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

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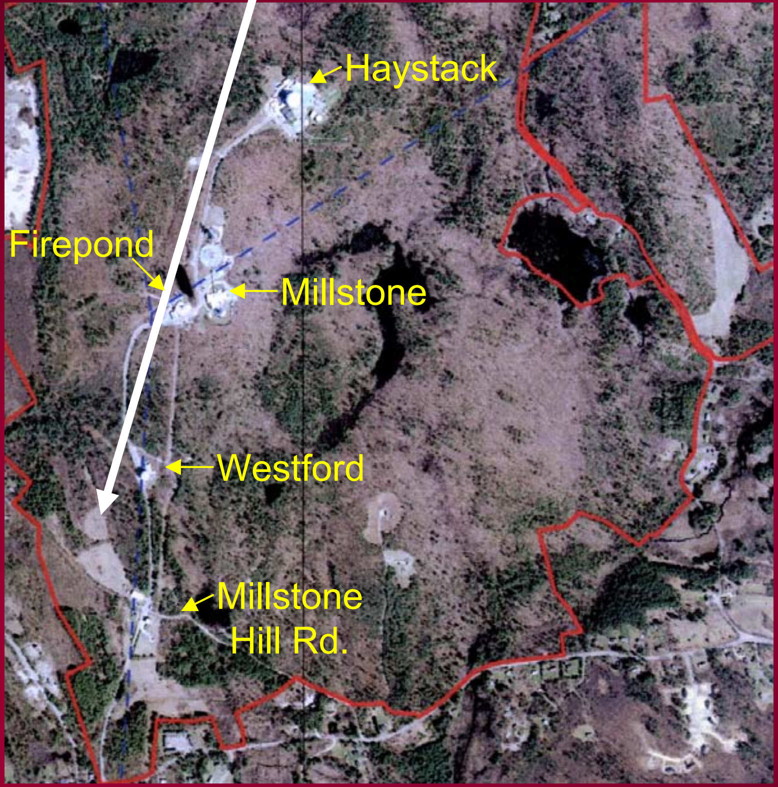
OVERVIEW

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

Deuterium Array

Location

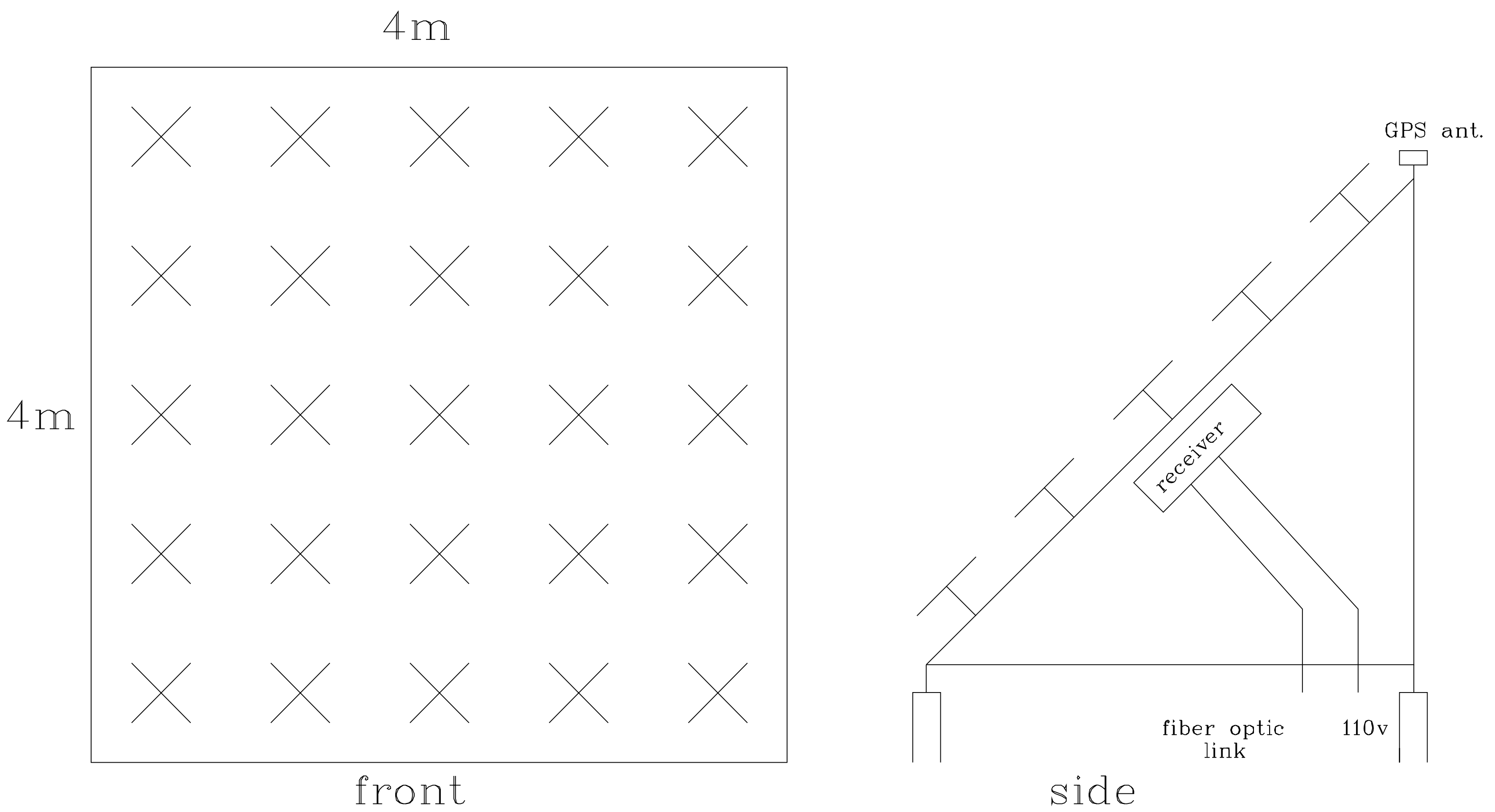


- Multibeam array at 327 MHz
- Soccer field sized
- Science
  - D/H ratios tell us about density of material in the early Universe → open vs. closed scenarios
  - Optically, H and D spectrally close
- Technical
  - Digital receiver
  - Allows deep integration
  - Active antenna design

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 Tsys close to sky noise
- Ameliorating RFI:

1 mK in 10kHz ~ -189 dBm

e.g. signals from Westford ~ 1K

ensuring adequate IP2

e.g. mix with TV signals (~ -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

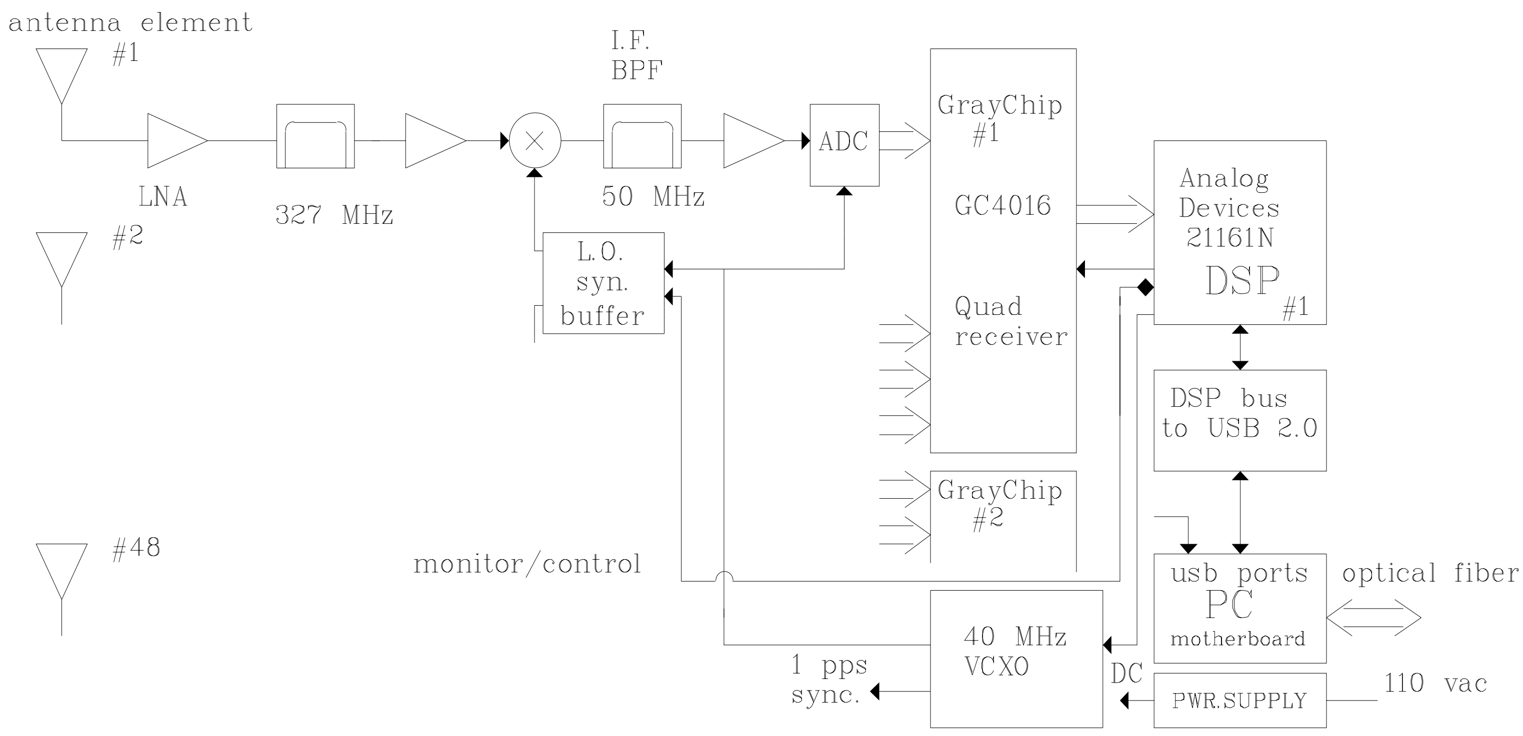
3] RFI leakage from box solved by adding more power line filtering and large number of screws to improve ohmic contact of box cover

Summary of array Characteristics:

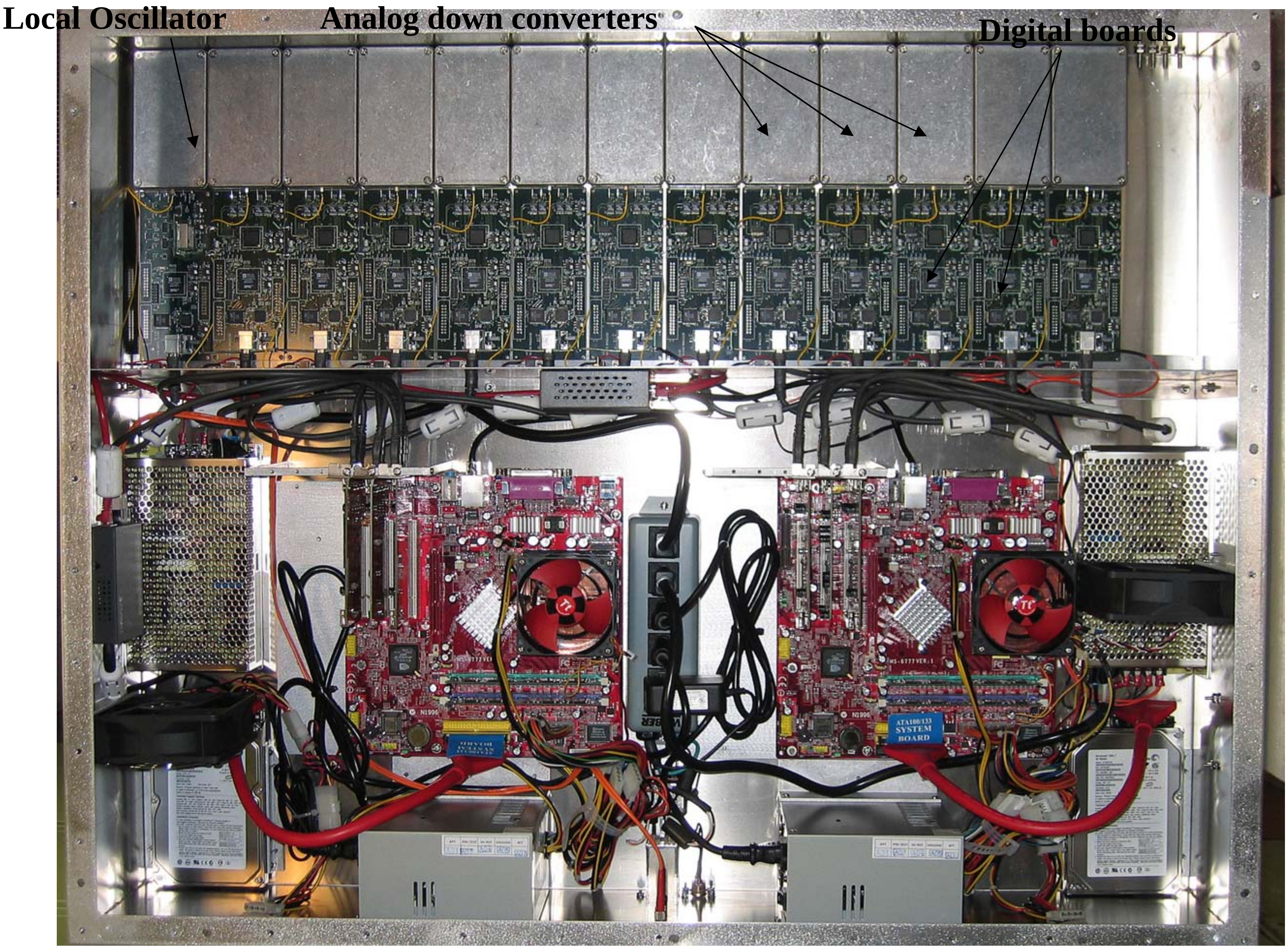
Configuration	quasi-regular array of 24 stations
	~ 15 m spacing
Each station	5 x 5 (24) compact array of crossed Yagis
	collecting area : 12 m^2
	beamwidth: 14 degrees
	electronic steering: ~ +/- 40 degrees 3 dB
	manual adjustment of elevation 30 – 90 deg
	number of available simultaneous beams: 4
Frequency 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

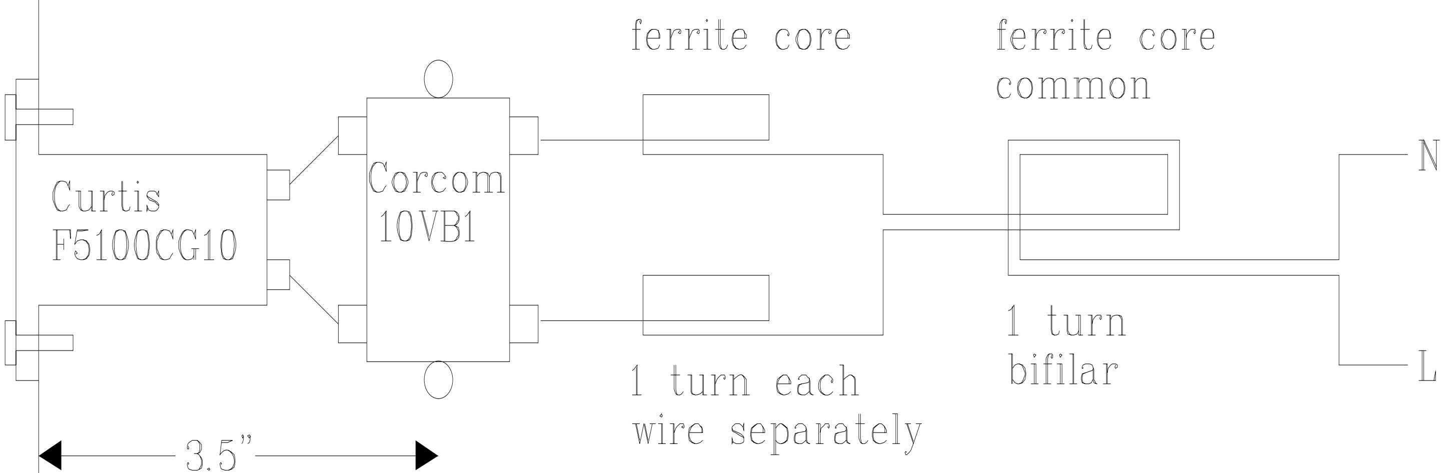
Tsys: 110 K (40 K recvr + 70 K sky)
Number antenna sub-arrays: 24
Number of polarizations: 2
For a resolution of 10 km/s ~ 10 kHz
1-sigma noise in 30 days: ~ 100 μK
(about 6 months observing a given point in sky)
For D/H ~ 1.5×10^{-5} expect ~ 300 μK
(towards Galactic anti-center)



D1 array receiver functional block diagram



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

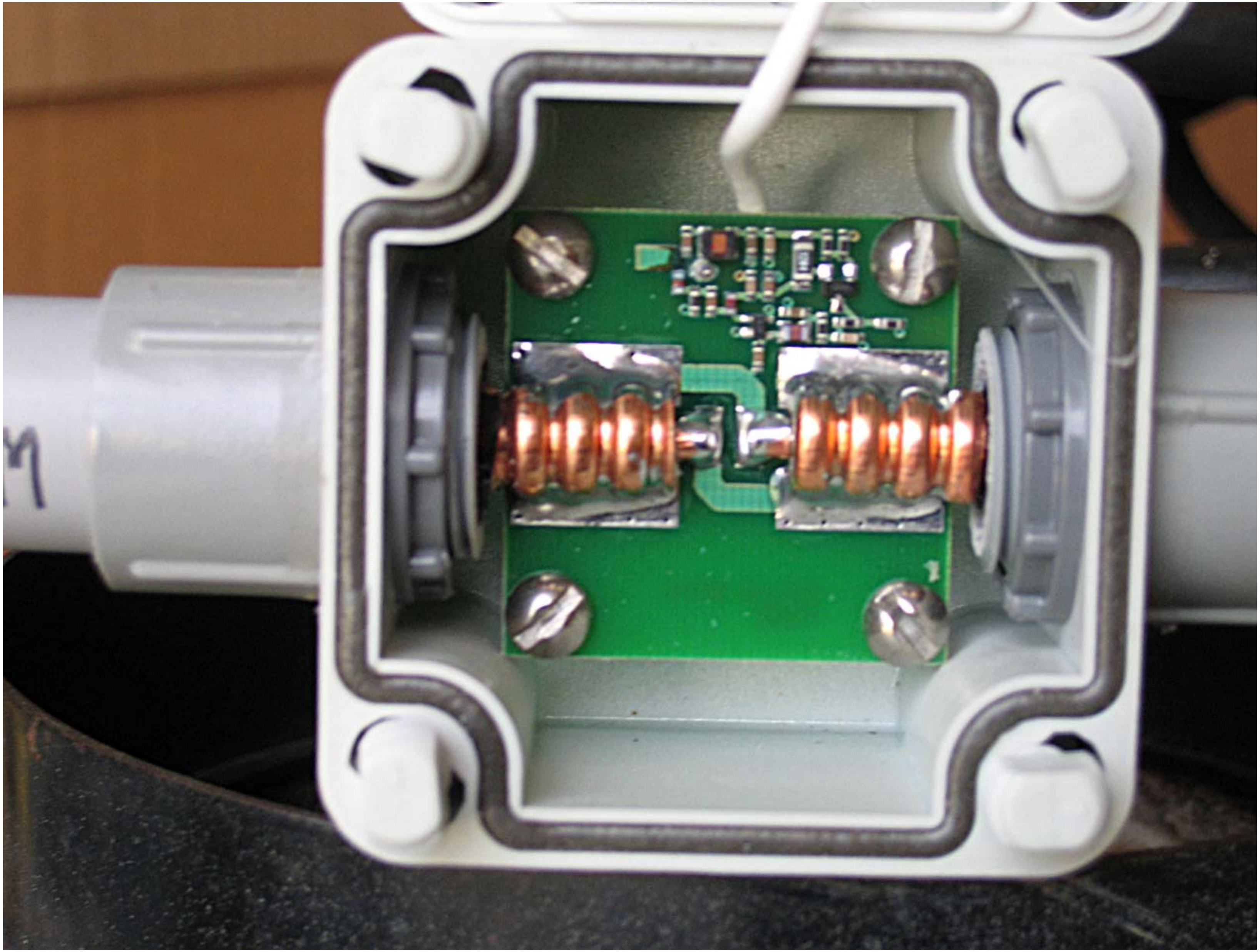


Notes: 1] do not connect ground wire between filters

2] Make sure filters have tight low ohmic contact with the box

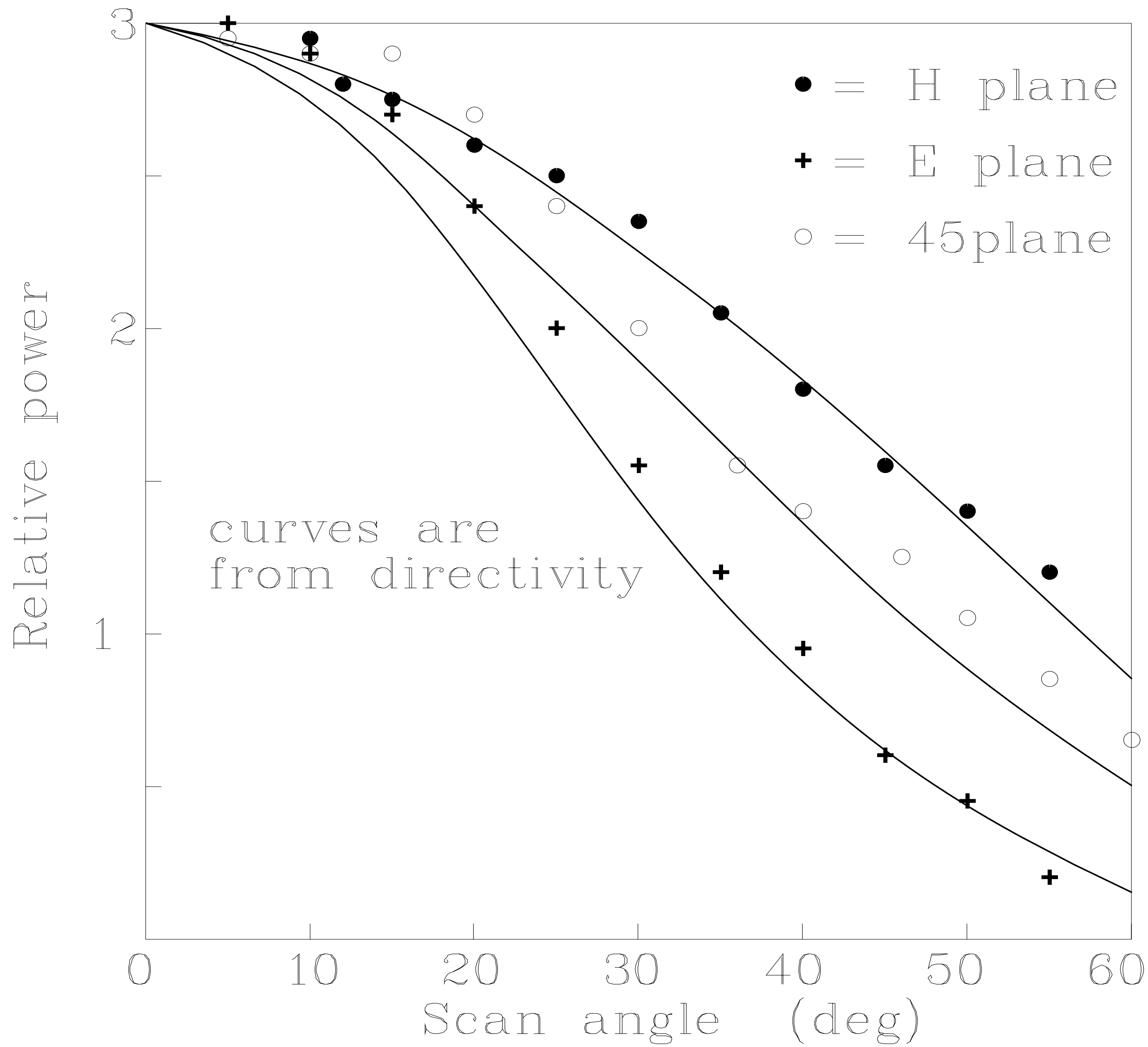
Power filtering
D1 array

AEER 1 Aug 03



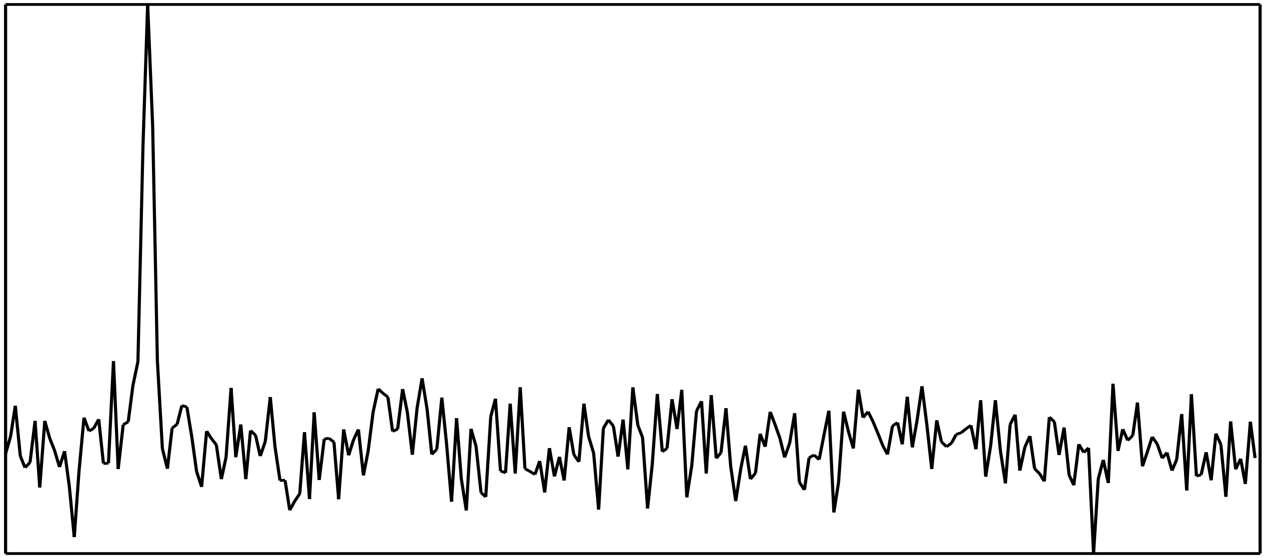
Coaxial stub filters form an integral part of the low noise active dipole antenna

Scan loss



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

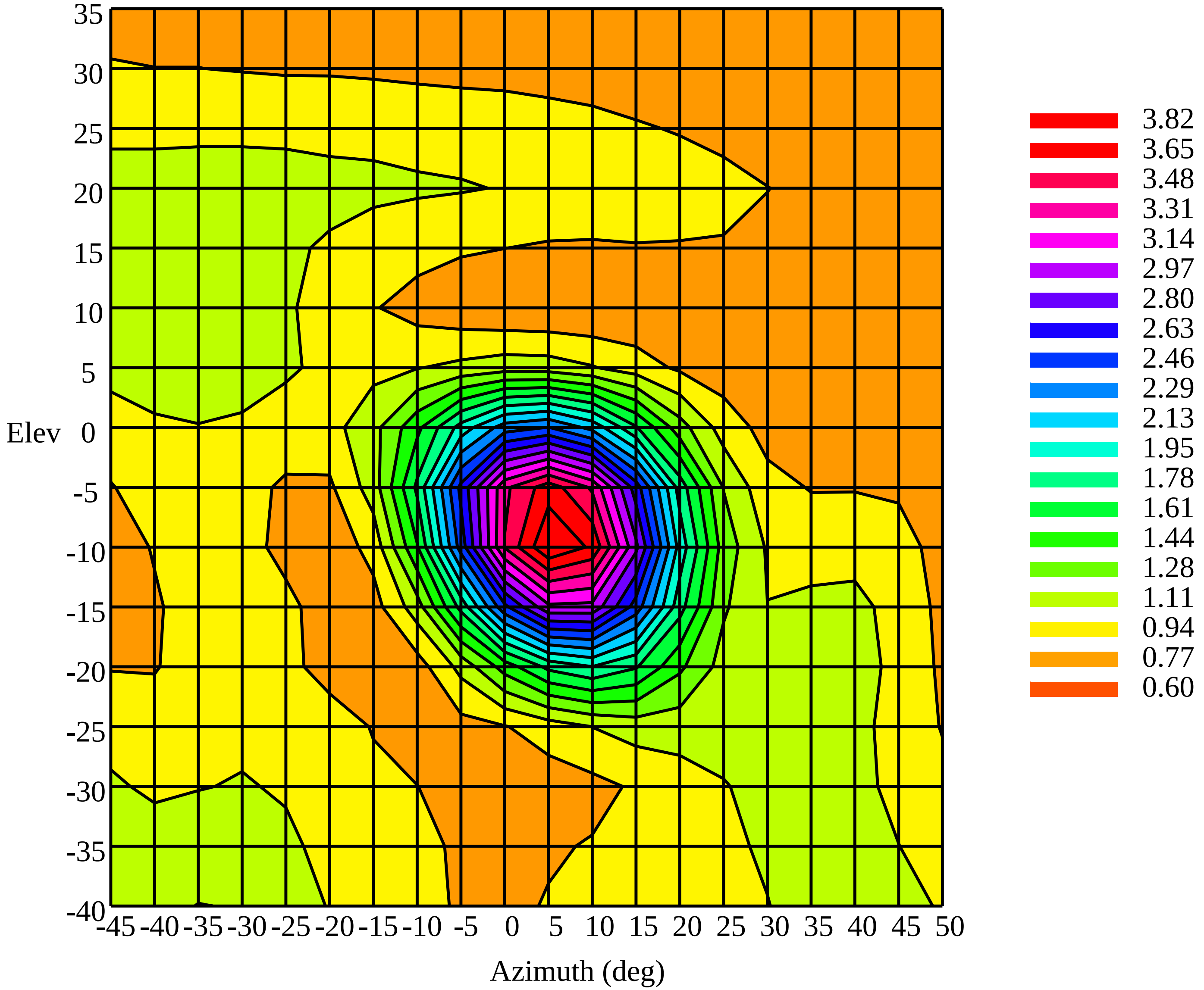
Pulsar test on 0957+56



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

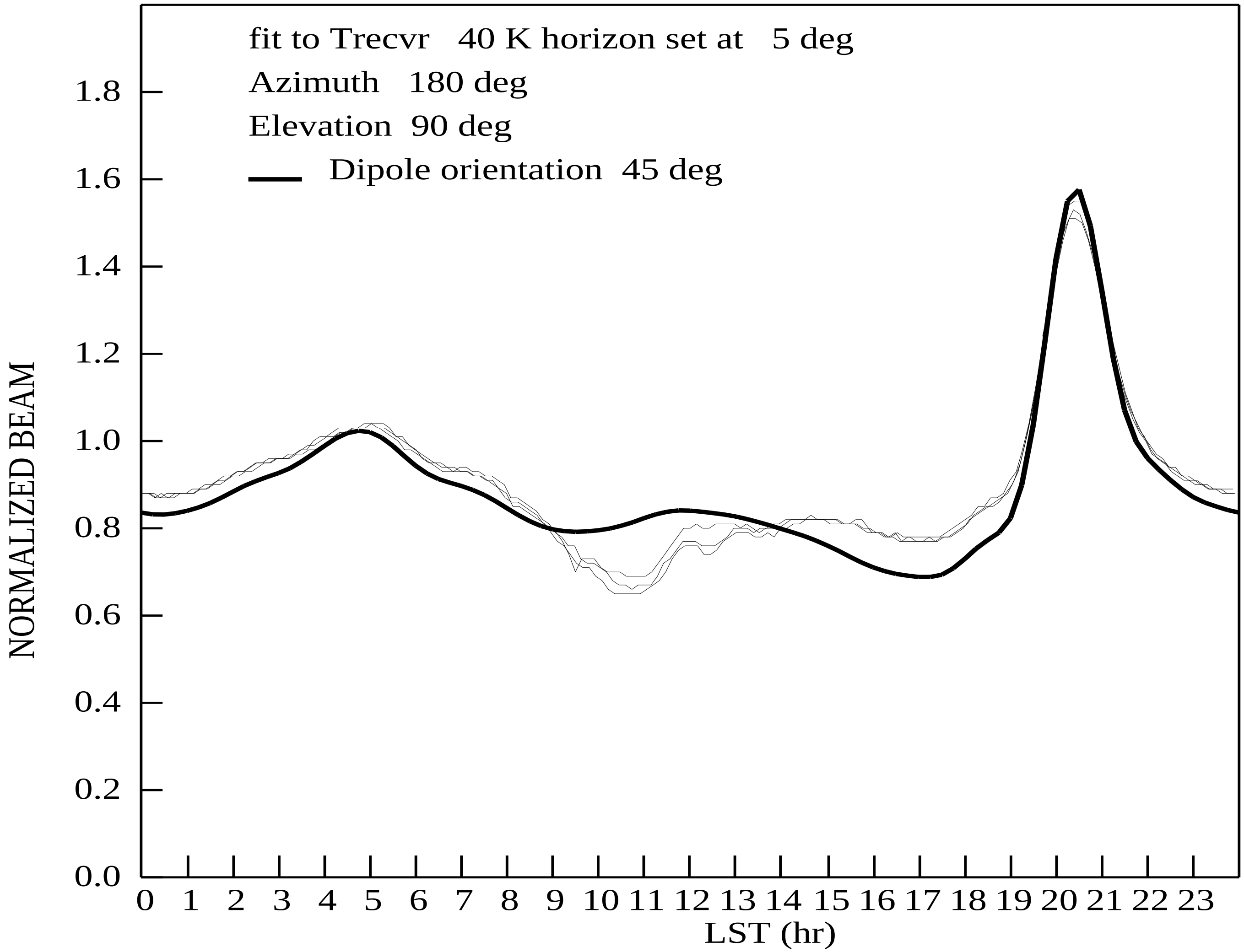
Beamscan on the Sun



Start 2003:107:14:20:15

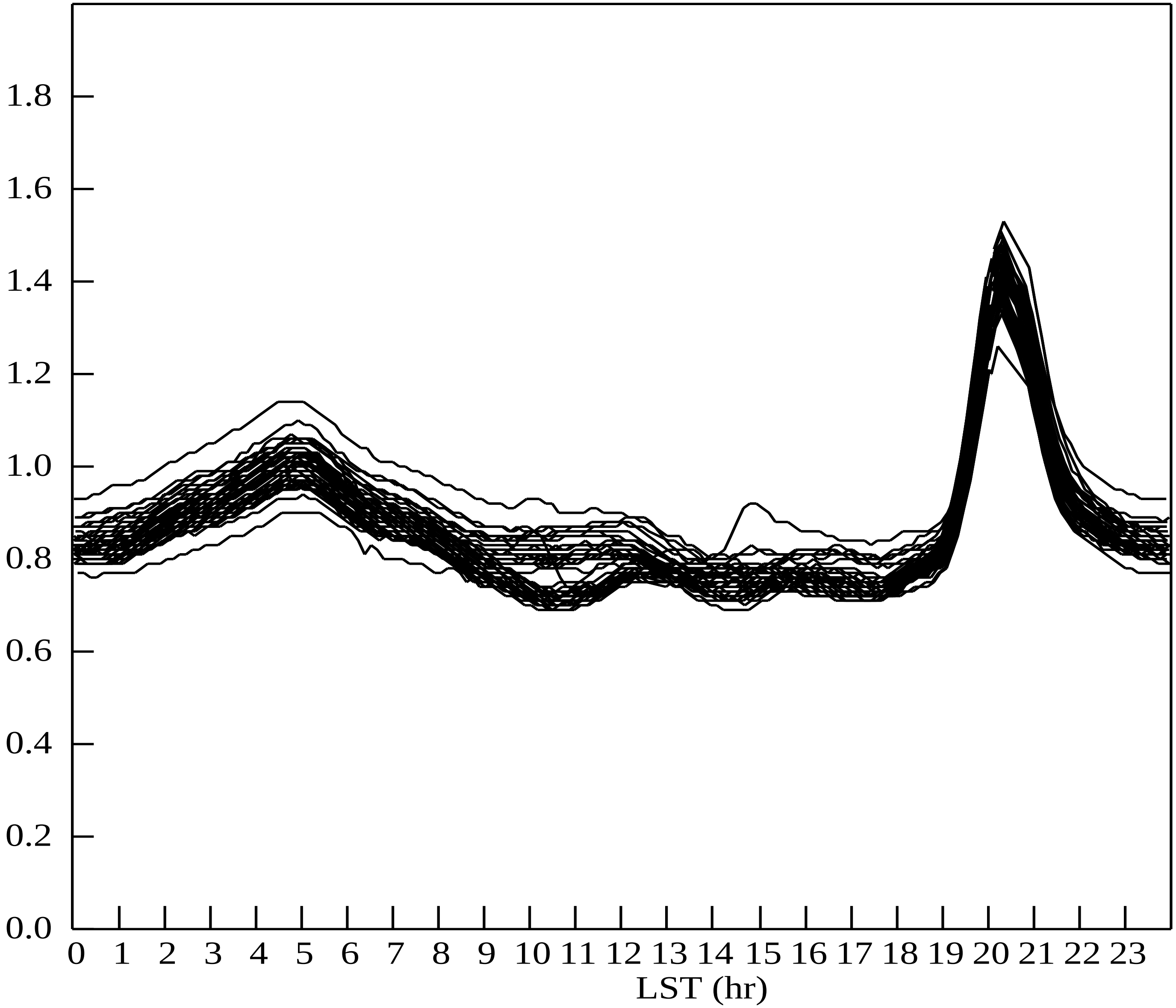
datamax 3.82 datamin 0.60

file: bmap5.txt

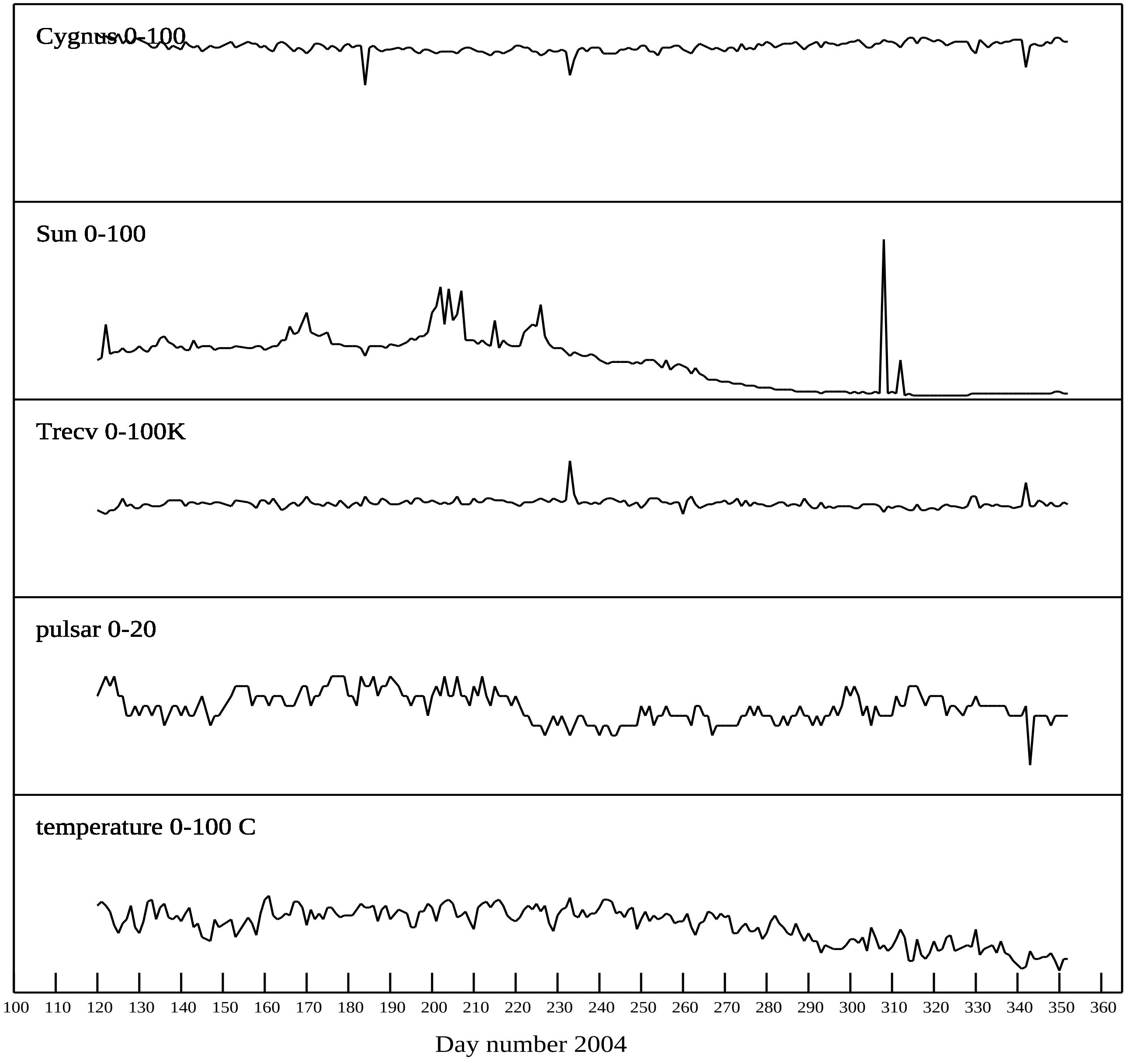


Calibration using Sky Models (Rogers et al. Radio Science,vol.39,RS2023,2004)

Measurement of Trecvr using zenith beam



VARIATION OF NORMALIZED ZENITH BEAM FOR ALL STATIONS DAY 2004_277

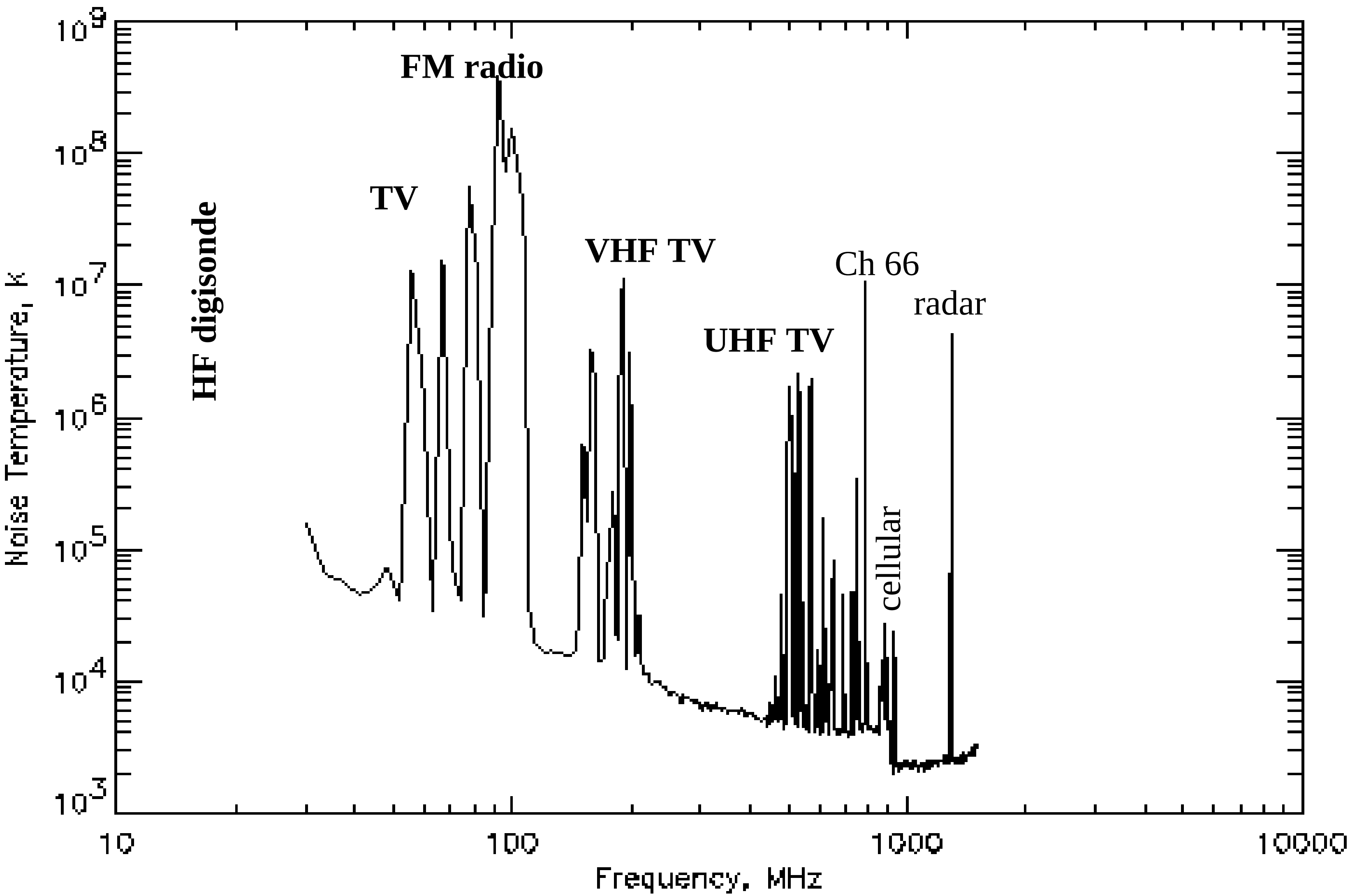


History of checks from each day averaged over all stations

file: temp

Sun Dec 19 01:33:16 2004

RFI environment at Haystack Observatory

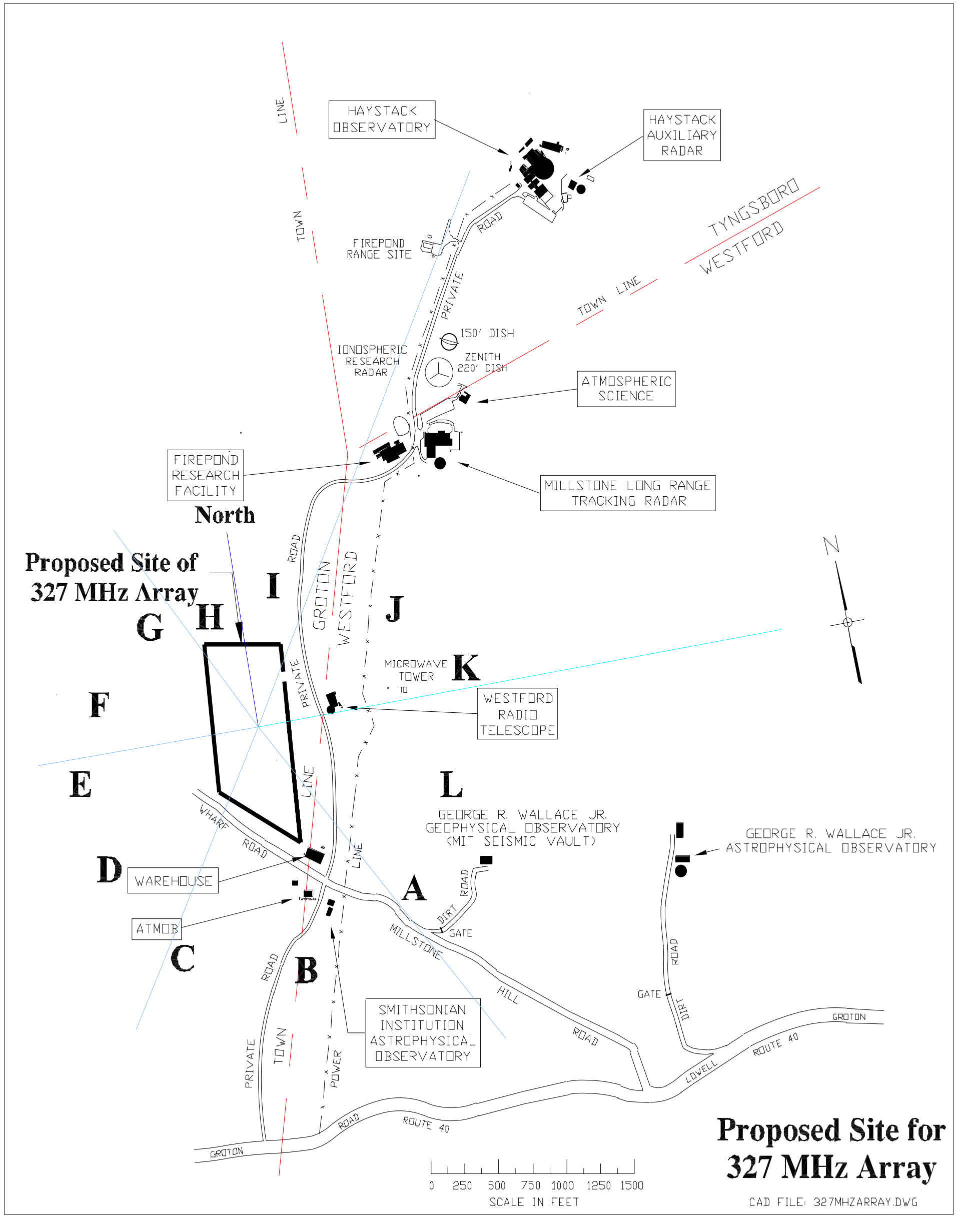


RFI noise temperature near Haystack BW = 1 MHz integration 100 s RBP 8 Dec 03

(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



Proposed Site for 327 MHz Array

CAD FILE: 327MHZARRAY.DWG

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.

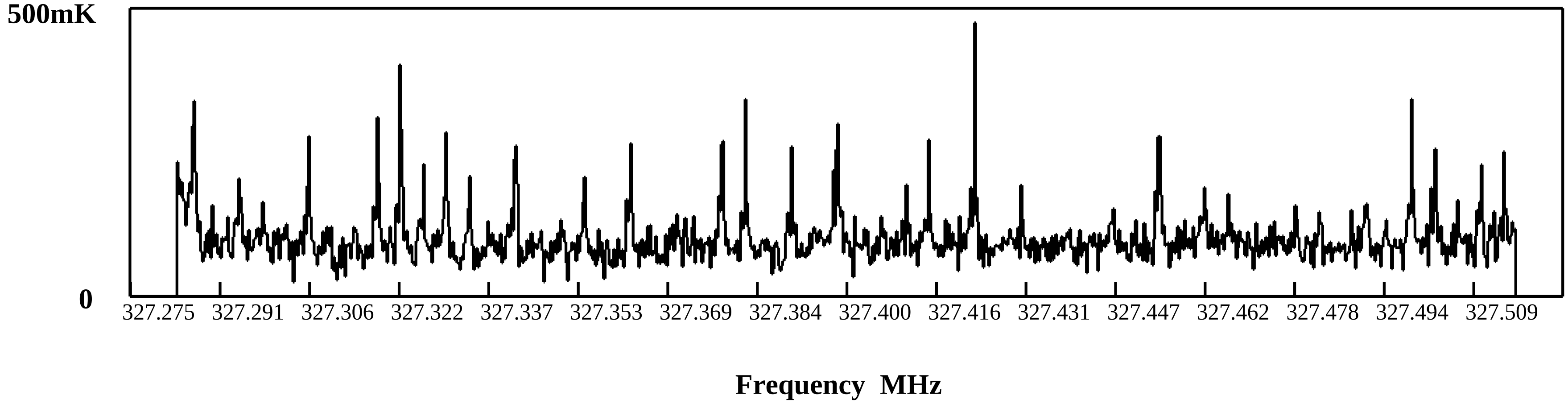
Sensitivity to detect* CW RFI (in EIRP at 100m from array)

- 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**

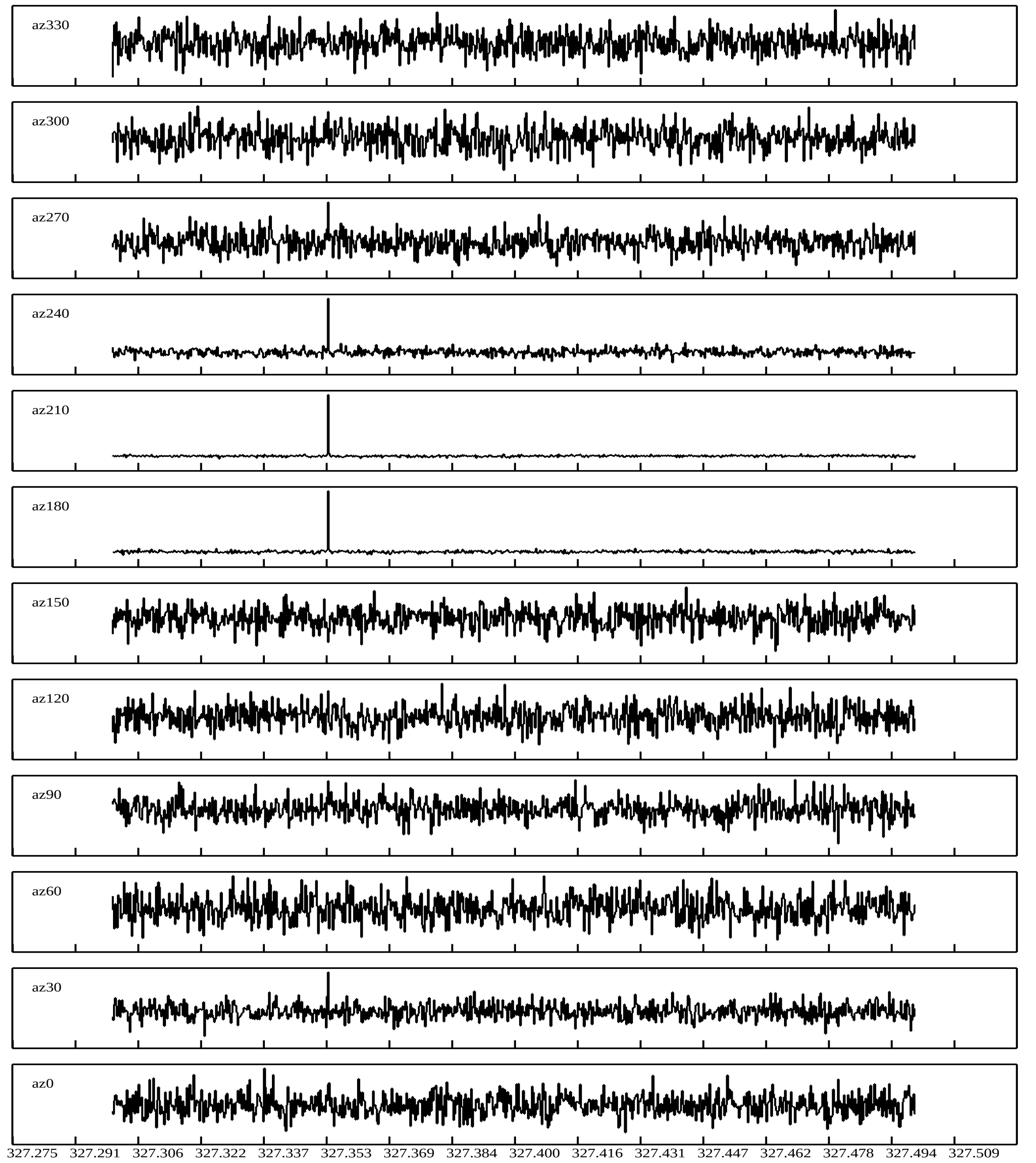
Note: FCC part 15 limit = 200uV/m at 3m = -49 dBm EIRP

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:

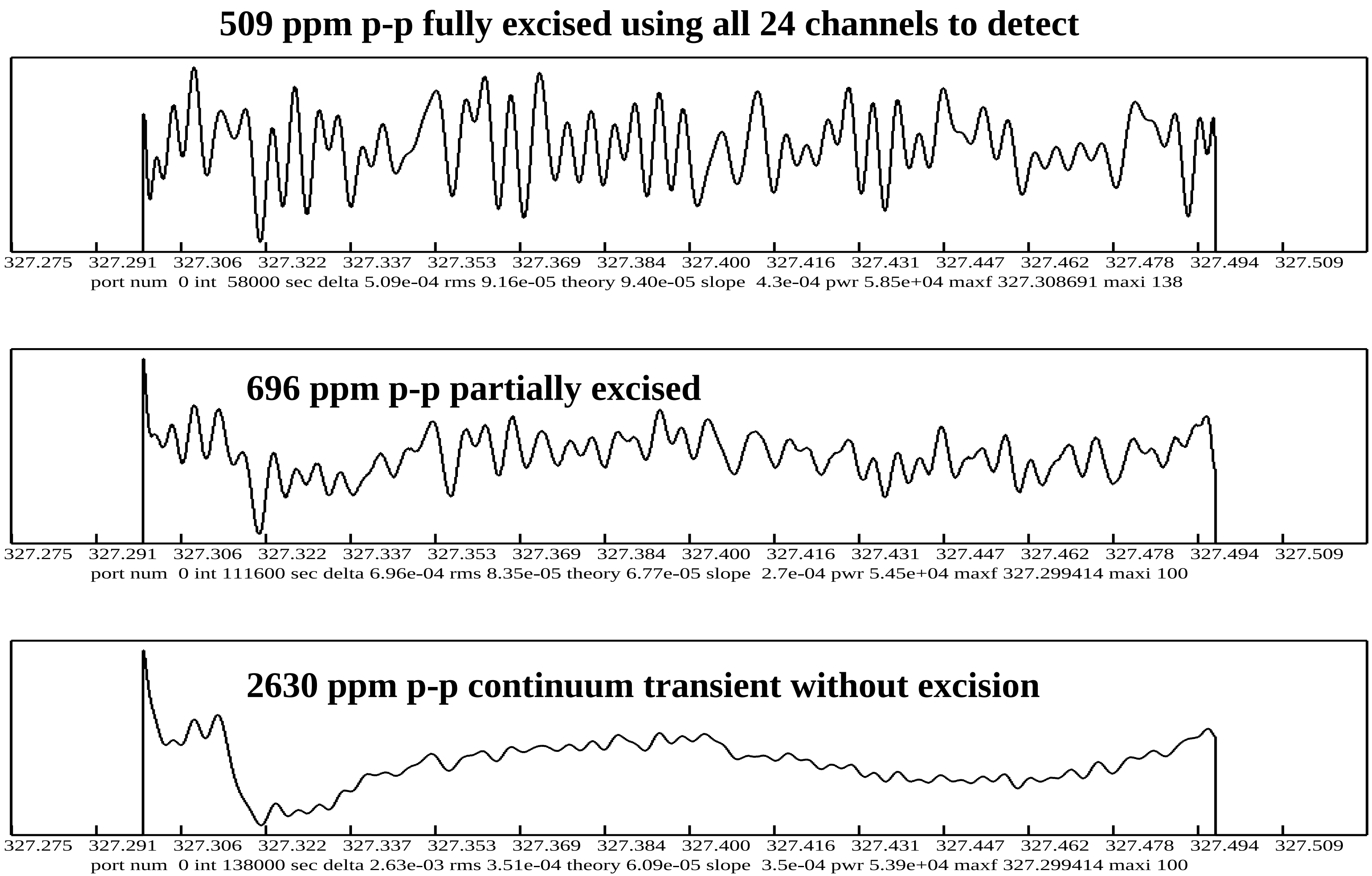
1] Reduce the horizon response – resonant directors reduced gain at horizon by 10 dB.

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.



Example of excision of multi-path-ed RFI transient

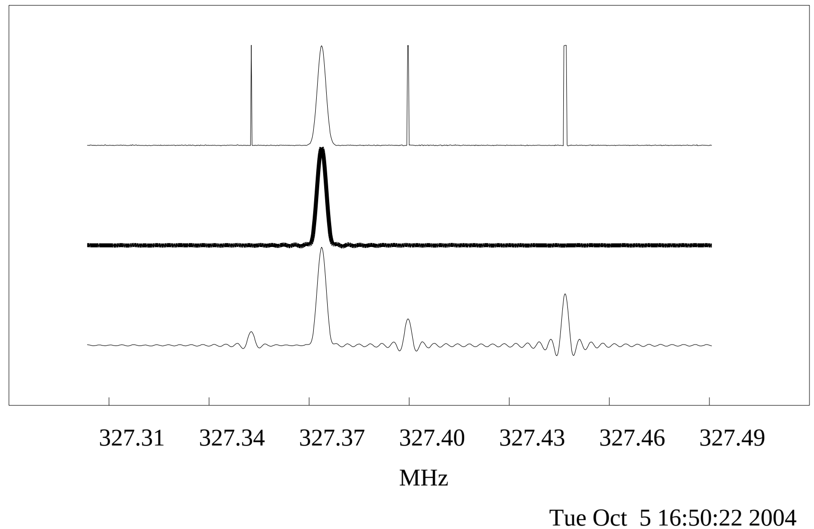
D1 Array vlsr= 39.4 s=G183 file: /data/d04/2004_099_00.d04b Thu Apr 15 22:45:17 2004

Method of spectral exclusion – simulated data

data

fit with exclusion

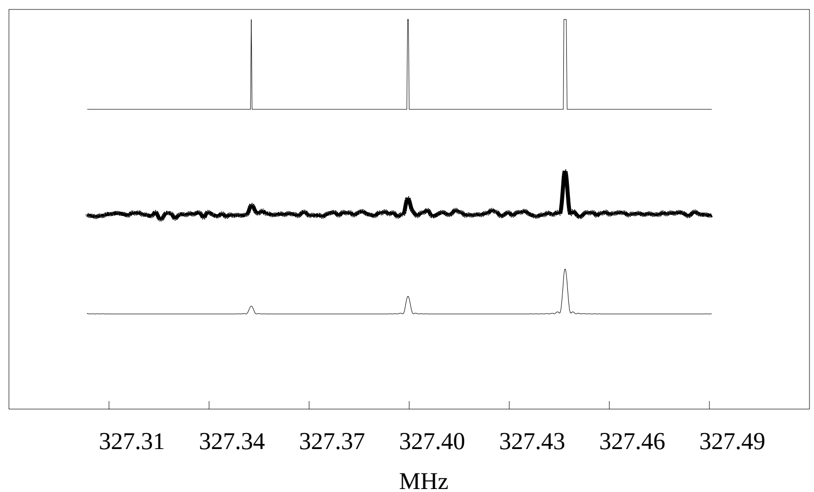
fit without exclusion



excluded frequencies

std dev from 2000 trials

std dev from covariance matrix



LEAST SQUARES SMOOTHING:

$$\hat{s} = \left(A^H w A\right)^{-1} A^H w X$$

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:

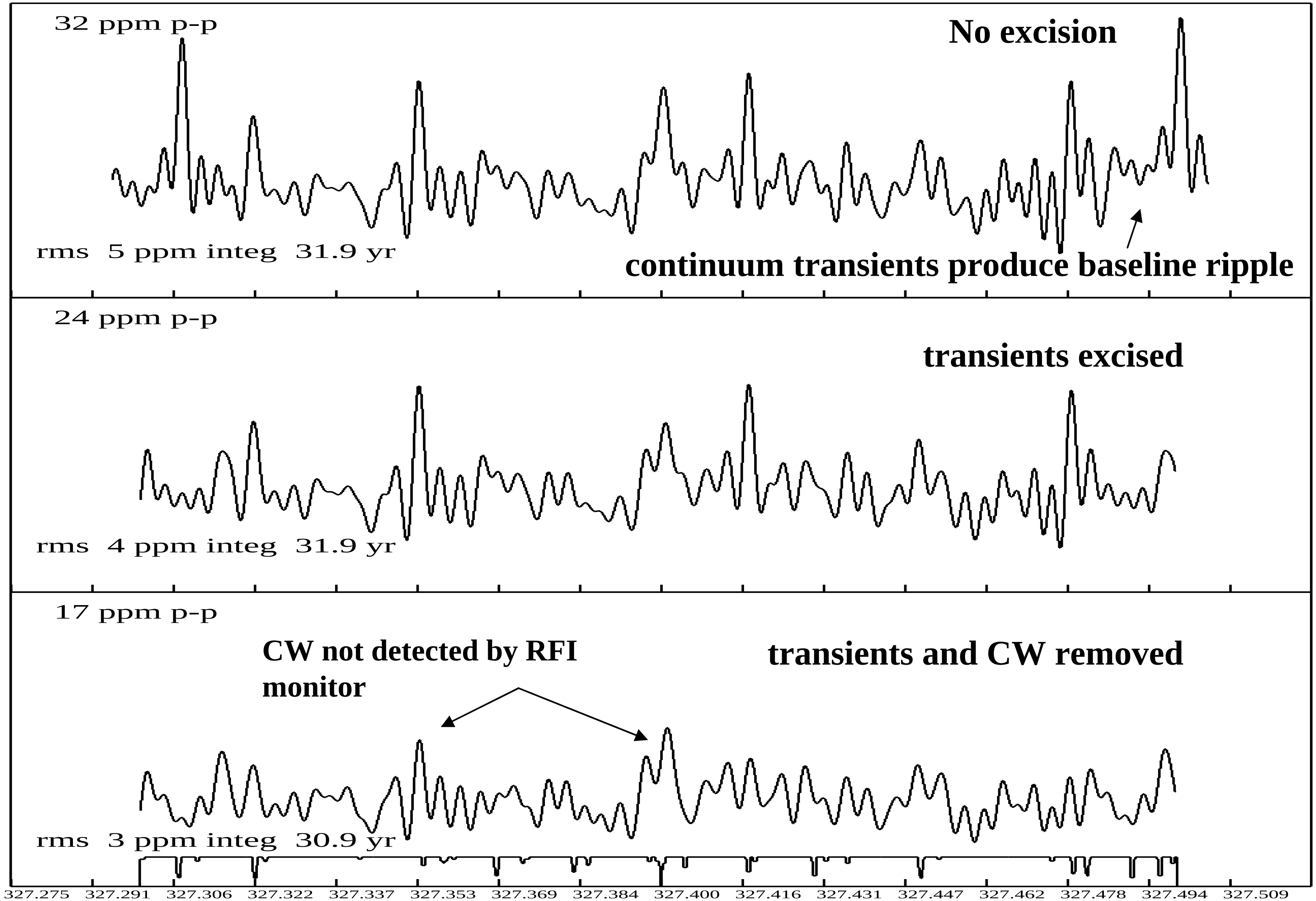
$$\sigma_i^2 = \left(A(\hat{s} - s)(\hat{s} - s)^H A^H\right)_{ii} = \left(A\left(A^H w A\right)^{-1} A^H\right)_{ii} \sigma_0^2$$

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

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



Observing schedule:

Stations set pointing at Zenith

Source	time span	maximum scan angle (deg)
Galactic Anti-center D1 emission (Galactic longitudes 171 183 and 195)	6 hours/day	40
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

Summary of data loss due to RFI

RFI	equivalent loss of integration
transient excision :	5%
CW exclusion:	15%

APPROXIMATE ESTIMATE OF EXPECTED SIGNAL:

$$s = 0.27 \times (n_D / n_H) \times (T_{spin} - T_{cont}) \times \tau / (T_R + T_{cont}) \approx 4.4\, ppm$$

n_D / n_H = Deuterium abundance ratio (1.5×10^{-5})

T_{spin} = spin temperature of Deuterium (130 K)
T_{cont} = Continuum temperature (70 K)
τ_H = hydrogen 21 cm opacity (2)
T_R = receiver noise contribution (40 K)

MORE ACCURATE ESTIMATE OF EXPECTED SIGNAL:

$$s' = (a \otimes bm) / (b \otimes bm)$$

$$a = 0.27 \times (n_D / n_H) \times (t_{spin} - t_{cont}(1, b))\, \tau(l, b)$$

$$b = T_{cont}(l, b)$$

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

T_H = hydrogen line temperature
T_{spin} = Hydrogen spin temperature

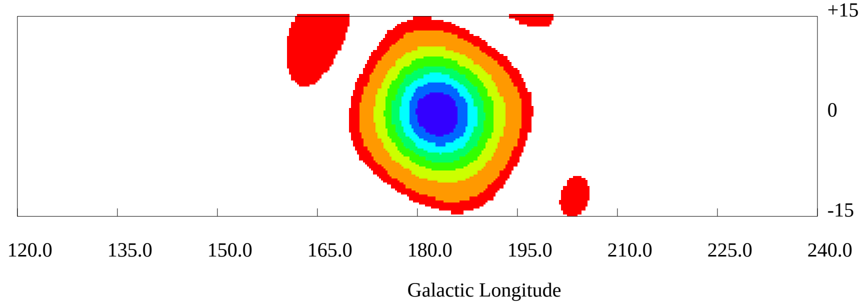
$$bm = \frac{\left| \sum_N e^{i\theta_k} \right|^2 |a_k|^2 s_k T_{sky}}{N \sum_K |a_k|^2 s_k} + T_R$$

$|a_k|^2$ = beam response of each dipole

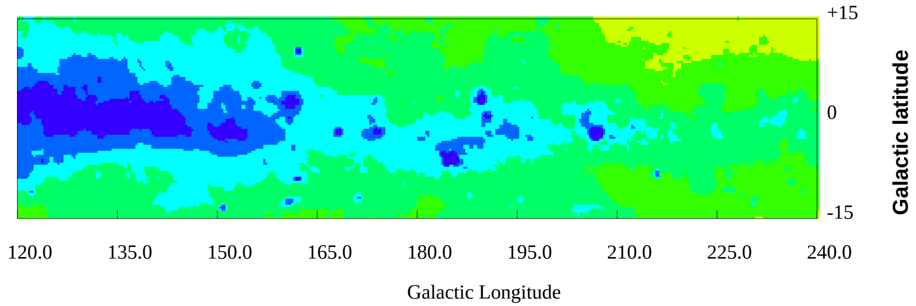
θ_k = beam steering phase to k^{th} sky patch

N = number of elements = 24
K = total number of sky patches

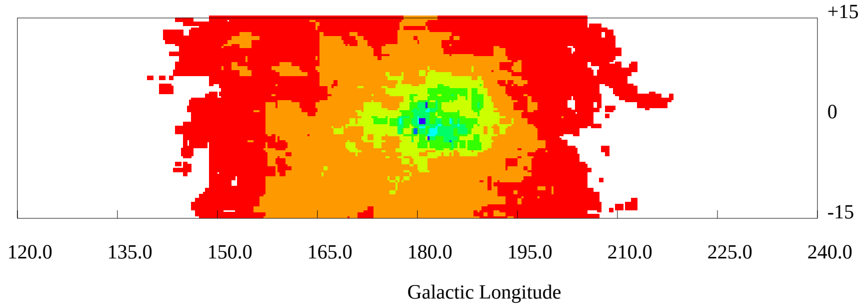
Station beam at 0 hour angle



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:

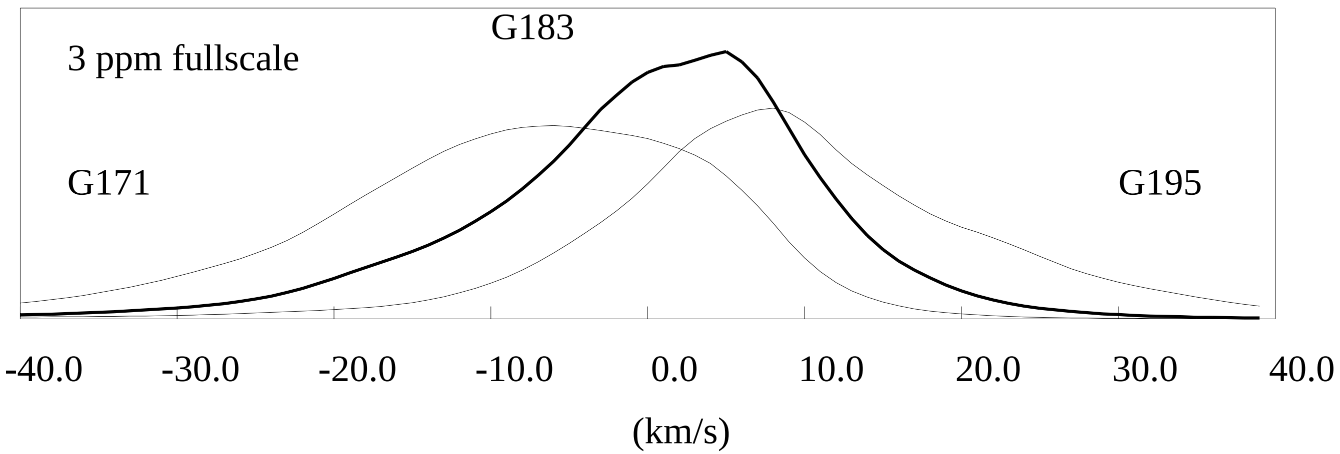
1] D1 spin temperature = 130 K

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

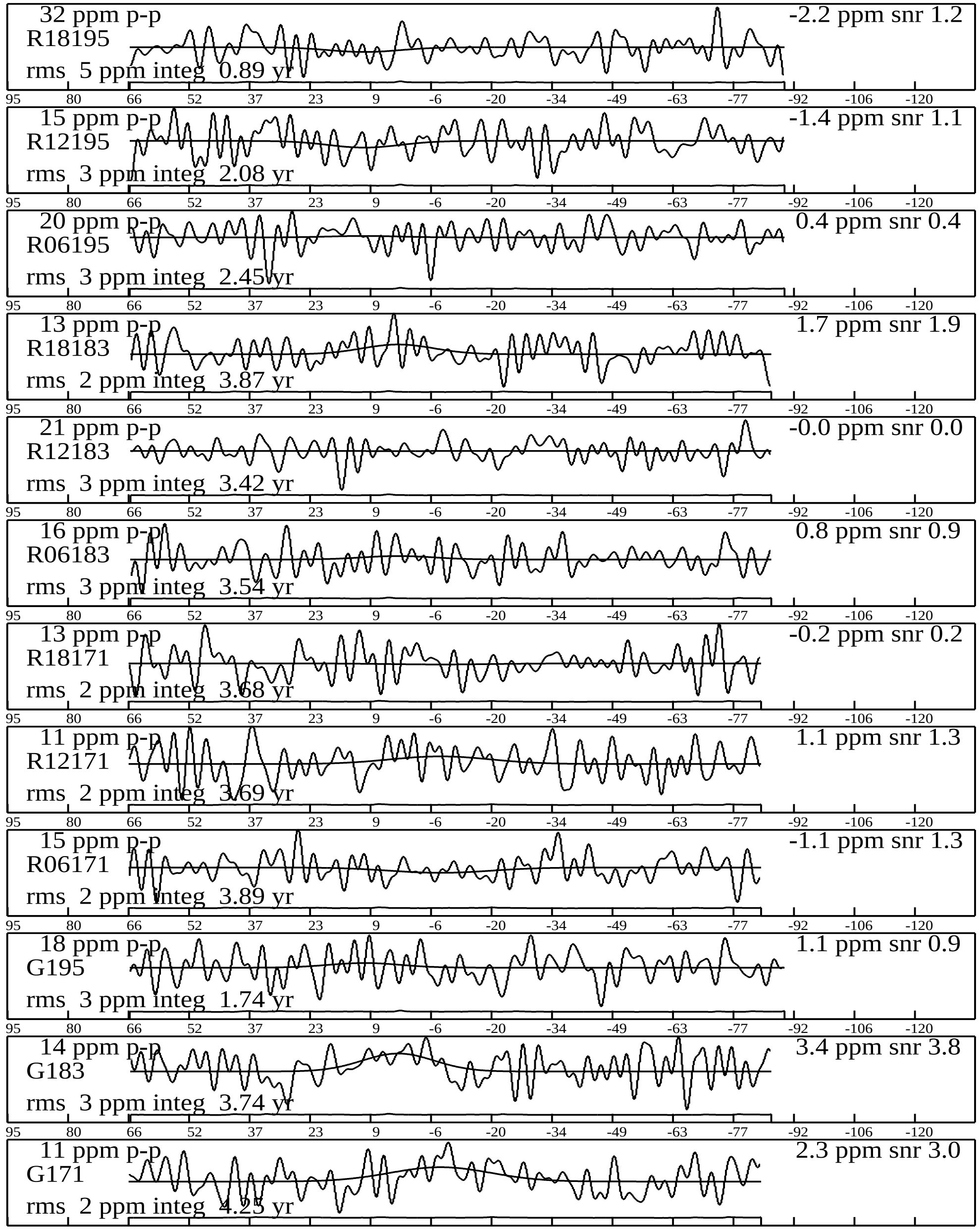


G183 peak = 2.6 ppm (1.6 ppm if all continuum behind, 3.6 ppm in all in front)

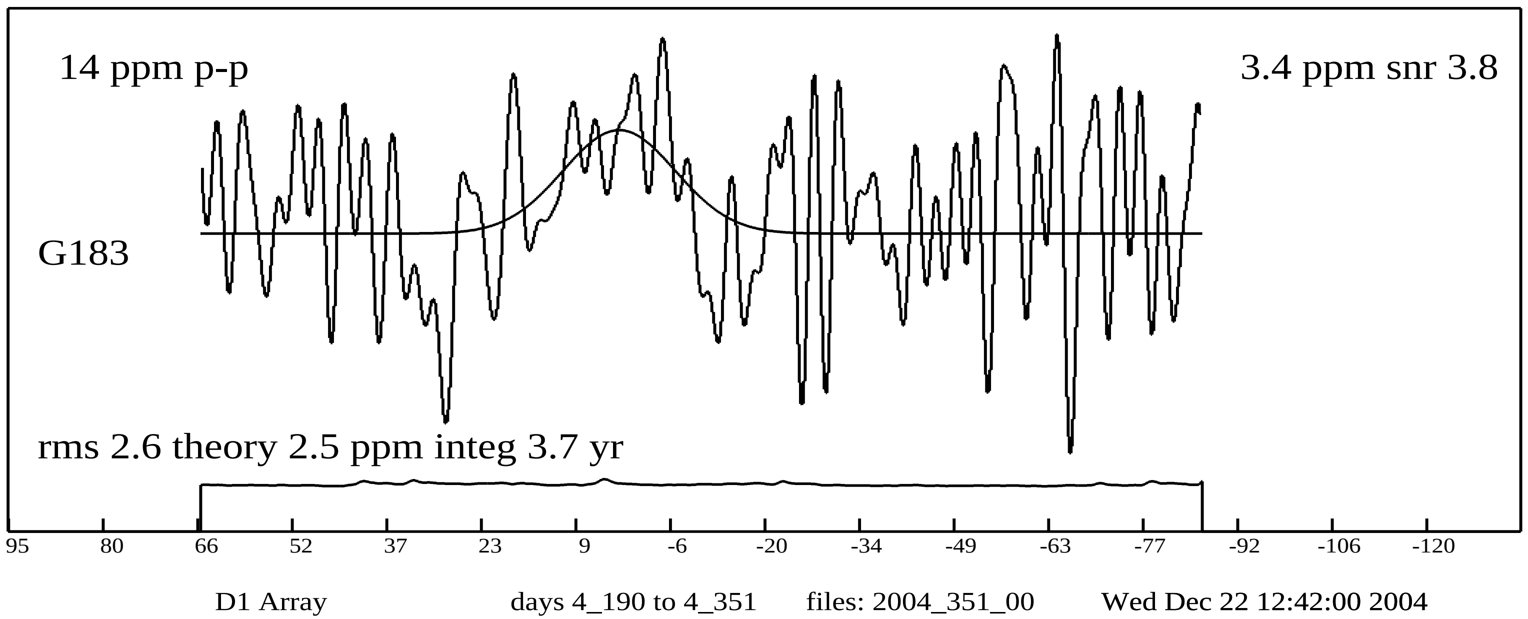
T_{spin} (K)	Continuum all behind H1 (ppm)	Continuum mixed with H1*	Continuum all in front of H1
110	1.7	3.2	4.7
120	1.7	2.9	4.1
130	1.6	2.6	3.6
140	1.6	2.6	3.6
150	1.7	2.4	3.2

* 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



days 4_190 to 4_351 Wed Dec 22 12:24:47 2004



14 ppm p-p
3.4 ppm snr 3.8
G183
rms 2.6 theory 2.5 ppm integ 3.7 yr
95
80
66
52
37
23
9
-6
-20
-34
-49
-63
-77
-92
-106
-120
D1 Array
days 4_190 to 4_351
files: 2004_351_00
Wed Dec 22 12:42:00 2004

Transient RFI excision 100 sec	Transient RFI excision daily	Spectral RFI exclusion	G183 SNR	Peak SNR on REF.	Integ. years
Y	Y	Y	3.0	1.8	2.72
Y	Y	N	3.0	2.4	2.85
Y	N	N	2.5	7.7	2.98

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

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