A Low Frequency Array Designed to Search for the 327 MHz line of Deuterium

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OVERVIEW

Description of the array
RFI monitor
RFI – transient excision and spectral exclusion
Summary of data taken to date
Deuterium Array

- Multibeam array at 327 MHz
- Soccer field sized
- Science
  - D/H ratios tell us about density of material in the early Universe → open vs. closed scenarios
  - Optically, H and D spectrally close
- Technical
  - Digital receiver
  - Allows deep integration
  - Active antenna design

Location

Alan Rogers
7 Jan 2005
D1 ARRAY of 24 STATIONS EACH WITH 24 CROSSED-DIPOLES
DEUTERIUM ARRAY PROJECT

5x5 crossed dipole array  
(24 dual pol elements) 
Separation between dipoles 0.8λ 29”  
frame 14.5 x 14.5 feet

Array station sub-array

Note: Receiver provides 24 channels per polarization so that one corner element is not used.
STATION D00 WITH RFI MONITOR IN BACKGROUND
Deuterium array challenges

• Achieving $T_{sys}$ close to sky noise
• Ameliorating RFI:
  1 mK in 10kHz $\sim$ -189 dBm
  e.g. signals from Westford $\sim$ 1K
  ensuring adequate IP2
  e.g. mix with TV signals ($\sim$ -159 dBm)
  (i.e. paging @ 152 + ch7 TV @ 175 = 327)
Array status:

24 stations completed 29 June 2004 and observations started

Technical solutions to problems:

1] Intermodulation reduced by adding stub filters to active dipoles

2] Horizon response reduced by adding resonant directors to crossed-dipoles

3] RFI leakage from box solved by adding more power line filtering and large number of screws to improve ohmic contact of box cover
Summary of array Characteristics:

**Configuration**
quasi-regular array of 24 stations

~ 15 m spacing

**Each station**
5 x 5 (24) compact array of crossed Yagis

collecting area: 12 m²

beamwidth: 14 degrees

electronic steering: ~ +/- 40 degrees 3 dB

manual adjustment of elevation 30 – 90 deg

number of available simultaneous beams: 4

**Frequency coverage**
322.0 – 328.6 MHz (centered at 327.4 MHz)

**Polarization**
dual linear

**System temperature**
limited by sky background 50 – 400 K

**Spectrum**
250 kHz with 1024 channels 244 Hz resolution

**Total number of receiver ports**
48x24 = 1152
Deuterium array sensitivity

Tsys: 110 K (40 K recvr + 70 K sky)
Number antenna sub-arrays: 24
Number of polarizations: 2
For a resolution of 10 km/s ~ 10 kHz
1-sigma noise in 30 days: ~ 100 μK
(about 6 months observing a given point in sky)
For D/H ~ 1.5x10\(^{-5}\) expect ~ 300 μK
(towards Galactic anti-center)
D1 array receiver functional block diagram
48 channel receiver for each station of the array – shown with cover removed
Notes: 1] do not connect ground wire between filters

2] Make sure filters have tight low ohmic contact with the box
Coaxial stub filters form an integral part of the low noise active dipole antenna
Scan loss

curves are from directivity

- = H plane
+ = E plane
○ = 45plane

Relative Power

Scan angle (deg)
Pulsar test on 0957+56

Beamscan on the Sun

datamax  3.82 datamin  0.60
file: bmap5.txt
fit to Trecvr  40 K horizon set at  5 deg
Azimuth  180 deg
Elevation  90 deg

Dipole orientation  45 deg

Measurement of Trecvr using zenith beam

VARIATION OF NORMALIZED ZENITH BEAM FOR ALL STATIONS  DAY2004_277
History of checks from each day averaged over all stations

file: temp
Sun Dec 19 01:33:16 2004
RFI environment at Haystack Observatory

RFI noise temperature near Haystack
BW = 1 MHz  integration  100 s  RBP  8 Dec 03

(noise floor is limited by noise figure of spectrum analyzer)
CLOSEUP VIEW OF ACTIVE ANTENNA ELEMENT SHOWING RESONANT DIRECTORS ADDED TO REDUCE GAIN AT THE HORIZON

RFI MONITOR WITH 12 ACTIVE YAGIS AND A CROSSED-DIPOLE IN BACKGROUND
RFI:

Almost all RFI has been identified as “local” i.e. within 2 km

RFI examples and fixes:

1] Litespan 2000 harmonics of 1.544 MHz i.e. 212x1.544 = 327.327 MHz shielded by adding missing cabinet doors and shield on building

2] IR camera electronics spur at 327.275 MHz – equipment removed

3] Emission from receiver box leaking out of power cable – added double power filtering

4] Panasonic answering machine emission at 327.410 MHz at Westford machine removed, modem on antenna shut-down

5] With cooperation of neighbors removed signals from various answering machines in the 327 MHz band.

6] GPS receiver 4.092 x 80 = 327.36 MHz – antenna moved

7] Surround sound 11.2896 x 29 = 327.3984 MHz – frequency excluded
Other sources of RFI at 327 MHz

- PC motherboard > 100 dB shielding needed
- Fiber optic ethernet converter > 100 dB req.
- Other PC and electronics within 500 m.
- Continuum transients mostly of unknown origin. These have spectral features due to multipath.
Sensitivity to detect* CW RFI
(in EIRP at 100m from array)

- RFI monitor active 12 dBi Yagi
  (Tsys = 200K) in 24 hours - 127 dBm
- Array active dipole (Tsys = 100K,
  -10 dBi at horizon) in 24 hours - 108 dBm
- Average of all 24x48 dipoles - 123 dBm
- All dipoles in 10 days - 128 dBm

* assumes 10 sigma detection and resolution of 244 Hz

Note: FCC part 15 limit = 200uV/m at 3m = -49 dBm EIRP
    Expected D1 strength = 300 uK in 20 kHz = -191 dBm =
    -119 dBm EIRP at 100m in -10 dBi sidelobe of dipole
Example of RFI spectrum from modem about 180m from RFI monitor

Sample spectra from Deuterium array RFI monitor
Example of finding direction from RFI monitor Yagis
RFI amelioration:

1] Reduce the horizon response – resonant directors reduced gain at horizon by 10 dB.

2] Excise all transients by excluding all time spans for which there is a greater than 8 sigma detection in 100 seconds of RFI monitor data from any Yagi or greater than 8 sigma detection in any 500 seconds of beam data.

3] Excise all transients for which there is a greater than 10 sigma curvature or third order polynomial coefficient in 100 seconds of RFI monitor data, beam data or average of all 24 channels. [This is useful in removing continuum ripple from multi-path-ed continuum data.]

4] Exclude all 244 Hz frequency channels with a greater than 8 sigma detection in 24 hours of RFI monitor data.

5] Perform weighted least squares fitting of 128 coefficient Fourier series to smooth spectrum giving the excluded channels zero weight. Estimate the standard deviation from the transform of the covariance matrix. Alternately make weighted least squares fit to expected D1 profile and average profile amplitudes.
509 ppm p-p fully excised using all 24 channels to detect

696 ppm p-p partially excised

2630 ppm p-p continuum transient without excision

Example of excision of multi-path-ed RFI transient
Method of spectral exclusion – simulated data

- **data**
- **fit with exclusion**
- **fit without exclusion**
- **excluded frequencies**
- **std dev from 2000 trials**
- **std dev from covariance matrix**

![Spectral Data Diagram]

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*Tue Oct 5 16:50:22 2004*
LEAST SQUARES SMOOTHING:

\[ \hat{s} = \left( A^H wA \right)^{-1} A^H wX \]

\( X = \) vector of original spectrum
\( A = \) steering or design matrix
\( s = \) vector of Fourier series coefficients
\( w = \) weight matrix
\( H = \) conjugate transpose or Hermitian conjugate

SPECTRAL ERROR ESTIMATE:

\[ \sigma_i^2 = \left( A(\hat{s} - s)(\hat{s} - s)^H A^H \right)_{ii} = \left( A\left( A^H wA \right)^{-1} A^H \right)_{ii} \sigma_0^2 \]

\( \sigma_0 = \left( bT \right)^{-\frac{1}{2}} \)

\( b = \) original spectral resolution = 244 Hz
\( T = \) integration time

SUMMARY OF MATRIX ALGEBRA FOR RFI SPECTRAL EXCLUSION
Days 2004_167 thru 2004_180 of array data – average of spectra from all elements as a test of RFI amelioration

No excision

32 ppm p-p

rms 5 ppm integ 31.9 yr

continuum transients produce baseline ripple

24 ppm p-p

transients excised

rms 4 ppm integ 31.9 yr

17 ppm p-p

CW not detected by RFI monitor

transients and CW removed

rms 3 ppm integ 30.9 yr
### Observing schedule:

Stations set pointing at Zenith

<table>
<thead>
<tr>
<th>Source</th>
<th>time span</th>
<th>maximum scan angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galactic Anti-center D1 emission</td>
<td>6 hours/day</td>
<td>40</td>
</tr>
<tr>
<td>(Galactic longitudes 171 183 and 195)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference regions at 171 183 195 plus 06 12 18 hours RA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cygnus</td>
<td>15 min/day</td>
<td>30</td>
</tr>
<tr>
<td>Cas A D1 absorption</td>
<td>3 hours/day</td>
<td>20</td>
</tr>
<tr>
<td>Sun Occasional phasing checks etc.</td>
<td>10 min/day</td>
<td>depends on season</td>
</tr>
<tr>
<td>Pulsar 0329+54</td>
<td>3 hours/day</td>
<td>20</td>
</tr>
<tr>
<td>Zenith beam</td>
<td>24 hours/day</td>
<td>0</td>
</tr>
</tbody>
</table>

Notes: 1] Zenith beam power variation with LST for Tsys calibration

2] Phasing and beamforming checks on the Sun and Cygnus
Summary of data loss due to RFI

<table>
<thead>
<tr>
<th>RFI</th>
<th>equivalent loss of integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>transient excision:</td>
<td>5%</td>
</tr>
<tr>
<td>CW exclusion:</td>
<td>15%</td>
</tr>
</tbody>
</table>
**APPROXIMATE ESTIMATE OF EXPECTED SIGNAL:**

\[
s = 0.27 \times \left( \frac{n_D}{n_H} \right) \times \left( T_{spin} - T_{cont} \right) \times \tau \times \left( T_R + T_{cont} \right) \approx 4.4 \text{ ppm}
\]

\( n_D / n_H \) = Deuterium abundance ratio  \( \left( 1.5 \times 10^{-5} \right) \)

\( T_{spin} \) = spin temperature of Deuterium \( (130 \text{ K}) \)

\( T_{cont} \) = Continuum temperature \( (70 \text{ K}) \)

\( \tau_H \) = hydrogen 21 cm opacity \( (2) \)

\( T_R \) = receiver noise contribution \( (40 \text{ K}) \)

**MORE ACCURATE ESTIMATE OF EXPECTED SIGNAL:**

\[
s' = \frac{(a \otimes bm)}{(b \otimes bm)}
\]

\[
a = 0.27 \times \left( \frac{n_D}{n_H} \right) \times \left( t_{spin} - t_{cont} \left( 1, b \right) \right) \tau \left( l, b \right)
\]

\[
b = T_{cont} \left( l, b \right)
\]

\[
\tau = -\log_e \left[ 1 - \frac{T_H}{T_{spin}} \right]
\]

\( T_H \) = hydrogen line temperature

\( T_{spin} \) = Hydrogen spin temperature

\[
bm = \frac{\sum_N e^{i\theta_k} \left| a_k \right|^2 s_k T_{sky}}{N \sum_K \left| a_k \right|^2 s_k} + T_R
\]

\[
\left| a_k \right|^2 = \text{beam response of each dipole}
\]

\( \theta_k \) = beam steering phase to \( k^{th} \) sky patch

\( N = \text{number of elements} = 24 \)

\( K = \text{total number of sky patches} \)
Station beam at 0 hour angle

Continuum

H1 opacity at 0 km/s

H1 data from Hartmann & Burton and Continuum from Haslam et al.
Expected D1 spectra from region near Galactic anticenter:

Assuming:

1] D1 spin temperature = 130 K
2] D/H ratio = 15 ppm
3] continuum uniformly mixed with H1 and 6 K (3K CMB + 3K) extragalactic
4] average for hour angle from -2 to +2 hours
5] H1 from Hartmann and Burton, continuum from Haslam et al

G183 peak = 2.6 ppm (1.6 ppm if all continuum behind, 3.6 ppm in all in front)
<table>
<thead>
<tr>
<th>$T_{\text{spin}}$ (K)</th>
<th>Continuum all behind H1 (ppm)</th>
<th>Continuum mixed with H1*</th>
<th>Continuum all in front of H1</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>1.7</td>
<td>3.2</td>
<td>4.7</td>
</tr>
<tr>
<td>120</td>
<td>1.7</td>
<td>2.9</td>
<td>4.1</td>
</tr>
<tr>
<td>130</td>
<td>1.6</td>
<td>2.6</td>
<td>3.6</td>
</tr>
<tr>
<td>140</td>
<td>1.6</td>
<td>2.6</td>
<td>3.6</td>
</tr>
<tr>
<td>150</td>
<td>1.7</td>
<td>2.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>

* Uniform mix of continuum with H1 and 6K (3K CMB +3K) extragalactic

**Expected D1 line peak vs spin temperature and assumed location of continuum for D/H = 15 ppm**
<table>
<thead>
<tr>
<th>Days</th>
<th>RMS (ppm)</th>
<th>Integ (yr)</th>
<th>P-P (ppm)</th>
<th>SNR (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 ppm p-p</td>
<td>R18195</td>
<td>0.89</td>
<td></td>
<td>-2.2</td>
</tr>
<tr>
<td>15 ppm p-p</td>
<td>R12195</td>
<td>2.08</td>
<td></td>
<td>-1.4</td>
</tr>
<tr>
<td>20 ppm p-p</td>
<td>R06195</td>
<td>2.45</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>13 ppm p-p</td>
<td>R18183</td>
<td>3.87</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>21 ppm p-p</td>
<td>R12183</td>
<td>3.42</td>
<td></td>
<td>-0.0</td>
</tr>
<tr>
<td>16 ppm p-p</td>
<td>R06183</td>
<td>3.54</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>13 ppm p-p</td>
<td>R18171</td>
<td>3.68</td>
<td></td>
<td>-0.2</td>
</tr>
<tr>
<td>11 ppm p-p</td>
<td>R12171</td>
<td>3.69</td>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>15 ppm p-p</td>
<td>R06171</td>
<td>3.89</td>
<td></td>
<td>-1.1</td>
</tr>
<tr>
<td>18 ppm p-p</td>
<td>G195</td>
<td>1.74</td>
<td></td>
<td>1.1</td>
</tr>
<tr>
<td>14 ppm p-p</td>
<td>G183</td>
<td>3.74</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>11 ppm p-p</td>
<td>G171</td>
<td>3.70</td>
<td></td>
<td>2.3</td>
</tr>
</tbody>
</table>

Days 4_190 to 4_351

Wed Dec 22 12:24:47 2004
rms 2.6 theory 2.5 ppm integ 3.7 yr

14 ppm p-p

G183

3.4 ppm snr 3.8

D1 Array days 4_190 to 4_351 files: 2004_351_00 Wed Dec 22 12:42:00 2004
<table>
<thead>
<tr>
<th>Transient RFI excision 100 sec</th>
<th>Transient RFI excision daily</th>
<th>Spectral RFI exclusion</th>
<th>G183 SNR</th>
<th>Peak SNR on REF.</th>
<th>Integ. years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>3.0</td>
<td>1.8</td>
<td>2.72</td>
</tr>
<tr>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>3.0</td>
<td>2.4</td>
<td>2.85</td>
</tr>
<tr>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>2.5</td>
<td>7.7</td>
<td>2.98</td>
</tr>
</tbody>
</table>

TESTS OF RFI AMELIORATION VS LEVELS OF EXCISION & EXCLUSION
SUMMARY

• Array has been operating with 24 stations since 29 June 04
• RFI/intermod issues have been the dominant challenge
• We have indications that we are seeing the D1 line consistent with D/H ~ 20 ppm
• SNR ~ 4 is marginal and we will need about 6 to 9 more months to approach a solid result
## Summary of 327 MHz searches

<table>
<thead>
<tr>
<th>Authors</th>
<th>year</th>
<th>D/H (ppm)</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weinreb</td>
<td>1962</td>
<td>&lt; 80</td>
<td>Cas A</td>
</tr>
<tr>
<td>Cesarsky et al</td>
<td>1973</td>
<td>30 – 500</td>
<td>Sgr A</td>
</tr>
<tr>
<td>Anantharamaiah</td>
<td>1979</td>
<td>&lt; 58</td>
<td>Sgr A</td>
</tr>
<tr>
<td>Blitz &amp; Heiles</td>
<td>1987</td>
<td>&lt; 60</td>
<td>anticenter</td>
</tr>
<tr>
<td>Heiles et al</td>
<td>1993</td>
<td>&lt; 50</td>
<td>Sgr A, Cas A</td>
</tr>
<tr>
<td>Chengalur</td>
<td>1997</td>
<td>29 – 49</td>
<td>anticenter</td>
</tr>
<tr>
<td>Linsky / FUSE</td>
<td>2004</td>
<td>primordial est. 28</td>
<td>Quasar Lyman-alpha</td>
</tr>
<tr>
<td>D1 array</td>
<td>2004</td>
<td>20 – 30</td>
<td>anticenter</td>
</tr>
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