Astronomy & Astrophysics manuscript no. aartfaac_sys_design
January 12, 2016

Design and Commissioning of the AARTFAAC all-sky monitor

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Received <date> / Accepted <date>

ABSTRACT

The Amsterdam-ASTRON Radio Transients Facility And Analysis Center (AARTFAAC) array is a sensitive, all-sky radio imager based on the Low Frequency Array (LOFAR). It generates images of the low frequency radio sky in near real-time with spatial resolution of 10s of arcmin, MHz bandwidths and a time cadence of a few seconds. The image timeseries are then monitored for short and bright radio transients. On detection of a transient, low latency triggers will be generated for LOFAR, which can carry out follow-up observations. In this paper, we describe the implementation of the instrumentation, and its capabilities.

Key words. Radio Interferometry - Imaging - Radio Transients - Correlators

1. Introduction

<TODO: Paragraph about transient sources, some stuff about spectral indices of coherent emission and expected class of sources, at what brightness levels can we expect to see things (take from Lazio LWA paper).>

<TODO: Paragraph summarizing the current state of knowledge of low frequency transients: Stewart NCP transient, other searches at low freq. Conclusion: Need for more monitoring.>

The AARTFAAC radio transient monitor is a leading effort among a group of new radio telescopes aiming for detection of bursts of radio emission by continuous monitoring of the low radio frequency sky. Such telescopes are characterized by having moderate resolution and sensitivity as compared to contemporary telescopes, but with extremely wide fields of view (typically all sky), high availabilities and autonomous calibration and imaging. The latter requirements make their implementations challenging. The antenna elements used to achieve the wide fields of view are typically dipoles, however, their low individual sensitivities requires an order of magnitude larger number of elements in the array. Bringing the resulting large number of data streams to a central location, as well as their correlation fora carrying out aperture synthesis imaging thus poses a significant I/O and compute challenge. Further, the wide fields of view at the sensitivities of operation also result in direction dependent effects on the incoming signals, mostly due to the ionosphere. These pose a challenge to calibration, especially when carried out in an autonomous manner.

In this paper, we describe the implementation of the instrumentation for the AARTFAAC array, and the commissioning of its various subsystems. Section 2 describes the array and the receiving antenna elements, its relationship with LOFAR, and introduces the full architecture of the instrument. Section 3 describes the hardware implementation in the field which allows creating a data path in parallel to LOFAR. This makes AARTFAAC processing independent of LOFAR to a large extent. In Section 4, we describe the implementation of a real-time, GPU based correlator for AARTFAAC, while Section 5 details the real-time, autonomous calibration and imaging implementation. Section 6 describes our control system for the full instrument, which also interfaces with LOFAR. In Section 7 we present performance metrics of the instrument as a whole.

2. The AARTFAAC array

We begin by summarizing the subsystems of the LOFAR telescope relevant for AARTFAAC processing in Section 2.1, and then elaborating on the scheme for creating a coupled data path for independent processing by AARTFAAC.

2.1. LOFAR telescope architecture

The LOFAR telescope **??** is a new generation radio interferometer covering the frequency range from 10-90 MHz using inverted V-dipoles known as Low Band Antenna (LBA), and from 110-240 MHz using Bowtie dipoles, also known as High Band Antenna (HBA). The antenna are linearly polarized, being made up of orthogonally placed dipoles in the E and H plane. The LBA dipole has a sensitivity pattern with a 6dB field of view of about 120^o, while the HBA dipoles first undergo an analog phasing within a 4x4 tile, which results in a field of view of about TODO. Due to this restriction, the AARTFAAC array utilizes only the LBA part of the telescope.

The telescope itself consists of a large collection of antennas, spatially organized into several 'stations', each spread over 60. The stations are laid out in a dense core: 24 (TODO: Check) stations within a 2km radius, while the long baselines of stations of upto a 1000km are also present. At the station level, the received and conditioned analog signals from a dipole are baseband sampled with a 200MHz clock and 10-bit quantized.(TODO: Check). The signal from each polarization is then split into spectral subbands of 200kHz via a polyphase filterbank implementation. In the regular LOFAR station level processing, the dipoles are then digitally phased in hardware towards the direction of an astronomical source to form a station beam, which is then transmitted over optical fiber for further processing.

A schematic representation of the LOFAR level processing is shown in Figure. TODO

2.2. The AARTFAAC system

The AARTFAAC array consists of 12-stations from within the core of the LOFAR telescope, with interdipole distances ranging from (TODO) within a station, and a maximum of TODO across stations. Due to the requirement of dipole level data in order to achieve all-sky imaging, the AARTFAAC creates a coupled data path to an independent processing architecture, prior to the phasing up of the dipoles.

Figure 2 shows the LOFAR stations that are part of the AARTFAAC system.

The overall architecture of the radio sky monitor is shown schematically in Figure 3, and illustrates the main processing subblocks of the instrument. A user selectable subset of subbands from every dipole is transferred as UDP packets over a dedicated 10Gbit fiber connection to the central processing systems. These are received by a streaming software correlator implementation which aligns the data and estimates the spatial covariance matrix between every pair of dipoles. The generated visibilities are streamed over TCP/IP to a calibration and imaging pipeline component which carries out autonomous imaging. The images are then analyzed by a software tool (The Transients Pipeline, TraP), which extracts the light curves of sources within the image, and analyses them for variability using a number of parameters. The TraP is described in more detail in **??**.

The specifications of the AARTFAAC monitor are listed in Table TODO.

TODO: For Eric. **Remote Station Processing:** The above processing is carried out in the Remote Station Processor (RSP), an FPGA board which can handle the beamforming of TODO: X subbands for 4 dipoles. The further stages of beamforming are carried out by distributing the 4-dipole beamformed data over a station level ring network.

Available bit modes:

Ring network sharing for dipole level data products:

Figure 5 depicts the station level ring network, whose bandwidth is shared between the beamformed subbands as well as the dipole level subbands. The ring network bandwidth constrains the processed AARTFAAC bandwidth to a fundamental maximum of 64 4-bit subbands, or about 12MHz. The URI boards in combination with the uniboards carry out a first level of the incoming data transposition.

2.3. Impact of sharing dipoles with LOFAR on AARTFAAC

LOFAR operates using either the LBA or the HBA antenna at a time. Further, due to limited station level electronics for stations within the core, only a subset of the available station dipoles can be utilized. This implies that the AARTFAAC telescope is dependent on LOFAR for the choice of antenna and station configuration, reducing the availability for all-sky monitoring. Within the station, only the LBA_OUTER station configuration is currently deemded suitable for real-time imaging. This mode of LOFAR operation favorable to AARTFAAC depends on the observing schedule and the proposed observations. Table TODO shows some statistics from previous cycles on the fraction of observing modes favorable to AARTFAAC. Based on this, it may be resonable to expect AARTFAAC to operate TODO fraction of time, typically.

3. Station level hardware for piggy-back operation

- URI board description, data coupling scheme, constraints on achievable bandwidth
- The uniboard data reformatting (transpose), uniboard data transfer, output data format
- Available diagnostics, performance, commissioning tests

4. The AARTFAAC real-time correlator

- Correlation for transit mode observations: logical blocks.
- Description of processing flow.
- Motivation of chosen architecture for implementation.
- Supported time and frequency binning, motivation of choice.
- Required compute and memory bandwidth.
- Synchronization of incoming data (input buffer), output data format.
- Commissioning tests, performance.

5. Real-time calibration and imaging

- Architecture, implementation choices, performance
- Unit test architecture
- Interface to TraP

6. The AARTFAAC control interface

Figure 6 shows the functional blocks of the AARTFAAC control system, and their interface to the LOFAR scheduling system.

- Control system description
- Interface with LOFAR
- Monitoring interface: AARTFAAC webpage

7. Commissioning results

- Long term performance of the entire system based on logs.
- Performance in various bit-modes, with different number of subbands, expected sensitivity.

8. Discussion

9. Conclusions

Acknowledgements. This work was funded by the ERC grant <num> awarded to Prof. Ralph Wijers, Universitiet Van Amsterdam. We thank The Netherlands Foundation for Radio Astronomy (ASTRON) for support provided in carrying out the commissioning observations.

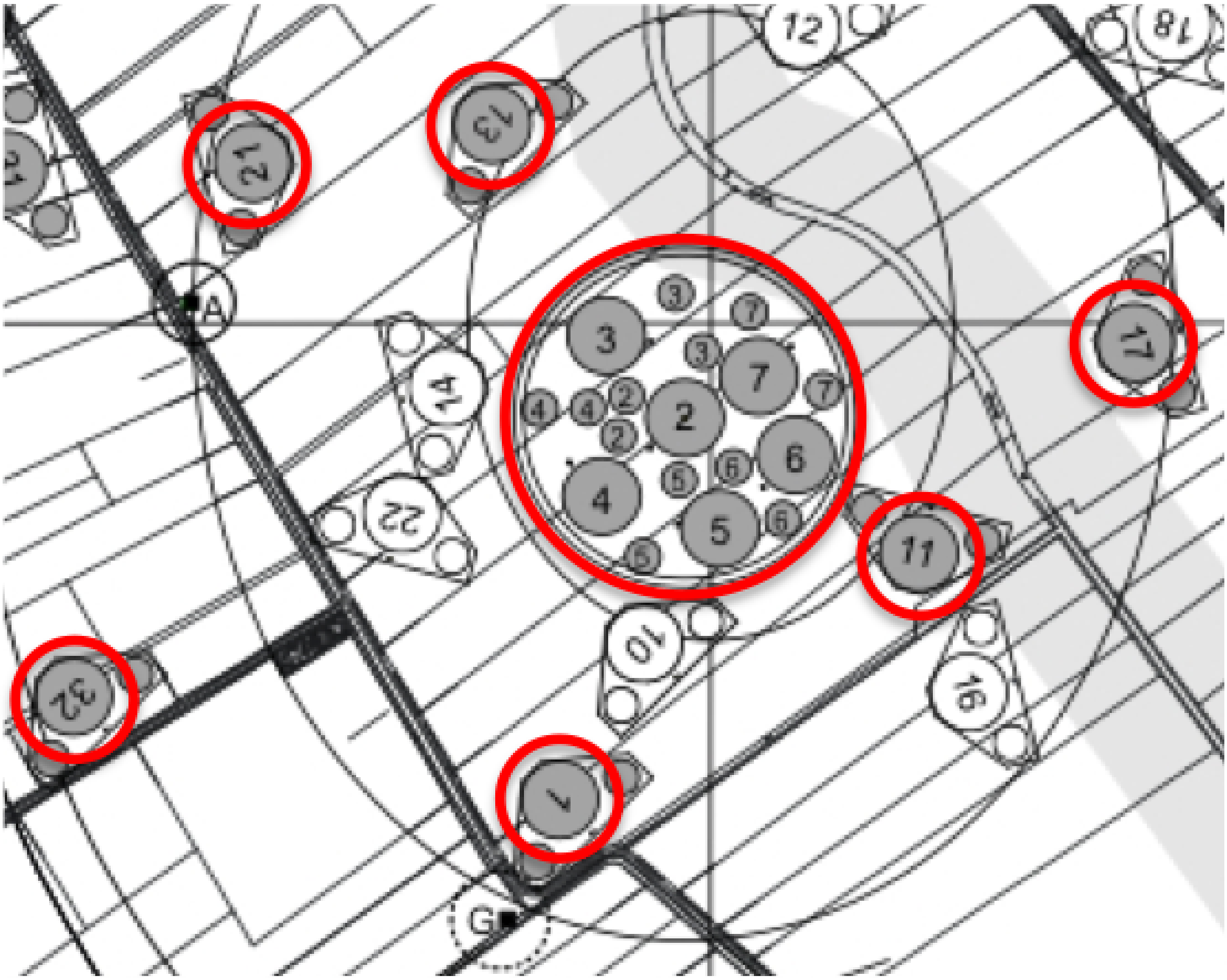


Fig. 1: The spatial distribution of AARTFAAC-12 stations within the core of LOFAR stations.

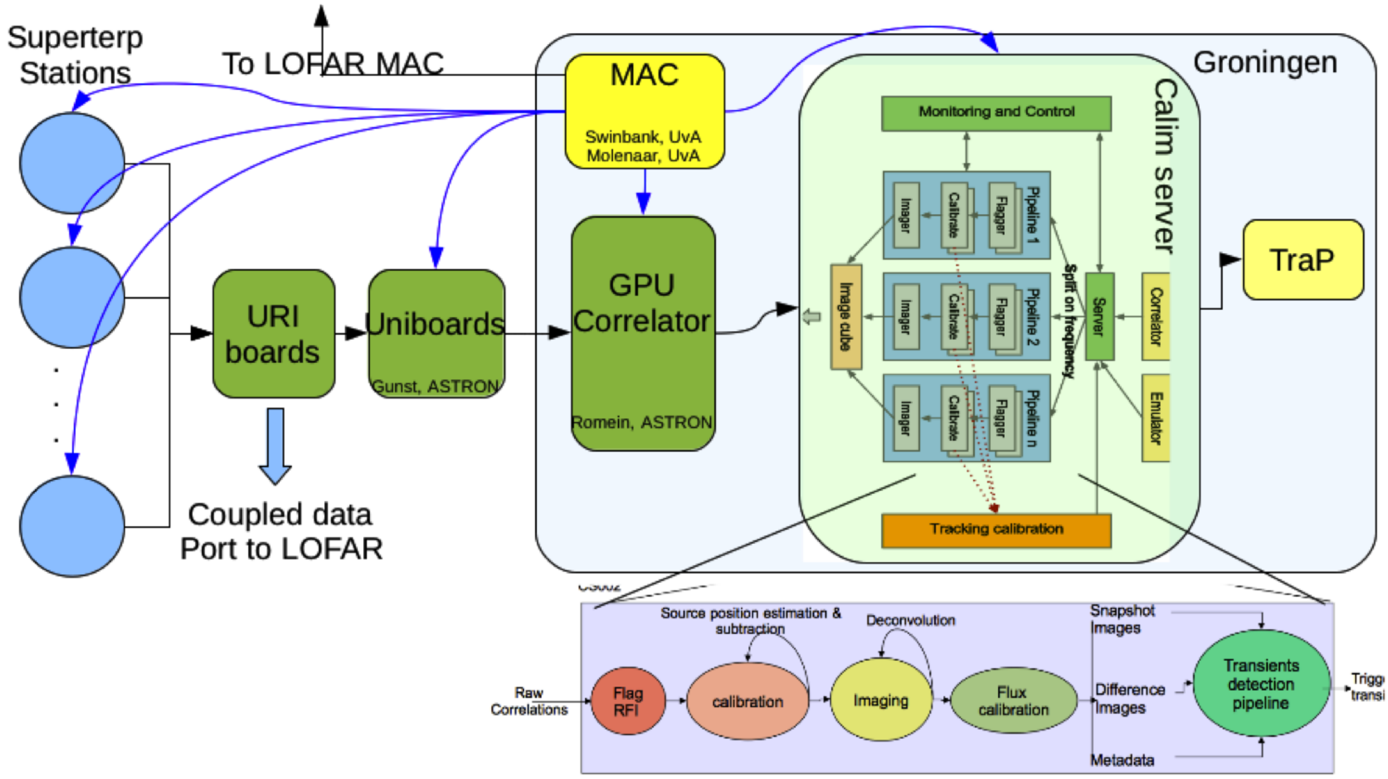
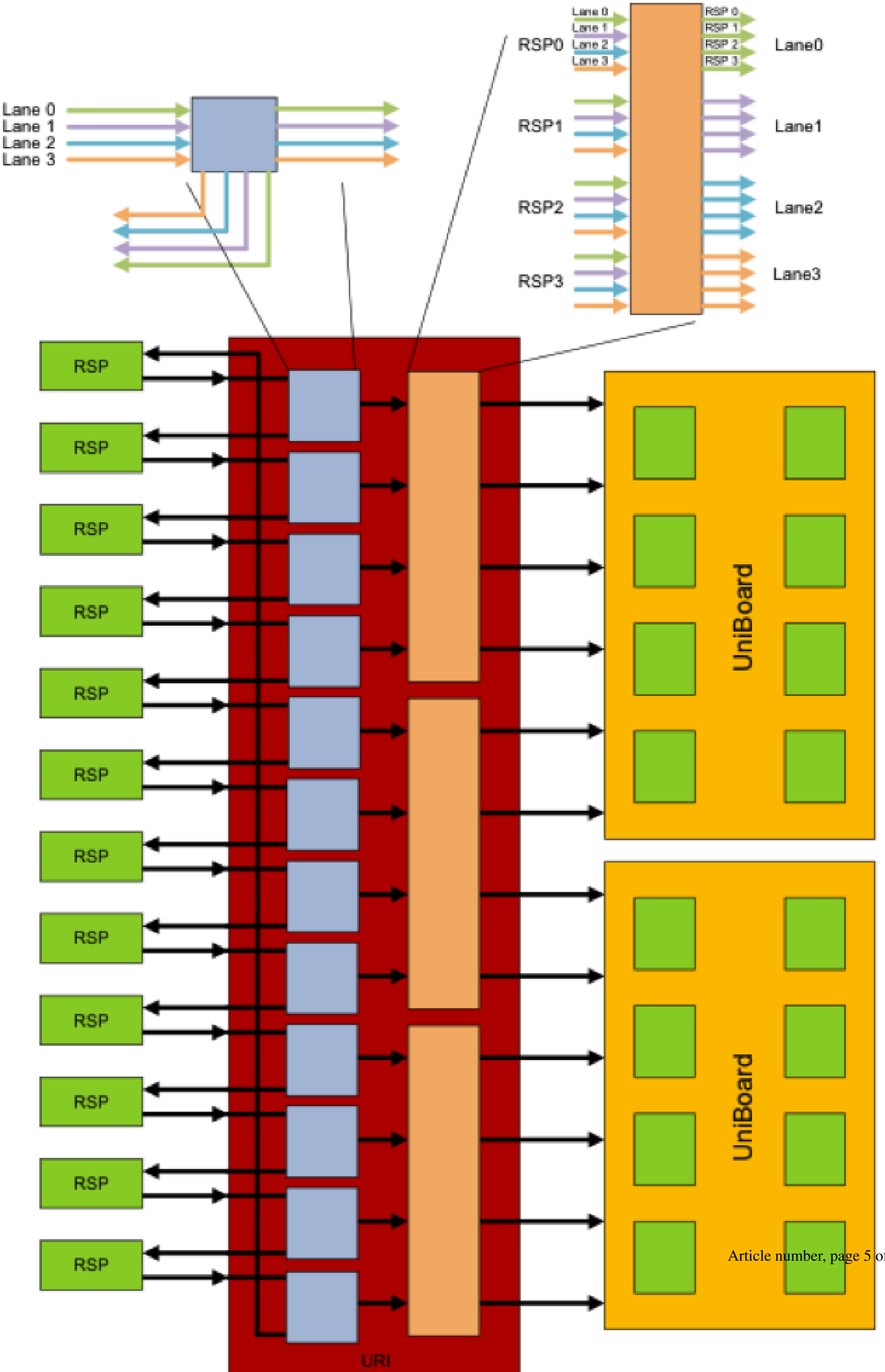


Fig. 2: Overall architecture of the AARTFAAC all-sky monitor depicting each processing subblock.


Lane 0
Lane 1
Lane 2
Lane 3
RSP0
RSP1
RSP2
RSP3
Lane0
Lane1
Lane2
Lane3
RSP
UniBoard
UniBoard
URI

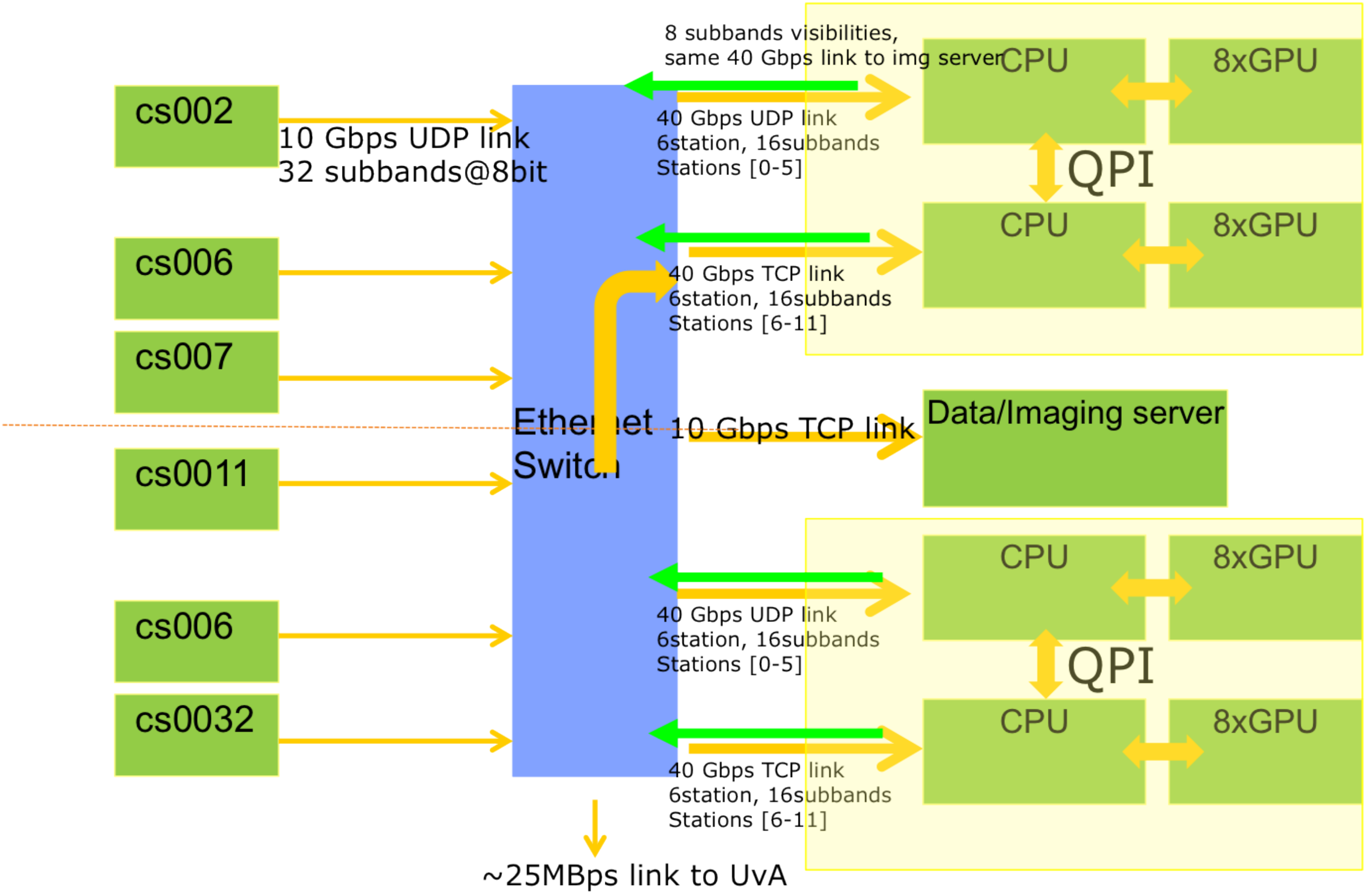


Fig. 4: The GPU correlator implementation using a pair of AMD(?) CPUs hosting AMD GPUs

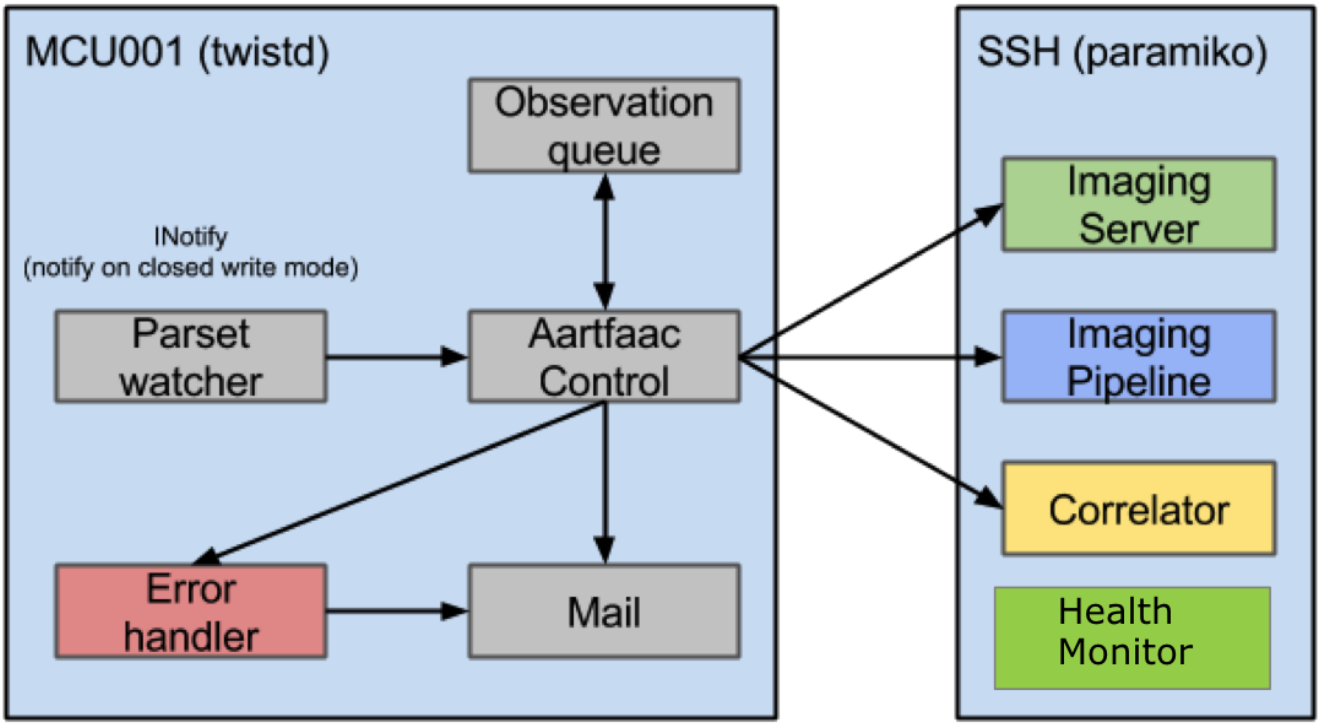


Fig. 5: The control system architecture which interfaces with the LOFAR observation scheduling system and triggers AARTFAAC observations.