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Realtime processing of LOFAR data for the detection of nano-second pulses from the Moon

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Abstract. The low flux of the ultra-high energy cosmic rays (UHECR) at the highest energies provides a challenge to answer the long standing question about their origin and nature. Even lower fluxes of neutrinos with energies above 10^{22} eV are predicted in certain Grand-Unifying-Theories (GUTs) and e.g. models for super-heavy dark matter (SHDM). The significant increase in detector volume required to detect these particles can be achieved by searching for the nano-second radio pulses that are emitted when a particle interacts in Earth's moon with current and future radio telescopes.

In this contribution we present the design of an online analysis and trigger pipeline for the detection of nano-second pulses with the LOFAR radio telescope. The most important steps of the processing pipeline are digital focusing of the antennas towards the Moon, correction of the signal for ionospheric dispersion, and synthesis of the time-domain signal from the polyphased-filtered signal in frequency domain. The implementation of the pipeline on a GPU/CPU cluster will be discussed together with the computing performance of the prototype.

1. Introduction

The intensity of the flux of cosmic-rays at the highest energies (UHECR) is below one particle per square kilometer and century. This makes answering the open questions about their origin, acceleration, and composition a challenging task, that in particular requires huge detector volumes (e.g. [1]). The same challenge arises in testing specific theories on super heavy dark



matter [2, 3] and grand-unification [4] that predict an even lower flux of neutrinos with energies beyond the Zetta-eV scale.

This challenge can be addressed by using Earth's moon as sensitive volume, and detect the particle interactions via the radio signal emitted by the Askaryan effect [5]. These radio signals can possibly be recorded by radio-observatories on Earth. However, previous searches have established only upper limits on the ZeV-scale neutrino flux, and have not been sensitive enough to constrain underlying production models or to observe UHECR [6, 7, 8, 9, 10], in particular because they used telescopes operate outside the optimal frequency range for lunar observations just above approximately 100 MHz [11].

2. Data processing with the Low Frequency Array

Currently the largest telescope covering the optimal frequency range for lunar detection of cosmic particles is the LOw Frequency ARray (LOFAR) [12], the first fully digital radio telescope. The antennas of LOFAR are grouped into more than 47 stations distributed throughout the Netherlands and with additional stations in France, Germany, Poland, the United Kingdom, and Sweden. Twenty-four of the stations are located in a dense core with approximately 2 km diameter in the Netherlands. The additional stations are distributed with increasing distances to this core yielding a maximum baseline of 1292 km. However, due to technical requirements discussed below, only the core stations can be used for lunar particle detection.

Each core station is equipped with fields of 96 low-band antennas (LBAs) with a frequency range from 10-90 MHz and fields of 192 high-band antennas (HBAs) with a frequency range from 110-240 MHz. The signal received by the antennas is sampled in intervals of 5 ns and copied to a ring buffer of 5 s length at antenna level before being processed further. The signals of the individual omni-directional antennas are then filtered into sub-bands by a polyphase filter (PPF) and combined into a single beam of approximately 5° width at 120 MHz per station pointing towards a user-defined direction in the sky. A selection of sub-bands is then transmitted to a computing cluster for further processing as e.g. combining the station beams to smaller 'tied-array' beams and integrating the signal over longer time spans. Each station thus assumes the role of a single dish in a classical radio telescope.

Detection of cosmic particles with LOFAR faces several technical challenges. The signals of multiple stations have to be combined to maximize the sensitive area of the antennas. As this reduces the size of the individual beam, multiple beams have to be formed to cover the entire Moon. As each station, respectively beam, produces data with a rate of more than 6.4 Gbit s^{-1} , analysis of the data in real-time is required to allow only selective storage of the data. Signals originating from the moon are dispersed in the Earth's atmosphere. Triggering on the amplitude of a pulse thus requires correction for the dispersion. The pulse from a particle interaction is of only ns duration. By the PPF the time-resolution of the signal is reduced from initially 5 ns to only about 5 μs in the individual subbands. Here thus the inversion of the PPF is required, which is not a loss-less procedure. We therefore use the recovered ns resolution signal only to trigger the read-out of the Transient-Buffer-Boards containing the original ADC traces. The offline analysis will thus not be limited by the accuracy of the PPF inversion which may produce artefacts, but all realtime-processing, i.e. beamforming, PPF inversion, and ionospheric de-dispersion, has to be done within 5 s.

The resulting sequence of the data processing steps necessary for the lunar detection of cosmic particles with LOFAR is sketched in figure 1. After submission to the computing cluster, the station beams, each covering the full moon, will first be combined into multiple smaller beam, each focussed to a small fraction of the moon. The signal in ns resolution within each beam will then be recovered by inversion of the PPF, before the signal will be de-dispersed and eventually a trigger will be send.

3. Computing Requirements

The individual processing steps are of varying computational demand as discussed in the following. To form a beam from the signal of N_S stations, the signal of each station has to be summed with a complex weight given by the station position and the beam direction. We thus require $8 \cdot N_S$ floating-point operations (FLOP) per sample. With $200 \times 10^6 \text{ s}^{-1}$ complex samples per station, the required computing power for beamforming is thus $N_S \cdot 1.6 \text{ GFLOP s}^{-1}$.

Inversion of the polyphase filter requires an inverse Fourier transformation (FFT) $\mathcal{F}^{-1}\tilde{y} = y$ of the filtered signal \tilde{y} and solving a sparse linear system $H\hat{x} = y$ to obtain the signal x with ns time resolution. In a prototype implementation [13] we solve the sparse system with the iterative LSMR algorithm [14] that requires $\mathcal{O}(100) \text{ GFLOP s}^{-1}$. As convergence in our tests is achieved after approximately 25 iterations, the PPF inversion step requires computing power of $\mathcal{O}(1000) \text{ GFLOP s}^{-1}$.

To correct for dispersion in the ionosphere the signal has to be multiplied in frequency domain by a complex weight depending on the current electron content of the ionosphere (STEC). For 6 FLOP per complex multiplication and $5N \log_2(N)$ floating point operations for a N -point FFT assuming the radix-2 Cooley-Tukey algorithm [15] we thus require approximately 27 GFLOP s^{-1} computing power per beam to correct for ionospheric dispersion. However, as the current STEC is not known exactly, multiple values have to be tried to reconstruct the original pulse amplitudes, what potentially increases significantly the required computing power.

In total, realtime processing of a single beam thus requires several thousand GFLOP s^{-1} of computing power, with solving the linear system for the PPF inversion as most costly processing step.

4. Available Computing and Network Resources

The necessary computing power to process approximately 50 beams as required to achieve full coverage of the moon is not available on the regular LOFAR data processing cluster COBALT [16]. The computations will thus be carried out on the DRAGNET cluster [17], a CPU/GPU cluster designed for pulsar searches consisting of 23 processing nodes. Each node is equipped with dual Xeon Haswell-EP 2.4 GHz 8 core CPUs, 128 GB RAM, and four NVIDIA GeForce GTX Titan X GPUs yielding a total theoretical peak performance of about 0.5 PFLOP s^{-1} . While DRAGNET thus in principle provides enough computational power to

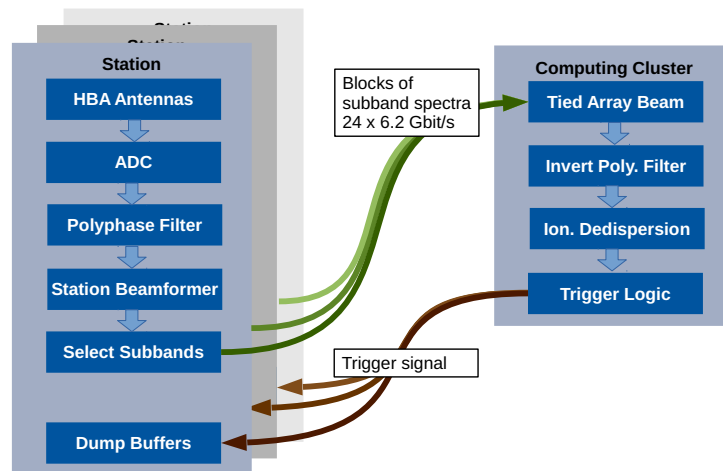


Figure 1. Overview of the online data analysis processing steps for the detection of ns-pulses with LOFAR [13].

process the approximately 50 beams required to cover the full moon, distributing the data over the network becomes a bottleneck.

All data has to be distributed on all processing nodes on DRAGNET. In a naive implementation where the data is copied in serial to N nodes, e.g. in a `for` loop, the required bandwidth is thus increased by a factor of $\mathcal{O}(N)$. As switches can maintain multiple parallel connections, copying the data to the nodes following a binary tree structure allows scaling of the data transfer costs with $\mathcal{O}(\log_2 N)$. However, the available InfiniBand switches allow also a hardware enabled multicast [18]. Here, the data is copied on switch level and distributed to multiple receiving nodes in parallel, thus allow scaling in in constant time $\mathcal{O}(1)$. These different data distribution schemes are visualized in figure 2.

Data distribution via hardware multicast is available for OpenMPI [19]. With the default implementation in OpenMPI 1.8.3, we achieved a speedup with a prototype implementation compared to serial or tree level data distributions schemes as function of the number of nodes as displayed in figure 3. Although scaling in constant time is not achieved, the scaling is significantly better than for copying in a binary tree and requires less than twice the time for a broadcast with 16 nodes than for a broadcast to a single target node. However, final evaluation of the networking performance is still pending as the prototype was not tested on the DRAGNET cluster but on a different cluster with similar networking hardware to not disturb the regular operation of DRAGNET.

The connection of DRAGNET to the LOFAR Network is sketched in figure 4. Each core station is connected to the COBALT cluster via 10 Gbit Ethernet, which is sufficient to transmit the data in the native 16bit integer format yielding a data rate of 6.4 Gbits s^{-1} per station. COBALT and DRAGNET are, however, only connected via 56 Gbit InfiniBand network and additionally a 10 Gbit Ethernet network. Thus even with perfect bandwidth utilization the data of only less then ten stations can be transported to DRAGNET. However, incorporation of data from more stations is possible by forming the beams in two separate steps, one processed on COBALT and one processed on DRAGNET. In the first step, several preliminary-beams are formed by combining the signal of only a subset of stations on the COBALT cluster with the regular LOFAR beamformer. The data is then transmitted to DRAGNET and the final beams are formed. The effect of this two-stage beamforming process on the size and shape of the final beams is currently under investigation.

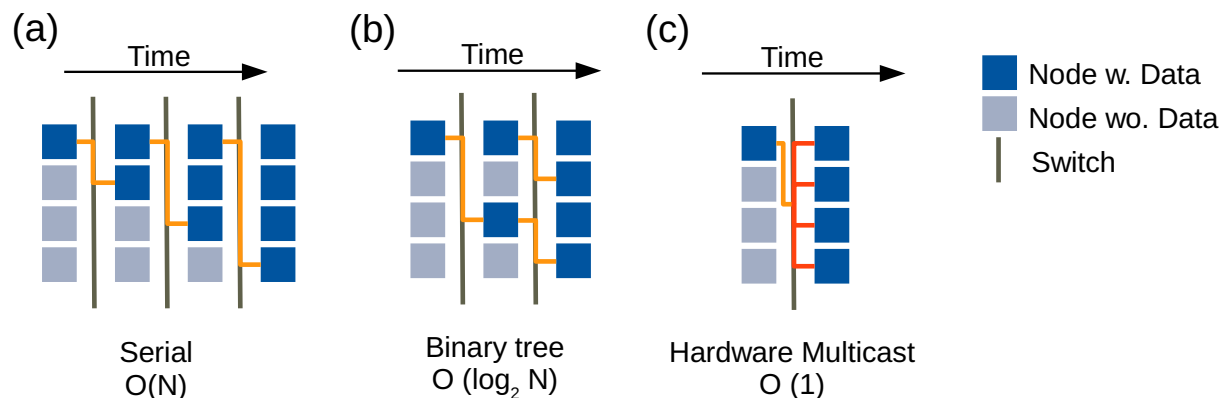


Figure 2. Different Methods of data-distribution on individual nodes connected to a switch. (a) Serial copy e.g. in a `for` loop. (b) Copy following a binary tree using parallel connections (c) Hardware-enabled multicast.

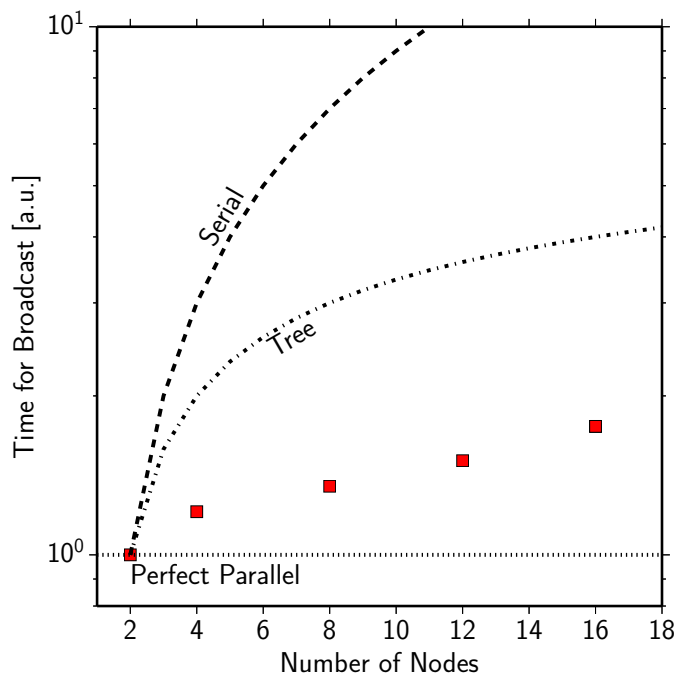


Figure 3. Broadcast performance achieved with the prototype implementation using OpenMPI 1.8.3 as function of the number of nodes. The total time for the copy is normalized to the time needed for a broadcast using only two nodes, i.e. a single copy operation.

5. Prototype Implementation

The prototype for the simulation and online software framework for lunar observation with LOFAR is designed around the `DataChunk` as central data container on which individual modules operate. A single `DataChunk` either contains one polarization of the electrical field or one channel of the digitized signal. The `DataChunk` is in a specified state, either `TimeDomain`, `FrequencyDomain`, or `PolyphaseFiltered`. These states define whether to interpret the stored trace as real or complex valued and the number of samples, thus allowing the reuse of the same memory block during processing.

Individual models operate on one or more objects of type `DataChunk` in one processing step and may change the state of the `DataChunk`. A simulated PPF for example takes a `DataChunk` in the `TimeDomain` state as input and modifies the state to `PolyphaseFiltered` after performing the actual filter operation on the data. As another example, a module for the simulation of the LOFAR beamformer takes as input a `DataChunk` for the beam and adds a second `DataChunk` containing the signal from a different stations to the beam with corresponding time delay. Here, all `DataChunks` remain in `PolyphaseFiltered` state. Internally the `DataChunk` allocates a single array of fixed size on the CPU and also on the GPU. A lazy update scheme is used to copy the data between host and device on access to avoid unnecessary data transfer between host and device memory while allowing code encapsulation in separated modules.

All objects can be accessed via a python interface generated using SWIG [20]. The `DataChunk` is equipped with an interface to numpy arrays. Modules are written in C++ and CUDA for GPU processing, or alternatively python. This enables writing efficient processing pipelines for the simulation of individual steps or the whole experiment as well as the final data processing pipeline as minimum python programs with a common code base.

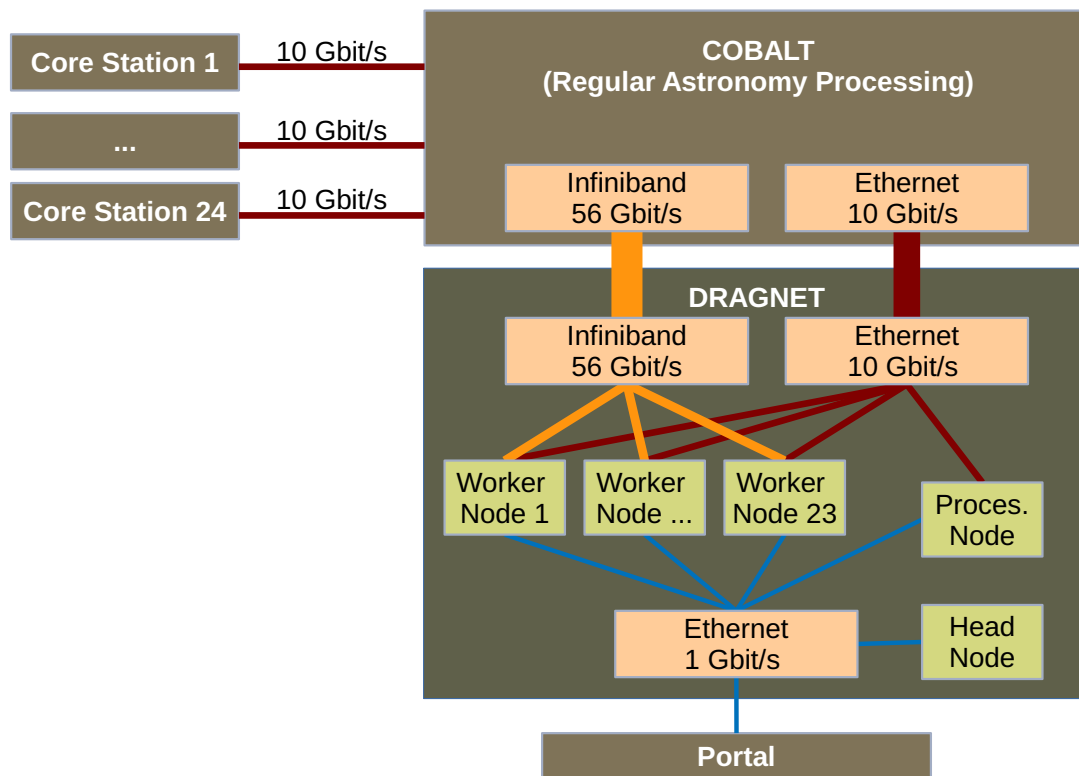


Figure 4. Schematic of the LOFAR computer network infrastructure.

6. Conclusions

To search for cosmic particles on the ZeV scale that hit Earth's moon with earth bound radio telescopes such as LOFAR, efficient realtime processing of the data is required. As LOFAR is optimized for astronomical observations, significant computing resources are required to use LOFAR and the Moon as particle detector. The necessary computing resources are, however, available at the DRAGNET computer cluster. The now available software framework enables development and testing of prototypes for the individual processing steps as discussed here, and thus preparation of measurement campaigns to search for particles beyond the Zetta-eV scale.

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