Observing the Sun at 21 cm Wavelength with a Two-element Radio Interferometer

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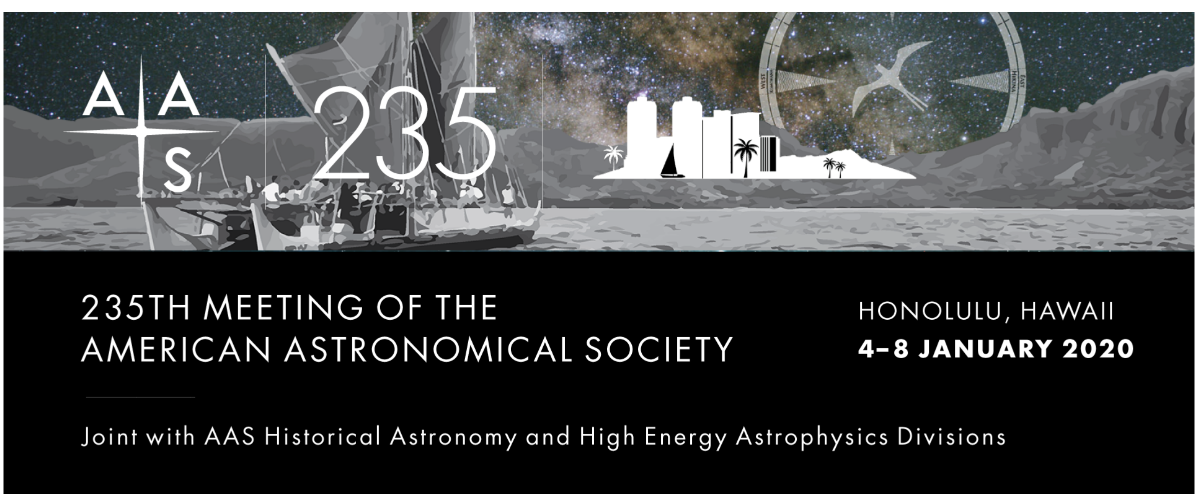


1. INTRODUCTION

Radio astronomy laboratory courses at undergraduate levels often use small radio telescopes for observations of the 21 cm atomic hydrogen emission from the Milky Way. Such projects have been established at many colleges and universities, following pioneering work by Rogers et al. [1] at MIT Haystack Observatory, and others. Typically a parabolic dish of 1 to 3 m diameter is used for such courses.

For Harvard University's Astro-191 course we have been teaching students to build their own pyramidal horn antennas with aperture size 75 cm x 60 cm, with a rectangular waveguide, and a Software Defined Radio (SDR) receiver, since 2014 [2]. Similar horn antenna experiments are also becoming popular at various institutes and among amateur radio astronomers [3]. A two-element interferometer using a pair of Yagi antennas [5], and a pair of helical antennas [6], to observe sources such as Cyg-A, Cas-A, the Galactic center, and the Sun have not been as popular, due to complexity in the construction, large sizes (for 100-400 MHz), and long required baselines (>1 km)

With a pair of horn antennas built by the students, we can easily implement an adding two-element interferometer as described in section 3. Such an interferometer can be used to observe the radio continuum emission from the Sun at 21 cm wavelength, which is a sweet spot wavelength to observe the Sun: it can be resolved and the radial profile studied with baselines as short as 30 m (can be set up on a rooftop). At 21 cm the emission profile is between the region of short wavelengths where the radio sun looks like the optical sun, and the long wavelengths where the very hot extended corona dominates (see Fig. 1). It is interesting that students can actually realize that the radio sun looks like a bright ring somewhat larger than the visual sun. This is a useful measurement to understand the concept of opacity.

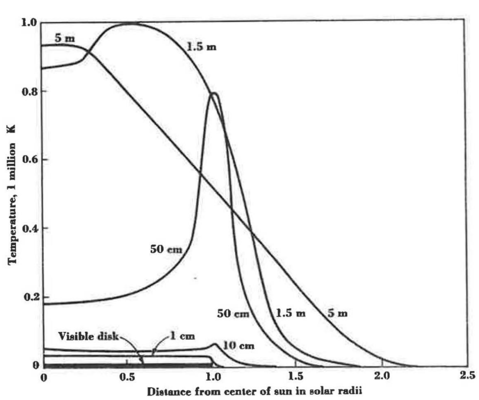


Fig. 8-35. Apparent blackbody temperature across the solar disk in solar radii for several values of wavelength. (*After Smerd*, 1950.)

Fig. 1: A radial profile of the radio continuum emission from Sun at various wavelengths (fig 8-35 from Kraus's textbook, Radio Astronomy [9]).

Solar Radio emission at 21 cm wavelength has been studied since the early 60s [6,7]. The emission comes from optical photospheric disk and the ring due to limb-brightening (see Fig. 1, e.g., 10 cm and 50 cm distributions). Because the corona is not fully ionized, the 21 cm line from neutral hydrogen can be observed from the Sun [8]. Mapping the Solar emission would require a very large antenna, but even with a pair of small antennas, one can model the visibility amplitudes as a function of baseline length, and learn about the brightness distribution of Solar radio emission. Although merely measuring the visibility vs baseline seems very naive, this type of experiment has been the basis of a number of truly breakthrough measurements in radio astronomy: (1) in the early 1950s when baselines were extended to 10s of kilometers to observe the archtypical radio galaxy, Cygnus, it was realized that the source was a double; (2) in the past few years the detection of the photon ring in the supermassive black hole in M87 is readily apparent from a simple inspection of the visibility vs radius dependence.

In section 2 we describe the basic theory of the two-element interferometer and the specific application to this problem. The hardware and software of the instrument is described in section 3. We present the observational results in section 4, describe the modeling and analysis in section 5, and summarize our conclusions in section 6.

2. THEORY OF TWO-ELEMENT INTERFEROMETER

A simple adding interferometer is discussed in section 6-10 of Radio Astronomy by Kraus [9]. A schematic diagram of such an interferometer is shown in FIgure 2:

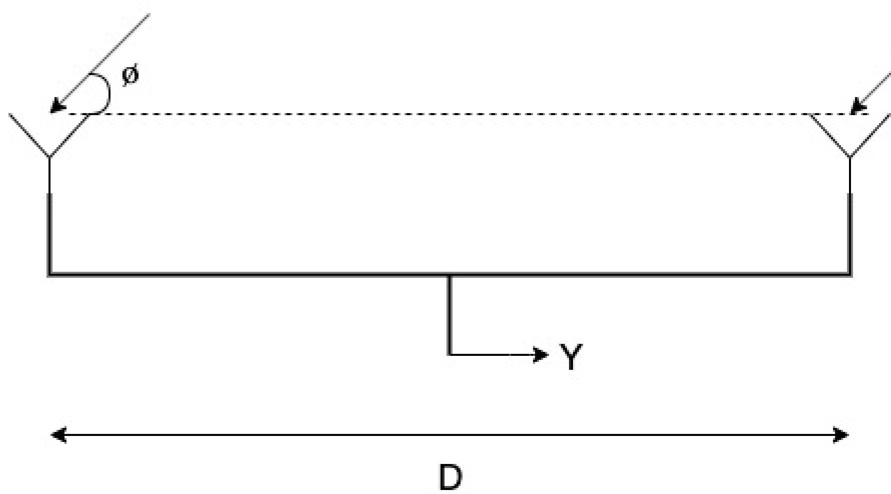


Fig. 2: Schematic diagram of a two element adding interferometer, where phi is the angle between the direction of the source and the baseline.

The output signal Y, squared output of the sum of the received voltages is sinusoidal as a function of time,

$$Y = a + b\cos(\omega \mathrm{t} + \mathrm{c})$$

since the phase difference between the antennas varies as

$$\frac{2\pi}{\lambda}\mathrm{D}\cos\phi$$

where λ is the wavelength.

For an east-west baseline, the projected baseline, $\mathrm{D_p} = \mathrm{D}\cos\phi$ is given by (see eqn 12.4 of [5]):

$$D_p = D(\cos^2 H_s + \sin^2\delta_s \sin^2 H_s)$$

The visibility as originally defined by Michelson, is

$$V_{app} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

as shown in Fig. 3.

The true visibility amplitude is given by

$$V = \frac{b}{a - I_{dc}}$$

Where I_{dc} is due to receiver noise.

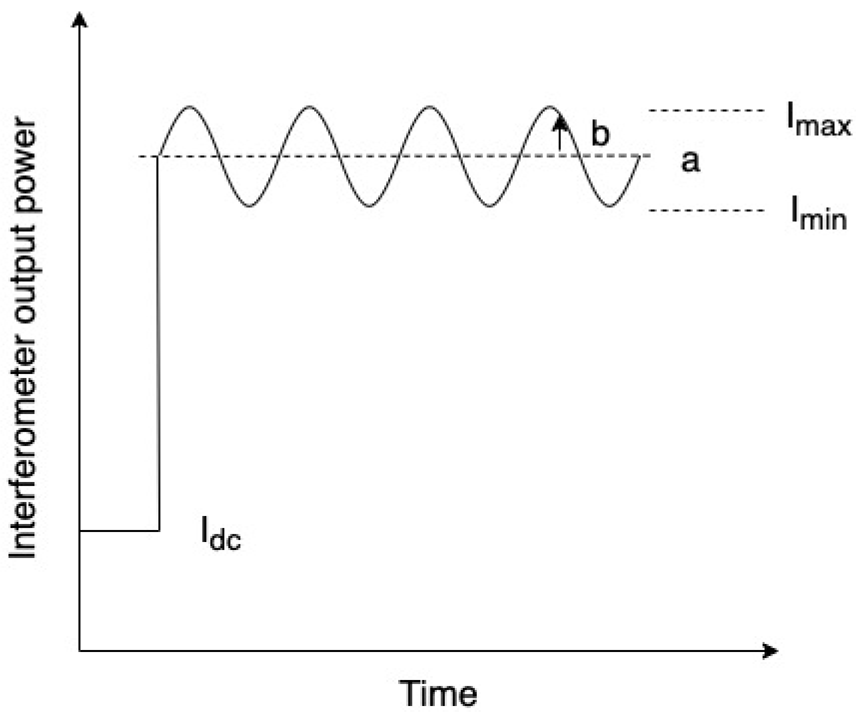


Fig. 3: Interferometer response as a function of time. I_{dc} represents the system noise, and needs to be calibrated by measurements of the actual "system temperature". This itself is a useful exercise for students (it involves measurement of total power output from each receiver, while terminating the input with a 50 ohm load at known room temperature, and dipped in liquid nitrogen (providing reference at 77.4 K).

I_{dc} can be determined from auxillary measurements of the antenna temperature, T_A, and the receiver temperature T_R, or from the power level away from the Sun. Alternatively we scale V_{app} (as listed in Table 1 in section 4) by a multiplicative correction factor Q such as to make the visibility on the shortest baseline equal to unity.

$$Q = \frac{T_A}{T_R+T_A}$$

T_R was measured from hot-cold calibration, to be 158 K. Q was measured to be 6.0, leading to TA=32 K. Correction for beam dilution using the beam size of 18.6 deg x 23.5 deg, we estimate the brightness temperature of the Sun to be about 110,000 K, which is in reasonable agreement with literature [7] for a quiet Sun.

3. APPARATUS AND METHOD

The radio interferometer consists of two horn antenna radio telescopes, a power combiner, a software defined radio (SDR) receiver, and a computer. The horn antennas were built by Harvard University undergraduate students. (One was built in February 2014, out of aluminum sheet metal, and the other from aluminum coated insulation board, in February 2019). Each of these antennas was used previously for observations of the Galactic 21 cm hydrogen line observations and measurements of the rotation curve of the Milky Way, as part of the Astronomy 191 laboratory astrophysics course. The dimensions of the horn antenna are shown in Fig. 4, and beam pattern measurements in Fig. 5.

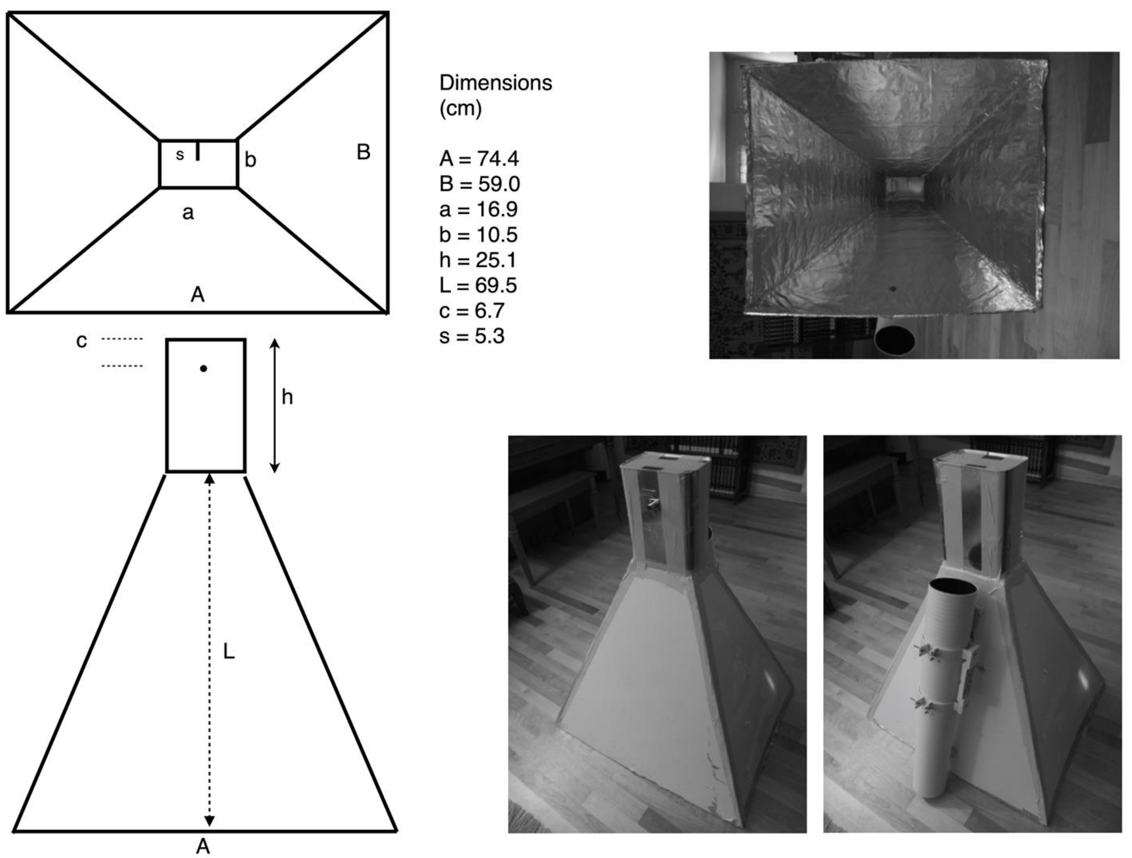


Fig. 4: Design and construction of the horn antenna. An earlier version of the horn antenna made from cardboard and aluminum foil version is shown here,

Two horn antennas were built, based on the same design, but using different materials for the panels of the pyramidal horn: 1) Aluminum sheet metal. 2) Insulation board (with aluminum foil coating). The rectangular waveguide feed for both horns was built from a standard 1 gallon paint thinner can which turns out to have the appropriate dimensions.

The aluminum sheet metal horn is more expensive but sturdier, and it is easy to add a bracket for telescope mount (directly bolted on the horn). The insulation board material is a good compromise for ease of construction, cost, and durability.

The gain of the horn antenna is 18.6 dB (calculated)

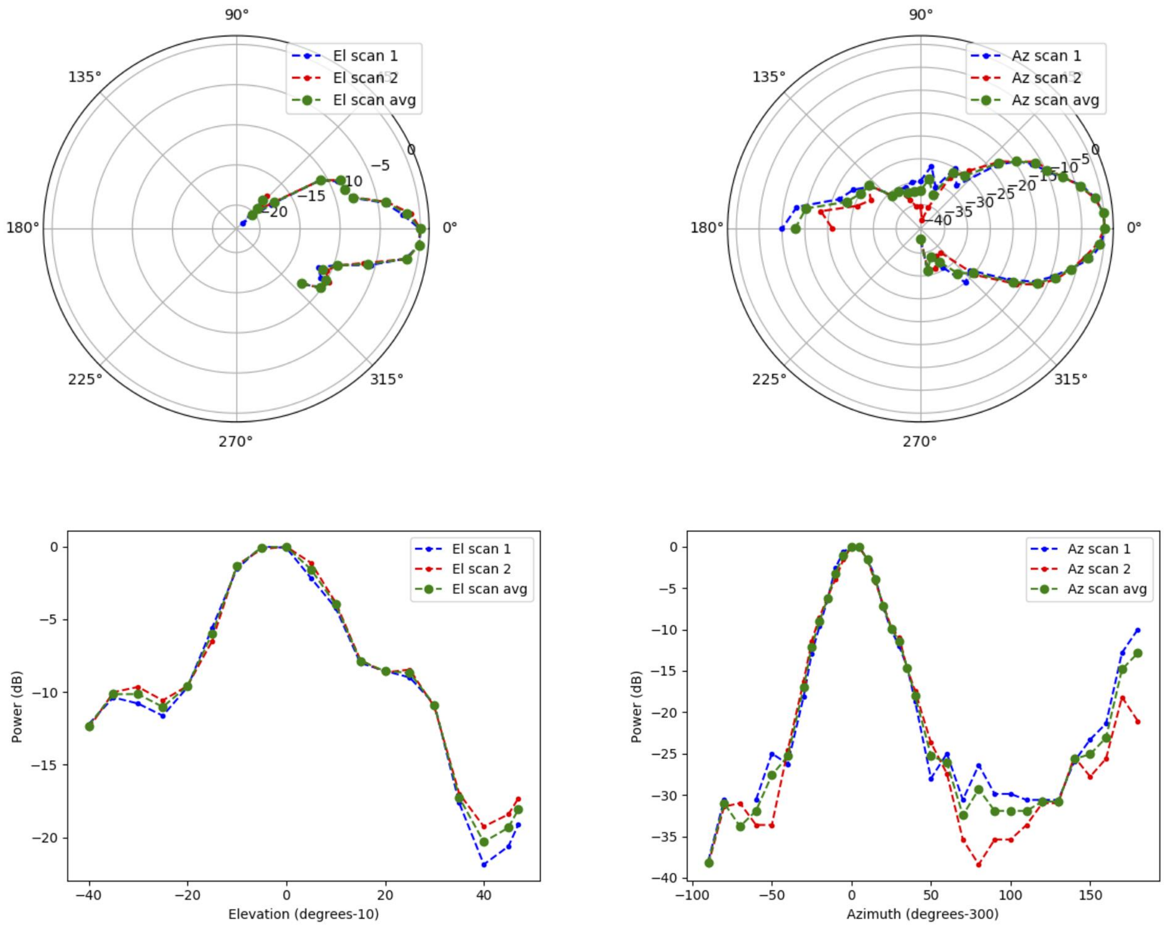


Fig. 5: Beam pattern measurements in polar (top) and cartesian coordinates (bottom). In the polar plots, the radial axis is power in dB; elevation scan is shown on left plot, and azimuth on right. The rear lobe in azimuth scan is an artifact due to multipath reflection from the back wall of a building. (These measurements were carried out in a parking lot at CfA, at 160 Concord Ave., Cambridge).

A quarter wavelength stub made from 12 guage wire is soldered to a male type N-type connector's probe, to form the antenna inside the rectangular waveguide. This connects directly to a low noise amplifier (LNA) of gain about 25 dB, and noise figure of about 0.5 dB. Fig. 6 shows a block diagram of the single radio telescope receiver.

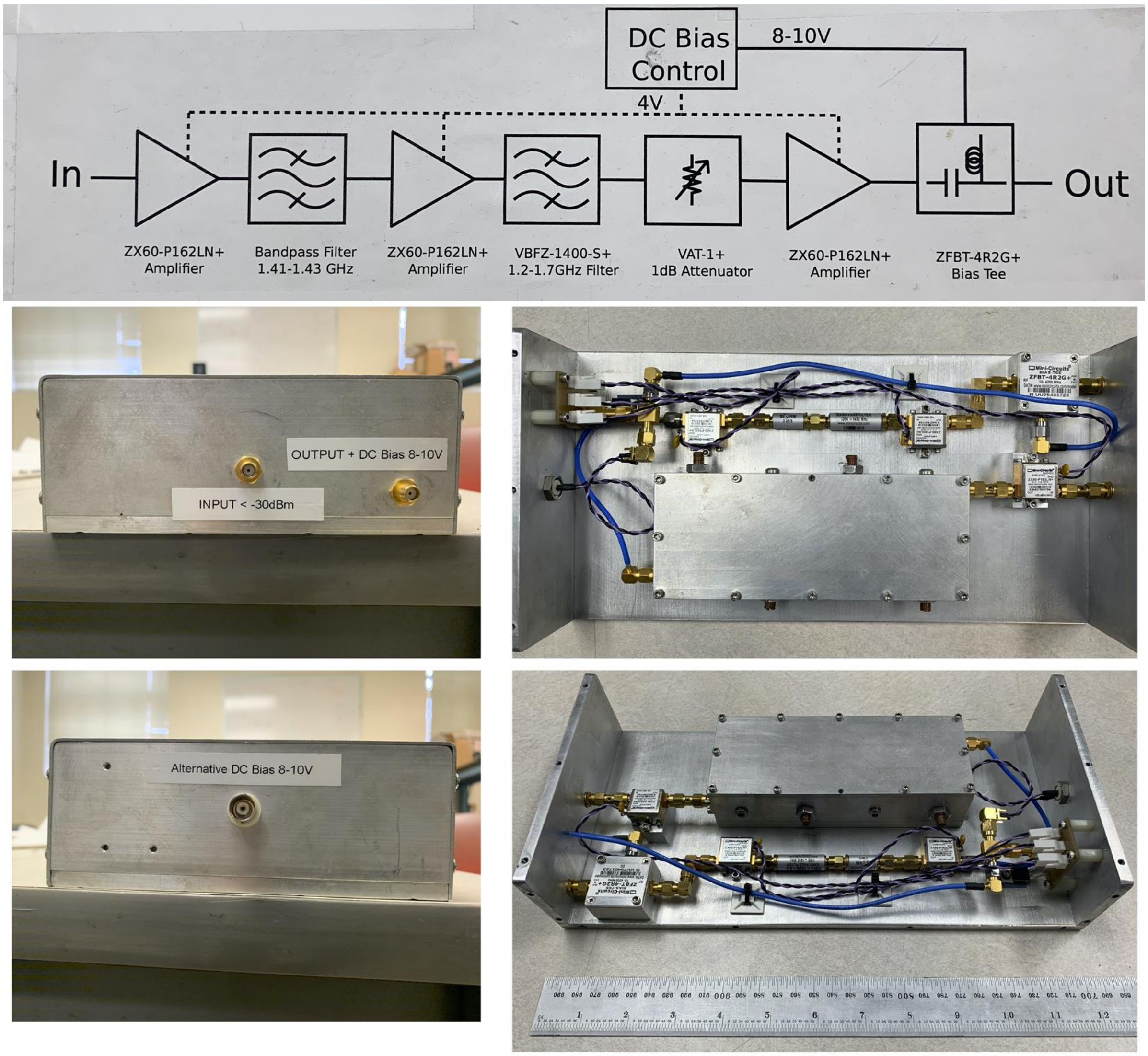


Fig. 6: (Top): Block diagram of the 1420 MHz single antenna receiver (built by Jake Connors). (Bottom four panels): Photographs of the receiver showing the components and connections.

Each of the horn antenna is mounted on a Celestron equatorial mount (that is usually used for small optical telescopes). The mounts have a clock drive for sidereal tracking, and setting circles for hour angle and declination. For the two element interferometer, the horn antennas are placed along an east-west baseline, with distances varying from about 3 m to about 20 m. A block diagram of the interferometer is shown in the top panel of Fig. 7

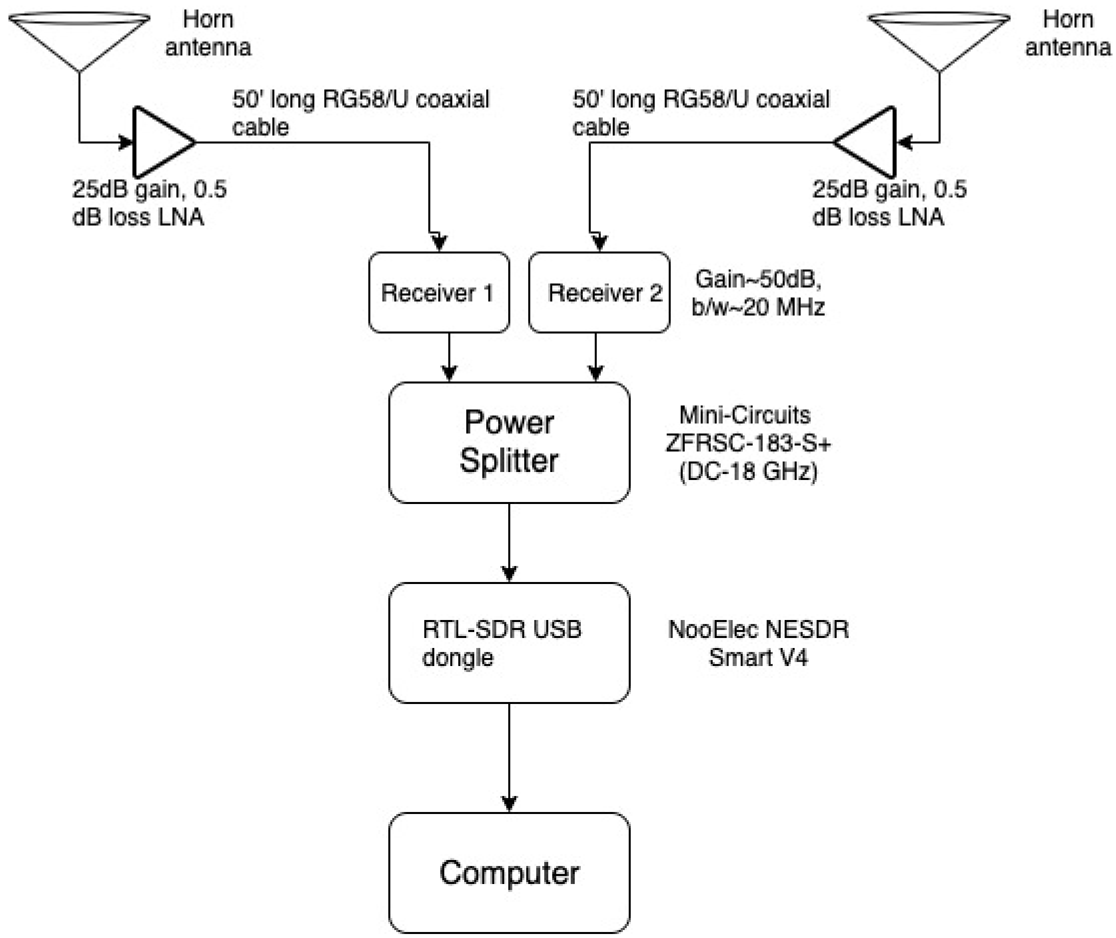


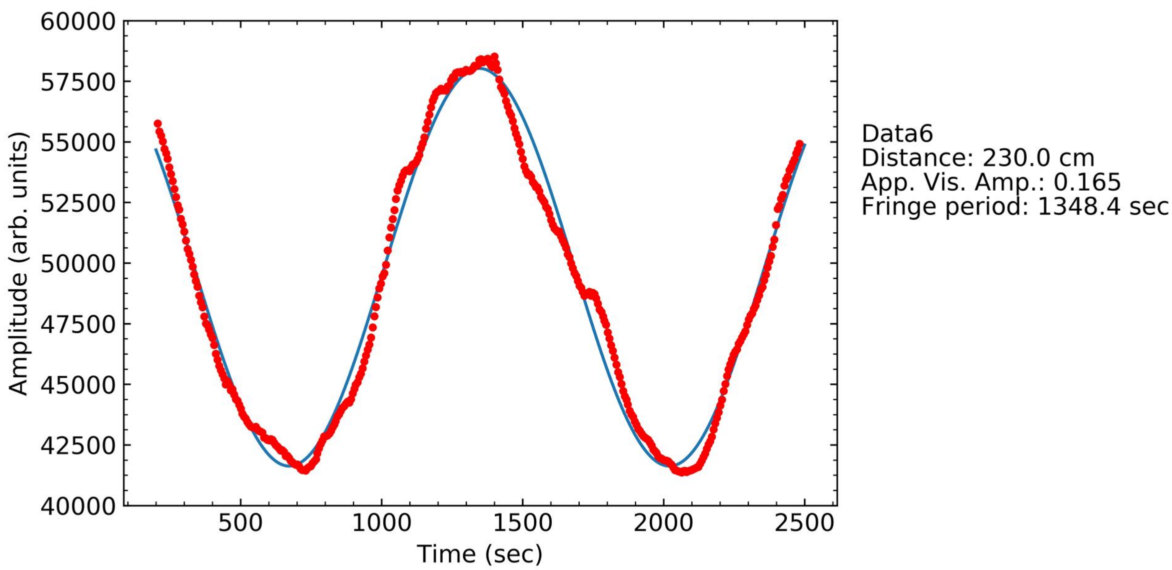
Fig. 7: Block diagram of the two element adding interferometer. Each of the receiver before the power splitter, is shown in Figure 6. These include a bandpass filter of bandwidth 20 MHz, which is small enough to avoid delay decorrelation.

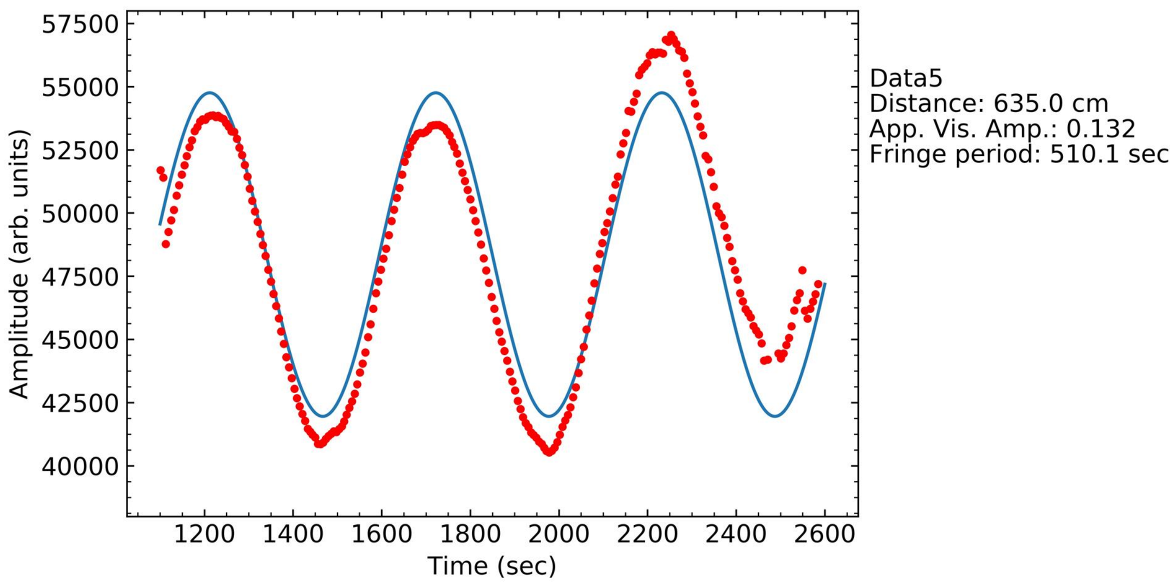
A single 25 dB gain LNA is at the output of the feed at the rectangular waveguide directly connected to the N-type connector. Output of this amplifier is connected to a long coaxial cable, which also has a twisted pair of wires for the 4V DC supply for the LNA. These cables from both the antennas, are fed as input to the receiver box. Outputs from both these receivers is fed to a power combiner, and the added signal is directly connected to the SMA connector of the SDR USB dongle receiver, which is connected to the computer via a USB connector.

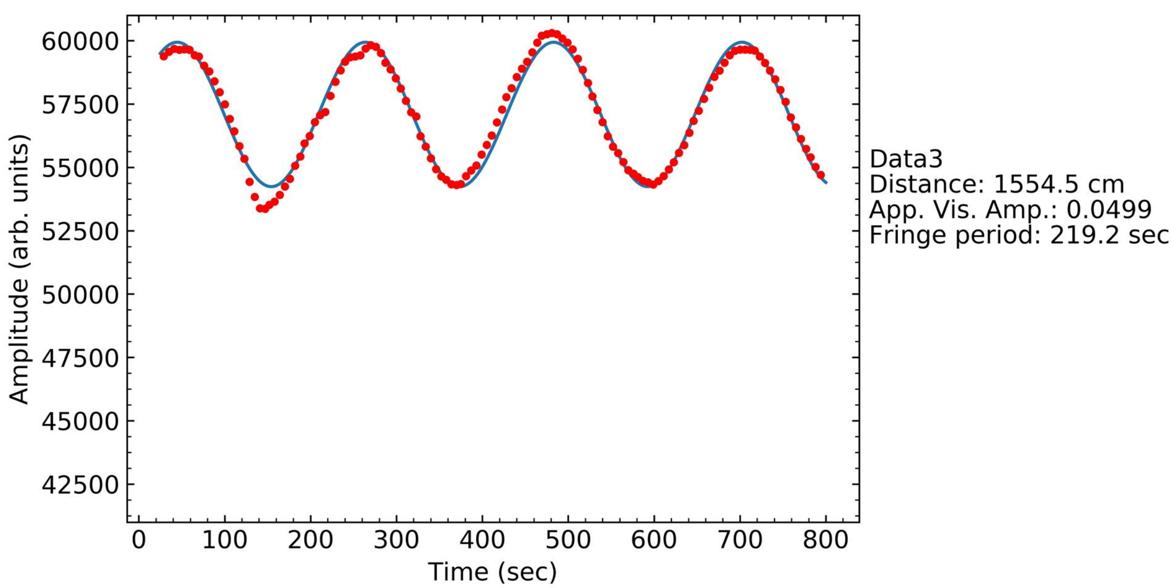
4. OBSERVATIONS AND RESULTS

Observations were made on 11 July 2019 from the Center for Astrophysics in Cambridge MA. Students used the python library *astropy* to obtain the Sun's coordinates, and used the setting circles on the mounts to point horn antennas to the Sun. Further pointing corrections were made by observing the shadow of the feed on the bottom of the rectangular waveguide backshort. Data were recorded using a python program (*totalPowerScan.py)* which acquires the stream of I and Q samples from the SDR dongle receiver, computes the amplitude and plots it in real-time. The experiment was repeated for varying baseline lengths, by lifting the western horn antenna and placing it at different distances from the eastern horn. Baseline lengths were measured using a tape measure between the base of the mounts.

Four of the sets of fringes were obtained as shown in Figure 8:




Amplitude (arb. units)
Time (sec)
Data5
Distance: 635.0 cm
App. Vis. Amp.: 0.132
Fringe period: 510.1 sec


Amplitude (arb. units)
Time (sec)
Data3
Distance: 1554.5 cm
App. Vis. Amp.: 0.0499
Fringe period: 219.2 sec

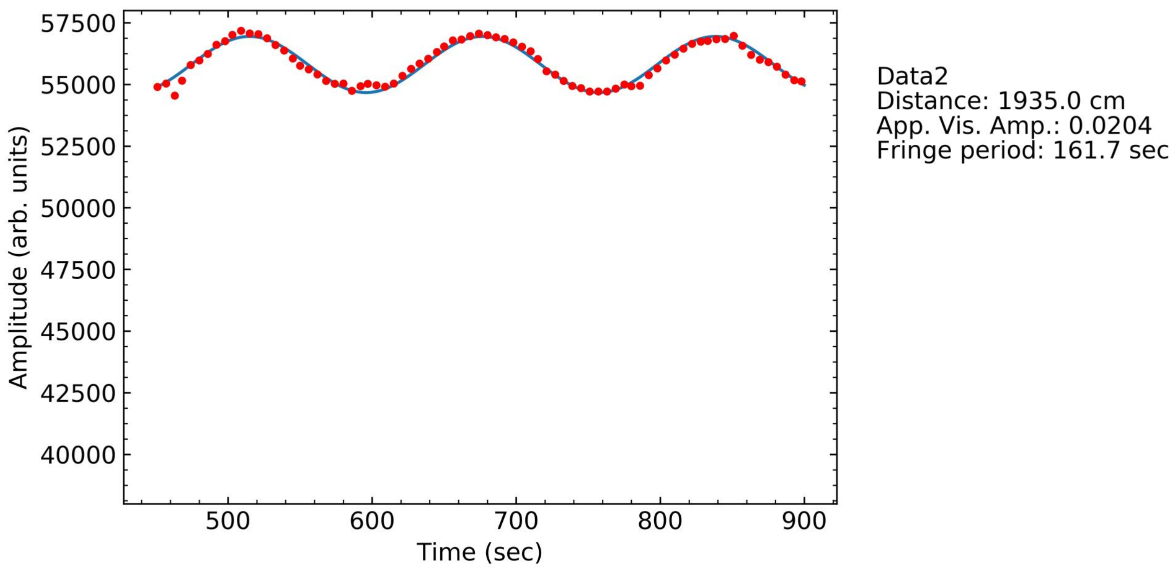


Fig. 8: Observed fringes on Sun for four baseline lengths. Sinusoidal fits are shown in red. Fit results are shown on the right side of each plot.

Sinusoidal fit results are shown to right of each panel above. Visibility amplitudes are normalized with the shortest-distance measurement (at 230 cm), and tabulated along with other parameters in Table 1:

Table 1

Data label	Distance (cm)	local time (hh:mm)	Sun (HA) (hh:mm)	Sun (dec) (dd:mm)	Proj Dist (cm)	Visibility amplitude
D6	230	11:54	23:04	22:05	223.9	1.00
D5	635	12:40	23:50	22:04:45	634.5	0.80
D2	1935	13:59	1:10	22:04:20	1858.4	0.35
D3	1554	14:19	1:29	22:04	1455.2	0.30
D4	1112.5	14:35	1:45	22:04	1014.8	0.12

5. MODELING AND INTERPRETATION

At wavelengths below 10 cm, the emission is well represented by a disk of diameter 30' (same as optical). At longer wavelengths, the ring-like emission starts to dominate, up to a wavelength of about 50 cm, due to limb brightening from coronal contribution in addition to the disk. At 21 cm, the radiation is likely to be a combination of disk and ring.

The interferometer measures the visibility, given by the Fourier transform of the brightness distribution, which for a disk+ring source, is given by:

$$V(z) = \frac{\frac{2J_1(2\pi Rz)}{Rz} + FJ_0(2\pi Rz)}{1+F}$$

(Tsiligaridis and Rogers, Haystack VSRT Memo #24, see also TMSIII [10], chapter 5).

where J_1 and J_0 are Bessel functions, R is the angular radius of the Sun in radians, $\mathrm{z} = \mathrm{D_p}/\lambda$ and F is the fraction of Solar emission in limb-brightened part (F=1 for totally ring like emission, 0 for only disk).

We have insufficient data for a full modeling but the observed 5 visibility measurements are compared to a disk and ring model in the Fig. 9:

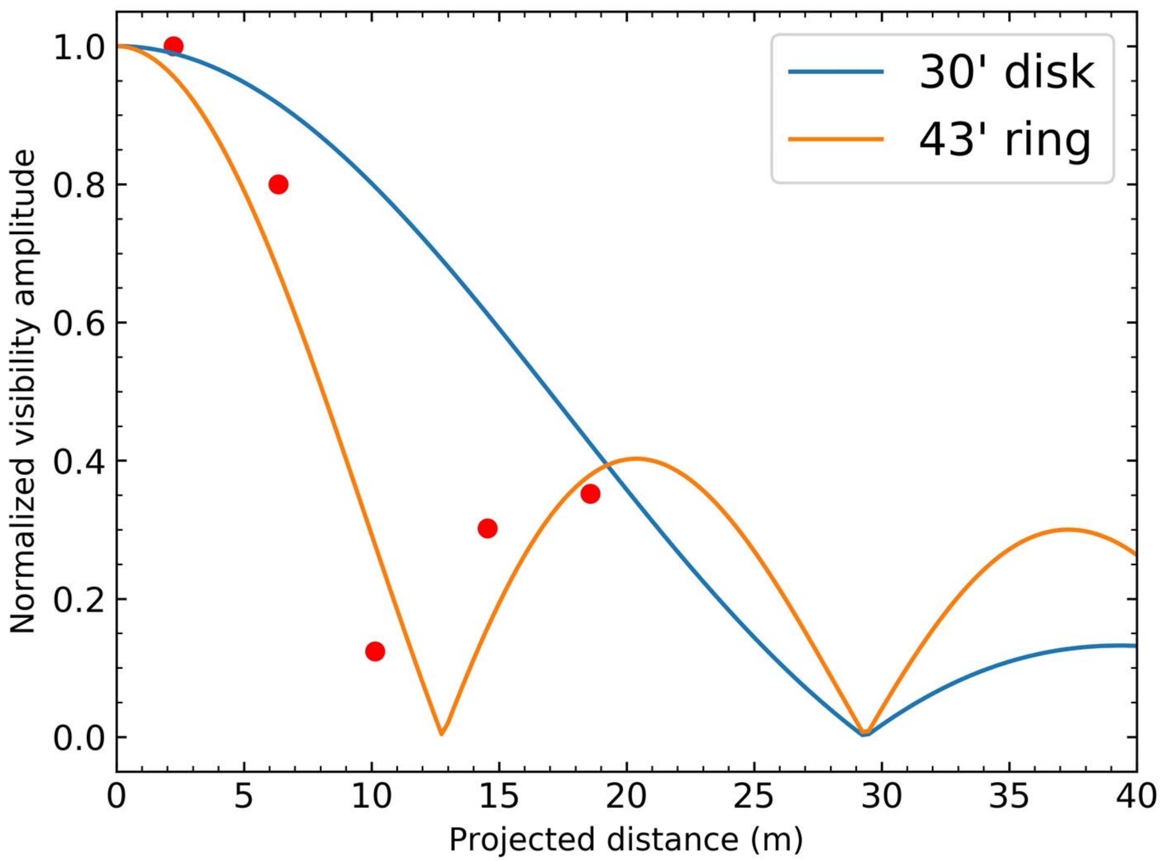


Fig. 9: Normalized visibility measurements versus Dp with two models..

6. CONCLUSIONS AND OUTLOOK

- We have developed a two-element radio interferometer operating at 1420 MHz, that can be used for observations of the Sun.

- The project is suitable for undergraduate radio astronomy course at junior or senior level with a strong hands-on element for student learning.

- The total cost of the interferometer is well within $1000, with all components readily available off-the-shelf. The antennas are easily built by students over a time-scale of about a week. The full experiment can fit within half a semester.

- Although the adding interferometer is simpler, the output suffers from gain fluctuations and the total power is harder to calibrate to measure the absolute brightness temperature of the Sun. A cross-correlating interferometer eliminates the DC offset term, its average output is zero, and is less sensitive to gain variations in the receivers. Additional amplification just before a mixer, and a sampler for analog output can be easily implemented to convert this into a cross-correlating interferometer.

- More finely sampled visibility amplitudes extending to shorter and longer baseline, will be carried out in future experiments.

- Students can also attempt to fit the observed visibility amplitude vs baseline length, to various models.

- The observational part of the experiment can be completed in about 3 hours, filling a lab period.

Sorry but time is up!

ABSTRACT

As part of the undergraduate astronomy course (Asro-191) at Harvard University, students have built pyramidal horn antennas with aperture size 75 cm x 60 cm, a rectangular waveguide, and a Software Defined Radio (SDR) receiver for 21 cm wavelength observations of the Galactic neutral hydrogen emission [Patel et al. 2014AAS...22441501P]. With two such antennas, a radio interferometer can be built rather simply, by just adding the signals using a power combiner, and feeding the output to the SDR receiver. The narrow bandwidth of this receiver (2.4 MHz) allows for easy detection of interferometric fringes, with minimal bandwidth smearing. Fringes are easily detected observing the Sun, with the two horn antennas along an east west baseline, with a fringe period of about 2.4 minutes for a 20 meter baseline. We compare our measurements of visibility amplitudes as a function of projected baseline length, with three theoretical models: 1) a disk of diameter 30', 2) a ring (due to limb brightening)of 43' diameter, and 3) a combination of disk plus ring models, also of 43' diameter. Our measurements appear to fit best the combination model, confirming the expectation of significant limb brightening and a slightly larger size of the Sun compared to the optical photospheric diameter. The radio interferometer has great educational value at both high-school and undergraduate levels. In addition to astronomy it is a useful tool to introduce concepts such as aperture efficiency, receiver noise temperature, and measurement errors.

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