High Sensitivity L-band Phased Array Feeds for the Westerbork Synthesis Radio Telescope

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Abstract— **A novel method to form multiple high-sensitivity beams with a reflector based radio telescope is to use a phased array feed (PAF). To accurately reconstruct the polarization state of the incident radio waves, the beam patterns of the PAF are of crucial importance. The co- and cross-polar element patterns of an oversampled L-band PAF prototype system have been measured in an interferometric setup. It is demonstrated that, although the antenna elements sampling the two orthogonal polarizations of the focal field are not co-located, dual polarized beams can be formed by combining the element responses in a beamformer. The capability of the PAF to optimize its beams in terms of sensitivity, sidelobes and polarization characteristics is demonstrated.**

Keywords-antenna arrays; polarimetry; antenna feeds; reflector antennas; beam steering; antenna radiation patterns

I. Introduction

The main objective of a radio telescope is to measure the intensity and polarization state of radio waves emitted by celestial sources. These signals are very weak compared to most telecommunication signals, but mostly stationary. To achieve the desired signal to noise ratio, the integration time per pointing can be up to hundreds of hours. The importance of surveying large regions of the radio sky with maximal sensitivity and high resolution is recognized as one of the key elements required to tackle some of the major questions in modern astronomy. Present day radio telescopes have limited survey capabilities because of the long integration times and restricted field of view. The survey speed can be improved by instantaneously forming multiple beams. A novel method to form multiple beams with reflector telescopes is to employ a phased array feed (PAF) [1]. A PAF is an array of electrically small antenna elements (< λ/2) in the focal plane of the reflector. Multiple compound beams are formed simultaneously by a weighted combination of the elements. PAFs also allow telescopes with relatively small f/D ratios to form closely packed beams on the sky, i.e. touching at their half power points. An additional advantage of this technique is that a PAF enables to optimize the beams in terms of sensitivity, sidelobes and polarization characteristics.

To reconstruct the polarization state of the incident signals, the PAF needs to sample the focal field in two sufficiently orthogonal polarizations. Depending on the beam former implementation, cross-polarization of the antenna elements can lead to a sensitivity loss in the polarization reconstruction [2,5]. To assess the polarimetric properties of the PAF, the beam patterns of a prototype system have been measured. The impact of different beam forming schemes on the cross-polarization level and sensitivity is evaluated.

II. System Overview

APERTIF ("APERture Tile In Focus") is a PAF system that is being developed to improve the survey speed of the Westerbork Synthesis Radio Telescope (WSRT) [3]. The WSRT consists of 14 prime-focus parabolic reflector telescopes of 25 m diameter and f/D = 0.35. APERTIF will operate in the frequency range 1000 – 1750 MHz, with an instantaneous bandwidth of 300 MHz, a system temperature of 55 K and an aperture efficiency of 75%. The goal is to have 37 beams on the sky for an effective field of view of 8 square degrees over the entire frequency range. The current horn feeds of the WSRT have a 30 K system temperature, 55% aperture efficiency and 160 MHz bandwidth. The net gain in survey speed of APERTIF compared to the existing system will be a factor 20. The on-axis cross-polarization of the horn telescopes is below 1% (-20 dB). The design goal of the PAF system is to remain below this level.

Figure 1. APERTIF L-band Phased Array Feed mounted in the primary focus of a 25-m reflector telescope.

A prototype PAF system has been installed in one of the WSRT telescopes (Figure 1). The PAF consists of 121 Vivaldi elements in a rectangular grid [4]. The elements are (mechanically) oriented in two orthogonal orientations to sample the focal field in two polarizations. We will refer to these orientations as X and Y. It is noted that the X- and Y-elements are not co-located, i.e. the two polarizations of the focal field are sampled at different locations (see Figure 2). Consequently, the X- and Y-elements will be sensitive to radiation from different positions on the sky. But because the focal field is oversampled, compound beams can be formed in the same direction for both polarizations, as demonstrated in section IV.

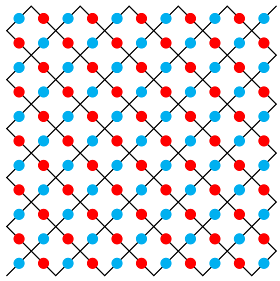

Figure 2. Schematic overview of the X (red) and Y (blue) element positions.

The signals received by the PAF elements are amplified and digitized. Digitization per element allows to form multiple beams simultaneously by an all-digital beam-former.

In the final APERTIF system, the signals from the X- and Y-elements are processed separately as if the system consisted of two independent single polarization systems. We will refer to such an approach as the bi-scalar approach. Its main advantage is that the front-end processing, consisting of beamforming and correlation, is reduced from a system with 2N inputs to two systems with N inputs reducing the complexity of the system design. Here N is the number of elements in each set. However, a rigorous analysis of phased array antenna systems indicates that an optimal beamforming scheme, which achieves maximum sensitivity and preserves the polarimetric properties of the incoming signal, exploits the output signals from both X- and Y-elements for every beam [5]. The current prototype system is capable to compare both methods. The results are presented below.

III. MEASUREMENT METHOD

The voltage beams (magnitude and phase) of 56 of the 121 PAF elements have been measured. For this measurement an interferometric observation using three telescopes has been performed. Two reference telescopes equipped with horn feeds continuously track 3C147, an un-polarized celestial point source. The PAF telescope samples a grid of points around the source as indicated in Figure 3. The integration time per point is 40 seconds. The PAF telescope periodically returns to the source to calibrate for phase and sensitivity drift of the system. During the observation, the correlation coefficients between all outputs are recorded. After correction for the varying geometric delay, the correlation coefficients between the PAF elements and the reference telescopes provide the complex (magnitude and phase) voltage beams. The element beams are combined into compound beams by a weighted summation. The weights that are used in this paper have been determined from a separate measurement. All results shown in this paper have been obtained at 1362 MHz.

The horn feeds of the reference telescopes are rotated 45 degrees with respect to the PAF. Therefore, the outputs of the reference telescopes are rotated 45 degrees in post-processing by applying a Jones matrix to their outputs. The rotated outputs of the horn telescopes serve as the polarization reference of the PAF measurements.

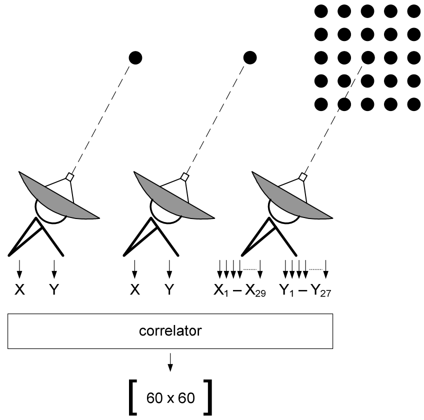

Figure 3. Schematic overview of the measurement setup.

IV. MEASUREMENT RESULTS

Figure 4 shows the measured relative co- and cross-polar patterns of the central element and an on-axis compound beam using the full-pol optimal beamformer (combining 56 elements). Several effects are observed: First, the beamforming process significantly improves the gain (and consequently the effective area) by 1.74 dB, or 49%. Second, the half-power beamwidth (HPBW) of the compound beam (0.62°) is larger than the single element HPBW (0.58°). And finally, the optimal full-pol beamformer reduced the peak cross-pol lobes from -19.4 dB to -28.7 dB.

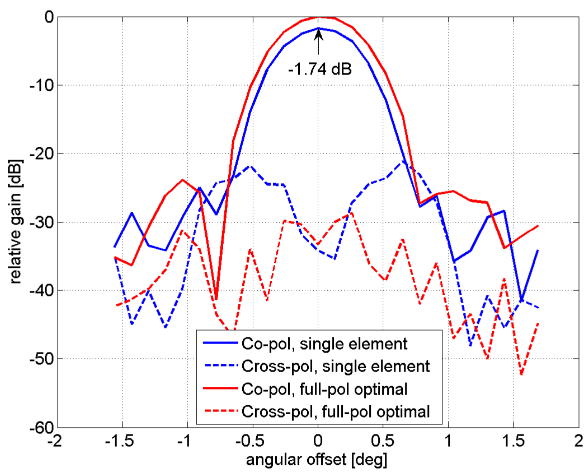

Figure 4. Measured relative gain of a single element beam and a compound beam.

The measured relative co- and cross-polar beam patterns of an on-axis beam for two beamforming schemes are compared in Figure 5. It is observed that the gain difference between the bi-scalar and optimal beamformer is small (3.3%). As expected, the peak cross-polar lobes of the bi-scalar beamformer are higher (8.4 dB) than the optimal full-pol beamfomer.

Figure 6 shows the measured 2D co-polar pattern of an on-axis beam formed by the bi-scalar beamformer. Besides the largely circular main lobe, four sidelobes about 14 dB below the main lobe are observed. These are caused by the four struts supporting the focus cabin. Figure 7 shows the 2D cross-polar pattern of the same beam. Four cross-polar lobes are clearly observed at a level of -20 dB. Figure 8 shows the cross-polar pattern of an on-axis beam formed by the optimal full-pol beamformer. The peak lobes are around 29 dB below the main lobe. The full-pol beamformer convincingly manages to suppress the cross-polar levels.

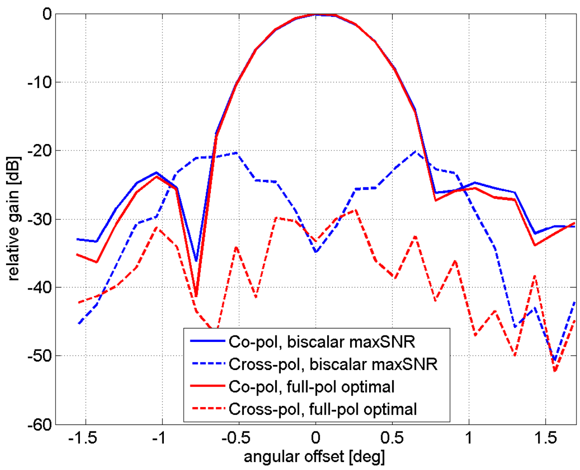

Figure 5. Measured co- and crosspol relative gain of an on-axis beam for various beamforming schemes.

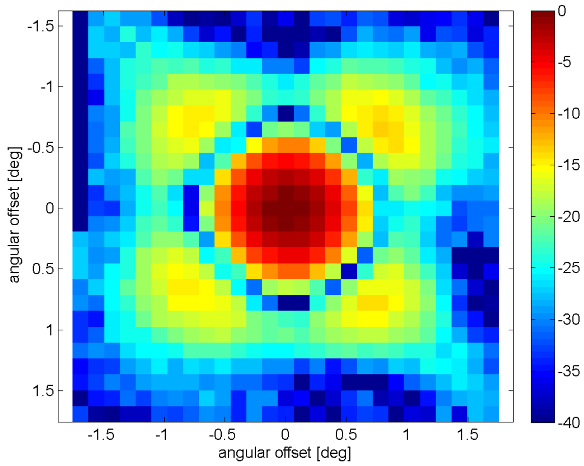

Figure 6. Measured co-polar pattern of an on-axis compound beam using the bi-scalar beamformer.

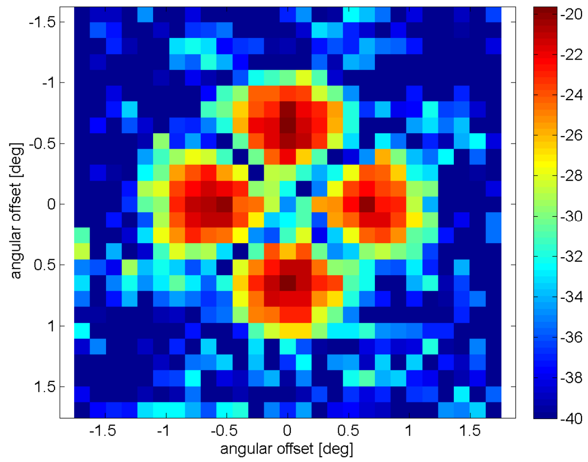

Figure 7. Measured cross-polar pattern of an on-axis compound beam using the bi-scalar beamformer.

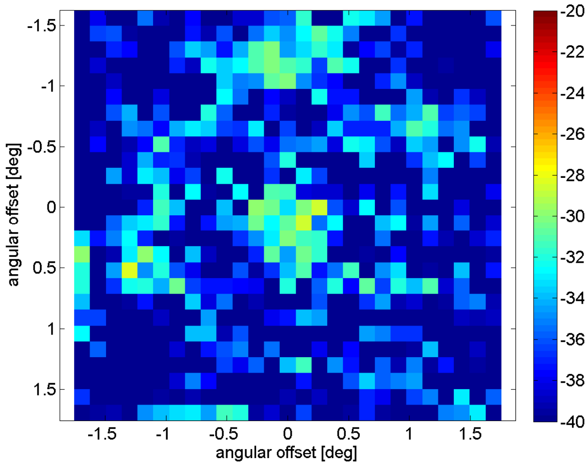

Figure 8. Measured cross-polar pattern of an on-axis compound beam using the full-pol optimal beamformer.

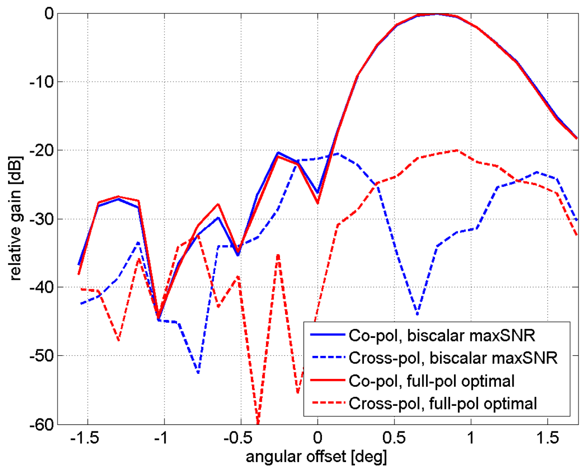

Figure 9. Measured co- and crosspol relative gain of a scanned beam for various beamforming schemes.

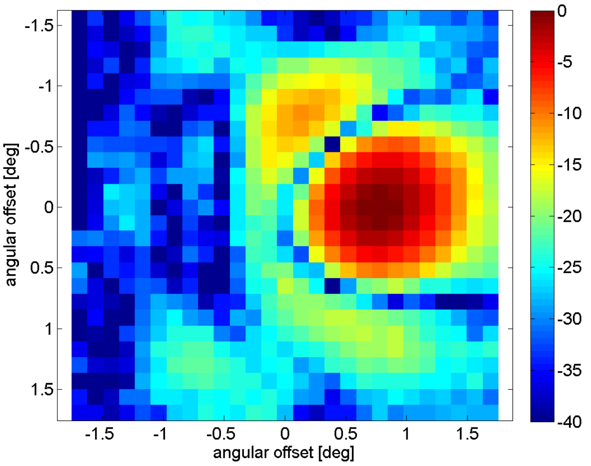

Figure 10. Measured co-polar pattern of a scanned compound beam using the bi-scalar beamformer.

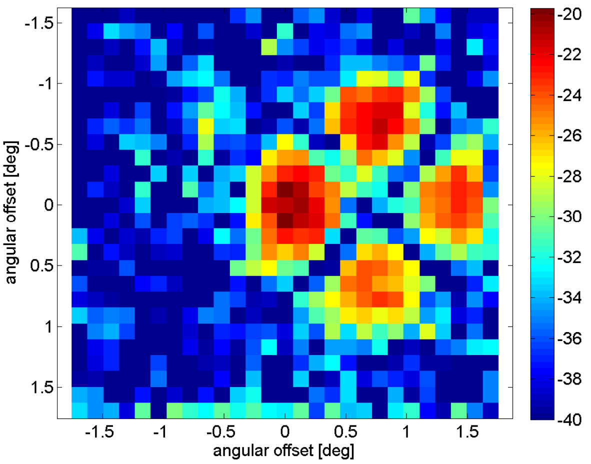

Figure 11. Measured cross-polar pattern of a scanned compound beam using the bi-scalar beamformer.

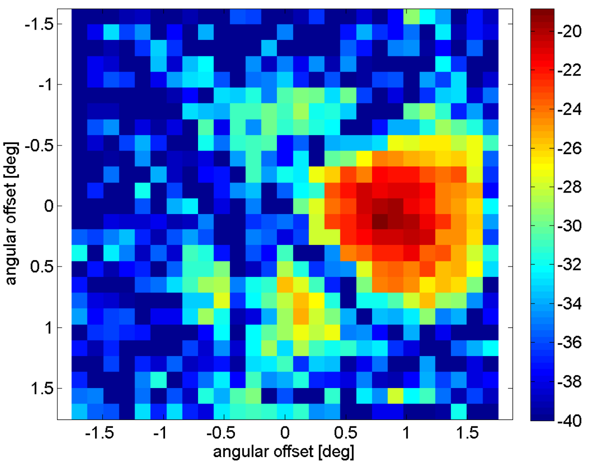

Figure 12. Measured cross-polar pattern of a scanned compound beam using the optimal full-pol beamformer.

The measured relative co- and cross-polar beam patterns of a scanned beam for bi-scalar and optimal beamforming schemes are compared in Figure 9 to 12. Again, the gain difference between the bi-scalar and optimal beamformer is small (2.6%). Surprisingly, the cross-polar level of the full-pol optimal beamformer is worse in the scan direction than the bi-scalar beamformer. This is in contradiction with the fact that the full-pol optimal beamformer should be equal or better than the bi-scalar scheme by definition. This result is not understood yet and will require further investigation.

V. CONCLUSIONS

The co- and cross-polar element patterns of an oversampled L-band Phased Array Feed (PAF) have been measured. It is demonstrated that, although the antenna elements sampling the two orthogonal polarizations of the focal field are not co-located, dual polarized beams with an improved sensitivity can be formed by combining the element responses in a beam-former. Cross-polar levels below -20 dB have been demonstrated using a bi-scalar beam-forming scheme for an on-axis and scanned beam. It is also demonstrated that the optimal beam-forming scheme can further reduce the peak cross-polar lobe to -29 dB for the on-axis beam. The measured sensitivity loss of the bi-scalar beam-former with respect to the optimal one is 3.3% for the on-axis beam and 2.6% for the scanned beam.

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