THE 74 MHZ SYSTEM ON THE VERY LARGE ARRAY

Richard A. Perley

National Radio Astronomy Observatory,
1003 Lopezville Road, Socorro, NM 87801 USA.
e-mail: rperley@nrao.edu

ABSTRACT

The National Radio Astronomy Observatory and the Naval Research Laboratory have outfitted the Very Large Array with a simple 74 MHz observing capability. The primary goals of this project were to test calibration methodologies of data taken at a frequency where ionospheric phase perturbations are very large, and to apply such methods to image the strongest radio sources with 25 arcseconds resolution. As expected, the ultimate limiting factor in imaging at these frequencies with the field of view and resolution of the VLA are the spatial gradients in the ionospheric phase screen. Nevertheless, the unique opportunities of this system – its unprecedented resolution and sensitivity – have made it one of the most heavily used frequency bands on the array.

THE DEVELOPMENT AND POTENTIAL OF LOW FREQUENCY ASTRONOMY

Although radio astronomy began at meter wavelengths, various factors – both scientific and technical – have resulted in most development ocurring at shorter wavelengths, where ionospheric phase perturbations are less troublesome or absent, and diffraction-limited resolutions are much higher. In particular, the development of powerful self-calibration techniques on long interferometer baselines was accomplished using centimeter-wavelength data. But there is no *a priori* reason why such methods should not be applicable to meter-wavelength VLA data, other than the fact that the VLA was not outfitted for observations at these frequencies at the time of its dedication.

The science potential from arcsecond observations at meter wavelenghts is very high. There are many astrophysical phenomena which can *only* be accessed through observations made at meter-wavelengths. These include, for example:

- Steep-spectrum objects, such as old synchrotron halos, pulsars, ’relic’ synchrotron sources, and high-redshift quasars. Such emission can often only be detected at low frequencies.
- Special emission mechanisms, such as pulsars, cyclotron emission from planets, coherent emission from the sun and stars, high-n recombination lines, and the anticipated signature of the epoch of reionization.
- Absorption and propagation effects, such as synchrotron self-absorption, thermal absorption, Faraday rotation, and the Razin-Tsytovich effect. These give unique information on thermal content and magnetic fields of the emitting and intervening gas.
- In addition, we add that the phases of low-frequency astronomical signals are strongly affected by gradients in the ionosphere. The calibration of these data gives very sensitive information on these perturbations, which should be of use in ionspheric studies.

These unique and exciting scientific goals encouraged us (Bill Erickson, Namir Kassim, and I, with the help of many others) to outfit the VLA for low-frequency observations.

THE 74 MHZ CAPABILITY

The first low-frequency system on the VLA, installed between 1980 and 1989, was at P-band (300 – 340 MHz). Despite rather poor sensitivity (due to an off-focus primary feed), this band has proven to be very successful, as calibration procedures at this frequency (and within the 2.2 degree primary beam) are essentially the same as at higher frequencies. Tests of a 74 MHz system began in 1984, but due to funding limitations, only 8 antennas were outfitted by 1991. However, even this small number was sufficient to indicate that calibration and imaging were entirely feasible. Thanks to the energetic efforts of Namir Kassim, the Naval Research Laboratory generously provided the needed funding for both a redesign of the system (by Bill Erickson), and full implementation. This was completed in early 1998.

Table 1 gives the essential characteristics of the system:

Table 1: **Characteristics of the VLA 74 MHz System**

Characteristic	Value
Center Frequency	73.8 MHz
Bandwidth	1.6 MHz
Primary Beamwidth	11.7 degrees
Sidelobe Rejection	20 – 30 dB (typ)
System Temperature	$>$1500 K
Efficiency	15%
Sensitivity (8 hr)	$\sim$ 25 mJy/beam
Resolution (A-config.)	25 arcseconds
Polarization leakage	$\sim$ 25%

There are many special problems in low-frequency, high-resolution radio astronomy which must be addressed before any facility can be expected to do cutting-edge astronomy. These key problems, and a brief summary of what we have learned, are given below.

Radio Frequency Interference (RFI) is a minor problem for most VLA data at 74 MHz. There is negligible external interference, and most internally generated interference is very narrow-band ($<$ 1KHz) and lie on multiples of 100 KHz. These 'lines' can be cleanly separated from the intervening (astronomical) emission by using the correlator in its spectral line mode, with at least 12 kHz of resolution. Fig. 1 demonstrates the problem and its solution. The left panel shows the raw spectrum, with frequency on the horizontal axis and time vertical. The bandwidth is 1.56 MHz, the resolution is 12.2 kHz, and the vertical 'bars' are the internally-generated RFI occuring at multiples of 100 KHz. The grey pixels are the desired astronomical data. The right panel shows the spectrum after the AIPS program `FLGIT` has removed the RFI.

Figure 1: Illustrating the removal of narrow-band RFI in 74 MHz VLA data. The left panel shows the original spectrum (time is vertical, frequency horizontal), the right panel shows the spectrum after RFI removal by `FLGIT`. Note that the greyscales for the two panels are different.

System efficiency is 15% – most of the desired signal is scattered by the feed legs, subreflector, and other small metal structures. There is nothing that can be done with the VLA to significantly increase efficiency – only a new, specially designed instrument can do better. The rms noise in a 12 kHz channel (in 10 seconds) is about 100 Jy. Integrating over the available bandwidth gives a noise of about 10 Jy – thus requiring at least 50 Jy of unresolved calibrator flux density for phase calibration. But number counts show that every primary beam contains at least 10 times this in total flux density, with the strongest dozen contributing about 100 Jy, easily sufficient for phase calibration, provided the differential phase effects are not severe. Unfortunately, these differential effects *are* commonly severe, the implications of which will be discussed below.

Ionospheric phases do change very rapidly (up to 10 degrees/second) and differentially across the primary beam. Fig. 2 shows the refraction of Virgo A during a ten-hour observation made in January 2001. This observation began just before midnight, local time.

The large-scale refraction is of little concern to imaging – it is nearly the same for all objects within the field of view. However, the wave-like oscillations have an angular scale of degrees or less, causing a notable differential offset in the positions of objects within the 11.7 degree primary beam. A representation of this is shown in Figure 3.

Shown in this figure are the differential declination offsets for five background objects in the field of Virgo A. Note that these detailed offsets are poorly correlated with each other, and even during the nighttime are of a size larger than the resolution. Even during the four hours of quiescent activity around meridian transit, the 'wanderings' of these objects are at least comparable to the synthesized beamsize – meaning the in a coherent image, the resultant images will be significantly blurred. During the period of TID activity, no coherent imaging is possible, with current calibration software.

The VLA's non-coplanar baselines problem is well understood, as are the various solutions, which are available within both the AIPS and **aips++** packages. Details of these will be discussed in the first two papers of Session J3. The currently

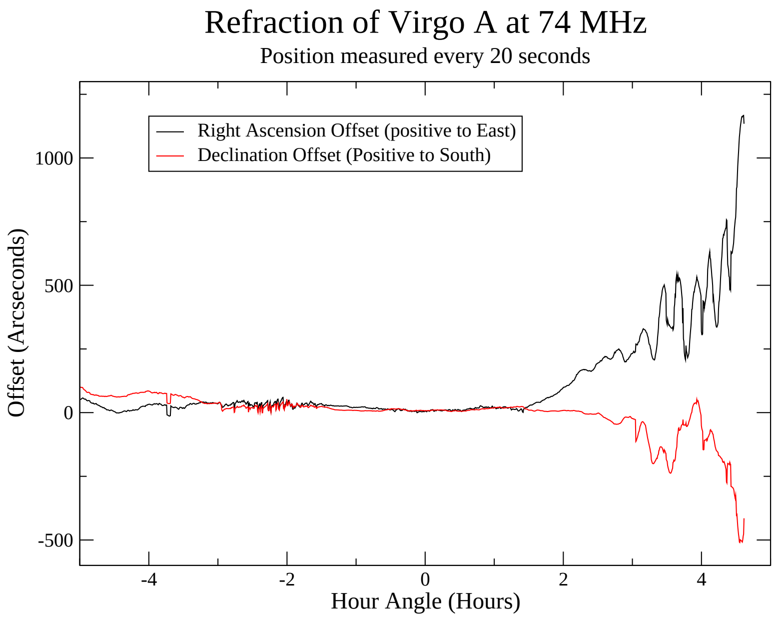

Figure 2: The refraction of Virgo A in January, 2001. Noteworthy is a period of scintillation near HA = -2h, a 4 hour period of exceptionally quiescent conditions around transit, large wedge refraction clearly associated with sunrise, and a period of very strong oscillations between 8 and 10 AM.

favored approach of ’polyhedron imaging’ has the natural advantage that a local calibration for each sub-image can be applied independently of the other sub-images.

As will be noted, each of these troubles – save the problem of sensitivity – can be reasonably addressed, with the result that the VLA’s 74 MHz system is very useful scientifically, despite its poor sensitivity. Two example images are shown in Fig. 4.

ADVANCED CALIBRATION DEVELOPMENT

It was earlier noted that there is sufficient flux density in the strongest few objects within each primary beam to permit good phase calibration on 10 second timescales, provided the differential phase gradients within the primary beam are negligible. Unfortunately, this rarely happens. The effect of applying simple self-calibration under these conditions is to give a marginal image only in the few square degrees around the strongest background source. Beyond this radius, sources ’fade away’ due to blurring caused by differential phase errors.

To correct for this, a methodology to solve for the ionospheric phases, as functions of *both* time and direction, must be developed. In Session J3, Bill Cotton will describe one promising approach, developed by him and Jim Condon for the ’4MASS’ survey. In this approach, the ionospheric phase screen above the array is modeled using Zernicke polynomials, using the measured position offsets of stronger background sources located within the antenna primary beam. These coefficients are then utilized for predicting the calibration phase for each of the small subfields of the overall image. Although this method can only corrrect for offsets, and in its current implementation cannot correct for distortions (’curvature’ in the screen), it does illustrate a promising initiatve. Interested readers should refer to Bill’s paper in these procedings.

Unfortunately, this methodology is only of limited use for the VLA. If the minimum flux density needed for a phase determination is 50 Jy, then known number counts can be used to tell us that the phases of no more than about eight regions (’isoplanatic patches’) within the VLA’s beam can be determined. Unfortunately, it appears that for the VLA’s B and A configurations, the number of necessary independent coefficients is significantly greater than this. The only way to improve the situation is to build a more sensitive instrument.

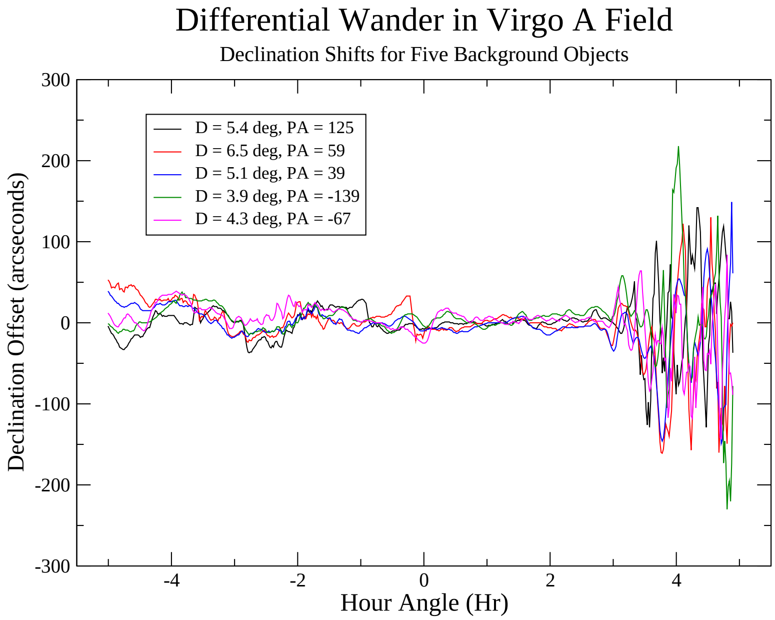

Figure 3: Differential Refraction in the Field of Virgo A. This shows the small-scale 'wandering' in declination of 5 strong background sources within 7 degrees of Virgo A, which provides the position reference. Note that even during quiet periods, these motions are uncorrelatored, and are larger than the resolution. The sunrise-induced ionspheric wedge is removed by the referencing to Virgo A, but the effects of the travelling save (likely to be Travelling Ionospheric Disturbances – TIDs) are hardly attenuated, showing that their angular scale is less than that of the separation between the sources.

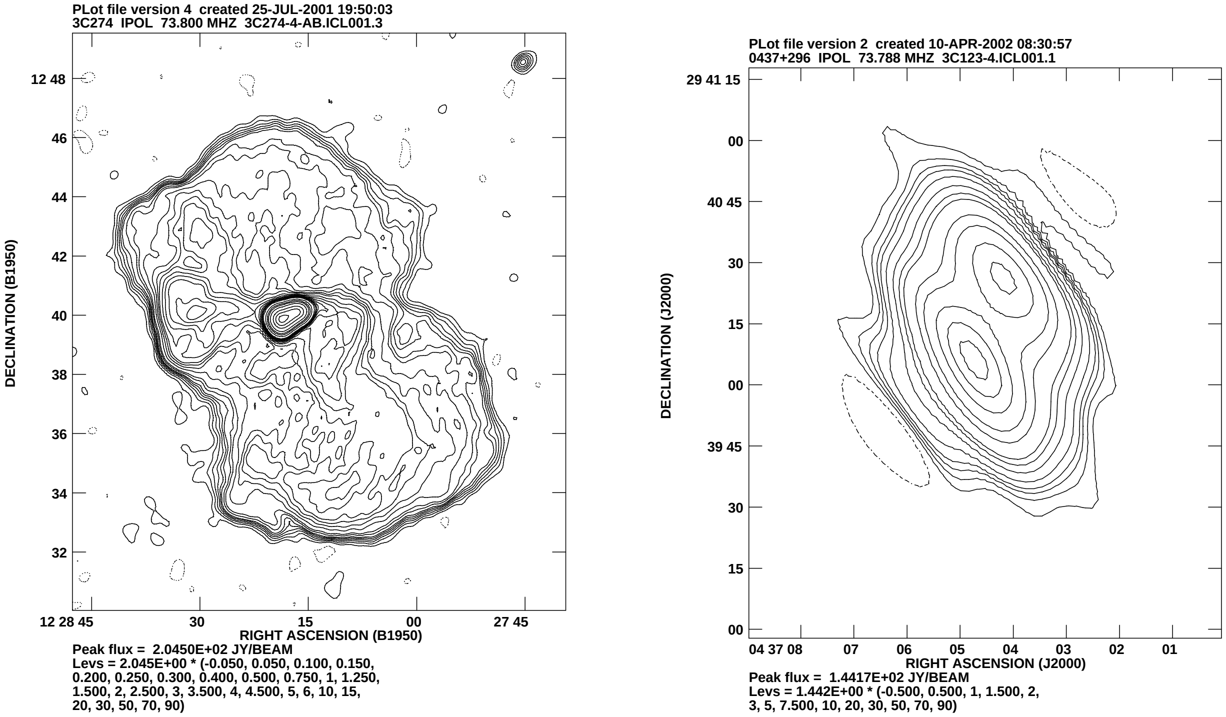

Figure 4: The left panel shows a 74 MHz image of Virgo A with 25 arcsec. resolution. The right panel shows an image of 3C123 at 74 MHz, using the VLA in its A-configuration with the VLBA's PieTown antenna, with 9 x 21 arcsecond resolution.