Focal Plane Arrays Evolve

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Abstract

The application of Focal Plane Arrays (FPAs) aims to substantially increase the survey speed of radio telescopes by increasing their field of view. FPAs are studied intensively by several groups around the globe to establish their feasibility. Each compound FPA beam is established as the weighted sum of the beams of multiple FPA elements. In this paper it is identified that the compound FPA beams depend on the (relative) electronic gain variations of the individual receiver channels. This is a complicating factor when compared to reflector systems with one horn per beam. It is also argued that the LNA design of array systems need to be more robust against variations of the source impedance than in the case of conventional systems. Finally, demonstrators to experimentally verify the performance of FPAs are presented along with their initial results.

1. Introduction

The increased field of view that Focal Plane Arrays (FPAs) offer can substantially increase the survey speed of radio telescopes. This enables a survey of the entire sky on shorter timescales and with higher sensitivity than currently possible. This will enable entirely new types of astronomical research. The dense FPAs described in this paper can be distinguished from traditional one-horn-per-beam systems by the fact that the compound beam is a complex weighted sum of multiple element beams. The FPA concept is of great importance for existing radio telescopes in the view of modifications and upgrades. Moreover, future systems such as the Square Kilometer Array (SKA) [1] can benefit from focal plane arrays. SKA pathfinders like the demonstrator projects described in this paper and the ASKAP project [2] plan to use FPAs. Also other groups are investigating the potentials and feasibility of dense FPAs [3],[4].

2. Unique aspects of Focal Plane Arrays

Dense FPAs have very interesting properties, like the possibility to improve the aperture efficiency by optimising the illumination of the reflector and of course a large field of view. However, close investigation revealed that a number of unique implementation issues need to be addressed for a successful design. These are primarily related to the calibration of FPAs and the presence of mutual coupling effects in the antenna array.

Calibration

The purpose of calibration is to characterise the system such that instrumental effects can be corrected. One key instrumental parameter is the compound beam pattern. In this respect, FPAs have an additional complexity compared to conventional systems. Due to for example changing temperatures and aging, the (electronic) gain of a receiving channel will vary over time. In one-horn-per-beam systems this gain variation leads to variations in detected power, but the beamshape is unaffected. Variations in detected power have only second order effects on the system sensitivity and can be corrected relatively easy. But in an FPA system, multiple elements are combined to form a compound beam on the sky. Each element has its own receiver channel. Consequently, relative gain variations of the receiver channels not only lead to a variation of the detected power, also the beam shape is affected. Calibration schemes to correct for electronic gain variations in FPAs are critical to ensure a stable beam pattern. One of the proposed solutions is to place a calibration source in the apex of the dish, but its effectiveness still has to be proven in practice.

Mutual Coupling

An important difference between horn fed reflector systems and array-based systems is the presence of mutual coupling between the antenna elements. The Low Noise Amplifiers (LNA's) connected to the antenna array generate noise waves towards their outputs, but also send noise waves back into the antenna array. Due to mutual coupling, these waves are coupled into other receiver channels, giving rise to an additional (correlated) noise

contribution. This effect is known as noise coupling. Its contribution to the system noise temperature is not straightforward since it depends on the antenna impedance, the (scattering and noise) parameters of the LNA and the weighting coefficients applied in the beamformer. Several numerical approaches to account for this effect are used: noise waves and scattering parameters [5], active reflection coefficients of the array elements [6] or by admittance matrices and noise voltage and current sources. It has been shown that these different numerical methods are fully equivalent.

The effect of noise coupling has recently been measured in a telescope equipped with an FPA feed (see Section 4). The FPA consists of 112 tapered slot (Vivaldi) elements in two polarizations: X and Y. Only 32 of the 56 X-polarised elements are active (measured). All other X polarized elements are terminated with 50 Ohm loads (at room temperature). The Y elements are open. The element separation is just below 0.5 wavelengths at the observed frequencies. The telescope is pointing to a cold region of the sky of which the noise temperature is negligible compared to the system temperature. In the experiment, the cross-correlation between the active outputs has been measured. For verification, the cross-correlation between the active outputs without the antenna connected was separately measured to be less than -25 dB. If there would be no coupling between the array elements, the cross-correlation between the individual output channels would ideally be 0 on a linear scale or - ∞ dB. But in this experiment, both the LNA's and loads at the passive elements couple energy to the active elements, giving rise to a correlated fraction at their outputs. In Figure 1 (left) we show the magnitude of 3 of the measured cross-correlations for several element separations in the E-plane. As expected, the highest cross-correlation is found between two neighboring elements (top curve). The correlation decreases when we observe outputs from elements that are separated 2 and 3 times the element spacing respectively. For comparison, the measured mutual coupling coefficient (S_{1x}) between the same elements is shown. It can be seen that although the measured power coupling is (only) -14 dB, the cross-correlation coefficient for two neighboring elements is typically -8 dB for this setup. This can be explained by the additional noise-wave powers coupled from other elements of the array.

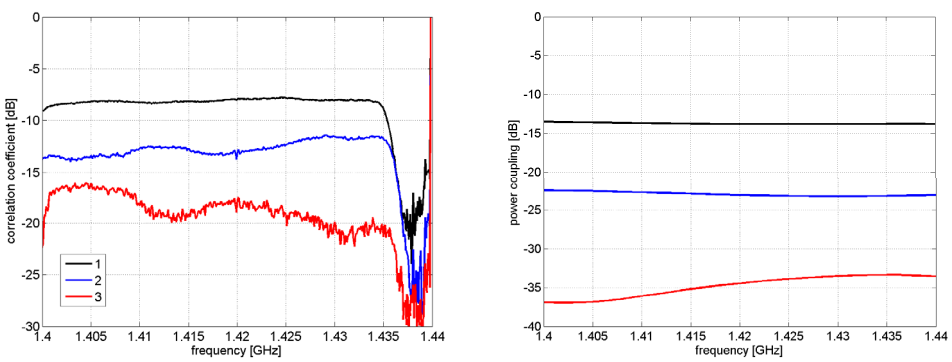

Figure 1 Measured cross-correlation between two antenna elements as function of their E-plane separation (left) and the mutual coupling coefficients between these elements measured in the lab (right).

The presence of mutual coupling also influences the LNA design. Two of the noise parameters of an LNA are T_{min} and R_n. T_{min} is the lowest equivalent noise temperature that can be achieved in case of an optimum noise match with the source. R_n gives the increase in noise temperature in case of an impedance mismatch between the source and the LNA. In practical designs, these parameters are coupled and cannot be optimized individually. In conventional horn-fed reflector systems, the antenna impedance is relatively constant due to the (usually) smaller frequency bandwidth and the antenna type. Consequently, the LNA's are typically optimized to have a very low T_{min}. The fact that the R_n is relatively high is irrelevant due to the stable source impedance. The LNA design of an array system requires a different approach. The active source impedance depends on the weighting coefficients and can show significant variations for different beams. Hence, a design that is more robust against source impedance variations (i.e. it has a lower R_n) can have better overall performance, even if this implies an increase of the minimum noise temperature. This is a direct consequence of the presence of mutual coupling.

3. PHAROS

A Joint Research Activity has been set up as part of RadioNet [7], an EU financed Framework-6 Project: Phased Arrays for Reflector Observing Systems (PHAROS). The PHAROS system prototype aims to accurately

characterize and improve the FPA noise performance with respect to initial prototypes. In order to realize this, cryogenic cooling will be applied which will enable the full capabilities of FPAs also in terms of noise temperature. Figure 2 gives a drawing of the complete system. The PHAROS specifications are summarized in Table 1. In particular the methanol spectral line at 6.7GHz is an important science driver in this frequency band.

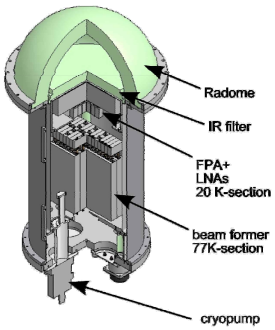

Figure 2 PHAROS system drawing

Table 1 PHAROS specification summary

Operating frequency range	4 – 8 GHz
Number antenna elements Including 2nd polarization	(10 x 11)x2 = 220
Number of beams	4
Number of antenna elements in a subarray (per beam)	13
Total number of elements in 4 FPA subarrays	24
Polarization	Single
System Noise Temperature	< 20 K

The complete RF system will be built in the cryostat, where the critical components, the Low Noise Amplifiers, will be cooled to 20 Kelvin and the beamforming components, phase- and amplitude control, for which cooling is not essential, will be cooled to 77 Kelvin. The array of Vivaldi elements will be placed inside the cryostat as well, which reduces potential dissipation losses in the antenna array and between the antenna array and the low noise amplifiers (and associated with these the noise temperature), however puts a constraint on the radome design: RF losses in the radome will directly impact the system noise temperature. The resulted beam synthesis of PHAROS, creating the optimal illumination of the reflector, will be fed into the existing telescope back ends. This is an important advantage of the applied *analogue* beamformer which makes a straightforward replacement of an existing antenna+LNA front end possible. PHAROS will be tested and operated at the 76m diameter Lovell telescope near Manchester.

4. APERTIF

APERTIF is an SKA Pathfinder that aims to equip the Westerbork Synthesis Radio Telescope (WSRT) with FPAs. APERTIF will operate from 850 to 1750 MHz and will use a full digital beam former. Recently, a demonstrator for APERTIF has been built. Its objective is to test and evaluate beam forming, calibration and imaging of focal-plane arrays. The demonstrator is integrated into one of the 25m Westerbork telescopes (Figure 3 left). A 112-element dual polarised Vivaldi array is mounted in the focal plane. Each element is attached to a Low Noise Amplifier. Receivers are connected to 60 elements, which are located in a shielded cabin next to the telescope. The individual channels have a receiver temperature of 85 K. The receivers sample at 80 MHz using 12 bit ADC's. The raw digital data is stored in RAM buffers with a total size of 60 GByte and further processed offline. This setup offers enormous flexibility since the weighting factors of the elements can be applied afterwards. This allows optimisation of the beam-former weights in software without re-measuring. This offers an excellent starting point for the planned beam-forming, calibration and imaging studies. Currently, the demonstrator operates as a stand-alone system. Interferometer measurements are planned later in the project.

5. Initial results

Figure 3 shows the first observations made with the APERTIF demonstrator. In the centre, a drift-scan through Virgo-A is shown. The red and the blue line show Virgo-A as detected by two of the elements of the focal-plane array. Because the two elements are offset from the telescope's optical axis, the peaks of the curves are offset as well. The black line shows the detection when the signal of the two elements is combined coherently. The combined response is stronger while it is also centered on the optical axis. On the right, a spectrum is shown of neutral hydrogen in our own Galaxy where the demonstrator detection is compared with the spectrum at the same location as observed in the Leiden - Dwingeloo survey. While these observations are in themselves not very special, they clearly demonstrate the use of focal-plane arrays on the real sky. Figure 4 shows measured beam patterns, each covering 3x3 degrees, of four antenna elements of the demonstrator. The two left most patterns are of the elements

that are just above and below the optical axis. The other two patterns are of elements that are more offset from the optical axis, resulting in a larger off-axis shift of the beam pattern. Note that these off-axis patterns are also more distorted. By combining the response of several elements, these distortions can be suppressed.

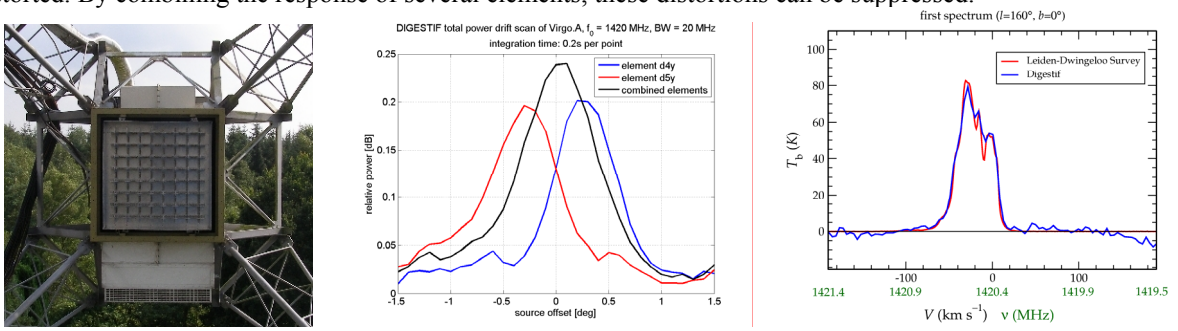

Figure 3. Photo of the mounted FPA in the WSRT (left), driftscan through Virgo A (centre) and measured Galactic neutral hydrogen spectrum (blue) compared with a catalog measurement (red) (right).

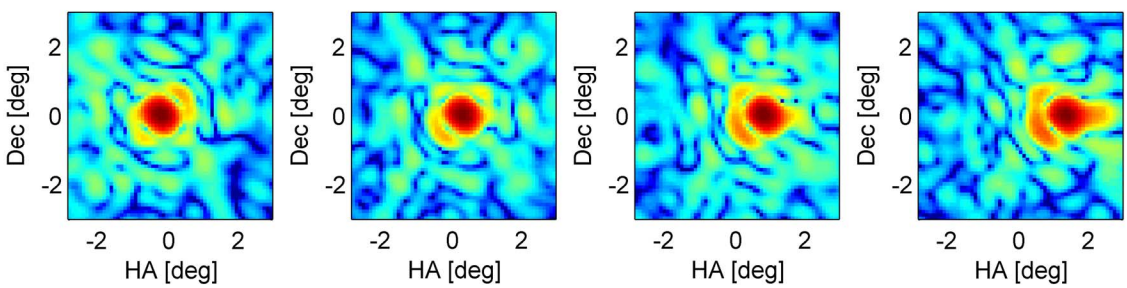

Figure 4. Measured beam patterns of four elements in a row.

6. Conclusion

Focal Plane Arrays have a high potential to increase the field of view of existing telescopes and are seriously considered for future systems like the SKA. It is concluded that, opposed to one-horn-per-beam systems where gain variations can be corrected relatively easy and only lead to second order effects, the beamshape of an FPA system depends on the relative gain variations of the receiving electronics. Hence an accurate calibration procedure is critical. It is also concluded that the LNA's for receiving array systems should be more robust against variations of the (active) source impedance. This might result in a better overall performance, at the cost of a slightly increased minimum noise figure.

7. Acknowledgments

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8. References

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