Experimental Results of the APERTIF Phased Array Feed

W.A. van Cappellen, L. Bakker, and T.A. Oosterloo

ASTRON, P.O. Box 2, 7990 AA, Dwingeloo, The Netherlands
cappellen@astron.nl, bakker@astron.nl, oosterloo@astron.nl

Abstract

APERTIF (APERture Tile In Focus) is a Phased Array Feed (PAF) system that is being developed for the Westerbork Synthesis Radio Telescope (WSRT) to increase its survey speed with a factor 20. This paper presents an overview of APERTIF and measurement results that demonstrate the unique capabilities of PAFs in practice: Wide field of view (scan range), low system temperature, excellent illumination efficiency, synthesis imaging and a significant reduction of the reflector feed interaction.

1. Introduction

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 [1]. Present day synthesis radio telescopes have limited survey capabilities because of their restricted field of view. Placing multiple conventional feeds in the focal plane of a reflector antenna can increase its field of view. However, the number of individual feeds is in principle limited since good aperture illumination requires a feed of sufficient diameter. Consequently, the beams are widely separated on the sky and the number of beams is limited. A novel method to form multiple beams on the sky with reflector telescopes is to employ a Phased Array Feed (PAF): An array of electrically small antenna elements ($< \lambda/2$) in the focal plane of the reflector. The outputs of all elements are combined to form multiple compound beams simultaneously. An additional advantage of this technique is that a PAF allows optimizing the beams in terms of sensitivity, sidelobes and polarization characteristics.

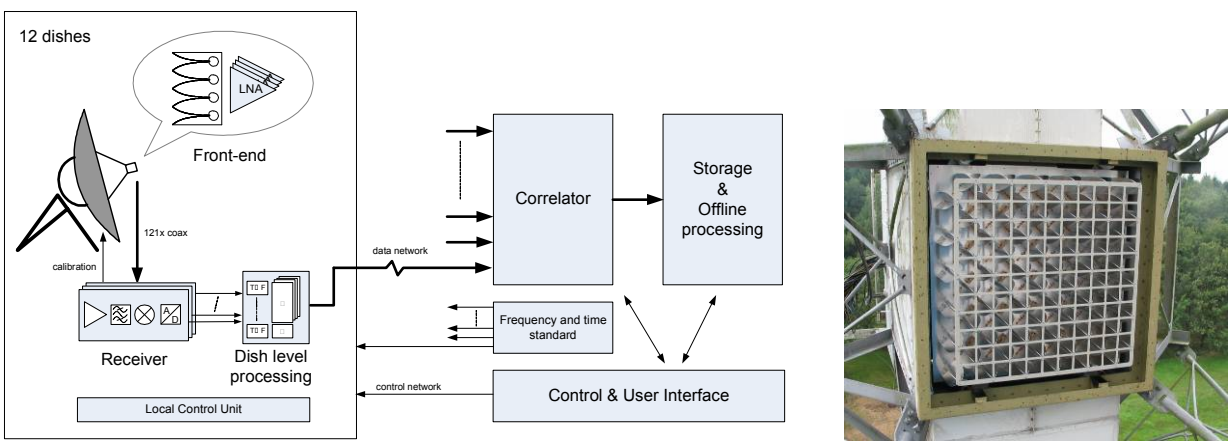

Figure 1. APERTIF block diagram (left) and a prototype PAF installed in the WSRT (right).

2. System Overview

APERTIF ("APERture Tile In Focus") is a PAF system that will be installed in the Westerbork Synthesis Radio Telescope (WSRT) to enhance its survey speed with a factor 20 [2]. APERTIF plans to be operational in 2013. It 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 overlapping beams on the sky for an effective field of view of 8 square degrees. Figure 1 shows the top-level block diagram of the APERTIF system.

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To produce radio astronomical images with a high dynamic range, the compound beam patterns on the sky should be well known and stable. In this respect, PAFs have an additional complexity compared to conventional systems. In one-horn-per-beam systems, gain variation of the receiver leads to variations in detected power, but the beam shape is unaffected. But in a PAF system, multiple elements are combined to form compound beams on the sky. Each element has its own receiver. Consequently, relative gain variations of the receivers will affect the compound beam patterns. Currently, the WSRT has typical magnitude variations of 1% at its half power points (relative to the field centre) due to mechanical pointing errors. This number forms an upper limit for the required stability of the PAF beams [3]. Receiver gain variations of the PAF can lead to larger variations of the compound beam and consequently a calibration scheme is required. This scheme will especially correct for the short term variations of the beams and provide an estimation of the beam patterns within a few percent.

The PAF consists of a dual polarized antenna array mounted in the prime focus of a symmetric 25 m diameter WSRT reflector (see Figure 1). The antenna array has 121 tapered slot elements at a pitch of 10 cm. The antenna elements are connected to single-ended LNAs operating at room temperature [4]. The output signals are transported to ground-level over coaxial RF cables. Receivers convert and digitize the RF signals using 8-bit A/D converters sampling at 800MHz. The cumulative output datarate of all ADCs is 774 Gbit/s per PAF. The digitized signals are split into subbands of 781 kHz, multiplied with complex weights and added. Different weights are applied for every subband and for every compound beam. The beam former generates 37 dual polarized beams (each with 300 MHz bandwidth), totaling a field of view of 8 deg^2. The beam data (178 Gbit/s per dish) is sent over 10 GbE fiber-links to the central processing facility for correlation, calibration, imaging and archiving.

3. Experimental Results

Since 2007, a prototype PAFs have been built and tested in a WSRT reflector to verify their performance and demonstrate the unique possibilities of PAFs in practice. Figure 2 (left) shows the radiation patterns of the individual PAF elements on the sky, clearly demonstrating that each element radiates in a slightly different direction. It also shows increasing coma lobes for beams that are further away from the optical axis of the dish. As mentioned above, signals from the individual array elements are weighted and combined digitally to form a synthesized beam. The weights are determined from calibration measurements on a strong celestial point source and a cold spot on the sky such that all instrumental effects (like gain and phase differences between receiving channels) are implicitly taken into account.

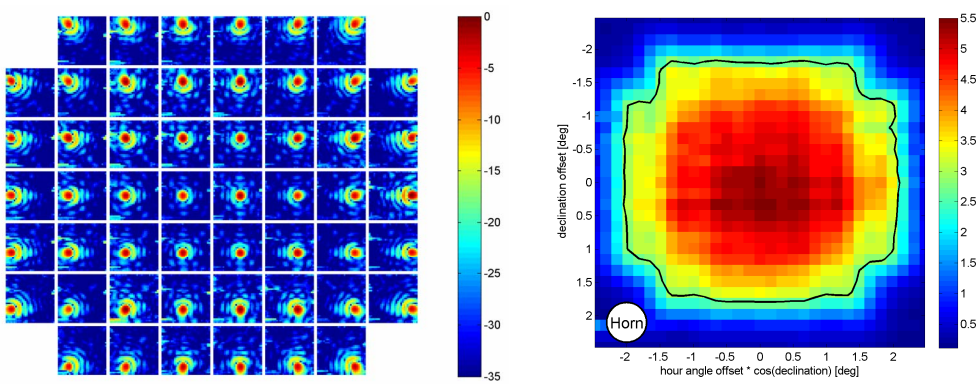

Figure 2. Measured radiation patterns on the sky of 52 PAF elements where each panel measures 5x5 degrees (left) and the measured sensitivity over the field of view at 1420 MHz (right).

Figure 2 (right) clearly demonstrates the enormous increase in field of view enabled by phased array feeds. Every pixel in this figure represents the sensitivity when a compound beam is formed in that direction. The black contour is at half the peak sensitivity, and demonstrates a field of view of more than 10 square deg. For reference, the white circle represents the field of view of the WSRT with horn feeds, i.e. the half-power contour of the beam (HPBW ~0.6 deg). The (irregular) shape of the field of view in this figure is due to the fact that only 52 elements are connected to the backend. In the final system all elements will be processed.

The illumination efficiency of the PAF system has been evaluated with a holographic measurement. The magnitude of the resulting aperture fields at 1300 MHz is shown in Figure 3. The right image shows the illumination pattern of the PAF using weights maximizing the sensitivity. The centre image shows the illumination pattern of the existing horn feed. It is observed that the PAF achieves a more uniform illumination of the reflector and has a sharper cut-off towards the edge of the reflector, minimizing spillover. The X-shaped pattern and the hole in the center are due to blockage by the struts and the feed cabin. The left image shows a front view of a WSRT reflector. The struts and the central blocked area are highlighted. The PAF has an excellent average illumination efficiency of 78%. The illumination efficiency of the horn varies between 67% and 71% due to the presence of standing waves. This effect is further discussed in Section 4.

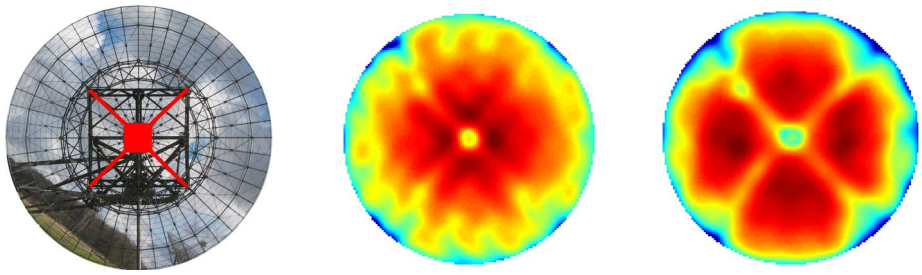

Figure 3. Front view of the reflector (left), magnitude of the reflector illumination of a horn feed (centre) and PAF (right).

The sensitivity of the PAF has been determined from an interferometric measurement with 2 other WSRT dishes. The results presented below used 3C147 as calibrator source. Figure 12 shows the measured A_e/T_{sys} of PAF dish. The average A_e/T_{sys} is 5.5 m^2/K and the T_{sys}/η is about 89 K. By assuming an antenna efficiency of 75%, the system temperature of the prototype PAF is 68 K. Note that the final APERTIF system will have a system temperature below 55 K. The sensitivity over the field of view, the antenna efficiencies and the system temperature are also modeled using an integrated EM and circuit modeling tool [5]. There is a very good agreement between the measurements and simulations.

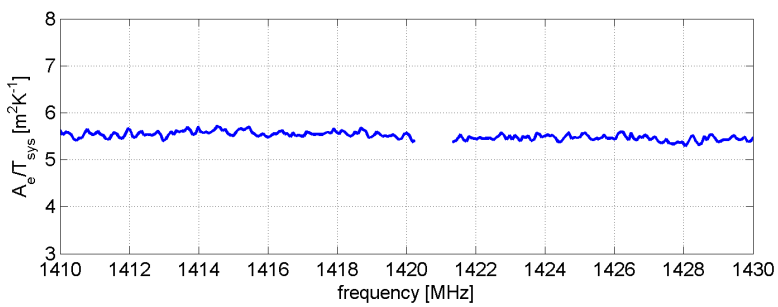

Figure 4. Measured A_e/T_{sys} of an on-axis PAF beam.

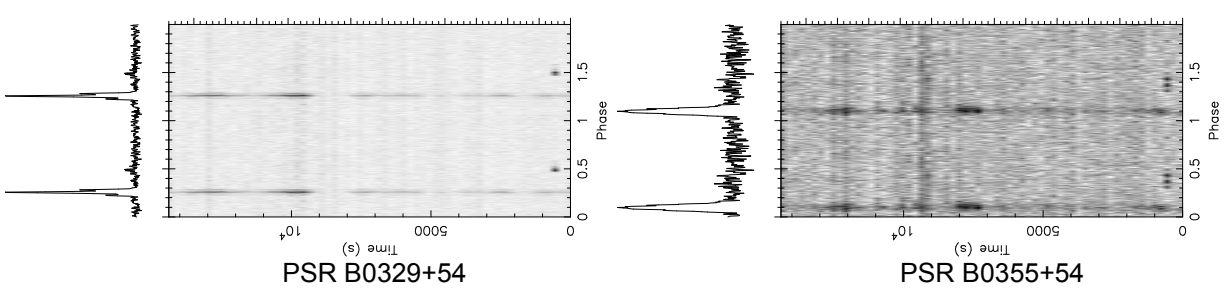

Figure 5. Simultaneous detection of two pulsars.

The WSRT as it currently stands can only simultaneously observe sources closer to each other than 0.5 degrees. A recent pulsar observation with the PAF prototype is another demonstration of the revolutionary wide-field capabilities of PAFs. Two pulsars (B0329+54 and B0355+54), which are separated by 3.8 degrees on the sky,

were simultaneously detected. Figure 5 show the folded profiles from the two sources, each repeated twice for clarity. The intensity variation in the gray scale plots are caused by interstellar scintillation. The observation ran for 4 hours, recording a 6 MHz band around 1420 MHz.

4. Standing Waves

A commonly observed effect plaguing wideband symmetrical reflector systems is an interaction between the feed and the reflector, commonly referred to as the 'standing wave' phenomenon. For the WSRT, it results in a beam pattern and sensitivity variation as function of observing frequency with a period of about 17 MHz. Consequently, the observed spectra are distorted and because the beam pattern variations are very different for the XX and YY beams, a frequency dependent instrumental polarization is introduced as well. The standing wave phenomenon in the WSRT significantly complicates the wideband calibration of the WSRT system. Figure 6 (left) shows the measured normalized sensitivity of a WSRT dish with the horn feed and a single PAF element (right). This figure clearly shows the 17 MHz periodic sensitivity variation of the horn fed dish due to the standing waves. However, the PAF results do not show this variation. The fact that the single element sensitivity does not show the periodic variation indicates that they are not just eliminated by optimizations in beam forming but that the effect is not present in the structure. It is concluded from Figure 4 that also the compound beam sensitivity has no visible variations due to standing waves.

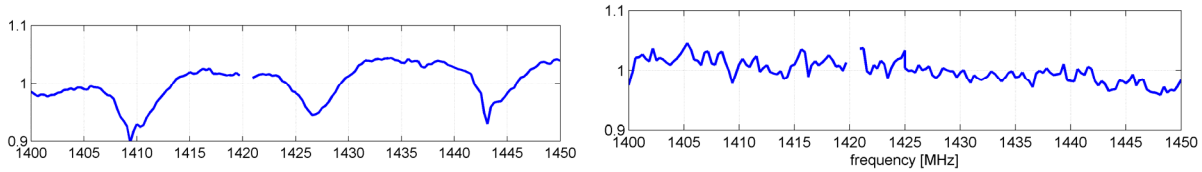

Figure 6. Measured sensitivity versus frequency of a horn-fed dish (left) and a single PAF element (right). All lines are normalized to unity mean.

6. Conclusions

This paper presents the APERTIF PAF system for the Westerbork Synthesis Radio Telescope that will boost its survey speed with a factor 20. Measurement results obtained with an APERTIF prototype demonstrate the unique capabilities of PAFs in practice. It is concluded that PAFs enable a wide contiguous field of view (scan range) in deep reflectors. High illumination efficiency (78%), a system temperature of 68 K and greatly reduced reflector – feed interactions have been demonstrated. These results are an important step in demonstrating the feasibility and competitiveness of the PAF for radio astronomy

8. References

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