detailed information sheet available from web site.
5. *Technical Services Laboratory*: NWS uses this company's products. Dew point accuracy not good enough (±0.5 C over ±50C).
6. *Vaisala*: See http://www.vaisala.com/. The DMP501 dewpoint sensing unit (used within the DM500 Precision SAW Hygrometer) appears to meet our specifications:
  - T_{dp} accuracy ±0.1 C (RH < 0.5%).
  - Comes with an optional ambient temperature and pressure sensors which meet our specifications.
  - Uses "Surface Acoustic Wave" (SAW) measurement technology, which allows for faster measurement response times and independence from contamination (*i.e.* such as mirror contamination in chilled mirror sensors).

- **Wind Speed and Direction:**
  1. *Metek*: The USA-1 Ultrasonic Anemometer (Figure 3) produced by Metek (http://www.metek.de) meets or exceeds our wind measurement requirements. This device can:
     (a) Measure 3-directional wind speeds with an accuracy of 0.01 m/s over a range of 0–60 m/s;
     (b) Measure wind direction with an accuracy of 1 deg;
     (c) Sample data at rates as high as 20 Hz in its standard configuration;
     (d) Transmits data via serial RS-232 or RS-422 to a computer;
     (e) Will be purchased with optional sensor heater and calibration kit.

     The USA-1 does not contain any moving parts. It measures the wind vector by exchanging short pulses of ultrasonic signals between sound probes over three different directions and measuring the sound propagation properties. The price for this instrument is 3297.83 Euros ($2860.38).
  2. *R. M. Young Company*: See http://www.youngusa.com/. For low frequency wind measurements, the R. M. Young Company model 09101 Wind Monitor SE worked well at the ATF. It measures wind speed over the range 0-60 m/s with ±0.3 m/s accuracy. The price for this unit is $1210. For high-frequency 3D wind measurements the Model 81000 sonic anemometer (Figure 3) has very similar capabilities to the Metek USA-1.
  3. *Campbell Scientific*: See http://www.campbellsci.com/csat3. The Model CSAT3 3D sonic anemometer (Figure 3) has very similar capabilities to the Metek USA-1. Can measure at rates up to 60 Hz.
  4. *Vaisala*: See http://www.vaisala.com/. The WS425 sonic anemometer (Figure 3) meets the ALMA specifications.

4 Instrument Siting Requirements

The instrument tower heights and locations for each of the five weather instrument towers should be assigned based on the following requirements:

1. Height (h_t): ≥ 15m.

Figure 3: Clockwise from upper-left: Metek USA-1, R. M. Young 81000, Campbell Scientific CSAT3, and Vaisala WS425 sonic anemometers.

Table 2: Recommended Surface Weather Measurement Devices

Parameter	Manufacturer	Model Number	Price
P_s	FILL IN	...	FILL IN
T_s	FILL IN	...	FILL IN
RH	FILL IN	...	FILL IN
High Frequency W_s/W_d	FILL IN	...	FILL IN
Low Frequency W_s/W_d	FILL IN	...	FILL IN

2. Location (d_t):
   (a) $20m < d_t < 50m$ from any antenna.
   (b) $d_t > 100$m from any other structure.
3. Power and ethernet access.

Distribution of the five weather towers over the ALMA site should be as follows:

— Tower 1: Near the OSF.
— Tower 2: Near the array center.
— Tower 3: Along the SE arm of the array approximately midway between Tower 2 and the furthest antenna pad.
— Tower 4: Along the NE arm of the array approximately midway between Tower 2 and the furthest antenna pad.
— Tower 5: Near the end of the W arm of the array.

A possible instrument tower vendor and cost is described in §4.1, which was the tower used for the ATF weather station instrumentation. Figure 4 shows the final main weather tower instrumentation layout at the ATF.

4.1 Instrument Tower Specification

Guy Stanzione from the VLA engineering staff investigated possible vendors for the ATF instrument towers. Rohn Industries provided a quote for a 29 foot (9m) tower (not including mast) which met our specifications. The specifications for this tower are as follows:

— Rohn Industries model 45G.
— 2 10 foot sections plus 9 foot top section (8.8m total height).
— 10 foot by 1.25 inch steel mast.
— Guyed installation for stability if needed.
— Standard base (no hinging).
— Grounded.
— Maximum top load area assuming 110 MPH (50 m/s) wind speed of about 6 square feet (0.6 square meters).
— Must be able to mount the following loads on these towers (weights are approximate):
   1. Hygrometer (10 lbs = 4.5 kg)
   2. Sonic Anemometer (15 lbs = 7.0 kg)
   3. Low Frequency Wind Gauge (2.2 lbs = 1.0 kg)
   4. Web Camera, Mount, and Enclosure (12 lbs = 5.5 kg)

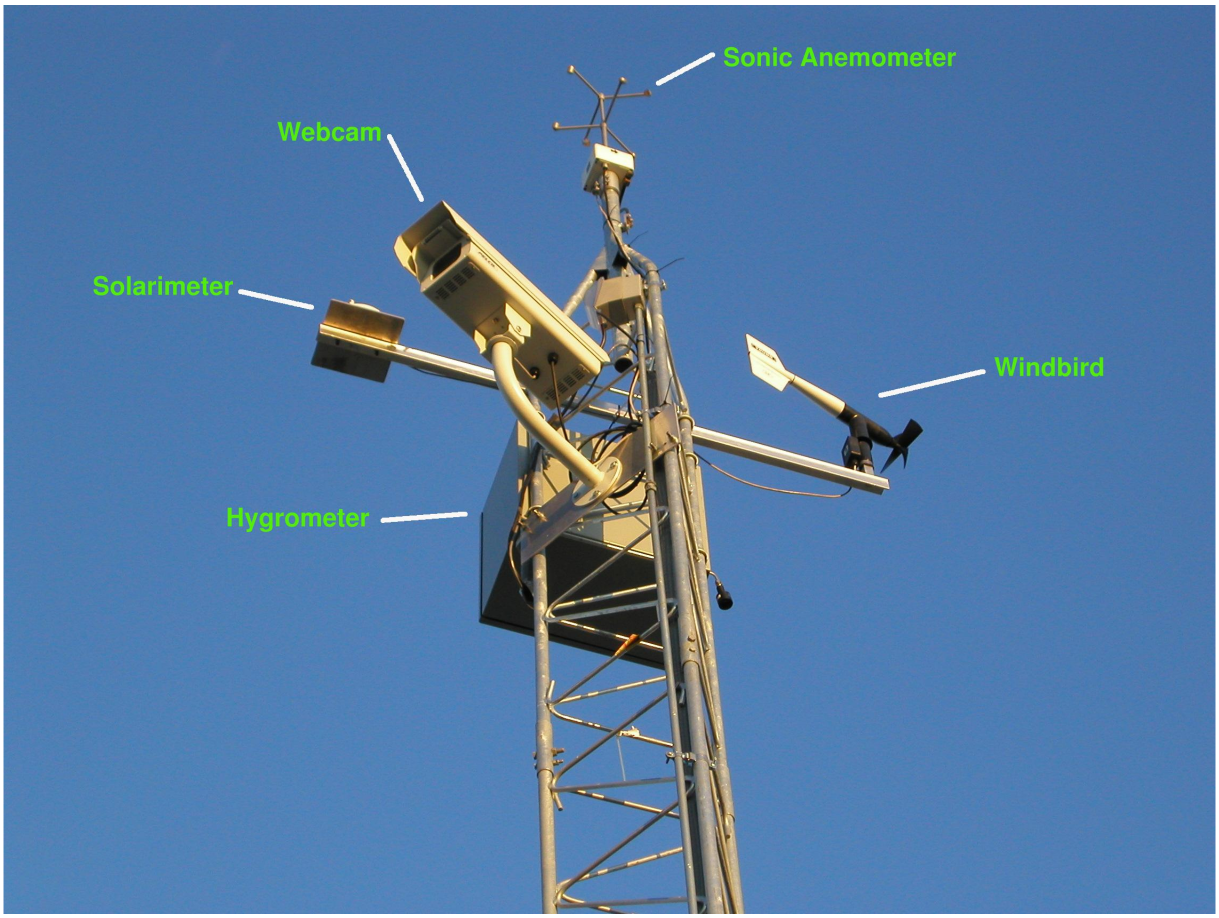

Figure 4: Final main weather instrumentation tower configuration.

5. Computer (22 lbs = 10 kg, probably located near base)

The approximate cost for this tower was $1300, excluding installation. The only difference between the ATF and ALMA weather tower specifications is the tower height (9m versus 15m).

5 Weather Instrument Data Recording

All weather instrumentation measurements are read at a default rate of 1 Hz. A simple Python script was used to do this at the ATF. Each measured value should then be delivered to the ALMA monitor and control database. Extraction and perusal of these data can then be done using a simple GUI.

References

[1] Richer & Mangum (2005), "Ancillary Calibration Instruments: Specifications and Requirements", ALMA SCID-90-05.13.00-001-A-SPE

[2] Mangum (2001), "A Telescope Pointing Algorithm for ALMA", ALMA Memo 366

[3] Buck (1981), "New Equations for Computing Vapor Pressure and Enhancement Factor", J. Appl. Met., 20, 1527-1532

[4] Buck (2001), "Model CR-4 Hygrometer Operating Manual"

A Relationship Between Acoustic, Virtual, and Ambient Temperature

Sonic anenometers measure a quantity called the "sonic virtual temperature". This sonic virtual temperature is defined as

$$T_{sv} = a\left(v_s^2 + v_n^2\right) \tag{1}$$

where v_n is the velocity component normal to the sonic path used to measure the speed of sound, $a = 2.48 \times 10^{-3} Ks^2/m^2$, and v_s is the speed of sound. T_{sv} is simply the temperature associated with the sound speed in the gas. Note that the sonic anemometer outputs three orthogonal wind components (u,v,w) plus the speed of sound, v_s. This means that v_n is defined as follows

$$v_n^2 = v^2 + \frac{(u+w)^2}{2} \tag{2}$$

This sonic virtual temperature is related to a fictitious temperature used by meteorologists called the "virtual temperature". The virtual temperature is defined as the temperature that dry air would have if its pressure and specific volume were equal to those of a given sample of moist air. Basically, the virtual temperature construct allows meteorologists to use the equation of state for dry air even though moisture is present. The virtual temperature T_v is related to the sonic virtual temperature T_{sv} as follows

$$T_{sv} = T_v\left(1 + 0.32\frac{e}{P_s}\right) \tag{3}$$

where e is the vapour pressure (in mb), P_s is the absolute pressure (in mb), and the temperatures are in degrees K. The relationship between T_v and ambient temperature T_s is

$$T_s = T_v\left(1 + 0.378\frac{e}{P_s}\right) \tag{4}$$

where the units and symbols are the same as in the relation between T_{sv} and T_v.

In summary, the USA-1 sonic anomemeter will measure T_{sv}, which is related to T_s as follows

$$T_s = T_{sv}\left[\frac{\left(1 + 0.378\frac{e}{P_s}\right)}{\left(1 + 0.32\frac{e}{P_s}\right)}\right] \tag{5}$$

B Relationship Between Relative Humidity, Dew Point Temperature, and Surface Temperature

As described in [3] and [4], the relative humidity (RH), dew point temperature (T_{dp} in C), and surface air temperature (T_s in C) are related through the vapour pressure for water (e_w in mb) or ice (e_i in mb), the "enhancement factor" (EF[1]), and the ambient pressure (P in hPa) as follows:

$$RH = 100 \times \frac{e_w(T_{dp})}{e_w(T_s)} \quad (6)$$

$$= 100 \times \frac{e_i(T_{dp})}{e_i(T_s)} \quad (7)$$

where

$$e_w(T) = EF \left\{ 6.1121 \exp \left[\left(18.678 - \frac{T}{234.5} \right) \left(\frac{T}{T + 257.14} \right) \right] \right\} \quad (8)$$

$$e_i(T) = EF \left\{ 6.1115 \exp \left[\left(23.036 - \frac{T}{333.7} \right) \left(\frac{T}{T + 279.82} \right) \right] \right\} \quad (9)$$

$$EF = 1 + 10^{-4} \left[2.2 + P \left(0.0383 + 6.4 \times 10^{-6} T^2 \right) \right] \quad (10)$$

[1]Note that the equation for EF in [4] contains two typographical errors.