DEUTERIUM ARRAY MEMO #001

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To: Deuterium Array Group

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Subject: Development of digital receiver technology and the construction of a 327 MHz array optimized for the detection of the hyperfine deuterium line.

Project Summary

Digital receivers achieve an extremely high level of bandpass stability and dynamic range compared with the traditional analog filtering used in most current radio astronomy instrumentation. A digital receiver whose algorithms are in software is well suited to the interference rejection and beam forming required for future arrays like the Square Kilometer Array (SKA) and the Low Frequency Array (LOFAR). We propose to develop a digital receiver for radio astronomy arrays. This represents a new approach to receiver design made possible by the current availability of inexpensive components, and allows much improved spectral stability and interference rejection. In addition, using the digital receiver, we propose to construct an array of antennas optimized for the detection of the 327 MHz deuterium line, the development of new signal processing algorithms, and the mapping of hydrogen and carbon recombination lines in the 322 to 328.6 MHz radio astronomy band. The array will have more than a factor of 5 better sensitivity for the detection of deuterium than the single dishes and arrays used in previous observations. This system can also be used as a test bed for array concepts and algorithms, and as an opportunity for training students in instrumentation development. We propose a 3-year program in which we develop the digital receiver in the first year, construct the array in the second year and start scientific programs at the beginning of the third year. Algorithms and software development will be ongoing for the 3-year program.

PROJECT DESCRIPTION

A. RESEARCH ACTIVITIES

A.1. Introduction

Haystack Observatory developed a digital receiver for the radiolocation of emergency calls from digital (CDMA) cellular phones. The receiver employs digital baseband conversion, FIR filtering and FX correlation for the measurement of time difference of arrival. The processing power needed has only recently become available at reasonable cost with the advent of the GrayChip digital receiver and the Texas Instruments C60 DSP. The advantages of digital processing are

1. High dynamic range ≈ 90 dB
2. High bandpass stability
3. Excellent out of band rejection
4. Software implementation of special algorithms

These advantages offer improvements in spectral line performance, electronic beam steering, simultaneous processing of multiple primary beams and interference rejection for radio astronomical and other applications. We propose to demonstrate these improvements by building an array at the Haystack Observatory for the following science projects:

a) A more sensitive search for the 327 MHz hyperfine line of deuterium than previous attempts. Detection will place better limits on the baryon density without the potential confusion with hydrogen that exists in the UV/optical Lyman series lines, for which the hydrogen and deuterium spectral features differ by only 0.03 percent in wavelength.
b) High sensitivity imaging of the hydrogen and carbon recombination lines (H271α, H272α, C271α, C272α) in the 322 to 328.6 MHz radio astronomy band.
c) Searches for other spectral lines like the recombination lines of other elements.

In addition the array will provide a test bed for technical developments of large arrays at low frequency, which can benefit the Low Frequency Array (LOFAR) and Square-Kilometer Array (SKA), such as mitigation of radio frequency interference, digital receivers, and wideband communication systems, as well as serve as a training opportunity for students in instrumentation.

A.2. Science goals

Starting in the late 1950s and early 1960s the detection of deuterium in the interstellar gas has been considered one of the most important efforts in radio astronomy. Its measurement constrains the photon to baryon ratio, and hence the cosmological baryon density. This measurement, combined with dynamical measurements in clusters and other estimates of the overall mass density, provide a gauge of the amount of non-baryonic dark matter in the universe. Furthermore, the degree to which deuterium is depleted in the interstellar medium of our Galaxy and other galaxies provide a tracer of stellar activity. As discussed below, the small isotope shift in the optical lines make the deuterium measurement extremely difficult and subject to systematic error at optical wavelengths. Recent estimates of the primordial deuterium-to-hydrogen ratio have differed by more than an order of magnitude. In contrast, at radio wavelengths the hyperfine lines of deuterium and hydrogen are separated by more than a factor of three in wavelength. Detection of the deuterium line at radio wavelengths would introduce a new tool, sharper than our existing tools, for studying deuterium abundances.

The primordial abundance of deuterium is determined by the competition between the nuclear reaction rates and the universal expansion rate. Deuterium is thought to be created by cosmological nucleosynthesis, but then is destroyed (astrated) by stellar nucleosynthesis (Epstein, Lattimer & Schramm 1976, Nature, 263, 198.) Measurement of the present D abundance is therefore a critical diagnostic of stellar and chemical evolution in the Galaxy, as well as an essential prelude to determining the primordial cosmic abundance. At present D/H ratios have been derived for cosmologically distant sources (quasars) and for local (< 500 pc) stellar Milky Way sources. The 327 MHz transition of deuterium offers the potential of measuring the ISM D/H abundance ratios for sources anywhere in the Galaxy. A deuterium abundance measurement good to a few tens of percent accuracy leads to very interesting constraints on stellar processing and chemical evolution models. With the instrument proposed here we should be able to achieve this level of accuracy, which will constitute an important step towards a full understanding of primordial deuterium abundances.

Several groups have tried to detect the deuterium hyperfine line including Sander Weinreb whose thesis experiments (Weinreb, 1962) set an upper limit for $N_D/N_H = 8\times10^{-5}$. More recent limits by Anantharamaiah and Radhakrishnan (1979), Chengalur et al (1997), Heiles et al (1993) and Blitz and Heiles (1987) are comparable or slightly better. UV/Optical measurements give $N_D/N_H \approx 2\times10^{-5}$ in the spectra of quasars and stars (Dupree et al, 1977), however these measurements are subject to confusion with hydrogen at a different redshift (Lemoine et al, 1999). Figure 1 shows the dependence of the baryon to photon ratio created in the Big Bang from the theory of nucleosynthesis (Walker et al, 1991) on the deuterium abundance. While most of the UV/optical measurements are consistent with the radio limit of S. Weinreb, some of the measurements of large deuterium abundance in the absorption spectra of quasars (Rugers and Hogan, 1996) are now thought (Burles et al, 1999) to be the result of the confusion with the strong hydrogen absorption which is very difficult to separate from any weak deuterium absorption. There are also UV/optical measurements of N_D/N_H as low as 7×10^{-6} (Jenkins et al, 1999). Modest destruction of deuterium through reprocessing (Tosi et al, 1998) may explain some of the variation. The current status of deuterium abundance is reviewed by Lemoine et al (1999).

Additional data from the radio spectrum could make an important contribution to a better understanding of deuterium abundance variations due to the destruction of deuterium by reprocessing or apparent enhancement in interstellar clouds where much of the hydrogen is molecular. To reliably detect the 327 MHz line for $N_D/N_H = 2\times10^{-5}$ we need to improve the sensitivity, over that achieved by Weinreb, by a substantial factor. Sensitivity can be improved by the following factors:

a) 12-bit/sample avoids 1-bit clipping correction to gain 1.6
b) No need for comparison switching gains a factor of 2
c) Use of the array of 64 stations each with both polarizations gains a factor of $\sqrt{128} \approx 11$

The largest sensitivity improvement, which comes from the averaging of the spectra from the array stations, is valid for the detection of interstellar lines if absorption or emission is sufficiently extended so that the signals received at each station are uncorrelated. For the search of the deuterium line we propose to make the station sub-arrays large enough to ensure that the deuterium line should appear in absorption against the Galactic synchrotron emission in the central part of the Galaxy. The Galactic center continuum should be about 500 K with a 25 element sub-array with 23 dB gain, 12 degree beamwidth and 12 m^2 effective aperture. If the sub-arrays are separated by about 15 m (4 degrees fringe spacing) the continuum emission which is extended will be largely resolved thereby decorrelating the signals. While the deuterium line is expected in absorption against a background brightness temperature greater than the excitation temperature, the hydrogen and carbon recombination lines, which have been previously observed, (for example see Roshi and Anantharamaiah, 1997) are seen in emission. We will also look for deuterium emission in the region of the Galactic anticenter. In this direction the non thermal background is only about 70 K and if the deuterium excitation temperature is about 130 K the line should appear in emission. Since the emission in this region should be diffuse the array has a large advantage over previous experiments, which used a single dish. While previous observations of the Galactic anticenter by Chengular et al. (1997) and Blitz and Heiles (1987) show a possible detection at 0 km/s of about 2-3 mK, the proposed array should reach 1 sigma noise of about 100 μK in 200 hours at a resolution of 10 km/s.

In addition we can simultaneously process spectra from different primary beams at each station, which would allow simultaneous mapping of any deuterium line with the 12 degree resolution of each station. This multibeaming capability multiplies the effective integration time, and for the purposes of measuring spectra in many different directions, constitutes a major additional sensitivity improvement over existing instruments and studies.

Chengular et al used the 14 separate antennas of the Westerbork array to improve sensitivity. The 64 station array we propose will be a factor of 5 more sensitive than the Westerbork array for the same amount of observing time. In addition we expect to dedicate most of the observing time to measurement of the deuterium line, with corresponding sensitivity gains over the time constrained Westerbork experiments.

In order to study the effects of the reprocessing of deuterium we propose to observe the deuterium line in at least two directions: towards the Galactic center and towards the anticenter. However, since this will be a dedicated instrument, and in contrast to any existing instrument, sufficient observing time will be available to observe at a variety of Galactic longitudes. This capability is powerfully leveraged by the multibeaming capacity of the dipole array design, mentioned above. Velocity crowding in the Galaxy occurs in several different directions, offering the opportunity to probe D/H over the entire Galactic disk. Such measurements can provide a powerful and detailed constraint on models of stellar processing, which predict a deuterium abundance gradient, with the lowest abundances occurring in the highly processed inner galaxy.

Recently Lubowich et al. (2000) have detected 2 millimeter wave transitions of DCN in emission in a molecular cloud near the Galactic center. Their result suggests that the higher than expected D/H ratio is the result of a recent infall of unprocessed gas. Our proposed absorption measurement towards the Galactic center will be able to map the D/H along the line of sight through the many regions which have different velocities, providing complementary information with which to help trace the processes affecting abundances in the region.

It is realized that the conversion of these measurements to a D/H ratio is difficult due to the lack of the precise knowledge of the optical depths and the excitation temperature of H in the gas clouds along the line of sight. The difficulty of making accurate isotopic abundance measurements has long been recognized (Wilson and Rood (1994); and Rogers and Barrett, (1966). However, systematic errors exist in every method of determining the isotopic abundance ratios so that it is important to make and compare measurements using different techniques.

With a change in the elevation of the stations we can also look for deuterium in absorption in Cassiopeia A. In this case we would need to combine adjacent stations to achieve sufficient collecting area to reach the point at which the Cas A signal dominates. Since Cas A is relatively compact we would not gain the advantage of many independent spectra, so that the sensitivity would not be significantly better than that obtained by Carl Heiles et al (1993) who accumulated very long integrations during which some narrow features were seen and then not confirmed. However, the use of digital receivers and the ability to simultaneously gather data from multiple primary beams combined with interference rejection should lead to smaller systematic errors, and the prospect of performing very long integrations without being limited by systematics. The success of such measurements would represent a strong incentive to develop 327 MHz capabilities in arrays of the future (as, perhaps, in LOFAR) and these arrays would have sufficient sensitivity and resolution to probe lines of sight toward many extragalactic sources.

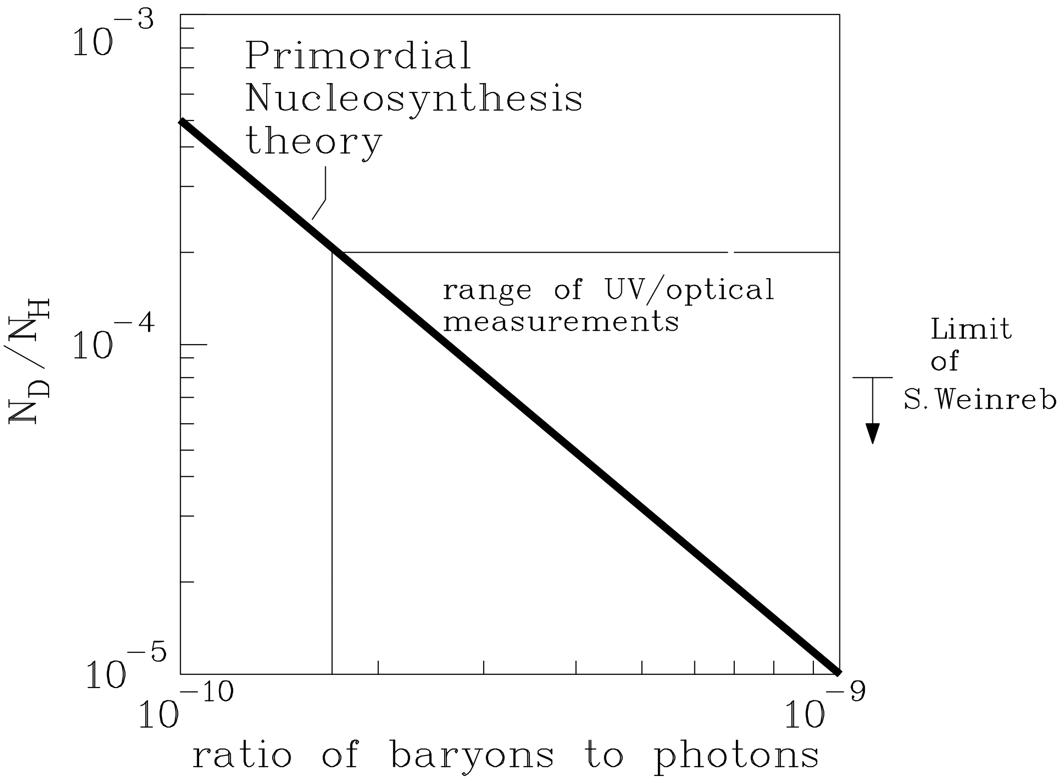


Figure 1. Predicted deuterium abundance from Big Bang theory (from Walker et al, 1991)

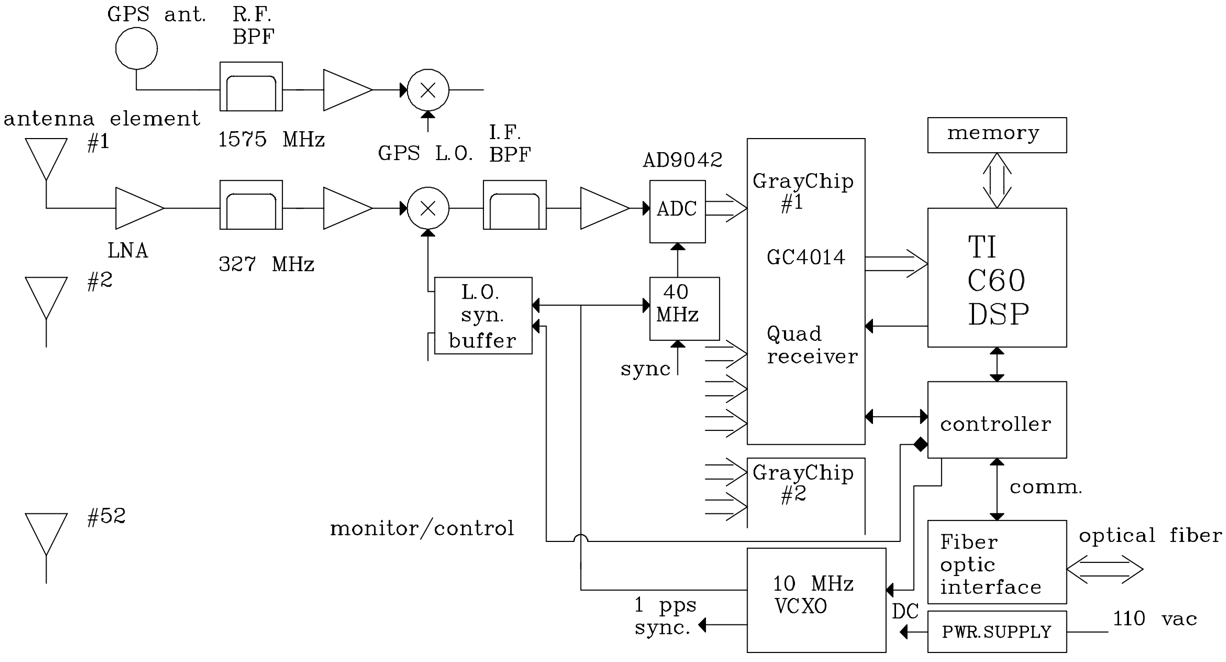


Figure 2. Block diagram of digital receiver for each station of the proposed array.

B. DESCRIPTION OF RESEARCH INSTRUMENTATION

B.1 Digital receiver

Each receiver port is amplified, filtered, and down converted to an IF frequency. The I.F. is then sampled and converted to a digital signal before being digitally filtered and down converted to baseband by a GrayChip digital receiver. Each GrayChip processes 4 receiver ports. The GrayChip outputs are passed to the TI C60 DSP for FFT and beam forming. Each C60 services 4 GrayChips. 13 GrayChips and 4 C60s are needed to process the 50 signals from the 5×5 crossed dipole array. One of the extra 2 channels is used to process the GPS signal and the other is connected to an omni-direction antenna for interference monitoring and cancellation. A block diagram of the proposed digital receiver is shown in Figure 2.

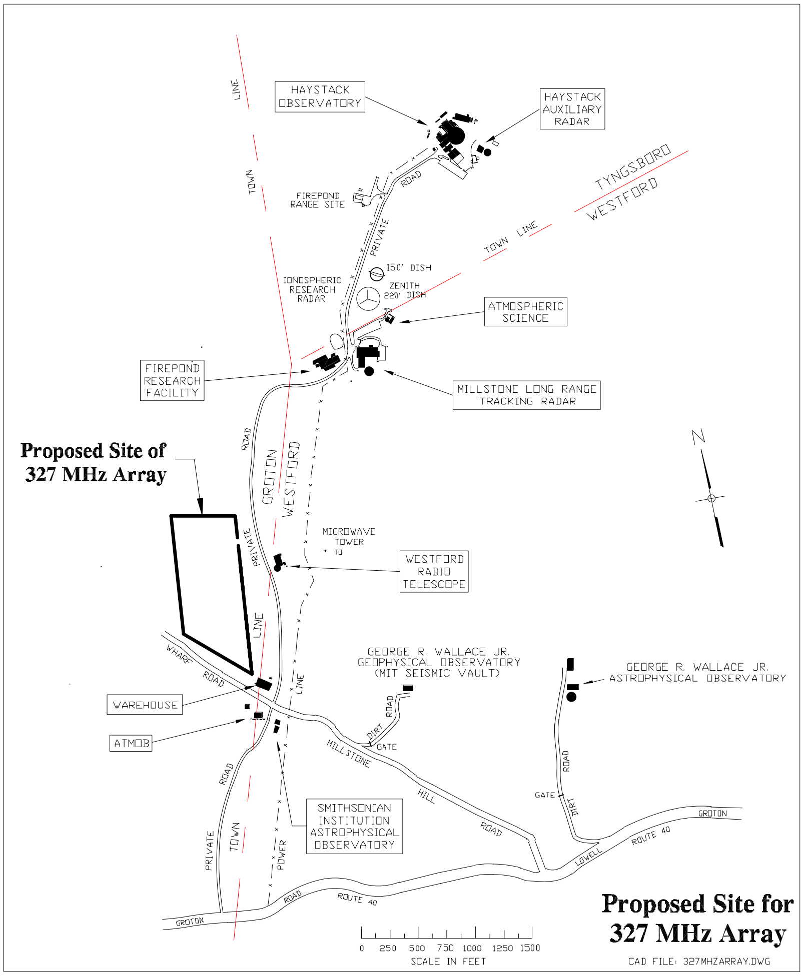
B.2. Array configuration

We propose a 64 station array 5×5 element sub-arrays arranged in a quasi-regular 8×8 array with 15m E-W and 45 m N-S spacing to give an instantaneous synthesized 30 minute of arc beam at 20 degrees elevation. We have identified a suitable site of about 15 acres of MIT land at the Haystack Observatory in Westford, MA shown in Figure 3. A preliminary check of interference levels show that there are no strong signals like harmonics of TV stations in the 322-328.6 MHz band. Our experience at the 440 MHz band used by the 45 m radar antenna at Haystack for ionospheric studies is good, especially considering that this band is shared with some amateur radio repeaters. Some of the interference to radio astronomy is the result of intermodulation products in the low noise amplifier. We plan the use of the new generation of HEMT transistors designed to have very low intermodulation. In addition we plan to minimize the gain in the LNA and follow it with a bandpass filter.

We plan to place the stations so that the configuration will deviate from regularity to provide some short spacings. The total collecting area of the array is 768 m^2 or the equivalent of a 40 meter dish. Each station is a sub-array of 25 crossed dipoles on a ground plane in a compact 5×5 array with 0.8 wavelengths between elements. It is important to have an overall array, which may be sparse to achieve the necessary overall resolution, consisting of compact sub-arrays in order to minimize the system temperature when observing spectral lines in the regions of low background brightness temperature.

B.3. Station sub-arrays

For each “station” of the array we propose a compact sub-array consisting of 5×5 array of crossed dipoles 0.8λ apart 0.2λ above a ground plane to form a $4\lambda \times 4\lambda$ square aperture. Figure 4 shows that the 0.8λ spacing maximizes the gain over system temperature at 20 degrees elevation. The assembly will be fixed to avoid moving mechanical parts. The beam can be electronically steered by ± 20 degrees with less than 1 dB loss at the extreme limits. If the assembly is fixed at a 30 degree elevation pointing south, a declination from –38 to +2 degrees is covered and a region of the sky can be tracked for about 2.5 hours. The crossed dipoles will be mounted on a ground plane (King and Wong, 1972, 1975) using a mesh large enough to avoid the accumulation of snow. The array assembly shown in Figure 5 can be attached to concrete piers raised 2 feet above the ground to account for normal winter snow cover. 110 v power and fiber will be distributed to the receiver at each station. The elevation of the station sub-arrays can be changed manually to point at any elevation.


HAYSTACK OBSERVATORY
HAYSTACK AUXILIARY RADAR
TYNGSBORO
WESTFORD
TOWN LINE
LINE
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ROAD
PRIVATE
FIREPOND RANGE SITE
150' DISH
ZENITH 220' DISH
IONOSPHERIC RESEARCH RADAR
ATMOSPHERIC SCIENCE
FIREPOND RESEARCH FACILITY
MILLSTONE LONG RANGE TRACKING RADAR
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Proposed Site of 327 MHz Array
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GROTON
WESTFORD
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WESTFORD RADIO TELESCOPE
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WAREHOUSE
ATMOB
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GEORGE R. WALLACE JR. GEOPHYSICAL OBSERVATORY (MIT SEISMIC VAULT)
GEORGE R. WALLACE JR. ASTROPHYSICAL OBSERVATORY
DIRT ROAD
GATE
MILLSTONE
HILL
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PRIVATE
TOWN
POWER
SMITHSONIAN INSTITUTION ASTROPHYSICAL OBSERVATORY
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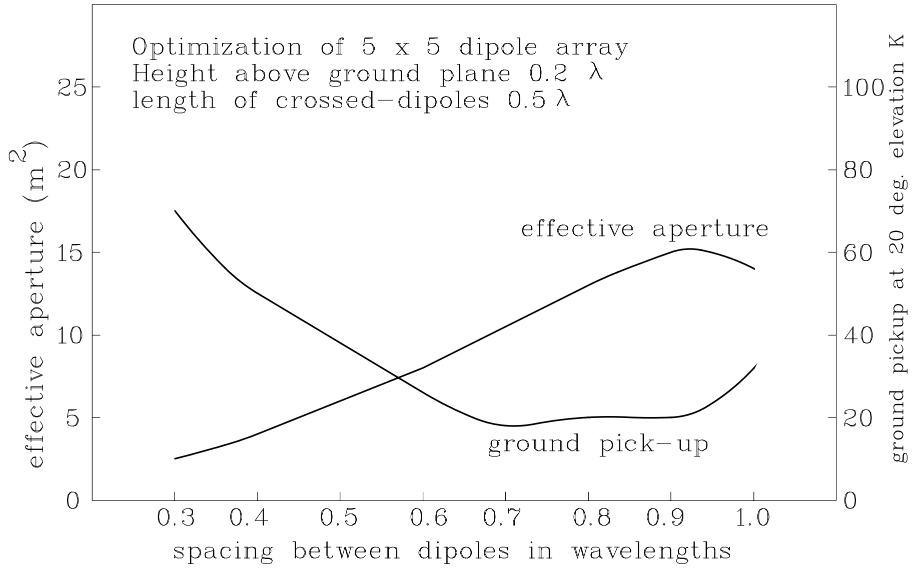
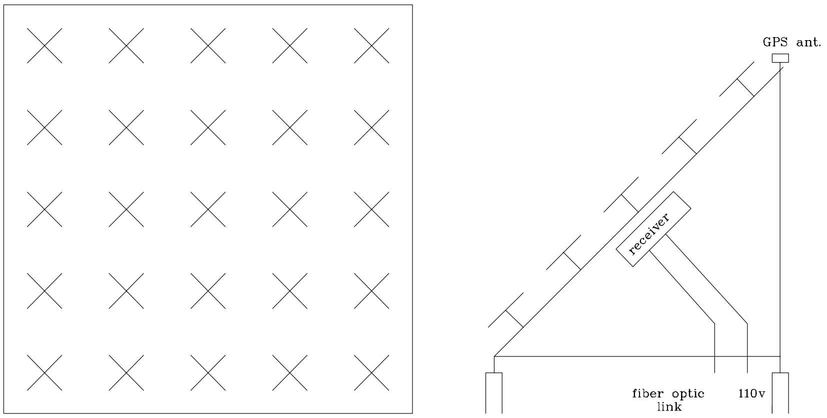


Figure 4. Optimization of dipole spacing



front

side

5x5 crossed dipole array

(dimension approx 14x14 feet)

Array station sub−array

Figure 5. Electronically sterrable array of crossed dipoles for each station of the proposed array.

B.4. Summary of array characteristics

Configuration 8 × 8 quasi-regular array of stations
≃ 15 m E-W spacing on ground
≃ 45m N-S spacing on ground

Each station
5×5 compact array of crossed dipoles
collecting area 12 m^2
beamwidth 12 degrees
electronic steering ± 20 degrees
mechanical reconfiguration of station elevation
number of available primary beams 25

synthesis resolution	30 minute of arc
frequency coverage	322.0-328.6 MHz
polarization	dual linear – full stokes
system temperature	limited by sky background 70-400 K
total collecting area	768 m^2
total number receiver ports	3200
number of stations (each with 2 polarizations)	64
number of baselines in each polarization (synthesis mode)	2016

B.5. Timing and array phasing

Each station will have also have antenna and receiver for GPS. At each station the GPS timing and carrier phase will be acquired by correlation with the public C/A code (1.023 MHz chiprate) to synchronize the 10 MHz reference and interferometric data acquisition timing. The central processor will have a commercially available GPS timing receiver to decode the orbital parameter and pass the apriori information to the stations.

B.6. Data Processing

Most of the data processing will be done in the C60 DSPs in the receivers at the stations. For example, in the search for the deuterium line the C60s will steer the station beams to track the sky, derive the spectra, edit the spectra to excise any interference and then accumulate the spectra. The simultaneous tracking and processing of several regions of the sky within the electronic steering capability of each station will be supported. Up to 25 independent primary beams can be supported The central processor will only need to average the spectra from the 64 stations for each polarization for each primary beam.

When the array is imaging spectral line data, as would be the case in observations of the recombination lines, the stations will provide the complex spectra (the “F” part) and the central processor will perform the cross-multiplications (the “X” part of the FX correlation). To cover the 640 km/s velocity band with 10 km/s resolution for a single station beam there will be 64 complex spectral points from each polarization from each antenna every 100 microseconds. Assuming 8 bits per complex sample, this corresponds to a data rate of 82 MB/s and a processing requirement of 2.5 GFLOPS for all baselines and both polarizations. This processing rate could be handled by a commercial SHARC, C60 or power PC VME board interfaced to the central processing computer.

B.7. Sensitivity

1] Spectral line detection in absorption

In this mode it is assumed that the noise at each station is dominated by the background over which the interviening interstellar medium acts as an absorber. It is assumed that the background is extended enough that the signals at each station are uncorrelated. In this case the 1-sigma noise in the measured opacity, $\Delta\tau$, is

$$\Delta\tau = (BT)^{-1/2}(N_p N_s)^{-1/2}$$
$$\approx 10^{-6}$$

where B = resolution bandwidth = 10 kHz = 9 km/s
T = observing integration = 10^6 sec
N_P = number of polarizations = 2
N_S = number of stations = 64

The expected opacity for the deuterium line absorption against the Galactic continuum is about 10^{-5} based upon $N_D/N_H \approx 2\times10^{-5}$. We expect therefore, to achieve a SNR ≈ 10.

2] D1 emission in the region of the galactic anti center

As pointed out by Blitz and Heiles (1987) and Chengulur et al (1997) the galactic anticenter is a good region to look for D1 in emission. The strong HI emission in this region extends over several degrees in galactic latitude and tens of degrees in galactic longitude. Further the velocities crowd to form brightness temperature of about 130 K. The sensitivity of the 64 station array is given by

$$DT_b = (BT)^{-1/2}(N_p N_s)^{-1/2} T_s \quad K$$

where Ts = system temperature
≈ 100 K in the region of the anticenter

for the same observing parameters as those considered above

$$\Delta T_b \approx 100\ \mu K$$

If we assume that the D1 is extended in the 12 degree beam the line temperature is expected to be

$$\Delta T_{D1} \approx T_{spinD1}\tau_{D1} = 0.3(N_D/N_H)\tau_{H1}T_{spinH1}$$
$$\approx 780\ \mu K$$

for $N_D/N_H = 2\times10^{-5}$
$\tau_{H1} \approx 1$
$T_{spinD1} = T_{spinH1} = 130K$

or an SNR of about 8. The sensitivity for the detection of D1 in emission the instrument we propose should be more than 5 times better than that achieved by Chengular et al. (1997). The reasons for the increased sensitivity, compared with the Westerbork array used by Chengular et al are

1) 64 antennas vs 14 gains a factor of 2.3
2) Multibit vs 2-bit sampling gains a factor of 1.13
3) Digital filtering should eliminate the need for spending half the time observing a comparison spectrum. This gains a factor of 2. Also the ability of each station to simultaneously process several different regions of the sky will allow simultaneous comparison spectra.

3] Spectral line detection in emission

For the hydrogen and carbon recombination lines which appear in emission the one-sigma line-to-continuum ratio for extended sources will be the same as the opacity that is

$$T_L / T_C \approx (BT)^{-1/2} (N_P N_S)^{-1/2}$$

The one-sigma noise in antenna temperature averaged over all stations and polarizations for a system temperature of 70 K, a resolution of 9 km/s and integration 10^6 sec is 60 μK.
For compact sources for which aperture synthesis is used

$$T_L / T_C \approx (BT)^{-1/2} (N_P)^{-1/2}$$

and in terms of flux density the one sigma noise, ΔJ in each polarization is

$$\Delta J = 2kT_S (BT)^{-1/2} A^{-1}$$

where *k*= Boltzman's constant
T_S = system temperature ≈ 100 K away from the Galactic center
A = effective area = 768 m^2

ΔJ = 30 mJ when the resolution is 9 km/s and the integration is 10^4 seconds.

4] The table below compared the proposed array with existing array capable of observing at 327 MHz.

Array	# antennas	# polarizations	Collection area m^2	# simultaneous primary beams	System temp toward anti-center K
Westerbork	14	2	4000	1	120
VLA	27	2	5200	1	180
GMRT	30	2	30000	1	100
Proposed	64	2	770	25	100

Notes: 1] Sensitivity for diffuse emission is proportional to square root of the number of antennas
2] Collecting area is important for absorption experiments of weak sources
3] Number of primary beams reduces observing time for same sensitivity when comparison spectra are needed or when diffuse emission is mapped.

The table shows that for mapping diffuse emission the proposed array is clearly superior to existing arrays owing to the larger number of antennas and primary beams. For measuring the absorption spectrum of the strong extended source like the Galactic center the proposed array will also provide added sensitivity over existing arrays due to the larger number of antennas and the advantages of the digital receiver. The arrays with larger collecting area become superior for absorption measurements of sources with insufficient flux density to dominate the system temperature.

B8. Questions

- Will the array be sensitive enough? In section B7 we show that the array will be sensitive enough to detect the 327 MHz deuterium line in absorption towards the Galactic center and in emission towards the anticenter.

- Why not use existing arrays like the GMRT? The measurement of D/H ratios using the 327 MHz line requires a lot of observing time and a clear understanding of instrumental effects. It is unlikely that adequate observing time would be available on other instruments.

- Does the instrument contribute to future instrumentation? The proposed digital receiver development and technique development will contribute to future arrays.

C. IMPACT OF INFRASTRUCTURE PROJECTS

C.1. Interaction with LOFAR and SKA systems:

U.S. radio astronomers, in collaboration with the international community, are working on the development of two array systems - the Low Frequency Array (LOFAR), and the Square Kilometer Array (SKA). Preliminary specifications for the frequency coverage of LOFAR extend from about 10 MHz to 240 MHz, and that of SKA extends from about 100 MHz to 20 GHz. The strawman design for LOFAR has 13,000 dipoles, arranged between 40 and 160 stations, while SKA may consist of up to 1000 stations, each of which comprises several small antennas. It is widely considered that LOFAR, a modest size array, will be a stepping stone towards the SKA, and will present opportunities for mitigating radio frequency interference, handling large data rates in signal processing and correlation instruments, and utilizing wideband communication links such as fiber optics. The schedule goals for LOFAR aim at the middle of this decade, while SKA development and construction is planned for the latter half of the decade and the next one. Design studies are in progress in the community, and our proposed array can provide a useful test bed for these instruments.

We plan a flexible array, re-configurable from a dense formation to a more sparse spacing, within the MIT land at the Haystack Observatory in Westford, MA (roughly 1400 acres). The location provides an excellent venue for dealing with RFI issues, and for wideband signal processing systems based on existing hardware such as the Mk4 VLBI correlator if desired for continuum processing, and spin-offs from the cellular phone E911 location project supported by industrial sources as noted above. RFI mitigation will be accomplished in several ways. Impulsive interference with power in the desired spectral band can be sensed and used to blank the integration. Directional interference can be cancelled by using the signal from the omni directional antenna combined with the station array to place a null response in the direction of the interference. Weak CW interference which can only be detected in long integrations can be excised by using higher spectral resolution than needed for the astronomy, deleting the effected spectral channels and then smoothing the remaining channels to the desired resolution. We can also use the array to locate and understand the sources of interference which should not be present in the protected radio astronomy band. Our plans will initially focus on a dense configuration as proposed here for the Deuterium detection, and then the system can be rearranged for other applications as needed in the future.

One of the key aspects of this proposal is that the proposed array will provide an important opportunity to train students in instrumentation so we can develop the necessary capabilities to contribute in the future to major projects. This has been a goal of the NSF in general and the Astronomy Division in particular. Our proposal seeks to involve at least 1 graduate student and 6 undergraduate students during the 3-year period of the grant request, and these may be supplemented with other graduate students part-time and post-docs associated with the MIT and NEROC universities and the Haystack Observatory.

D. PROJECT AND MANAGEMENT PLANS

D.1. Digital receiver development

The digital and interface portions of the digital receiver design and firmware will be done by Will Aldrich and Alan Rogers. The receiver is similar to the digital CDMA receiver for the location of 911 calls from cellular phones developed by Haystack. Will Aldrich is an experienced digital engineer who was responsible for the design of the Mark IV digital correlator VLSI chip. Alan Rogers will be responsible for the low noise amplifiers and other analog portions of the receiver.

D.2. Dipole array design

Alan Rogers and Brian Corey will be responsible for design of the array of crossed dipoles.

D.3. Array system design and testing

Alan Rogers and Brian Corey, and Will Aldrich, and the graduate students will be jointly responsible for the overall array system design. Alan Rogers and Brian Corey will concentrate mainly on the R.F., testing and specification of processing algorithms, while Will Aldrich will concentrate on the firmware and C60 software and the fiber optic network. John Ball will be responsible for the array control and observing software as well as for the array correlation and imaging software. Some software and testing tasks will be given to graduate and undergraduate students under the supervision of the senior people responsible for subsystems.

D.4. Construction of the array

Prior to the building of the array we plan to thoroughly test two 25 element stations, exercising the beam steering, acquisition using multiple beams and interference excision. Assuming we find that it is possible to reach theoretical noise levels with long integrations at the Haystack Observatory site we will start construction of the remaining 62 stations. The construction requires some clearing of new growth in areas which used to be open, installation of power and fibers in buried PVC pipe and the pouring of concrete piers to support the 5×5 cross dipole station arrays. The ground planes, and dipoles will be assembled on site from pre-cut materials.

The physical construction of the array will be supervised by the facilities group at the Observatory. The replication of the digital receivers will use local electronics companies for pc board manufacture and automated surface mounting of the components. Final assembly and testing will be carried out using a Haystack technician.

D.5. Maintenance

The array will be maintained as a research instrument by the Observatory. Given the lack of moving parts this effort should be quite minimal.

D.6. Scientific research

Alan Rogers and Brian Corey will lead the scientific direction of the project together with the scientific staff at Haystack, and will involve graduate and undergraduate students in the program particularly in the scientific data analysis phase.

In addition Professor Tom Bania of Boston University, who has made significant contributions in the field of interstellar abundances and the origin and evolution of the elements, will collaborate with Haystack in the scientific research. He has contributed to the proposal. Boston University is a member of NEROC.

D.7. Schedule

We propose to develop and test a prototype station array and receiver in the first year. Construct the 327 MHz array in the second year and conduct the science starting at the beginning of the third year. Algorithm and software development will be ongoing for the 3 year program.

E. SUMMARY

We propose the construction of a novel 327 MHz array, using modern high-speed digital signal processing techniques to yield superior performance for studies of Galactic deuterium abundances. Sensitivity gains over existing instruments stem from a combination of digital receiver stability, a large number of independent apertures, large amounts of available observing time, and a powerful multibeaming capability. Deuterium abundance information from the array will provide an important complement to the existing body of knowledge pertaining to this fundamental cosmological topic.

The proposed project offers the following benefits:

- Enables important science by creating a new instrument dedicated to low-frequency radioastronomical research.
- Drives technological development, featuring digital receivers together with wideband signal processing issues, including RFI excision.
- Leverages private sector capital via the E911 cellphone location project.
- Helps to train the next generation of radio wavelength instrumentalists.
- Builds on existing MIT/Haystack/NEROC (via Boston University) synergy, which combines research, instrumentation, and education.
- Generates knowledge and experience relevant to the U.S. LOFAR and SKA efforts, especially with regard to LOFAR antenna design and beamforming techniques.
- Contributes 37% MIT cost sharing fraction.

REFERENCES

Anantharamaiah, K.P., Radhakrishnan, V. “A New Upper Limit to the Abundance Ratio of Atomic Deuterium to Hydrogen in the Direction of the Galactic Centre,” *Astron. Astrophys*, **79**, L9, 1979.

Blitz, L., Heiles, C., “A New Assault on the 92 Centimeter Line of D_I,” *Ap.J.*, **313**:L95-L98, 1987.

Burles, S., Kirkman, D., Tytler, D., “Deuterium Toward Quasar Q0014+813,” *Ap.J.* **519**:18-21, 1999.

Chengular J.N., Braun, R., and Butler Burton, W., “D1 in the outer Galaxy,” Astron. Astrophysics 318, L35-L38, 1997.

Dupree, A.K., Baliunas, S.L., Shipman, H.L., “Deuterium and Hydrogen in the Local Interstellar Medium,” *Ap.J.*, **218:**361, 1977

Heiles, C., McCullough, P.R., Glassgold, A.E., “Radio Observations of D_I and Fractionation,” *Ap.J.,* **89**:271-292, 1993.

Jenkins, E.B., Tripp, T.M., Wozniak, P.R., Sofie, U.J., Sonneborn, G., “Spatial Variability In The Ratio Of Interstellar Atomic Deuterium To Hydrogen I. Observations Toward δ Orionis By The Interstellar Medium Absorption Profile,” *Ap.J.*, **520**:182-195, 1999.

King, H.E., Wong, J.L., “1.81 bandwidth UHF 3×3 array of crossed open-sleeve dipoles,” *Aerospace Corporation, Electronics Research Laboratory,* TR-0074(4624)1, 1973.

King, H.E., Wong, J.L., “Directivity of Uniformly Excited N × N Array of Directive Elements,” *IEEE*, AP-23:**3**, p., 1975.

Lemoine, M., Audouze, J., Jaffel, L.B., Feldman, P., Ferlet, R., Hebrard, G., Jenkins, E.B., Mallouris, C., Moos, W., Sembach, K., Sonneborn, G., Vidal-Madjar, A., York, D.G., “Deuterium abundances,” *New Astronomy*, **4**, 231, 1999.

Lubowich, D.A., Pasachoff, J.M., Balonek, T.J., Millar, T.J., Tremonti, C. Roberts, H & Galloway, R.P., “Deuterium in the Galactic Centre as a result of recent infall of low-metallicity gas,” *Nature*, **405**, 2000.

Rogers, A.E.E., Barrett, A.H. “Radio Detection of Interstellar $^{18}O^{1}H$,” *Astronomical Journal*, **71**, 868, 1966.

Roshi, D.A., Anantharamaiah, K.R., “Hydrogen And Carbon Recombination Lines Towards The Galactic Centre Near 328 MHz, ”*MNRAS*, **292**, p63, 1997

Rugers, M., Hogan, C.J., “High Deuterium Abundance in a New Quasar Absorber,” *AJ*, **111**, 2135, 1996.

Tosi, M., Steigman, G., Matteucci, F., Chiappini, C., “Is High Primordial Deuterium Consistent with Galactic Evolution,” *Ap.J.*, **498**:226-235, 1998.

Walker T.P., Steigman, G., Schramm, D.N., Olive K.A., Kang H-S., “Primordial Nucleosynthesis Redux,” *Ap.J.* **376**:51-69, 1991.

Weinreb, S., “A New Upper Limit to the Galactic Deuterium to Hydrogen Ratio,” *Nature*, **195**, 367, 1962

Wilson, T.L., Rood, R., “Abundances in the Interstellar Medium,” *Annu. Rev. Astron. Astrophys*., **32**: 191-226 1994.