Surveys, Sources, and Resolution with the 74-MHz VLA

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Abstract

The 74 MHz system on the Very Large Array can obtain point-source sensitivities and resolutions of 100 mJy (1σ in 1 hr) and $25''$, respectively. These capabilities have engendered diverse observations, including of extrasolar planets, Galactic supernova remnants, and distant clusters of galaxies and radio galaxies. Limited observations have been conducted with the "VLA+PT link," in which the Pie Town antenna from the Very Long Baseline Array is joined with the VLA, providing $10''$ angular resolution. Finally, the VLA Low-frequency Sky Survey (VLSS) exploits the large field of view (10° FWHM) to cover the sky above a declination of -30° to a sensitivity of 0.5 Jy beam^{-1} (5σ) at $80''$ resolution. We summarize these various observations, with a focus on the VLSS and the VLA+PT observations.

1 The 74 MHz VLA The Naval Research Laboratory and the National Radio Astronomy Observatory have implemented a low frequency capability on the VLA at 73.8 MHz (4 m wavelength). This frequency band offers unprecedented sensitivity ($\approx$ 25 mJy beam^{-1}) and resolution for low-frequency observations. The longest baselines in the VLA itself (36 km) provide $25''$ resolution, and the system recently has been extended to the nearby Pie Town antenna of the Very Long Baseline Array, which provides a baseline of 73 km and angular resolutions of $10''$.

High-dynamic range imaging at frequencies below 100 MHz presents a number of challenges, including ionospheric phase fluctuations, the large field of view, and radio frequency interference (RFI). Ionospheric phase fluctuations influence the choice of calibration strategy. Over restricted fields of view (e.g., when imaging a strong source) or at times of extremely quiescent ionospheric "weather" (when the ionospheric isoplanatic patch size is larger than the field of view), a traditional angle-invariant calibration strategy can be used. In this approach a single phase correction is devised for each antenna, typically via standard self-calibration methods used at higher frequencies. Over larger fields of view or when the ionospheric isoplanatic patch size is smaller than the field of view, we adopt a field-based strategy in which the phase correction depends upon location within the field of view [4]. In practice we have chosen to implement this second calibration strategy by modeling the ionosphere above the array using Zernike polynomials. Angle-variant self-calibration schemes have been proposed as an alternative but have yet to be implemented.

Wide-field imaging is required as the assumption that the array is coplanar breaks down over the large primary beam size ($\approx 10^\circ$) at this frequency. In order to compensate for this problem, a polyhedron mapping algorithm [3] is used in which a "fly's eye" of small overlapping images (facets) is made to cover a large field of view (typically 7.5° radius). An additional facet(s) at the position

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of a strong outlier source can be inserted if the outlier source would be strong enough to produce sidelobes in the field of view. Depending upon their strengths, outlier sources can be as far away as 40° and still be included in the imaging. Depending on the desired field of view, anywhere from roughly 50 to 1500 facets are needed for this method. After CLEANing and imaging the facets are combined into one large undistorted image.

Finally, if not removed from the data stream, RFI limits severely the dynamic range that could be obtained. RFI can be generated either external or internal to the array; the latter is a particular problem at the VLA, where an oscillator at each of the antennas often can be seen coherently by the other antennas, producing a "comb" of narrowband RFI, separated by 100 kHz, across the entire 1.5 MHz observing band. It is essential to observe in a multi-channel (pseudo-continuum) mode so as to identify and excise RFI. Typically, we excise about 10-20% of the data due to RFI. A variety of algorithms have been developed in an effort to remove the bulk of the RFI in an automated fashion. These are effective, particularly against the narrow band interference generated by the VLA itself, but some hand-editing of the data is still necessary for the most sensitive experiments.

We now illustrate two particular successes with the 74 MHz VLA: The VLA Low-Frequency Survey and high resolution observations with the VLA-Pie Town system.

2 VLSS: the VLA Low-Frequency Survey

2.1 Description The VLSS is an ongoing effort to map an area of 3π sr covering the entire sky above a declination of $-30°$, at a frequency of 74 MHz. The survey has $80''$ resolution and a point-source sensitivity (5σ) of 0.5 Jy on average; in areas near the Galactic plane and very bright sources the noise levels are higher. The principal data products from the survey will be a set of publicly available images and a catalog of approximately 80,000 sources.

The scientific goals of this survey are multiple. Samples of sources with steep spectral indices at low frequencies can be used to detect pulsars, high redshift radio galaxies, and cluster haloes and relics. Using these low frequency data it is also possible to study absorption effects in supernova remnants, normal galaxies, and in H II regions in the Galactic plane. Another main goal of this survey is to make a low frequency counterpart to the 1400 MHz NRAO VLA Sky Survey (NVSS [1]), which will be available for public use by all astronomers. Finally we will produce a low-frequency sky model which can be used to plan and calibrate more sensitive 74 MHz VLA experiments, as well as providing an initial calibration grid for planned radio telescopes such as the Long Wavelength Array (LWA), and the Low Frequency Array (LOFAR), and the Square Kilometer Array (SKA).

2.2 Latest Results Currently, most of the sky above declination $-10°$ has been observed. The observations were conducted in two extensive campaigns. Observations from the first campaign (2003) have been released to the public in the form of a source catalog and postage stamp image server (URL:http://lwa.nrl.navy.mil/VLSS/); processing of the observations from the second campaign (2005) is in progess, with the eventual aim of also making them public. Fig. 1 shows a sample image along with the region of the sky currently mapped. It will take several more years to finish the sky between $-10°$ and $-30°$ due to instrumental limitations on observing at low declinations.

From the images resulting from the first observing campaign, we have detected over 32,000 sources. Most of these sources are not resolved by the $80''$ beam, however a small fraction are large enough that their structure can be determined by our survey images.

3 VLA-Pie Town Observations

While the 74 MHz VLA illustrates that ionospheric compensation, wide-field imaging, and RFI excision can be accomplished on a routine basis for imaging at unprecedented resolutions and sensitivities below 100 MHz, the actual resolution obtained

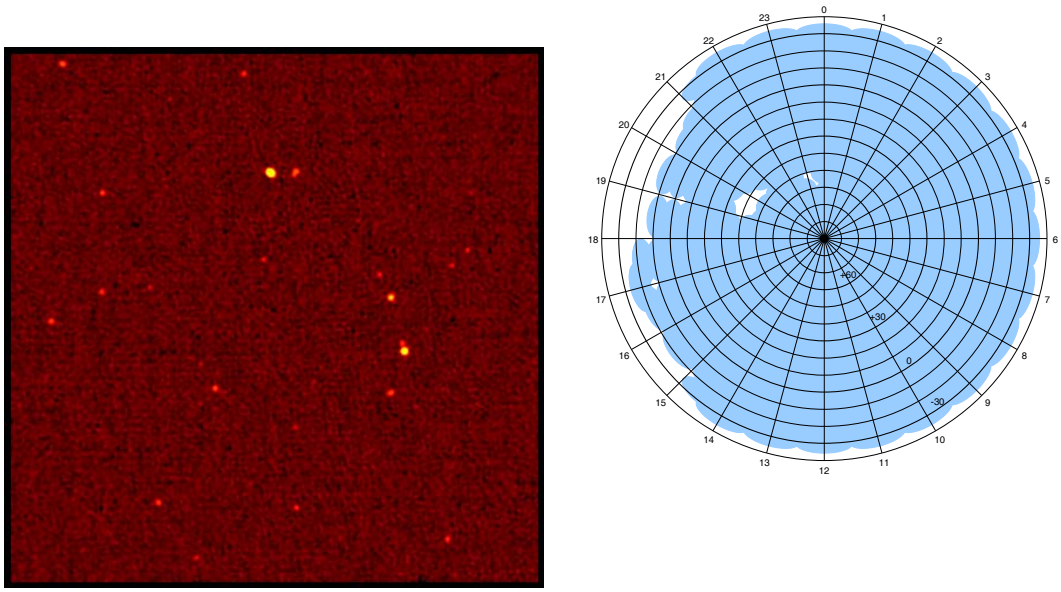

Figure 1: *Left*: A $2^\circ \times 2^\circ$ section from the VLSS test observations showing a typical image quality and source density. *Right*: Approximate sky area observed. Approximately half of this area was made publicly available in 2004 June. The remainder of the data will be made public as soon as they are imaged and a source catalog is constructed; the tentative release date is in the latter half of 2005.

($\approx 25''$) is still substantially lower than can be obtained either at higher radio frequencies or at other wavelengths. Higher angular resolution requires baselines longer than the 36 km of the VLA's A configuration. To this end, NRL and NRAO outfitted the Pie Town antenna of the Very Long Baseline Array with a 74 MHz receiver. The VLA-Pie Town 74 MHz system provides a longest baseline of 73 km, for an angular resolution of $10''$.

The initial observations with the VLA-Pie Town 74 MHz system focussed on strong sources, such as Her A [6], Cas A [5], Cyg A, with the aim of demonstrating that self-calibration based methods for ionospheric compensation would continue to work on these baseline lengths. By restricting our focus to the strongest sources, we largely reduced the need for wide-field imaging (though observations of Per A are a notable exception). Fig. 2 illustrates a typical example; a notable aspect of this figure is that the hot spots of Cyg A, normally quite prominent in higher frequency images, are apparently absent at 74 MHz. Work is on-going to assess what their absence indicates about acceleration processes within Cyg A.

4 Summary The 74 MHz VLA system has demonstrated that high dynamic range, high angular resolution imaging at frequencies below 100 MHz is feasible. On-going work involves connecting the ionospheric phase fluctuations determined from astronomical observations with ionospheric physics, in the hopes of improving the robustness of the phase corrections, and investigating the use of the w-projection for wide-field imaging [2]. While significant challenges in terms of simultaneous wide

Figure 2: The VLA-Pie Town 74 MHz image of Cygnus A. The angular resolution is $10'' \times 7''$, the noise level is 0.97 Jy beam^{-1}, the contour levels are 0.97 Jy beam^{-1} $\times$ -5, 5, 7.07, 10, 14.1, 20, ..., and the gray scale is linear.

field imaging and ionospheric compensation and automated RFI excision remain, nonetheless, the existing progress on these topics bodes well for future arrays such as the LWA, LOFAR, and the SKA.

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