DEUTERIUM ARRAY MEMO #068

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To: Deuterium Array Group

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Subject: Low Cost Array for the 327 MHz Deuterium Line

A low cost array of 24 small radio telescopes was designed and constructed in order to make dedicated, optimally efficient observations of the 327 MHz line in the Galactic plane. Each telescope, is a subarray of 24 dual polarized Yagi elements, on a 4.8 x 4.8 wavelength ground plane. Simultaneous multiple beams are produced by appropriate phasing of the individual elements in software. The beamwidth of each telescope is approximately matched to the extent of the gaseous medium in order to optimize the deuterium emission signal from extended regions. For observations of the line in the anticenter of the Galaxy the subarrays were spaced far enough apart to make the signals from extended regions uncorrelated, so that the 2 years of observations of the anticenter region of the Galaxy, made from June 2004 to July 2006, were equivalent to 48 years observing with a single telescope. The receiving element of each Yagi is an "active dipole" achieving a 40 K noise temperature. The mechanical support for the antenna elements used inexpensive PVC pipes. The 327 MHz signals from the elements are amplified, filtered, and downconverted to a 50 MHz I.F. prior to sampling and analog to digital conversion. The 8-bit samples are then digitally downconverted and filtered to a 250 kHz bandwidth using a Graychip GC4016, Fourier transformed in an Analog Devices 21161N DSP and then transferred to PC motherboard via USB 2.0. Cost is minimized with the use of surface mount components and a very modular design with 4 channels per board for a total of 288 identical analog downconversion boards and 288 digital boards for the entire array. One inexpensive motherboard is used to combine the signals from 24 elements of one polarization of each subarray and another motherboard for the other polarization for a total of 48 motherboards for the array. The computing power in each motherboard was sufficient to form 4 simultaneous beams each with 1024 spectral channels covering the 250 kHz bandwidth centered on the Deuterium line. The digital bandpass proved to be extremely stable and allowed years of spectral accumulation to reach levels of about 1 part per million of the system noise without the need for comparison switching although the multiple beams did allow the simultaneous observation of comparison regions to assess the level of instrumental error. Deuterium line measurements with signal to noise ratios from 6 to 8 were obtained on the regions centered on Galactic longitudes 171, 183 and 195 degrees. Upon completion of the observations of the anticenter the array has been put in storage awaiting possible deployment at a southern site for observations of the Magellanic clouds. For this project the Yagi elements would need to be reconstructed for more gain and placed on larger ground planes to narrow the beamwidth and increase the collecting area in order to match the extent of the gaseous clouds which are about 6 degrees in angular extent compared with the 14 degree beamwidth of the array configuration used for the Galactic observations.

Low Cost Array for the 327 MHz Deuterium Line

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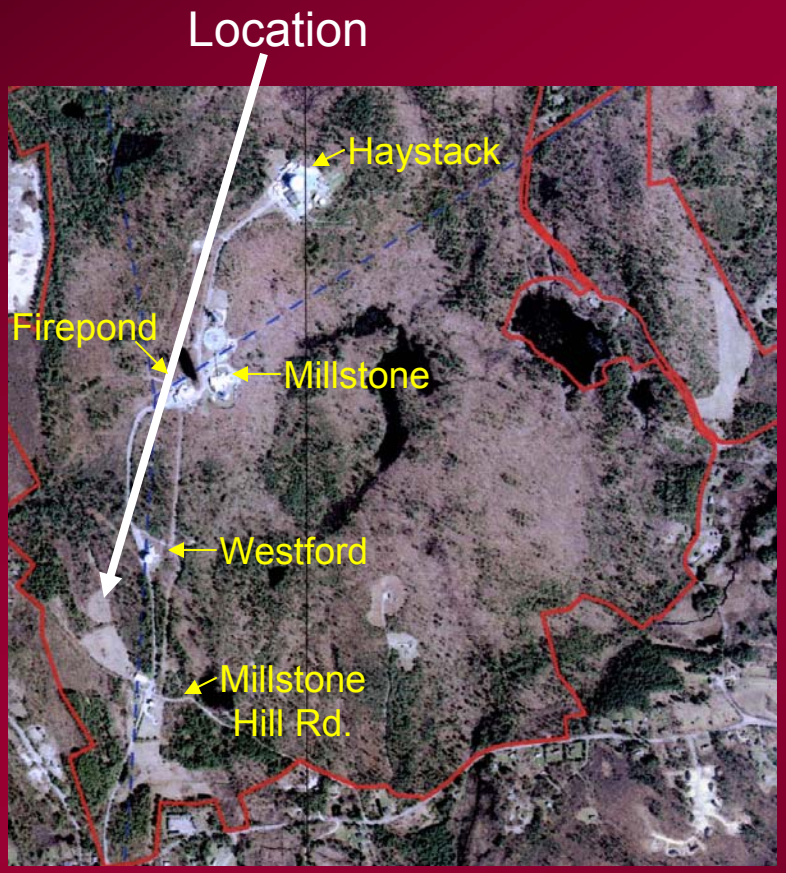
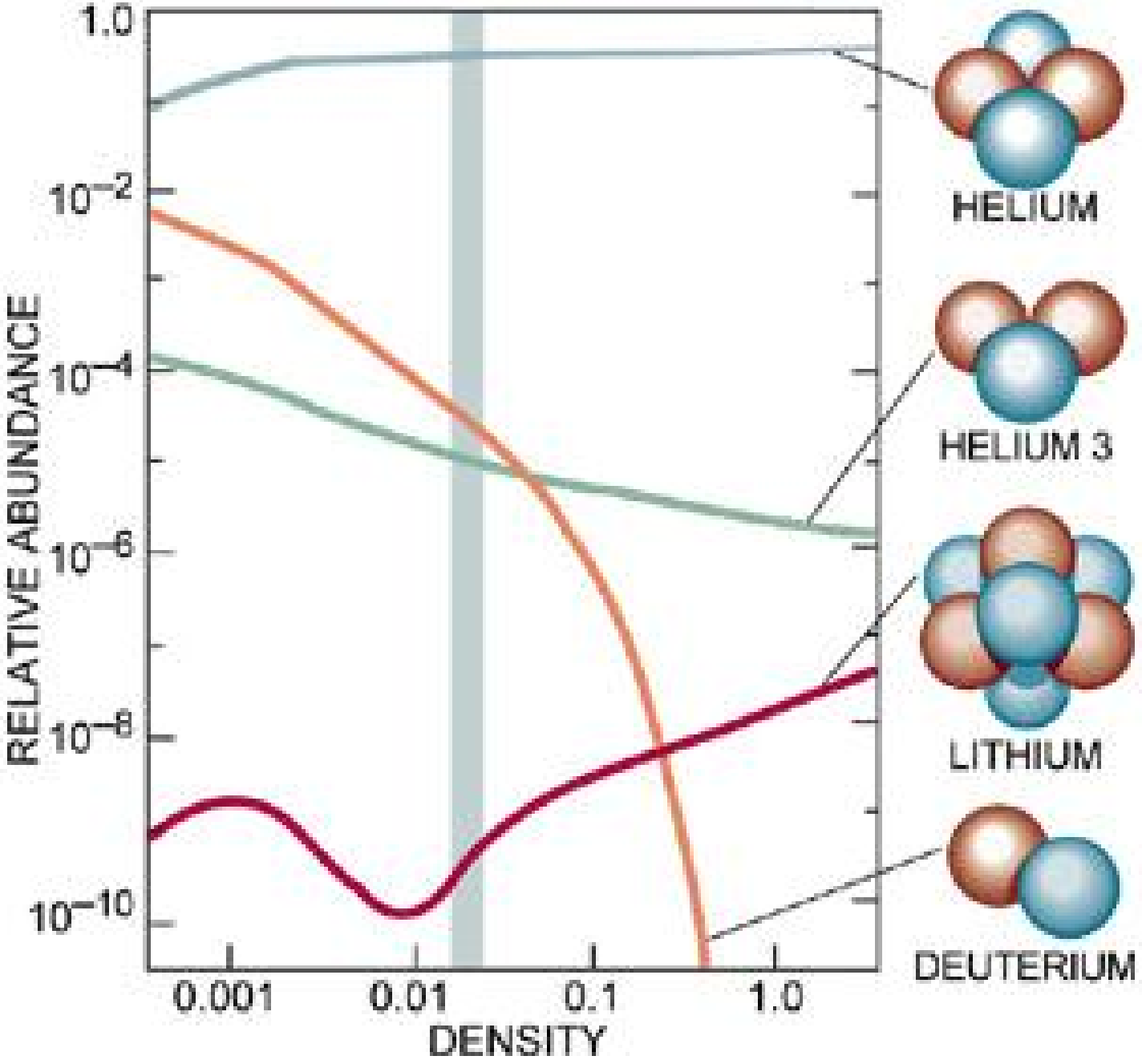


- Multibeam “stations”
- Soccer field sized
- Science
  - D/H ratios tell us about density of material in the early Universe → open vs. closed scenarios
  - Optically, H and D spectrally close
- Technical
  - Digital receiver
  - Allows deep integration
  - Active antenna design

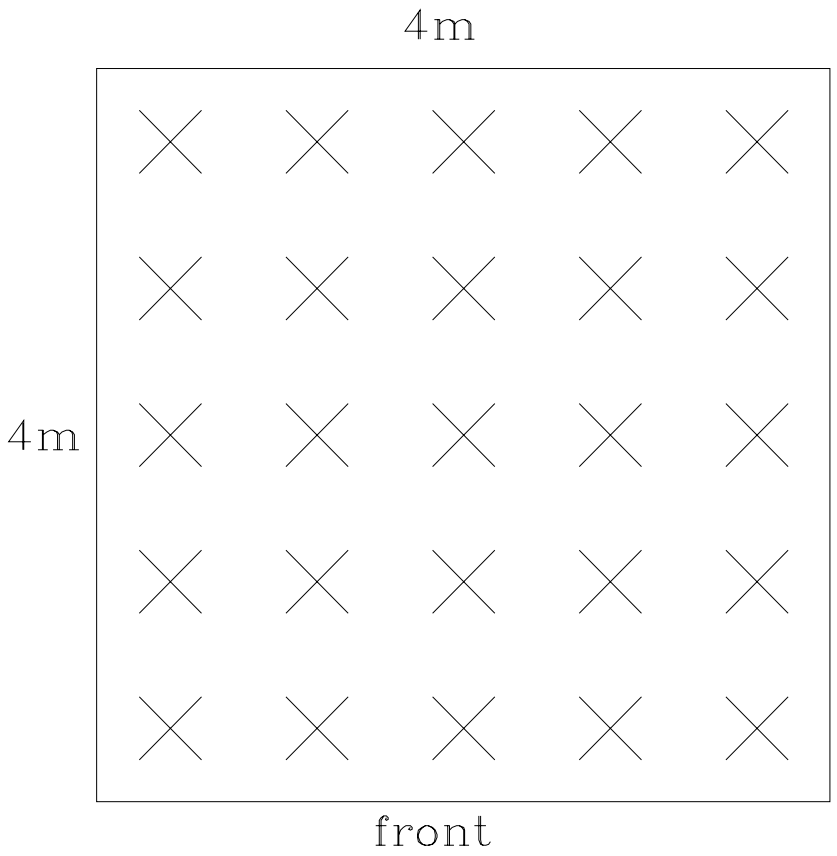
Alan Rogers
URSI 2007
24 July 2007

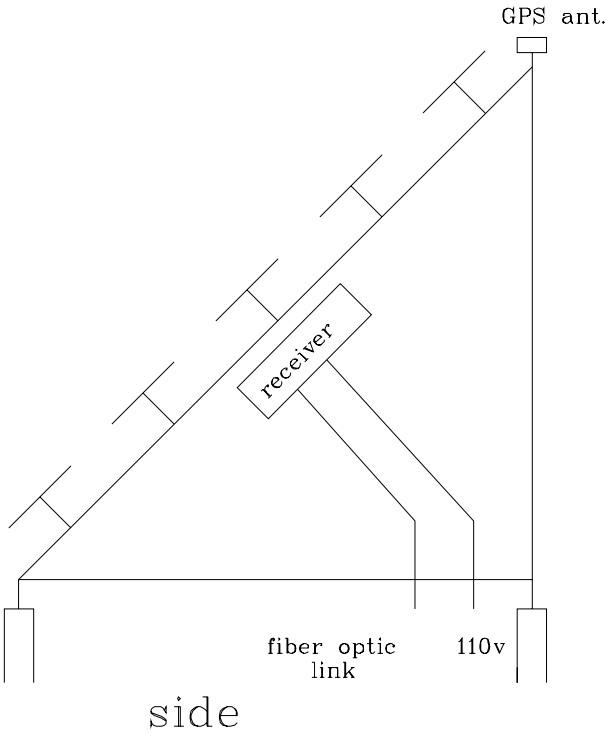

1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
RELATIVE ABUNDANCE
0.001
0.01
0.1
1.0
DENSITY
HELIUM
HELIUM 3
LITHIUM
DEUTERIUM

D1 ARRAY of 24 STATIONS EACH WITH 24 CROSSED-DIPOLES

View of Deuterium array from Google earth – array disassembled in 2006 for possible future deployment in the southern hemisphere

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.

Deuterium array challenges

- Achieving Tsys close to sky noise
- Ameliorating RFI:

Expected D1 signal

0.3 mK in 10kHz ~ -193 dBm

signals from Westford ~ 1K

ensuring adequate IP2

e.g. mix with TV signals (~ -159 dBm)

(i.e. paging @ 152 + ch7 TV @ 175 = 327)

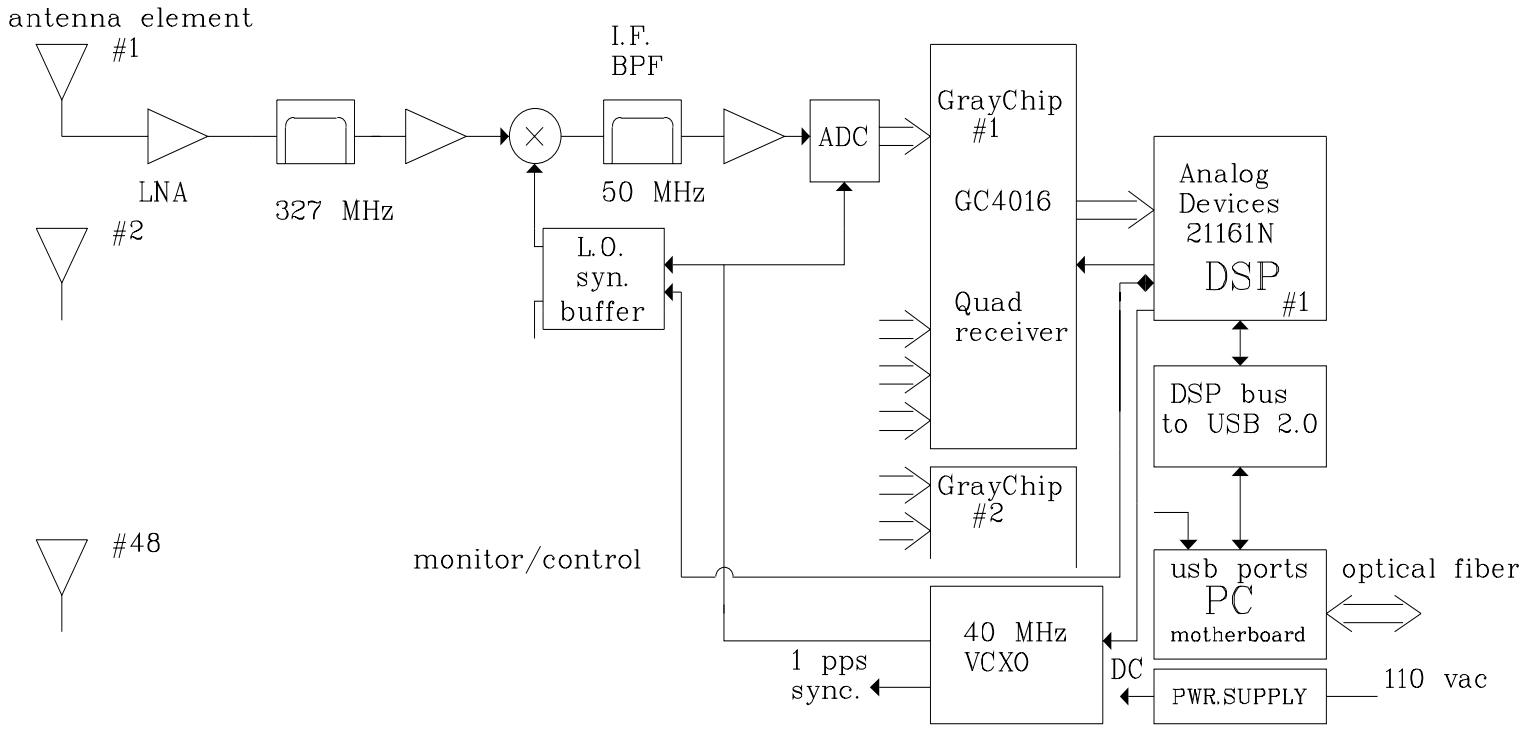
Summary of array Characteristics:

Configuration	**quasi-regular array of 24 stations**
	~ 15 m spacing
Each station	**5 x 5 (24) compact array of crossed Yagis**
	collecting area : 12 m^2
	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**

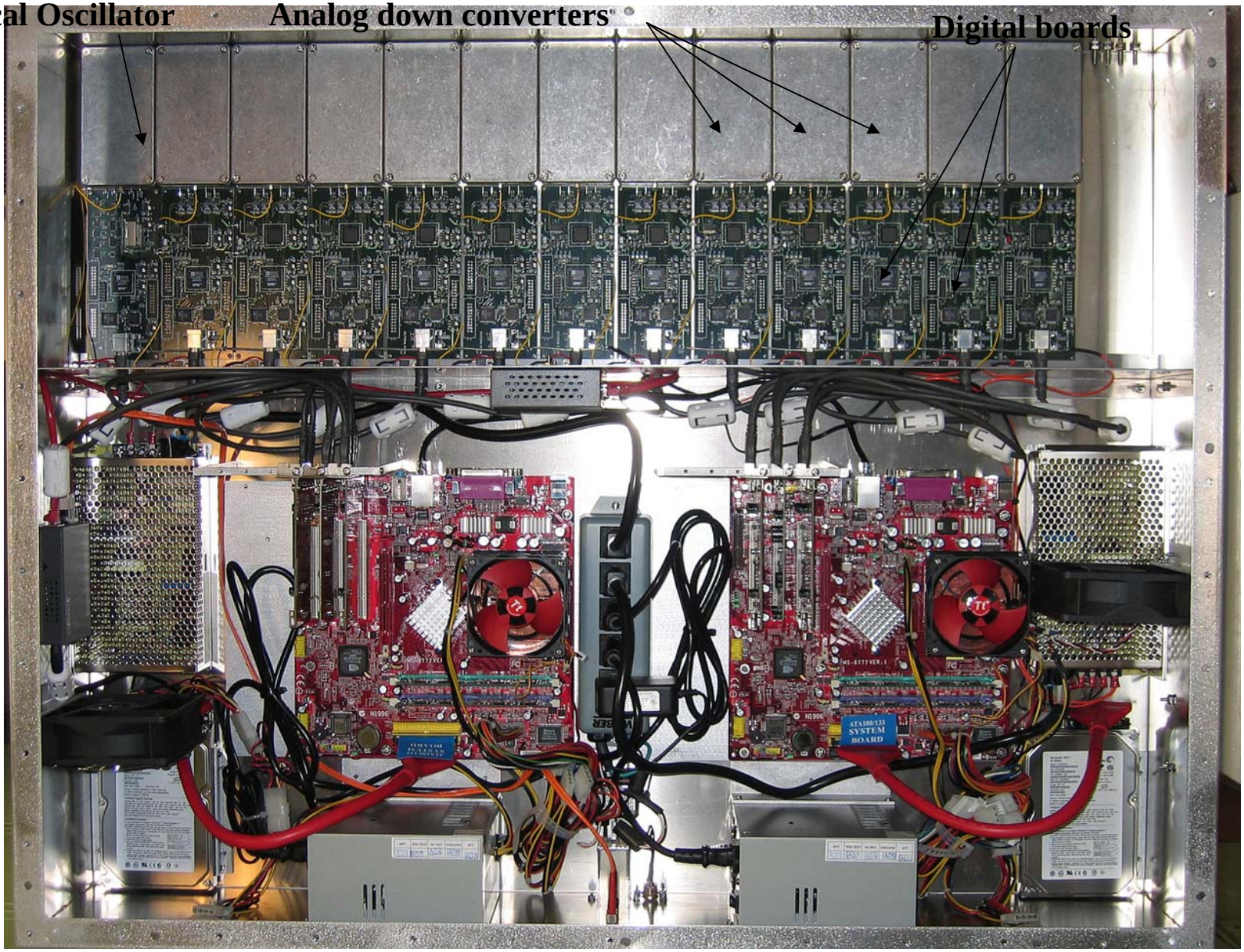
Total number of receiver ports 48x24 = 1152

Deuterium array sensitivity

Tsys: 110 K (40 K recvr + 70 K sky)
Number “station” 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 ~ 1.5×10^{-5} expect ~ 300 μK
(towards Galactic anti-center)

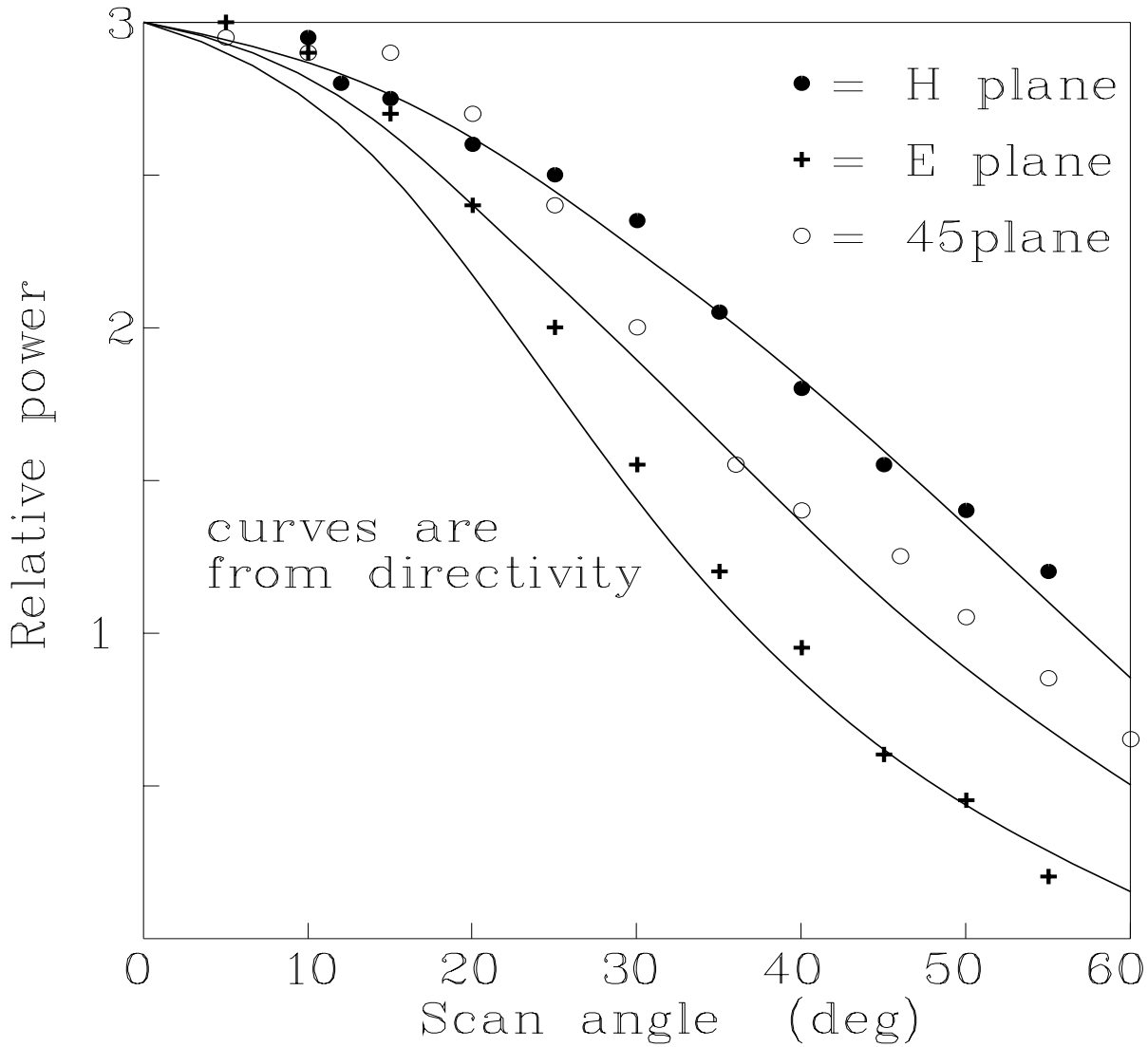


D1 array receiver functional block diagram

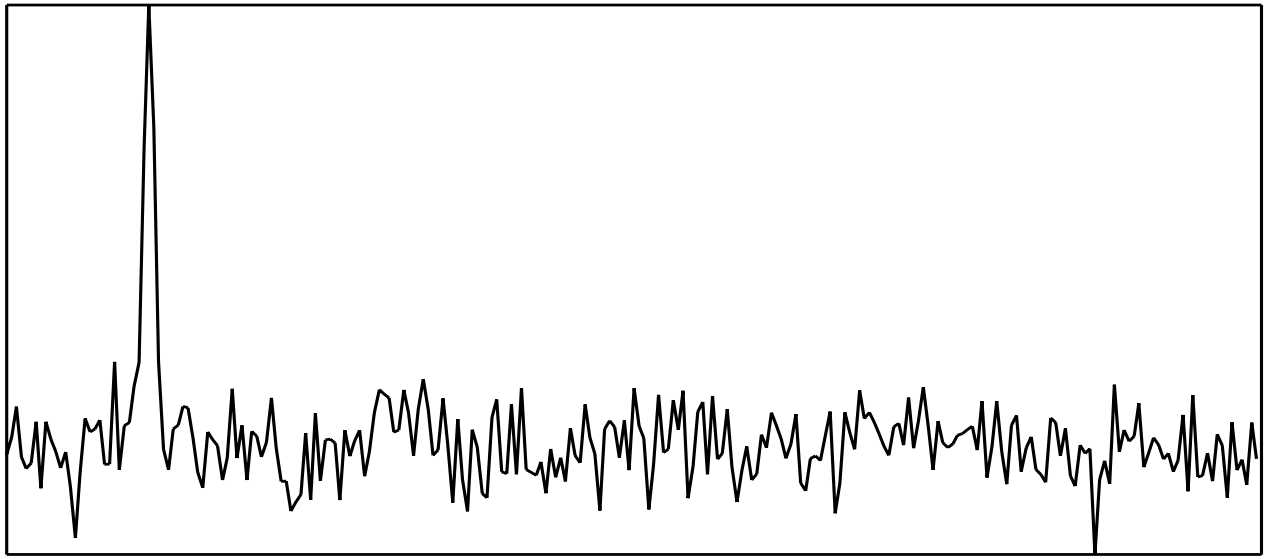


48 channel receiver for each station of the array – shown with cover removed

Scan loss


Relative power
3
2
1
0
10
20
30
40
50
60
Scan angle (deg)
• = H plane
+ = E plane
○ = 45plane
curves are
from directivity

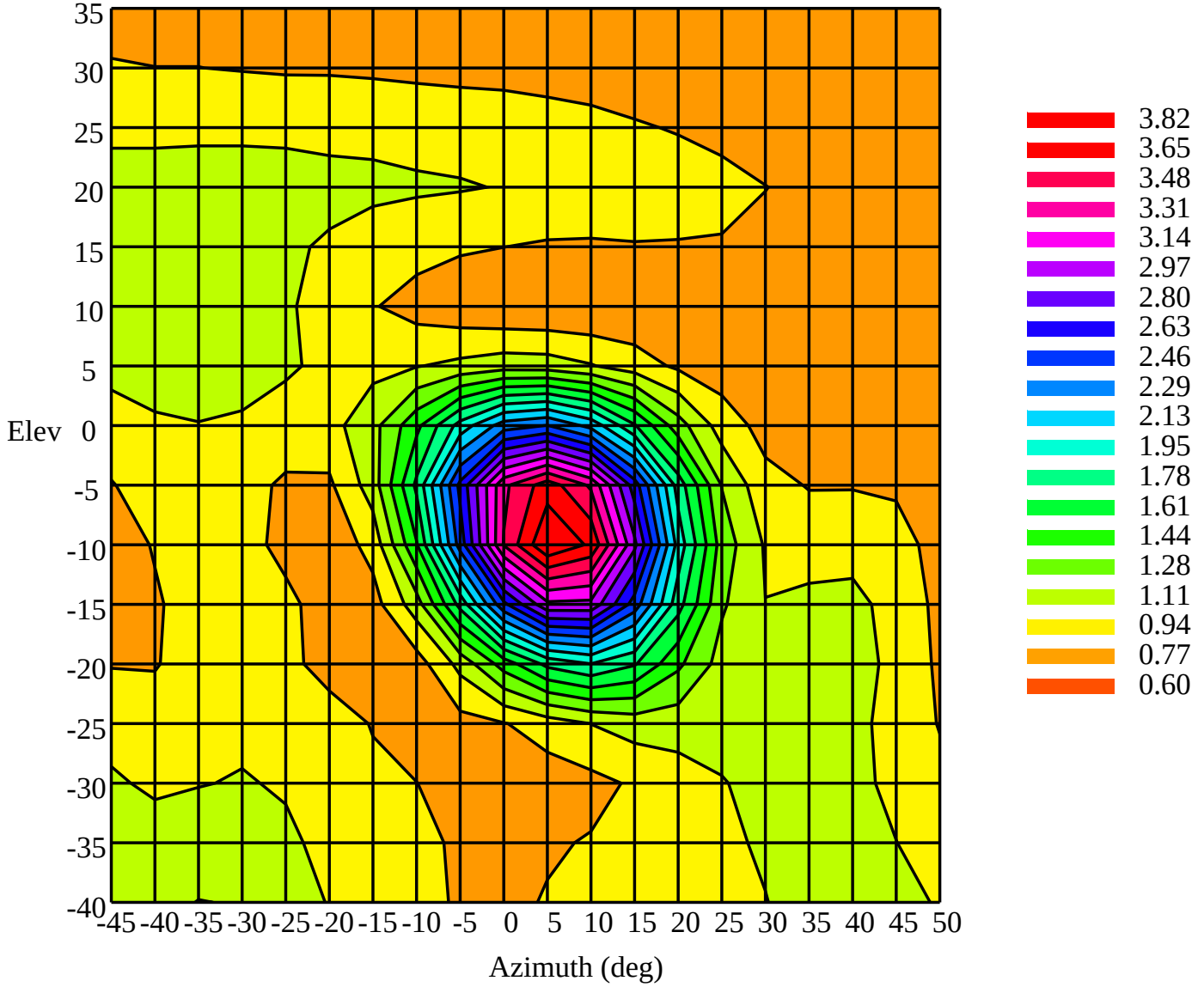
Pulsar test on 0957+56



max 6.820327e-03 Start 202:11:01:16 end 202:13:56:17 scanlim 20 4ms resolution

D1 Array file: /da/d13/2004_202_00.d13a Mon Oct 4 20:29:51 2004

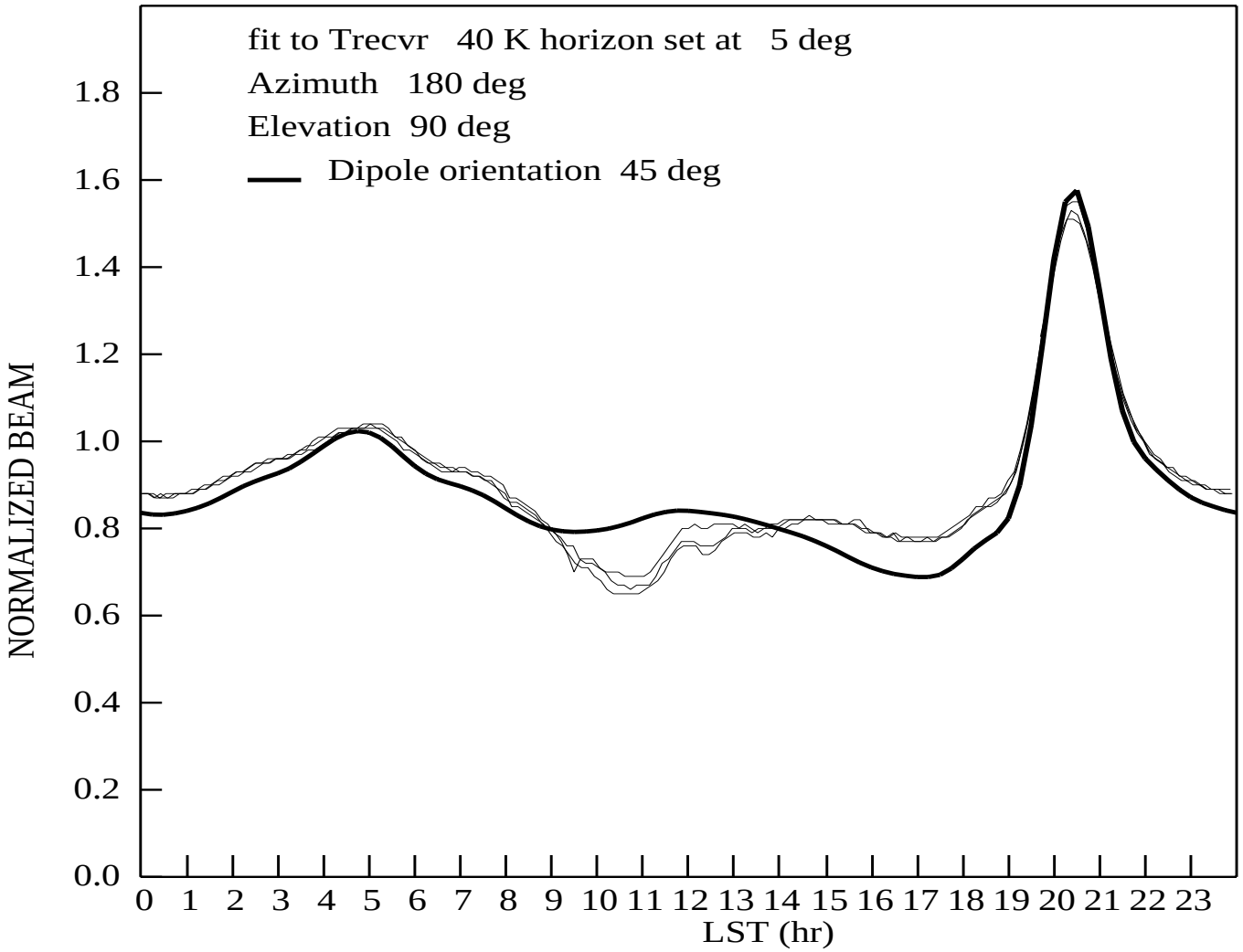
Beamscan on the Sun



Start 2003:107:14:20:15

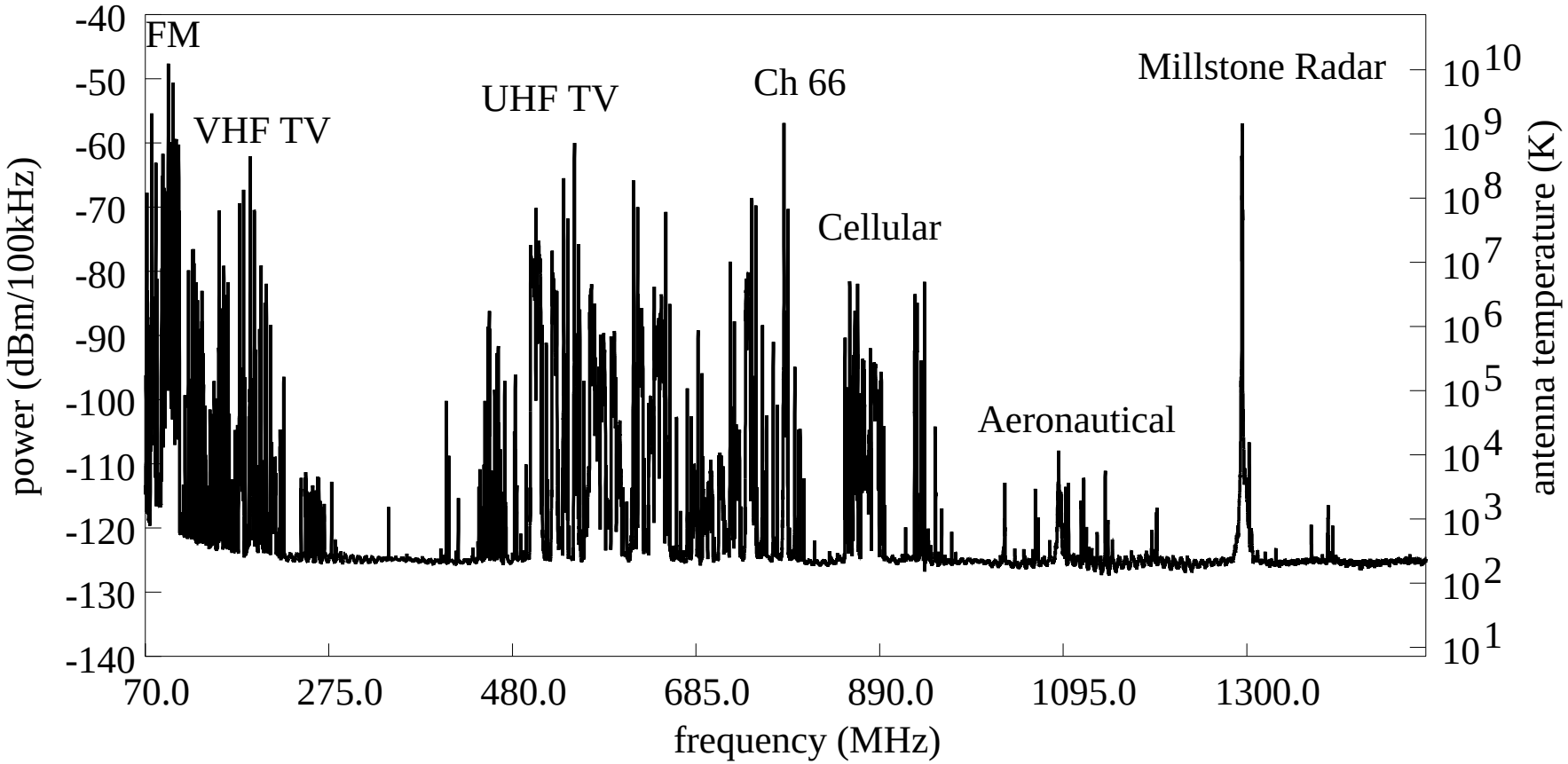
datamax 3.82 datamin 0.60

file: bmap5.txt



Calibration using Sky Models (Rogers et al. Radio Science,vol.39,RS2023,2004)

RFI environment at the Deuterium array site



CLOSEUP VIEW OF ACTIVE ANTENNA ELEMENT SHOWING RESONANT DIRECTORS ADDED TO REDUCE GAIN AT THE HORIZON ~ 10 dB

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

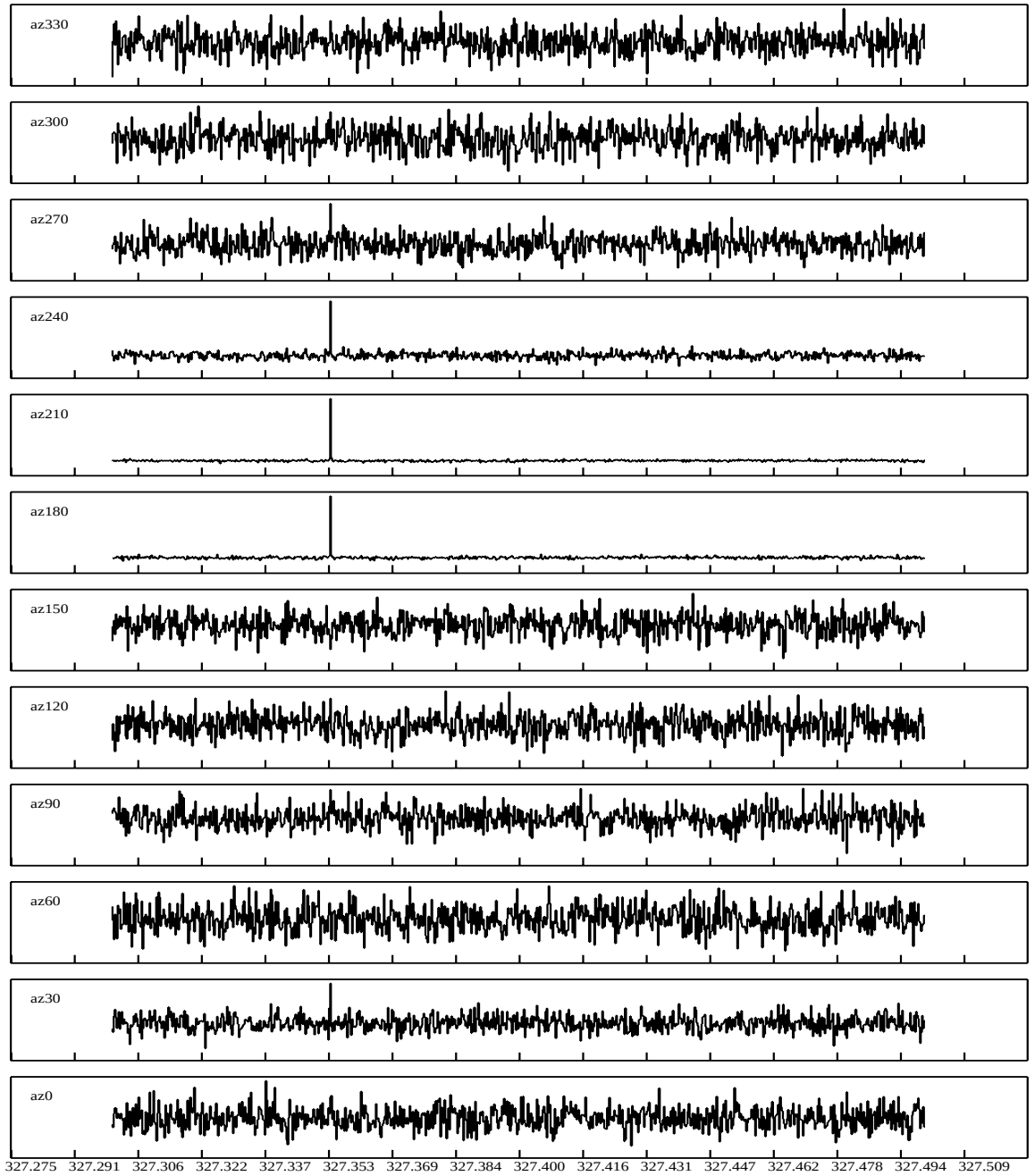
Sensitivity to detect* CW RFI (in EIRP at 100m from array)

- 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

D1 strength ~ 300 uK in 10 kHz = - 122 dBm
EIRP in -10 dBi sidelobe of individual dipoles

*** assumes 10 sigma detection and resolution of 244 Hz**

Note: FCC part 15 limit = 200uV/m at 3m = -49 dBm EIRP



Example of finding direction from RFI monitor Yagis

D array hardware (materials and services):

part	qty	unit_cost	cost
PC_motherboard	24x2	$100	$4800
Processor	24x2	$100	$4800
Disk,usb cards etc.	24x6	$50	$7200
GC4016	24x12	$48	$13824
NET2270	24x13	$20	$6240
ADSP-2116N	24x13	$14	$4368
Misc.R&C	24x~1600	$0.20	$7680
PC board assembly	24x39	$50	$46800
boxes,fans etc	24	$1000	$24000
Machined parts	24x60	$25	$30000
Analog filters	24x144	$25	$86400
Dual-pol active dipole	24x24	$80	$46080
Ground plane frames	24	$800	$19200
Fiber optics, server etc.			$40000
Total			~ $350000

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.

Observing schedule:

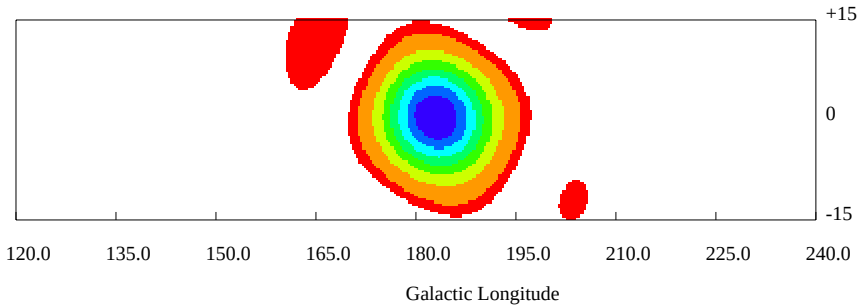
Stations set pointing at Zenith

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

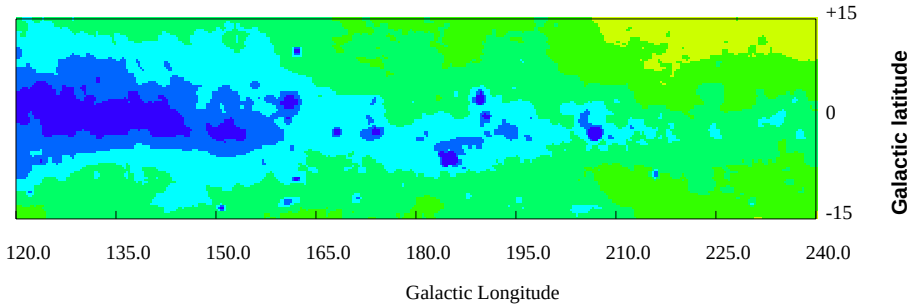
Notes: 1] Zenith beam power variation with LST for Tsys calibration

2] Phasing and beamforming checks on the Sun and Cygnus

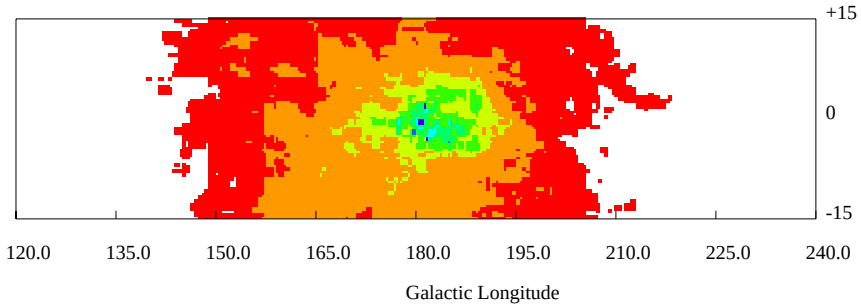
Station beam at 0 hour angle



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:

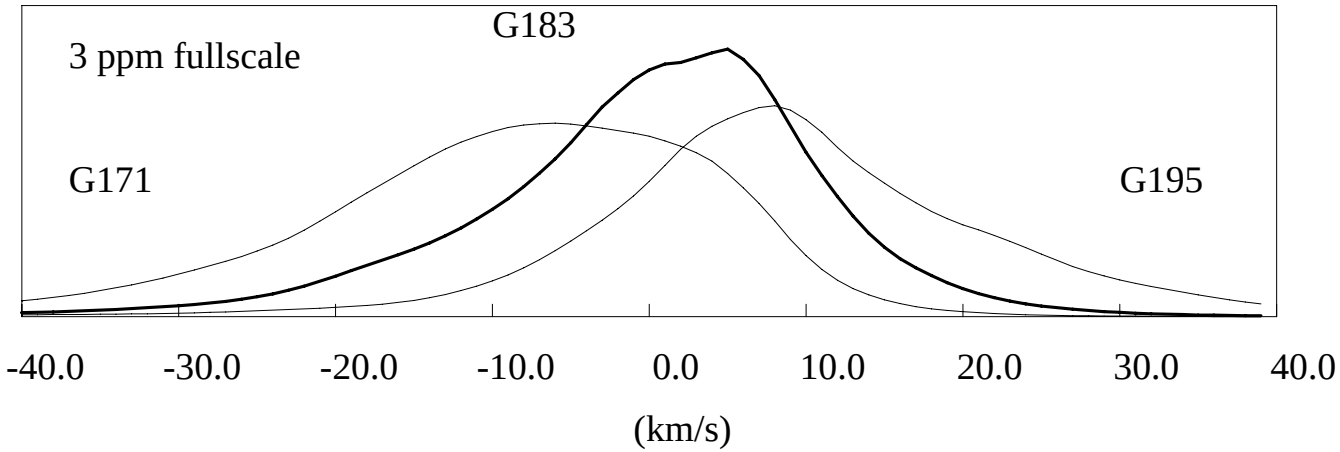
1] D1 spin temperature = 130 K

2] D/H ratio = 15 ppm

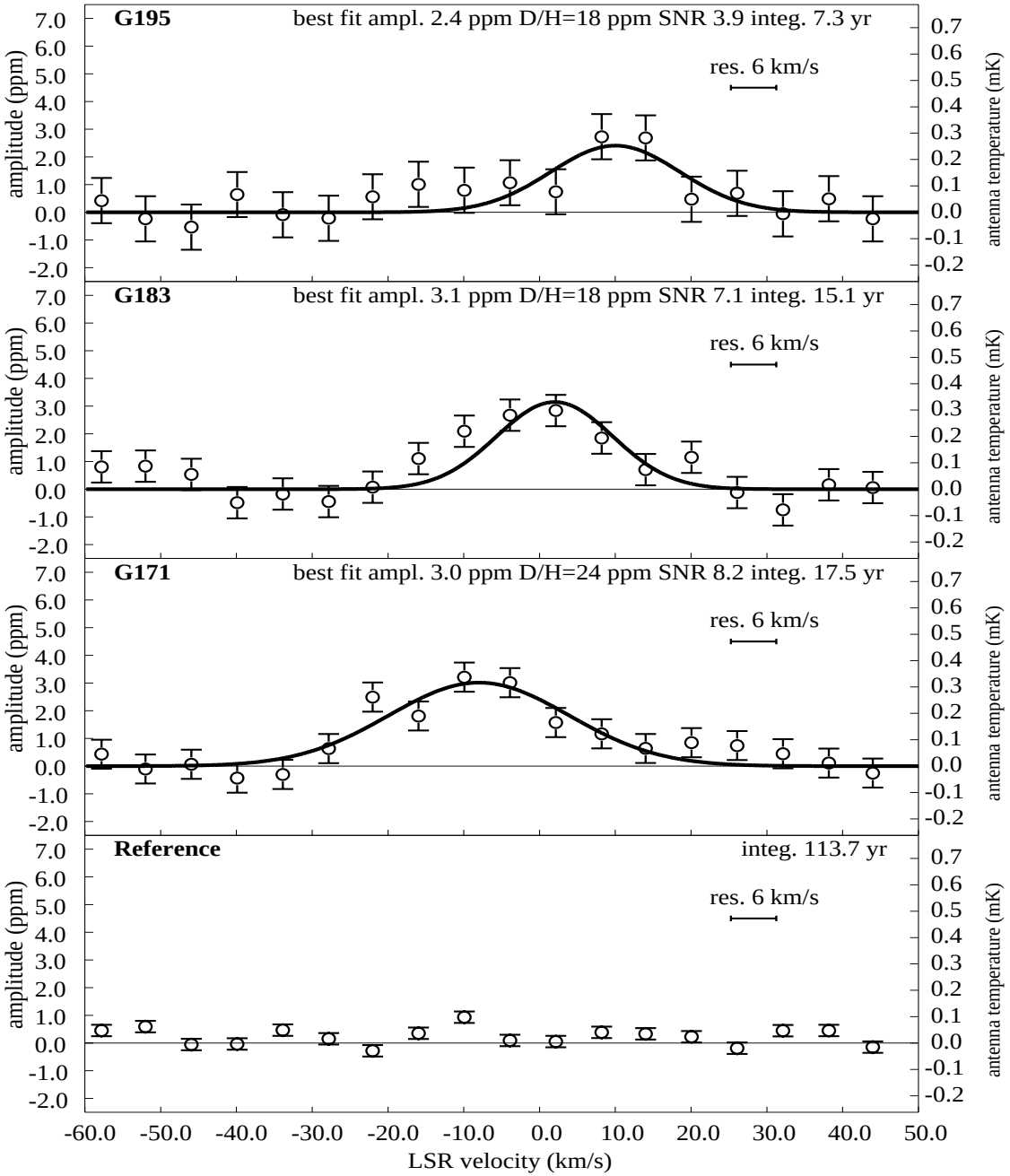
3] continuum uniformly mixed with H1 and 6 K (3K CMB + 3K) extragalactic

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)



Final results of 2 years observing – Rogers et al. A.J.; 133, 1625-1632, 2007

SUMMARY

- Array was operated with 24 stations from June 2004 to July 2006 – total hardware cost ~ 350k$
- RFI/intermod issues have been the dominant challenge
- The Deuterium line was observed in the Galactic anticenter consistent with D/H ~ 20 ppm
- SNR ~ 6 – Ap.J. Letters Sept. 2005
- SNR ~ 8 – A.J. April 2007