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Real-time searches for fast transients with Apertif and LOFAR

Yogesh Maan*(1) and Joeri van Leeuwen(1)(2)
(1) ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA Dwingeloo, The Netherlands
(2) Astronomical Institute "Anton Pannekoek", University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands

Abstract

With the installation of a new phased array system called Apertif, the instantaneous field of view of the Westerbork Synthesis Radio Telescope (WSRT) has increased to 8.7 deg^2. This system has turned the WSRT in to an highly effective telescope to conduct Fast Radio Burst (FRB) and pulsar surveys. To exploit this advantage, an advanced and real-time backend, called the Apertif Radio Transient System (ARTS), is being developed and commissioned at the WSRT. In addition to the real-time detection of FRBs, ARTS will localize the events to about 1/2600 of the field of view — essential information for identifying the nature of FRBs. ARTS will also trigger real-time follow up with LOFAR of newly detected FRBs, to achieve localization at arcsecond precision. We review the upcoming time-domain surveys with Apertif, and present the current status of the ongoing commissioning of the time domain capabilities of Apertif.

1 Introduction

The majority of searches for pulsars and fast transients have been conducted using single dish radio telescopes. Despite providing a poor handle on sky position of detected objects, single dish surveys have been largely successful due to their capability of searching a large sky volume for a given sensitivity and observing time. Pulsars generally emit persistently, and are further localized in post-discovery follow-up. However, Fast Radio Bursts (FRBs) — bright pulses of a few millisecond duration — are generally one-off events. Only one FRB is known to repeat out of the 18 published discoveries to date [1, 2]. While it is nearly certain that FRBs are generated at cosmological distances [see, e.g. 3], any further clue about their progenitors is awaited even after 10 years of the first FRB discovery [4]. Probing the progenitors and physical processes giving rise to such one-off events needs their immediate follow-up at other parts of the spectrum, which in turn demands well-constrained positions. A survey that can couple discovery with immediate tight constraints on the sky position is also extremely useful for certain classes of pulsars, e.g., rotating radio transients (RRAT) and intermittent pulsars. The upcoming pulsar and transient survey with the Westerbork Synthesis Radio Telescope (WSRT) will combine the advantages of a single dish and an interferometer: a large field-of-view (FoV) as well as ability to tightly localize the source. In the following sections, we describe the unique features of the survey and the instrumental developments that are in progress to realize these features.

2 Exploring pulsars and FRBs with Apertif

A recently installed phased array system, the APERture Tile In Focus, or Apertif [5], facilitates 37 beams on the sky for 12 of the WSRT dishes, and therefore increases the instantaneous FoV by nearly 37 times (see panel (a) in Figure 1) to about 8.7 deg^2. Apertif also doubles the operating bandwidth to 300 MHz, placed anywhere between $1100-1750$ MHz. Such a large FoV and bandwidth, and the accumulated collecting area of several 25 m diameter dishes of the WSRT present an ideal combination for surveying the transient radio sky. To exploit this combination, a new, advanced, real-time backend, called the Apertif Radio Transient System (ARTS) is being developed and commissioned at the WSRT. Within each of the 37 beams (hereonwards compound beams or CB), ARTS will make several coherent or tied-array beams (TABs; also see Section 2.2) to retain the full sensitivity of the collecting area of 12 WSRT dishes. ARTS further comprises of 40 computing nodes, each one consisting of dual 8-core CPUs with 128 GB memory, 10 GE cards, $2-6$ GPUs providing a minimum performance of 15 Tflops/s and 30 TB of disk for $8-12$ hr data caching. Different nodes will process data from all the TABs within individual CBs and search for FRBs and radio pulsars in *real-time*. These technical advances enable a number of science cases, including a pulsar and FRB survey called ALERT, The Apertif LOFAR Exploration of the Radio Transient Sky [`www.alert.eu`; 6].

ALERT primarily consists of 4 science cases. In the most compute intensive science case, about 1-year of the WSRT time will be dedicated to survey the whole northern sky with declination$\geq 0°$. FRBs will be detected in *real-time* and high time-resolution data for each detection will be saved for detailed offline studies. The detections will also trigger a *real-time follow-up* of the bursts at much lower frequencies using LOFAR, and quasi-real time follow-up at other energy bands (e.g., X-rays, gamma-rays, etc.). In this dedicated survey, periodicity search will be conducted us-

Table 1. Comparison of ALERT's parameters with CHIME and Parkes surveys

	Field of View (sq. deg.)	Localization precision	S_{min} (mJy)	FRB Detection Rate ($week^{-1}$)
ALERT	8.7	$\sim$arcsec (ARTS: $25'' \times 15'$) ($ARTS_{repeat}$: $25'' \times 25''$)	460	$\sim$1
Parkes	0.56	$\sim 14.1'$	180–250	$0.05 - 0.5$
CHIME	134	$\sim 15' - 30'$	160–270	$20 - 380$

See Section 2.1 for details on the conservative approach taken to estimate ALERT's sensitivity and detection-rate, and Section 2.2 for those on stand-alone localization by ARTS. S_{min} is computed for 10σ detection of a 5 ms burst. ALERT and Parkes surveys operate at L-band with similar bandwidths, while CHIME will survey the sky between 400 and 800 MHz. CHIME and Parkes survey parameters are either directly noted or deduced from the information in: [7], [8], [9], [10], [11].

ing data cached in a 12-hr ring buffer. All the time-domain survey data downsampled to 1 ms, 1 MHz and 1-bit will be archived. ARTS will also conduct FRB and pulsar searches *commensal* with the Apertif imaging surveys [12]. In these commensal searches, a newly developed beam-former operating in parallel to the correlator will form coherent TABs. As in the dedicated search, potential FRB detections will trigger follow-up at other frequencies and energy bands, and periodicity searches will be conducted using the data from the ring buffer.

The pulsar timing science case utilizes a single TAB in the central CB for timing studies, and ARTS will facilitate a timing precision with systematic instrumental errors less than 20 ns. The pulsar data from the single TAB are coherently dedispersed and folded in *real-time*. In the fourth science case, ARTS shall contribute to standard VLBI imaging, with a FoV of 0.000015 deg^2 initially, based in a central TAB, and 0.25 deg^2 eventually, when individual dishes are streamed for VLBI. The following subsections provide a few salient features of ALERT, primarily focusing on the dedicated search science case.

2.1 Survey speed, sensitivity and FRB detection rate

ARTS potentially facilitates full sensitivity of WSRT within Apertif's large FoV. Assuming a 75% aperture efficiency of 10 WSRT dishes, ARTS will detect a 5 ms wide 320 mJy burst at a 10σ level. If we also assume a *TAB-forming efficiency*[1] of 0.7, a 460 mJy burst will be detected at 10σ significance. Even with our conservative estimate of the sensitivity, more than 80% of the FRBs discovered so far[2] would be detectable, and most with high signal-to-noise ratio (S/N). So far, majority of the FRBs have been discovered by Parkes telescope. With nearly 16 times larger FoV, competing sensitivity and similar operating frequency, ALERT will survey the sky an order of magnitude faster than Parkes (see Table 1).

[1] This efficiency factor also includes contribution from losses while forming various combinations of TABs (see Section 2.2). However, we expect it to be better than the value assumed here.

[2] See FRB Catalogue at `http://www.astronomy.swin.edu.au/pulsar/frbcat/`

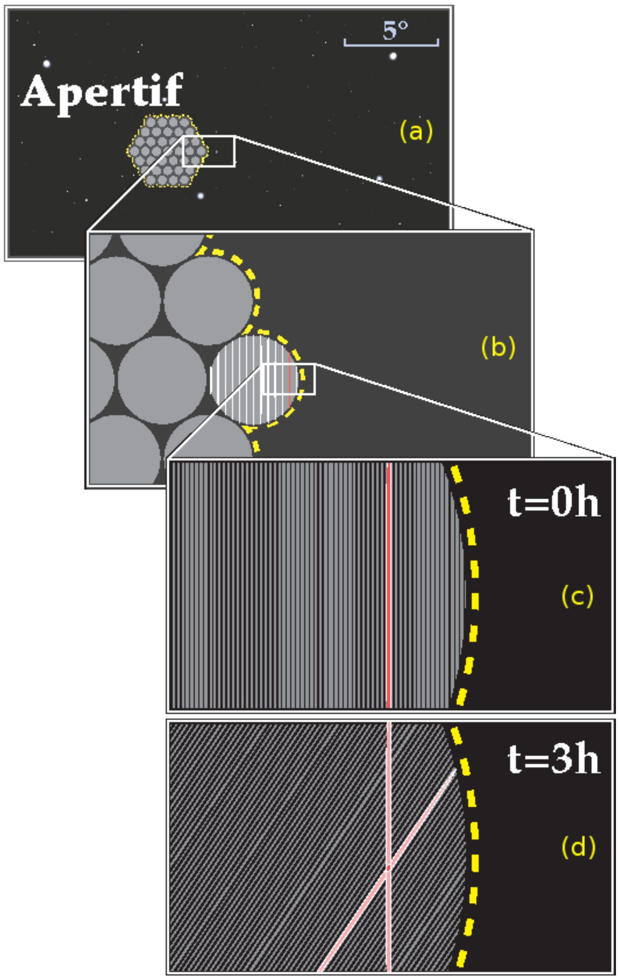

Figure 1. Panel (a) shows the 37 on-sky compound beams that Apertif facilitates for each of the WSRT dishes. One of the tied-array beams and its grating lobes are shown as vertical white lines within one compound beam in panel (b). Synthesized beams — position dependent combinations of various tied-array beams — are shown in panel (c). The red colored beam in this panel demonstrates constraints on the position of an event detected in this beam. Panel (d) shows the drastic improvement in localization from the second detection of a repeating event. The position is constrained within the small, red circle at the intersection of the two pink colored beams in this panel.

Constraints on the all-sky FRB rate are improving as the combined on-sky time from various surveys increases. The recent all-sky rate of FRBs is estimated to be $3.3^{+3.7}_{-2.2} \times 10^3$/day above a fluence level of 3.8 Jy ms at 1.4 GHz [13]. With this rate and Apertif's large FoV, ALERT will detect $0.2-1.5$ FRBs for every 24 hrs of observing time. This estimate is consistent with that predicted using Monte Carlo simulations in [11]; see their Figure 10. However, the effects of TAB-forming efficiency parameter may not have been considered there. Furthermore, the true underlying fluence and width distributions of FRBs are still unknown and an excess of fainter, narrower FRBs can skew the detection rate estimates. So, with a conservative approach, we expect the detection rate to be at the lower end of the above estimated range, i.e., about 1 burst/week.

Intermittent pulsars, RRATs, radio-transient magnetars and extremely nulling pulsars are active only very sporadically — some are on for less than 1 s per day! Most of such objects are prone to be missed in typical short duration pulsar surveys. The long integration times in ALERT (typically $3-6$ hrs per pointing) will be particularly sensitive to such neutron star types. This survey will potentially double the number of currently known intermittent pulsars.

2.2 Event localization by ARTS

Given the uniform spacing of the WSRT dishes, the TABs within individual CBs have equally sensitive grating lobes. Hence each $\sim 30'$ CB can be covered by only about 12 TABs and their grating lobes (see panel (b) in Figure 1). However, the grating lobe separations are frequency dependent, and the difference in these separations for beams at the twos edges of ALERT's large fractional bandwidth is quite significant. FRBs are broadband events, and to integrate any weak signals over the entire band, ARTS combines various TABs such that the complete telescope response for a certain location on the sky is recovered. This results in *synthesized beams (SB)*, and by positioning these SBs at the locations of the highest-frequency TABs, each compound beam is covered by 71 SBs (see panel (c) in Figure 1). Hence, Apertif's full FoV is covered by over 2600 (71×37) coherent SBs, and data from each of the SBs will be searched for transients in real-time.

The TABs also posed a degeneracy in the sky position of an event to any of their grating lobes. The synthesized beams break this degeneracy, and the sky position of a single event could be constrained to one SB, i.e., within $25'' \times 15'$. As the earth rotates, the position of the SBs will change with time. This aspect implies that the sky position of an event could be constrained to $25'' \times 25''$, even with just one repeat detection of the same event (see panel (d) in Figure 1). Hence, ARTS will provide discovery positions of *repeating* FRBs, RRATS, and all the new pulsars constrained within $25'' \times 25''$.

2.3 ALERT triggers: Immediate follow-ups and *arcsecond* localization

The frequency-dependent propagation delays and the cosmological origins of FRBs imply their arrival at low frequencies (e.g. LOFAR's 150 MHz) would be delayed by several minutes compared to that at 1.4 GHz. ARTS will exploit this aspect to trigger immediate LOFAR follow-ups of each of the FRBs that it will detect in real-time. A detection in one of the LOFAR TABs will provide (1) an unprecedented FRB detection at such low frequencies, (2) crucial information about the spectral behavior and hence the underlying emission mechanism, and (3) constraints on the sky position to arcsecond precision. The accurate positions thus obtained will be used to trigger optical and high energy follow-ups, to locate faint host galaxies and detect possible afterglows, among other probes.

With these unique features, ALERT will facilitate FRB population studies by detecting several tens to hundreds of new bursts, studying their radio spectra, and enabling a detections at optical and high energy bands by localizing with arcsecond precision.

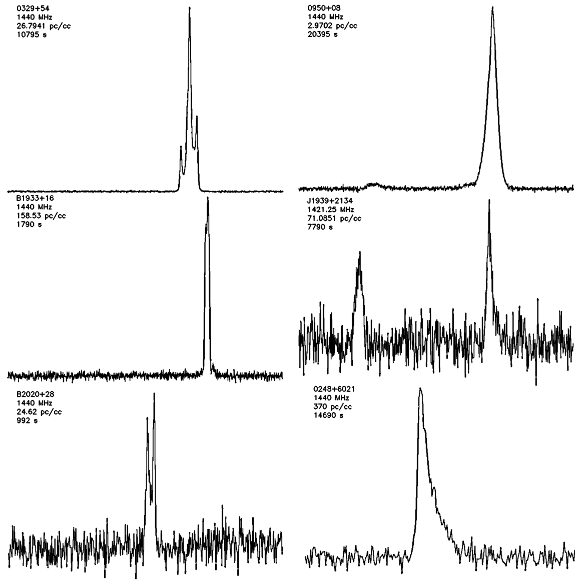

Figure 2. Average profiles of several pulsars detected in commissioning observations.

3 ARTS development and commissioning: Current status

The first hardware component of ARTS enables the pulsar timing science case, and is currently (Feb. 2017) being commissioned. The high precision pulsar timing pipeline is implemented on a powerful machine consisting of two CPUs with 12 cores each, 128 GB of memory, with a dual Titan-X (Maxwell) GPU, and more than 30 TB of disk space to store the pulsar timing observations. Data from a single TAB are coherently dedispersed and folded over the pulsar period in *real-time*. Folded profiles with 384 channels across 300 MHz bandwidth are written out every 10 s for offline processing and timing studies. The instrument saw the first light from the bright pulsar B0329+54 in August 2016 using only 1 polarization and a small bandwidth of 18.75 MHz. Since then, extensive commission has been underway testing and ironing out wrinkles at various processing steps and making steady progress. We have now progressed to the timing pipeline operating flawlessly on the dual-polarization, full bandwidth (300 MHz) data streams.

Using a single element of the phased-array feed and only one WSRT dish, we have successfully detected several pulsars during commissioning. These detections sample a variety of pulsar parameters, viz. faint to strong (5−200 mJy), fast to slow (1.5−720 ms), and low to high dispersion measure (3−370 pc cm^{-3}). Average profiles obtained during commissioning observations of some of these pulsars are shown in Figure 2.

The software pipeline to be used in dedicated as well as commensal FRB searches has been completed and successfully tested on archive data of a burst discovered by the Parkes telescope. The computing performance of the pipeline to carry out real-time searches on more than 2600 SBs has been achieved, and was benchmarked for various GPUs. The complete GPU back-end cluster arrives in 2017Q3. We expect to complete the commissioning, and start the dedicated observations and detecting FRBs towards the end of 2017.

4 Summary

The ALERT real-time searches through over 2600 full-sensitivity synthesized beams within Apertif's large FoV will potentially discover several 10s to 100s of new FRBs. The arcsecond precision localization of the bursts by ARTS-triggered LOFAR follow up is a unique feature of ALERT, and such a precision seems to remain unsurpassed by any of the current or upcoming surveys in next few years. This much needed localization will enable the follow-ups in optical, X-ray and gamma-ray wavelengths as well as in other radio frequency bands to identify the host galaxies, detect any possible afterglows in high energy bands and understand the progenitors of these mysterious bursts.

5 Acknowledgements

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