# VLA OBSERVING APPLICATION

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| A |
| rcvd: |

DEADLINES: 1st of Feb., June., Oct. for next configuration following review
INSTRUCTIONS: Each numbered item must have an entry or N/A
E-MAIL TO: propsoc@nrao.edu (different for some Rapid Response Science)
OR MAIL TO: Director NRAO, 520 Edgemont Rd., Charlottesville, VA 22903-2475

**(1)** Date Prepared: June 1, 2005

**(2)** Title of Proposal: Mapping HI Structures Present During the Epoch of Reionization II



| **(3)** AUTHORS (Add * for new location) | INSTITUTION | E-mail | G/U (Students Only) | For Thesis? (Students Only) | Ph.D. Year (Students Only) |
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| | | | | | |



**(4)** Related VLA previous proposal number(s): AG686



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**(7)** Scientific Category: ○ solar system ○ galactic ○ extragalactic ⊗ other: Cosmology

Rapid Response Science: ○ Known Transient ○ Exploratory ○ Target of Opportunity
Joint Proposal: ○ VLA/VLBA ○ VLA/GBT ○ VLA/VLBA/GBT

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|---|---|---|---|---|---|
| **(8)** Configurations (one per column) (A+Pt, A, B, C, D, BnA, CnB, DnC, Any) | D (2007) | | | | |
| **(9)** Wavelength(s) (400, 90, 20, 6, 3.5, 2, 1.3, 0.7 cm) | 160 (new) | | | | |
| **(10)** Time requested (hours) | 750 | | | | |

**(11)** Type of observation: ○ continuum ⊗ spectroscopy ○ multichannel continuum ○ polarimetry ○ solar
(check all that apply) ○ pulsar ○ high-time resolution ○ Pie Town link ○ other:

**(12)** Suitable for dynamic scheduling? ⊗ Suitable ○ Unsuitable


**(13)** ABSTRACT: We propose to search for HI emission from material surrounding the HII regions of quasars during the Epoch of Reionization (EOR) and to measure the power spectrum of HI brightness fluctuations in the surrounding 4° fields. Our goal is to quantify fundamentals, such as the IGM neutral fraction ($x_{HI}$) and quasar ages. Few data exist that constrain models of the EOR. For the three known "EOR quasars" detected by Sloan, the HI line lies at 192-196 MHz. SAO is field-testing VHF receivers on the VLA and will outfit the full array (for our own and for community use) if performance is adequate for EOR science. HI brightness may be a few to a few hundred mK, depending on physical conditions. Time allocated for the 2005 D-array (AG686; $150^h$) will be used to (1) demonstrate noise-limited deep imaging and (2) look for EOR signatures indicating a large $x_{HI}$ at late times and low Ly$\alpha$ background. Though unlikely, this strong signal case is a possibility. We propose $750^h$ in the 2007 D-array so that we may test (more likely) weak signal cases. The 2007 configuration is the last while the targets are up at night and before purpose-built VHF arrays are likely to surpass the VLA for EOR science. Until then, the SAO VHF system will leverage the VLA infrastructure to accomplish pathfinding EOR science at very low cost. The June 1 deadline precedes completion of field-testing; to facilitate proposal review, we will submit monthly updates to NRAO during 2005. If critical performance milestones cannot be met, we will withdraw our proposal.


NRAO use only
(10/04)

**(14)** Observer present for observations? ⊗ Yes ○ No  Data analysis at? ⊗ Home ⊗ AOC or CV (2 weeks notice)

**(15)** Help required: ○ None ⊗ Consultation ○ Friend (extensive help)

| **(16)** Spectroscopy only | line 1 | line 2 | line 3 | line 4 |
|---|---|---|---|---|
| Transition (HI, OH, etc.) | HI | | | |
| Rest Frequency (MHz) | 1420 | | | |
| Velocity (km/s) | $z = 6.2$-$6.4$ | | | |
| Observing frequency (MHz) | 192-196 MHz | | | |
| Correlator mode | 2AD | | | |
| IF bandwidth(s) (MHz) | 6.25 | | | |
| Hanning smoothing (y/n) | y | | | |
| Number of channels per IF | 32 | | | |
| Frequency Resolution (kHz/channel) | 195 | | | |
| Rms noise (mJy/bm, nat. weight., 1 hr) | see text | | | |
| Rms noise (K, nat. weight., 1 hr) | see text | | | |

| **(17)** Number of sources: | **3** |
|---|---|

(If more than 10 please attach list. If more than 30 give only selection criteria and LST range(s).)

| **(18)** NAME | Coordinates 1950 ○ 2000 ⊗ RA hh mm | Dec. ± xx.x° | Conf. | $\lambda$ (cm) | Corr. mode | Band-width per IF (MHz) | Total Flux (Jy)* | LAS | Required rms (mJy/bm) | Required dynamic range | Time request (hr) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SDSS1148+5251 | 11 48 | +52.9 | D | 160 | 2AD | 6.25 | 0.02 K$^{(*)}$ | 20′ | 3 mK | $\sim 10^{3\,(\dagger)}$ | 250 |
| SDSS1048+4637 | 10 48 | +46.6 | D | 160 | 2AD | 6.25 | 0.02 K$^{(*)}$ | 20′ | 3 mK | $\sim 10^{3\,(\dagger)}$ | 250 |
| SDSS1030+0524 | 10 30 | +05.4 | D | 160 | 2AD | 6.25 | 0.02 K$^{(*)}$ | 20′ | 3 mK | $\sim 10^{3\,(\dagger)}$ | 250 |
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*For spectral line, this should be the total flux at the peak of the line

Notes to the table (if any):

$^{(\dagger)}$– DNR required by the presence of foreground continuum emission.

$^{(*)}$– Brightness for a 100% neutral, cold IGM ($T_{spin} \gg T_{CMB}$). Actual brightness is proportional to the neutral fraction and filling factor of cold material. If $T_{spin} < T_{CMB}$, the brightness will be $\sim 0.3$ K.

**(19)** Restrictions to elevation (other than hardware limits) or HA range (give reason):

**(20)** Preferred range of dates for scheduling (give reason):
We must observe at night to avoid solar interference and an active ionosphere.

**(21)** Dates which are not acceptable:

**(22)** Special hardware, software, or operating requirements: We require a 160 cm receiving system. SAO will fund construction if performance goals are met during field-testing. The new system will operate largely as does the 92 cm system (i.e., a dipole feed assembly hung beneath the sub-reflector with signals fed directly to the A-racks of the antennas. Standard AIPS software will be sufficient for most purposes. RFI subtraction will probably require modification of existing TASKS. Polarization beam calibration may be required and would require use of AIPS++. Otherwise, we note that the measures required for calibration of 4m data will probably not be needed.

**(23)** Please attach a self-contained Scientific Justification **not in excess of 1000 words.** (Preprints or reprints will be ignored.)

Please include the full addresses (postal and e-mail) for first-time users or for those that have moved (if not contact author).

When your proposal is scheduled, the contents of the cover sheets become public information (Any supporting pages are for refereeing only).

## 1. Scientific Justification

The structure and evolution of the universe during the Epoch of Reionization (EOR) are essentially unknown. Analyses of Cosmic Microwave Background (CMB) temperature and polarization fluctuations detected with WMAP have been used to infer reionization began between redshifts 11 and 30 (Kogut et al. 2003, ApJS, 148, 161). Study of Ly$\alpha$ absorption in the optical spectra of quasars indicates a rapid change in the HI neutral fraction of the intergalactic medium (IGM) toward the end of the EOR (Fan et al. 2002, ApJ, 123, 1247), with a substantial neutral fraction as late as $z \sim 6.3$ (Mesinger & Haiman 2004, ApJ, 611, L69). On the other hand, surveys of Ly$\alpha$ selected galaxies at $z \sim 6.6$ have been used to argue for earlier completion of reionization (Hu et al. 2002, ApJ, 568, L75; Malhotra & Rhoads, astro-ph/0407408; Stern et al. astro-ph/0407409), although the interpretation of these results is difficult (e.g., Santos 2004, MNRAS, 349, 1137; Haiman 2002, ApJ, 576, L1). Together these results indicate that the history of reionization probably extended over a large redshift interval and was complex, with multiple peaks (Wyithe & Loeb 2004a, Nature, 427, 815, and references therein).

Characterization of how reionization proceeded may be achieved directly through detection and interferometric mapping of the HI heated in advance of the ionization fronts that expand relativistically into the IGM during the EOR. Estimation for any redshift of (1) the shape and size of the bubbles on the sky, (2) velocity structure, and (3) amplitude of the signal would provide critical constraints for theory (Wyithe & Loeb 2004b, ApJ, 610, 117). The amplitude is proportional to the neutral fraction ($x_{HI}$) of the IGM, and the magnitude may be used to estimate whether the IGM is warm ($T_{spin} \gg T_{CMB}$) or cold ($T_{spin} < T_{CMB}$) - Figures 1 and 2. In addition, the sizes and shapes of the regions are governed by the ages of the quasars and the anisotropy of ionizing flux emitted by them. From measurement of size it might be possible to constrain how soon after cosmological recombination the first stars and massive dense objects formed.

*We propose to directly characterize the IGM and many-Mpc-scale ionized bubbles driven by the three quasars (Figure 3) known within the EOR* (Fan et al. 2001, 2003; AJ, 122, 2833; AJ, 125, 1649): SDSS114816.64 +525150.3 (z = 6.43), SDSS104845.05 +463718.3 (z = 6.23), and SDSS103027.10 +052455.0 (z=6.28). Measurements for three widely spaced targets should provide an initial foundation for a general understanding of conditions during the EOR and specific constraint of cosmological theory.

A second means by which to characterize reionization is study of the redshift-dependent power spectra of HI brightness temperature fluctuations driven by evolution of IGM density and ionization (Zaldarriaga et al. 2004, ApJ, 608, 622). In a parallel study, we will attempt to do this for the 4.3° field of view around each target quasar. It is important to realize that the VLA and EVLA will not have the sensitivity to image the fluctuations. But an interferometer is a natural "Fourier filter," and the data can be averaged in the (u,v) plane (i.e., annuli) to obtain a power spectrum of density fluctuations. Adopting reasonable assumptions about symmetry enables a dramatic improvement in detectability of the fluctuations on a given scale, *in a statistical sense.* The situation is analogous to COBE and WMAP studies of fluctuations in the CMB, with COBE determining the statistics of the signal, and WMAP making a real image of the fluctuations (White et al. 1999, ApJ, 514, 12).

For the three targeted "EOR quasars," the HI line is redshifted to frequencies of 192-196 MHz and cannot be mapped sensitively with existing low frequency facilities (i.e., GMRT, Westerbork/LFFE). Innovative new facilities are proposed (i.e., MWA) or under construction (i.e., LOFAR, PAST), but regular scientific observing is probably at least several years away. We have proposed to build and contribute to the VLA/EVLA 28 VHF receiver systems (four of which are now being field-tested) that will enable study in the 190-200 MHz window. This VHF system will be a pathfinder for EOR science and the new facilities. *It will also be a long term addition to the VLA/EVLA, available to the community* once commissioned. We note that we have chosen a fast pace for construction and deployment (Table 1) because we require two D-configurations to complete the project and the targets are up at night only during the 2005 and 2007 compact configurations. Beyond then, the new facilities are anticipated to be online. The 2005 configuration will be used to demonstrate that the system can be used for deep, noise-limited integrations over $\sim 50^h$ and to look for signatures of the EOR at the upper end of what is reasonable to expect for brightness (Wyithe & Loeb 2004a). The second configuration will be used for sensitive testing of the weak signal case, where $T_{spin} \gg T_{CMB}$ and $x_{HI} < 1$.

## 2. Technical Justification

The anticipated diameters of the HI emission regions are 10-20′, which is well matched to the tapered beam of the VLA/EVLA in D-configuration at $\sim 194$ MHz (Figure 4). The angular scales of fluctuations are also well matched to the range of (u,v) spacings for the VLA/EVLA (Figure 5). Due to cosmological expansion, the line profile is on the order of 2 MHz wide. In the event RFI subtraction is necessary (see below), the overall best matched VLA correlator mode that is 6.25 MHz total bandwidth with 0.2 MHz channel width. For a 15% loss to support calibration (e.g., polarization) and $300^h$ total per target ($50^h$ from AG686 and $250^h$ from this proposal), the VLA will achieve $\sim$ 3.1 mK RMS due to thermal noise, assuming detection of two polarizations, system temperature of 160 K (Table 2), 26 antennas, 40% aperture efficiency, 78% correlator efficiency, tapering to achieve a $15'$ beam, and averaging over $\sim$ 1.6 MHz. (In practice, optimal filtering of image data will be used to match the source in frequency and angle, but the listed parameters are reasonable estimates of the results.) To achieve this high sensitivity, we must mitigate the effects of RFI (see below) and eliminate foreground continuum emission from galactic and extragalactic sources. With regard to the latter, first, we will subtract strong point sources identified in a single track with an extended configuration (to be proposed later). Second, we will interpolate in frequency and subtract images made off the HI line from images made on the line, incurring a $\sim$ 20% penalty in the RMS. The diffuse polarized galactic foreground will be removed through calibration of antenna polarization response and construction of LCP and RCP data streams. In the foregoing analysis, we have adopted the published VLA efficiency at 320 MHz until we can complete measurements at 194 MHz. However, we anticipate the 194 MHz system will have similar *or higher* efficiency because it will operate closer to in-focus than the 320 MHz system, $\sim \frac{1}{3}\lambda$ vs $\sim \frac{1}{2}\lambda$ - a difference of $\sim$ 30% in efficiency, which should more than offset at 194 MHz the heightened impact of aperture obstructions. We have also assumed loss of one antenna due to EVLA testing, though loss of three would be acceptable.

Depending on the state of the IGM, the HI signal will be on the order of $23x_{HI}$ mK (warm IGM) or $320x_{HI}$ mK (cold IGM). In an integration of $250^h$ per quasar, it should be possible to achieve a signal-to-noise ratio (SNR) of $\sim 50fx_{HI}$ for a cold IGM, where $f$ is the beam filling factor of cold material (conceivably $\ll 1$ at late times). It is arguable that toward the end of the EOR a (cold) IGM largely devoid of Ly$\alpha$ background is unlikely. However, we note that there are currently no definitive measurements either way and through the proposed observations we would be able to constrain the range of $fx_{HI}$ over more than an order of magnitude. For the weak signal case, a $7\sigma$ detection could be achieved for $x_{HI} = 1$. (Patchiness, $f$, is not a factor here because we presuppose there is no cold HI.) Since the position of the quasar is known *a priori*, even a $3\sigma$ result would be statistically significant, and it would be possible to detect emission for $x_{HI}$ as small as $\sim 0.4$.

In addition, we would attempt to detect HI temperature fluctuations due to the evolution of the IGM density and ionization in the $4.3^\circ$ fields around the targets. Figure 5 shows the predicted angular power spectrum for $z = 7$ due to the evolution of the neutral IGM (Zaldarriaga et al. 2004) and $1\sigma$ error bars for $250^h$ on source in an 0.8 MHz spectral bin. For $x_{HI} = 0.75$, we can obtain a 3 to 5 $\sigma$ detection of the power spectrum of the fluctuations in at least two (u,v) annuli per 0.8 MHz spectral bin (4 correlator channels). There are 32 channels in our desired configuration, and an optimal filtering can be performed to best match the size scale of the fluctuations to their frequency structure.

## 3. General Advantages of a VLA/EVLA System for EOR Studies

The VLA/ELVA is an attractive instrument for pathfinder EOR science and VHF-band interferometry because fortuitously the (u,v) coverage and primary beam are reasonably well matched to what is required, the array provides extant large collecting area and IF/correlator electronics, it is available now, and equipping it is relatively inexpensive.[(1)] It will be competitive with and complementary to other near-term experiments intended to detect HI during the EOR, such as the MWA and PAST. Indeed, one could argue that having two or more complementary experiments is crucial when considering the scientific importance of these programs, and the potential systematic problems that could dominate the errors.

Another advantage in using the VLA/ELVA is operation at the high end of the frequency range for EOR signals. Consequently, problems related to the ionosphere and wide field imaging are mitigated. Experience at the GMRT at 230 MHz shows that the ionosphere is often reasonably well behaved, even on baselines out to 10 km, such that normal phase and amplitude calibration procedures can be employed. In particular, the $\sim 4.3^\circ$ field of the VLA/EVLA is comparable to the isoplanatic patch for ionospheric phase fluctuations, such that existing single-solution self-calibration techniques can be employed. Of course, a disadvantage could be that the neutral fraction toward the end of the EOR ($z \sim 6.2$) may be low ($x_{HI} < 0.1$), but testing this possibility is exactly what drives the proposed program. Indeed, all EOR programs have been or are being designed such that even non-detections lead to ground-breaking, fundamental conclusions concerning the process of cosmic reionization.

Critical aspects of the VHF system relative to the other proposed and in-construction experiments are low cost and short timeline. The low cost is due to the highly leveraged aspect of the program, i.e., we already have telescopes, etc. The time-line has been aggressive for the same reasons, as well as the relative simplicity of the required VHF receivers. LOFAR and the MWA have significantly longer timescales and

[(1)]–The GMRT is another operational facility that could be used for EOR science, but we note that only half of the antennas (14) lie within the $\sim$ 1 km spacing required for $\sim 10'$ resolution, and the distribution is too sparse to support effective tapering of (u,v) data. Sensitivity between the 150 and 230 MHz bands has also not been demonstrated.

much greater complexity. PAST has already fielded a substantial fraction of its intended large collecting area and produced a synthesis image of 6C sources. One important difference between the VLA/EVLA and PAST is that the latter has only one polarization channel. In the context of known polarized galactic foreground emission over scales on the order of 10K and a few to a few tens of arcminutes (M. Haverkorn, Ph.D. Thesis, Leiden), calibration of cross terms in feed response may be a critical requirement. On the other hand, the peak sensitivities of the two instruments to brightness fluctuations on different angular scales are complementary because the VLA/EVLA is centrally condensed (good for scales of $\theta = 0.1^\circ$ to $0.3^\circ$) while PAST has uniform (u,v) coverage distributed over 3-10 times the range of baseline.

**4. What We Have Done So Far**

*We obtained the first ever VHF-band (195 MHz) synthesis image (3C147) on 2005 May 20 (Figure 6).*

Table 1 summarizes other milestones for the project. Following successful peer review, an initial $150^h$ has been approved for late 2005/early 2006 (AG686) contingent on our meeting performance goals. The $150^h$ is intended (1) to demonstrate noise-limited imaging over tens of hours, (2) to enable detection of EOR structures in the strong signal case, and perhaps (3) to identify any problems with particular fields that would hinder deeper integrations (e.g., anomalous foreground emission). The present proposal to enable these deep integrations is the next step.

If field-testing demonstrates that the VHF system meets performance requirements dictated by the EOR science program (and NRAO), then deployment beyond the initial four prototype receivers will begin in summer 2005 (Table 2). Experience has shown that two receivers can be deployed per week and entire array outfitted in about 4 months, contingent on availability of manpower (antenna techs) at the VLA site.

Unfortunately, the June 1 large proposal deadline precedes completion of field testing and commencement of AG686, which complicates peer review. To help address this, we will submit monthly updates regarding system performance and initial synthesis results to NRAO throughout 2005. Documents submitted (to NRAO) for project reviews and resulting panel reports will also be available. The information will be compiled at http://www.cfa.harvard.edu/dawn. However, we emphasize that declared performance milestones for this project are taken seriously, and if we find that they cannot be met and investigation of the EOR with the VLA/ELVA turns out to be impractical, we will withdraw this proposal.

**5. RFI**

The proposed observing band covers TV channels 9-11, making RFI mitigation a significant challenge. Initial site surveys obtained with NRAO monitors underestimated the problem. Figure 7 presents a sample *total power*, high-sensitivity sweep obtained using the VLA correlator, in which the RFI comprises narrow audio and video carrier lines (one each for each 6 MHz analog station allocation). Additional lines may arise from the broadband modulated power associated with each channel or RFI generated at the site. Digital television (not shown in the figure) displays uniform power across each channel allocation without carriers.

Ultimately, the RFI of significance is that which correlates among antennas. Figure 8 shows a much reduced density of RFI lines observed in cross power for a strong astronomical source. Characterization for weaker sources has only just begun and will be a key subject of our monthly program updates. We propose to combine different techniques in managing RFI. First, we will coordinate with broadcasters to the extent possible. This is the best strategy. We successfully arranged for KNMD-TV (channel 9, digital, controlled by the University of New Mexico) to turn off after midnight for one night as a test. (That test is the subject of Figure 7. Were KNMD present, it would disrupt the 186-192 MHz interval). KNMD is open to further discussion. We have identified the Socorro channel 10 translator as another source is interference and opened discussions as well.

Second, we will employ receiver front-end notch filters to remove video and audio carriers because tests have shown these will correlate well across the D-configuration. The response of inexpensive crystal filters we have modeled will provide -20 to -30 dB attenuation at line center (which is sufficient), and a width that is well matched to the width of a correlator channel.

Third, we will use post-correlation RFI subtraction techniques. The way in which this may be done, given the low time (10s) and frequency resolution 200 kHz) of the correlator, is being developed conceptually, and will be applied to test data obtained during summer 2005, by which time a significant number of receivers will have been deployed. In principle, cross correlations to a reference antenna on each arm that is pointed off source may be used to construct a template to be applied, using closure, to cross correlations for the other antennas that are on source. Other possible techniques include nodding to obtain differential maps of the sky free of RFI contamination, though success in this case will depend on the phase and amplitude stability of the RFI.

Table 1: Milestones

| | |
|---|---|
| 04 Oct 01 | Proposal for $150^h$ demonstration and first science in Q4:2005 (approved contingent on performance) |
| 05 Jan 06 | Technical & Management Plan submitted |
| 05 Jan 28 | NRAO design review (passed) |
| 05 Mar 09 | Receiver 1 mounted on antenna 6; first light |
| 05 Mar 16 | Receiver 2 mounted on antenna 17; first fringes |
| 05 May 11 | Receivers 3 & 4 on antennas 8 & 26 |
| 05 May 20 | First synthesis image |
| 05 Jun 01 | Large proposal for full science program for Q1:2007 |
| 05 Jul – | Second NRAO review (pre-deployment) |
| 05 Nov – | Final NRAO review |
| 05Dec/06Jan | First science tracks ($150^h$) |
| 07Feb/07Apr | Proposed second science tracks |

Table 2: Current Performance

| | Target | Achieved$^{(+)}$ |
|---|---|---|
| 195 MHz | | |
| $T_{sys}$(night) | 160 – 200 K | 160 K$^{(*)}$ |
| $A_e$ | $\sim 0.4$ | 0.1-0.2$^{(\dagger)}$ |
| FOV | $\sim 4°$ | 4.3° |
| Polz. Leakage | a few % | TBD |
| Leakage stability | $\sim$ 1 wk | TBD |
| L-band Impact | | |
| $\delta T_{sys}$ | < 1 K | < 1 K (at zenith) |
| $\delta$SEFD$^{(\ddagger)}$ | < 1% | < 1% (at zenith) |
| P-band Impact | | |
| $\delta$SEFD$^{(\ddagger)}$ | < 10% | TBD |

$^{(+)}$ Upfront critical performance requirements are (1) low $T_{sys}$, (2) efficiency equal to or in excess of the P-band efficiency, and (3) *no harm done to other users' science (e.g., at L and P-band).*

$^{(*)}$ $T_{sys}$ for $17^h$ and $+33°$.

$^{(\dagger)}$ Daytime measurement. Solar interference may have been significant. Preliminary estimate of nighttime efficiency is several times larger. Testing continues.

$^{(\ddagger)}$ System equivalent flux density.

**6. Data Processing and Rights**

We anticipate standard AIPS software will be sufficient for most purposes. As noted above, the $\sim 4.3°$ field of the VLA/EVLA is comparable to the isoplanatic patch for ionospheric phase fluctuations, such that existing single-solution self-calibration techniques can be employed. (The innovative techniques developed for calibration of 4-band data will not be required.) On the other hand, the polarization response of the dipole feeds and 25-m antenna may be complex, especially because the sidelobe response is high and the source density on the sky is high. If polarization beam calibration is required, we would probably use AIPS++ for some or all of the calibration. Pipeline RFI subtraction will be another challenge, though it is conceptually simple. It should be possible to obtain the necessary function using modified AIPS TASKS, though here too, AIPS++ may be required. Consultation with LOFAR software developers will be a priority when the time comes.

Because the processing of the proposed VHF datasets will be complicated and may require use of custom software, we intend to make public calibrated data as a supplement to the raw data available from NRAO. We request an 18 month proprietary interval because development of the necessary tools will involve some degree of trial and error. If this extended period is not acceptable, then we request 12 months from the last track.

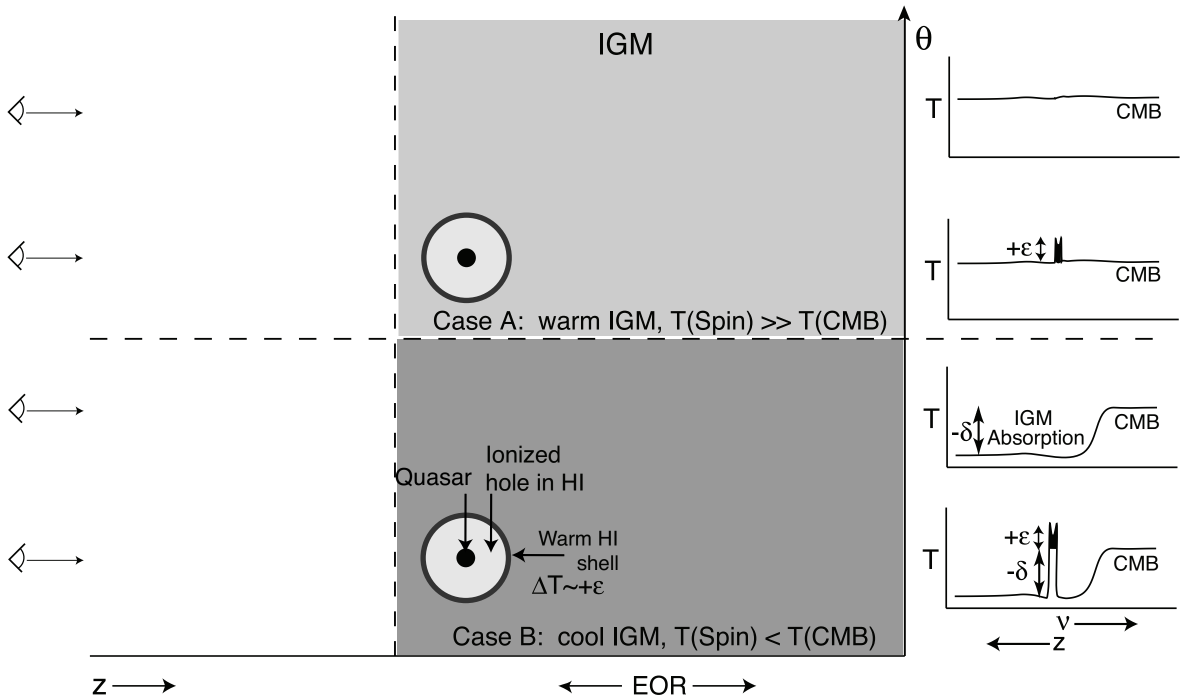


Figure 1: HI emission signature of the ionized region around a quasar prior to cosmological reionization. *(bottom)*– Ly$\alpha$ background in the IGM elevates the spin temperature of Hydrogen. If the IGM is largely opaque, then the background is low, and the IGM is cold. In this case $T_{spin} < T_{CMB}$, and HI absorption depresses the CMB (by $\delta$) for frequencies that correspond to $z > 6.2$. However, along lines of sight where a quasar has ionized the HI, the CMB will be unabsorbed. On top of this, there will be emission ($\epsilon$) from a shell of hydrogen surrounding the ionized region and heated by X-rays. The total signal is visible to an interferometer ($\delta + \epsilon$). *(top)*– If $T_{spin} \gg T_{CMB}$, then there is no absorption and only emission from the warm hydrogen is detectable ($\epsilon$).

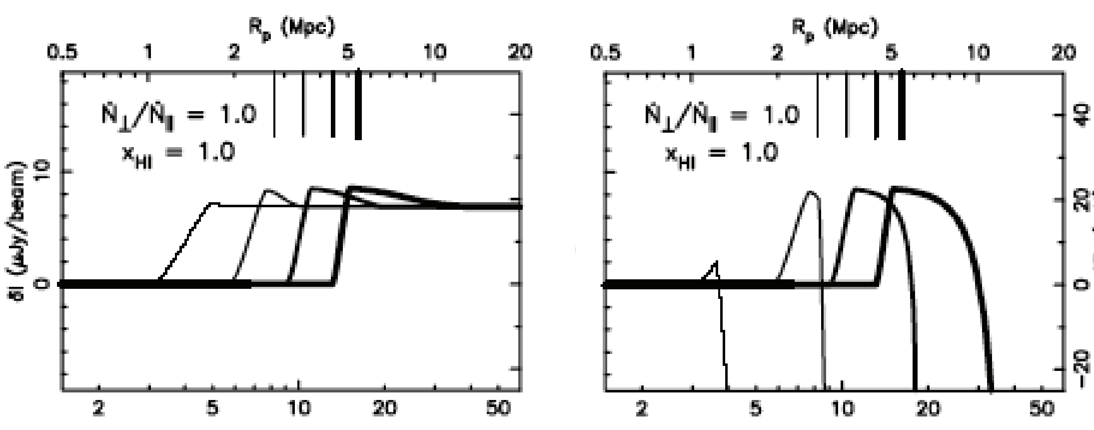


Figure 2: Radius of an ionized region in the sky plane and HI line strength, for isotropic quasar emission ($z = 6.5$, $N = 10^{57}$ Ly$\alpha\, s^{-1}$) and a uniform neutral IGM. *(left)*– Warm IGM. *(right)*– Cold IGM, where absorption of the CMB creates a local $\sim$ 320 mK contrast that is detectable by an interferometer. The traces are for quasar ages of (0.5 - 4)$\times 10^7$ yr. The bottom axis is angle on the sky ($'$). From Wyithe & Loeb 2004b.

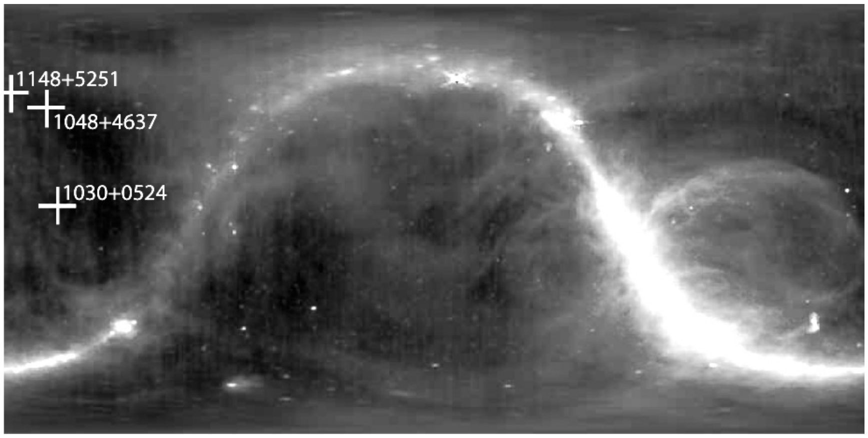


Figure 3: All-sky map at 408 MHz (Haslam et al. 1982, A&A, 47, 1; shading by D. Emerson). The proposed targets lie in regions with among the lowest levels of galactic background emission, 14-16K. All lie well away from the galactic plane ($b > 50°$). For 194 MHz, the anticipated sky temperature is $\sim$ 100 K based on global measurements (D. Emerson, www.tuc.nrao.edu/~demerson/radiosky/rsky_p3.htm; Kraus 1986, Fig. 8-6) or scaling of the Haslam results with frequency ($T_{sky} \propto \nu^{-2.7}$).

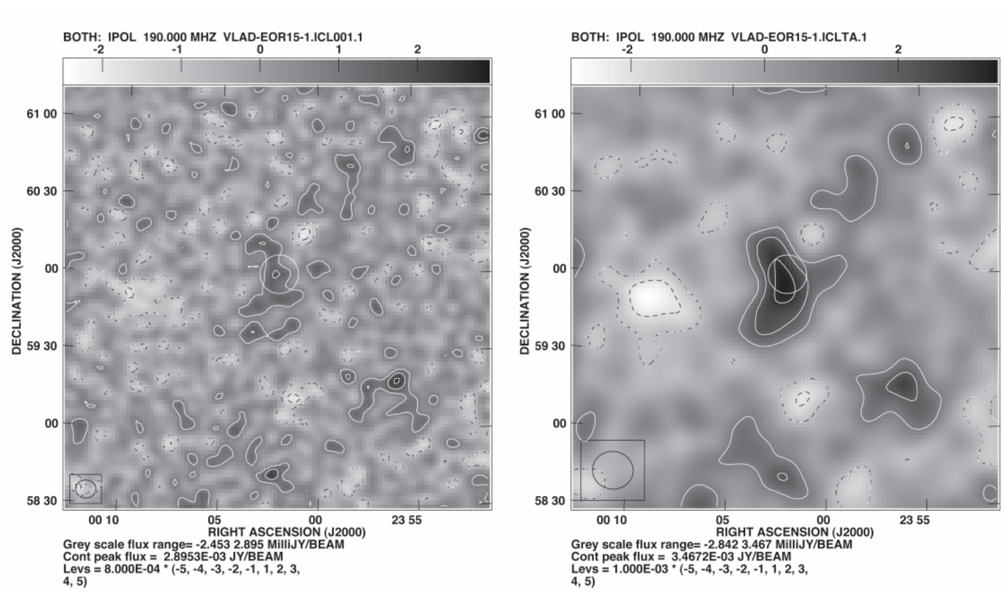


Figure 4: Simulation of VLA/EVLA observations of the HI signal from an HI shell around a quasar at $z = 6.2$, assuming 250 hrs on source and a 0.8 MHz spectral bin. *(left)* A naturally weighted image ($7\farcm5$ resolution, 0.09 mJy rms). *(right)* A tapered image ($15'$ resolution, 0.12 mJy rms). The circle shows the size of the HI shell. The contour levels are linear, starting at 0.18 mJy beam$^{-1}$ *(left)* and 0.22 mJy beam$^{-1}$ *(right)*.

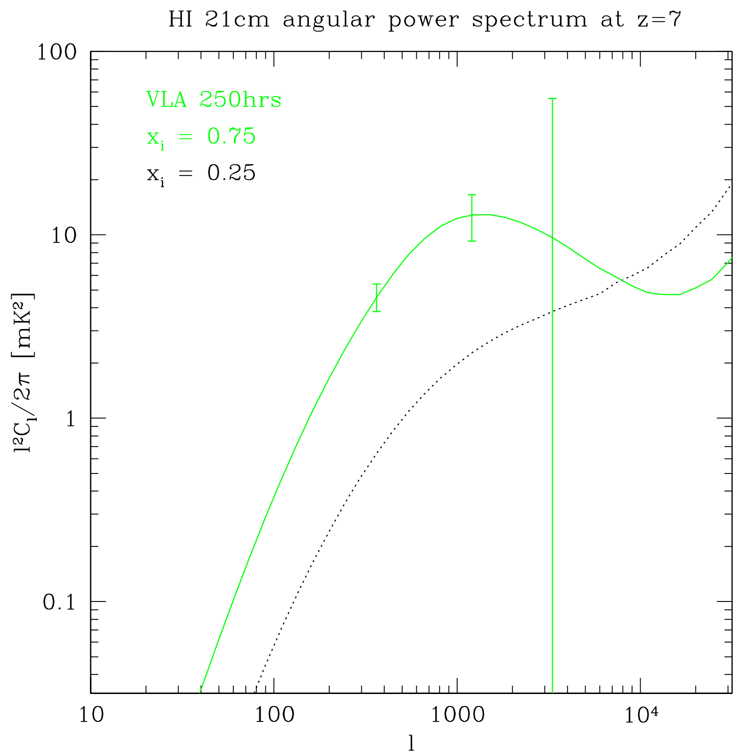


Figure 5: The predicted angular power spectrum of HI brightness fluctuations for $z = 7$, due to the evolution of the neutral IGM (Zaldarriaga et al. 2004). Results for the high redshift end of our observing band ($z = 6.2 - 6.5$) are similar. Angular scale of 0.2° corresponds to an inverse scale of $l \sim 1000$. Error bars represent the VLA/EVLA $1\sigma$ errors after $250^h$ on source. For an ionization fraction of 0.75 (solid line), we obtain a 3 to 5 $\sigma$ detection of the power spectrum in at least two (u,v) annuli per 0.8 MHz spectral bin (4 correlator channels). An ionization fraction of 0.25 is also shown (dotted line). There are 32 channels in our desired configuration, and an optimal filtering can be performed to best match the size scale of the fluctuations to their frequency structure.

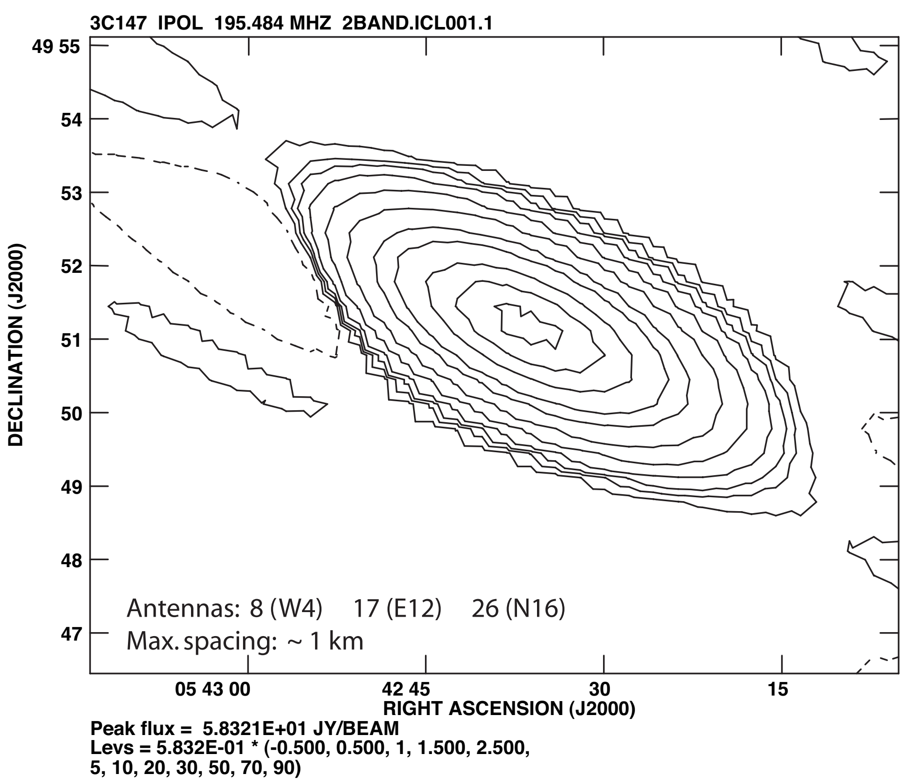


Figure 6: *The first synthesis map ever made with the VLA at 195 MHz.* The data were self-calibrated, and the source model was a point-like. The total integration with 3 antennas is 8 minutes.

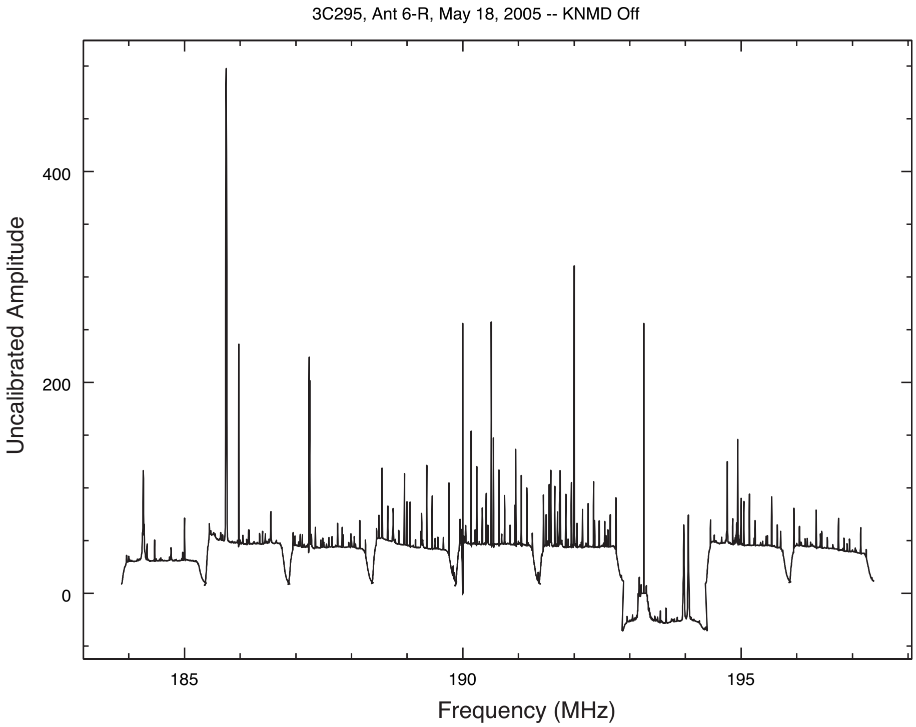


Figure 7: Sample RFI sweep from 184 to 197 MHz in total power, obtained with the VLA correlator (1.5 MHz IF and 6 kHz channel spacing, after Hanning smoothing). The density of RFI is daunting, *but few appear in cross power,* where the density is on the order of one per 1.5 MHz. Baseline levels differ from IF to IF because no amplitude calibration has been applied. All RFI enters through the feed. The lines that appear in cross power are typically TV audio and video carriers (two per 6 MHz channel). Because these interfere with the VLA auto gain control systems, our production receivers will use notch filters (20-30 dB attenuation over 100-200 kHz) as part of our layered RFI mitigation strategy.

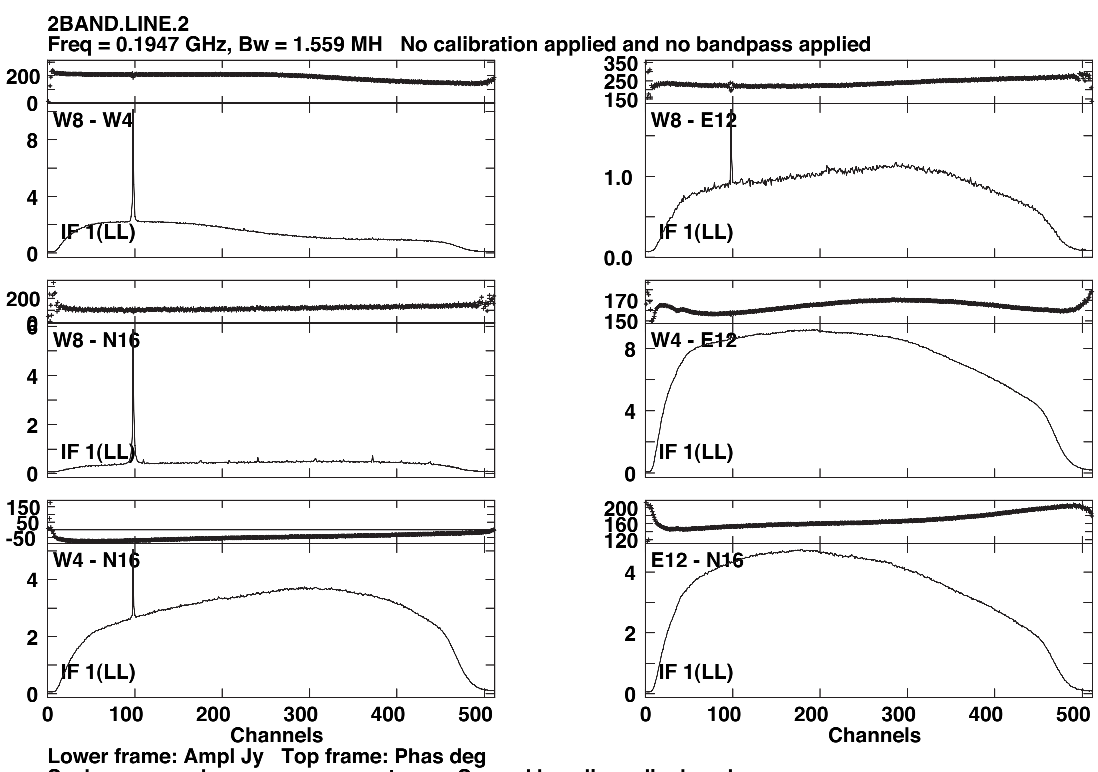


Figure 8: Fringes on 3C461 over 30 seconds (scalar average), obtained with antennas 6 (W8), 17 (E12), 8 (W4), and 26 (N16). The cross power spectra show one RFI line and a well behaved bandpass. No calibration has been applied.