A low-cost 21 cm horn-antenna radio telescope for education and outreach

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Abstract

Small radio telescopes (1-3m) for observations of the 21 cm hydrogen line are widely used for education and outreach. A pyramidal horn was used by Ewen & Purcell (1951) to first detect the 21cm line at Harvard. Such a horn is simple to design and build, compared to a parabolic antenna which is usually purchased ready-made. Here we present a design of a horn antenna radio telescope that can be built entirely by students, using simple components costing less than $300. The horn has an aperture of 75 cm along the H-plane, 59 cm along the E-plane, and gain of about 20 dB. The receiver system consists of low noise amplifiers, band-pass filters and a software-defined-radio USB receiver that provides digitized samples for spectral processing in a computer. Starting from construction of the horn antenna, and ending with the measurement of the Galactic rotation curve, took about 6 weeks, as part of an undergraduate course at Harvard University. The project can also grow towards building a two-element interferometer for follow-up studies.

Galactic emission from the atomic hydrogen spin-flip transition was first predicted by H. van de Hulst in 1945, and detected by H. Ewen and E. Purcell in 1951 at Harvard. **Figures 1 and 2** show these historic results. With modern electronics and powerful digital signal processing techniques, the original HI line detection experiment is made easily feasible at the level of undergraduate education in experimental physics and introductory radio astronomy courses. Here we describe a low-cost horn-antenna radio telescope that is suitable for outreach and education. **Figures 3-5** describe the system. Theoretical design considerations are presented in **Figures 6-8**. Astronomical results made with the horn-antenna are shown in **Figures 9 & 10.**

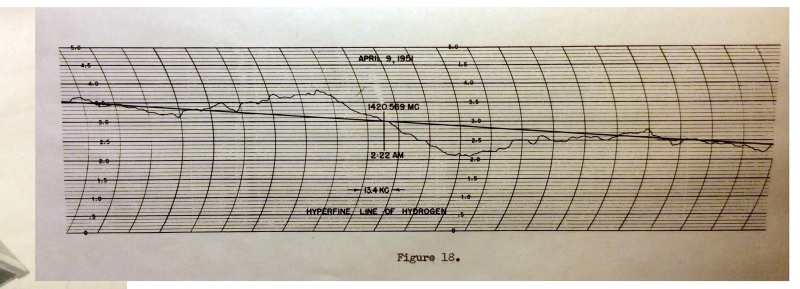


Fig. 2: The first detection of the hydrogen spin-flip transition from the Milky Way, obtained on 9 April 1951. The spectrum was obtained in frequency switching mode.

Fig. 1: The original horn antenna built by H. Ewen and E. Purcell (1951) to detect the Galactic hydrogen spin-flip transition 21 cm wavelength emission. The horn was used as a transit instrument, mounted in Lyman lab. building on Oxford St., Cambridge MA.

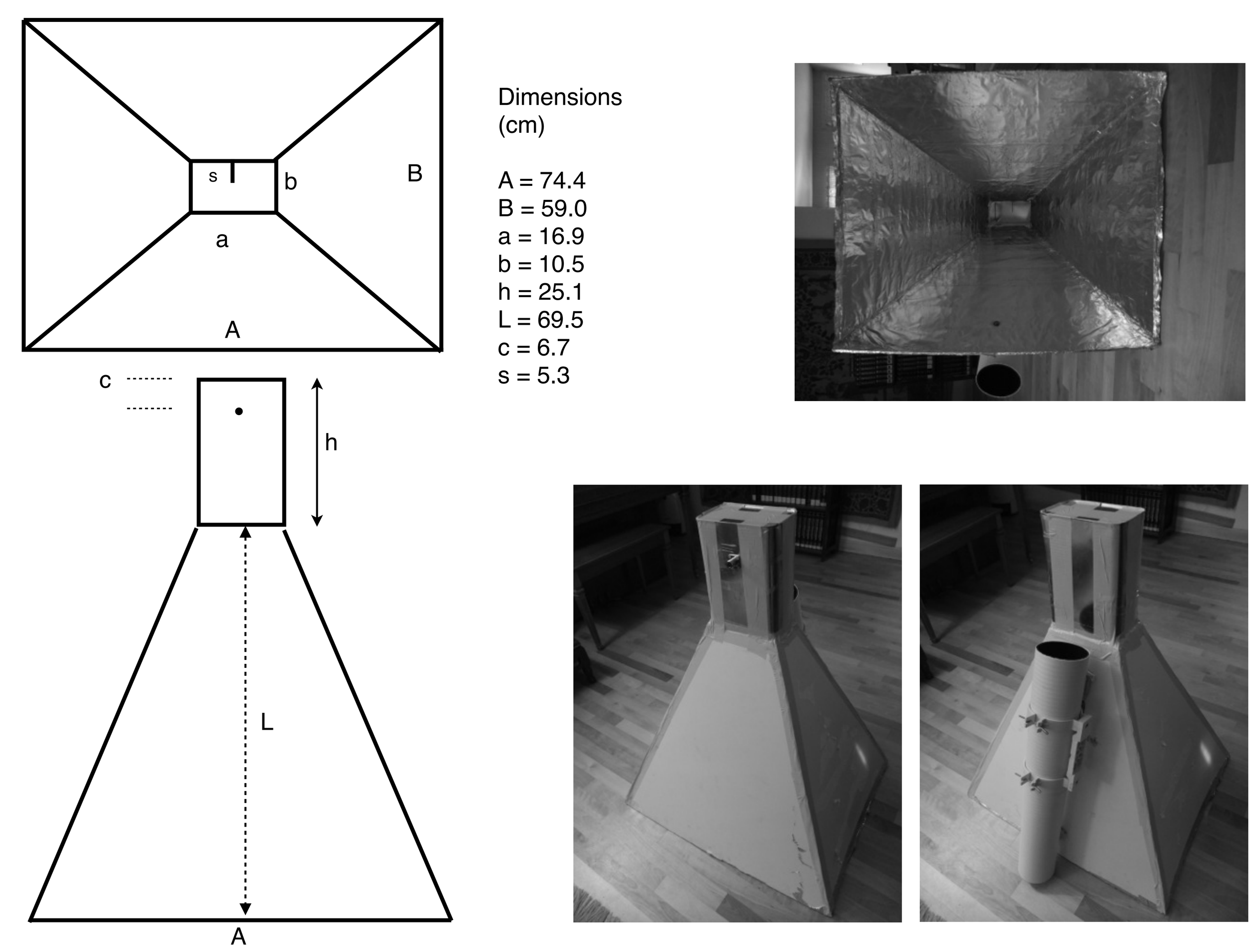
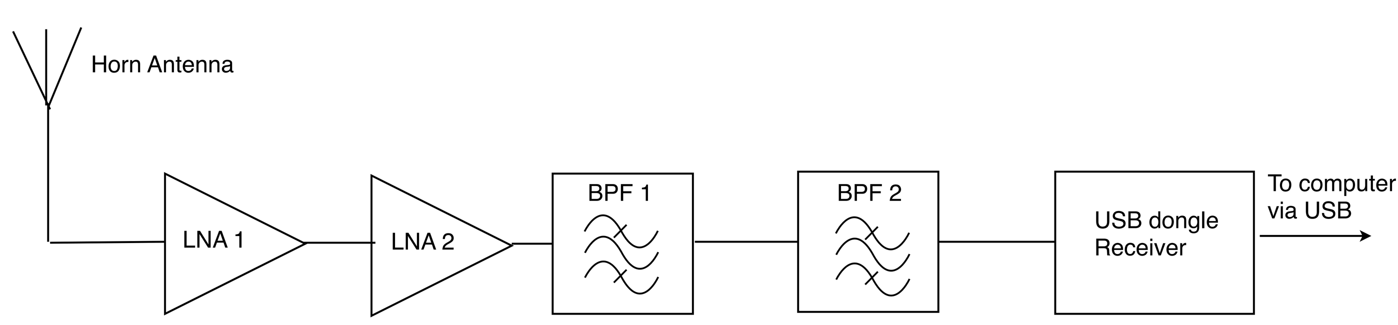


Fig. 3: Two horn antennas were built, based on the same design, but using different materials for the panels of the pyramidal horn: 1) cardboard (foam board) and aluminum foil. 2) Aluminum sheet metal. The rectangular waveguide feed was built from a standard 1 gallon paint thinner can which has appropriate dimensions. The gain of the horn antenna is 18.6 dB (calculated).



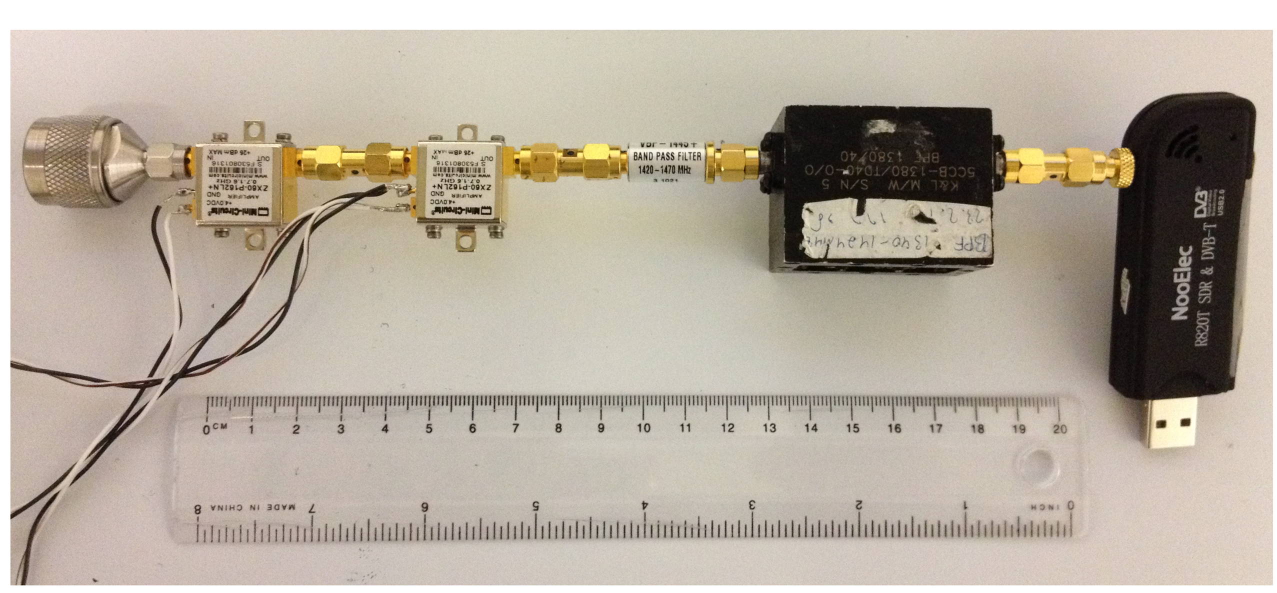


Fig. 4: The receiver system consists of two Low Noise Amplifiers (LNA, Mini Circuits ZX60-P162LN+ $55), bandpass filters (Mini-Circuits V BF – 1445+, $30, K&L M/W S/N 5 5CCB-1380/TD40-0/0 BPF, $30- surplus) and a USB Software Defined Radio broadband receiver (NooElec R820T SDR DVB-T, $20). The input is fed via the N-type connector into the LNAs, and the digital output (I and Q complex demodulated signal) is captured by a computer via USB interface for FFT processing to obtain a spectrum (e.g., see M. Higginson-Rollins & A. Rogers, 2013, http://www.haystack.mit.edu/edu/undergrad/srt/). We used the RTL-SDR python software package downloaded from https://github.com/roger-/pyrtlsdr. The receiver temperature is measured to be 84 ± 16 K.

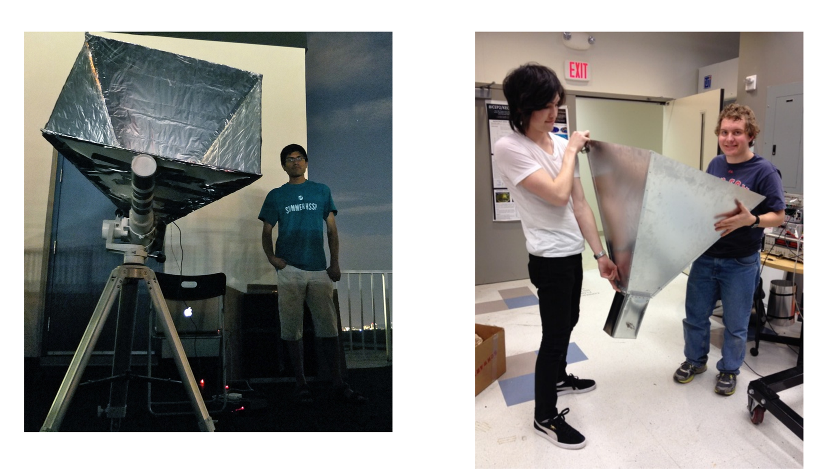


Fig. 5: *Left*: Cardboard+Al foil horn antenna mounted on a standard alt-az telescope mount in an urban environment. HI spectra toward the Galactic plane are easily detected in just 30 seconds of integration with the system described here. *Right*: Horn of same dimensions made with aluminum sheet metal riveted at edges. This horn is also light enough to be mounted on standard amateur telescope mounts.

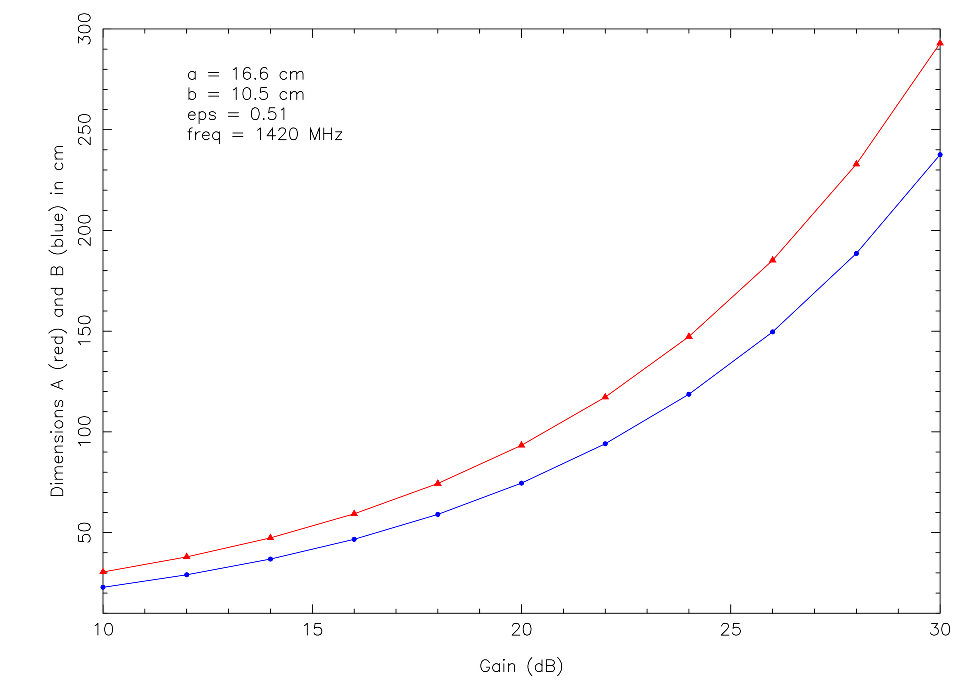


Fig. 6: The dimensions of the pyramidal horn antenna can be calculated for a specified gain (e.g., see http://www.ece.mcmaster.ca/faculty/nikolova/antenna_dload/current_lectures/L18_Horns.pdf). Our design goals were a compromise for portability, cost and ease of construction and operation. The gain of our horn antenna is 18.6 dB. This figure gives the dimensions of A and B constrained by the feed dimensions (a, b), which also give the slant length L.

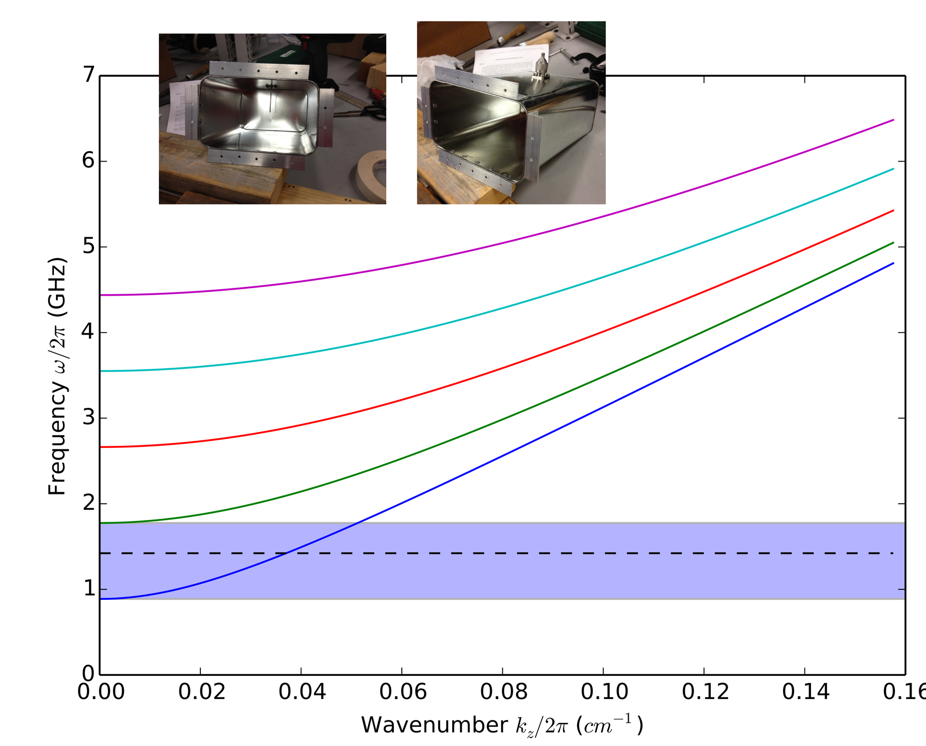


Fig. 7 shows the dispersion relations for the first five transverse electric (TE) modes of the rectangular waveguide used for our system. TE modes 1,2,3,4,5 correspond to blue, green, red, cyan and purple solid lines, respectively. The dotted black line shows the center of the frequency band of interest, 1.42 GHz. The intersection of this line with the solid blue line shows the operating point of the waveguide corresponding to a guided wavelength of approximately 27 cm. The output feed should thus be selected as one fourth of this, or 6.75 cm from the back wall of the waveguide. The blue band corresponds to the range of input frequencies to the antenna which result in single mode operation of the guide.

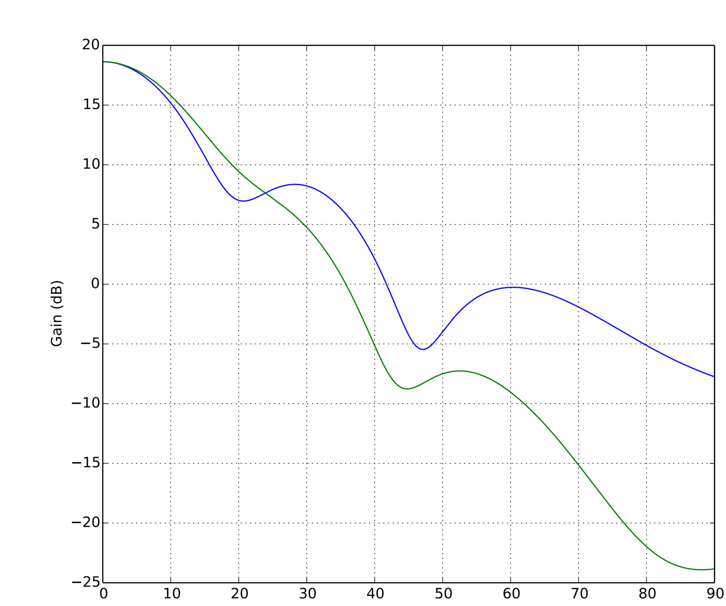
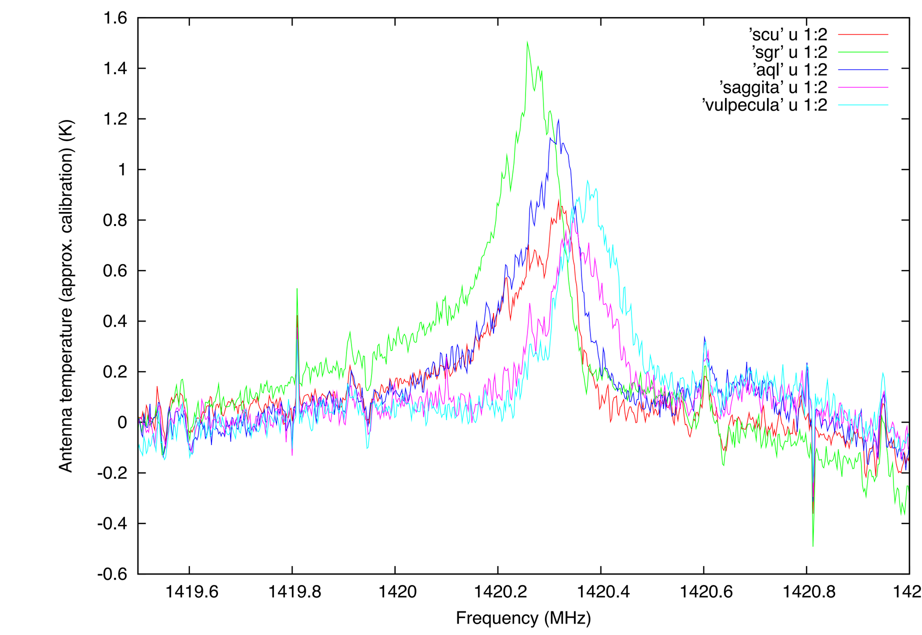


Fig. 8: The horn antenna's response normalized to an isotropic antenna, calculated using the COMSOL software (http://www.comsol.com), for the parameters shown in Fig. 3 and frequency of 1420 MHz. The FWHM beam size is approximately 20 degrees.



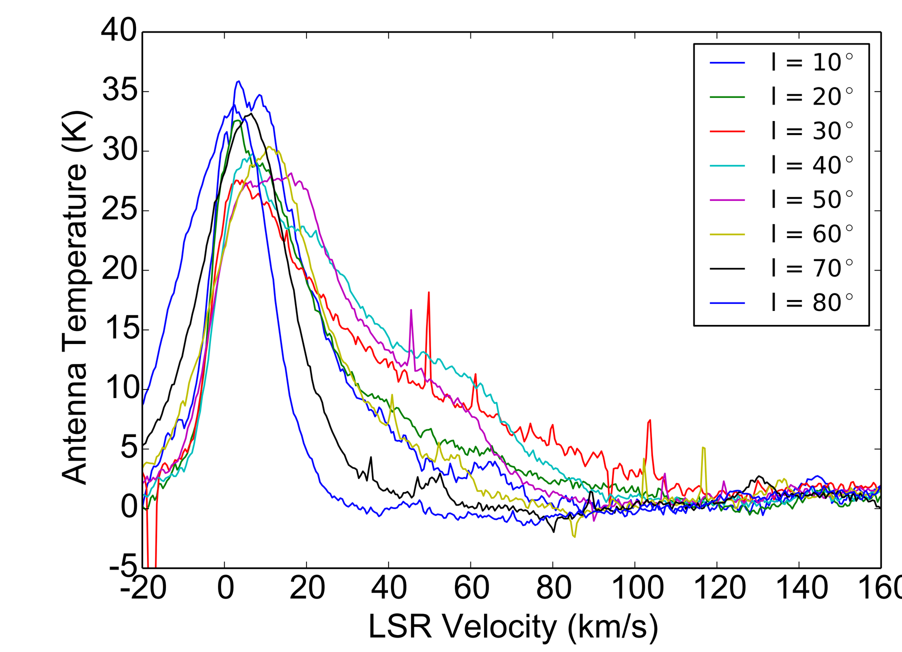


Fig. 9: Frequency-switched HI 21 cm line spectra obtained with the cardboard+foil horn antenna (*Top*) and the metal horn antenna (*Bottom*). Each spectrum has an integration time of about 30 seconds in the top plot, and about 150 seconds in the bottom plot. Narrow features are Radio Frequency Interference from unidentified sources. The spectra shown in the bottom plot, at various Galactic longitudes, were used to obtain the rotation curve shown below.

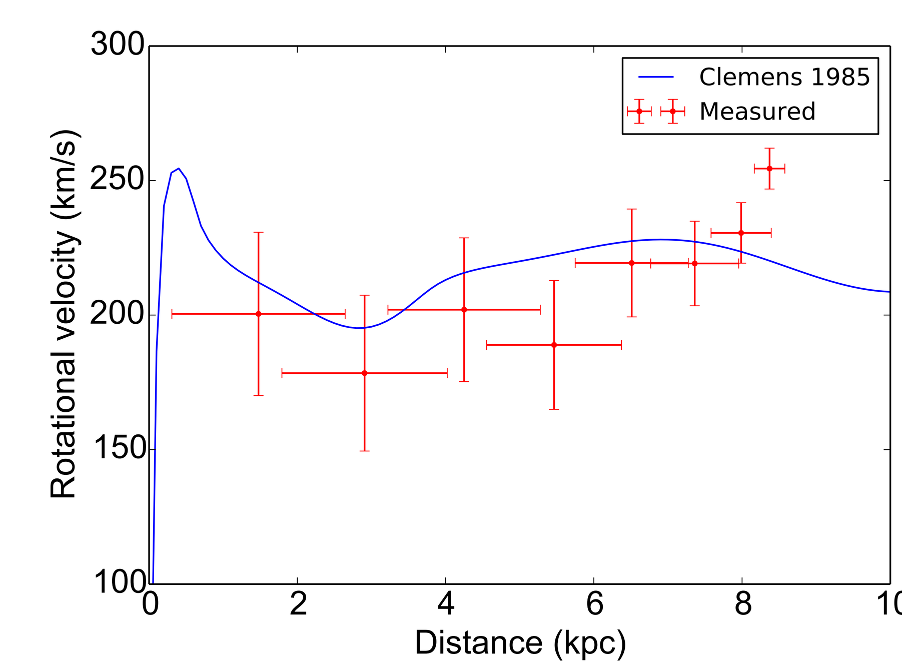


Fig. 10: Red symbols plot the rotation curve of the Milky Way, obtained with the metal horn antenna using spectra shown in Fig. 8. The blue curve is a composite of piece-wise polynomial fits to measured rotation curve from published CO and HI observations (from D. Clemens, 1985, ApJ, 295, 422). Error bars are large along x-axis, mainly due to the large beam size of the horn, smoothing the observations along different longitudes, resulting in blended spectra (contributing to error bars along y-axis). The overall frequency calibration may be in error as suggested by a small negative shift in the measurements compared to the published rotation curve.