Memo No. 115

Environmental Monitoring Requirements for the ngVLA

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1 Introduction

Measurement of environmental parameters is one of the basic requirements for the proper operation of a telescope. Therefore, the subject has been addressed by several observatories. This memo is intended to provide guidance for the measurement accuracy requirements in the context of the ngVLA. It relies on previous work for the EVLA (Butler & Perley, 2008) and ALMA (Mangum, 2001) and a review of the subject by Mangum & Wallace (2015).

The local operational environment can be broadly divided into two categories: electromagnetic and physical. Meteorological parameters (weather) primarily constitute the physical environmental component and radio frequency interference (RFI) is the essential element of the electromagnetic environment. This memo focuses on the weather component and does not address the RFI, safety and physical infrastructure components.

Under weather, the relevant topics are (1) the correction to pointing arising from refraction in the atmosphere (2) the different delays in the arrival times of signals at different antennas due to propagation in the atmosphere (3) monitoring weather parameters to provide operations support, e.g. in determining prevalence of precision or normal conditions, dynamic scheduling and the choice of antennas to constitute a sub-array with a given set of characteristics, among others, and (4) archival. Here we restrict ourselves to the first two topics which impact the data obtained and its calibration.

2 Pointing Sensitivity to Weather

Closed form analytic expressions exist for the dependence of refraction correction to antenna pointing in elevation on surface temperature, pressure, and relative humidity at the location of the antenna (commonly used approximations of sufficient accuracy; reviews and references can be found in Mangum (2001), Butler & Perley (2008) and Mangum & Wallace (2015), and are not repeated here). To estimate the sensitivity of the pointing correction to weather, we take the approach of deriving the partial derivatives of these expressions with respect to the respective weather parameters. Starting from Mangum & Wallace (2015) (which also includes more information and citations to the origin of these equations), replacing R_0 with Δz for the refraction correction (Equation 11) we have

$$\Delta z = 0.206265 N_0(ppm) \tan z_o \text{ (arcsec)} \tag{1}$$

and for refractivity (Equation 66):

$$
\begin{aligned}
^{Rueger} N_0^{rad} &= 77.6890 \frac{P_d}{T} + 71.2952 \frac{P_w}{T} + 3.75463 \times 10^5 \frac{P_w}{T^2} \text{ (ppm)} \\
&= 77.6890 \frac{P}{T} - 6.3938 \frac{P_w}{T} + 3.75463 \times 10^5 \frac{P_w}{T^2} \text{ (ppm)}
\end{aligned}
\tag{2}
$$

where

P_d is the partial pressure of dry gases in the atmosphere (in hPa),

P_w is the partial pressure of water vapor (in hPa),

P is the total barometric pressure (in hPa), which is equal to $P_d + P_w$, and

T is the ambient air temperature (in Kelvin).

z_0 is the zenith angle of the observation

$^{Rueger}N_0^{rad}$ is the radio refractivity (Rueger formulation)

While the calculations for ngVLA requirements do not need the number of significant digits included here for the various coefficients, we retain full precision for completeness. Noting that the total atmospheric pressure P must be measured by a barometer at the telescope site, P_w may be calculated from the expression:

$$P_w = RH \frac{e_{sat}}{100} \tag{3}$$

where RH is the surface relative humidity (in percent) and e_{sat} is the surface saturated water vapour pressure (in hPa). There are two forms for e_{sat} that we can use. The first, from Crane (1976) (which is used by Butler & Perley (2008)), is given by:

$$
\begin{aligned}
e_{sat}^{crane} &= 6.105 \exp\left[25.22\left(\frac{T-273}{T}\right) - 5.31\ln\left(\frac{T}{273}\right)\right] \text{ (hPa)} \\
&= 6.105 \left(\frac{T}{273}\right)^{-5.31} \exp\left[25.22\left(\frac{T-273}{T}\right)\right] \text{ (hPa)}.
\end{aligned}
\tag{4}
$$

A second expression commonly used is given by Buck (1981) (Equation C1 in Mangum & Wallace (2015)):

$$e_{sat}^{buck} = \left(1.0007 + 3.46 \times 10^{-6}P\right) 6.1121 \exp\left[\frac{17.502\left(T - 273.15\right)}{T - 32.18}\right] \text{ (hPa)}. \tag{5}$$

The difference between the Crane (1976) and Buck (1981) formalisms for e_{sat} is $\lesssim 1\%$ over the range of surface pressure and temperature from 500 to 1000 mb and 255 to 300 K, respectively, appropriate for the ngVLA. In the following we will use the Buck (1981) formalism for e_{sat}.

We now derive the partial derivatives of Equation 1 with respect to the respective weather parameters. We start with the partial derivative with respect to total pressure P. Noting that $P_w = P - P_d$ and that $P_d \gg P_w$, so that $\frac{\partial P_d}{\partial P} \sim 1$ and $\frac{\partial P_w}{\partial P} \ll 1$, only the first term in Equation 2 is retained:

$$
\begin{aligned}
\frac{\partial \Delta z}{\partial P} &= 0.206265 \tan z_o \left(\frac{77.6890}{T}\right) \text{ (arcsec)} \\
&\simeq \left(\frac{16.024}{T}\right) \tan z_o \text{ (arcsec)}
\end{aligned}
\tag{6}
$$

where we have ignored the insignificant dependence of e_{sat} on the pressure P. Figure 1 shows Equation 6 for a representative range of ground temperatures.

The partial derivative with respect to relative humidity RH (in percent) requires substitution of Equation 3 into Equation 2:

$$
\begin{aligned}
\frac{\partial \Delta z}{\partial RH} &= 0.206265 \tan z_o \left(\frac{77.6890 e_{sat}^{buck}}{100T} - \frac{6.3938 e_{sat}^{buck}}{100T} + \frac{3.75463 \times 10^5 e_{sat}^{buck}}{100T^2}\right) \text{ (arcsec)} \\
&\simeq \tan z_o \left(\frac{0.160 e_{sat}^{buck}}{T} - \frac{0.013 e_{sat}^{buck}}{T} + \frac{774.45 e_{sat}^{buck}}{T^2}\right) \text{ (arcsec)} \\
&\simeq \tan z_o \left(\frac{0.147 e_{sat}^{buck}}{T} + \frac{774.45 e_{sat}^{buck}}{T^2}\right) \text{ (arcsec)}
\end{aligned}
\tag{7}
$$

with e_{sat}^{buck} given by Equation 5. There is a negligibly weak dependence of the partial derivative on pressure through e_{sat}^{buck}. Figure 2 shows Equation 7 for a representative range of ground temperatures and pressures.
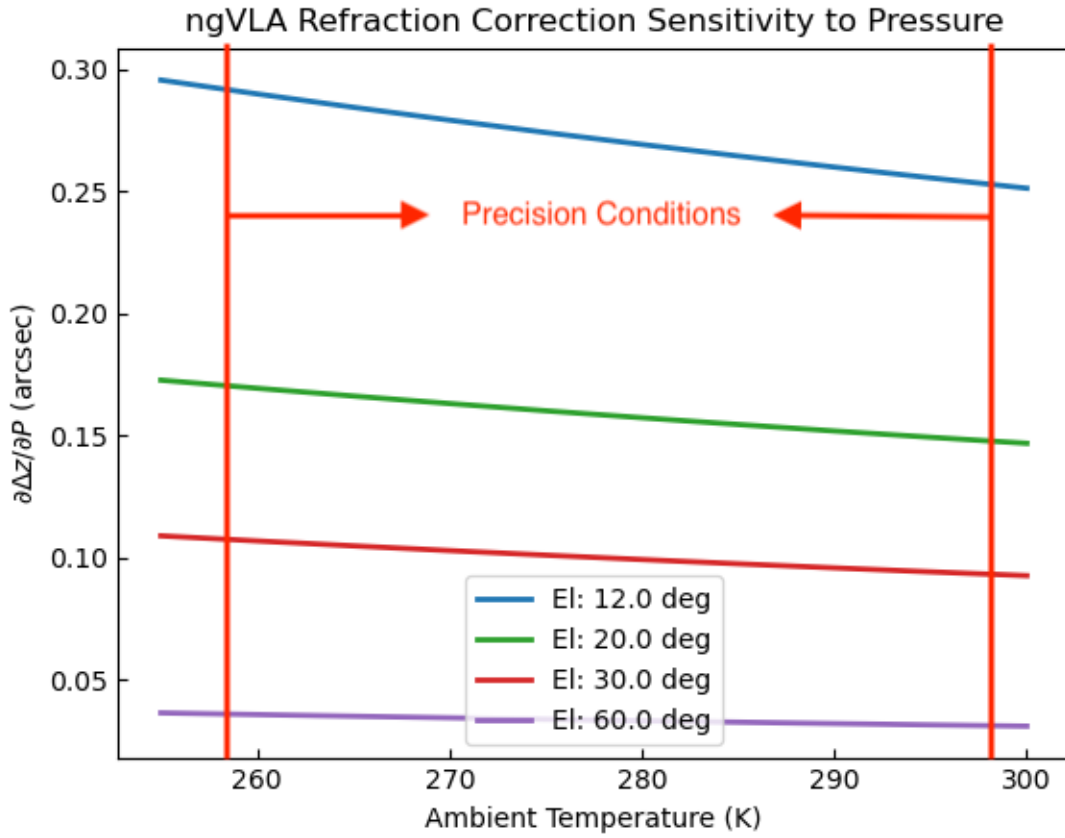
Figure 1: Refraction correction dependence on ground pressure (Equation 6) per mbar for a representative range of ground temperatures T and observing elevations. The temperature range for precision conditions is marked. The required pointing correction accuracy of $<0.5''$ (Section 3) is outside the box and can be met with a 4.5 mbar pressure measurement accuracy for elevations $> 30°$
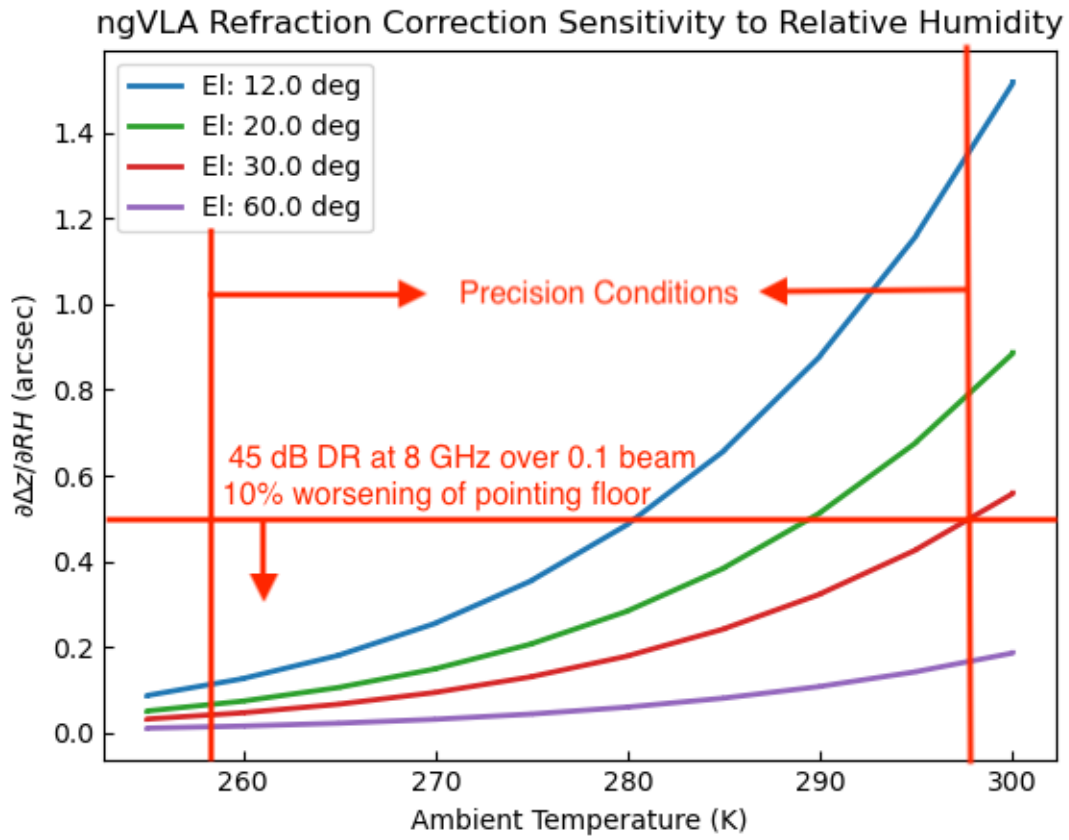
Figure 2: Refraction correction dependence on ground relative humidity (Equation 7), per 1% for a representative range of ground temperatures T, pressures P (whose effect is not discernible) and observing elevations. The temperature range for precision conditions is marked. The required pointing correction accuracy of $<0.5''$ shown (section 3) can be met with a 1% relative humidity measurement accuracy for elevations $> 30°$

Finally, the partial derivative with respect to temperature T (in Kelvin) is a bit more complicated to derive as both N_0 and P_w (through the temperature dependence in e_{sat}^{buck}) have dependencies on T:

$$
\begin{aligned}
\frac{\partial \Delta z}{\partial T} &= 0.206265 \tan z_o \left[\frac{\partial}{\partial T}\left(77.6890\frac{P_d}{T}\right) + \frac{\partial}{\partial T}\left(71.2952\frac{P_w}{T}\right) + \frac{\partial}{\partial T}\left(3.75463\times 10^5\frac{P_w}{T^2}\right)\right]\\
&\simeq \tan z_o \left[\frac{\partial}{\partial T}\left(16.02\frac{P_d}{T}\right) + \frac{\partial}{\partial T}\left(14.71\frac{P_w}{T}\right) + \frac{\partial}{\partial T}\left(7.74\times 10^4\frac{P_w}{T^2}\right)\right] \text{ (arcsec)}
\end{aligned}
\tag{8}
$$

The derivative of the second term in Equation 8 is given by:

$$
\begin{aligned}
\frac{\partial}{\partial T}\left(14.71\frac{P_w}{T}\right) &= 14.71\left(\frac{T\frac{\partial}{\partial T}\left(RH\frac{e_{sat}^{buck}}{100}\right) - RH\frac{e_{sat}^{buck}}{100}}{T^2}\right)\\
&= 0.1471 RH\left(\frac{T\frac{\partial e_{sat}^{buck}}{\partial T} - e_{sat}^{buck}}{T^2}\right)
\end{aligned}
\tag{9}
$$

with the partial derivative of e_{sat} with respect to T given by:

$$
\begin{aligned}
\frac{\partial e_{sat}^{buck}}{\partial T} &= \left(1.0007 + 3.46\times 10^{-6}P\right)6.1121\exp\left(\frac{17.502\left(T - 273.15\right)}{T - 32.18}\right)\left(\frac{4217.46}{(T - 32.18)^2}\right)\\
&= \frac{4217.46}{(T - 32.18)^2}e_{sat}^{buck} \text{ (hPa)}.
\end{aligned}
\tag{10}
$$

The derivative of the third term in Equation 8 is given by:

$$
\begin{aligned}
\frac{\partial}{\partial T}\left(7.74\times 10^4\frac{P_w}{T^2}\right) &= 7.74\times 10^4\left(\frac{T^2\frac{\partial}{\partial T}\left(RH\frac{e_{sat}^{buck}}{100}\right) - 2TRH\frac{e_{sat}^{buck}}{100}}{T^4}\right)\\
&= 774 RH\left(\frac{T\frac{\partial e_{sat}^{buck}}{\partial T} - 2e_{sat}^{buck}}{T^3}\right)
\end{aligned}
\tag{11}
$$

with the partial derivative of e_{sat} with respect to T given by Equation 10. Combining Equations 9 and 11 into Equation 8 we find:

$$
\begin{aligned}
\frac{\partial \Delta z}{\partial T} &\simeq \tan z_o\left[-16.02\frac{P_d}{T^2} + 0.1471 RH\left(\frac{T\frac{\partial e_{sat}^{buck}}{\partial T} - e_{sat}^{buck}}{T^2}\right) + 774 RH\left(\frac{T\frac{\partial e_{sat}^{buck}}{\partial T} - 2e_{sat}^{buck}}{T^3}\right)\right]\\
&\simeq \tan z_o\left[\frac{-16.02}{T^2}\left(P - P_w\right) + 0.1471 RH\left(\frac{T\frac{\partial e_{sat}^{buck}}{\partial T} - e_{sat}^{buck}}{T^2}\right) + 774 RH\left(\frac{T\frac{\partial e_{sat}^{buck}}{\partial T} - 2e_{sat}}{T^3}\right)\right]\\
&\simeq \frac{-16.02\tan z_o}{T^2}\left[\left(P - P_w\right) - 0.009 RH\left(T\frac{\partial e_{sat}^{buck}}{\partial T} - e_{sat}^{buck}\right) - 48.31 RH\left(\frac{T\frac{\partial e_{sat}^{buck}}{\partial T} - 2e_{sat}^{buck}}{T}\right)\right] \text{ (arcsec)}
\end{aligned}
\tag{12}
$$

with P_w and the derivative of e_{sat}^{buck} with respect to T given by Equations 3 and 10, respectively. Figure 3 shows Equation 12 for a representative range of ground temperatures and pressures.

As a check of this derivation we have verified numerical agreement between these expressions and the computational results for specific cases presented in Mangum (2001) for ALMA, where we find agreement to $< 0.03''$. We also find them to be consistent with the results of a numerical variational analysis presented in Butler & Perley (2008) for the EVLA.

These expressions are used below to determine the accuracies to which the weather parameters need to be measured. As can be seen, the sensitivities for humidity and pressure only depend on temperature and the temperature sensitivity depends on all three weather parameters. The functional dependence of all sensitivities on elevation is $tan(z)$.
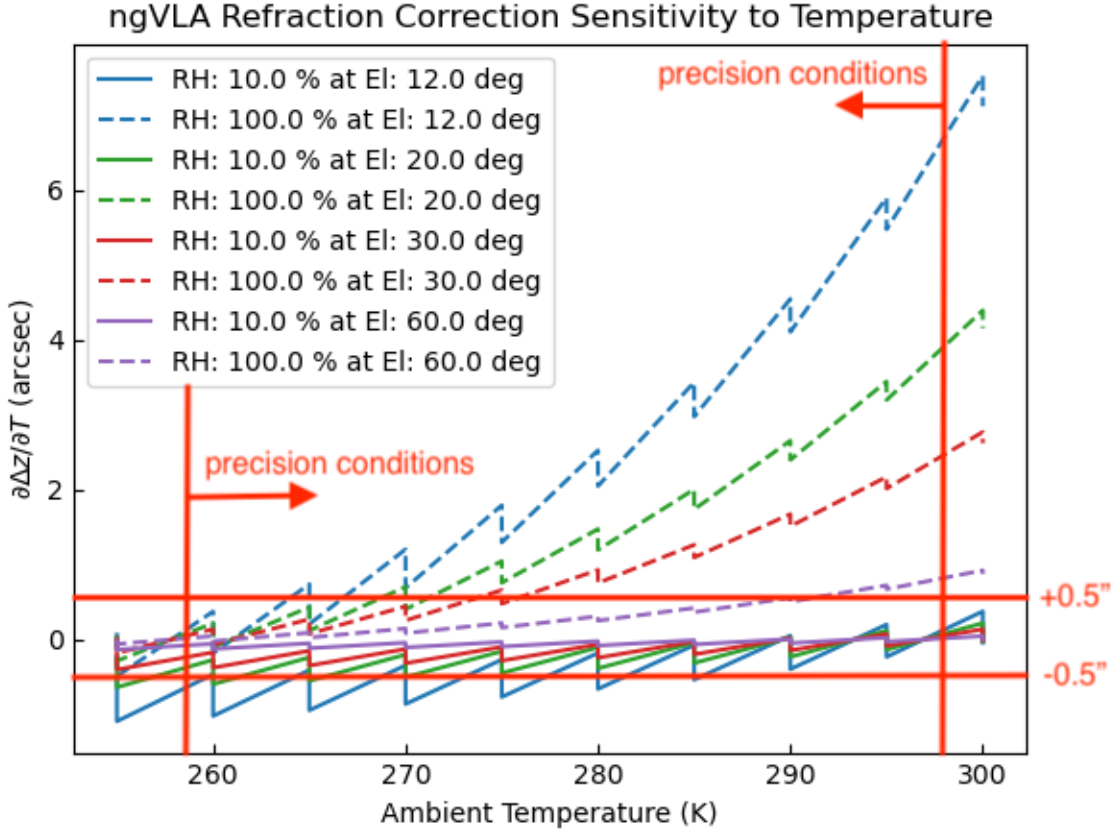
Figure 3: Refraction correction dependence on ground temperature (Equation 12) for a representative range of ground temperatures T, pressure P, observing elevations and two relative humidities. In order to present the T and P dependences in a single plot, 5 deg intervals in T are each spanned by a 500-1100 hPa range in pressure leading to the saw tooth patterns. The temperature range for precision conditions is marked. The required pointing correction accuracy of $<0.5''$ shown (Section 3) is readily met at low humidities. A 0.3° temperature measurement accuracy meets the requirements for elevations $> 30°$, even at 100% humidity.

3   Refraction Correction Error Requirement

The pointing specification and expected performance of the prototype antenna are taken as indicative references for feasibility. The $3''$ pointing specification for the prototype antenna under precision conditions (Selina & Dunbar (2022)) translates to a primary beam gain factor as high as 0.97 even at the highest operating frequencies. Given the stringent ngVLA image dynamic range requirements (Selina, R. et al (2020)), the main consideration, therefore, is the impact of inadequate refraction correction on the dynamic range achieved in the constructed images.

We adopt two guiding principles to assess the allowable error in the refraction correction to elevation pointing calculated from weather parameters: (1) the error should not limit dynamic range to below 45 dB at 8 GHz in the central region of the primary beam without requiring pointing self calibration. This is estimated to be $0.5''$ within 10% of the primary beam half-power beamwidth for 107 antennas (achieving 45 dB over the full HPBW requires pointing self-calibration; Jagannathan et al. (2023)). (2) the error should not limit the best pointing performance achieved by the antennas under windless conditions. Numerically, requiring that the increase in pointing error due to this correction be less than 10% of the best pointing errors under windless conditions that the antenna control systems are able to deliver, which is $1.2''$ for the prototype antenna, also results in a $0.5''$ limit. We adopt $0.5''$ as the pointing error correction accuracy requirement for further discussions.

The assessment here only considers the precision operating conditions temperature range of 258-298K, relevant for the most stringent ngVLA performance requirements. Next, although not explicitly identified as a science or system requirement, we consider the fact that the highest dynamic range performance will not be required over the full elevation range, in particular at elevations as low as 12 deg. Specifically, for the dynamic range requirement which drives pointing requirement we adopt an elevation limit of 30 deg.

Figures 1, 2 and 3 already presented the adopted $0.5''$ requirement and the precision condition temperature range. As can be seen from these figures and the above discussion, measurement accuracies of 4.5 mbar in pressure, 1% in relative humidity and 0.3 deg in temperature meet the adopted requirements and are therefore identified as the required surface weather parameter measurement accuracies.

We note that the ngVLA science and system requirements do not specify an elevation limit for the achievement of the image dynamic range requirements. Additionally, both reference pointing and pointing self-calibration, which is the strategy adopted for the attainment of the image dynamic range requirements, will also correct for residual errors in refraction correction (Jagannathan et al., 2023; Bhatnagar & Cornwell, 2017). The requirements presented here will eliminate refraction correction as a limiting factor in cases where pointing self-calibration may not be viable.

Based on the above analysis, the weather parameter measurement accuracies summarized below are recommended, where an elevation limit $> 30\,$deg is adopted:

(1) Temperature: $\Delta T = \quad 0.3$ K
(2) Relative humidity: $\Delta RH = \quad 1\%$
(3) Pressure: $\Delta P = \quad 4.5$ mbar

No recommendations for wind measurement requirements, which are expected to be coarse, are provided, as they pertain primarily to operational aspects of safety and the determination of the prevalence of precision vs normal conditions.

4   Weather Station Distribution

The distribution of weather stations needed to provide the required measurements for all antennas in the array depends on the lateral distance scale over which the parameters change by the amounts derived above as the measurement accuracy requirements. In general, in a well mixed, isothermal atmosphere we do not expect significant variations of weather parameters from antenna to antenna in the inner core area. Altitude difference would be expected to be the primary cause of variations in addition to location specific atmospheric boundary layer and geographical effects. While future ground truth measurements at the chosen sites should guide the distribution of weather stations as we are not aware of available measurements with sufficient spatial granularity, we can arrive at some broad conclusions using general considerations.

Using a tropospheric adiabatic lapse rate of 9.8 K/km for dry air (worst case; lower for wet air), a 0.3 K change occurs with an altitude change of 30 m. Similarly, a pressure change of 5 mbar (or hPa) occurs with an altitude variation of 55 m using a scale height of 8.5 km for the earth's atmosphere at a pressure of 780 mbar applicable to the ngVLA sites. The temperature variation provides a more stringent altitude variation range of ±30m. We recommend that antennas within a ±30 m (±100 ft) range in altitude be grouped to share a weather station. As

already noted, while ground truth measurements should ultimately determine the distribution, we expect that the 114 antennas of the Main Array within a 2.2 km radius and the SBA can be served by a small number (perhaps one) of weather stations. Each of the Long Baseline Array antennas will clearly need separate stations. The choice for the remaining Main Array antennas (spiral) will critically depend on future measurements to characterize variations, with suitably grouped antennas sharing a set of weather stations. Interpolation of weather data from the distribution of stations can provide additional granularity for application to individual antennas.

5   Delay Correction Error Requirements

We now turn to the measurement accuracy of surface weather parameters arising from delay estimation requirements. Bulk delays which will be applied to data from each antenna before correlation include an important contribution from the atmosphere. This is typically estimated from measured surface meteorological parameters (temperature, dew point temperature or humidity, and pressure) and an assumed atmospheric vertical structure above the antenna. This structure usually incorporates hydrostatic equilibrium for the bulk atmosphere with some assumed scale height and different scale heights for O_2 and H_2O (water vapor), which are the primary atmospheric constituents of relevance at the wavelengths of interest here (see references in Butler & Perley (2008) and Mangum & Wallace (2015).

Past investigations of the measurement accuracy needed for the weather parameters to be used as inputs to the atmospheric delay calculation for the VLBA and VLA have treated this in various ways (Clark, 1986, 1987; Butler & Perley, 2008) but all have come to a similar conclusion - the driving consideration for the measurement accuracy of surface meteorological parameters is in the refraction (pointing) correction. The main point is that once you get to delay accuracy levels that drive the surface quantity measurement accuracy to better than the refraction calculation, uncertainties in the vertical structure of the atmosphere (mostly the water vapor), which are not captured by the surface measurements, dominate the uncertainty in the overall delay calculation, rather than the measurement accuracies of the surface parameters. We recognize these previous conclusions and do not perform a detailed analysis of uncertainties and requirements from a delay estimate perspective. While the measured surface weather parameters should still be used in the bulk delay calculation, the accuracy of their measurements is not driven by this consideration. Whatever is required for the refraction calculation is good enough for the purposes of estimating the atmospheric delay.

We note that the surface weather parameters alone will not be used to determine delays and observations of delay calibrators and further corrections from periodic observations of complex gain (amplitude and phase vs. time) calibrators will be sufficient for calibrating delay (or phase). Where self-calibration can be used, even those are not necessarily needed, although observations will certainly include calibrator measurements.

6   Measurement Cadence

The fastest measurement cadence requirement arises from the expected use of surface weather data as empirical inputs to water vapor radiometry. While the details of the tropospheric delay correction algorithm are yet to be worked out, we anticipate seconds time scale as appropriate from this perspective. Accordingly, we set 1 second as the measurement cadence requirement.

7   Weather Sensor Location

From the pointing correction perspective the conditions that matter are the ones closest the antenna including any influence from the antenna itself. Unlike delay, the amount (angle) of refraction correction only depends on the refractive index at the final wavefront location and is independent of the detailed structure of the refractive index distribution along the line of sight (Smart (1962), Mangum & Wallace (2015) and references therein). The sensors can be mounted either on the antenna or on a nearby tower such that the measurements correspond to the mean height of the aperture/focal plane. We leave this decision to implementation convenience. We note, however, that wind sensors mounted on the antenna may suffer from shadowing effects and the modification of the flow due to the antenna structure which will have to be considered before a final decision. This may be evaluated through a comparison of data from instruments mounted on the prototype antenna and on a nearby tower.

8 Recommended Requirements

The recommended weather parameter measurement requirements are summarized below:

(1)	Temperature:	$\Delta T =$	0.3 K
(2)	Relative humidity:	$\Delta RH =$	1%
(3)	Pressure:	$\Delta P =$	4.5 mbar
(4)	Measurement cadence:		1 sec
(5)	Station distribution:		TBD using ground truth measurements
(6)	Sensor location:		TBD using prototype antenna tests & implementation convenience

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