Dark HI Cloud Observation using the Deep Space Exploration Society Plishner 18-Meter Dish with the RASDR4

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Abstract:

Members of the Deep Space Exploration Society (DSES) designed a small study to replicate findings from a 2014 study that that detected an absorption feature in a dark HI cloud and that used a RASDR2 and the NRAO 20m system in tracking mode. Using a RASDR4 and the Plishner 60-foot/ 18-meter system, the team executed multiple drift scans generating both real time results and integrating multiple passes during post-hoc processing to identify the Doppler shifted absorption feature. Results exceeded the 2014 study published results and were commensurate with the 2015 Parkes 64m telescope survey results when adjusting for beam size.

Introduction:

The Radio Astronomy Software Defined Receiver 4 (RASDR4) [1] is the newest development by the Society of Amateur Radio Astronomers (SARA) [2] to provide a receiver that is economical and suitable for radio astronomy. Based on the Lime Microsystems Software Defined Radio (LimeSDR) [3], it provides a sensitive receiver that is able to support collection of a wide variety of radio astronomy target wavelengths. (Figure 1) Since completing RASDR4 production, the RASDR4 team has developed custom software to focus on common radio astronomy tasks, and sought to use the newly upgraded Plishner 18m system to test various functions. Some of these functions include: "flat top" windowing; Fast Fourier Transform (FFT) transformation; and integrating/averaging in real time.

Figure 1: Tony Bigbee with RASDR 4 [1]

History:

In 2014 the RASDR2 was installed on the NRAO 20-meter dish at Green Bank, West Virginia (figure 2). The goal was to detect and differentiate a distinct absorption feature related to a cold dark cloud near Messier object M24 at coordinates RA J2000 (18h09m01.26s) and DEC (-19d59m58.1s). This dark cloud contains a narrow hydrogen absorption line feature. [4] Since the RASDR4 is more capable than the RASDR2, and the Plishner 18m physical system is roughly comparable to the NRAO 20m system, DSES members identified the absorption feature as an initial target to test the new RASDR4 capabilities.

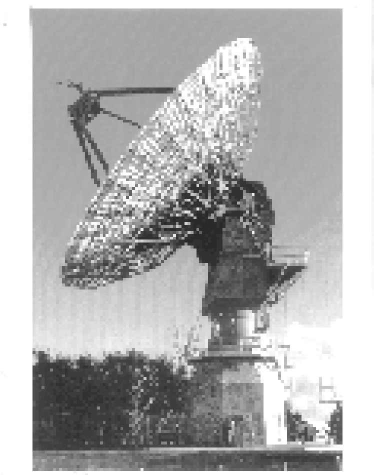

Figure 2: NRAO 20-meter dish [5]

The RASDR2 observation of the dark cloud is shown in figure 3. Note that the absorption feature is centered close to the 1420.4 Mhz. neutral HI line.

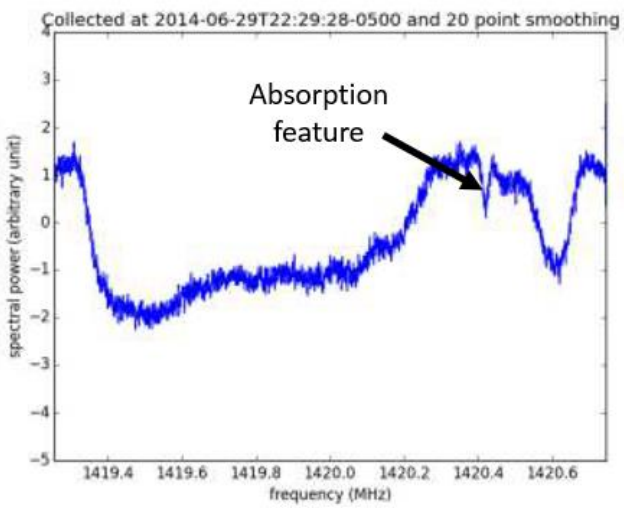

Figure 3: 2014 RASDR2 Dark Cloud Observation [4]

Research:

The HI4PI 2015 Galactic All-Sky Survey (GASS) used the Parkes 64m system (figure 4) [6] to contribute to an all-sky HI survey. "The EBHIS and GASS Milky Way data provide an excellent database to approach a wealth of scientific questions." [7] This survey included the region containing the same HI cloud in the RASDR2/NRAO 20m study. The GASS team created a web-based profile tool to exploit the data. A feature of this profile tool allows users to specify a synthetic beam size to approximate results that might be obtainable by other radio telescopes.

Caption: CSIRO's Parkes radio telescope. Credit: David McClenaghan, CSIRO

Figure 4: Parks 64-meter Radio Telescope [6]

The GASS plot of the dark cloud is shown in figure 5 [7].

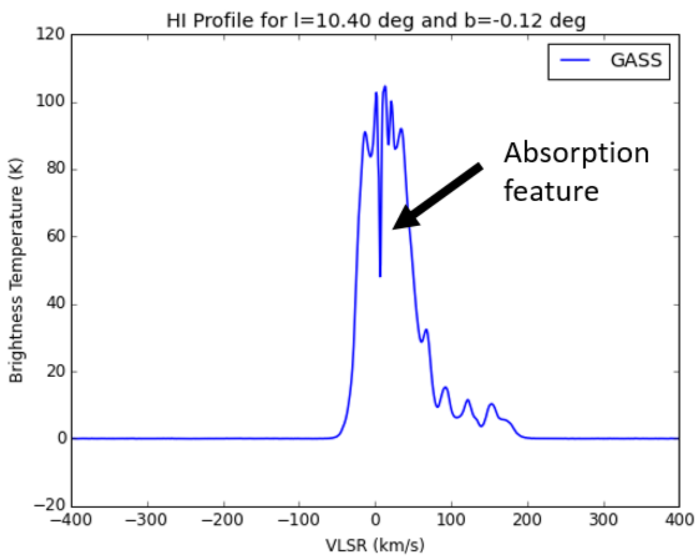

Figure 5: Dark Cloud Target from the GASS Database [7]

Plishner 18m Radio Telescope:

The Plishner 60-ft. (18m) radio telescope is located near Haswell, Colorado. (figure 6)

Figure 6: DSES 60-foot Dish near Haswell, Colorado

The coordinates are:

N38° 22′ 51.10″ W103° 9′ 22.96″
Elevation: 1666m (5465 ft.)

The antenna specifications are:

- **Frequencies:** 400 Mhz. to 2 Ghz.
- **Diameter:** 60 feet
- **Antenna Gain:** 42.5 dBi. at 1 Ghz.
- **Beam Width:** 2.6 degree at 400 Mhz. (0.8 degree at 1.2 Ghz.)
- **Noise Figure:** 0.29 dB at 1420 Mhz.
- **Coverage:** Full Hemisphere
- **Slew Rate Max Az/El:** 40/40 deg/min

Feed:

The current 21cm feed (figure 7) was constructed by Steve Plock and entered service on 28 June, 2018. It was based on the SETI League design [8] [9] A 3-1/2 W.L. cylindrical waveguide section length was chosen to enhance feed filter function and to co-locate the input at the phase center of the DSES 18 meter instrument. Also, mutually orthogonal antenna probes were combined using a quadrature hybrid coupler to obtain desired circular polarization. The 1/4" base plate was professionally welded to the cylindrical waveguide section. Specifications are as follows:

- Gain = 40 dB;
- NF = 0.29 dB

Figure 7: 21 cm Feed during assembly and Feed Installed on Plishner 18m Dish

From the feed, an RF over fiber optic system delivered the signal to a L-band (1-2 Ghz) coupler that's coupled port is -6dB in the communications trailer. For the experiment, a short SMA cable was connected from the coupler to the RASDR4.

Task Goal:

The goal of the RASDR4 team was to collect and identify the cold spectral HI Feature at RA 18:09:01.26 DEC -19:59:58.10 (18.15035 -19.999472) using short drift scans.

The authors installed a RASDR4 unit in the communications trailer and the pointed the dish at the dark cloud coordinates. (figure 8)

Figure 8: Communications Trailer with Observation Team

Benefits:

The following benefits can be derived from this test program:

- Demonstrate capability of RASDR4 using a sensitive instrument.
- Pilot methodology for elements of sky mapping with raster scans.
- Evaluate RASDR4 sensitivity for HI drift scanning and local rest frame Doppler phenomenology.
- Test new RASDR4 software suitability for HI drift scanning.
- Provide performance data to compare with RASDR2 data on the same and similar telescopes.
- Demonstrate amateur links and relationships to professional science results [7]--HI4PI/GASS Survey and Figure 3.

Approach:

- During calculated windows of opportunity during the night of 10 Aug, conduct 2-3 10 minute drift scans using calculated azimuth and elevation/altitude pointing angles. Position telescope 10 minutes prior to target time.
- Configure RASDR4 for maximum sampling rate and decimation with a 10 MHz low pass filter bandwidth setting.
- Record amplitude values from each FFT frame, averaging 512 sample blocks after FFT processing.
- Separate scans by at least 30 minutes.

Results:

The 18m dish was manually pointed until the absorption line was maximized. This allowed the DSES team to validate the accuracy of the pointing system as well as providing the RASDR4 with the excellent signal for the observation. The RASDR4 observation is shown in figure 9.

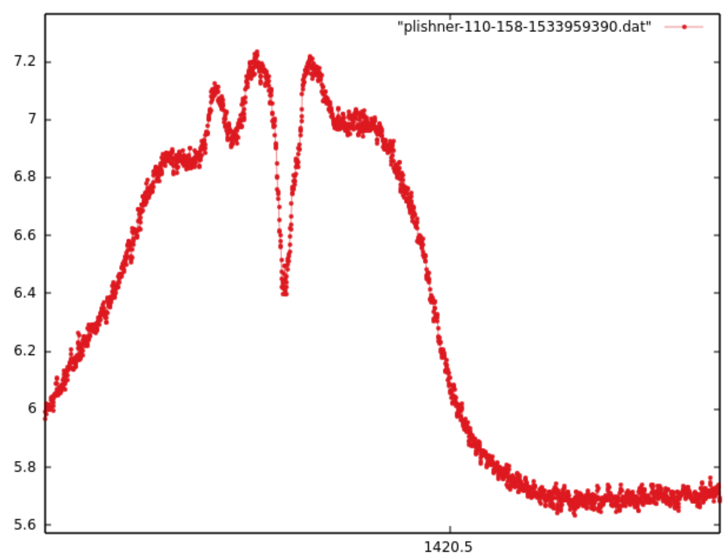

Figure 9: RASDR4 Dark Cloud Observation

Comparing the Data:

A preliminary comparison between the RASDR2, GASS, and the RASDR4 observations is shown in figure 10. The RASDR4 results, using the Plishner 18m telescope, is comparable to the GASS data using the Parkes 20m telescope.

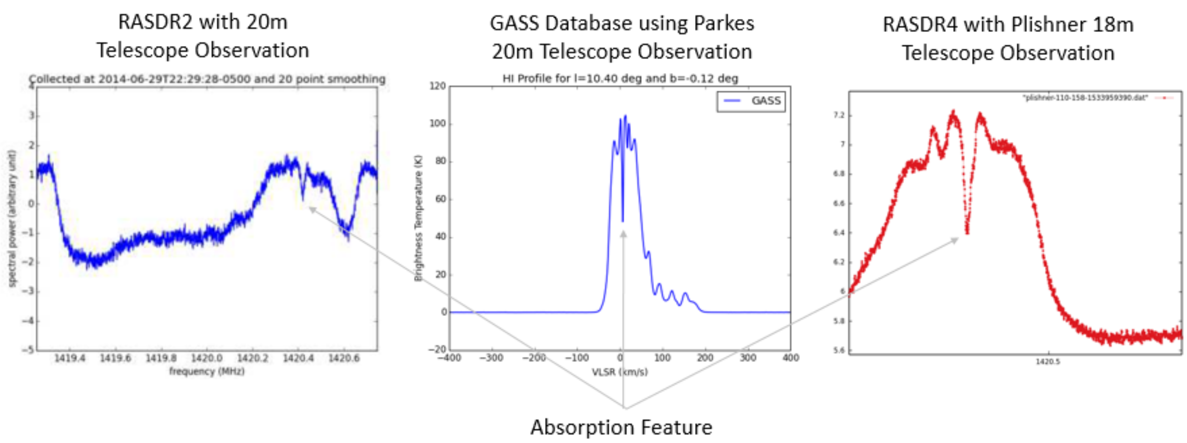

Figure 10: Dark Cloud Results Comparison

Other Surveys Showing the Dark Cloud:

The Aladin Lite [10] software was used to view the dark cloud coordinates using composite frequencies. This shows a darkened area approximately where the HI absorption feature is located. The cross denotes the location of the cloud. (figure 11)

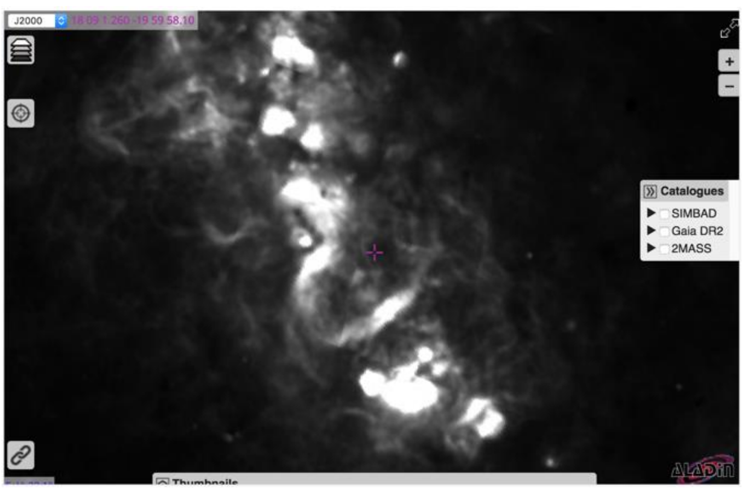

Figure 11: Aladin Lite screenshot of Finkbeiner Hα Composite of WHAM, SHASSA, and VTSS surveys (FOV is approximately 2.9 degrees) [10]

Post Processing:

Figures 12 shows the hardware and software collection processes used. The first box represents key functions performed onboard the RASDR4 in hardware and firmware. The second box represents processing after USB 3 transfer of digitized quadrature samples to a laptop running

Ubuntu Linux 16. The third box represents offline, post processing software used to generate the third graph and figure 13.

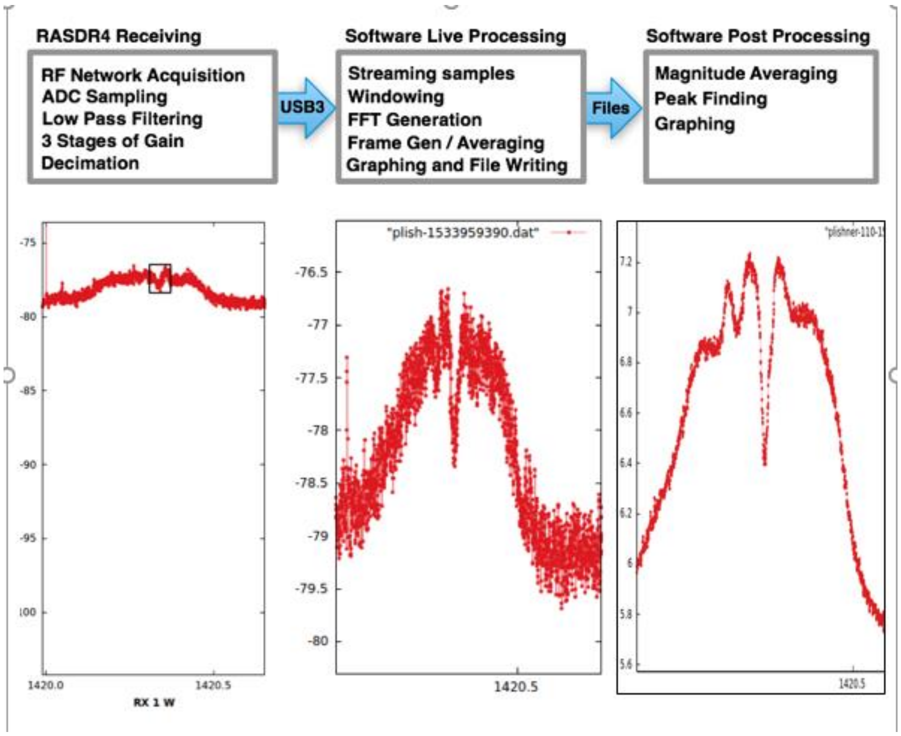

Figure 12: Post Processing

The first graph in figure 12 represents what experiment participants viewed in real time. The second graph depicts a screen snapshot of the same real time graph zoomed in to the region of interest. This graph shows a Doppler shift where the absorption feature is a lower frequency than 1420.4 MHz, thus the positive relative radial velocity of the dark cloud means movement away from the earth relative to the local standard of rest (LSR). We analyze velocity aspects later in the discussion section.

The second graph represents an FFT frame consisting of 512 blocks and 16384 samples per block x 512 blocks per frame / 5Msps (effective) = 1.68 seconds per frame. The software writes an average amplitude value for each FFT frame to a text file for post-processing, embedding the streaming start timestamp in the filename, as well as parameters used for the hardware and FFT processing.

After the experiment, the team developed new Python software to integrate multiple FFT files and perform other post-processing analysis using the well-known Python **matplotlib** library. The effect of integrating 164.4 seconds of drift collection are evident in the third graph. Minimal detectable signal ΔT and SNR are inversely related to the square root of integration time [11, p. 62]:

$$\Delta T = \frac{T_{sys}}{\sqrt{\Delta \upsilon \, \tau}}$$

Tsys: System Temperature (°K)
$\Delta\upsilon$: Bandwidth (Hz)
(τ) Integration time (seconds)

Experiments with different numbers of FFT frames yielded an optimum value of approximately 82 seconds (49 frames x 1.68 seconds per frame) for each drift collection, shown in the third graph; we informally define optimum as integration time that provides the smallest obtainable amplitude for the notch/absorption feature. The optimal time depends on the spatial extent of the absorption feature and the half power full beamwidth (HPBW) of the antenna: 0.866 degrees; the earth rotates at 15 arc seconds per second; thus, the antenna pattern moves to a new "pixel" in the sky every 208 seconds:

1 second/15 arc seconds x 3600 arc seconds/1 arc degree x .866 arc degrees/1 HPBW = 207.8 seconds/HPBW

As a heuristic, using half this time as a starting point for integration time analysis ensures that the heart of the antenna beam collects on 1 pixel. These numbers are simply starting points for planning and analysis as the main lobe of the antenna pattern has a non-linear drop off in power and there is an arbitrary choice of -3dB decrease in gain of the main lobe for HPBW.

The fourth graph (figure 13) also shows automatically identified peaks using the RASDR4 **scipy.signal.find_peaks** function.

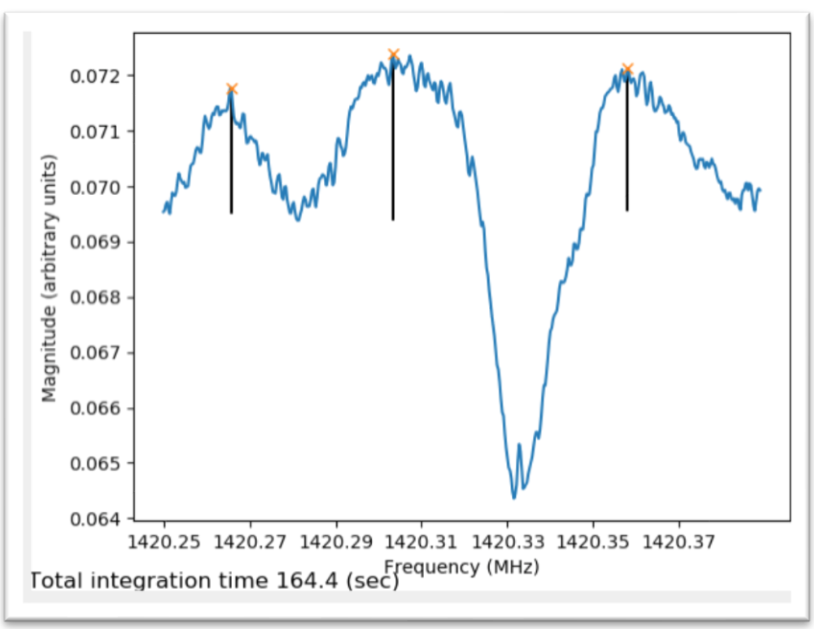

Figure 13: Peak Determination Software Results

The software allows a frequency range of interest to be processed—the graph shows the selected range as 1400.25 MHz to 1420.39 MHz, a subset of the original bandwidth collected.

The number of FFT bins, stream block size, and effective bandwidth, results in a frequency resolution of 305.2 Hz/bin. The use of the **HFT70** windowing function provides low amplitude error (< .1%), [12], but results in a Normalized Equivalent Noise Bandwidth (NENBW) of 3.41 bins and thus a frequency resolution of 305.2 Hz/bin x 3.41 bins = 1.041 KHz. The software allows selection of other windows and automatically selects optimum overlap for the window used.

Tables 1, 2 and 3 below summarize key parameters used in the experiment, and are the parameter names and values that correspond to the functions in the three boxes of figure 12. RASDR4 real time software uses a flat text configuration file that has entries corresponding the first column in the first two table tables. The third table represents command line parameters provided to an integration program.

Table 1: RASDR4 Key Parameters

RASDR4	
network-port = W	Wideband RF network port
center-frequencies = 1420e6	Center frequency 1420 MHz
Lowpass-bandwidth = 10000000	Low pass filter bandwidth
effective-sample-rate = 5000000	Sets clock generator / ADC clock rate
lna = 31	Low noise amplifier dB, if < 31, PGA and TIA are set to zero automatically
decimation ratio = 32	Decimation after ADC
stream-samples = 16384	Samples per block

Table 2: Software Processing

Software Processing	
window = hft70	HFT70 is a high dynamic range differentiable flat top window function with maximum sidelobe level of -70 dB. Flat top windows provide more accurate amplitude values. An optimal overlap value for the window type is automatically selected from Heinzel et al. 2002; in this case an optimum overlap of 72.2%.
fft-frame-size = 512	The number of FFT blocks to integrate/average for each frame.

Table 3: Software Post Processing

Software Post Processing	
minfreq_interest = 1420250000	Minimum frequency of interest Hz
maxfreq_interest = 1420390000	Maximum frequency of interest Hz
plotpeaks = True	Use scipy peak finding algorithm and plot peaks and prominences in graph
scipi.signal.find_peaks peak_width = 20	Required width of peak in samples (bins). The required height parameter is supplied by computing the average amplitude across the frequency range of interest

Discussion

Hagen and McLain [13] first reported on observations of hydrogen as an absorber of 21 cm radiation and Hagen, Lilley, and McLain [14] used a 50 foot dish radio telescope to study absorption effects and build HI (neutral hydrogen) absorption profiles. Although we have not yet been unable to determine the scientific provenance of the cold, dark cloud identified in the 2014 RASDR2 and NRAO 20m dish studies, the absorption feature depicted in the graph from those studies visually matches results obtained from the H I 4π survey (HI4PI) [15], an all-sky database of Galactic H I. The web query tool for the HI4PI survey also provides velocity (relative to local rest) and brightness data. From this data, the minimum brightness of 48.076 for the absorption feature corresponds to a velocity of 6.6 km/sec for the "object." Using the Doppler shifted frequency associated with the bottom of the notch from post processed results, we calculated velocity relative to the local standard of rest using a web tool [16]. The first frequency in the table below is the measured frequency, and the second and third frequencies are addition and subtraction of 1.041 KHz resolution—3.41 bins of NENBW from HFT70 windowing—in order to identify error bounds.

Frequency MHz	**Velocity m/sec (LSRK)**	
1420.33203	(measured)	7.02
1420.33323	(upper)	6.76
1420.33083	(lower)	7.27

These results are compatible with the GASS survey results of 6.6 km/sec, which featured a spectral resolution of 1.00 km/sec [15].

Future Work:

The collection and analysis in this study are a small, first step towards a range of hydrogen line based studies intended for the Plishner radio telescope. Specific improvements we intend to pursue are:

1. Implementing calibration methods
2. Developing a graphical user interface to aid in collection planning and situational awareness of telescope pointing relative to the Milk Way, coordinates, and targets positions
3. Adding a cavity filter to the RF path
4. Revisiting the current hydrogen absorption feature as part of a larger study on hydrogen absorption sources.

Summary:

The RASDR4 team has developed a radio telescope receiver that is easily installed and operated by amateur radio astronomers. The observation of the dark cloud using the RASDR4 with the Deep Space Exploration Society's 18m antenna system shows excellent signal characteristics. The RASDR4 result also is commensurate with both the RASDR2 and Green Bank 20m telescope and the GASS survey which used the Parkes 64m telescope.

Future observations are planned with the RASDR4 and the Plishner 18m radio telescope. This will allow the RASDR4 team to improve the software and processes for amateur and profession radio astronomer use. The upgrades to the RASDR4 will be documented on the RASDR4 blog. [1]

Credits

The authors wish thank members of the DSES who have spent years restoring the Plishner radio telescope site.

Special thanks to DSES members who helped during the observation: Bill Miller, Paul Berge, and Ed Corn.

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