Polarimetric Calibration Results of an APERTIF Phased Array Feed

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Abstract **– The field-of-view of a reflector-based radio telescope can be significantly increased by using phased array feeds (PAFs). Such PAFs need to be polarimetrically calibrated to allow proper reconstruction of the polarization state of the radio waves received. In this paper, we present far field radiation patterns of the Aperture Tile-in-Focus (APERTIF) system on the Westerbork Synthesis Radio Telescope (WSRT) obtained for polarimetric characterization of the instrument. We also demonstrate successful application of these calibration results by reconstructing the rotation measure towards BL Lac over a frequency range from 1190 to 1390 MHz.**

1 INTRODUCTION

A radio telescope measures the intensity and polarization state of radio waves emitted by celestial sources. These radio signals are very weak compared to telecommunication signals, but they are stationary. A typical radio astronomical observation therefore takes several hours per field. The field-of-view, and hence the survey speed, of reflector-based radio telescopes can be increased dramatically by using phased array feeds (PAFs). The goal of the Aperture Tile-in-Focus (APERTIF) project is to develop and build a PAF system for the Westerbork Synthesis Radio Telescope (WSRT) [1].

In a PAF system, the (secondary) far field radiation patterns are the result of weighted superpositions of the far field radiation patterns of multiple antenna elements. The polarimetric properties of these beams do therefore not only depend on the reflector optics and PAF element radiation patterns, but also on the beamforming scheme and calibration accuracy. Recently, various beamforming schemes have been proposed and compared [2-4].

In this paper, we present measurements done for polarimetric characterization of the APERTIF prototype system. These measurements show that the central compound beam produced by a bi-scalar beamforming scheme has a peak cross-pol level below -20 dB. In the bi-scalar beamforming scheme, the receptors associated with each polarization are beamformed separately assuming that their polarimetric responses are perfectly orthogonal [5]. This cross-pol performance should allow to do proper polarimetric observations, which we demonstrate by measuring the Faraday rotation along the line-of-sight towards the astronomical source BL Lac over the frequency range from 1190 to 1390 MHz.

2 FAR FIELD PATTERN MEASUREMENTS

The APERTIF prototype system is installed on one of the WSRT dishes. The PAF system consists of 121 Vivaldi elements in a dense rectangular grid [5]. The elements are mechanically oriented in two orthogonal directions, 61 and 60 in the X- and Y-direction respectively, to sample the incoming radio waves in two polarizations. For our extensive far field pattern measurements, we connected 29 X-elements and 27 Y-elements as well as both feeds of two neighboring WSRT dishes to our backend. The latter were used as reference antennas. In the backend, all 60 signals (56 PAF elements, two dual-pol WSRT antennas) were digitized and correlated.

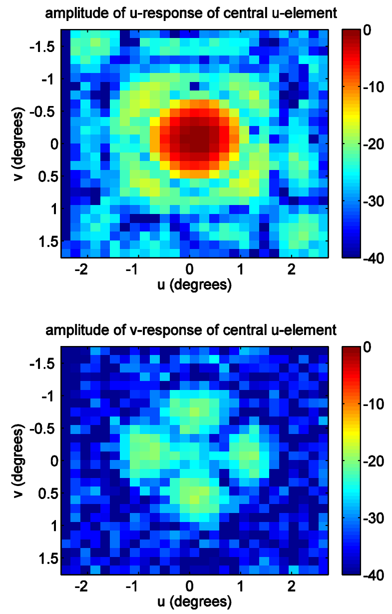

Figure 1. Measured co- (top) and cross-pol (bottom) far-field amplitude of a single PAF element at 1360 MHz.

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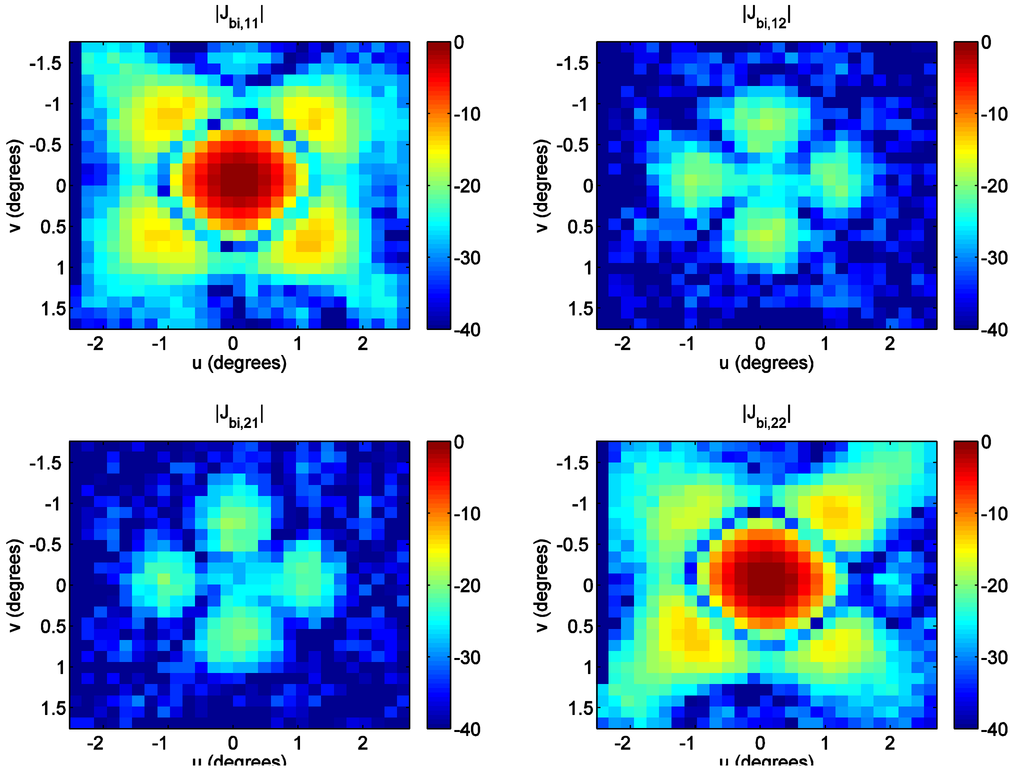

Figure 2. Measured co- and cross pol response of the on-axis X and Y polarized compound beams at 1360 MHz using a bi-scalar beam former.

With this setup, we observed radio source 3C147 at 1.36 GHz keeping the two reference antennas pointed at the source while the PAF dish was scanning a grid around 3C147. At regular intervals, a noise source on the reflector surface of the PAF dish was turned on to track electronic drift in the PAF system. The grid resolution was 0.13° and the integration time per pointing was 40 s.

The main polarimetric axes of the WSRT receivers are oriented at an angle of 45° with respect to the orientation of the PAF elements. This proved to be a useful feature for calibration of the phase variations of the reference antennas since each of the four single polarization reference signals has significant correlation with the signal from a central PAF element, which we used as phase reference during our measurement. After phase calibration of the reference feeds, we performed the following steps for each pointing:

1. Correct the phases of the reference feeds.
2. Equalize the gains of the reference feeds.
3. Rotate the polarimetric response of the reference antennas by 45° to align the main polarimetric axes of the reference antennas with the co-pols of the PAF elements.
4. Stabilize the gain and phase variations over time of the PAF elements using the noise source measurements with the central PAF elements used for phase calibration of the reference feeds as phase reference.
5. Determine the co- and cross-pol far field response towards the source based on the cross-correlation of the signal from each PAF element with the reference feeds.

Figure 1 shows the amplitude of the far field co- and cross-pol pattern of a single PAF element. In the PAF beam former, the 29 X-signals and 27 Y-signals are combined separately to produce an X-polarized beam and a Y-polarized beam. Since these compound beams are superpositions of the element beams, we can use this measurement to assess the polarimetric performance of the X- and Y-polarized compound beams as well. Figure 2 shows the co- and cross-pol response of on-axis X- and Y-polarized compound beams. The beam patterns of the X and Y beams are very similar. The cross-pol level in the center of the beam is well below -20 dB. Although not perfect, this should allow decent reconstruction of the polarization state of the incoming radio wave.

3 MEASURING FARADAY ROTATION

To verify the PAF performance in a real-world application, the rotation measure of BL Lac has been

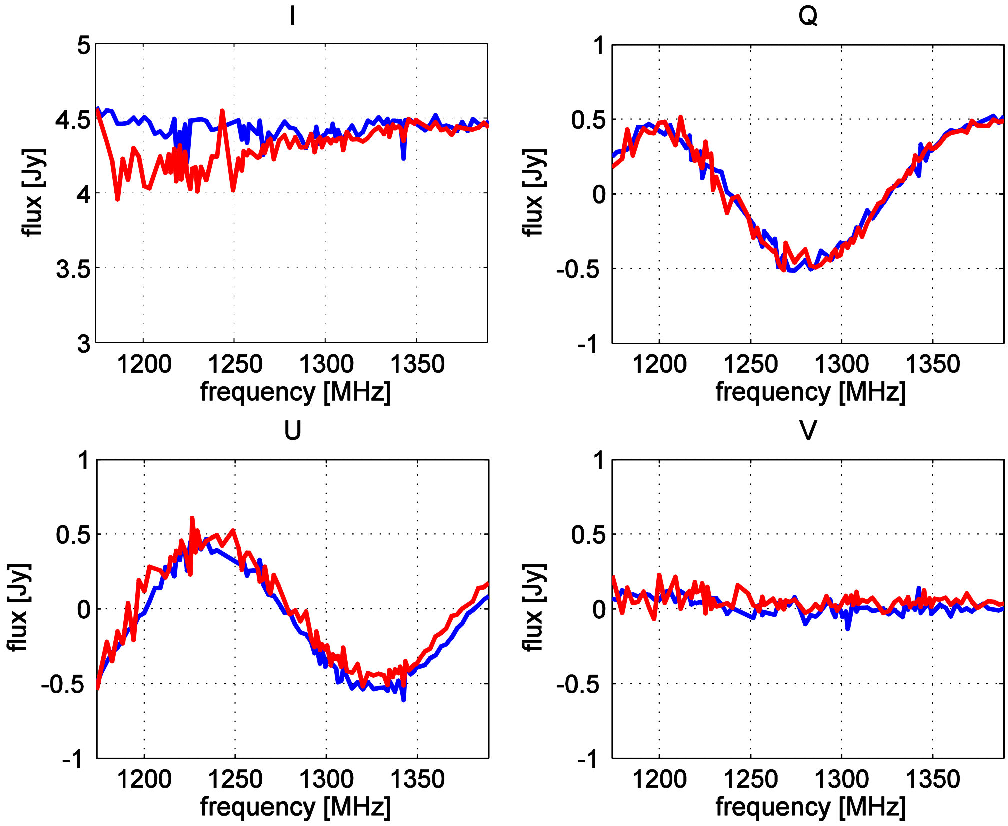

Figure 3. Observed Stokes parameters of BL Lac as function of frequency using an on-axis (blue) and 1 degree scanned PAF beam (red).

measured. BL Lac is a well-known, partly polarized and strong point source with a large Rotation Measure (RM). Due to the RM, the observed polarization angle of the source changes as function of frequency. Such measurement is very challenging since it requires a wideband, polarimetrically calibrated and stable interferometer system. Five measurements at successive frequency bands were performed and aggregated, resulting in an overall frequency coverage from 1190 to 1390 MHz. These observations were performed twice: In the first one BL lac was observed through an on-axis PAF beam. In the second observation BL lac was observed with a beam scanned to a 1 degree offset from the telescope axis, i.e. twice the half-power beamwidth. Both observations were performed during daytime.

The RM measurement used 60 signals (56 PAF elements and two dual-pol WSRT antennas). The PAF elements were beamformed into an X and Y beam using a bi-scalar beam forming scheme. Next, the PAF beams were correlated with the dual polarized beams of the reference telescopes. The experiment consists of two observations: First 3C147 was observed to calibrate the system. Next, BL Lac was observed.

In postprocessing, the following steps have been performed:

Using the 3C147 observation:
1. Determine and correct the phases of the reference telescopes.
2. Rotate the polarimetric response of the reference antennas by 45º to align the main polarimetric axes of the reference antennas with the co-pols of the PAF elements.
3. Determine the sensitivities of both the (rotated) reference telescopes and the PAF.
4. Apply the sensitivity calibration to the measured correlation coefficients
5. Determine the flux calibration from measured Stokes I and literature model of 3C147.

Using the BL Lac observation:
1. Apply phase calibration determined on 3C147
2. Rotate the polarimetric response of the reference antennas by 45º
3. Apply sensitivity calibration determined on 3C147
4. Calculate Stokes parameters
5. Flag data affected by RFI (Stokes V > 0.25 Jy).

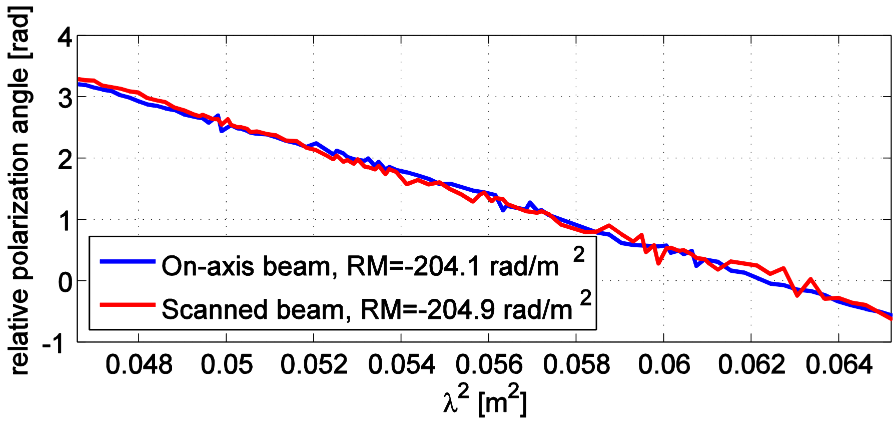

Figure 4. Observed polarization angle of BL Lac as function of wavelength squared using an on-axis and 1 degree scanned PAF beam.

The observed Stokes parameters are shown in Figure 3. Due to a significant elevation difference in the 3C147 and BL Lac measurements, there is a substantial difference in the system temperature of both measurements. Since the system temperature variation was not monitored nor corrected, an error in the flux calibration will occur. This was accepted as it does not affect the polarimetric performance. The Stokes I variation over frequency of the scanned beam is also attributed to this effect. Stokes Q and U vary due to the rotating polarization angle as function of frequency. Their level is, as expected, about 10% of I. Stokes V is close to 0, as it should be.

The observed polarization angle of BL Lac has been derived from Stokes Q and U and plotted as function of wavelength squared in Figure 4. Using a linear least-squares fit, an RM of -204.1 rad/m^2 was found for the on-axis measurement and -204.9 rad/m^2 for the 1 degree scanned beam. These results agree very well with a recent measurement using the WSRT in which an RM of -205.1 rad/m^2 was obtained [7]. The slight differences can be explained by measurement accuracy, variations of the source and ionospheric conditions.

4 CONCLUSIONS

A technique for the polarimetric calibration of the APERTIF PAF prototype, and successful measurements of the Rotation Measure of BL Lac have been demonstrated. It is concluded that accurate polarimetric measurements can be performed with on-axis and scanned beams of a Vivaldi-based PAF system using a bi-scalar beamformer over a 200 MHz frequency range.

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