Sky Watch Array Network- Analysis of Solar Data

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The Sky Watch Array Network (SWAN) is a radio interferometric array formerly located at the Gauribidanur observatory near Bangalore, India and is now distributed in various institutes across India including the Indian Institute of Technology Kanpur. In this project, we look at the structure of this interferometric array and how different parts function. We also carry out data analysis of solar data collected by tiles 3 and 7 on April 14, 2021.

I. INTRODUCTION

Radio astronomy is a field that studies celestial bodies emitting at the radio region of the electromagnetic spectrum, specifically from 10MHz to 1 THz. The radio region of the EM spectrum is a crucial area of study as many phenomena and objects are visible in this frequency but invisible at other wavelengths. Most gases in galaxies are invisible in the visible light region, but can be seen by radio telescopes. Historically, the cosmic microwave background radiation and pulsars were first discovered by radio telescopes.
Radio telescopes like the Giant Metrewave Radio Telescope (GMRT), Very Large Array, Arecibo Observatory, etc. have dishes with large areas as radio waves come from very far away and are weak, so the radio waves are required to be concentrated from a large area to a small feed at the center of the dish. Also, for good angular resolution, gigantic telescopes are needed as the diffraction is inversely proportional to diameter and directly proportional to wavelength of incoming waves. However, this has limitations such as high cost, difficulty in maintenance, etc.

Radio interferometric arrays overcome this disadvantage of traditional radio telescopes. They involve using many antennae at different locations on the Earth's surface, and these antennae coherently act as a large radio telescope. The Sky Watch Array Network (SWAN) is a radio interferometry array initiative headed by Prof. Avinash Deshpande of Raman Research Institute, Bangalore, India. The initial phase of this initiative involved 7 tiles placed at the Gauribidanur Radio Observatory near Bangalore. Now, tiles are being distributed to various institutes across the country including the Indian Institute of Technology Kanpur.
In this project, we review the hardware and working of SWAN. We also analyze the data collected by SWAN tiles 3 and 7 on April 14 2021. This involves single tile analysis in the form of histogram plots and power spectra, as well as cross correlation of data.

II. SWAN- HARDWARE AND FUNCTIONING

A SWAN tile consists of 16 dipole antennae (Murchison Widefield Array antennae) arranged in a 4x4 matrix, a beamformer that combines the signals from the antennae and a data acquisition system.

A. Structure of Tile

The components of a SWAN tile are as follows:
1. 16 dual polarization antenna elements that are arranged in a 4x4 grid with 1.1 meter spacing.
2. These tiles have a tunable frequency range of 80-300 MHz and a bandwidth around 32 MHz.

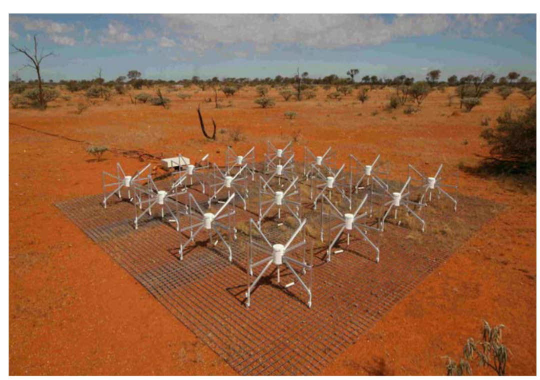

FIG. 1. MWA Tile with 16 dipole antennae

Each antenna element is a bowtie element with orthogonally crossed arms as shown in figure 2. The 2 sets of perpendicular arms account for X and Y polarizations respectively. Within each bowtie element are 2 PC boards,

FIG. 2. Bowtie element

each consisting of a Low Noise Amplifier (LNA). A LNA consists of a transformer balun and is responsible for changing the input signal's impedance to 50 Ω.

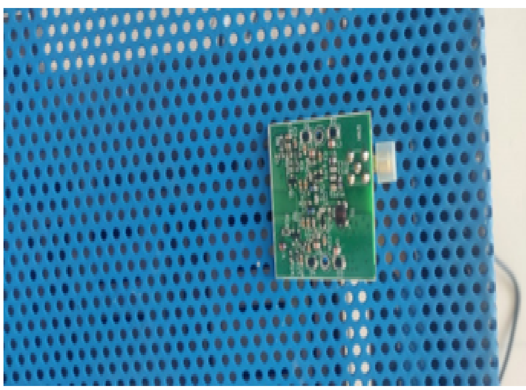

FIG. 3. Low Noise Amplifier chip

The groundscreen is a 5x5 meter square made of galvanized steel wire of diameter 3.15mm. The structure consists of 5x5 cm grid squares, so the system acts as a mesh and reduces noise contribution from the ground.

B. Beamformer

The beamformer is a device responsible for coherent addition of all signals collected by a tile. A tile has a field of view of about 30^o from the Zenith, and the beamformer combines these signals in phase. The resultant beam is passed through RF filters and power amplifiers and sent to a receiver at a different location. The beamformer has 2 delayline boards to account for the geometric delay between signals from the bowtie antennae. Progressively higher delay is added to the dipoles that are closer to the source, starting with no delay for the furthest one.

FIG. 4. Beamformer with 32 cables to connect to the 16 bowtie antennae, 1 cable per polarization

C. RRI- GBT Receiver System

From the beamformer, the data is sent to the multiband receiver(MBR) system. The first step is a dual linear polarization multi-band feed sensitive to 10 discrete bands in the range of 100-1600 MHz. After this, various processes like pre-amplification, filtering and upconversion are done to reduce loss during transmission. The signal is then transmitted over the optical fiber, down-converted and split into bands of interest. Finally, the signal is brought to a intermediate frequency by superheterodyning, then digitized and recorded. The final data recorded by a data acquisition system is voltage at the Nyquist sampling rate time intervals (30.3ns), and this is stored in a binary file.

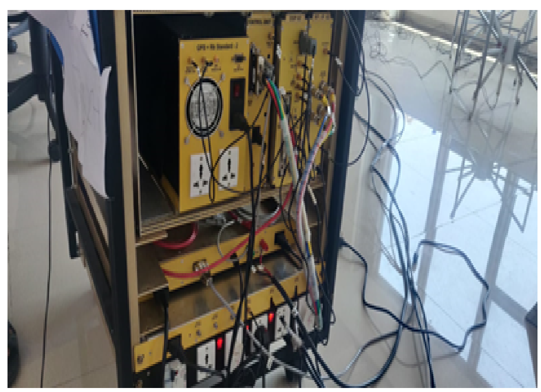

FIG. 5. Back-end of the receiver system, including DSP and RF-IF blocks along with the data acquisition system machine.

III. ANALYSIS OF SOLAR DATA

The data analyzed in this project is the data collected by tiles 3 and 7 on April 14 2021 when placed in the Gauribidanur observatory. SWAN uses software to both point the tile to the required source and set parameters like observation frequency and length of observation, as

well as for data acquisition. The observations are taken when the source is at its Zenith as this reduces delay between bowtie elements of a tile.
For these observations in particular, the local oscillator(LO) frequency was set at 311 MHz. The intermediate frequency(IF) of SWAN is 140MHz. Therefore, the radio frequency RF= LO- IF= 171 MHz.

A. Single Tile Analysis

We have plotted the histogram plots and power spectra of the data collected by tiles 3 and 7 for both polarizations. This involved converting the data in binary format to ascii using Python's binascii module, and storing it in 2-dimensional array format. Figure 6 shows the structure of a packet of data. Each element of this, like the source name, local oscillator frequency and the data can be accessed by traversing the array. Following the conversion, the histogram plot and data statistics are fairly straightforward to obtain using Python's plotting functions and by using loops to calculate the mean and standard deviation of the voltage. Figures 7 and 8 show the number of occurences of various voltage values for the X-polarization data of both tiles. Similar plots were obtained for Y-polarization. As expected, these follow near-normal distributions. The Sun emits black-body radiation, so for a large dataset, central limit theorem applies and voltage follows a gaussian distribution.
The power spectrum for the data was obtained by computing the Fourier transform of the voltage and taking its square. The frequency binning was done by taking a Fourier transform using the sampling rate of 33 MHz. These are again conveniently obtained using Python's fft.fft() and fft.fftfreq() methods which are part of the numpy library. Similar power spectra were also ob-

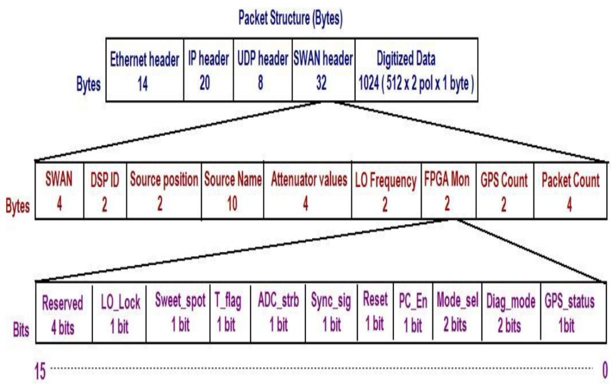

FIG. 6. SWAN binary data packet structure

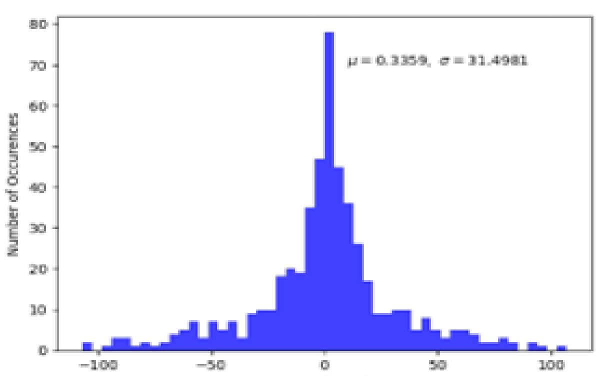

FIG. 7. Voltage histogram plot for X polarization, tile 3 data

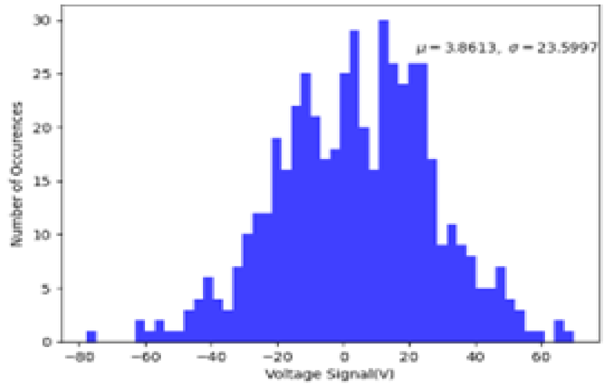

FIG. 8. Voltage histogram plot for X polarization, tile 7 data

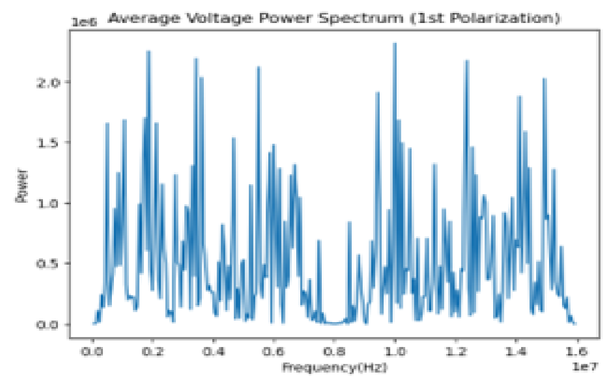

FIG. 9. Power Spectrum for X polarization, tile 3 data

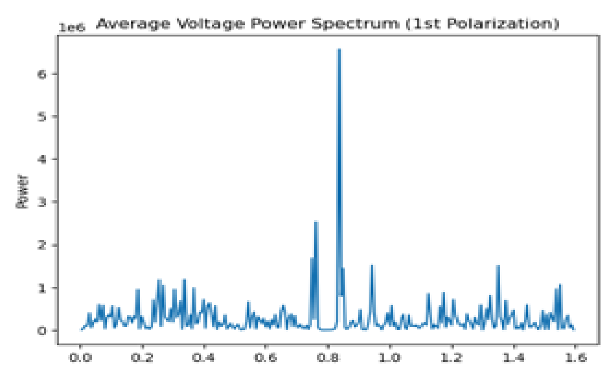

FIG. 10. Power Spectrum for X polarization, tile 7 data

tained for the Y polarization. These power spectra can be modified by taking average values across intervals of time then taking rms values to extract the temperature of the source. However, in this case, we see that the spectra from the 2 tiles have some significant differences. For tile 3, we see that the peaks of the power spectra lie around $\sim$2 x 10^6, while that for tile 7 lie around $\sim$1 x 10^6. In addition to this, there is also an abnormally large spike at around 8.5 MHz for the tile 7 plot. In an ideal scenario, the power spectra obtained by both tiles should be nearly identical as these 2 tiles are close to each other geographically. This indicates that there has been some instrumental error (likely something with the electronics) at some periods of time in one or both of the tiles. Cross-correlation removes such errors.

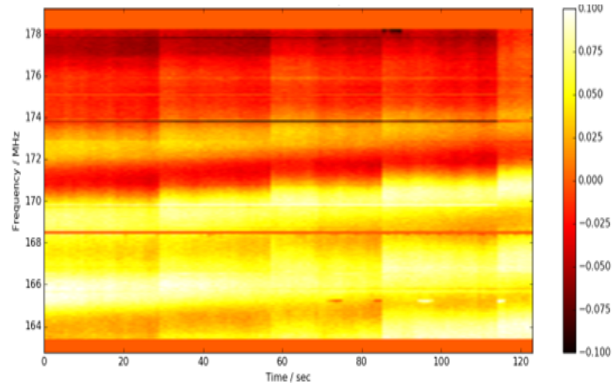

FIG. 11. Real part of the cross-correlated spectrum of X polarization data

B. Cross-Correlation

Cross-correlation is a powerful mathematical tool for analyzing radio signals. It involves multiplying two signals and integrating the result over time. For cross-correlation of data collected by SWAN tiles, Pavan Uttarkar and Devansh Shukla of the Raman Research Institute have developed a code base that generates auto-correlation and cross-correlation spectra upon giving the .mbr files as input. The algorithm for cross-correlation is FX correlation and can be explained as follows:
1. First, the starting point of correlation is computed. The two files are compared for synchronization by using the 2 byte GPS component in the data packets which records GPS time from the nearest 12 o'clock, and the 1 bit GPS status bit in the FPGA component.
2. Coherence between data files can often be lost due to packet loss. To account for packet loss, a buffer is fixed, then memory mapping is used to read the file and lost packets are filled with zeros. The packets that are not to be correlated due to packet loss are then removed.
3. The final data is then Fourier transformed. Geometric delay between tiles is accounted for, then the correlation matrix is generated with 4 auto-correlation and 2 cross correlation (X3X7 and Y3Y7 in our case) spectra.
The codebase is majorly written in Cython. This is a C compiled version of Python that takes advantage of the high level nature of Python and uses it to link the synchronization, packet loss and geometric delay parts to the main cross-correlation module. Cython is used for the computational parts of the code like reading binary data, plotting, etc. The Fourier transforms are done using the FFTW function in FORTRAN and a Python wrapper called f2py is used to link it to the correlator.
To finally implement the code and get the desired spectra, we run the correlation code giving inputs including the binary file names, right ascension and declination of the source, the GPS compensation flag (1 if synchronization is needed, 0 if not), the length of the Fourier transform and a rfi reject flag (1 to reject RFI, 0 to pass) The cross-correlation process generates a spectrum with real and imaginary parts. Figure 11 shows the real part for 2 minutes of data. We can clearly observe parallel horizontal fringes in the plot with uniform visibility (relative values indicated by the gradient in the right), indicating constructive interference and proper delay compensation, synchronization and no incoherence due to packet loss. Note that this is true for the entire 16 MHz bandwidth. Quantitatively, the graph indicates that the source may be brighter towards the lower frequencies as there is higher or equal real value away from the central frequency of 171 MHz that the tiles are tuned to.

Figure 12 shows variation of phase for 30 minutes of data in the X-polarization. Phase is defined here as $tan^{-1}\frac{imaginary}{real}$ We notice that there are similar fringes in the inital time domain, and for the lower frequencies (till around 167 MHz), there are fringes for the entire 30 minutes. For two signals from the same source, we would expect there to be no phase evolution, and these fringes agree with that. However, there are regions of negative phase at the central and higher frequencies. This indicates that there are some delays that are yet to be compensated for. One likely explanation is that the delay is accounted for the tiles pointing at a particular direction (Zenith), but since the Sun is a relatively close source, the

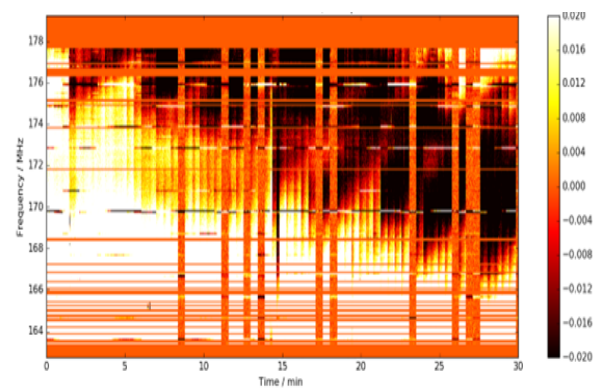

FIG. 12. Variation of phase for cross-correlated spectrum, X polarization data

angle changes relatively quickly. Once we can account for this, we can plot amplitude and phase of cross-correlated spectra and make definitive conclusions about the source.

IV. DISCUSSION AND CONCLUSIONS

In this project, we have understood the working of the SWAN interferometric array and briefly worked on and observed the setting up of a tile. A spectrum analyzer has also been used to test the radio interference at the site. Currently, the software for the beamformer is not available at the radio laboratory at the Indian Insitute of Technology Kanpur. However, once this has been set up, the SWAN tile will be fully installed and data collection can begin.
Single and two tile analysis of solar data collected by tiles 3 and 7 were carried out. As expected, a normal distribution was obtained for the histogram plot of voltage signals. Power spectra showed some unexpected differences which were likely due to malfunctioning of electronics in one of the tiles for a short period. This is evident from the correlation spectra- the real part shows good fringes with near constant visibility for a decent time interval. There may still be some issues in compensating for delay and this is crucial to discuss with others working on SWAN like Pavan Uttarkar and Prof. Avinash Deshpande.

V. ACKNOWLEDGEMENTS

I am very grateful to Dr. Pankaj Jain for giving me this opportunity to work in a field that is relatively new to me, namely radio astronomy. I am indebted to Dr. Nilay Kundu who readily agreed to be a co-supervisor for this project as a faculty member of the Physics department. I was also greatly aided constantly by Ashish Kumar, PhD student of Dr. Pankaj Jain, and I am thankful to Pavan Uttarkar and others at RRI for expanding the SWAN initiative to IIT Kanpur.

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