# EVLA Memo 126
# Accuracy Requirements for EVLA Meteorological Measurements

Bryan Butler and Rick Perley
NRAO

August 4, 2008

**Abstract**

Analysis of the sensitivity of refraction and phase correction upon meteorological measurements suggests an accuracy in temperature of 0.2 deg C, in dew point of 1.0 deg C, and of relative humidity of 0.8%.

## 1 Introduction

Meteorological observations are required for proper operation of a radio telescope. The primary uses for these data are: (i) to calculate the atmospheric refraction so the antennas may be properly pointed, (ii) to calculate the excess atmospheric path between two antennas of an interferometer so the corresponding phase difference may be estimated, and (iii) to monitor wind speed at the antennas, to ensure their stowing in high winds. For the EVLA, the first two uses can be satisfied by accurate observations at a central local. For the third, wind measures at the antennas themselves will be required.

This memo lays out the requirements for the weather station at the center of the EVLA, including mechanical, measurements and associated uncertainties, interface, and reliability. We also include requirements for weather instrumentation at the antennas.

## 2 Mechanical

The central weather station shall be located where the VLA central weather station is. A goal is to have it at the height of the vertex of the antennas, or 20 meters, a requirement is that it be at least at the height of the current weather station. For the antennas, measurement devices should be where they are currently – one on each side of the outside edge of the antenna reflector.

## 3 Interface

The central weather station shall interface with the EVLA M&C system via a MIB. Whether this MIB is dedicated to only this task, or includes others (one could imagine interfacing to the API with this MIB as well) is a decision for the engineers. The exact quantities to be monitored and controlled via the MIB are to be determined, but certainly the sampling rate for all of the measurements will need to be controlled, and the measured quantities will need to be monitored. Any controls on, for instance, a chilled hygrometer unit to measure dew point temperature, shall be exposed through this interface.

The interface of the instruments at the antennas is yet to be determined.

# 4 Measured Quantities

The following measurements shall made at the central weather station at the rates given:

- Ambient Temperature ($T_0$) every 10 seconds
- Dew Point Temperature ($T_d$) every 10 seconds
- Ambient Pressure ($P_0$) every 10 seconds
- Wind Speed (V) every 1 second
- Wind Direction (D) every 1 second

At the antenna, only the wind speed need be monitored, at a rate of once every 10 seconds.

Any combination of devices that can measure these quantities at the necessary rates and with the uncertainties described below is acceptable.

# 5 Measurement Uncertainties

## 5.1 Central Station

### 5.1.1 Wind Speed

The wind speed shall be measured to an accuracy of 5%, except at low wind speeds (below 6 m/s) where it is to be measured to an accuracy of 0.3 m/s.

### 5.1.2 Wind Direction

The wind direction shall be measured to an accuracy of 5 degrees.

### 5.1.3 Temperature, Dew Point Temperature, and Ambient Pressure

We set the requirements for accuracy of these quantities through analysis of their influence upon the refraction, and phase correction requirements.

**Pointing**

The EVLA has a blind pointing requirement of 6" between 30 and 70 degrees in elevation. For the refraction correction, the largest errors due to inaccurately measured surface parameters will be at the lowest elevations, so we consider 30 degrees here. In order to have this refraction error be a small part of the overall pointing error, we allow for 1/10th of the total error to be due to errors in meteorological parameters that propagate to the pointing error – or 0.6".

For the refraction calculation, we use the formalism in Yan (1996). The difference between geometric and refracted zenith angles at the telescope, $dz_0$, for geometric angle $z$, is:

$$dz_0 = 10^{-6} N_0 \sin(z) * m'(z), \tag{1}$$

where

- $N_0$ is the surface air refractivity
- $m'(z)$ is a 'mapping function' which is an approximation to the refraction integral through the atmosphere.

For $N_0$, use Smith & Weintraub (1953):

$$N_0 = 77.6(P_0/T_0) - 12.8(e_0/T_0) + 3.776 \times 10^5(e_0/T_0^2). \tag{2}$$

In this expression, surface barometric pressure $P_0$ is in mbar, surface temperature $T_0$ is in degrees C, and $e_0$ is the water vapor partial pressure in mbar.

If we have a measurement of the relative humidity (RH), instead of a direct measure of $e_0$, then:

$$e0 = RH * e_{sat} \tag{3}$$

for water vapor saturation pressure $e_{sat}$. This quantity is provided by the Clausius-Clapeyron equation, and is approximated with an accuracy of better of 1% by

$$e_{sat} = 6.11 \left(\frac{T}{273}\right)^{-5.3} e^{25.2(T-273)/T}. \tag{4}$$

The mapping function $m'(z)$ is written:

$$m'(z) = \cfrac{1}{\cos(z) + \cfrac{A1}{I^2 \sec z + \cfrac{A2}{\cos z + \cfrac{13.24969}{I^2 \sec(z) + 173.4233}}}} \tag{5}$$

where:

- $I = \sqrt{r_0/(2H)}\cot(z)$
- $r_0$ = distance from geocenter to the telescope
- $H = \frac{1}{N_0}\int_{h_0}^{\infty} N dh$ is the 'effective height of atmosphere' (Rowlandson & Moldt 1969). This is the integral of the refractivity from the telescope location through the atmosphere)
- The parameters A1 and A2 are functions of surface meteorological parameters. For zenith angles from 0 to 75 degrees, A2 is a constant (A2 = 1.302642). A1 is still a function of the surface weather and is taken directly from Yan (1996).

The effective height, $H$, could be calculated precisely using an approximation of the atmosphere above the VLA and one of the Liebe models that explicitly calculates refraction, but a very good approximation for altitudes below the homopause (around 100 km; the atmosphere is well-mixed below that altitude) is to take H as the same as the normal scale height of the atmosphere $H = kT/(mg)$, since the refractivity must follow number density.

We note that a commonly utilized approximation to the refraction integral gives the following expression for the change in zenith distance, in arcseconds, due to refraction:

$$\Delta z = 0.206 N_0 \tan z_0 - a_2 \tan z_0 \sec^2 z_0 \tag{6}$$

where $a_2 = 0.07$ arcseconds. The following analysis can be applied to this equation, with the same results.

For given meteorological surface quantities $P_0$, $T_0$, and $RH$, we can calculate the error, $dR$ in the refractive pointing that would result from an error in the measurement of those quantities:

$$dR = |R(P_0, T_0, RH_0) - R(P_0 + dP_0, T_0 + dT_0, RH_0 + dRH_0)| \tag{7}$$

We allow each of the parameters ($P_0 + dP_0, T_0 + dT_0, RH_0 + dRH_0$) to vary one at a time, holding the other two fixed. Again, we consider only the calculation at 30 degrees, since that is the lowest elevation where the requirements apply. We make this calculation over the full range of conditions expected at the VLA site, however, we should note that we will almost certainly not be observing at high frequencies (which the requirement is driven by) during hot, wet periods. The range in meterological parameters utilized in this was -20 to +40 C in temperature, 750 to 820 mb in atmospheric pressure, and from 10 to 80% in relative humidity.

From this variational analysis, the errors in the parameters that individually result in a refractive pointing error of 0.6" are:

- max $dP_0 = \pm$ 6 mbar
- max $dT_0 = \pm$ 0.2 degrees C
- max $dRH_0 = \pm$ 0.8%
- max $dT_d = \pm$ 1.0 degrees C

Although in most cases the horizontal variations in these parameters along the line of sight will dominate the errors, we can on occasion (especially on mid-winter nights) have extremely stable and calm conditions, for which it can be plausibly argued that the refraction accuracy will be dominated by these measurement errors.

**Delay**

If the surface meteorological parameters are in error, there will be an error in the calculation of the excess atmospheric path. This will be a function of antenna location, baseline length, and source position.

One approach to estimating the errors resulting from an error in measurement of weather paramters is to utilize the program CALC to calculate the differential delay from the end of one arm in the A-configuration to the end of the other arms, given errors in the measured surface meteorological parameters [1], at an elevation of 30 degrees.

We calculate:

$$d_3 = d_2 - d_1 \tag{8}$$

where

- $d_1$ = delay to end of west arm for given $P_0, T_0, RH_0$
- $d_2$ = delay to end of east arm for given $P_0, T_0, RH_0$

and

$$d_6 = d_4 - d_3 \tag{9}$$

where

- $d_4$ = delay to end of west arm for given $P_0 + dP_0, T - 0 + dT_0, RH - 0 + dRH_0$
- $d_5$ = delay to end of east arm for given $P_0 + dP_0, T_0 + dT_0, RH_0 + dRH_0$

and take the absolute difference $|d6 - d3|$. For the limit on this difference, we take an allowable phase error of 0.5 radian at 50 GHz, or about 0.5 mm, or 1.5 picosec.

The derived requirements from this calculation are:

- max $dP_0 = \pm$ 11 mbar

[1] We thank John Benson for doing this calculation for us.

- max $dT_0 = \pm$ 3.8 degrees C
- max $dRH_0 = \pm$ 7.5%

In all cases, the required accuracy is less than the requirements from the pointing calculation.

## 6 Antennas

Wind speed at the antennas should be measured at two locations on the rim of the antenna, with accuracies the same as at the central station.

## 7 Reliability

The weather station should not require unscheduled maintenance more than once per year.