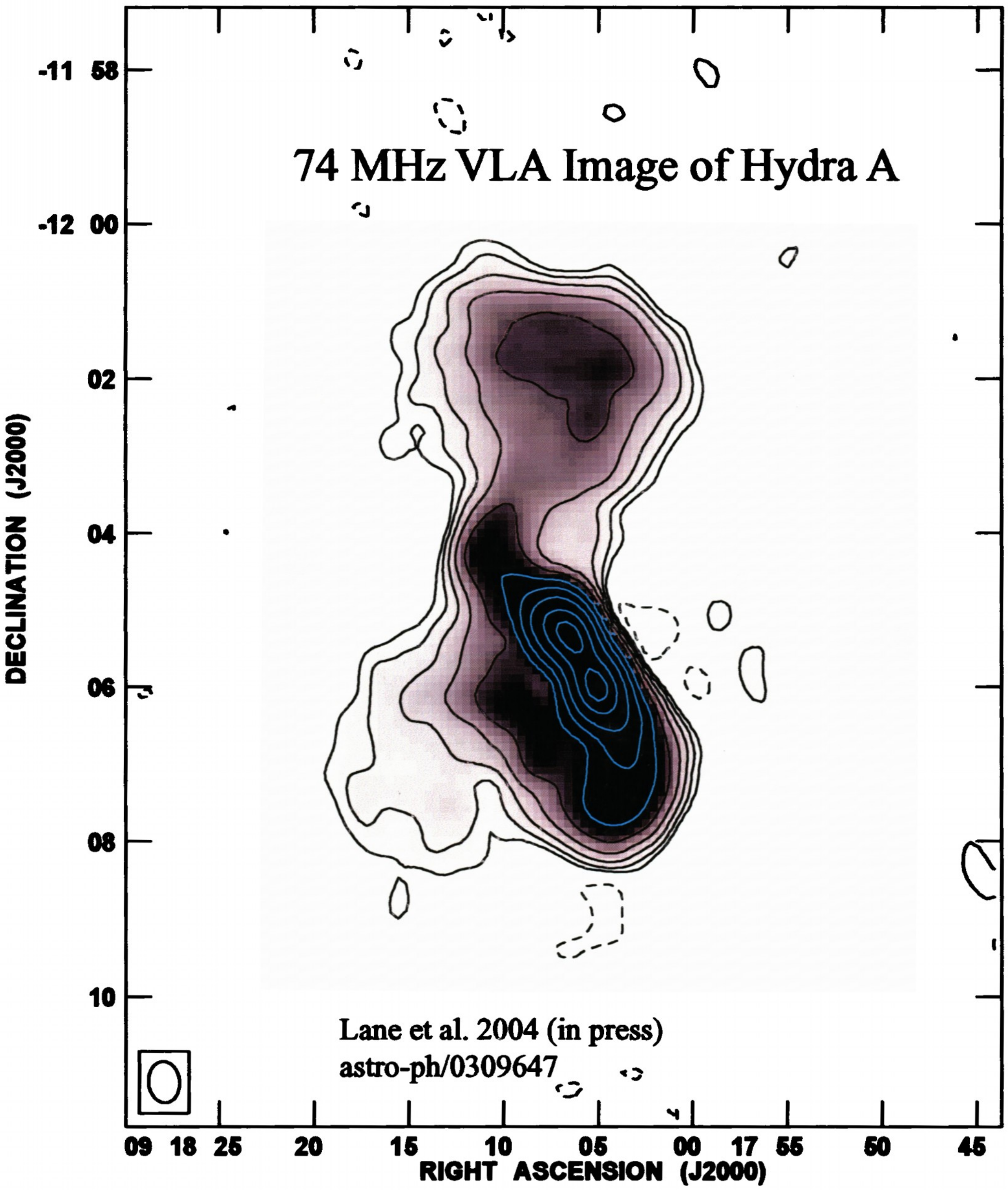
Proposal to Establish Low Frequency Stations at the VLA



Sub-title: Enhancing the scientific productivity of VLA low frequency systems and developing low frequency array software and hardware technology

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Executive Summary

Scientific and Technical Goals

The aim of this work is to build upon the foundation of scientific and technical breakthroughs in low-frequency radio astronomy realized by NRL and NRAO over the past decade by expanding the depth and breadth of scientific results of the low-frequency systems at the VLA, and developing the new technology required to construct and operate a low frequency array such as LOFAR.

One immediate scientific aim of the program is to utilize the existing VLA 74 MHz system to generate a sky-noise-limited, all-sky, low-frequency survey, the VLA Low Frequency Sky Survey (VLSS) which, in addition to its direct scientific value, will provide an essential calibration grid for the low-frequency VLA and, eventually, for LOFAR. This already commenced survey, along with targeted low-frequency VLA observations, continue to spawn innovative techniques in data reduction, such as wide-field imaging, RFI excision, and pipeline reduction procedures that can benefit all users of the VLA. Extensive use of the VLA 74 MHz system for research and publication by NRL as well as the world-wide community will continue.

The technical aim of the program is to develop low-frequency dipole-antenna based prototype array *stations* which will: 1) increase the efficiency, sensitivity, and angular resolution of the 74 MHz VLA, and 2) be able to be used independently of the VLA to explore the technology needed for planned, multi-beam array telescopes such as LOFAR and the SKA. The prototyping work will allow us to surmount the major remaining obstacles to full exploitation of low-frequency radio astronomy, by: 1) improving the sophistication of calibration, ionospheric correction, and imaging algorithms; 2) developing techniques of RFI mitigation; and 3) developing the broad-band digital technology for fully electronic, multi-beam arrays. A stand-alone low-frequency station-based interferometer will also be able to conduct unique scientific investigations.

Technical Plan

Number of elements:	≥ 256
Polarization:	Dual
Frequency range:	30-90 MHz
Sensitivity:	Sky-noise limited
Station diameter:	50-100 m

The preliminary specs for the prototype station are summarized in the inset. The elements will be connected to a nearby electronics hut by coaxial cables. Inside the hut each signal will be sampled by a high-speed, multiple-bit analog-to-digital converter. A digital filter will tune and select a narrower bandwidth. A digital beamformer will combine the baseband, narrowband signals from all the elements. The combined signal will be available for local processing, as in single-antenna mode, or for transmission over an optical-fiber link to a more central location for technical study of the single station or, on occasion, combination with some or all VLA antennas. Detailed design of the prototype stations is not yet available, because final element designs have not yet been completed. Prototyping is underway both at the NRL Low Frequency Test Array (NLTA) site at the Goddard Space Flight Center in Maryland and at ASTRON (NL) to develop these elements. A key operational requirement is that the prototyping work must not adversely impact VLA operations.

NRL LOW FREQUENCY PROGRAM

1. Low Frequency Radio Astronomy

1.1 Background and Motivation

Even though radio astronomy began at 20 MHz with Karl Jansky, until recently ionospheric effects severely limited the angular resolution and sensitivity of all existing low-frequency telescopes. Other barriers included radio frequency interference (RFI), the need for non-coplanar-array imaging, and other problems exacerbated by past limitations in computational power. As a result, low-frequency ($\nu < 150$ MHz) imaging was largely abandoned in the race for higher angular resolution.

Steps to Low Frequency Astrophysics

- 1 VLA antenna (1991)
- 8 VLA antennas (1994)
- 27 VLA antennas (1998)
- 74 MHz Pie Town link (2002)
- 2 prototype stations (2005)
- Full LF array (under development)

Today this region remains one of the most poorly explored regions of the electromagnetic spectrum despite its great scientific potential. It is a region that favors studies of non-thermal and coherent emission processes, and provides an intrinsic link to shock physics, high-energy phenomena, and the high-red-shift Universe. It can provide unique insights into the interaction of thermal and non-thermal sources through absorption and scattering processes, and the intrinsically large field of view and high surface-brightness sensitivity

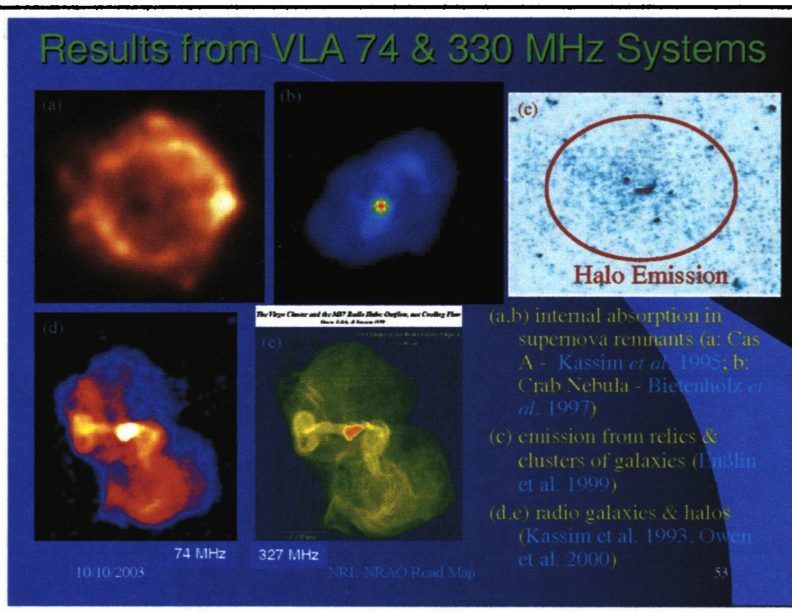


Figure 1: Early images from 74 and 330 MHz VLA systems.

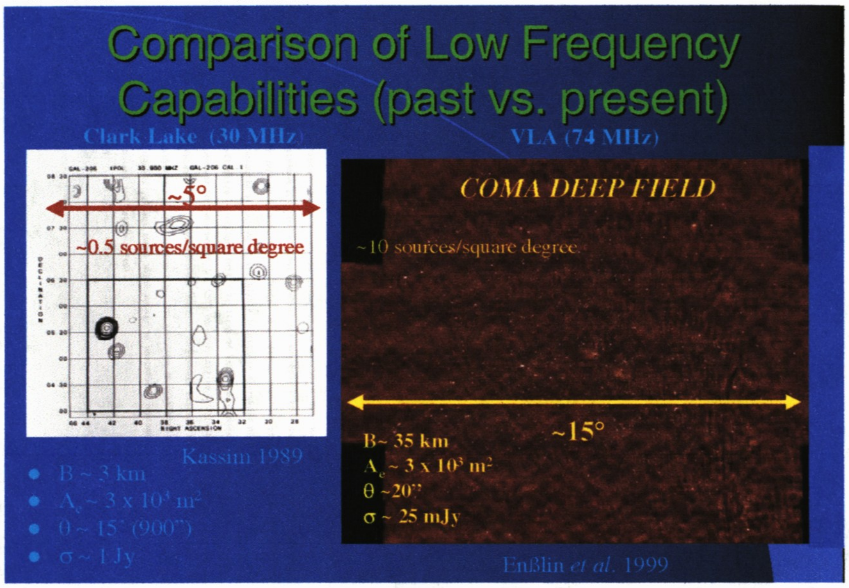


Figure 2: Comparison of past and present low frequency systems.

are often of great advantage.

During the period of 1993-1997, NRL and NRAO worked together to develop a 74 MHz system using 8 antennas at the VLA. The system was a narrow-band, modest implementation of a much more sensitive, broad-band system originally envisaged in VLA Technical Memorandum #146 (Perley and Erickson 1984). That earlier vision had been motivated by the recognition that the then new technique of self-calibration might be capable of lifting the ionospheric limitation on baseline length. That limitation had restricted the aperture size of previous low frequency telescopes to < 5 km, thereby greatly restricting their angular resolution, and because of confusion, their sensitivity as well.

The initial 8-antenna system developed at the VLA was a clear success, being the first low-frequency interferometer to overcome the "ionospheric barrier" (Kassim et al. 1993). It successfully demonstrated that self-calibration could, at least to first order remove ionospheric effects and permit imaging on long baselines (> 5 km). Its reliance on an over-determined problem in which antenna-based corrections to ionospheric phase distortions could be readily extracted worked well at the VLA. The required antenna-based phase corrections were derived from simultaneously obtained 330 MHz data which utilized all 27 antennas and made use of much greater intrinsic signal to noise. Using this new system, several of the best known sources in the sky were resolved and imaged for the first time (Fig. 1), and a number of unique scientific results were extracted.

Based on this success, NRL obtained additional funding to build the receivers and to work with NRAO to extend the system to all 27 antennas of the VLA. In a parallel track, NRL and NRAO had been developing, mainly in context of 330 MHz data reduction, innovative "3D" wide-field-imaging algorithms and RFI-excision software which were enabled by the still ongoing revolution in computational power. When these techniques were implemented for the completed 27-antenna 74 MHz system, it immediately demonstrated the ability to map thousands of sources, beyond the modest handful of the very brightest sources which were available to the initial 8 antenna system (Fig. 2). In fact the full system made self-calibration so much more robust that the previous prerequisite for "phase-transfer" from simultaneous 330 MHz observations was no longer required. As a result, the 74 MHz VLA system is now by far the most powerful interferometer in the world working below 150 MHz (Fig. 3).

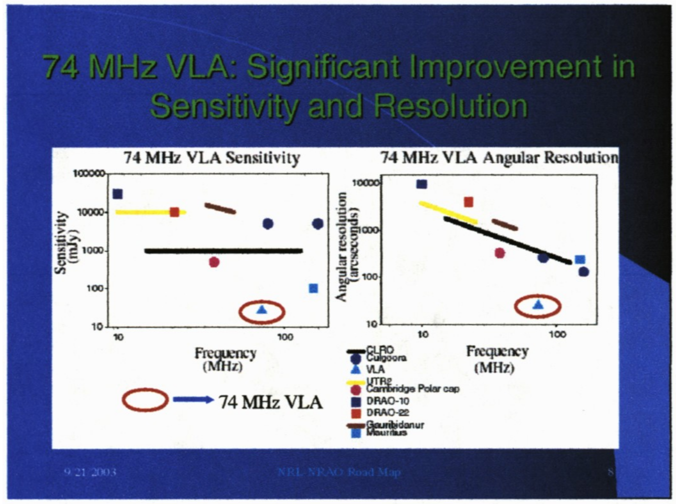


Figure 3: Sensitivity and angular resolution of 74 MHz VLA (blue triangles) compared with other current and past low frequency instruments.

The full 74 MHz VLA system has been available to the general scientific community since 1998, and has a growing international user community conducting unique observations in many different areas of astrophysics. Many of the technical innovations developed during the course of its development have also had tangible benefits for 330 MHz, and higher frequency observations, as well. In the next section we describe some of the new scientific results and technical innovations that are the result of this successful collaborative effort

SNR Cas A at 74 MHz

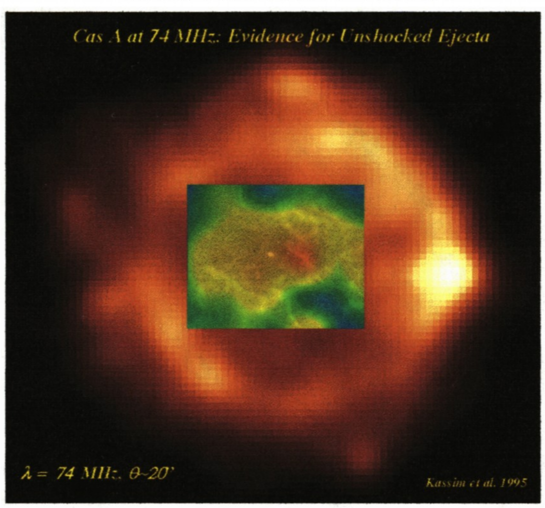


Figure 4: 74 MHz image of Cas A – inset highlights region of strongest 74 MHz absorption centered on CHANDRA detected neutron star (Delaney & Rudnick, in preparation).

between NRL and NRAO.

1.2 New Scientific and Technical Results

New and unique science is being conducted using both the 74 and 330 MHz systems at the VLA, and here we describe only a subset of results from the many and varied research programs currently underway.

1.2.1 Thermal Absorption: Supernova Remnants and the ISM

Of some surprise has been the extent to which thermal absorption processes have played a role even at the relatively "high" frequency of 74 MHz. The initial discovery of the presumed un-shocked ejecta interior to the reverse shock in the supernova remnant (SNR) Cas A provided only the second direct line of evidence for this poorly constrained constituent of very young SNRs, and the first ever in the radio (Fig. 4, Kassim et al. 1995). Since the initial discovery using the 8-antenna system, observations with the full 27 antennas and most recently using the Pie Town link have confirmed the initial observations and suggested an alternative interpretation for the absorption – shocked, and later cooled ejecta. Combined with observations at 330 MHz and 1400 MHz, it is now possible to disentangle the competing effects of spectral index variations arising from thermal absorption and those due to intrinsic diffusive shock acceleration processes (Fig. 5).

Spatially resolved *intrinsic* thermal absorption towards Cas A was a surprise. However, it had long been known from the turnover in the integrated spectrum of SNRs at low frequencies (Kassim 1989)

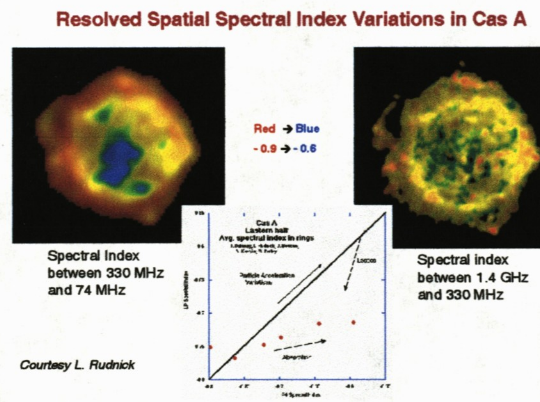


Figure 5: Competing absorption (left) and shock acceleration (right) effects revealed on resolved spectral-index maps of Cas A. (Figure courtesy

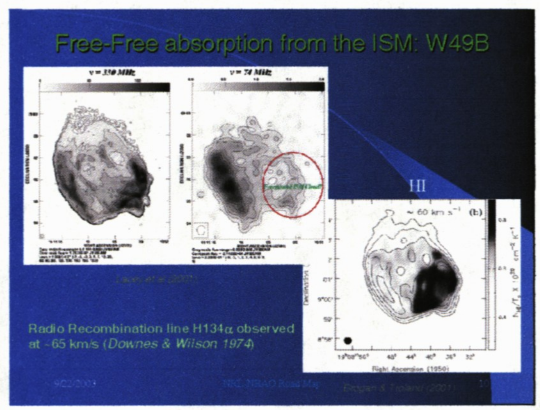


Figure 6: Resolved absorption towards the SNR W49B (left). HI correspondence (right).

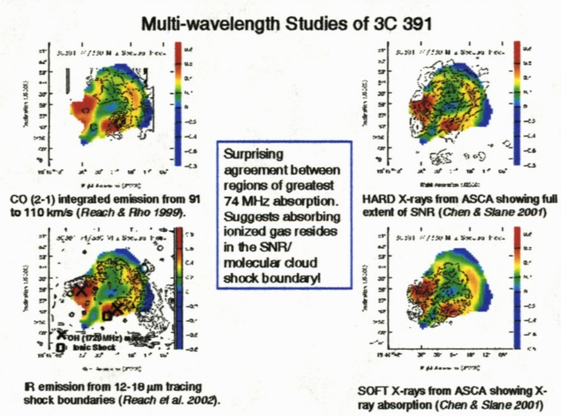


Figure 7: Direct evidence of molecular cloud/SNR interaction in 3C391 star-formation region (Brogan et al. 2002).

that the interstellar medium (ISM) could also cause thermal absorption of non-thermal emission. A beautiful result, however, was the first ever detection of spatially resolved ISM absorption towards a Galactic SNR, as demonstrated by the 74 MHz observations of W49B (Fig. 6). Those observations conclusively demonstrated what had previously only been indirectly inferred from statistics, that the absorption was due to discrete clouds in the ISM. The observations have also been related to HI data, beginning to provide us our first comprehensive understanding of the physical properties of this previously very poorly constrained, low-density ionized constituent of the ISM. In another ongoing study of the star-formation region near 3C391, 74 MHz images link spatially resolved thermal absorption at the interface of a molecular cloud/SNR interaction boundary to 21cm, CO, near and far IR, and even soft and hard x-ray observations, providing a striking example of the power of a true multi-wavelength study of a star formation region (Fig. 7, Brogan et al. 2004).

Further cases of Galactic ISM thermal absorption, each with differing character, together with new SNRs, continue to emerge from ongoing low-frequency VLA observations in the Galactic plane (Brogan et al. 2004). Particularly exciting is what is

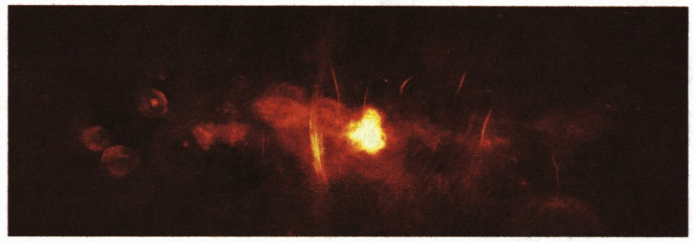


Figure 8: Preliminary ABCD + GBT 330 MHz image of the Galactic center (courtesy M. Nord). Shown in Galactic coordinates.

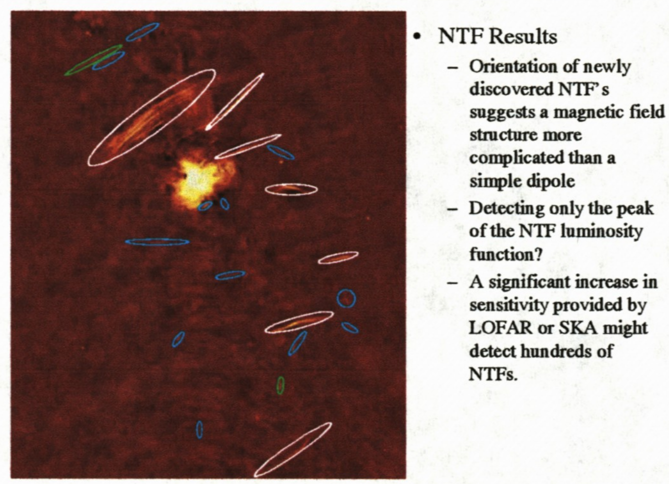


Figure 9: New nonthermal filaments discovered on next generation VLA 330 MHz GC image (Nord et al. 2003b).

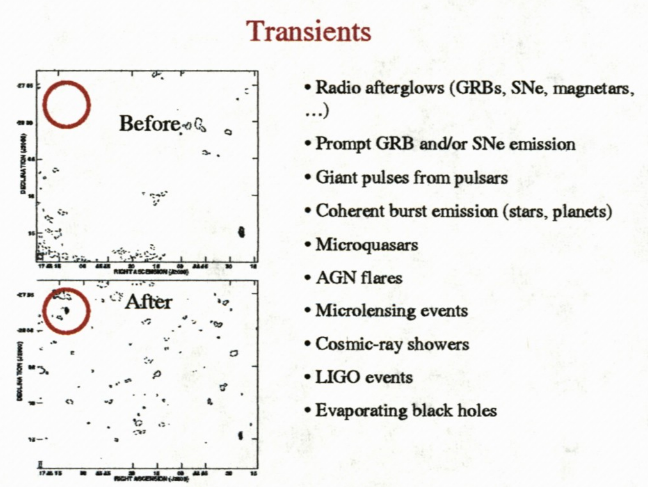


Figure 10: VLA discovered low-frequency GC transient (Hyman et al. 2002).

tentatively the first spatially resolved thermal absorption in an external galaxy, from recent 74 MHz observations of the edge-on Galaxy NGC891 (Cohen and Israel, in preparation).

1.2.2 Galactic Center Studies

The most striking demonstration of the power of wide-field imaging has been the 330 MHz image of the Galactic Center (GC) (Kassim et al. 1999, LaRosa et al. 2000) that by itself launched a renaissance in low-frequency GC research. Fig. 8 shows a preliminary version of the next generation VLA 330 MHz image that incorporates data from all VLA configurations in addition to data from the Green Bank Telescope (GBT). This image was made with a combination of now standard 3D imaging techniques and the relatively new techniques of multi-scale CLEAN and "feathering". The new image is much more sensitive than the original VLA 330 MHz GC image, and is leading to a number of important discoveries. These include uncovering a population of GC-centered pulsar candidates and more than tripling the number of known GC non-thermal filaments (NTFs) – thereby gaining unique insights into the GC magnetic field (Fig. 9).

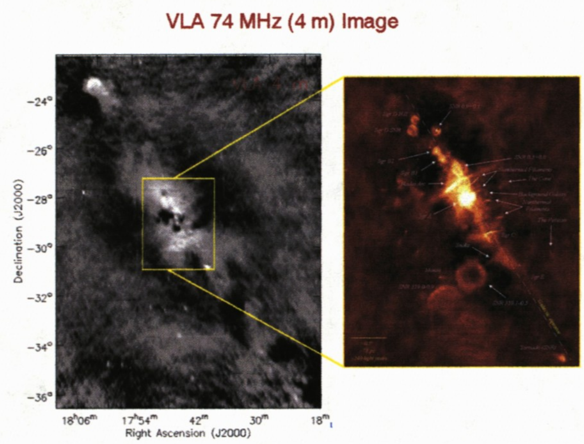


Figure 11: Comparison of 74 and 330 MHz images of the Galactic Center (LaRosa et al. 2000, Brogan et al. 2003).

Another striking result has been the unexpected detection of 330 MHz emission from Sgr A* itself, the lowest frequency at which emission has yet been associated with a black hole (Nord et al. 2003a). Detection of two low frequency GC transient sources has motivated a dedicated VLA and GMRT GC transient monitoring program (Hyman et al. 2002 – Fig. 10). VLA GC observations have now been extended to 74 MHz as well (Fig. 11). The detection in absorption of known HII regions at kinematically well-determined distances serves as a powerful 3D probe of the distribution of cosmic-ray-electron gas in the

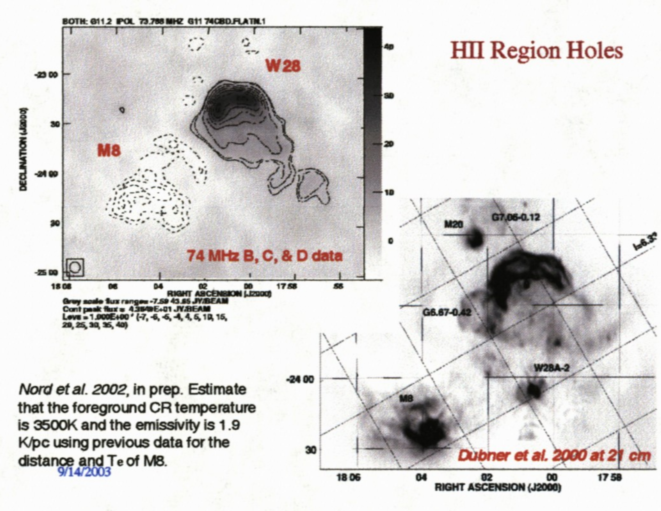


Figure 12: Detection of giant HII region W28, located 6 degrees north of the Galactic center, in absorption at 74

ISM, and validates exploitation of this technique as key scientific goal for LOFAR. A specific example is the case of the well known HII region M8 (the Lagoon Nebula) – located ~6° north of the GC, this source is at a well defined distance of ~ 4 kpc (Fig. 12).

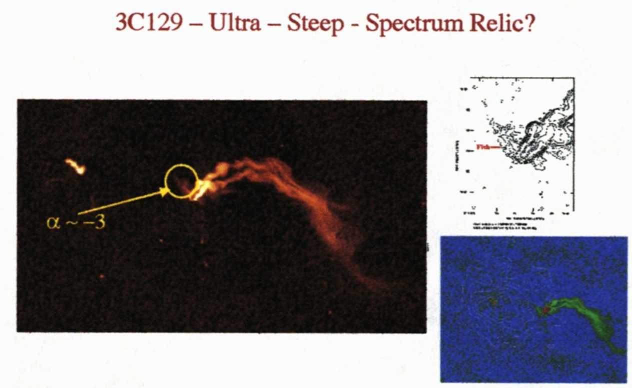


Figure13: Detection of ultra-steep-spectrum emission towards 3C129 (Lane et al. 2002).

Other results from 74 MHz GC observations include the spectral characterization of previously poorly understood phenomena (e.g. the Omega lobe), delineation of the relative superposition of thermal and non-thermal sources along complex lines of sight (e.g., for the Sgr D complex), and the detection of a discrete, non-thermal envelope coincident with the well known Central Molecular Zone (Brogan et al. 2003).

1.2.3 Radio Galaxies and Clusters

Equally impressive results are emerging in extragalactic observations with the low-frequency systems at the VLA. Lane et al. (2002) detected an extremely steep spectrum ($\alpha < -3$, where $S \sim \nu^{+\alpha}$) structure that appears to be a relic radio source awakened by the passage of the head of the radio galaxy 3C129 (Fig. 13), a result that has just been confirmed and extended to 74 MHz with VLA-Pie Town observations (Harris and Lane, in preparation). This may provide one of the best concrete examples of the long-predicted "fossil" radio sources (Enßlin and Gopal-Krishna 2001) postulated to reside at the periphery of clusters. A new cluster and relic system was recently detected in A754 (Kassim et al. 2001), supporting the idea that cluster mergers generate turbulence that

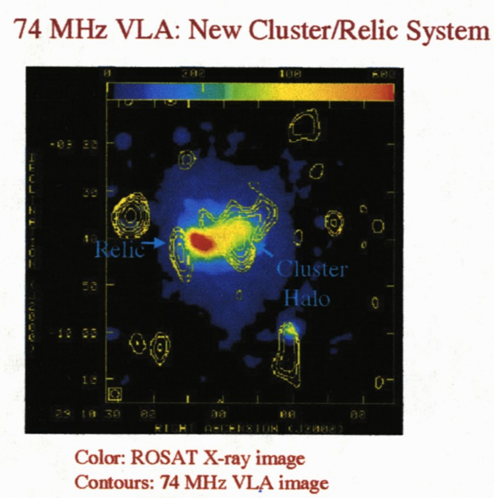


Figure 14: Discovery of new halo/relic system in A754 with 74 MHz VLA (Kassim et al. 2001).

accelerates relativistic particles in the inter-cluster medium (Fig. 14). An especially exciting result was the detection of steep-spectrum emission associated with an X-ray "bubble" in Per A (Fabian et al. 2002 – Fig. 15) – a result which has spurred a flurry of VLA low frequency "bubble proposals".

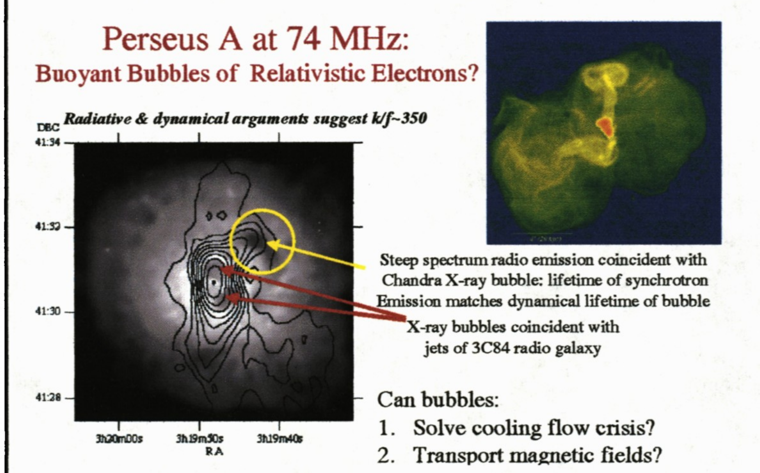


Figure15: 74 MHz VLA detection of steep spectrum counterpart to X-ray cavities in Per A (Fabian et al. 2002).

The bubble concept plays a prominent role in the context of current discussions in cluster astrophysics. In addition to explaining the observed morphology in the X-ray and radio images, they provide a possible source of heat to solve the "cooling flow crisis" – the lack of cool gas detected in the cores of cooling flow clusters by *XMM Newton* and *CHANDRA*. They also provide a means of transporting magnetic field from the inner accretion disks around the black holes at the center of clusters to their outer regions where they are detected (Carilli and Taylor 2002). Recent low-frequency radio observations of Hydra A (Lane et al. 2004, Fig. 16) may provide an example of the largest known "cluster bubble" source.

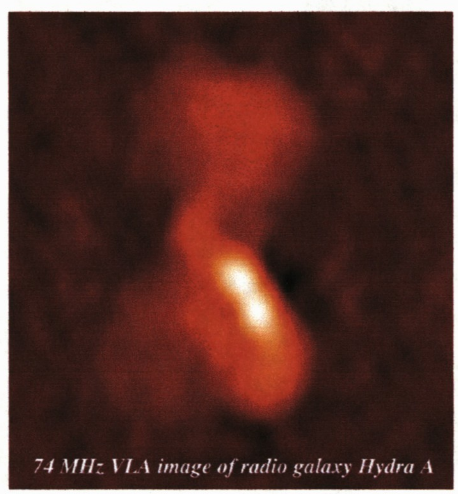


Figure16: The northern lobe of Hydra A may be one the largest cluster bubble sources known (Lane et al. 2004).

1.2.4 Additional Studies

We have highlighted studies that are mainly the subject of ongoing NRL research, because those are the ones with which we are most familiar. A list of those collaborations is presented in Appendix A. We note that there are many other scientific programs that utilize the low frequency VLA systems. Appendix B provides a list of publications mainly involving 74 MHz observations. However, we also include a sub-set of 330 MHz projects (as noted) that have benefited directly from our general program of improved algorithm development for all low-frequency VLA observations.

2. Opportunities and Obstacles

2.1 Algorithm Limitations

In this section we describe limitations of available algorithms for reducing low-frequency VLA data. However, we note that the many scientific projects currently being conducted by the VLA 74 MHz system are only possible because of already achieved breakthroughs in data reduction algorithms, notably in the areas of ionospheric calibration, RFI excision, and wide-field imaging (Kassim et al. 2003). We also note that many of the benefits of these algorithms have also positively impacted 330 MHz VLA data reduction (e.g. Kassim et al. 1999, LaRosa et al. 2001). As has been our practice, we will continue to make all of our developing methods and experiences accessible to the low-frequency user community, so that they can be utilized immediately to increase the scientific value of existing VLA data. All of our work is extensively documented and available in our on-line Low Frequency Data Reduction Tutorial at: *http://lofar.nrl.navy.mil/pubs/tutorial/*, which is also linked directly to the main NRAO VLA calibration web resources.

2.1.1 Radio Frequency Interference Mitigation

In the technical arena, strides in the sophistication of the excision of radio-frequency interference (RFI), self-calibration, and wide-field-imaging techniques continue to provide benefits for observers at more than just the lowest VLA observing frequencies. However, in all of these areas significant limitations remain and prevent us from exploiting the full power of the present VLA system. For example, while the sophistication of RFI excision software has advanced significantly as a direct result of its need at 74 MHz (Fig. 17), data editing remains by far the most tedious step at both 74 and 330 MHz. Even now, the best approach is "by eye", and there is a strong need for automated procedures that can handle the massive data sets involved with multi-channel, long-track, low-frequency data sets. A major goal of our ongoing algorithm development plans are to develop completely automated RFI excision algorithms. Such routines can be made general enough to be useful for cm-wavelength VLA data editing as well.

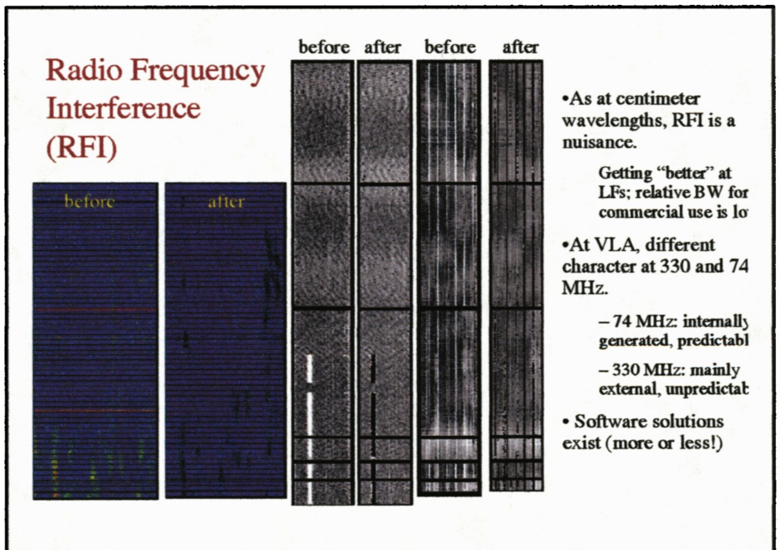


Figure17: Examples of RFI excision with 74 MHz VLA data. While existing techniques continue to increase in sophistication, the lack of automated procedures is an ongoing challenge.

2.1.2 Ionospheric Calibration

The application of standard self-calibration to 74 MHz VLA data provided a revolutionary step forward in low-frequency radio astronomy. However, with the increased resolution and sensitivity of the new system came dramatic illustration of the limitations of existing software solutions.

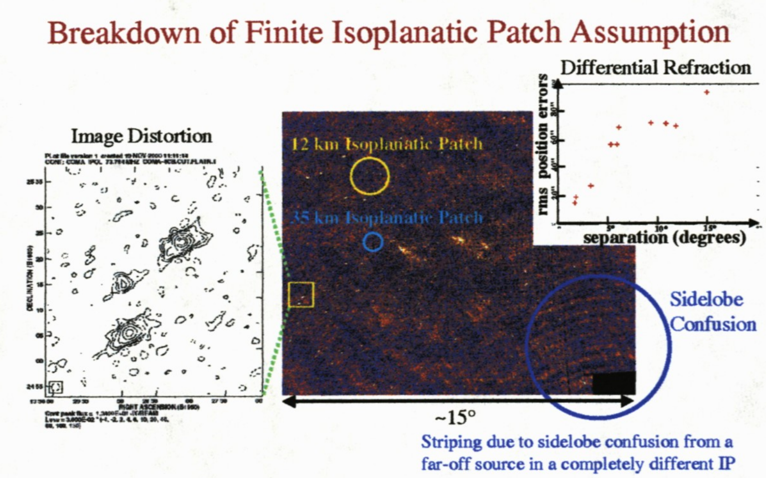


Figure 18: Illustration of breakdown of the finite isoplanatic patch assumption.

The finite size of the ionospheric isoplanatic patch, which is smaller than the field of view for the larger configurations of the VLA, revealed the short-comings of the first generation of ionospheric-compensation algorithms (Fig. 18). The lack of angle-variant self-calibration posed a fundamental challenge to full-field, thermal-noise limited imaging of fields devoid of bright sources, especially in the A and B configurations. This limitation posed an immediate challenge to the goal of conducting a large, B-configuration based sky survey that in addition to its scientific benefits would provide a calibration grid for routine, full-field imaging data reduction. The VLA Low Frequency Sky Survey (VLSS) would also serve as an initial calibration grid for LOFAR.

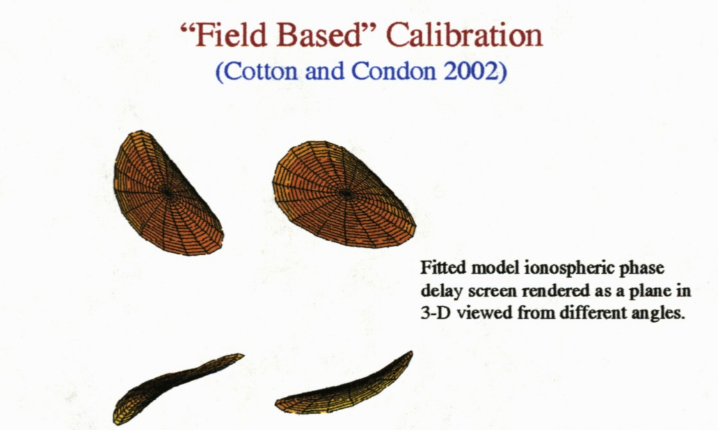


Figure 19: Zernike polynomial based phase screen modeling of ionosphere over the VLA.

In order to address this chicken-and-egg problem, NRL and NRAO again successfully worked together to develop a completely new calibration technique for low-frequency radio astronomy. The so-called "*field-based*" calibration technique (Cotton and Condon, 2002) has now been successfully demonstrated using VLSS test data, and has allowed the full survey to proceed (Fig. 19). Key science goals of the VLSS are to: 1) study cosmological radio source evolution, 2) search for ultra-steep spectrum objects, 3) probe the temperature and density structure of the interstellar and intergalactic medium, and 4) and discover new radio galaxies, clusters, supernova remnants, and pulsars

In addition to enabling the VLSS (Fig. 20), field-based calibration has stimulated an emerging scientific program of deep field observations. These have led to discovery of a number of candidates for pulsars, high-z radio galaxies, and clusters now being pursued at higher radio frequencies as well as in the optical and IR. A major ongoing project is deep VLA 74 and 330 MHz imaging of the XMM Large Scale Structure field - a region of the sky surveyed by the XMM X-ray satellite (Fig. 21, Cohen et al. 2003). The survey is important for cosmology, and aims to connect the development of large scale structure in the Universe with the evolution of black-hole-powered galaxies. With the success of field-based calibration, the VLSS can proceed and, following the path demonstrated by the NVSS, become readily available as a powerful scientific tool to all astronomers.

However, as suggested earlier, except under favorable ionospheric weather conditions, even field-based calibration does not allow routine, full-field, thermal-noise-limited imaging in the A configuration. Furthermore, residual "seeing errors" in all configurations degrade the effective resolution of the observations – thus

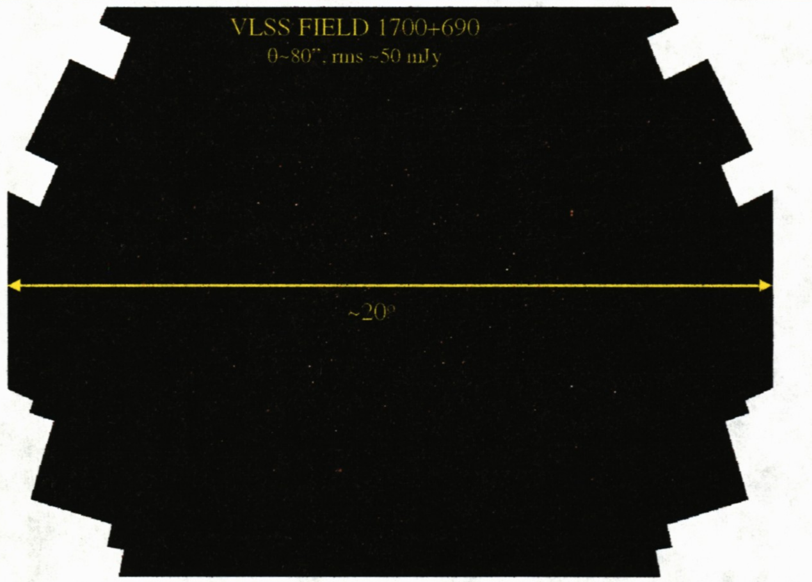


Figure20: Thermal noise limited imaging of VLSS field using field-based calibration.

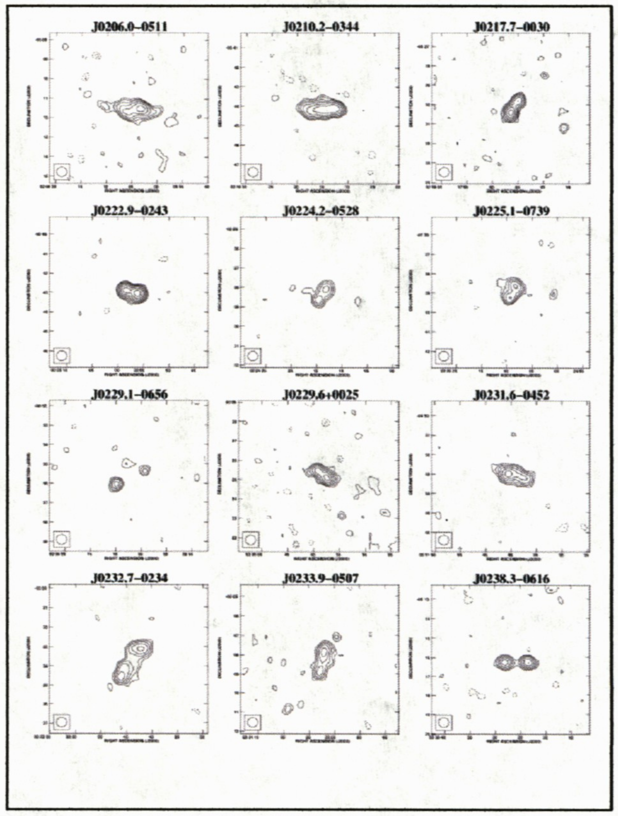


Figure 21: Sample of resolved 74 MHz sources from the Low-Frequency Radio Counterpart of the XMM Large-Scale Structure survey (Cohen et al. 2003). The angular scale is the same in each image. Contour levels are at 150 mJy beam^{-1} times (-2, -1.4, -1, 1, 1.4, 2, 2.8, 4, 5.8, 8, ...).

point sources are slightly smeared out, and because of finite surface brightness sensitivity, less sources are detected. (In the Galactic plane, field-based calibration often fails completely.) Thus there remains a critical need to improve the efficiency of field based calibration and to explore angle-variant approaches to self-calibration. Over the next few years, we will use the emerging calibration grid provided by the VLSS, in conjunction with the improved calibration empowered by the proposed low frequency dipoles stations described in the following sections, to greatly improve the throughput efficiency and scientific value of future low frequency VLA observations.

2.2 Hardware Limitations

Despite the considerable and still ongoing progress that has been made at the VLA, hardware restrictions impose fundamental limits that cannot be overcome by 25-m antennas not optimized to work at such low frequencies. The three key limitations are 1) angular resolution - while the 25" afforded by the A configuration is revolutionary at such frequencies, it is still woefully lacking with respect to the standards at centimeter wavelengths; 2) sensitivity – the sky-noise-limited system temperature, which can be overcome only by significantly increased collecting area, limits the sensitivity of the array and, equally important, restricts the successful convergence of calibration algorithms which could realize the thermal noise limits of the existing 27 antennas; and 3) the narrow-band limitation imposed by feeding the VLA antennas with resonant dipoles. The technical work outlined in following sections of this proposal is aimed at implementing solutions which can significantly mitigate the first two of these challenges on the present VLA system itself, and pave the way for implementing future, low frequency arrays, such as LOFAR.

2.2.1 Improved Angular Resolution

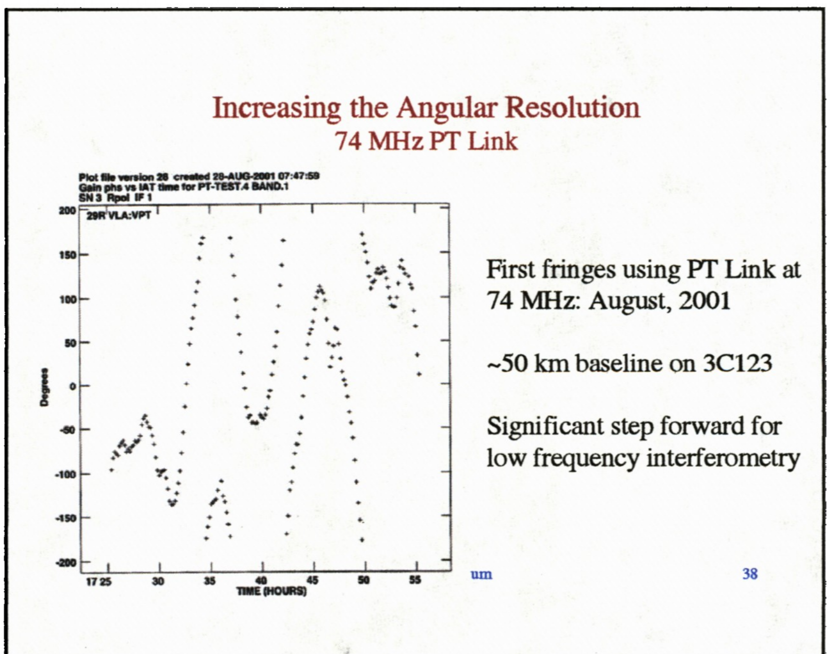


Figure 22: First fringes with the VLA+PT at 74 MHz.

Despite the significant breakthrough to sub-arc-minute resolution achieved with the current 74 MHz VLA, both the 74 and 330 MHz systems at the VLA remain starved for angular resolution. As it turns out, fundamental limitations imposed by interplanetary and interstellar scattering (θ ~1" at 30 MHz), do impose a fundamental limit on the longest feasible baselines desirable (~500 km);

however, those are still at least more than an order of magnitude longer than currently provided by the VLA.

One means of improving the angular resolution of the VLA low-frequency systems is to expand the current VLA. This goal has been partially realized with successful observations using the VLA-Pie Town link. NRL and NRAO successfully worked together to design and install a 74 MHz receiver on the Pie Town antenna, and the detection of fringes on baselines longer than 50 km (Fig. 22) represented another major step forward in low-frequency interferometry.

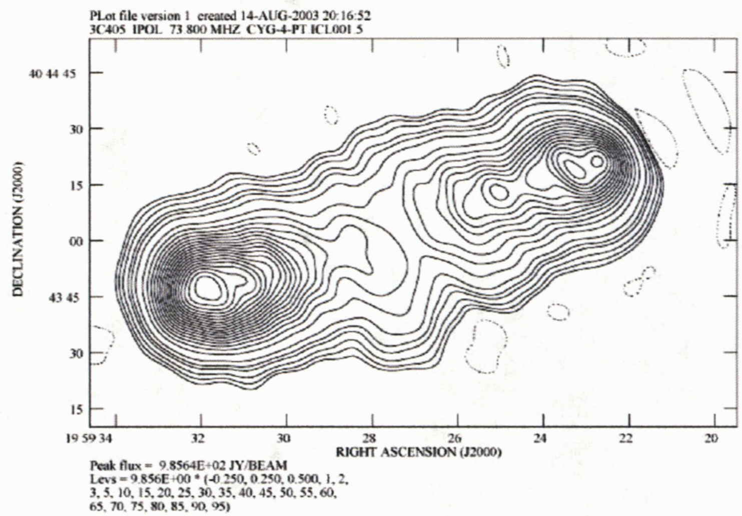


Figure 23: 9 arc-second VLA + PT image of the powerful FR-II radio galaxy Cygnus A. This image will constrain the turnover mechanism in the hotspots. It will also serve as the primary calibration image for all 74 MHz PT-link observations.

The first, striking VLA+PT 74 MHz images have spurred a number of scientific projects and will undoubtedly continue to stimulate future innovative observing programs (Figs. 23 and 24). Despite this success, the limitations on *uv* coverage of a single, distant antenna are well known. One means of mitigating this limitation would be to develop at least two stand-alone, multiple dipole-based stations, each of which would be analogous to a large antenna. In following sections of this proposal we will describe our plans to locate one near the center of the VLA where its higher sensitivity can be used to improve the robustness of our ionospheric calibration algorithms. However, we also

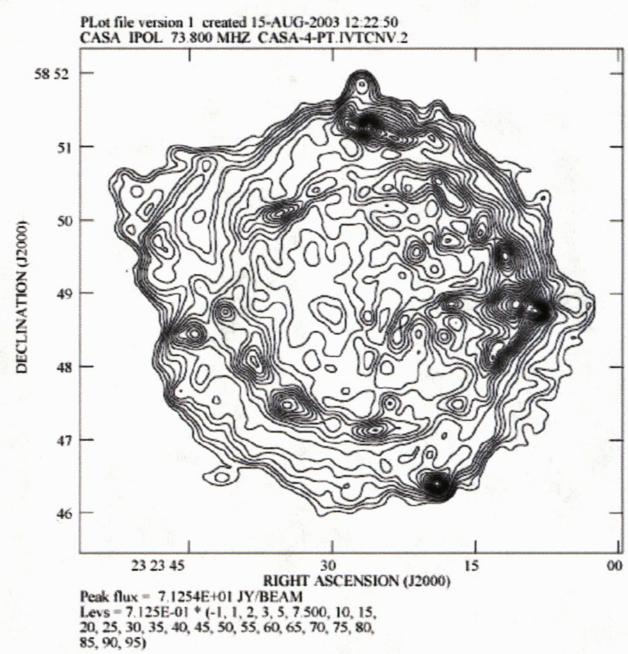


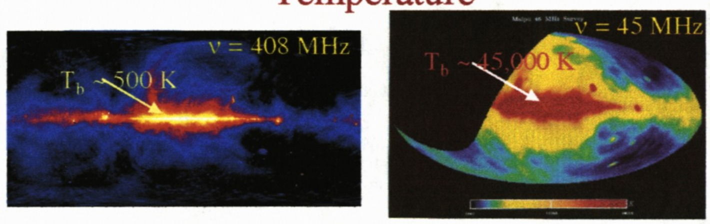
Figure 24: 8-arcsecond VLA+ PT image of the SNR Cas A. This image will provide a much more accurate constraint on the distribution of ionized ejecta, and its relation to the CHANDRA discovered neutron star (Delaney and Rudnick, in preparation).

propose future placement of at least one outlying station in order to complement the *uv* coverage provided by the current VLA+PT system.

2.2.2 Improved Sensitivity

The 74 MHz VLA is much less sensitive than higher-frequency systems because of the sky-noise-limited system temperature (Fig. 25) coupled with antennas which are less than 15% efficient at 74 MHz. However, as mentioned earlier, for full-field, high-resolution (A- and B-configuration) imaging, the lack of angle-variant self-calibration imposes a further barrier to sensitivity that prevents realization of thermal-noise-limited imaging. The poor signal-to-noise also restricts the sophistication of the newly developed technique of ***field-based*** calibration (Cotton and Condon 2002). A prototype station of large collecting area (≥ 10 times that of a VLA antenna) and larger aperture (up to ~4 times the diameter of a VLA antenna), while not appreciably impacting the thermal noise limit of the entire array, could address this problem.

Sky Noise Dominated System Temperature



Frequency (GHz)	Band Name approximate wavelength	letter code	System Temperature (K)	Antenna Efficiency (%)	RMS (10 min) Sensitivity (mJy/beam)
0.073 – 0.0745	400 cm	4	1000–10000	20	150[3]
0.3 – 0.34	90 cm	P	150–180	40	1.4[3]
1.3 – 1.70	20 cm	L	35	55	0.056
4.5 - 5.0	6 cm	C	45	69	0.054
8.1 - 8.8	3.6 cm	X	35	63	0.045
14.6 - 15.3	2 cm	U	120	58	0.17
22.0 - 24.0	1.3 cm	K	150 - 180	40	0.31[4]
40.0 - 50.0	0.7 cm	Q	100 - 140	35	0.60[5]

rms ~ T_{sys}/A_e

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Figure 25: Illustration of sky noise dominated system temperaure from the Galactic background.

Standard self-calibration currently provides a single, time-variable phase per antenna, φ(t), while what is ideally required is an angle variant phase correction φ(α,δ,t). However the large field of view of the current VLA antennas (~11 degrees FWHP) coupled with poor relative S/N on individual baselines currently precludes the development of such a scheme. The new technique of ***field-based calibration,*** described earlier, does permit efficient observations in the B configuration barring poor ionospheric conditions, and has allowed the VLSS to proceed. However, full-field, thermal-noise-limited imaging in the A configuration or even B configuration under poor ionospheric weather conditions, is still very problematic. In the following sections we describe how a large, centrally located station of dipole antennas can improve the robustness of field-based calibration, as well as allow us to investigate viable means of implementing angle-variant self-calibration.

2.3 Roadmap to Future Radio Telescopes

Inspired by the initial dramatic images produced by the 74 MHz VLA, a proposal for a large, long wavelength array was successfully presented to the National Academy of

Sciences (Kassim 1999) and subsequently recommended in the US Decadal Report on Astronomy (AASC 2001). In the interim, an international consortium has formed to develop the Low Frequency ARray (LOFAR). LOFAR will be a high-resolution (~400 km baselines), large-collecting-area (1 square km at 15 MHz), broad-band (10-240 MHz), multi-beaming instrument. In addition to providing immediate and significant improvements for users of the current low-frequency systems at the VLA, this proposal also initiates a realistic technical roadmap towards developing LOFAR. In 2003, a panel of scientists including Nobel laureate Joseph Taylor, then-NRAO-director Paul van den Bout, and Cornell Professor James Cordes, recommended a 5-year, $9.3M proposal to the NRL Research Advisory Council to develop such a technical roadmap around the existing VLA systems. In the next section of this proposal, we outline those proposed technical activities in detail.

2.3.1 Relationship of Proposed Activities to LOFAR

This proposal presents the opportunity to move forward with realistic prototyping activities that will yield immediate scientific benefits, and do so by leveraging off of one of the most powerful existing low-frequency radio telescopes in the world, the VLA. By continuing to increase the sophistication of the VLA, in coordination with its expansion at higher frequencies and in concert with the goal to develop infrastructure that might eventually accommodate a northern SKA, the proposed program lays the groundwork for development of a significant low-frequency capability in the Southwest. As of this writing, potential sites for LOFAR have been evaluated. Western Australia has been identified as the scientifically most desirable site because of low RFI and optimal sky coverage. However the other sites, including the southwest (SW) US, were also considered viable locations for a successful scientific instrument. While not as optimal as western Australia in the two areas mentioned, the SW US does offer a significantly more developed scientific and technical infrastructure. Given the uncertainty in the final site choice, we can at least say that the proposed activities will support realistic and tangible prototyping for development of LOFAR in either hemisphere, and may serve as the preparation for a SW US LOFAR site - or of a northern array to complement an Australian LOFAR. Discussions to augment our proposed technical activities are ongoing with the SW Consortium (SWC) of universities, which is interested in developing scientific and technical infrastructure that could accommodate future radio telescopes in the SW US. A low frequency instrument in the SW US might also be an excellent compliment to the planned Frequency Agile Solar Radio-telescope (FASR), and also serve as a receiver for a solar radar based transmitter at the Arecibo telescope.

3. Benefits of Proposed Prototype Station Development

As described earlier, modest improvements in software can be implemented which will continue to improve the scientific capabilities of the existing VLA low-frequency systems with little or no change in hardware. However, overcoming the fundamental limitations imposed by the poor sensitivity of the VLA antennas and their narrow-band performance requires development of a fundamentally different approach to collecting area: large, broad-band, multiple-dipole-based arrays hereafter referred to as "*stations*". Furthermore, improvements in angular resolution can only be realized by development of baselines that can extend well beyond the nominal size of the VLA+Pie Town.

In the next section we describe our proposal to develop two low-frequency stations near the VLA. Here we describe the scientific and technical benefits of that proposed work. When used with the VLA, these two stations will improve the calibration and angular resolution of the existing 74 MHz VLA, enhancing its scientific value. Used together as a stand-alone low-frequency interferometer, these two stations will explore RFI mitigation strategies together with the broad-band, beam-forming digital technology required to realize future generation low-frequency instruments such as LOFAR. Lastly, two or more prototype stations could engage in a meaningful and unique program of scientific investigations. We describe some of these applications in the next section before presenting our technical plan for achieving the low frequency stations. Some of this technical work is being developed in collaboration with other groups, as noted in Appendix C.

3.1 Benefits to the VLA

In section 4 we describe plans to develop low-frequency dipole-based stations of significantly greater sensitivity than a single VLA antenna - the latter estimated to have ~100 m^2 effective collecting area at 74 MHz. A centrally located station of ~256 dipoles, comparable in physical size to a VLA antenna but operating at much higher efficiency, would have a collecting area ~1000 m^2, increasing the nominal sensitivity of the entire array. While such an improvement would appear modest, it would nonetheless have a significant impact on calibration, as described below. Furthermore, one or more strategically placed outlier stations would complement the improved resolution now afforded by using the Pie Town antenna. One practical difficulty in utilizing such stations to enhance the scientific value of the 74 MHz VLA, however, is that their projected aperture distribution and field of view will vary as a function of elevation. This will complicate integration into 74 MHz VLA operations, particularly at low elevations. However a natural advantage of a digital beam-forming station is that the beam can be shaped to match a VLA primary beam.

To address this challenge, we plan to develop low-frequency stations utilizing compound antenna elements, consisting of 4 or 9 dipole elements each. This would increase the physical size of the station (≤ 100 m), and it would then become feasible to taper their illumination as a function of elevation, in order to simulate the round primary beam of a similar size VLA antenna. This could be accomplished with modest modification of the station complex beam-forming matrix (amplitude and phase). A uniformly filled, round ~ 34 m station could maintain 25 m VLA antenna emulation down to ~ 45° elevation, while a larger station could go lower. When utilized independently of the VLA, increased station collecting area would enhance both stand-alone low frequency technology development and scientific applications.

Below we describe specific benefits of the proposed low frequency stations. We note that in parallel to our hardware development program we will continue to develop improved algorithms for RFI excision, calibration, wide-field imaging, and pipe-line data reduction procedures that can benefit all users of the VLA.

3.1.1 Central Station: Improved Ionospheric Calibration

The development of *field based* calibration was described in the last section. It relies on the ability to detect a grid of background sources, in order to measure the refraction imposed by the ionosphere. A Zernike-polynomial based phase delay screen model is then generated to compensate for ionospheric refraction. The addition of a centrally located station of at least comparable physical size to a VLA antenna would increase the overall collecting area of the array by ≥ 15%. This would improve both the accuracy of field-based calibration and the efficiency of observations, by detecting more sources and allowing for models including higher order terms in the Zernike expansion (B. Cotton, private communication). This is especially important in the A configuration where field based calibration is far less reliable then for B or smaller configuration observations.

For example, in quiet ionospheric conditions, five or more sources of flux ~ 4 Jy are now typically detected in the standard integration time of two minutes normally used for field based calibration. In worse conditions, two or fewer sources are detected, and the data are discarded. An improvement in overall sensitivity of ≥ 15%, allowing detection of 3 or more sources in fields that previously could detect 2 or less, could preserve such data, and also allow the integration times to be reduced, resulting in more accurate modeling of rapidly changing ionospheric refraction. The modest improvement in sensitivity has a significant impact on the number of detectable sources because the sensitivity level of the current system corresponds to a steep part of the 74 MHz log N - log S curve. Under good ionospheric conditions the ability to consistently get 12-15 calibrators would allow fitting of higher order Zernike terms, resulting in lower noise and improved image fidelity. Furthermore, even when images are nominally thermal noise limited, residual seeing errors smear point sources and thereby lower their peak surface brightness, resulting in fewer detected sources. By mitigating these effects a centrally located low frequency station would improve the observational throughput and scientific quality of future 74 MHz VLA observations.

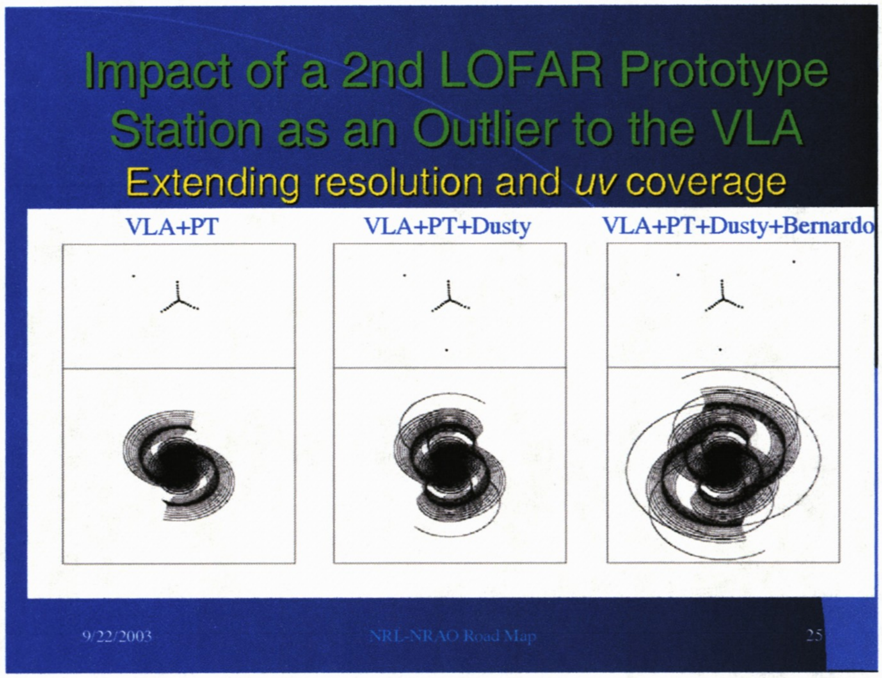

Figure 26: Improved uv coverage provided by one to three prototype station outliers to the VLA.

3.1.2 Outlier Station: Improved High Angular Resolution Imaging

The successful demonstration of 74 and 330 MHz observations with the Pie Town link, as described earlier, has spurred a number of innovative observing projects for the frequency range at the VLA most starved for angular resolution. However, it is clear that further improvements in angular resolution can only be realized by development of additional stations beyond the VLA that could complement and possibly extend the advantage afforded by the Pie Town link. We therefore propose to place at least one additional prototype station as an outlier station for the VLA. Such an outlier could clearly improve the limited *uv* coverage capabilities and angular resolution of the current VLA (Fig. 26). Such an outlier could also coincide with the development of a future EVLA-2 antenna site.

3.2 Benefits Independent of the VLA

3.2.1 Scientific Applications of a Station-based Interferometer

A stand-alone interferometer consisting of two large low-frequency stations would open the door to a number of unique scientific investigations. Beyond its digital sophistication and broad-band capability, an immediate advantage over the current VLA system would be the relatively unconstrained availability of observing time for exclusive low-frequency observations. With a collecting area of ≥ 20 VLA antennas at 74 MHz (and larger at lower frequencies), its raw sensitivity would be comparable to or greater than the 74 MHz VLA, and unlimited observing time would mitigate restrictions imposed by the admittedly limited mapping capabilities reminiscent of early VLBI systems.

Among the viable scientific programs we consider are searches for transient radio sources, extra-solar planets, radio-recombination-line studies, and long-term, broad-band monitoring of solar bursts. By pushing deep integrations to the limits imposed by current technology, these stations will make pioneering inroads into demonstrating the regime of very high dynamic range and sensitivity required to realize major scientific goals in low frequency radio astronomy such as detecting the highly red-shifted signature of neutral hydrogen from the Epoch of Re-Ionization.

Transients

A number of transient phenomena can be explored with two low-frequency stations, including lightning studies, extra-solar planet searches, and detection of cosmic ray air-showers. Serendipitous discoveries, as in the case of the discovery of γ-ray bursts (GRBs), are also possible. We elaborate on two of those applications below.

Air-showers: As ultra-high-energy cosmic rays (UHECRs, $E \geq 5 \times 10^{19}$ eV ~10 J) propagate, they should see a low-energy "bath" of cosmic microwave background photons through the IGM, off which they should scatter and lose energy. This means that we should see few cosmic rays above the Greisen-Zatsepin-Kuzmin (GZK) limit ($E \sim 5 \times 10^{19}$ eV), contrary to what is observed. The current understanding is that the mere existence of these particles requires either as-yet-unidentified accelerator(s) fairly nearby ($\leq$ 50 Mpc) or unknown massive particles whose decay results in UHECRs. Moreover, UHECRs are anticipated to have counterparts in ultra-high-energy neutrinos and extreme-energy γ-ray photons. The number of such particles would be small, so large detector volumes are required in order to detect reasonable numbers. A radio telescope can exploit the atmosphere as a huge particle detector. When UHECRs hit the Earth's atmosphere, they produce extensive air showers (EASs) of secondary particles, propagating relativistically toward the ground in thin "pancakes" of order a hundred meters across, but only a meter or two thick. These showers can develop an excess of electrons (~ 10%), which interact with the Earth's magnetic field to give rise to an intense broadband pulse of highly beamed, coherent emission. These pulses are relatively easy to detect; the first detection was at 44 MHz by Jelley et al. (1965), followed by detections at various frequencies below ~1000 MHz by a number of other groups over roughly the next decade. Difficulties in data capture and processing as well as increasing interference from other users of the radio spectrum discouraged development of this technique. The proposed low frequency dipole stations will be useful instruments for studying UHECR radio pulses, as their planned operating frequency range (~30-90 MHz) covers the range over which radio pulses from cosmic rays have been detected, and they will possess wide-field detection capabilities. Moreover, UHECR radio pulses are sufficiently strong that the signal-to-noise ratio is not an issue. Rather, the challenge is to achieve useful event rates, because such particles are extremely rare, with rates at the GZK limit estimated at 0.4 $km^{-2}yr^{-1}$.

The proposed stations can also contribute to searches for lunar neutrino pulses. The predicted radio spectrum of these pulses scales as ν, but the loss tangent of the lunar regolith should scale as ν^{-1} so that they suffer less absorption at lower frequencies. To first order, the radio emission from lunar neutrino pulses should therefore be frequency independent. Moreover, the field of view of the proposed station is larger than the Moon itself, in contrast to the existing searches which have been able to view only a fraction of the lunar disk (Hankins et al. 1996). By viewing the entire surface of the Moon, the effective detector volume could be as large as 10^{13} m^3, much larger than can be obtained with terrestrial detectors. Results from the proposed station are expected to complement those from optical Cerenkov detectors such as the Southern Auger facility and anticipated space detectors of atmospheric events.

The LOFAR Science Consortium Board was recently tasked by the NSF to provide examples of LOFAR applications that could address questions raised in the Turner report (CPU 2003), and air-shower detection was identified as a key application. Falcke and Gorham (2003) have discussed sensitivities, count rates and possible detection algorithms, and conclude that detection is possible with much less collecting area, such as would be provided by just a few stations of the type proposed in the next section of this proposal. With only one or two stations, one might be limited to detecting particles of energy ~10^{17} eV, but this would be an important path-finding detection to verify the experimental approach that could be conducted with more stations for higher energy particles. The technique could be easily extended to include air shower arrays consisting of particle detectors (KASCADE, Auger), thus providing crucial additional information for obtaining energy and chemical composition of cosmic rays. Such observations would also pave the road for future, much larger instruments such as LOFAR, to extend the cosmic-ray search well beyond an energy of 10^{21} eV if isotropic radio signatures can be found. Other issues that can be addressed are to determine the neutral component of the cosmic-ray spectrum, possibly look for neutron bursts, and do actual cosmic ray astronomy.

Extra-solar planets: The past few years have been an exciting time as extra-solar planets have been demonstrated to be widespread and multiple planetary systems have been found. The current census now numbers more than 100 extra-solar planets, in over 90 planetary systems.

The vast majority of these planets have been detected via the reflex motion of the host star. As the existing census shows, this method has proven to be wildly successful. Nonetheless, the reflex motion of the star is a measure of the planet's gravitational influence and is necessarily an *indirect* detection of the planet. As a consequence, the only property of the planet that one can infer is its mass, and because of the mass function's dependence on the inclination angle (sin *i*), one can infer only a minimum mass. In a few cases planets have been detected transiting their parent star, providing more information.

Farrell et al. (1999) and Zarka et al. (2001) suggest that, by analogy to solar system planets, extra-solar planets may be detected via their natural radio emissions. The Earth and gas giants of our solar system are described commonly as ``magnetic planets" because they contain internal dynamo currents that generate planetary-scale magnetic fields. The dynamo currents themselves arise from the rapid rotation of a conducting fluid. The composition of the fluid varies from planet to planet, being liquid iron in the Earth, probably metallic hydrogen in Jupiter and Saturn, and probably a salty ocean in Uranus and Neptune. In turn, these planetary magnetic fields are immersed in the high-speed electrical plasma emitted by the Sun. Via a coupling between the solar wind and the planetary magnetic field, all of these magnetic planets produce radio emission.

The existence of radio emission from a planetary-scale magnetic field suggests a means for *direct* detection of extra-solar giant planets. Detection of planetary radio emission can yield fundamental information about the planet. First, a measurement of the radio emission is directly indicative of the polar-magnetic-field strength at the planet. For example, the high-frequency cutoff of the Jovian decametric bursts is interpreted as being associated with the Jovian polar-magnetic-field strength, which allowed an early estimate of the strength of the Jovian magnetic field nearly 20 yr prior to the first *in situ* magnetic field observations. In turn, of course, the presence of a magnetic field provides a rough measure of the composition of the planet, insofar as it requires the planet's interior to have a conducting fluid. Combined with an estimate of the planet's mass, one could deduce the composition of the fluid by analogy to the solar-system planets (liquid iron vs. metallic hydrogen vs. salty ocean).

Second, the periodic nature of the radio emission has been used to define precisely the planetary rotation periods of all of the gas giant planets in the solar system. As the magnetic field is presumed tied to the interior of the planet, it provides a more accurate measure of the planet's rotation rate than atmospheric phenomena such as clouds. For instance, the rotation period of Neptune was determined initially by observations of the differentially rotating cloud tops but then was redefined after detection of the Neptunian radio emission (Lecacheux et al. 1993).

Farrell et al. (1999) and Lazio et al. (in preparation) predict the flux-densities expected from the known extra-solar planets, based on scalings developed from the solar system. Presuming that these scalings can be extended to these other planetary systems, the nominal flux densities expected are well below what would be detectable with the VLA, even with the enhanced sensitivity provided by the proposed stations. However, Jupiter produces large, low-duty-cycle bursts. If extra-solar planets also produce radio bursts, they may be detectable. Indeed, the bursts from the planet orbiting Tau Boo may be strong enough to be detected with the current VLA (few hundred mJy).

The low duty cycle, however, means that long integrations are needed, far longer than can be obtained realistically on the VLA. The two-element interferometer consisting of the prototype dipole array stations described in the next section of this proposal could possibly detect, and certainly place strong constraints (at the hundreds of mJy level) on existence of radio bursts from extra-solar planets.

Recombination Lines

Recombination lines of carbon from the poorly understood cold ISM have been studied using low-frequency single-antenna observations (e.g. Erickson et al. 1995). The typical line-to-continuum ratios are $T_L/T_C \sim 3\times10^{-4}$, where T_C is typically ~2000-5000 K at 74 MHz. By simultaneously observing up to 7 lines across 4 MHz of bandwidth in two polarizations, they were able to reduce the time required to detect the lines from ~24 hours to ~1.5 hours when using the Parkes 64-m antenna at 74 MHz. A single prototype station will have comparable (or greater) 74 MHz collecting area, and it will therefore be feasible to detect these lines and to extend measurements to other frequencies. Given the availability of observing time it should be possible to conduct a survey for these lines throughout the region of the inner Galaxy accessible from near the VLA site.

Solar bursts

Initial prototyping of active dipole antennas has already shown how even a single dipole can be useful for broad-band monitoring of solar bursts (Fig. 27). Development is already underway to develop a northern counterpart to the Tasmania-based Bruny Island Radio Spectrometer (BIRS). A so-called "BIRS-north", recently renamed the Goddard Decametric Radio Telescope (GDRT), solar-monitoring system is already being exploited for solar-burst observations in collaboration with NRAO scientists at NRAO-CV and with GSFC, and plans are ongoing to implement an operational system in Green Bank next to the 16 m antenna, the latter to conduct simultaneous measurements at higher frequencies. Together these systems will provide monitoring of solar bursts over the range ~10-5000 MHz. However, while a single element can detect strong bursts, it cannot detect weaker phenomena and, equally important, its lack of angular resolution precludes relating weaker signatures to the sun because they lack the signature of classic solar bursts. The greater sensitivity and angular resolution that would be afforded by an interferometer consisting of two large, dipole antenna array stations, could easily mitigate these limitations.

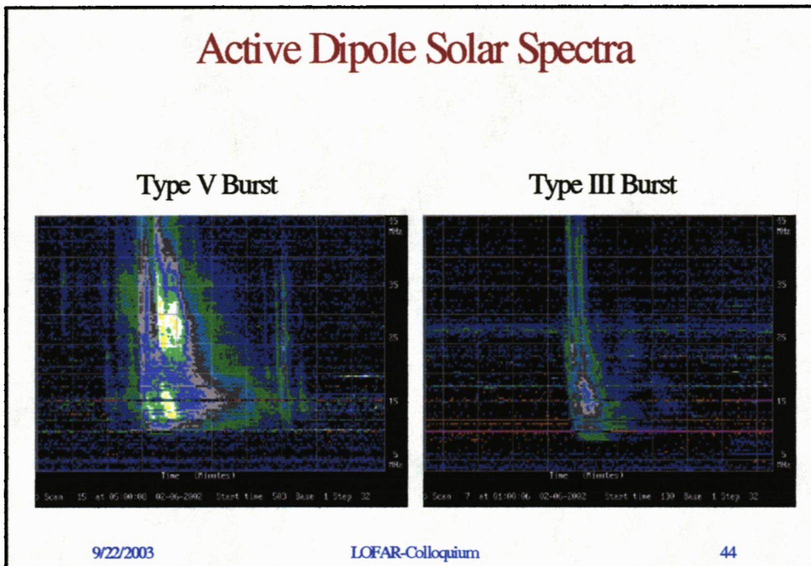

Figure 27: Solar bursts detected by LOFAR prototype antenna.

3.2.2 Benefits for LOFAR Technology

Development of angle-variant self-calibration would be a valuable step towards the type of sophisticated self-calibration algorithms that LOFAR will demand. Moreover, the architecture of a large, centrally located station surrounded by many much smaller stations is analogous to the proposed LOFAR architecture which places ~25% of the collecting area in a large "central core". Thus a centrally located prototype station, used with the VLA, could explore concepts, such as "station-core self-calibration", currently being developed for LOFAR. Utilized in conjunction with the VLA, one or more outlying stations would allow us to extend ionospheric calibration schemes to unprecedented baseline lengths.

The stand-alone two-element interferometer consisting of the two prototype stations is an obvious and sensible prototype of basic LOFAR technology. It could be used to exercise sophisticated digital-signal processing techniques, including RFI mitigation, broad-band beam forming and other proposed LOFAR signal-processing schemes. Individual dipoles within a station could even be cross-correlated, serving as a test-bed for planned cross-correlation of all elements within the central portion of LOFAR.

4. Proposed Technical Program: Prototype Station Development

In Fiscal Year 2003, the Remote Sensing Division of the Naval Research Laboratory initiated an Advanced Research Initiative (ARI) in the amount of $9.3M over five years in Low-Frequency Radio Astronomy under Principal Investigator Dr. Namir E. Kassim. The ARI includes $500,000 each in Fiscal Years 2004 and 2005 for the construction of two prototype low-frequency beam-forming arrays.

Table 1: Technology for next-generation low-frequency radio telescopes
Element designs
High-dynamic-range broadband receivers
Multiple-frequency, multiple-beam digital receivers and beam formers
Delay interpolation filters
Local oscillators and clocks
Broad-bandwidth digital-data transmission
Station configurations
Station calibration
Array calibration
Very large field-of-view mapping
Ionospheric isoplanatic-patch corrections
Monitor and control software
PC-based correlator design
RFI monitoring
RFI mitigation

Conceptually, each array could be a station in a larger, synthesis-imaging array such as the proposed Low Frequency Array (LOFAR), but they are intended, primarily, to enhance the scientific value of the current VLA and to serve as a test-bed for the development and evaluation of technology – hardware and software – for the next generation of low-frequency radio telescopes (Table 1).

4.1 First Prototype Station Plans

4.1.1 Prototype Station Description

The preliminary specifications for the prototype station are summarized in Table 2. As described earlier, the number of dipole elements might be increased 4 or 9 fold, if a suitabe compound antenna architecture is developed. This would enhance the collecting area for stand-alone technology and scientific applications,.and through suitable tapering of their illumination, facilitate emulation of a 25 m VLA antenna when utilized with the current 74 MHz system. The elements will be connected to a central electronics hut by coaxial cables. Inside the hut each signal will be sampled by a high-speed, multiple-bit analog-to-digital converter. A digital filter will tune and select a narrower bandwidth. A digital beam-

Table 2: Characteristics of the Prototype Low-Frequency Stations	
Number of elements	≥ 256
Diameter	≥ 30 m
Polarization	Dual
Frequency range	30-90 MHz
Power	30 kW
Sensitivity	Sky-noise limited

former will combine the base-band, narrow-band signals from all the elements. The combined signal will be available for local processing, as in single-antenna mode, or for transmission over an optical-fiber link to a more central location for technical study of the single station or, on occasion, for combination with some or all VLA antennas.

Detailed design of the prototype stations is not yet available, because final element designs have not yet been completed. Efforts are underway both at the NRL Low Frequency Test Array (NLTA) site at the Goddard Space Flight Center in Maryland and at ASTRON (NL) to develop these elements. Fig. 28 shows one arm of a two-station interferometer set up at the NLTA. Each arm of the interferometer consists of 4 prototype elements designed by Bill Erickson in Tasmania. Fig. 29 shows the first fringes acquired by this system on the radio sources Cyg A and Cas A.

An artist's conception of full-sized prototype station is shown in Figure 30.

4.1.2 The Site of the First Prototype Station

Because the funds are limited to $500,000 per station and constrained in time and because the optimum approach to testing an antenna or station is in a radio interferometer or array, we propose to construct our two low-frequency stations in the vicinity of the Very Large Array (VLA) radio telescope. The first station we propose to build on the central section of the VLA for a number of practical reasons:

Figure 28: Four elements of NRL Low-Frequency Test Array. The other arm of the array is located at a distance of ~200 m southwest.

1. The VLA site includes large flat areas which may require minimal preparation.

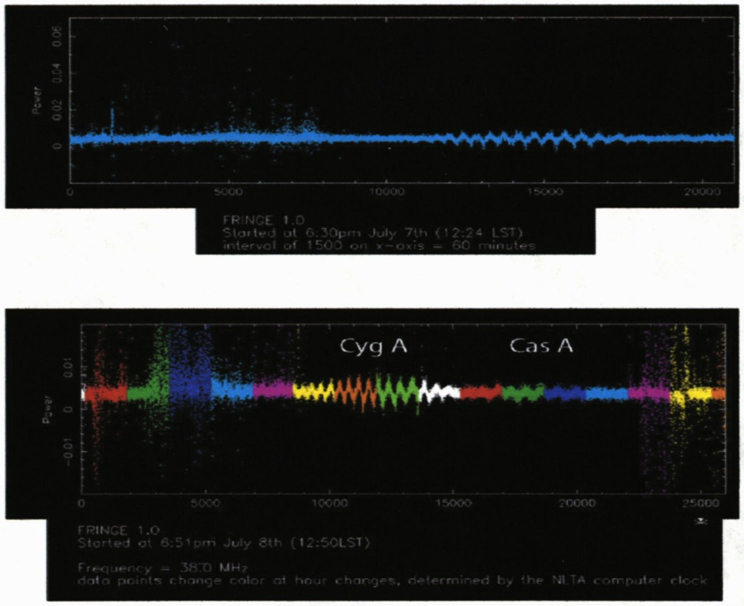

Figure 29: First fringes from the NRL Low-Frequency Test Array – baseline ~ 200 m, ν = 38 MHz.

2. Some areas are distant from highways, roads, power lines, and buildings.
3. Low acquisition and operating costs are desirable.
4. Minimal environmental assessment process is anticipated.
5. The existing electric-power distribution network can be tapped at a VLA station or possibly from a junction box near the Antenna Assembly Building.
6. The new optical-fiber network for the EVLA has spare capacity that can be tapped at a VLA station and used to reach the Central Electronics Room for IFs, Gbit Ethernet, communications, local-oscillator and clock signals.
7. Road access can be obtained by extending an existing road.
8. Access to the base-band IFs from individual VLA antennas is available in the Central Electronics Room.
9. Access to the T4C base-band filter modules and T6C base-band control module for individual VLA antennas is available in the Central Electronics Room.
10. There is room in the Central Electronics Room for a control computer for the prototype station, for a computer-based software correlator, and for interfaces to the base-band IFs and the T4C modules.
11. The Central Electronics Room provides access to the local area network at the VLA and to the Internet.

We have examined the central 1 square mile section of the VLA (Figure 31) for possible sites, roughly divided it into four areas – (1) south of NM 166, (2) east of the ALMA Test Facility (ATF), and (3) east of the north arm and (4) west of the north arm. We rated the first and third areas unsatisfactory; the second, satisfactory; and the fourth, preferred:

1. South of NM 166 (unsatisfactory). This area is rugged, is adjacent to the two 24.9-kV power lines, and is close to VLA facilities.

2. East of the ATF (satisfactory). This area is generally flat but hummocky (~1-2 m), adjacent to the ATF, and close to the two 24.9-kV power lines.
3. East of the north arm (unsatisfactory). This area comprises White Lake on the topographic map and is the lowest area on the VLA site. In fact, a French drain and pumping system drains water from west of the north arm to this area.
4. West of the north arm (preferred). We favor the northwest corner of this area because it is flat (with ~30-cm hummocks, Figure 32, from northwest corner of the sewage ponds), distant from most VLA facilities, uphill from White Lake, and on a level with the sewage ponds. The power and optical-fiber network are located on the west side of the north arm and can be accessed without crossing the railroad track. Road access is available either from the northeast corner of the sewage ponds or from the access road along the west side of the north arm.

The nominal position for the prototype station (34° 04.917' N, 107° 37.683' W) is labeled PS in Figure 31, with dashed lines connecting it to station N7 (~860 m) and to the northeast corner of sewage ponds (~365 m). An "x" marks the location of a possible electrical junction box north of the Antenna Assembly Building near the road to the sewage ponds.

The NRL expects to issue a Request for Proposals (RFP) for construction of the first prototype station on or before 01 February 2004 (see projected schedule in Table 3). The RFP will require that the contractor have minimal impact on the equipment, personnel, and operations of the VLA. Any VLA resources that will be used must be identified, planned, negotiated, and paid in full. [The first three steps should handled by NRL and fixed in the RFP.] Preparation, construction, completion, debugging, and operation of the prototype

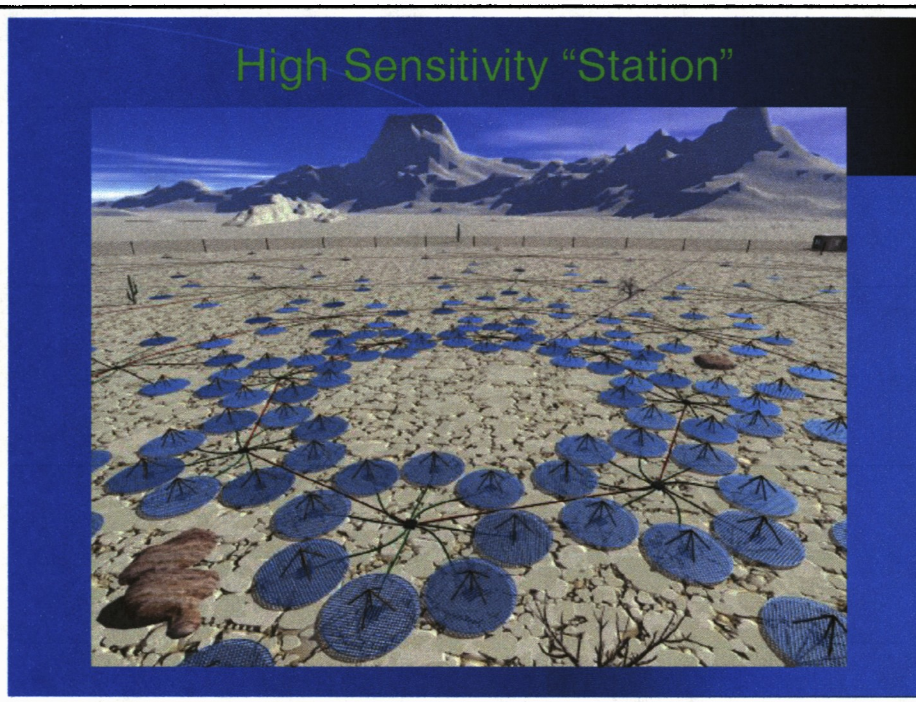

Figure 30: Artist conception of high sensitivity low frequency "station".

Table 3: Schedule for Construction of the First Prototype Station

• 20 October 2003	Submit proposal covering scientific, technical, and logistical parameters of NRL plan
• 01 December 2003	Present draft request for proposals (RFP) for prototype station #1
• 20 December 2003	NRL PoC (PCC) relocates to Socorro
• 01 February 2004	Issue final RFP for prototype station #1
• 01 April 2004	Award contract for construction of prototype station #1
• 01 July 2004	Start construction of prototype station #1

station are totally the responsibility of NRL. Any long-term use of VLA resources (e.g., power) will be negotiated and paid by NRL.

To oversee these tasks and to interface with NRAO on a daily basis, Dr. Patrick C. Crane is being relocated from Washington, D.C. to Socorro, New Mexico.

4.1.3 Site Preparation

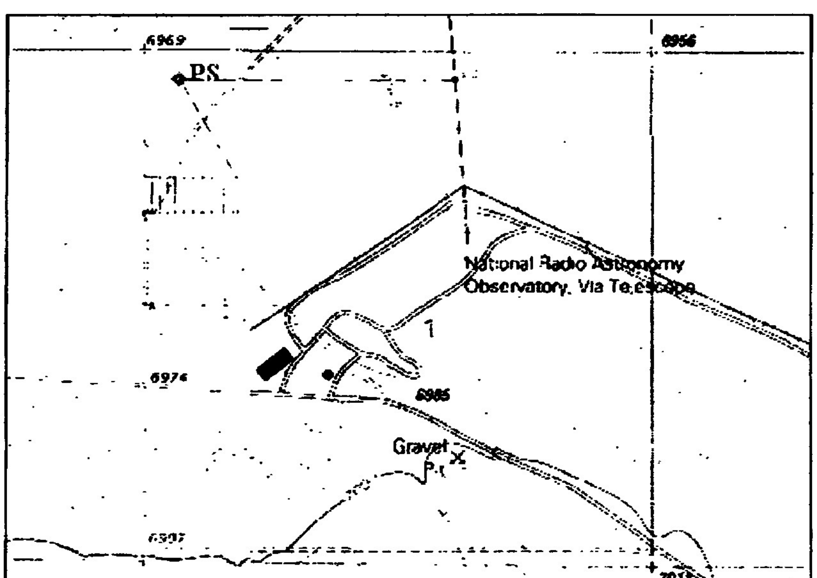

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Figure 31: Schematic of central sector at VLA site.

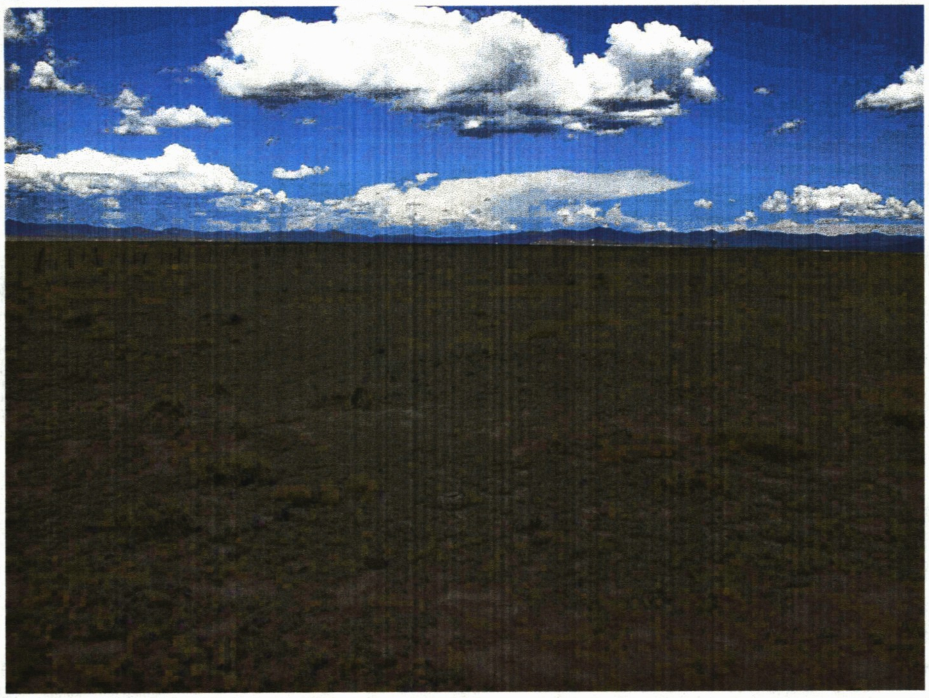

Figure 32: Subsection within central sector of the VLA site –northwest corner of region west of north arm. Preferred location of first prototype station.

The site for the first prototype station will need to be prepared before the actual construction of the station begins. This work will encompass five main steps – building an access road, installing a power line, burying a bundle of optical fibers, fencing the site, and perhaps grading the site.

4.1.4 Facilities

In addition to the site of the prototype station and its connections to roads, power, and optical fiber, NRL also requests space in the Central Electronics Room for operations, laboratory and office space in the Control Building if available, access to the Visiting Science Quarters at the site and Guest House in Socorro, and normal transport in the VLA busses and shuttles. Negotiations for office space in Socorro are under way with New Mexico Tech.

4.1.5 Prototype Station Operations

The availability of an optical-fiber connection between the prototype station and the Central Electronics Room will permit single station tests and scientific observations as well as possible combinations of the prototype station on occasion with individual VLA antennas or with the array as a whole.

4.1.6 Stand-Alone

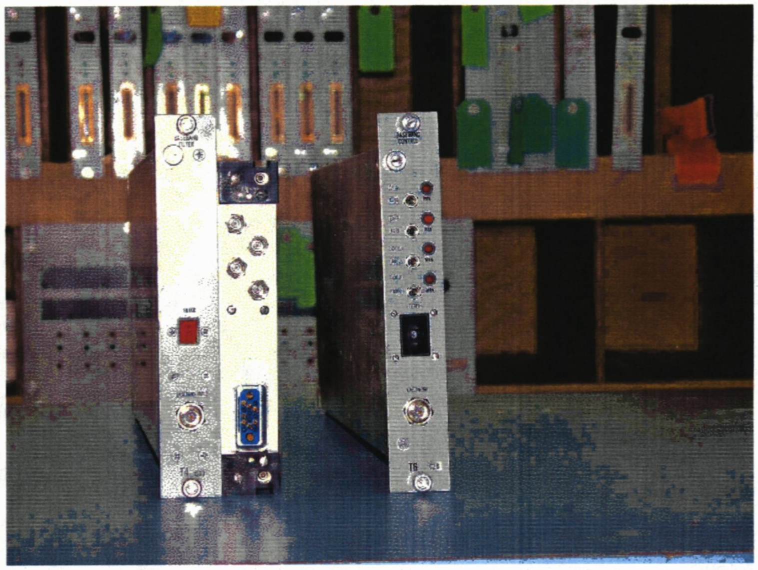

Figure 33: T4C base-band filter and T6C base-band control modules.

The station should be operable from the local station computer. However, since the optical-fiber connection to the Central Electronics Room provides Gbit-Ethernet service and broadband data transmission, the station could be operated from a control computer located there. This arrangement will allow tests of remote operation and data transmission, and will provide a more convenient and comfortable working environment for the operator. The control computer should be able to operate multiple stations, when more are completed.

4.1.7 With Individual VLA antennas

One advantage of being located in the Central Electronics Room is access to the outputs of the T5B base-band driver modules for individual antennas, in the same manner as is done for single-antenna VLBI observations with the VLA. Perhaps the current Analog Sum Patch Panel can be used to provide connections or additional coaxial cables can be run from the front-panel BNC connectors on the T5B modules. The control computer would be supplemented by a pc-based correlator to correlate the VLA baseband signals and the base-band signal from the prototype station. To turn off the phase switching and fringe rotation normally applied to signals from the VLA antennas being used with the prototype station, the VLA antennas would each be assigned to a separate sub-array and operated in single-antenna (VS) VLBI mode. Since the VLA supports as many as five (5) sub-arrays, that would be the limit on the number of VLA antennas that can be utilized for such observations. Access to the 19.2-Hz blanking signal for the waveguide switching cycle is desirable.

4.1.8 As Part of VLA

When fully operational, some tests and astronomical observations at 74 MHz will require that the prototype station be swapped for a VLA antenna. This can be done without any changes to the MODCOMP software by connecting the base-band signals from the prototype station to the J4 connectors for the external filter inputs to the T4C baseband filter modules for the antenna IF being swapped out and selecting those inputs with the manual control on the T6C baseband control module (Figure 33). The corresponding entries in the ANTENNAS, BASELINE, ROT, and IF files may require modification. Access to the 19.2-Hz blanking signal for the waveguide switching cycle is desirable.

4.2 The Second Prototype Station – Considerations

The second prototype station, planned for construction in 2005, is not expected to duplicate the first one; instead its design will be modified based upon the lessons learned from the first one. Also its location will be chosen with a greater emphasis on longer baselines and scientific utility, in particular to provide baselines complementary to the VLA+Pie Town baseline. Primary considerations:

1. Site near a possible EVLA-2 site.
2. Access to optical-fiber network, either existing or installed on appropriate time scale – possibly near Horse Springs or along optical fiber going to Beaverhead.
3. Short optical-fiber connection from fiber network to the VLA and access to Central Electronics Room.
4. Position complementary to Pie Town (Pie Town ring).

The site for the second prototype station will be remote from the VLA. It will be connected to the commercial optical-fiber network, and the connection between that network and the VLA is likely the only part of the site preparation of immediate interest to NRAO. However, if schedule and location permit, coordination with EVLA-2 site development could be mutually beneficial. NRL has secured an additional $500K (FY05) for development of the second prototype station, with construction planned about one year after completion of the first (in CY 2005).

Technology Development Plan

- Fully funded
- Fully coordinated with NRAO through on-site POCs
- Minimum to zero impact on NRAO operations and personnel

Access to the signals from both prototype stations in the Central Electronics Room will provide the opportunity to test frequency flexibility, multi-beaming, multiple frequency channels, and fast switching using a pc-based correlator. Exercising broad-band digital LOFAR technology at frequencies other than 74 MHz is a major goal of the prototype station technology development plan.

4.3 Impact on NRAO

NRL intends to carry out its technical development plan in full coordination and consideration of NRAO's own ongoing operational requirements and future development plans. We appreciate that NRAO is fully engaged in EVLA and ALMA activities at the VLA site, and will endeavor to have a minimal impact upon them. NRL's proposed activities are fully funded; we are fully prepared to compensate the NRAO for any unanticipated costs of our activities. On-site program and technical PoCs will be stationed in Socorro (Dr. Sergio Restaino and Dr. Patrick Crane) to efficiently manage the project and facilitate communications.

Summary of Proposed Scientific and Technical Plan

The current 74 MHz VLA system is the most powerful low-frequency interferometer in the world. We propose a modest program of software and hardware development that will increase its scientific value to a growing user community. These activities will also develop and test the technology for planned low-frequency telescopes such as LOFAR, FASR, and the SKA. We also hope our activities, with their strong emphasis on University involvement, will help re-invigorate the scientific and technical infrastructure for radio astronomy in the US as a whole.

We plan improvements in RFI excision, self-calibration, wide-field-imaging, and pipeline data reduction procedures that can benefit all users of the VLA. We will complete the science rich VLSS all-sky survey, and make it immediately available to the world-wide user community, following in the footsteps of the highly successful NVSS.

We will construct two prototype, high-sensitivity stations to test and develop RFI mitigation and, broad-band, digital-beam-forming technology required by future radio telescopes. The first central low-frequency station will improve calibration of the existing 74 MHz VLA system. At least one outlier station, which could be located at a future EVLA-2 site, will be constructed to improve low-frequency resolution. Acting as a stand-alone interferometer, the two stations will be able to engage in a unique program of scientific investigations, such as detecting the radio signature of high-energy air-showers and searching for extra-solar planets.

Finally, we will continue our current program of targeted observations to more fully exploit the current VLA low frequency systems for cutting edge science. We emphasize collaboration with academic institutions and student involvement. We will also continue to provide support and expertise to outside groups so that they may independently pursue their own scientific programs.

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Appendix A: NRL collaborations utilizing low frequency VLA systems

T. Bastian – NRAO
P. Best – Edinburgh (UK)
K. Blundell – Oxford (UK)
M. Birkinshaw – Bristol (UK)
R. Bradley – NRAO
M. Bremer – Bristol (UK)
W. Brisken – NRAO
W. van Breugel – LLNL
C. Brogan – UHI
C. Carilli – NRAO
T. Clarke – UVA
J. Condon – NRAO
J. Cordes – Cornell
W. Cotton – NRAO
K. Dawson – UC-Berkeley
I. de Pater – UC-Berkeley
G. Dubner – IAFE (AR)
N. Duric – UNM/SWC
K. Dwarakanath – RRI (India)
T. Ensslin – MPIFR (Germany)
W. Erickson – UTAS (Australia)
A. Fabian – Cambridge (UK)
W. Farrell – GSFC
L. Ferreti – CNR (IT)
B. Gaensler – CFA
G. Giovannini – Bologna (IT)
N. Gizani – Lisbon (PO)
W. Goss – NRAO
D. Harris – CFA
J. Hewitt – MIT
S. Hyman – SBC
F. Israel – Leiden (NL)
C. Jackson – CSIRO (AU)
M. Jarvis – Oxford (UK)
D. Jones – JPL
W. Junor – LANL
D. Katz – USNA
H. Krawczynski – WU-St.Louis
P. Kronberg – LANL
M. Lacy – IPAC
A. LaRosa – KSU
R. Liang – Bristol (UK)
C. Lonsdale – MIT
D. Neumann – CEA/Saclay (FR)
F. Owen – NRAO
R. Perley – NRAO
M. Pierre – Saclay (FR)
A. Rao – NCRA (India)
A. Refregier – Saclay (FR)
R. Rengelink – Leiden (NL)
M. Roberts – McMaster (CA)
H. Roetgerring – Leiden
S. Roy – NCRA (India)
L. Rudnick – UMN
A. Schoenmakers – ASTRON (NL)
G. Taylor – NRAO
W. de Vries – LLNL
R. Wilman – Durham (UK)
F. Yusef-Zadeh - NWU
A. Zanichelli – Milano (IT)

Appendix B: Selected Low Frequency VLA Publications

Below is a compendium of refereed journal papers presented in chronological order. Papers are based on 74 MHz VLA data unless otherwise noted – a selected number of 330 MHz papers that benefited from parallel algorithm development are listed as noted.

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