An S-band Polarimeter for the Determination of Spacecraft Attitude Behaviour

Scott Tilley, VE7TIL

ABSTRACT

Measurement of the polarization of radio emissions from natural and artificial sources in space has long been done by professionals and amateurs alike. This paper presents a practical approach using Software Defined Radio (SDR) techniques and hardware that is within the range of amateur observers to create a practical polarimeter. A hardware apparatus in a specific form will be presented that was designed to highlight making polarization measurements of spacecraft. A general software architecture is described to reduce the measured radio emissions into Stokes parameters. The concepts and procedure of instrument calibration are presented. Examples of the instrument's initial observations are provided to highlight the usefulness of the polarimeter to determine the attitude behaviour of spacecraft on orbit.

Introduction

The measurement of polarization from space based radio emissions has been conducted by professionals and amateurs for various reasons for decades. Astronomer's can study the effects of magnetic fields in space using radio polarimetry techniques[1]. Radio amateurs have used the technique to improve Earth-Moon-Earth (EME) communications through put by being able to match the polarization of the reflected radio emissions off the Moon and prevent Faraday lock out from occurring[2]. It will be shown that the polarization of a spacecraft's radio emissions can vary with the viewing geometry of the emitting antenna thus allowing the study of the spacecraft's attitude by investigating the polarization of the emitted radio signal.

Real World Spacecraft Antennas and Axial Ratio Effects

By studying the highly polarized radio emissions from satellites one can determine more information about the spacecraft's attitude and behaviour without the benefit of being able to monitor and interpret any of the mission's telemetry emissions. The technique discussed below strongly relies on the fact that radio antennas which are designed for a particular polarization are only capable of presenting a high percentage of the designed polarization characteristic when the observer is viewing the boresight of the emitting antenna[3].

This is particularly the case with antennas designed to have circular polarization which is commonly used on spacecraft to overcome issues related to ionospheric effects like Faraday rotation. The spacecraft antenna will present a different polarization characteristic as the viewing angle changes from directly down the boresight of the antenna. This results in an increase in the axial ratio of the polarization ellipse and in the case of a highly circularly polarized antenna the introduction of a greater linear polarization component.[4]

In ***Figure 1*** below, the polarization ellipse is shown. As the ratio of semi-major and semi-minor axis changes with the viewing angle the amount of linear polarization present will increase or decrease with viewing angle. If the spacecraft attitude changes the linear polarization component and linear polarization angle of the emission will change and will also affect the other polarization parameters we will discuss later. The latter allows the observer with a fixed observation antenna to view changes in spacecraft attitude.

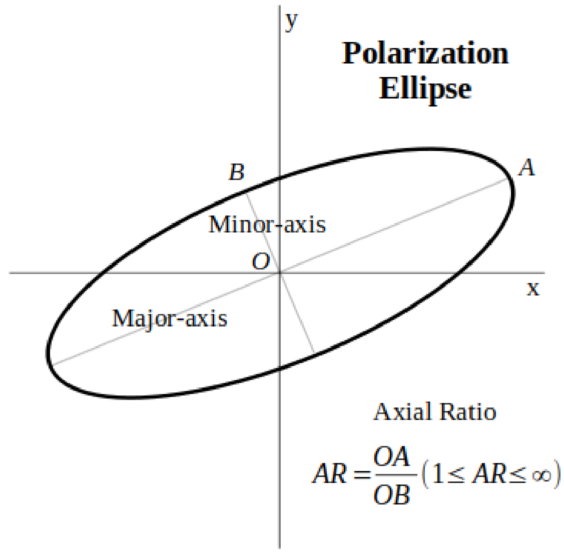

Figure 1 *– The polarization ellipse used to define the axial ratio. By understanding that the axial ratio of a viewed antenna will change based on the viewing geometry off the boresight of the emitting antenna the observer can gain insight about the attitude of a spacecraft from its radio emissions.*

Therefore, the following technique can present another tool to characterize spacecraft behaviour in addition to Doppler and the amplitude of the emitted signal.

Stokes Parameters

In order to study polarization of radio emissions we require a system to organize all of the values that completely describe the polarization of the emission. In 1852, George Gabriel Stokes defined what we presently call the Stokes parameters for this purpose. In a system of fixed x and y unit vectors with an increasing phase convention the Stokes parameters can be written as:

$$I=|E_x^2|+|E_y^2|,$$
$$Q=|E_x^2|-|E_y^2|,$$
$$U=2\Re(E_x E_y),$$
$$V=-2\Im(E_x E_y)$$

The Stokes I parameter represents the total intensity of the emission. The linear horizontal and vertical component is represented by the Q parameter. The linear +45° and -45° component by the U parameter. Finally the circular component in the V parameter. Our convention denotes that a $+V$ term represents right hand circular polarization (RHCP). We will discuss the polarization as seen from the emitter.

With the above parameters and declaration an observer has all the knowledge of the polarization state of the emission. From these parameters the linear polarization component and polarization angle of that component can also be derived amoung others. Its beyond the scope of this paper to discuss this in great detail as the references will provide adequate treatment[5].

Practical Application of Polarimetry in Satellite Observation

Observations of amateur radio satellites and even lunar probes have been conducted using a polarimetric measurement instrument found on the Allen Telescope Array (ATA) in Northern California[6]. Observations where conducted to determine the status of the deployment of antennas on a cubesat[7] in one case and in another insight was gained into the behaviour of the Chang'e 5 mission[8]. This work while using expensive and professionally constructed instruments was conducted using many of the common SDR techniques amateurs have access to today and greatly influenced this work. This work provided a basis on the general techniques required to construct, calibrate and operate a polarimeter for the study of spacecraft attitude dynamics.

Polarimeter Hardware Description

The polarimeter described here is shown in ***Figure 2***. It is based on a 1.8m dish antenna with two probes mounted at the focus in an orthogonal manner. The instrument is mounted on an azimuth elevation rotor system. Low noise LNAs are connected to each probe and cabling to the remote observing site is closely matched in physical length. Line amplifiers are used after the initial flexible drops to get around the moving components of the antenna to overcome coax attenuation loses. The cabling is equalized in electrical length at the observing location before connection to the dual coherent inputs of an SDR receiver.

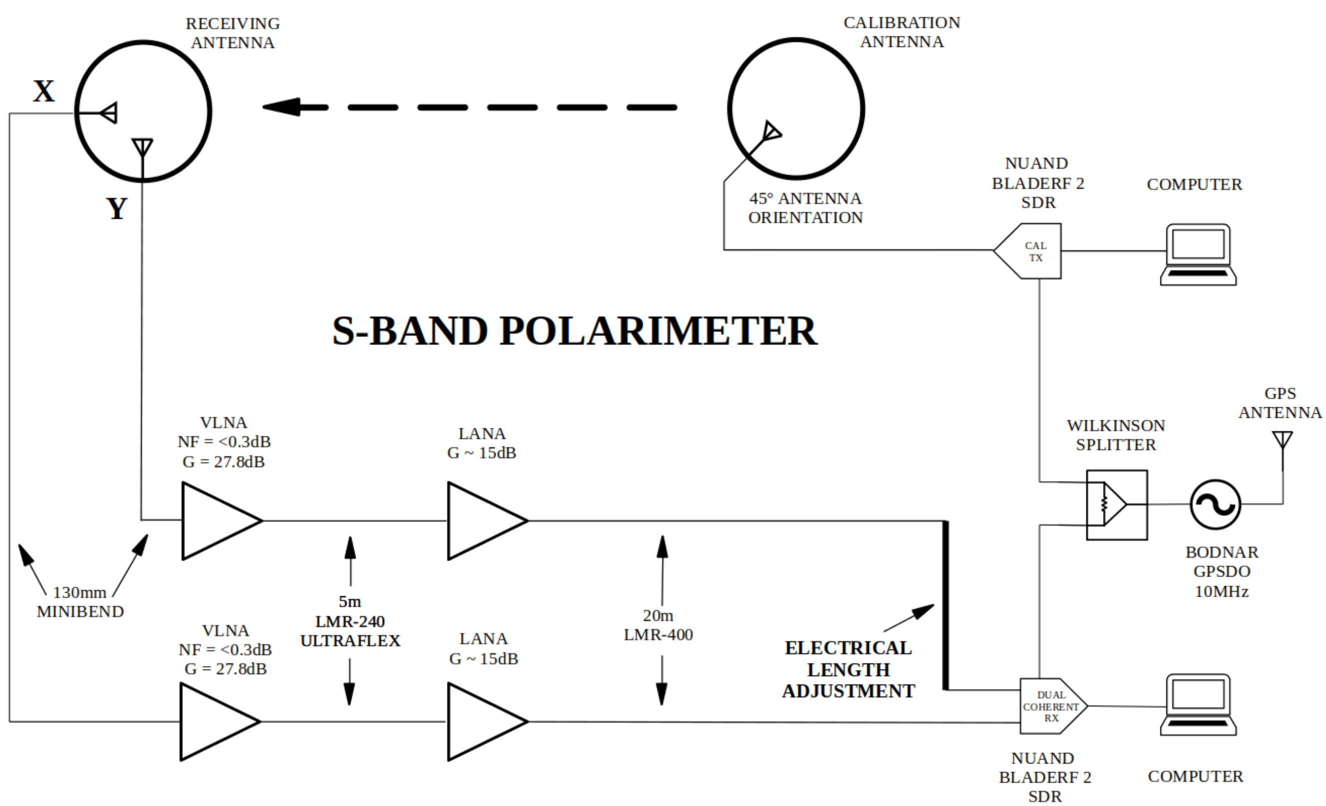

***Figure 2** – The S-band polarimeter system block diagram. Care is taken to layout the system in such a manner as that all of the components are identical including coax cables. An electrical length adjustment cable is added to the system to equalize the electrical length of the Y leg to deal with inevitable differences in the exact electrical lengths of both of the runs. The calibration antenna orientations with respect to the receiving antenna are also shown.*

For calibration a separate circular wave guide with a single linear probe is placed in the far field of the primary receiving antenna at the same height so the calibration source antenna can look into the boresight of the primary receiving antenna during the calibration process.

Software Workflow

The software workflow is presently broken into two discrete blocks. There is a GNU Radio block (link to gnuradio flow graph here) shown in ***Figure 3*** which does the following:

- SDR data capture,
- Filtering and frequency translation,
- FFT,
- Producing the X, Y and XY terms with complex to magnitude^2 conversion of the X and Y terms, this partially completes the Stokes calculation that are ultimately completed in the second software block
- Multiply conjugate application to create the complex XY term needed in the final computation of the Stokes U and V parameter in the next software block,
- Integration,
- Saving to a X, Y and XY data file.

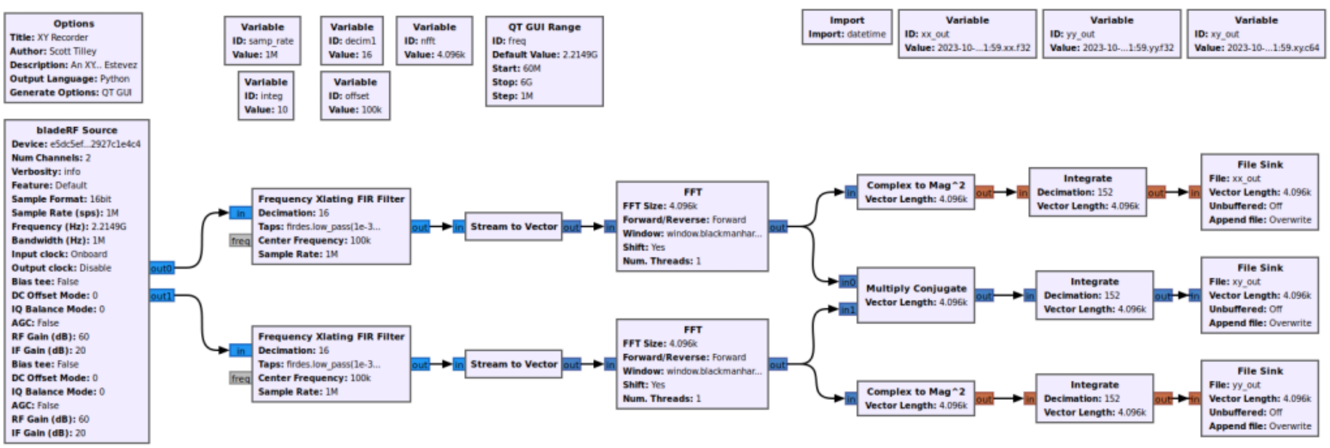

Figure 3 *- The GNU Radio flow graph that accepts the raw dual coherent IQ data from the SDR, performs frequency translation/decimation, FFT and the conversion of the X and Y streams to magnitude squared and a multiply conjugate of the X and Y streams to create the complex XY stream, integration and finally saves the data for post analysis.*

The second block is a Jupyter-notebook (link to analysis notebook here) written in Python that reads in the data files and performs the following functions:

- Application of the gain offset,
- Application of the phase offset,
- Presents plots and data values to allow for determination of correct tuning and signal levels,
- Doppler and Stokes *I* plot and saves data in Sattools RF (STRF format),
- Extract peak features, adjust gains and normalize the data arrays,
- Calculates Stokes parameters and derived values,

- Plot Stokes parameters,
- Plot linear polarization and polarization angle,
- Plots other parameters based on analysis requirements.

System Calibration

Calibration of the system is critical to its proper operation. Therefore, having a means to reliably calibrate the system is required. There are three items that are required to be calibrated to study highly polarized radio emissions. Further calibration efforts would need to be performed to calibrate the system to measure largely unpolarized sources such as many natural radio emissions[9]. As our intent is to measure highly polarized sources the following general methodology will produce acceptable results.

There are three general items of particular interest to calibrate:

- The electrical length of the X and Y sides of the hardware system before the SDR receiver inputs,
- The gain offset at a particular frequency of observation,
- The phase offset at a particular frequency of observation.

Equalizing Electrical Length of X and Y

To equalize the electrical lengths one could observe a wide band satellite emission over a band width of a few MHz and plot the resulting phase angle of the XY complex value. The plot should ideally present a linear curve or a flat response over that bandwidth. If presented with a curve with a high slope one can add/remove coax on one of the channels from the orthogonal outputs of the feed. Iterate the lengths by adding or removing until the flattest response possible is obtained. One can determine the ideal length of the adjustment and fabricate the ideal length required after the iterative process with random coax jumpers.

Gain and Phase Offsets

The gain and phase offsets are dealt with in software but additional calibration hardware is used. The establishment of these offsets prior to an observation on a specific frequency should be performed prior to beginning that observation as they can be influenced by local environmental factors which will be noted below in the discussion on sources of error.

With the calibration reference antenna oriented at 45°, begin a transmission from the calibration source antenna close to the desired observation frequency. Ensure the orthogonal probes on the receiving antenna are orientated horizontally and vertically. Allow that signal to integrate over time and average the difference in the peak X and Y values of the calibration signal's amplitude for a few minutes until the value becomes asymptotic. Once asymptotic the gain offset value should result in an average reading of zero for the Stokes Q parameter when applied. Once the gain offset is stable, iterate the value of the phase offset to zero Stokes *V* parameter.

The reason why this works is that the two orthogonal antennas should by definition see equal signals as the calibration antenna is mounted at +45° with respect to the horizontal and vertical elements in the receiving antenna. There should be no linear component (Q), recall, Q = X – Y, and as the calibrator is linear no circular component V should be present once the phase offset is set correctly. Conversely, the U (+/-45° component) should be close to +1 as the geometry is setup to ensure the maximum value from U equaling twice the imaginary component of XY.

The final step is to ensure you have dealt with the ambiguity in the sign of the V parameter. A simple test is to aim the calibrated system at a satellite with known circular polarization sense. If the emitter is LHCP then a -V should result, if RHCP a +V parameter should be present. If reversed remove the – from the *V Stokes equation*. This usually accounts for the reflection of the signal in the dish antenna inverting the circular polarization Stokes parameter as we desire to see the polarization from the source not the receive antenna's perspective. (link to calibration notebook here)

Sources of Error

The primary source of error of the initial system was in the selection of a calibration source. Our initial assumption was to use a known RHCP signal from a geostationary satellite and the phase difference between the vertical and horizontal polarization should be 90°. However, this assumption proved problematic as we found that the phase angle offset offered by various satellites in different geostationary slots yet same frequencies did vary and as it turns out the circularity of their signals was not close to ideal for calibration purposes. This resulted in considerable error and unreliable data. This is the reason a local calibration method where all the parameters could be controlled and measured was used.

Another source of error that forces the observer to re-calibrate often is the fact that common dielectrics used in low loss coax cable have very high phase changes with temperature. Unfortunately, the most sensitive range of temperatures is between 10° - 20°C[10]. Rapid solar heating of exposed cables could be problematic as a result too. Unfortunately phase stable coax is very expensive. Mitigation measures could be to locate the SDR closer to the receiving antenna and minimize the cabling lengths to just what is required to move and aim the antenna structure. Perhaps at such lengths consideration of the phase stable cabling could enter the realm of affordability.

The result of this knowledge is to use a defined and controlled calibration source and calibrate often to manage the phase shifts caused by temperature.

First Observations

GOES 17 is a geostationary weather satellite that had a cooling issue and was pulled from active service and was placed in a storage orbit at ~105W longitude. It was determined that while in a storage orbit the GOES-R family undergoes a yaw flip once per day[11]. A yaw flip is a maneuver were the spacecraft rotates 180° on the axis facing the Earth. Effectively it flips the side holding the solar panel from 'up' to 'down' and the opposite the next day and repeats. In the process the telemetry tracking and control (TT&C) antenna also undergoes a 180° flip.

This makes for a good initial observation target. As the GOES-R TT&C is suppose to be RHCP and we are not viewing the TT&C antenna on the boresight but rather to the side somewhat. Therefore, the polarization of the emission will have a linear component that can be observed and we can therefore measure the change of the polarization angle during the yaw flip. ***Figure 4*** provides details of the effect of the yaw flip on polarization angle of the TT&C emission where the 180° change in polarization angle is clearly evident.

Another target of initial interest is DSP F20 aka USA 149, which is a Defense Support Program missile launch detection satellite over the central Pacific Ocean. The spacecraft is in an inclined geostationary orbit and is known through various public sources to rotate at 6 RPM[12]. Analysis of the TT&C emission of the spacecraft supports the public statements.

We see in ***Figure 5*** below, the Stokes parameters Q, U and V. The three have sinusoidal behaviour. The parameters Q and U have the same amplitude and are in quadrature, which means that the linear polarization fraction is constant and the polarization angle changes linearly with time. The V parameter, which gives the circular polarization has less amplitude. This indicates the spacecraft is rotating periodically.

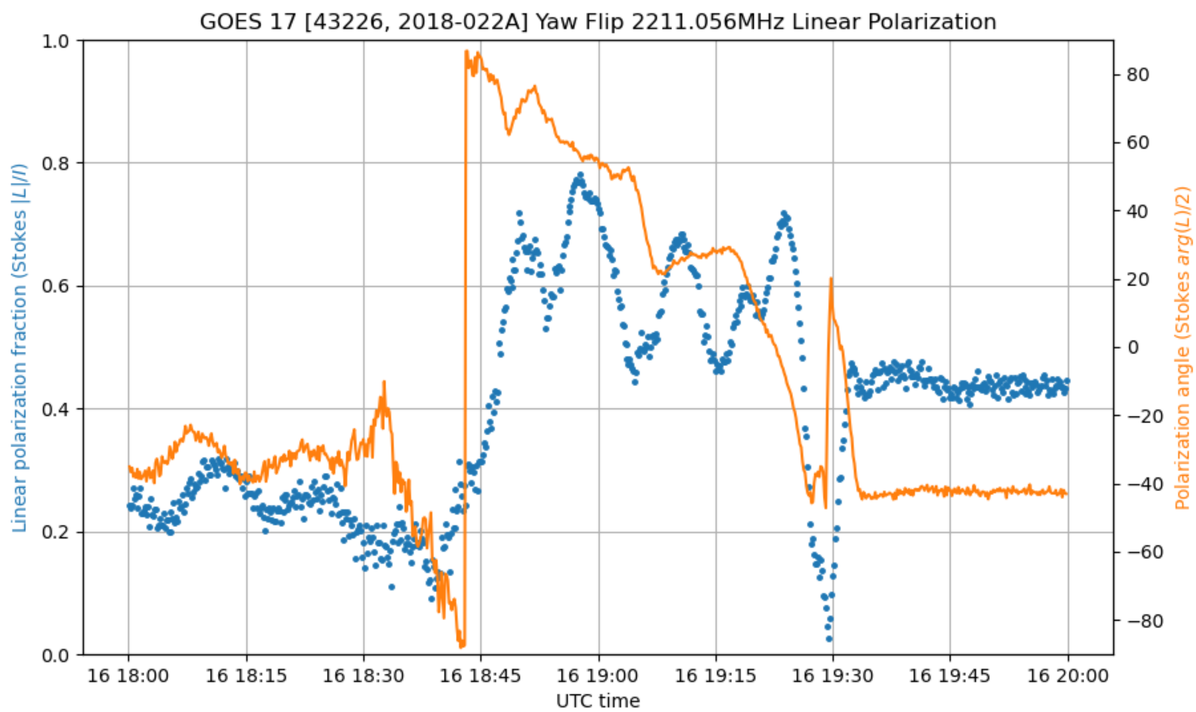

Figure 4 – *GOES 17 undergoes a yaw flip and which causes the spacecraft's TT&C antenna to rotate 180° which is evident in the linear polarization angle change of the TT&C emission. Just after 18:30 UTC the spacecraft begins the flip and ends just after 19:30 UTC.*

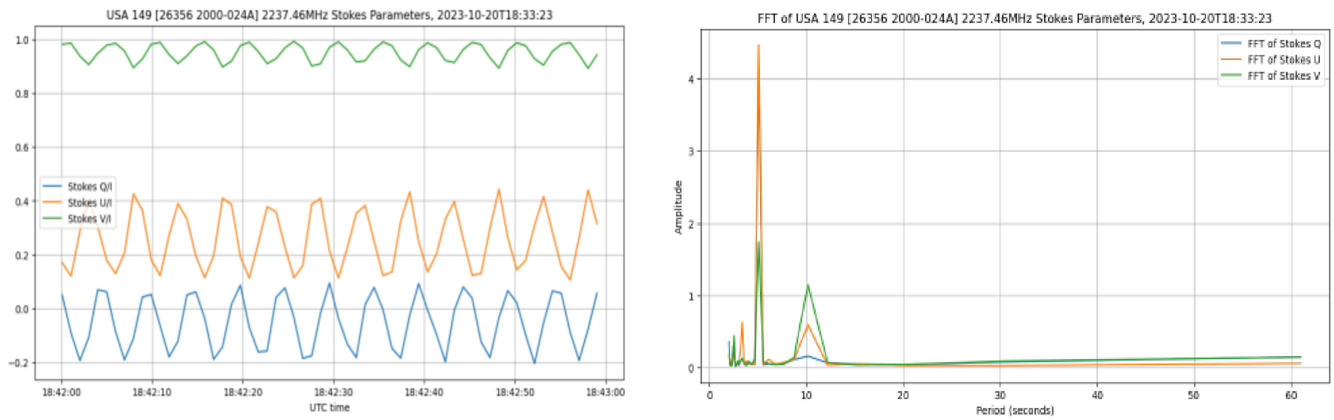

Figure 5 – *Left panel shows the Q/I, U/I and V/I Stokes parameters. Notice the quadrature nature of the Q/I and U/I terms also note the amplitude of the V/I term being half that of the other terms. This is indicative of a rotating spacecraft. The right panel provides an FFT of the Stokes parameters and shows a very high spectral component with a period of 5 seconds which is half the rotation rate. The real rate being 10 second indicated by the second largest peak. Much like light curves from satellites, the actually rotation rate is usually noted as twice the observed rate.*

Conclusion

A functioning system to measure the Stokes parameters of spacecraft or even Earth bound antennas with practical equipment has been demonstrated with observations that correlate to expected behaviour of two spacecraft on orbit. The observations support using the changing axial ratio property of emitting antennas on spacecraft as viewing angles change can be used to understand their attitude characteristics. The next step is to improve the system. Areas of improvement and new techniques to consider are as follows:

- Implement amplitude calibration using solar reference and noise sources to maintain it,
- Implement parallactic angle correction,
- Develop an automated method of plotting the gain offset and phase angle offset over frequency and determine if a function can be fit to them to simplify calibration or a look up table used,
- Implement all of the functionality in Python or C in the hopes of being able to improve short sample rate performance,
- Improve the system's resistance to temperature fluctuations,
- Research and consider application of the Lomb-Scargle algorithm for spectral analysis of non-continuous samples,
- Develop waterfall plotting of the Stokes parameters to allow for more information to be on the plot.
- Implement a means of displaying the Stokes data in a Polarization Ellipse to animate the results in real time.

Acknowledgments

The author would like to acknowledge the work of Daniel Estévez, EA4GPZ, as his work formed the analytical basis of the author's and he provided code, advice and feedback as the author developed the polarimeter presented here. He maintains a very informative blog on topics of interest to scientific and technically minded radio amateurs which can be found here.

1 C. Heiles, The Interstellar Magnetic Field, Annual review of astronomy and astrophysics. Volume 14. (A76-46826 24-90) Palo Alto, Calif., Annual Reviews, Inc., 1976, p. 1-22.
2 J. Taylor and J. Johnson, EME with Adaptive Polarization at 432 MHz, website: https://wsjt.sourceforge.io, accessed 2023-10-22.
3 Yu Luo, Qing-Xin Chu, Jens Bornemann, Enhancing cross-polarisation discrimination or axial ratio beam width of diagonally dual or circularly polarised base station antennas by using vertical parasitic elements. IET Microwaves, Antennas & Propagation, Accessed 2023-10-22.
4 Bin Li, Axial ratio measurements of circularly polarised antennas based on polarisation rotation. IET Microwaves, Antennas & Propagation, Accessed 2023-10-22.
5 J. B. Tatum, Polarized Light and the Stokes Parameters. University of Victoria website Accessed 2023-10-22.
6 Allen Telescope Array Overview, Accessed 2023-10-22.
7 Daniel Estévez, Radiometry for DELFI-PQ, EASAT-2 and HADES, Blog of Daniel Estévez, Accessed 2022-10-22.
8 Daniel Estévez, Chang'e 5 polarization in the ATA observations, Blog of Daniel Estévez, Accessed 2022-10-22.
9 C. Heiles, A Heurustic Introduction to Radioastronomical Polarization. Accessed on 2023-10-22.
10 David Slack, Minimizing Temperature Induced Phase Errors in Coaxial Cables. Microwave Journal, Wallingford Conn. March 13, 2017, Accessed 2022-10-22.
11 GOES-R Post-Launch Activities (Lockheed Martin), @NOAASatellites YouTube Channel. Accessed 2023-10-22.
12 DSP: The Silent Sentry. @tmk8118 YouTube Channel. Accessed 2023-10-22.