Polarization Calibration of the phased array mode of the GMRT

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The Giant Meterwave Radio Telescope (GMRT) is an multi-aperture synthesis radio interferometer operating at low radio frequencies and can be used like a single dish telescope in the phased array (PA) mode of operation. We describe an experiment for polarization calibration of the PA mode of GMRT at 325 MHz using pulsar PSR B1929+10 as our polarization calibrator to find the response matrix and obtain the true Stokes parameters.

1 Introduction

Several celestial sources that are bright in the radio frequencies are known to be polarized. In most sources the degree of polarization is relatively small and hence it is of upmost importance to do careful calibration of the measurements to improve the reliability of the results.

The main goal of polarization calibration is to quantify the complex gain and leakage terms that arise due to the cross-coupling of the signals from two originally orthogonal polarization states, due to the improper/non-ideal response of the antenna, the feed and the electronics receiver chain of a radio telescope. Here we describe the procedure used by us for polarization calibration of the phased array (PA) mode of observation of the GMRT at 325 MHz and present some of the results.

2 GMRT as a phased array

The GMRT (Swarup et al 1991) operating at meter wavelengths is an array of 30 antennas with alt-az mounts, each of 45 meter diameter, spread out over a 25 km region. It is designed to operate at multiple frequencies (150, 235 , 325, 610 and 1000 - 1450 MHz respectively) having a maximum bandwidth of 32 MHz split into upper and lower side band of 16 MHz each. It is primarily an aperture synthesis interferometer as well as a PA instrument. In the PA mode of the GMRT (Gupta et al. 2000), which forms the focus of our study here, signals from any selected set of the antennas are added together after appropriate delay and phase compensation to synthesize a single, larger antenna with a narrower beam. Signals of 16 MHz from each side band of each antenna are available across 256 channels which can be summed in the GMRT array combiner. The summed voltage signal output from the PA is then processed like any other single dish telescope signal, including generation of the observed Stokes parameters by the pulsar backend. At 325 MHz, which is the frequency of interest here, GMRT has Kildal feeds which gives two linearly polarized outputs for each antenna. These signals are further mixed in a quadrature hybrid to produce two circular polarized signals which goes further into the front end electronics and rest of the signal chain.

3 Method for polarization calibration of a single dish

Since the PA mode of an interferometer can be considered as an equivalent single dish, techniques developed for single dish polarization calibration can be readily applied. In the mathematical formalism for single dish polarization calibration (e.g. Johnston 2002, Hamakar et al. 1996) the observed stokes parameters are related to the true stokes parameters via a response matrix (called the Müller matrix), whose elements need to be determined from the polarization calibration measurements. Johnston (2002) have developed the mathematical formalism for obtaining the response matrix and has applied it to the case of linear feeds. Here we follow the mathematical formalism developed by Johnston (2002) and apply it for the circular polarization case. Let v_r and v_l be the right and left circular polarization voltages after the signal has passed through the whole receiver chain. At this stage the sky signal is affected due to: Faraday rotation due to the interstellar medium and the ionosphere; Parallactic angle rotation; the cross-coupling and the gain parameters introduced by the non-ideal feed and receiver system of the radio telescope. Ignoring the effect of rotation and rewriting equation 8 of Johnston (2002) for the circular polarization case, the self and cross products of these voltages are related to the true stokes I, Q, U and V as,

$$\begin{pmatrix} v_{rr^*} \\ v_{rl^*} \\ v_{lr^*} \\ v_{ll^*} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} GG^* & GB^* & BG^* & BB^* \\ -GC^* & GH^* & -BC^* & BH^* \\ -CG^* & -CB^* & HG^* & HB^* \\ CC^* & -CH^* & -HC^* & HH^* \end{pmatrix} \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & i \\ 0 & 0 & 1 & -i \\ 1 & -1 & 0 & 0 \end{pmatrix} \begin{pmatrix} I \\ V \\ Q \\ U \end{pmatrix} \tag{1}$$

where B, C and their complex conjugates are the complex cross-coupling parameters (CCPs) and G, H and their complex conjugate describes the sensitivity and the phase difference of the two probes. The measured stokes parameters are $I_m = v_{rr^*} + v_{ll^*}, Q_m = v_{rl^*} + v_{lr^*}, iU_m = v_{rl^*} - v_{lr^*}$ and $V_m = v_{rr^*} - v_{ll^*}$. Writing the complex parameters like G as $g_1 + ig_2$ and so on, and ignoring the second order terms in B and C, we can rewrite equation 11 of Johnston (2002) for the circular case as

$$\begin{aligned} I_m &= \frac{1}{2}I(g_1^2 + g_2^2 + h_1^2 + h_2^2) + \frac{1}{2}V(g_1^2 + g_2^2 - h_1^2 - h_2^2) + \\ &\quad Q(g_1b_1 + g_2b_2 - h_1c_1 - h_2c_2) + U(g_1b_2 - g_2b_1 + h_1c_2 - h_2c_1) \\ V_m &= \frac{1}{2}I(g_1^2 + g_2^2 - h_1^2 - h_2^2) + \frac{1}{2}V(g_1^2 + g_2^2 + h_1^2 + h_2^2) + \\ &\quad Q(g_1b_1 + g_2b_2 + h_1c_1 + h_2c_2) + U(g_1b_2 - g_2b_1 - h_1c_2 + h_2c_1) \\ Q_m &= I(h_1b_1 + h_2b_2 - g_1c_1 - g_2c_2) + V(-g_1c_1 - g_2c_2 - h_1b_1 - h_2b_2) + \\ &\quad Q(g_1h_1 + g_2h_2) + U(g_1h_2 - g_2h_1) \\ U_m &= I(g_1c_2 - g_2c_1 + h_1b_2 - h_2b_1) + V(g_1c_2 - g_2c_1 - h_1b_2 + h_2b_1) + \\ &\quad Q(-g_1h_2 + g_2h_1) + U(g_1h_1 + g_2h_2) \end{aligned} \tag{2}$$

which is the relation between the measured stokes parameter and the true stokes parameters via a response matrix.

The aim of polarization calibration is to determine the response matrix, i.e. the complex terms B, C, G , H and the true stokes parameters I, Q, U and V. There is also an unknown angle ϕ such that $Q = Lcos\phi$ and $U = Lsin\phi$ where L is the linear polarization and ϕ is a combination of the parallactic angle plus any difference in phase that arises between the right and left hand circular polarization due to the signals propagation through various stages. To obtain these parameters in an alt-az mounted telescope like GMRT one needs to observe a polarized source as a function of parallactic angle and solve equation 2 and obtain the 13 unknown parameters (for details on the method of calibration refer to Johnston 2002). The true stokes parameters is finally obtained by inverting the response matrix in equation 2.

4 Observations and Results

In GMRT polarization observations in currently possible using the PA mode and the pulsar receiver as backend. The user has the flexibility to choose a set of antennas and define it as an array which can be phased. Phasing is achieved by first choosing a reference antenna with respect to which

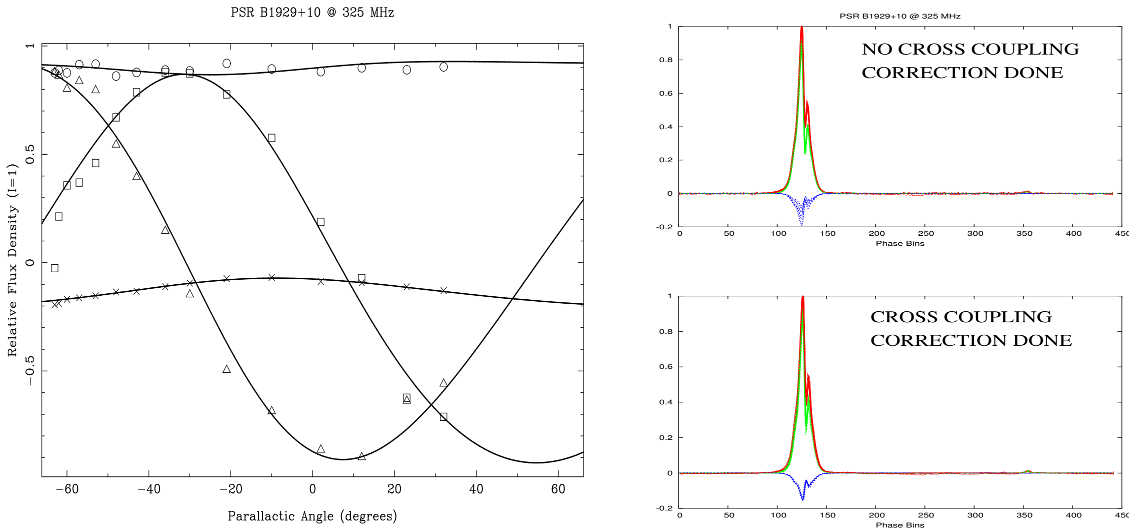

Figure 1: *Left Panel*: The figure shows the variation of the measured linear polarization (circles), stokes U_m (boxes), Q_m (triangles) and V_m (crosses) as a function of parallactic angle with measurements done in the peak bin of the profile of PSR B1929+10 for observations done on 12th October 2004 using 14 GMRT antenna's as the PA. The solid lines are best fit to the data. *Right Panel*: The top plot show the overlay of 7 min integrated total intensity (red), linear polarization (green) and circular polarization (blue) of PSR B1929+10 as a function of phase bins for various parallactic angles. The data is not corrected for cross-coupling. Notice the 15% spread in the circular polarization. The bottom panel shows the same data corrected for the cross-coupling parameters. Notice that the spread in the circular polarization is reduced to 2%.

the array is phased by observing a phase calibrator. More specifically in this process the left and right circular polarization are phased separately. Hence a fixed delay existing between the left and right circular polarization of the reference antenna exists which appears as a linear gradient in the observed position angle of the source across the observing band and needs to be compensated separately in the offline data analysis. For our experiments we have observed the pulsar PSR B1929+10 as our polarization calibrator in the PA mode using a set of selected antennas. This pulsar is a good calibrator as it is known to be almost 100% linearly polarized and also has about 13% circular polarization. The pulsar was observed from rise to set and short integrations of 7 mins were made to obtain a stable folded integrated profiles (by collapsing all 256 channels across 16 MHz band after correcting for the fixed delay, interstellar faraday rotation and pulsar dedispersion) for each stoke parameters (i.e. I_m, V_m, Q_m, U_m) for each parallactic angle. Since pulsars are known to scintillate each stokes parameters were normalized by the total intensity as these normalized quantities remains unaffected due to scintillation.[1] Finally the measured stokes parameter as a function of parallactic angles were obtained and a least square fitting algorithm (the same program as used by Johnston 2002 but modified for circular polarization) was used to minimize the residuals of $(\mid Q_m - Q \mid + \mid U_m - U \mid + \mid V_m - V \mid)$ and solve for the 13 unknowns.

Fig. 1 shows the result of the observations done on 12 October 2004 at 325 MHz (see caption for details). Here we demonstrate that the methods of single dish polarization calibration can be readily used to calibrate the PA mode. The CCPs obtained for this experiment are $b_1 = -0.04, b_2 = -0.02, c_1 = 0.08$ and $c_2 = 0.10$. As seen in the right panel of fig. 1 the CCP causes the circular polarization to spread by almost 15%. By applying the polarization calibration the spread reduces to about 2%. We have performed several similar experiment but with different group of antennas as the PA and obtained slightly different values of the CCPs. There were however two occasion

[1] This procedure prevents one from determining the true value of the total intensity and thus introduces some error in the polarization calibration method as discussed in Johnston 2002.

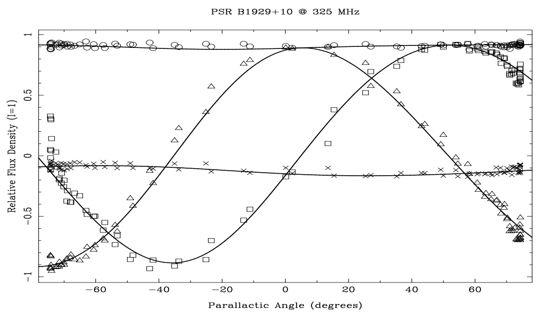

Figure 2: Details of the figure is same as the left panel of Fig. 1 except that the data are from observations form 8th June 2005 and 20th July 2005 using 9 GMRT antennas as the PA.

(8th June 2005 and 20th July 2005) where we observed using the same set of 9 antennas. In fig. 3 we show the data combined for two different days and as expected the data sets are very similar. For these data set we obtain the CCPs as $b_1 = 0.02, b_2 = 0.01, c_1 = -0.04$ and $c_2 = -0.01$ (note that these results differ from the 12th October 2004 results). It should be noted that even for same set of antennas the ionospheric conditions might vary with time which causes only a change in ϕ. Under such circumstances the pattern of the measured stokes parameters (e.g. Fig. 3) will shift in parallactic angle axis keeping the overall variation same.

5 Conclusion

Theoretically the CCPs of the PA is a vector addition of all the complex CCP of the individual antenna's. Our observation that the CCPs are slightly different for different groups of antennas chosen can thus be explained as slightly different vector addition of the different CCPs of individual antennas. We have demonstrated here that the polarization calibration of the PA mode is similar to a single dish and due to the nature of the vector addition of the CCPs of individual antennas, the CCP of the phased array can be smaller than the individual antennas. We have also shown that the CCP for the same set of antenna's are rather stable. The success of the calibration procedure described here for the PA demonstrates that similar schemes can be applied to future array kind of instruments like LOFAR and SKA at meter wavelengths.

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