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Apertif: lessons learned operating a Phased Array Feed array.

E. Orrú(1), E. A. K. Adams(1), M. Bouwhuis(2), A. Coolen(1), H. Holties(1), J. van Leeuwen(1), V. A. Moss(3)(4), H. Mulder(1), M. Norden(1), L. C. Oostrum(1)(5), A. Schoenmakers(1), S. van der Tol(1), N. Veermas(1) and the Apertif Team.
(1) ASTRON, the Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD, Dwingeloo, The Netherlands
(2) NIKHEF, National Institute for Subatomic Physics, Amsterdam, The Netherlands
(3) ATNF, CSIRO Astronomy and Space Science, PO Box 76, Epping, New South Wales 1710, Australia
(4) Sydney Institute for Astronomy, School of Physics, University of Sydney, Sydney, New South Wales 2006, Australia.
(5) Anton Pannekoek Institute for Astronomy, University of Amsterdam, PO Box 94249, 1090 GE, Amsterdam, The Netherlands

Abstract

Apertif is the phased array feeds (PAFs) system operational on the Westerbork Synthesis Radio Telescope. This paper will cover various aspects of the system describing how the instrument is operated on a daily basis. Focus will be given to the use of new technology adopted for the hardware monitoring, automation of operational routines, calibration of the instrument and the results and lessons learned by operating it.

1 Introduction

The APERture Tile In Focus (Apertif) is the phased array feeds (PAFs) system installed on the focal plane of 12 of the 14 25-m dishes of the Westerbork Synthesis Radio Telescope (WSRT). The PAFs increase the field of view covering an area of 8 deg^2, with respect to 0.5deg^2 of the single feed "multi frequency front end" receiver (MFFE) earlier installed (and still available on 2 of the dishes). A single PAF consists of 121 electrically connected Vivaldi antennas with integrated LNAs (low noise amplifiers), 61 of which measure X polarised signal and 60 of them recording Y polarised emission. Apertif operates in the frequency range between 1130 and 1750 MHz. Up to 40 digital beams can be simultaneously formed with an instantaneous bandwidth of 300 MHz.
The instrument is operational since July 1st 2019, and together with the Australian SKA Pathfinder (ASKAP), Apertif is one of just two operational PAF interferometers in the world. The two instruments are complementary and together will survey the Northern and Southern hemispheres. This paper will describe challenges faced and lessons learned in one and a half years of operations.

2 Science with Apertif

A wide instantaneous bandwidth and a wide field of view make Apertif an excellent survey instrument. The Apertif system is used as a normal interferometer for imaging surveys and as tied-array for time-domain surveys. It can also be used with a single element receiver for pulsar-timing studies.
The imaging surveys will study HI out to a redshift of 0.256 and take radio continuum data in full polarization. There are two tiers: a shallow and medium-deep survey which will cover an area of 3500 deg^2 and 350^2, respectively, in the full survey plan [1, 2]. Resolving HI structures over a wide range of galaxies allows investigation of the connection between the gas and total mass distribution, including studying how these relations vary with different environmental conditions. The unique synergy between LOw Frequency ARray (LOFAR) and Apertif, given by a matched sensitivity and resolution of these two instruments, enables studies in the field of variable stars, nearby galaxies, AGN and clusters of galaxies.
A time-domain survey covering over 15,000 deg^2 allows the detection, follow-up, characterisation and arcsec-localisation of fast radio bursts (FRBs) over the Northern sky [3, 4, 5, 6]. Also pulsar studies and follow-up of gravitational waves are key topic for the Apertif time-domain science group.
Different levels of data products are archived in the Apertif Long Term Archive (ALTA)[1]. Survey data are made available to the scientific community via the ASTRON VO[2] interface.
The first release of data from the Apertif imaging surveys was done in November 2020, covering the first year of observations. The released data products include continuum multi-frequency synthesis (mfs) images, Stokes V mfs images, Stokes Q U cubes, and uncleaned line cubes, along with the primary beam images for each Apertif primary beam. The first release of time-domain data is also planned in the course of 2021.

[1] https://alta.astron.nl/
[2] https://vo.astron.nl/

3 Hardware

The hardware of Apertif consists of several sub-systems and can be divided into three main categories:

1. The WSRT dishes, including the receivers (PAFs) and the coaxial cables that transport the analog signal to a cabin.
2. The cabin, one for each telescope, is an air-conditioned Faraday cage where the analog signals from the phased array feeds are converted to baseband and digitised in the Analog Digital Unit (ADU). The digital beam former, consisting of 8 Uniboards (FPGA-based), calculates a weighted sum of the signals in order to form compound beams. The digitised data are transported from the telescopes to a central building over dedicated fiber connections.
3. In the central building, after being filtered into channels, the signals of all 40 compound beams are digitally correlated. The correlator consists of 16 Uniboards. Correlated and coherently added data are sent to the imaging and time-domain on-line clusters respectively.

3.1 Hardware monitoring

The hardware is monitored in real time using ARTAMIS (All-Round Telescope Array Monitoring Information System) which is based on Siemens' WinCC-OA SCADA platform.

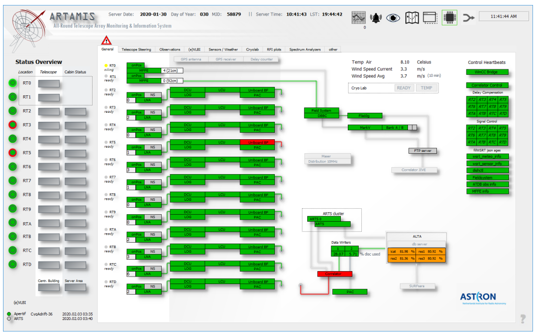

Figure 1. The main page of the ARTAMIS monitoring system.

Information is acquired mostly in two ways: through custom-build interfaces using the WinCC-OA C++-API, and through readily available SNMP-based input channels. The WSRT Operator is provided with an instantaneous view of the status of the whole system on a single screen (Fig. 1). With one single look at figure 1 from left to right it is possible to perceive the health of the dishes (RTs), the PAF elements (LNA), the cabin (ADU, DCU), beam-former (Uniboard BF), the correlator, the on-line systems (Data Writers and ARTS cluster), and the data archive (ALTA). On the top right corner the status of the controller services can be monitored. Distinct screens and tabs can be opened to display more detailed views about the systems described above. Since all database value changes are kept in the internal database of WinCC-OA, it provides out-of-the-box trend graphs for any selected data-point. This helps enormously with diagnosing root causes of issues, early and preventive warning systems, and understanding data quality issues reported by science users. Several flaws in the system have only been found thanks to the intuitive UI interface built for ARTAMIS.

3.2 Hardware maintenance

Since Apertif entered science operations, the maintenance performed in the Apertif system has been mainly corrective. The information identifying which part of the system required maintenance, was provided by alerts from the ARTAMIS monitoring system [7]. A few of the most common cases, summarised here, will be extensively described during the talk:

- Broken or malfunctioning components corresponding to single elements in a PAF signal chain.
- Broken or malfunctioning optical components responsible for the signal transport between the beam former and the correlator or between the correlator and the on-line clusters.
- Increases of cabin temperature due to malfunctioning of the air-conditioning system

In particular, concerning the monitoring of the elements in the PAF, the plan is to use the parameters accumulated so far, in order to perform predictive maintenance and prevent the malfunction of elements and offline time. Replacing individual PAF elements involves a significant effort and working at height. The replacement of malfunctioning elements (e.g. LNA elements or the coaxial cables) in the feed arrays is therefore postponed until the sensitivity of multiple beams is affected. Then a number of elements in the array are repaired at once.

4 Instrument calibration

A fundamental aspect of phase array feeds is their calibration. As described early in this paper, the beam former weights and sums the signal from each element in order to generate compound beams. Only a small set of elements contributes to the signal of one compound beam, and this is determined by the weights. Figure 2 shows the average amplitude of the beam weights for compound beam CBM3 of telescope RT5. Yellow blocks highlight the dominant elements which are highly weighted. The rest of the blocks are dark blue, corresponding to elements with low weights values. The broken element, which has zero weight, is shown as a red block. The goal of the calibration is to produce a smooth sensitivity over the field of view and to compensate

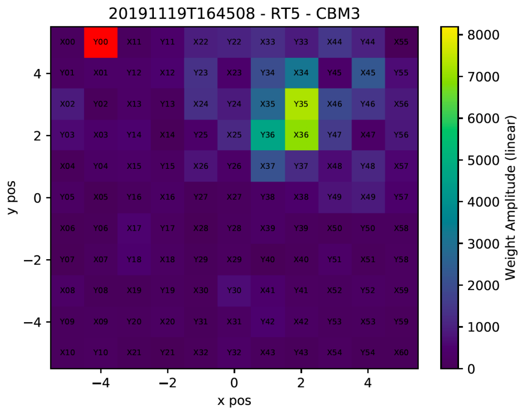

Figure 2. Beam weight average amplitude for telescope RT5 and compound beam CBM3. Yellow blocks are highly weighted elements, blue blocks correspond to elements with low weights values and the red block is a zero weighted element.

the electronic gain differences between various elements. The difference in the gains are introduced by degradation of the signal path or delays introduced when starting the FPGAs.

The instrumental calibration consists of measuring beam weights (BWs hereafter). These are used by the beam former to create compound beams. How are beam weights obtained? The cross correlation matrix of each PAF is calculated using the beam former as a correlator. Several methods of measuring BWs have been proposed [8]. One is having every element over the whole frequency range observe a celestial source (CasA). Another method, often referred to as on-line calibration, updates the electronic gains by using the difference between the measure obtained using a noise calibrator source positioned on the dish and a set of BWs obtained using a celestial source. Finally, they can be obtained directly using a noise calibrator source. Some of these methods are still under development and commissioning at the moment of writing. The method adopted by Apertif at the moment makes use of observations of CasA. The advantage of this method is that it provides a robust estimate of the BWs, though it is time consuming (about 4 hours) and depends on CasA visibility during that whole time. The measures using CasA are heavily affected by radio frequency interference (RFI). It is crucial for the accuracy of the calibration to retain the purity the astronomical signal. Excision of RFI is performed on the correlation matrix data, these are identified using the second Eigenvalue decomposition analysis. When the BWs are calculated these are uploaded into the system to enable the beam former to use them to form the compound beams. A diagnostic tool used for assessing the BW quality is shown in figure 3. In this plot, the sensitivity of the beam weight as a function of frequency (sub-band number) for compound beam 2, YY polarisation is plotted for all the telescopes. While the majority of the telescopes have a good well behaved sensitivity , one telescope, RTC, shows low sensitivity, this will be reflected on the data quality of that specific compound beam.

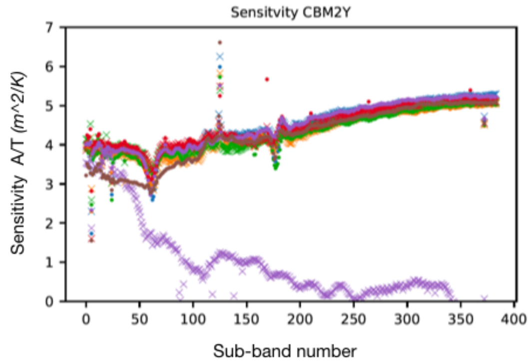

Figure 3. Beam weigh sensitivity plot as a function of sub-band number (frequency) for compound beam 2 YY polarisation.

Once the beam weights are uploaded, another aspect of the instrument calibration needs to be addressed: phase tuning. Phase tuning is the phase alignment of all telescopes. This is done to compensate phase delays between telescopes (or phased arrays) and enables the reconstruction to a plane weave front of the incoming signal. Tuning is performed by observing a strong unresolved calibrator source at the center of each beam. Doing this ensures maximum sensitivity when coherently adding the signals from each telescope as a tied array, which is used for high time resolution studies.

5 Operational procedures

The weight-bearing structure of the operational software is the Apertif Task Database (ATDB), which manages the full data-flow process, starting from the observation specification, up to the data ingest in the archive (ALTA). Factors contributing to the robustness and flexibility of ATDB are its simple 'micro services' architecture, its independence from other systems and its self-correcting capabilities. A distinguish feature of Apertif's operations is the employment of automation for the majority of the operational routines. Procedures were analysed during the commissioning phase and automatise according to the requirements of the operational model. Few of these automatic procedures are summarised here, more will be discussed during the talk:

- Unified machine-readable system specification parameters and semi-automated translation of schedule files to system schedule.
- Automated system setup.
- Semi-automated calibration processes.
- Automatic triggering of processing pipelines.

The steadiness of ATDB and a fair amount of automation enable Apertif's operations to run smoothly, limiting risks of human errors and any potential bottlenecks.

6 Lesson learned

In this section we will share the main lessons learned during the first one and a half years of APERTIF operations, more will be discussed during the talk. The most relevant can be conveyed in one single message: the health of the PAF's single elements and the beam weight calibration are the ultimate essence of PAF's arrays operations. If one element in the PAF is indeed broken or malfunctioning, the power of that element will typically be 20 dB lower than the power of the properly working elements. As a result, this element will be excluded in the calculations of the beam weights and it will be given a zero weight value. Therefore, for those compound beams for which the now zero weight element was supposed to be dominant (see figure 2), the trend of the beam weight values over frequency will differ from those with all working elements. This results in two main effects when compound beams are either correlated or summed-up.

In *interferometric* observations, the sensitivity over the field of view (primary beam) of the telescope with a broken element is different with respect to the rest of the telescopes. This leads to a loss of sensitivity and direction dependent errors (DDEs) in calibration and imaging, which are reflected as artefacts in the final images. While the loss of sensitivity can not be recovered, the DDEs can be easily treated in the data processing steps. One option is to exclude the telescope with the faulty element and proceed with standard calibration and imaging. Another option is to take into account for DDEs in the calibration and imaging steps. To assist the latter process, the APERTIF imaging team is collecting "drift scans" during the observing campaign, in order to model the primary beam of each compound beam such that these can be integrated in the imaging steps in the future [9, 10, 11].

In the case of *tied-array* observations, where the signal of all telescopes are coherently added together, the compound beam with different beam weight trend over frequency will be summed with those which present a nominal trend. This will result in a loss of sensitivity for that tied-array beam. Unfortunately there is no way to recover from this, the only option is to go back in the chain of maintenance of the PAFs elements and beam weight measurement. This is done when the reached threshold of sensitivity is critical for achieving science quality data.

Another critical factor to take into account in order to preserve the system's stability is the temperature and air-flow inside the cabins that contain the hardware (e.g. ADU units and beamformer Uniboards). We noticed indeed that when the temperature inside the cabin reaches 40 degrees, the stability of the delay synchronisation between the beamformer Uniboards of some telescopes and the correlator Uniboards gets lost. Because of this a full reset of the system is needed; consisting of the power-off of the FPGAs and the full PAF re-calibration, resulting in the loss of observing time. Another temperature related effect results in the loss of the phase coherence, this is due to the increase of the residual delays of individual telescopes up to nonphysical values (hundred nano-seconds). Also in this case a full reset of the system and a reset of the delays are needed in order to bring the telescope back to an operational state. The cause of these abrupt temperature variations have been nailed down to malfunctioning in the cabin air-conditioning system or due to the wrong orientation of the flaps that direct the air-conditioning airflow.

7 Conclusions

Operating PAF arrays means managing complex systems. APERTIF is a cutting edge in the technology adopted for signal processing, system monitoring, data acquisition, processing and archiving of the data. It is innovative in the application of new algorithms for the instrument calibration and data processing. All the above makes APERTIF a *new telescope on the frontier*.

8 Acknowledgements

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