ATA Memo # 63 — 13 February 2004

Notes on Deuterium Detection with the Allen Telescope Array

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ABSTRACT

Detection of the 92 cm deuterium spin-flip transition (DI) with the ATA is discussed. Minimal system requirements are given. Eight antennas integrating at maximum efficiency for 3 weeks will give a 4σ detection.

1. Science Goals and Past Results

The 92 cm deuterium spin flip transition is one of the most important radio spectroscopic lines that has not yet been detected. The transition is the deuterium analog of the HI 21 cm line and arises from a flip in the spin direction of the electron with respect to the nuclear spin. The deuterium to hydrogen ratio ($N(D)/N(H)$) is an important constraint on cosmic nucleosynthesis. UV determinations of this ratio probe the solar neighborhood, in which the deuterium has been subject to considerable processing by stars. Radio observations at 327 MHz may probe a region that has experienced considerably less processing. This is especially true of observations towards the Galactic anti-center.

There is a long history of searching for DI in absorption and in emission (Weinreb 1962, Anantharamiah & Radhakrishnan 1979, Blitz & Heiles 1987, Chengular 1997). A convincing detection has not yet been made. Blitz & Heiles (1987) place an upper limit of $N(D)/N(H) < 3 \times 10^{-5}$, which is consistent with UV detections at 2×10^{-5}. We assume this value throughout this memo.

A dipole array is currently in use at Haystack Observatory in the search for DI (`http://web.haystack.mit.edu/deuterium/deuterium.html`).

Searches have typically been performed towards the Galactic center in absorption and towards the Galactic anti-center in emission. The velocity dispersion along the line of sight is at a minimum in these directions. The line width of HI is ~ 10 km/s towards the anti-center, corresponding to a frequency resolution of 10 kHz.

We show the HI distribution in the Galactic anti-center (Figures 1 and 2), the profile of the HI emission in latitude and longitude (Figure 3) and the mean spectrum of HI in the 327 MHz primary of the ATA (Figure 4).

We show here that the sensitivities of absorption and emission line experiments are roughly the same.

1.1. Absorption Line Searches

Galactic backgrounds can reach a temperature ~ 500 K, which is sufficient to dominate receiver temperature. In this limit, the sensitivity in opacity for an absorption line experiment is

$$\tau = \frac{1}{\sqrt{2 * B * T * N_a}}, \tag{1}$$

where B is the absorption bandwidth, T is the integration time and N_a is the number of independent beams. For $B = 10$ kHz, $T = 10^6$ s and $N_a = 1$, we find $\tau = 7 \times 10^-6$. This corresponds to a SNR ~ 1 detection using $\tau_{DI} = 0.3N(D)/N(H)$. Thus, either multiple beams or a longer integration time are necessary to achieve a significant detection.

1.2. Emission Line Searches

The brightness temperature sensitivity is

$$T_b = \frac{T_{sys}}{\sqrt{2 * B * T * N_a}}, \tag{2}$$

where $T_{sys} = T_{rx} + T_{bg}$. Towards the Galactic anti-anticenter, $T_{bg} = 70$ K. $T_{rx} = 70$ K for the ATA at 327 MHz (DeBoer 2004). Thus, for the same parameters as above, $T_b = 1$ mK. The expected signal strength is $\sim T_{HI}\tau_{DI} \approx 0.8$ mK. Thus, we require either multiple beams or a longer integration time. For 32 antennas, for instance, we achieve a $> 4\sigma$ detection with these parameters.

2. ATA System Requirements

2.1. Antennas & Control

Antennas must be capable of tracking a celestial source with modest pointing accuracy. The primary beam full width half-maximum of the ATA at 327 MHz is ~ 11 deg. The pointing requirement of 0.5 deg has already been met. The system must be capable of switching to an off-source or calibrator.

Velocity tracking of the source should be maintained by adjusting the local oscillator frequency.

2.2. Frontend & Signal Path

Extension of the feed arms to increase sensitivity at 327 MHz or use of a different feed is necessary. Single polarization feed is acceptable although the experiment will proceed $\sqrt{2}$ as rapidly with dual polarization feeds.

A low-noise frontend is necessary for the emission line experiment. If the noise temperature exceeds ~ 100 K, then it is preferrable to perform an absorption line experiment against a bright background source.

The total bandwidth necessary for this experiment is ~ 100 kHz. In order to reject RFI and provide a stable bandpass, it may be wise to include a bandpass filter at the frontend. The PAM can be used for transmission of the signal. Headroom in the amplifier and PAM are necessary to prevent RFI.

2.3. Signal Processing

The minimal requirements for signal processing are for construction of auto-correlation spectra with 100 kHz of bandwidth and 16 channels for N_a antennas. 8-bit sampling is necessary to prevent saturation due to RFI. Spectra should be stored without averaging for the purpose of RFI mitigation. In this extreme case, the data rate is $6.4 \times N_a$ MB/sec and the total data storage is $6.4 \times N_a$ TB for 4-byte correlation values. The data rate for one antenna is comparable to the write speed of a hard disk drive. 10 TB storage can be obtained for <$10,000.

These requirements may be relaxed or expanded given experience with the RFI environment. For instance, the number of channels may need to increase in the presence of narrow band interference. On the other hand, the averaging timescale could increase dramatically, depending on the frequency of interference.

2.4. Calibration

Amplitude calibration can be achieved by looking at bright sources. The Sun has a typical $T \sim 10^5$ Jy. With the effects of beam dilution this will have an apparent $T_b \sim 100$ K, which can be seen readily above the Galactic background.

2.5. RFI Mitigation

There will be RFI at this wavelength at the Hat Creek site (Figure 6). Blitz & Heiles reported, however, that after processing the data to reject RFI, they were able to obtain noise-limited results. Their rejection scheme involved identification of bad channels on the basis of recent auto-correlation statistics and identification of bad times on the basis of number of bad times.

The ATA experiment can do something more sophisticated. We can generate cross-correlation spectra. The DI emission (or absorption) will be resolved out in these spectra since the deuterium is broady distributed. Point-like RFI will not be resolved out nor will it suffer fringe-washing for short integrations. The average of the cross-correlation spectra are $\sqrt{N_a - 1}$ more sensitive than the average of the auto-correlation spectra. Thus, it can be a more sensitive indicator of interference for flagging in channel and time. The cross-correlation spectra may also be used to construct a bandpass that can be used to normalize the auto-correlation spectra.

The requirement of including the cross-correlation spectrum significantly expands the signal processing requirements. Data rates and storage rates increase by a factor $\sim N_a$. This may be manageable for a software/PC-based system for $N_a < 8$ but it is probably too much for $N_a = 32$. Real time RFI mitigation will probably be necessary to reduce data rates.

3. Beyond the Basic Experiment

There is more science to be obtained with deep observations of this kind.

3.1. Recombination Lines

There are several recombination lines in the frequency band near 327 MHz: H271α (328.8 MHz), H272α (325.3 MHz) and associated Cα lines. This can be done in either the emission or absorption spectrum method with auto-correlation spectra only.

3.2. Transients

This is an excellent opportunity to search for transient radio sources on timescales of 10 μsec to a year. This requires creation of cross-correlation spectra and calibrated images.

3.3. Imaging Deuterium

Deuterium will be substantially resolved on baselines > 20 m (Figure 5). Approximately 10% of ATA-32 baselines are shorter than 20 m. Thus a cross-correlation experiment limited to < 20 m baselines will be 1/3 as sensitive as an auto-correlation experiment. A cross-correlation experiment may be necessary to deal with the systematic effects associated with single dish measurements. An increase in integration time may permit a measurement of the scale-height of deuterium in the Galactic plane.

4. Action Item List

- Detailed RFI survey of Hat Creek at 327 MHz

- More detailed thinking about RFI mitigation using cross-correlations
- Construction of feed operable at 327 MHz, with narrow bandpass
- Test measurements of feed sensitivity
- Signal processing tests: what is the maximum N_a achievable with a simple system?
- Begin observing as soon as possible to determine stability of bandpass, RFI, etc.

5. References

- Anantharamiah & Radhakrishnan, 1979, A&A, 79, L9
- Blitz & Heiles, 1987, ApJL, 313, L95
- Chengular *et al.* , 1997, A&A, 318, L35
- DeBoer *et al.* , 2004, ATA Memo # ??
- Weinreb, 1962, Nature, 195, 367

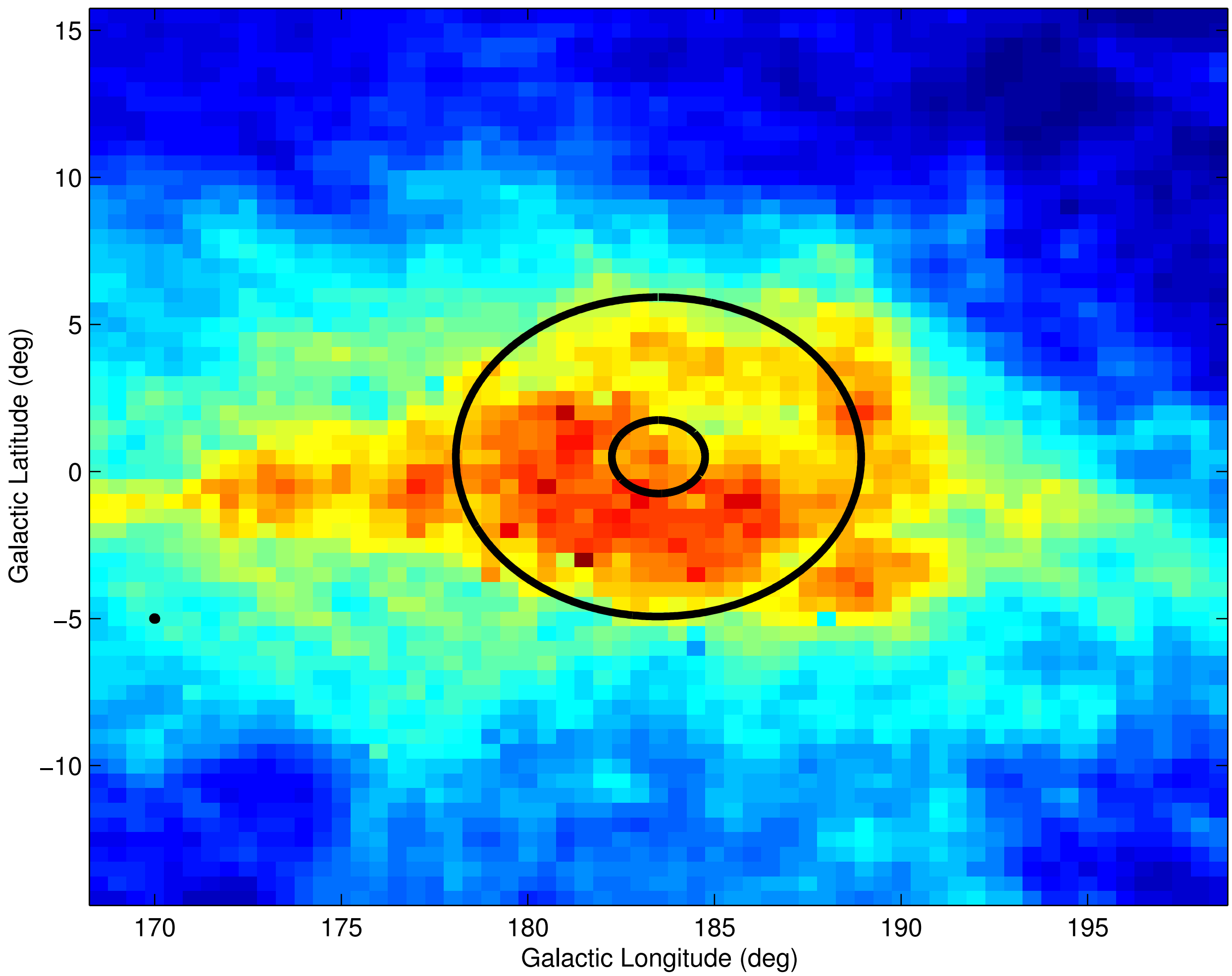

Fig. 1.— Map of HI brightness temperature at zero LSR in the Galactic anti-center from the Leiden-Dwingeloo survey. The ATA primary beams at 21 cm and 90 cm are shown. The 90 cm synthesized beam for the ATA-32 is also shown.

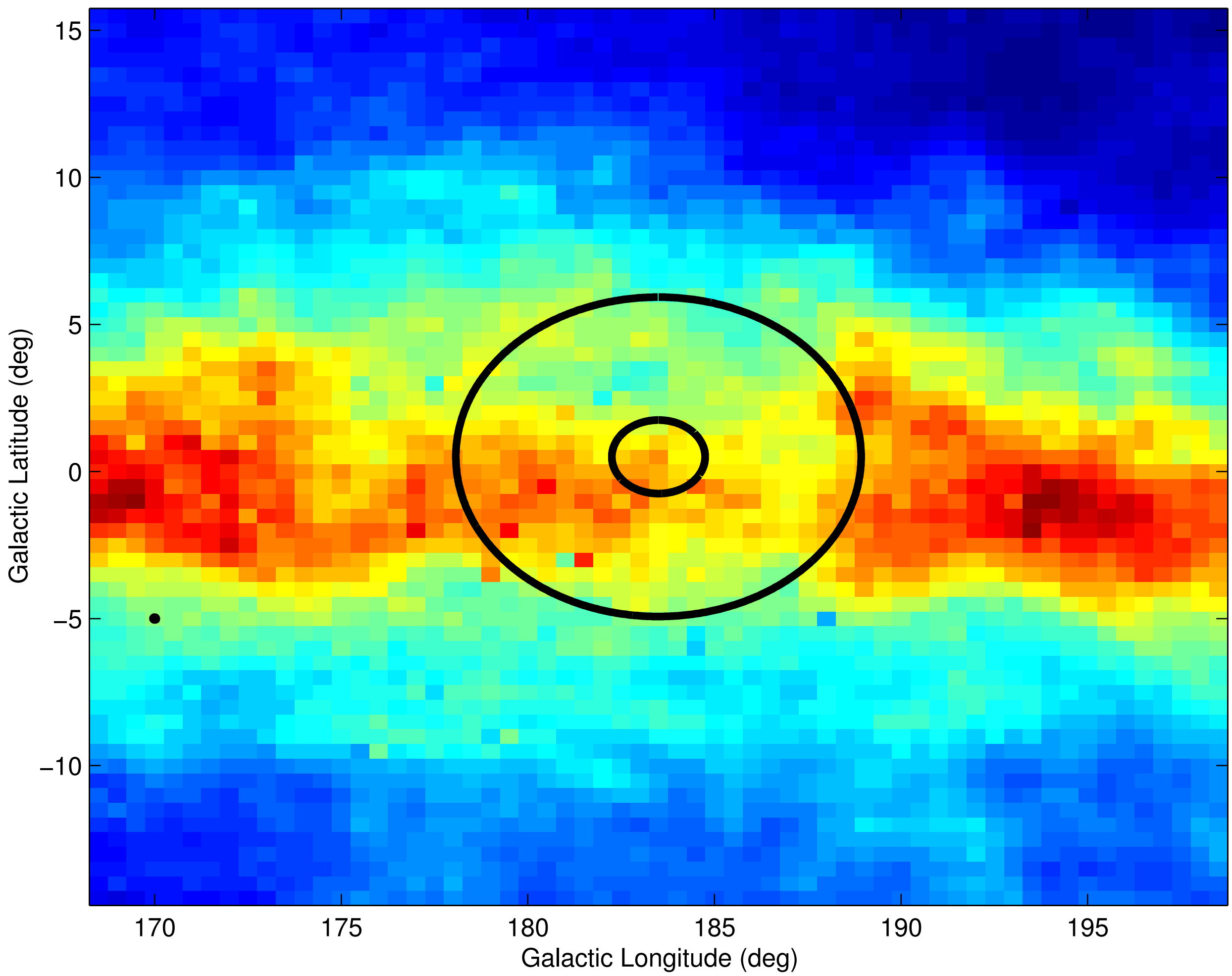

Fig. 2.— Map of HI brightness temperature integrated over velocity in the Galactic anti-center from the Leiden-Dwingeloo survey. The ATA primary beams at 21 cm and 90 cm are shown. The 90 cm synthesized beam for the ATA-32 is also shown.

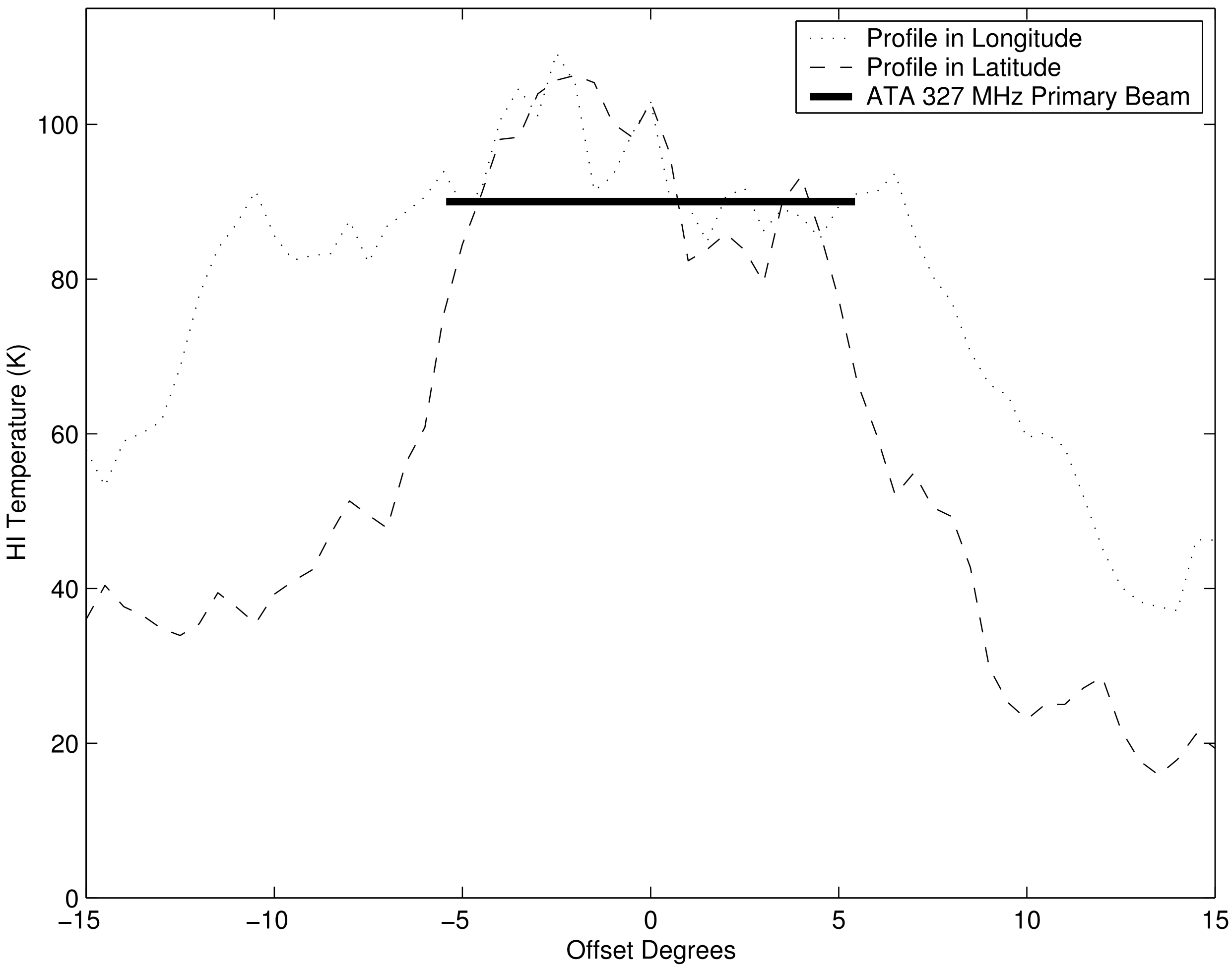

Fig. 3.— Profiles of HI brightness temperature at zero LSR in the Galactic anti-center in latitude and longitude centered at $l = 183.5$ and $b = 0.5$. The ATA primary beam at 90 cm is shown.

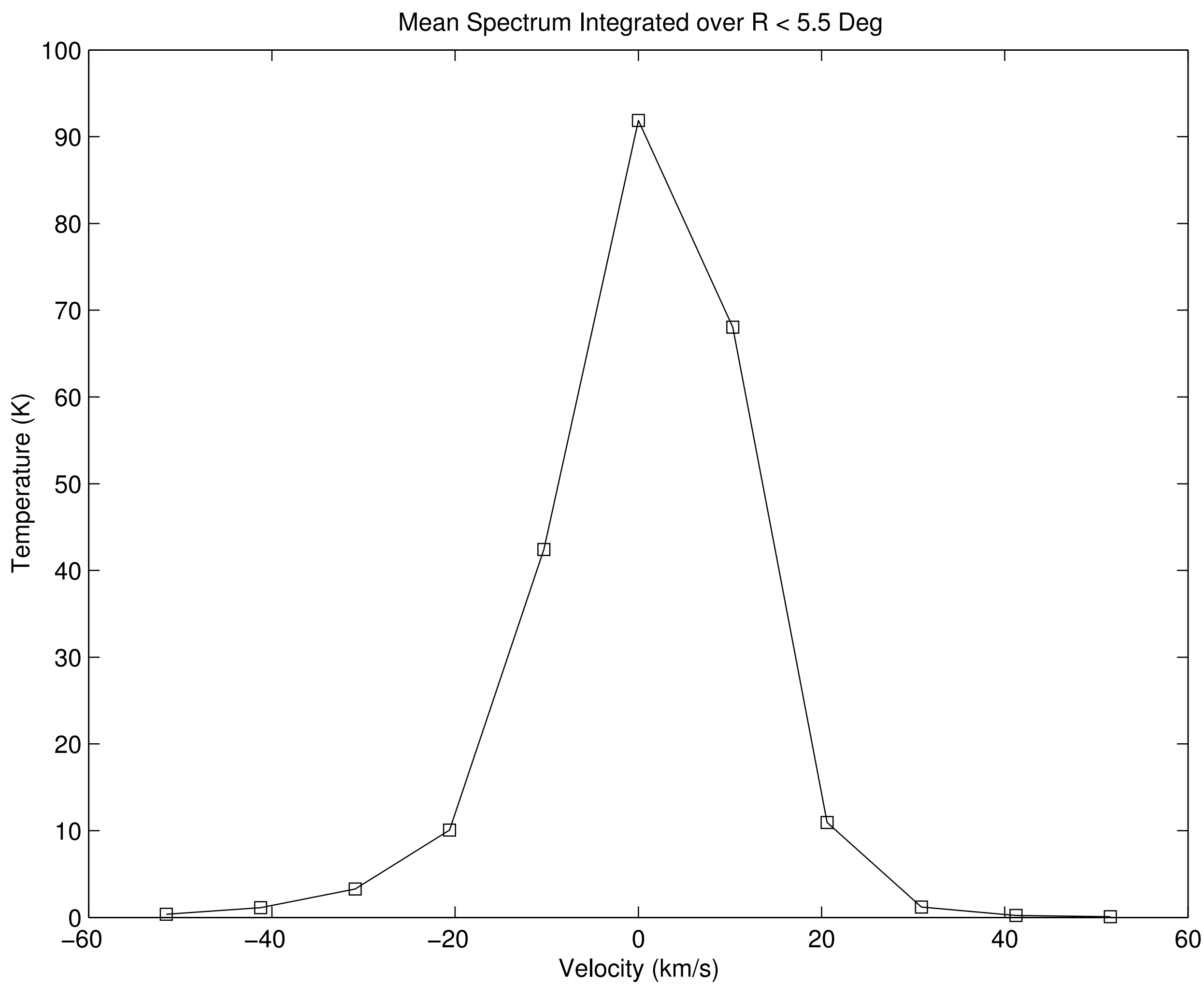

Fig. 4.— The mean HI spectrum in the ATA primary beam at 90 cm.

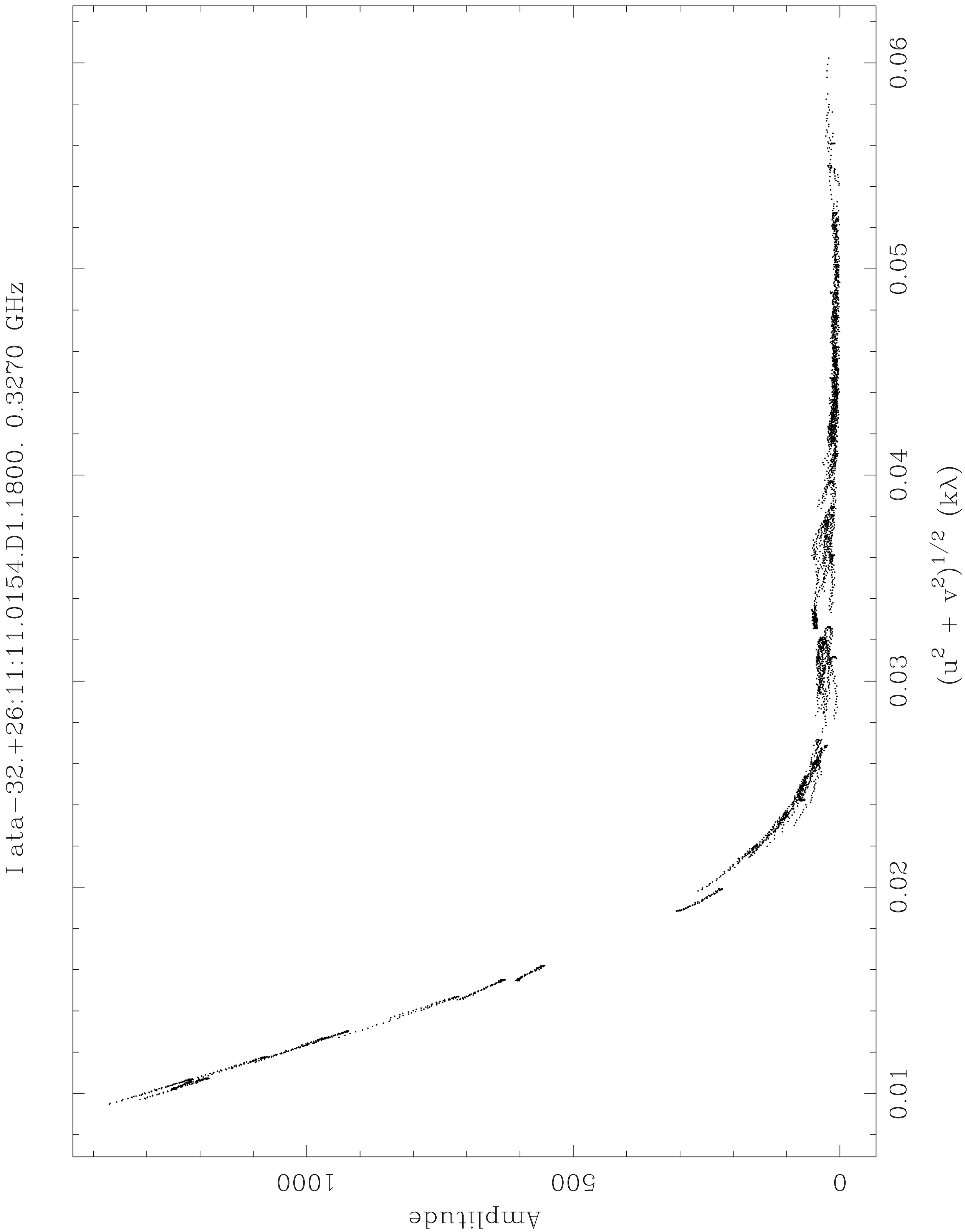
I ata−32.+26:11:11.0154.D1.1800. 0.3270 GHz
Amplitude
$(u^2 + v^2)^{1/2}$ (kλ)
0
500
1000
0.01
0.02
0.03
0.04
0.05
0.06

Fig. 5.— Visibility amplitude as a function of uv distance for the ATA-32 in the zero LSR velocity channel using the LDS HI map as a proxy for DI distribution.

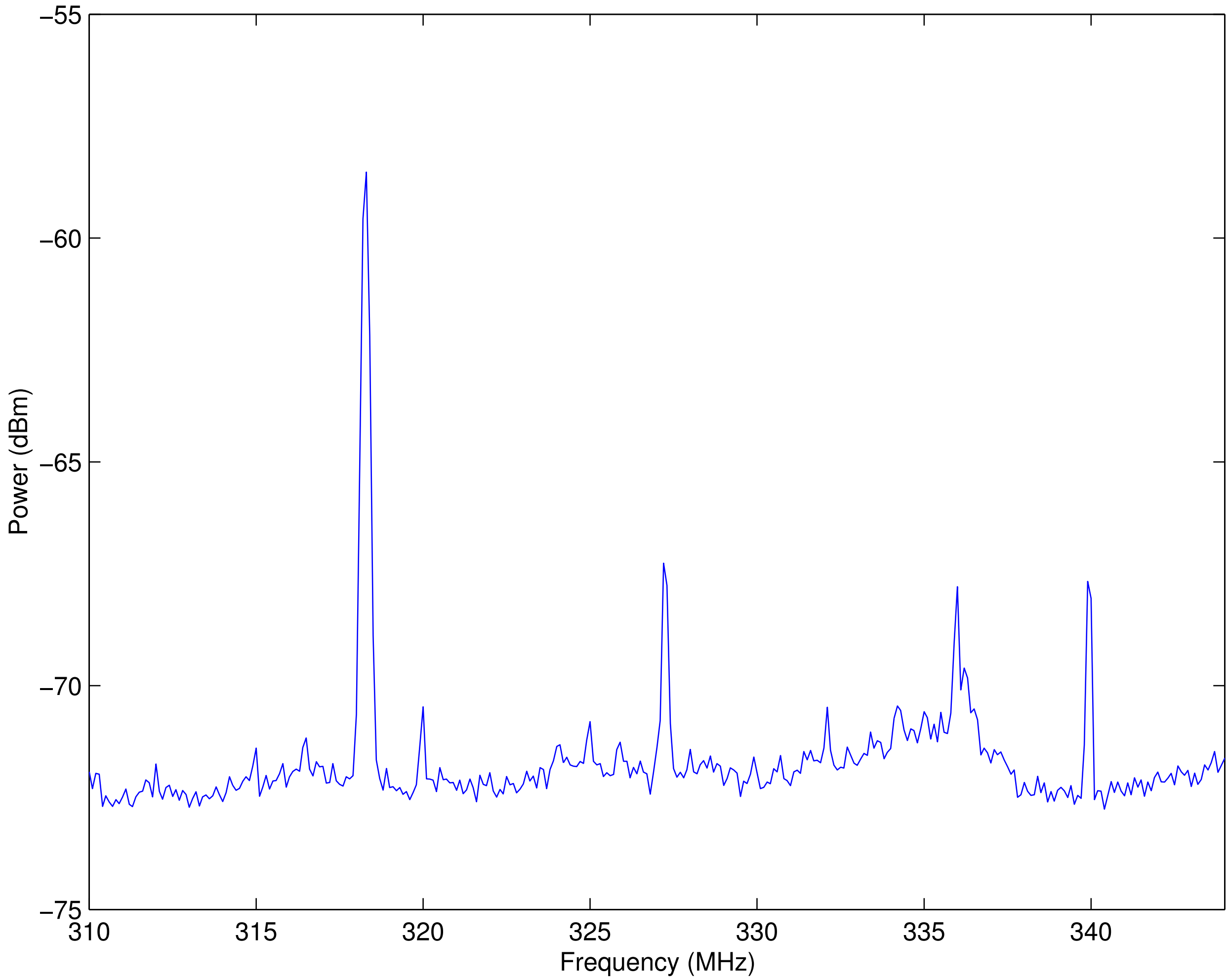

Fig. 6.— RFI spectrum captured on 11 September 2002 at Hat Creek. This is the mean of 35 2-minute integrations. The feature at 327 MHz is present in each integration. The feature also appeared in each of 12 1-hour integrations on the same day. The feature was not apparent in 5-minute integrations on 25 September 2001.