Circular polarization observations of Sun's magnetic field using commercial dish TV antennas

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Abstract

The radio astronomy group in the Indian Institute of Astrophysics (IIA) has been carrying out routine observations of radio emission from the solar corona at low frequencies (≈40 – 440 MHz) at the Gauribidanur observatory, about 100 km north of Bangalore. Since IIA has been performing regular observations of the solar photosphere and chromosphere using different optical telescopes in its Kodaikanal Solar Observatory (KSO) also[a], the possibilities of carrying out Stokes-I and Stokes-V observations of the solar chromosphere using low-cost radio instrumentation to supplement the optical observations are being explored. Note that measurements of Stokes-V help to infer the magnetic field strength of the sunspots. As a part of the exercise, recently the group has developed prototype instrumentation for interferometric observations of radio emission from the solar chromosphere at high frequencies (≈11.2 GHz) using three commercial dish TV antennas. The hardware set-up and initial observations are presented.

1. Introduction

Commercial dish TV antennas are parabolic structures designed to receive radio waves from a communication satellite. The antennas and the associated front end receiver systems have improved with advances in the TV systems. They operate typically over the frequency range 10.7 – 11.7 GHz (Ku-band) and provide very good signal-to-noise ratio (SNR). So we attempted to observe the Sun in the microwave frequency range mentioned above with three commercial dish TV antennas. The observations were made in the correlation interferometer mode since it provides better sensitivity. Further, any contribution from the galactic background will also be negligible **[1]**.

2. Antenna and Receiver System

Figure 1 shows the three commercial dish TV antennas set-up in the Gauribidanur observatory[b] for solar observations **[2,3]**. Each dish is a parabolic reflector of diameter D ≈ 62 cm. It is an equatorial mount system. There is a feed horn and Low Noise Block (LNB, otherwise called the front-end receiver) at the focus of the reflector. Note that among the three feeds two (path A & B) are oriented in the same direction and the third one (path C) in an orthogonal position with respect to the other two (refer Figure 1). They receive and amplify the signal reflected by the parabolic dish. The LNB[c] has a noise figure (NF) ≈ 0.6 dB (corresponding to a noise temperature of ≈45 K), and gain (G) ≈ 60 dB. The characteristic impedance (Z_o) of the LNB is ≈75 Ω. But the co-axial cables and other components used in the subsequent stages of the analog receiver system have Z_o ≈50 Ω. Due to this, there will be reflection of signal from the load and hence standing waves in the corresponding signal path. But we found that the reflected power due to the above impedance mismatch is small (≈4%). The measured reflection coefficient (Γ) is ≈0.2. This indicates that the amount of transmitted power that gets attenuated due to signal reflection is, $10 \log(1 - \Gamma^2) \approx 0.2$ dB. Nevertheless, we have connected a 1 dB fixed attenuator between the LNB and the following amplifier (see Figure 2) to minimize the effects of the reflected signal[d] and also in the process of designing an impedance converter.

The response pattern ('beam') of each dish has a theoretical half-power beamwidth (HPBW ≈ $70^\circ \lambda/D$) of ≈$3.02^\circ \times 3.02^\circ$ (R.A. × Dec.) at a typical frequency like 11.2 GHz. The feed horn receives radio frequency (RF) signal in the frequency range ≈10.7 – 11.7 GHz. The LNB has a frequency translating unit or a 'mixer' which converts the aforementioned RF signal to an intermediate frequency (IF) range of ≈950 – 1950 MHz by using a local oscillator (LO) signal of frequency 9.75 GHz. We have set up a correlation interferometer with a separation of ≈2.5 m between the two dish antennas for Stokes-I and Stokes-V measurements. The baseline between the antennas is oriented in the east–west direction. So, the theoretical angular resolution in that direction (for observations near the zenith), specified by separation between the interference fringes, is ≈37′ at 11.2 GHz. The angular size of the Sun at 11 GHz is ≈33′ **[4]**. Since this is smaller than the aforementioned fringe spacing, the Sun can be assumed to be a 'point' source for our observations. The corresponding resolution in the north–

[a] https://www.iiap.res.in/kodai.htm
[b] https://www.iiap.res.in/?q=centers/radio

[c] https://www.solid.sale/lnbf/ku-band-lnb/fs-108-ku-band-lnb
[d] https://www.minicircuits.com/app/AN70-001.pdf, etc.

south direction is ≈3.02°, i.e., the HPBW of the dish mentioned above.

A pair of motors, one for R.A. and other for Dec., are used for each dish antenna to tilt it towards the source position in the sky. Both motors are controlled by a common Arduino board interfaced to a computer[e]. In the interferometric mode of observations, the phase of LO signal at the three feeds must be synchronized. To achieve temporal coherence, we used a common external 25 MHz clock signal to trigger the oscillators in the three LNBs. DC power supply for each LNB was provided using a Bias-Tee. It is a 3-port network[f] having (i) RF port where only RF signal can be extracted by blocking DC with the help of a capacitor, (ii) RF+DC port where DC is sent to bias the module (LNB in our case) and receive RF signal from the latter, and (iii) DC port where the DC source for biasing the module is connected. We used 'Nikou' make (10 MHz – 6 GHz) Broadband Radio Frequency Microwave Coaxial Bias-Tee 1 – 50 V, 0.5 A (max) for the present work.

The IF signal from each of the three antennas are independently amplified, filtered (≈1080 – 1450 MHz) and then transmitted to an analog receiver after down converting to ≈191.4 MHz by mixing with another LO signal (triggered by the same 25 MHz clock signal mentioned above) of frequency 1097.8 MHz. A bandpass filter with center frequency 191.4 MHz and bandwidth ≈6 MHz is used at the output of the 'mixer'. In the analog receiver, the 191.4 MHz signal is further amplified and down converted to 10.7 MHz by mixing with a LO signal (triggered by the same 25 MHz clock signal mentioned above) of frequency 180.7 MHz. Here a bandpass filter with center frequency 10.7 MHz and bandwidth ≈1 MHz is used at the output of the 'mixer'.

The 10.7 MHz IF signal is split into in-phase and quadrature phase components using a quadrature power splitter and then connected to a 1-bit correlator which can be assembled with simple digital logic circuits (refer Figure 2). The 10.7 MHz signal from the analog receiver are digitized using a 2-level (+1 or 0) high-speed comparator (AD790). The digitized signals are then sampled in a D-type flip-flop (74LS74) at a rate of 4 MHz. Later they are passed on to an Ex-NOR gate for correlation. The output of the correlator is counted with the help of a 24-bit counter, which acts as an integrator **[5]**. The counter output (i.e., the correlation count) is read by a computer via a 8-bit micro-controller (Microchip's PIC16f877A). The integration time is ≈1 sec.

3. Observations

Figure 3 show observations of the Sun (12 June 2022) with the above set-up (i.e. the 3-element Ku-band interferometer). The observations were carried out in the drift scan mode after tilting the three dish antennas towards the direction of the sources using the motors as mentioned earlier. While the 'cosine' fringes correspond to the correlation between in-phase 10.7 MHz IF signal from the two antennas, the 'sine' fringes correspond to the correlation between in-phase 10.7 MHz IF signal from one of the antennas and quadrature phase 10.7 MHz IF signal from the other antenna. The observed fringe spacing in Figure 3 is ≈40′. The half-width of the fringe envelope is ≈3.2°. The observations were carried out when the Sun was above the local meridian in Gauribidanur. The declination of the Sun was ≈23°30′ N. Taking into consideration the projected baseline length (≈2.3 m) as seen by the source, the aforementioned fringe spacing derived from the observations is reasonably consistent with the expected value mentioned earlier. The extent of the observed fringe envelope is supposed to be same as the theoretical HPBW (≈3.02°) of the individual dish antenna. But it is ≈1.06 times wider. In fact, estimates from observations on different days also gave the same result (i.e., ≈3.2°). Therefore, the above difference is most likely due to the design parameters of the dish. For e.g., if the electric field distribution across the aperture is parabolic, then HPBW ≈73°λ/D **[1]**. The visibility amplitude for each observation was calculated using the Visibility Amplitude ($=\sqrt{C_t^2+S_t^2}$), where C_t and S_t are the amplitudes of the cosine and sine fringes at time t. At a given time, the correlation between the signals received by the antennas A and B gives information on Stokes-I (since the two feeds have identical orientation) and the same between B and C gives information on Stokes-V (since the two feeds are mutually orthogonal). The antenna B is the reference for generating both Stokes-I and Stokes-V profiles.

The maximum radiation from the Moon is usually observed at the Earth after ≈3 – 4 days of the full moon day[g]. Using this, we can estimate the total and circularly polarized flux of the Sun. However, observations of the Sun and the Moon could be at different epochs and the receivers are not temperature controlled also. So, there could be gain variations. We can verify and correct this by monitoring the Ku-band transmission from geostationary satellites such as INSAT 3A & 4A (located at ≈93.5° E longitude and ≈83° E longitude, respectively)[h]. The equivalent isotropic radiated power (EIRP) of the above two satellites in the frequency range 11 – 11.25 GHz and 11.55 – 11.70 GHz are ≈48 dBW and ≈52 dBW, respectively. Note that the coordinates of Gauribidanur observatory are ≈77°26′ E longitude and ≈13°36′ N

[e] http://www.e-callisto.org/Hardware/Callisto-Hardware.html
[f] https://www.microwaves101.com/encyclopedias/bias-tee

[g] https://doi.org/10.3929/ethz-a-004322130
[h] https://en.wikipedia.org/wiki/Indian_National_Satellite_System

latitude. We can observe the aforementioned satellite signal transmission on a daily basis, particularly before and after the observations of the Sun and the Moon. By identifying the different possible sources of error, we can calculate the overall error in the polarization leakage due to the instrument.

A set of trial observations both in Stokes-I (correlating signals received from antennas A & B) and Stokes-V (correlating signals received from antennas B & C) were recorded. The consecutive days of observations show us a certain range of deflections. The least deflection in Stokes-V corresponds to the instrumental polarization leakage. The deflection above this was considered for estimating Stokes-V. The calculated peak values of Stokes-I and Stokes-V from the trial observations carried out on different days were used to estimate the flux density. The estimated flux density values for different days of observations reported are shown in Table 1. The observed Stokes-I and Stokes-V profiles after calibration for flux density corresponding to 12 June 2022 are shown in Figure 4.

4. Results

Figure 1. The correlation interferometer that was set up using three commercial dish TV antennas at the Gauribidanur observatory for observing the Sun in the Ku-band.

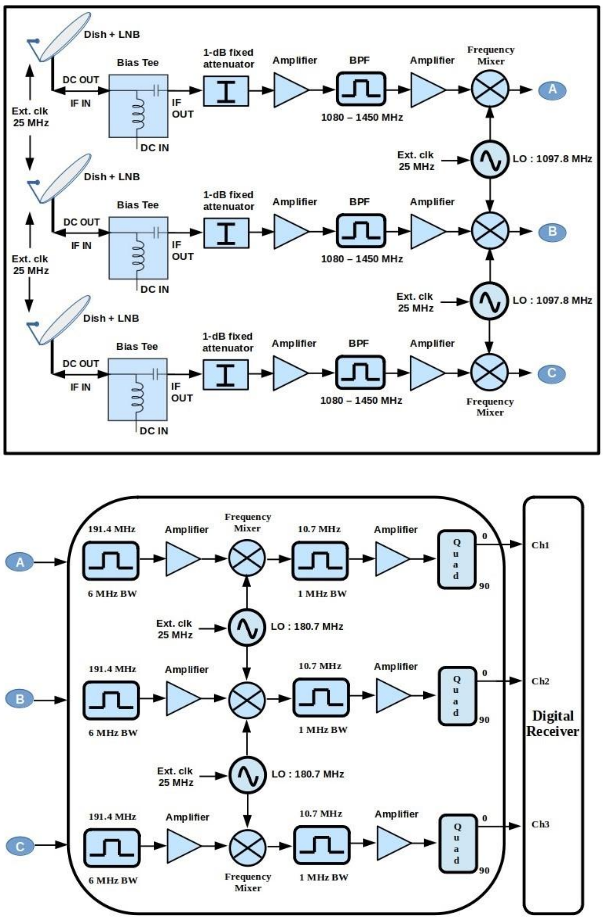
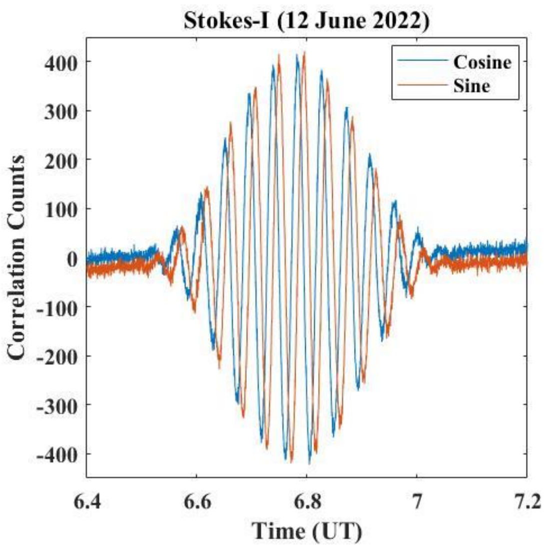


Figure 2. The analog receiver section corresponding to the three-element interferometer in Figure 1. ‘Quad’ is for quadrature power-splitter. The 25 MHz external clock is common to all the blocks.



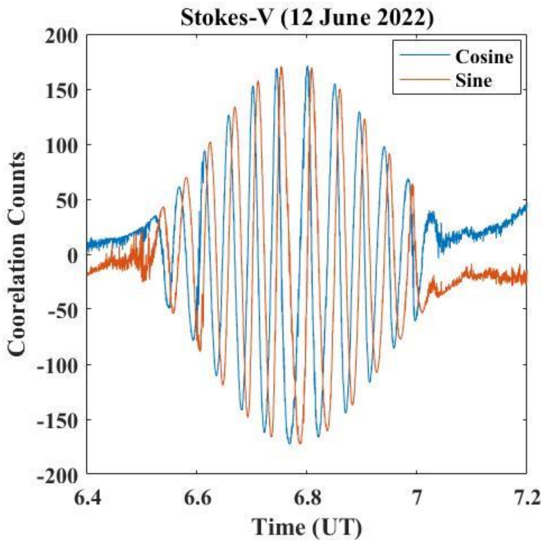


Figure 3. Observations of the Sun on 12 June 2022 at ≈11.2 GHz during its transit over the local meridian in Gauribidanur. Upper panel shows Stokes-I and Lower panel shows Stokes-V.

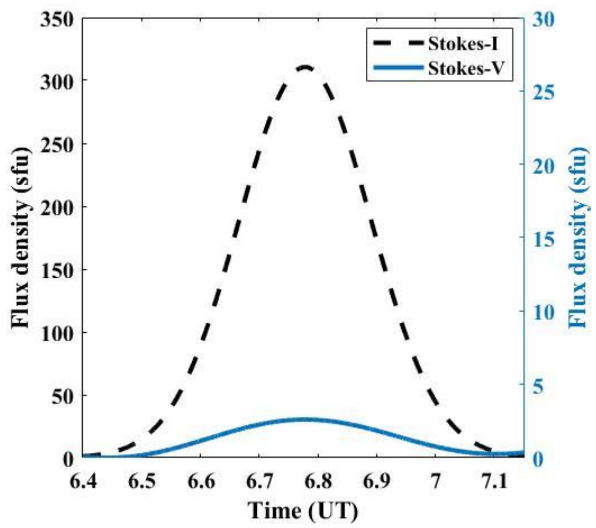


Figure 4. Estimated flux density of Stokes-I and Stokes-V obtained on 12 June 2022 (1 sfu = 10^{-22} W/m^2/Hz).

Table 1. Estimated flux density of Stokes-I and Stokes-V.

	Flux density (sfu)	
Date	Stokes-I	Stokes-V
10 June 2022	332.03	31.08
12 June 2022	310.65	2.6
13 June 2022	327.88	reference
14 June 2022	321.94	4.36
15 June 2022	329.06	18.75
16 June 2022	316	23.94
17 June 2022	324.91	18.97

5. Acknowledgements

We express our gratitude to the staff of the Gauribidanur observatory for their help in setting up the antenna / receiver systems, and carrying out the observations.

6. References

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