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NGVLA MEMO 4

THE CONCEPT OF A REFERENCE ARRAY FOR NGVLA

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ABSTRACT

The concept of a reference array of smaller antennas for phase calibration of ngVLA is explored. An array of 100 4m antennas is studied as an example of the approach. The reference array approach is compared briefly with other approaches. The conclusion is that this technique is promising and needs to be studied in more detail to evaluate the relative costs compared with fast switching.

1. INTRODUCTION

A very important issue for ngVLA is how to correct for the changing atmospheric, and perhaps ionospheric, electrical path length over each antenna as a function of time in the frequency range $\sim 10 - 100$ GHz. For the VLA and VLBA this is accomplished by switching the antenna pointing to a a nearby calibrator as rapidly as is practical. For ngVLA, this technique loses a significant amount of observing time, thus reducing the sensitivity of the the array (or its effective collecting area), as well as increasing the cost of the antennas due to the requirement that they can move quickly between sources. Another approach is to use part of the collecting area to monitor a nearby calibrator. This avoids the fast switching but requires antennas to be grouped near enough to one another to be used for this purpose. This technique also reduces the effective collecting area, as well as the uv-coverage.

This memo proposes the construction of a "reference array" designed to calibrate science data. The antennas of this array would be located near to each science antenna (or group of science antennas). This reference array can consist of smaller, less costly, antennas operating in a lower frequency range. The higher-quality science antennas could thus spend almost all their time observing science targets, thus optimizing sensitivity.

2. GENERAL CONCEPT

Except for a possible ionospheric component, the atmosphere is non-dispersive at all useful ngVLA frequencies. That means that the delay can be measured at one frequency and applied to another. The phase correction needed at a given frequency due to the atmosphere thus scales with frequency. Thus this correction gets bigger as the frequency increases. If the ionosphere is an important part of the delay, then one can measure across a significant bandpass that component as well and apply a correction at any frequency. The ionospheric phase correction scales like 1/frequency and thus decreases in importance relative to the atmospheric term like 1/frequency^2. With enough S/N and a wide enough bandwidth, one can solve for both delay components.

Normally for astronomical arrays, the delay/phase corrections are determined by measuring the phase of nearby calibrators at some time interval using the same antennas that are making the astronomical, science observations. For the troposphere, which normally at the high frequencies proposed for ngVLA dominates the phase variations, one can approximate the problem as a fixed phase screen with local fluctuations moving over the array. The power spectrum of these variations increases out to some outer scale which under good conditions is $\sim$ 3km. The typical speed of the screen is 10 m/s. Thus in $\sim$ 5 minutes an almost entirely uncorrelated pattern has moved over a given antenna. If one measures the phase on shorter intervals than the largest scale/calibration time interval, one can cancel out the fraction of the fluctuation power on larger scales. The shorter the calibration interval, the better one does at correcting for the phase variations.

One can accomplish the same calibration using a nearby reference antenna and continually observing a nearby calibrator. Fast switching on the time scale of 10s is equivalent to continuously observing with a reference antenna 100m away from the science antenna. If the reference array observes at the same frequency range as the science array then the corrections are simple, just the phase observed by the reference array across the observed band. However, one can also correct a different frequency range if one knows how to scale the reference array results. At the relatively high frequencies planned for ngVLA, $\sim 10 - 100$GHz, the phase errors should be dominated by delay proportional to frequency; however, with a relatively wide band for the reference array, it should also be possible to solve for 1/frequency, ionospheric term and correct for both as a function of frequency.

3. REFERENCE ARRAY REQUIREMENTS

I picture a reference antenna near each outlying station. Near the array core, one reference antenna may serve several antennas and the goal is to sample a grid of phases over the core. Also if groups of antennas are located close together at remote locations, only one reference antenna would be needed per station.

In order to make the reference array as cheap as possible, one probably would want to observe at a lower frequency. Although it is not required that the frequency range overlap with the ngVLA science bands, I will assume 10-20 GHz is the frequency range for the reference array. In ngVLA memo 2, Barry Clark considers a reference array operating at 40 GHz or 100 GHz. I would argue for a lower frequency. At 10-20 GHz, the S/N required to extrapolate to the highest frequency would be higher; however, the individual antennas would be less demanding, and the system temperature would probably be lower. Furthermore the larger range in wavelength would make the measurement of the ionospheric term much easier. In ngVLA memo 1, Chris Carilli argued for 25mJy calibrator sources in order to have a very high probability of finding one within 2 degrees of any target. It is not clear such nearby calibrators are needed and, of course, almost all fields would have a stronger source available within 2 degrees based on this argument. Also I am told that almost always one can find a 100mJy sources within 2 degrees. Furthermore, the troposphere, where most of the fast phase variations are thought to occur has an average scale height of ~ 1.5km. The pierce point at 1.5km altitude for sources ~ 6 degrees away from a science field would be ~ 150m away, close enough for good calibration for the science target field. Thus for the purposes of this calculation I will assume we can use calibrators up to at least 6 degrees from the science field, at least as strong as ~ 200mJy. These requirements should be refined and tested with the existing VLA. I will assume 30s is a reasonable integration time, corresponding typically to ~ 300m baselines. I will assume 100 reference antennas. The number of reference antennas might well be larger. Note that the collecting area of the antenna needed for the reference array is inversely proportional to the number of reference array antennas. What is important is the total collecting area of the reference array.

Using the VLA exposure calculator, in 30s with a 10GHz bandwidth centered at 15GHz and 25 antennas, one gets 21μJy rms in 10s. The noise for each antenna needs to be increase by $\sqrt{N}$ to scale to noise per antenna, i.e 210μJy. Assuming 100 4m antennas with the same efficiency and T_{sys} as the VLA antennas, one gets $\sim 10\times$ higher noise, or in detail, ~ 2mJy or $\sim 100:1$ S/N.

One might like to reduce the cooling somewhat as well to reduce the overall construction and maintenance costs for the reference antennas. Marion Pospieszalski tells me that at 70K cooling, one might expect a receiver temperature of 20-25K, instead of 10K for 15K cooling. So to be conservative, let's assume T_{sys} is increased by $2\times$ from the VLA case. The result of backing off on cooling combined with an antenna design optimized just for this frequency range might well lose less than this factor of two.

Given that one can use all 100 antennas to solve for delays proportional to f and 1/f at each antenna, one needs 2 parameters from almost 100 phases and thus it is a good approximation to assume the S/N for the entire reference array collecting area correlated with each antenna. At the highest frequency, one needs to scale the correction phase by ~ 7 for the delay proportional to frequency. Thus at 100 GHz for a 30s integration time, a 200mJy calibration source and correcting for a $2\times$ worse sensitivity, one gets a residual phase error of about 8 degrees rms contributed due to the sensitivity of the reference array. This seems adequate for our purposes and in most cases the phase error would be smaller given the considerations above.

4. COMPARISON WITH OTHER CALIBRATION TECHNIQUES

Fast switching is the obvious default approach. However, that technique costs perhaps half of the observing time. Except for some brief cross-calibration at the beginning of a track, a reference array allows almost all the time to be spent on-source. It would also allow the fast switching demands on the antenna design for the main array to be relaxed. Supposedly less rapid movement of the antennas would also save maintenance costs. However, a comparative study of the reference array approach with fast switching is needed to pin down the costs.

Water vapor radiometry (WVR) is another possible approach which seems to work well for ALMA. In principle, either the 183 GHZ or the 22 GHz line could be used. However, the 183 GHz line on the much lower ngVLA sites (some perhaps as low as an elevation of 3000ft) would very often be optically thick and thus some use of the line edges would be required. The 22 GHz line is optically thin but has not been demonstrated to be successful for phase correction a large fraction of the time. Furthermore, WVR only addresses the tropospheric phase, not the dry term variations or the ionospheric component. On short baselines, it seems likely that troposphere dominates but on VLBI baselines, the ionosphere can be be important in the 10-20 GHz range. It seems worth studying WVR but it seems risky to depend on that approach as the only technique.

The reference array approach certainly needs to be demonstrated but it is based on simple, well-established concepts which seem likely to work. It simplifies dramatically the operation of the array by letting the astronomical antennas spend almost all their time simply on-source.

5. DISCUSSION

The calculation above is an example. The point is that the reference array can be engineered to be optimum for the problem to be solved. The cooling, the antenna size, the frequency, the number of antennas, etc can all be optimized to a more carefully considered reality.

Analysis of maintenance details and cost depend on a more detailed design. An approach one can envision is for the observatory to have a set of spare reference antennas, perhaps 10%. When one fails a replacement could be driven in a truck to the site and the entire unit replaced. However, hopefully, an antenna with limited cooling might be very reliable.

Besides the antenna, fiber would be needed to send the signal to a central correlator which would be much simpler and more limited than the main astronomical correlator. After solution for the f and 1/f correction for each antenna, the phases could be corrected online. For strong sources one could always do better with further post-processing, so saving the uv data seems necessary by default. However, for some experiments, e.g. transient detections and simple imaging, one might be able to make the images immediately.

6. CONCLUSIONS

Given the wide bandwidths and good, reliable centimeter wave receivers, the reference array approach seems worthwhile to study carefully as a new approach to calibration of ngVLA. A real engineering design should be developed so that cost tradeoffs can be evaluated of this approach versus other possibilities.

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