Next Generation Very Large Array Memo No. 2

Calibration Strategies for the Next Generation VLA

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Introduction

Calibration will be a serious issue for the ngVLA. It must be considered early in the design, and consideration given to it throughout the process. I address here almost entirely phase calibration. Tying the flux scale to an absolute standard is beyond the scope of this memo. Previous experience at the VLA site has indicated clear paths for phase calibration at lower frequencies; the discussion below is therefore directed at calibration at 3mm wavelength. The several possible calibration strategies that have been suggested are discussed in the sections below. The objective of this memo is to set out the considerations of the various strategies and not to make a choice between them. Much of the discussion is independent of number or size of the antenna elements, but where it does enter, an array of 255 18m antennas is used.

Self Calibration

For self calibration to work on a point source, it suffices that in a solution time T_s there is a good signal-to-noise ratio on the sum of all baselines to a given antenna element. That is, for a set of antennas with a given SEFD S_s and bandwidth B, to get an SNR of a requires a source of flux S_c

$$S_c = a\ S_s\ (T_s\ B)^{-0.5}\ (N-1)^{-0.5}$$

It is interesting to compare with the minimum detectable flux of an observation of length T_i.

$$S_{min} = a\ S_s\ (T_i\ B)^{-0.5}\ (N\ (N-1)/2)^{-0.5}$$

So the ratio of flux needed for self calibration flux to eventual sensitivity is

$$S_s/S_{smin} = (T_i/T_s)^{0.5}\ N^{0.5}\ 2^{-0.5}$$

The factor of the square root of N is a consequence of the “small D large N” approach to telescope design. With large N, a stronger self calibration source is needed, relative to the eventual sensitivity.

For resolved source, the situation is much more complicated. In this case one needs to consider how much visibility flux remains on baselines of the order of the maximum of the distance from one element to its nearest neighbor.

The expected flux of the brightest small diameter source in the small (30”) beam of the ngVLA antennas is less than 50 uJy. It is clear that, even with the great sensitivity of the ngVLA, the likelihood of a sufficiently strong source within the antenna element beam to self calibrate is sufficiently small that self calibration cannot be a primary calibration mechanism.

Fast Switching

This is covered by Chris Carilli in Next Generation VLA Memo No. 1. The general conclusion there is that, to calibrate at 3mm, a thirty second calibration cycle will be often necessary, and that the calibrator should be located within two degrees of the source field. He concludes that there will be sufficient calibrators to meet these criteria.

This has implications that the antenna design must have very short settling times after short moves, of order three seconds or so, to avoid excessive overhead with a 30 second cycle. A second consideration is that the fast switching cycle should probably be built into the software from the beginning, not built of smaller atoms as in the current VLA. It would probably be worthwhile to implement an adaptive switching cycle, to be able to lower overhead with a longer cycle when the atmosphere is exceptionally stable.

For a canonical array of 255 18m antennas, with 25 GHz at 3mm, the required calibrator flux is less than 1mJy. There are plenty of small diameter sources much stronger than this; the problem is locating them. For this, we may want to abandon the traditional VLA strategy of relying on a list of calibrators, and instead adopt a dynamic calibrator allocation. The ngVLA will have sufficient sensitivity that it can start with an extensive catalog of sources, VLASS or even NVSS, and check out nearby sources for suitability as calibrators. This will take at most a few minutes, maybe less, depending on how picky one is about the calibrator properties.

Paired Elements

One possible calibration strategy is to locate pairs of elements close to each other, so that one element of the pair is delegated to constantly observe a calibrator to monitor the atmosphere. The correction derived from this antenna would then be applied to the other, which is constantly observing the unknown field of interest. This results in a factor of two loss in sensitivity. If instead antennas are located in close triads rather than pairs, detailing one of the triad to calibration loses only a factor of 1.5 in sensitivity, about the same as the loss to overhead of fast switching. The paired elements need to be fairly close, within about 300m. With only a third of the array in the calibration subarray, a calibrator of 2 mJy is required. Again, there are plenty of them.

This approach will have serious repercussions on the array configuration. In effect, for the larger scales, one has only a third as many elements to arrange. This will not be discussed further here.

Calibration Array

It has been suggested that each element of the array should have, next to it or mounted on it, a small antenna directed at the nearest calibrator, for calibrating the atmospheric phase. This is a substantial capital cost, but might improve the percentage of time spent on source by a factor approaching two. The calibration array need not operate in the three millimeter band it is being used to calibrate. And the receiver system can be much simple than that of the main array element. There is also a question of whether the calibration array might be equipped with room temperature receivers rather than cryogenic ones. Using cooled receivers in the calibration array imposes an undesirable maintenance burden.

A critical element for this approach to calibration is how far from the target source the calibrator source is permitted to be. There does not appear to have been a definitive experimental study of this question, and, theoretically, it depends on the vertical distribution of water vapor, which can be quite changeable. If we take two degrees (which corresponds to 400 meters at the height of the tropopause), we can almost always find a calibrator source of 100 mJy at 3 mm wavelength, or a source of 140 mJy at 40 GHz. If we can go as far as four degrees, we can usually find a source of 250 mJy at 100 GHz, or 350 mJy at 40 GHz.

For three millimeter calibration, the calibration array will need to achieve a signal-to-noise ratio of about five (to each element) if operating at 100 GHz, about 15 if operating at 40 GHz (to allow multiplication to 120 GHz). These need to be attained in a 30 second solution interval. The system temperatures for a cooled system might be 50 K at 100 GHz, 40 K at 40 GHz. An uncooled system might have system temperatures of 300 at 100 GHz, 150 at 40 GHz. Considering, for the moment, the full available bandwidth, 25 GHz at 100 GHz, 18 GHz at 40 GHz, one can calculate the antenna diameter for the calibration array to achieve the desired signal-to-noise ratios.

	At 100 GHz	At 40 GHz	At 100 GHz	At 40 GHz
	100 mJy	140 mJy	250 mJy	350 mJy
Cooled receiver	1.4 m	2.0 m	0.9 m	1.3 m
Uncooled receiver	3.7 m	4.8 m	2.3 m	3.0 m

As well as the other capital costs, approach requires doubling the bandwidth on the link to the correlator. This is not a major consideration, because much of the cost of that link is right of way and installation, which will remain unchanged. For the cooled receiver case, it might be possible to attach the antenna to the main antenna element with, for instance, a small range, screw driven xy mount. This would have the advantage that the calibration antenna is never shadowed. A warm receiver would probably require an independently mounted antenna.

Water Vapor Radiometers

The physics of the situation are absolutely clear and are discussed by Bryan Butler in VLA Scientific Memo 177. Under reasonably benign conditions, path length variations are dominated by water vapor. The main constituents of the atmosphere and hydrosols contribute negligibly. Water vapor in the atmosphere can be measured by the atmospheric emission in the 22 GHz water line. The relation of line brightness to the refractive path length has only very weak dependencies on the absolute temperature and the pressure in the region where the line is formed. Memo 177 also discusses an implementation as an addition to the VLA K band receiver. The primary limitation of that implementation was that only three spectral channels were provided, requiring assumptions about the spectral dependencies of atmospheric hydrosols and the receiver spectral baseline. Much more convincing results could be attained with a full spectrometer of the 18-31 GHz band. A fully digital spectrometer of that band could be implemented with modern electronics; it would not be inexpensive, but seems to provide corresponding benefits. 50 or 100 MHz resolution seems called for. The system could be implemented in the same way as that of Memo 177, as a part of the K band receiver. However, the are advantages in design and construction to having a fully independent system. The sensitivity required is not very high. An RMS of 0.05 K in a 50 MHz channel for 30 seconds integration would be sufficient. (The conversion factor from line brightness to path length is about 3mm/K.) This can be met with a room temperature receiver, possibly even with a commercially available amplifier. A separate antenna system would need about a three degree beam – 500 meters at the tropopause. This can be met with a 20 cm antenna, mounted on the antenna element with its beam in the same direction.

A more serious consideration is the calibration of the receiver (which single dish spectral observers call the “baseline”). It is possible that the baseline is sufficiently stable and slowly varying with frequency that this will not be a problem. To get maximum independence of the instrumental baseline, a reasonable approach would be to average the spectra for the duration of the scan, or more likely, for scan plus calibrator, and consider only deviations from the average. These could be fitted with water vapor plus hydrosol to chart the path length variations during the scan, relying on intervening calibrators to connect scans.

If a calibration system is found to be necessary, simplest would be a switched noise source or the ability to switch to a warm load, to take out gain variation with frequency, In the worst case, one might need both the noise source and the ability to switch to a warm load, or both a warm load and a hot load. Switching to a load might be done by a mechanical switch, always a bit of a worry, or by physically aiming the telescope at a large absorber.

Conclusion

All of the methods above appear feasible, and a cost analysis is required to choose between them. This must also take into account the sensitivity loss incurred by the fast-switching and paired element methods.