On the calibration of polarized radio signal

Stanisław Ryś[1] and Eugeniusz Pazderski[2]

1. Astronomical Observatory of the Jagiellonian University, Orla 171, 30–244 Kraków, Poland
2. Centre for Astronomy, Nicolaus Copernicus University, Grudziądzka 5, 87–100 Toruń, Poland

Polarized radiation measurements are limited by the sensitivity and stability of the receiving systems and external interferences. We found that the signal recorded during observation is not well corrected using the standard automatic calibration procedure. We have noticed that most of the instability can be corrected using the calibration procedure that takes into account the calibration signal phase. The method proposed by us allows to eliminate jumps on the level of the recorded signal, which are caused by changes in the relative phase between two channels of the receiver. The elimination of those phase jumps leads to more consistent final results from multiple measurements of the same source. Below you will find examples of differences between the reduced data of the standard calibration procedure and the data obtained using the new method with phase instability correction.

1 Introduction

Toruń Polarimetric Survey (ToPoS) is performed on a 32-meter radio-telescope in Piwnice near Toruń in the frequency band 4.45-4.95 GHz. From two circular polarity probes: R (counter clockwise) and L (clockwise), installed on the focal plane of the antenna we receive a voltage signal proportional to these two components of the incoming electromagnetic signal. Two independent receivers amplify the small signals and deliver them to correlator in the aim to cross-correlate them. The polarized radiation is usually described by Stokes's parameters, which are signal values consisting of measurements in four channels of analog polarimeter:

1. R – the power of a signal from the first probe,
2. L – the power of a signal from the second probe,
3. Q – power of the correlated signals from the first and second probe,
4. U – power of the cross correlates signals from the first and second probe.

The Stokes parameters are calculated as: $T = R^2 + L^2$, $Q = R^*L + RL^*$, $U = R^*L - RL^*$, $V = R^2 - L^2$ where an asterisk stands for complex conjugate. Voltage amplitudes induced by radio waves are amplified and modified by the apparatus used for observation and we have to remove this modification if we want to obtain real values of Stokes parametes. The V value displays the difference between the signal levels in R and L channels. This means that the measured circular polarization is very sensitive to variations of the amplification factors of both receivers. Artificial circular polarization can be easily reduced when we make independent calibration of L and R channels instead of calibrating $V = R - L$ using a calibration signal calculated for total power (T).

Changes in receivers gain coefficients also affect the measured values of Stokes parameters Q and U. Therefore, we need to calibrate them as accurate as possible including corrections for the circular polarity introduced by our instrument.

2 Standard method of data reduction

There are two main objectives for the automatic data reduction and calibration, i. e. the correction of instability of amplification and the correction of modifications of the signal introduced by the measuring device.

Amplitude calibration – The first step of data reduction is performed by comparing the sky signal with a well-defined and stable calibration signal from an artificial noise source. In our measurements the calibration signal was injected 127 times per second. Calibration is performed by dividing the recorded signal from the sky by the amplitudes of the calibration signal. This eliminates amplification instability in both receiver circuits.

Leakage correction – It was found experimentally that a small portion of the signal from channel L is recorded in the right-hand polarity probe R and vice versa (the so-called leakage). This is due to the design of the radiotelescope antenna and the characteristics of the orthomode transducer. This known fact led to the formulation of formalism of the Müller matrix (Müller, 1947), which is a model of linear corrections for all Stokes channels in the polarimetric receiver. Using the measured values we can construct the Stokes vector in the following way: $S_m = (T_m, Q_m, U_m, V_m)$, where m mean the measured values. The correction model in linear approximation can be written as: $S_m = \bar{M} \times S$, where $\bar{M}$ is the so-called Müller matrix, and S is the vector of Stokes true parameters. The calculation of inverse matrix allows us to recreate the actual (true) values of Stokes parameters based on the measured values. Standard procedure for determining all elements of a Müller's matrice are a few-hour observations of the calibration source (in the sky) in a wide range of paralactic angles. The recorded variations in the flux due to the change of paralactic angle are assigned to the rotation of linearly polarized component of electromagnetic radiation. Measurements of the polarized source with known parameters and good model of inter-channel leaks allow to calculate all elements of Müller's matrix.

The Müller matrix is sometimes determined by two measurements of two calibration sources: one polarized and one not polarized e.g. Cenacchi et al. (2009). However, the circular polarity signal introduced by the measuring instrument must not be ignored during the data reduction (Myserlis et al., 2018).

3 New method – vectorized calibration

We propose modifications to the method of calibration of polarized signal registered with a polarimeter. In particular, we suggest that the calibration of the signal in Q and U channels using the internal noise source should include the phase of the recorded calibration signal.

For total power channels, i.e. R and L a relative phase changes are not important. However, in case of polarized signal, the change in phase path length of the signal in L channel in relation to the R channel is critical, because the result of signal correlation is very sensitive to such phase variation. A registered example of such

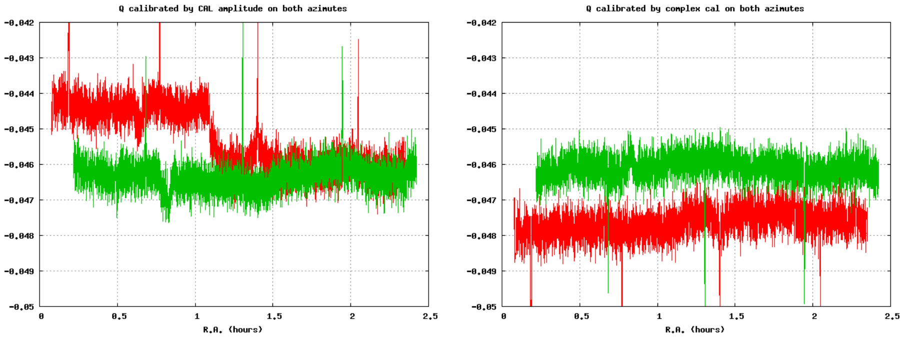

Fig. 1: Two measurements of the Stokes Q parameter made over the same sky path. On the left panel: first scan in green and second in red, corrected with the use of standard method. It is easily to see the jump in the red. This jump can be eliminated by a vector calibration method as shown on the right panel.

a phase shift is shown in the left panel of Fig. 1. Therefore, we assume that from a measured values of the parameters Q_m and U_m we can compose $(Q_m + iU_m)$ vector and calibrate it using a similar vector consisting of a $(Q_{\rm cal} + iU_{\rm cal})$ noise source signal.

$$Q + iU = (Q_m + iU_m)/(Q_{\rm cal} + iU_{\rm cal}) \quad (1)$$

$$Q + iU = (Q_m + iU_m)(Q_{\rm cal} - iU_{\rm cal})/(Q_{\rm cal}^2 + U_{\rm cal}^2) \quad (2)$$

We identify the real part as a calibrated value of Q and the imaginary part as a calibrated value of U.

$$U = (U_m \cos\psi - Q_m \sin\psi)/P, \qquad Q = (Q_m \cos\psi + U_m \sin\psi)/P. \quad (3)$$

where $P = \sqrt{Q_{\rm cal}^2 + U_{\rm cal}^2}$ is an amplitude, and ψ is calibration signal angle from the noise source. Such calculations allow to eliminate changes in the relative phase length of the signals (R to L), i.e. correction of jumps in the recorded values as presented in right panel of Fig. 1.

4 Conclusion

Our conducted experiments clearly show the requirement of better control and correction of phase differences between two channels of polarimetric receiver. This means that during calibration of a linearly polarized signal we have to take into account the whole information from calibrating signal including the phase.

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