Calibration and Imaging of 74 MHz data from the Very Large Array

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ABSTRACT

Traditional antenna-based calibration assigns a single time-dependent phase error to each antenna in an array. It is sufficient for removing tropospheric phase errors at short wavelengths because tropospheric phase (1) can vary rapidly with position across the array but (2) is nearly constant over the field-of-view of each antenna. It fails for wide-field high-resolution imaging at low frequencies because ionospheric phase errors vary significantly across the field-of-view. Fortunately, ionospheric phase changes are nearly linear across arrays up to 30 km in size, so their dominant effect is refractive, not diffractive. We present a new field-based calibration method that models time-dependent ionospheric phases over the field-of-view with Zernike polynomials and corrects for the model phase errors. Time-independent antenna-based instrumental phases must be measured and removed independently. Field-based calibration significantly improves 74 MHz VLA images of faint sources and survey fields. The sensitivity requirements and array size limitations of field-based calibration will constrain the design of future low-frequency arrays.

INTRODUCTION

Antenna-based calibration assigns a single time-dependent phase error to each antenna (or receiver) in a telescope array. It is appropriate for removing most instrumental phase errors. It is also both necessary and sufficient for removing tropospheric phase errors at short wavelengths because tropospheric phase can vary irregularly over distances comparable with interferometric baselines but are nearly constant over the field-of-view of each antenna. Antenna-based calibration fails for wide-field imaging at low frequencies because ionospheric phase errors vary significantly across the field-of-view: no single phase correction is sufficient to remove them. This radical difference between high-frequency tropospheric and low-frequency ionospheric phase calibration has two origins. (1) The effective heights of the tropospheric and ionospheric screens are quite different, about 2 km and 400, respectively. (2) The angular field-of-view is inversely proportional to frequency. At high frequencies, the projected linear size of the small field of view of each antenna onto the low troposphere is smaller than both interferometric baselines and significant tropospheric irregularities. A single phase error describes the field seen by each antenna, and these phase errors may have an irregular distribution across arrays larger than about 2 km. At low frequencies, the projected linear size of the field-of-view can be much larger than both the array and significant ionospheric irregularities. Each antenna sees nearly the same phase variations across the field. The field, not the antenna, must be calibrated.

ISOPLANATIC PATCH PROBLEM

Irregularities in the ionosphere larger than the array cause refraction and shift the apparent positions of radio sources at low frequencies. Owing to the large primary beam of the Very Large Array (VLA) antennas, these offsets also vary across the field of view. Fig. 1 gives a schematic view of a variable ionospheric wedge across an array. The effect on real observations is well illustrated in Fig. 2 which shows the apparent position offsets of the eleven strongest sources in a series of one-minute snapshots in one field of view. The jitter in apparent source positions is comparable with the resolution of the array. It will blur images based on uncorrected observations spanning timescales longer than several minutes. During periods of bad ionospheric "weather", significant phase curvature across the array defocuses the snapshot images as well, reducing the peak flux densities of individual point sources and increasing their sidelobe levels.

Antenna-based calibration assigns only one phase to each antenna and removes the ionospheric phase error at only one sky position, that of the calibrator. Since the isoplanatic patch is often smaller than the field-of-view at low frequencies, external calibration by an astronomical source or GPS satellite outside the field-of-view does more harm than good.

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[1] The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

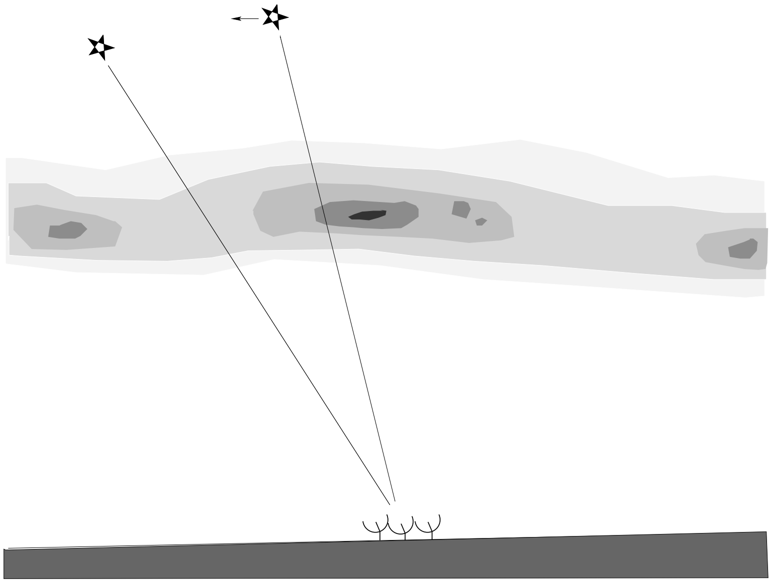

Figure 1: This cartoon shows how a variable ionospheric refractive wedge can affect observations of astronomical sources. If the size scale of the dominant structure in the ionosphere is larger than the array, the principal effect is refractive–it shifts the apparent positions of sources but not completely defocus them.

Antenna-based selfcalibration corrects for ionospheric phase in the direction of the strongest source in the field and is suitable for imaging strong, isolated sources smaller than the isoplanatic patch. However, it generally increases the phases errors in the rest of the field, smearing out all other sources and reducing their apparent brightnesses.

FIELD-BASED CALIBRATION

We developed FIELD-BASED CALIBRATION to correct ionospheric phase errors in a planned 74 MHz sky survey with the VLA B configuration. The 12 deg FWHM primary beam spans about 100 km at the 400 km effective height of the ionosphere, while the longest baseline is only 10 km. Phase differences within the field-of-view of each antenna are much larger than the phase curvature across the array in the direction of any one source, so the primary ionospheric effect is refraction. Point sources appear only slightly distorted in a snapshot image, but their positions wander randomly (and independently if the isoplanatic patch is smaller than the field) on time scales of minutes. To determine the two-dimensional time-dependent image distortion, we image all of the bright sources in the primary beam every two minutes and measure their offsets from the accurate NVSS positions measured at 1400 MHz. We fit Zernike polynomials to approximate the phase changes implied by the distortion across each field at each time. Zernike polynomials were chosen because they are orthogonal on a unit circle and have the unique property that they contain a polynomial for each pair of values of n, the degree of the radial polynomial, and m, the frequency of the azimuthal polynomial, subject to the constraint $n \geq m \geq 0$. They require a minimum number of measured coefficients to model smooth phase variations across a circular field. To make a full-synthesis image, we tile the field with a hexagonal pattern of circular facets tangent to the sky plane. The Zernike polynomials determine the time-dependent position offsets of each facet. The CLEAN deconvolution subtracts image components from the (u,v) data at their original positions.

There are typically 10 sources detectable in two minutes by the entire VLA in each 74 MHz snapshot field, enough to specify the five parameters defining a second-degree Zernike polynomial, but only if the phase variation across the ionospheric puncture points of the full array at any celestial position can be approximated by a simple linear gradient (which corresponds to a position shift with no distortion). The sensitivity requirements for correcting large antenna-dependent phase errors are more severe because at least one source must be detectable on baselines between each individual antenna and the rest of the array. That multiplies the sensitivity needed by $\sqrt{N}$, where $N = 27$ is the number of VLA antennas, so the VLA is not sensitive enough at 74 MHz to measure antenna-based ionospheric phases except in those few fields that contain very strong sources. Field-based calibration alone is incapable of correcting antenna-based phase errors, either ionospheric or instrumental. Our method is not likely to work well at 74 MHz for arrays larger than about 30 km because ionospheric phase curvature across the array will often be large. Fortunately, antenna-

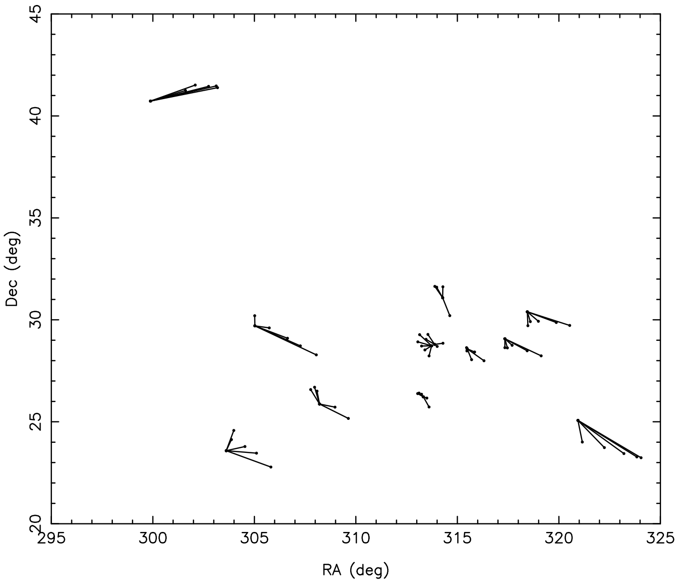

Figure 2: A sequence of position offsets (magnified ×100) derived from a series of one-minute snapshot images at 74 MHz. The pointing center was ra = 315°, dec = 29.8°. The strong source Cygnus A is in the upper left corner..

based instrumental phases remain constant for days, so they can be measured in traditional ways from multiple snapshot observations of a strong point source (for which the average ionospheric phase is nearly the same at all antennas) and subtracted from all data prior to field-based calibration.

A comparison of the results of self-calibration and field-based calibration is shown in Fig. 3. This figure includes the data shown in Fig. 2. The left-hand plot is the result of imaging a source relatively far from the brightest source in the field after antenna-based self-calibration. Uncorrected ionospheric phase errors in the direction of the source illustrated cause it to wander significantly over the period of the synthesis, producing serious distortions. The right-hand plot shows the same source after we applied only time-independent instrumental calibration and field-based calibration. This results in much improved focusing of the image by compensating for the apparent movement of the source.

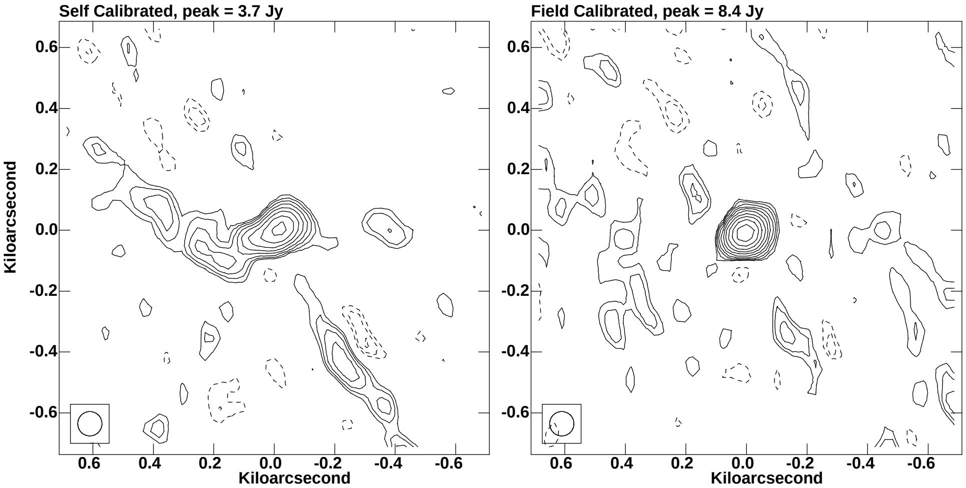

Figure 3: Left: Example image of a source after antenna-based self-calibration. Right: Same source and contouring after field-based calibration.

We note that antenna-based self-calibration is normally sufficient for imaging a strong source that dominates the primary beam. However, the resulting ionospheric phase corrections at the strong-source position do not apply outside the small isoplanatic patch (typically one or two degrees in angular radius at 74 MHz), and sources in the rest of the field are suppressed by defocussing. The full field may "look good" and have a high dynamic range but it is unsuitable for survey work.

Antenna-based calibration has also proven adequate for wide-field imaging with very short arrays whose synthesized beamwidths are much larger than the angular wander produced by ionospheric refraction. Thus, antenna-based calibration has been used successfully to image isolated strong sources with high resolution and to make sky surveys with low resolution, but high-resolution images of faint sources and high-resolution sky surveys need field-based calibration.

Field-based calibration strongly constrains the design of future low-frequency arrays such as LOFAR because it requires that the array be able to detect about one source per isoplanatic patch or per primary beam area, whichever is smaller, on the short time scale (minutes) of ionospheric phase changes. This sensitivity requirement favors arrays with high surface-brightness sensitivity (e.g. large array elements having high filling factors, low receiver noise, and wide bandwidth). Arrays with baselines longer than the angular size of the isoplanatic patch projected onto the ionosphere (several tens of km at 74 MHz) will be much more difficult to calibrate because ionospheric phase curvature across the array will be large.

SUMMARY

At low frequencies, the ionosphere can seriously degrade wide-field images at arcminute or finer resolution if the traditional antenna-based phase calibration is applied. We have presented a field-based calibration method that models a smoothly varying ionospheric phase screen across the array field-of-view; this allows the phase calibration to vary with sky position. Significant improvements in high-resolution images of faint sources and wide survey fields are demonstrated using this method. The necessity and limitations of field-based calibration may constrain the basic features (frequency coverage, field-of-view, sensitivity, angular resolution, etc.) of future low-frequency arrays such a LOFAR.