Overview of the LOFAR signal processing architecture

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***Abstract*—LOFAR is the first of a new generation of phased-array radio telescopes, that combines the signals from many thousands of simple, omni-directional antennas, rather than from expensive dishes. Its revolutionary design and unprecedented size enables observations in the hardly-explored 10–250 MHz frequency range, and allows the study of a vast amount of new science cases.**

This paper describes the LOFAR signal processing chain from the stations, where the signals are received, via the Wide Area Network to the Central Processors. The Central processing is split in real-time correlation and off-line calibration and imaging.

I. Introduction

In the Netherlands a LO(w) Frequency ARray (LOFAR) is developed optimized for the low frequency band from 30–240 MHz. LOFAR is the first large scale radio telescope based fully on the phased array technique. This prevents the use of moving large constructions and enables multi-beaming. The total collecting area of LOFAR is achieved by many small dipoles which are grouped in stations to reduce the data rate to an acceptable level. The main reduction is achieved by selecting only a part of the sky by using the phased array technique. The number of stations installed in the Netherlands will be at least 36. Half of the number of stations will be core stations and the other half remote stations. The main difference between them is that the core stations can be split up in two independent arrays delivering the two fold of the remote station bandwidth.

All data of the stations is transported to one central place via a Wide Area Network (WAN) and using owned and leased light paths. In Groningen all station data is processed. The processing is done by off the shelf hardware, varying from a supercomputer to clusters of computers. The processing done will vary from correlation for the standard imaging mode to tied-array beamforming for the transients and pulsar mode for example. However, also more sophisticated processing will be done to enable various energy cosmic ray modes of different intensities.

The heart of LOFAR will be installed in the Northern part of the Netherlands. The maximum baseline of LOFAR including only the Dutch stations is about 100 km. Since, also other European institutes showed interest and are building LOFAR stations the maximal baseline of LOFAR will be extended to several hundreds kilometer.

In this paper the LOFAR architecture will be discussed with a focus on the data flow.

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II. Station processing

In the LOFAR stations the electromagnetic signals of interest are received by multiple dipoles and combined in such a way that only a part of the sky is selected. The main architecture is depicted in Figure **??**. Each subsystem will be discussed in subsections.

A. Antennas

The station baseline design consists of 96 dual polarized Low Band High (LBH) antennas optimized for the 30–80 MHz frequency range and 48 dual polarized High Band compound Antenna arrays (HBA) optimized for the 120–240 MHz frequency range. One HBA is composed of 16 individual antenna elements, which are combined through analog beamforming with true time delays. Both the low band and combined high band antenna signals are pre-filtered and amplified near the antenna prior to transportation over coaxial cables to a central location within a station. The low band array will be a randomized and exponentially space tapered configuration [1] with a size of about 85 m in diameter, while the HBA array will be installed as a dense and more regular array.

B. Receiver

In a LOFAR station one receiver is used for one polarization of both the LBH and HBA. The receiver accomodates also for a third antenna input (Low Band Low) operating in the 10–30 MHz band. At the central station location the receiver unit selects one out of these three antennas. After selecting an antenna, the signal is filtered with one of the integrated filters. These filters select one of the four available observing bands. After filtering, the signal is amplified and filtered again to reduce the out of band noise contribution (anti-aliasing). A pre-amplifier in front of the A/D converter converts the single ended signal into a differential signal prior to A/D conversion. For the receiver a wideband direct digital conversion architecture is adopted. This reduces the number of analog devices used in the signal path. The maximum sampling rate is 200 MHz, which is sufficient to directly convert the analog signals. To fill the gaps in between the Nyquist zones, a sample frequency of 160 MHz can be chosen as well. The Nyquist zones I to III of the A/D converter with a sample frequency of 200 MHz and 160 MHz respectively are depicted in **??**. Since the LOFAR stations are installed in civilized areas the dynamic range of the A/D converter must be sufficient to handle the Radio Frequency Interference (RFI) signals in the band of interest. Hence, the A/D converter converts the analog signal into a 12 bit digital signal.

C. Digital Processing

The antennas in the station form a phased array, producing one or many station beams on the sky. Multi-beaming is a major advantage of the phased array concept. It is not only used to increase observational efficiency, but may be vital for calibration purposes.

To form a phased array at station level, the analog antenna signals must be delayed and added to form a beam on the sky. Moreover the beamformer should be able to track sources on the sky and be flexible in exchanging beams for bandwidth.

The beamformer can be implemented by using true time delays or by applying phase shifts on narrow subbands. For the last solution an error is made at the edges of each subband (Figure **??**), since the phase is frequency dependent and only one phase can be set per subband.

Since, the correlator in the LOFAR system is an FX correlator (first Fourier transform and then correlation) a certain frequency resolution is required for that. For the beamformer a certain (other) frequency resolution is required as well (if implemented by phase shifts). This led to the decision to implement the station beamforming with phase shifts after a first stage filterbank which realizes a frequency resolution sufficient for the beamforming operation. A second stage filterbank will make an even higher frequency resolution which is required before the correlator. Another reason to split the filter banks up is that the first stage filter bank is more expensive than the second stage filter bank because the first stage filter bank operates per antenna while the second stage filter bank operates on beams. Since no extra significant data reduction will be done after the second stage filterbank, that functionality will be implemented in the central systems.

The first stage filter bank in the stations splits up the total band into 512 equidistant subbands. After the filtering operation, specific subbands can be selected. The selected subbands can be arbitrary and will add up to in total 32 MHz. This bandwidth is matched to the current capacity of the central processor.

To form beams, the antenna signals are combined in a complex weighted sum. This is done with independent beamformers for each subband. In this way the number of pointings on the sky can be exchanged against the bandwidth per pointing, i.e. a user can choose between 1 beam of 32 MHz to a maximal of 8 beams of 4 MHz.

The station output signal is coded in 16 bit complex samples. Each second a timestamp is added to the output stream because the signal transported via UDP (User Datagram Protocol) packets. That means that the station signals are transported asynchronously. In the central processing facility the station signals will be synchronized with each other as is discussed in Section **??**.

Additionally the station processing is able to calculate the full cross correlation matrix of all dipoles in the station for one subband. This information is used for the station calibration [**?**]. The goal of the station calibration is to calibrate for gain and phase differences of the individual analog signal paths.

In parallel with the filtering and beamforming the raw data can be stored in a transient buffer as well. Freezing of the buffer content can be controlled by internal or external triggers. The stored data or selections thereof can be sent to the central processing facility for further processing. This extension is primarily used for the transients and cosmic ray community.

max 54 subband/RSP board ==¿ wil ik eigenlijk niet doen omdat ik het niet over implementatie heb ==¿ discuss

III. Central Processing: the Correlator

The station data are centrally received and combined in the correlator [2]. LOFAR uses an IBM Blue Gene/L supercomputer to correlate all data, unlike traditional telescopes that typically use customized hardware. The desire for a flexible and reconfigurable instrument demands a *software* solution, but the data rates and processing requirements demand a supercomputer.

Explain: BG/L characteristics The heart of the Central Processor is a six-rack IBM Blue Gene/L supercomputer that provides 34 TFLOPS peak performance and has a fast internal interconnect: the 3-D torus. A total of 768 Gigabit Ethernet interfaces are available for external I/O. Each processor is extended by two double-precision floating point units that are very suitable for signal processing, since a variety of operations on complex numbers are natively supported.

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Explain: input buffer & station synchronization, transpose, delay compenstation, PPF, correlator

The input section receives all station data that are sent via the wide-area network. Since UDP is an unreliable protocol, the input section handles duplicated, lost, and out-of-order packets. Lost data is appropriately flagged as being ”invalid”, and the remainder of the processing pipeline takes this into account. The data are received into a circular buffer, that holds the most recent six seconds of data.

The buffer serves three purposes. First, it synchronizes the station data, since the difference in path lengths between the stations and the correlator result in different travel times over the WAN link. Second, the buffer is used to compensate for the bulk of the delay that is due to the fact that the stations receive a wave at a different time (see Figure **??**). Third, it provides some headroom to recover from small hiccups in the remainder of the processing pipeline, without data loss.

Each input node receives data from up to 54 subbands from a single RSP board of one station. Unfortunately, this data distribution is not suitable for the correlator, because to correlate a subband, the data from all stations are needed. Also, we need hundreds of CPUs to correlate 54 subbands. The next step is to redistribute all data over the CPUs, using a fast interconnect. Initially, we did this on a separate input cluster connected by a high-speed infiniband network, but we found that the internal 3-D torus network within the Blue Gene/L can do this job much faster.

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Next in the pipeline is the second-stage PolyPhase (PPF) filter, that splits each 195 KHz (resp. 156 KHz) subband

Fig. 1. Real-time filters on the Central Processor. For simplicity, the figure shows two stations, one subband, one polarization. The numbers are valid for the 200 MHz mode.

into 256 channels of 763 Hz (resp. 610 Hz) wide. Splitting the subbands into narrow frequency channels allows flagging of narrow-band RFI without much data loss (see Section sec:RFI). The PPF filter consists of 256 Finite Impulse Filters (FIR) filters and a Fast Fourier Transform (see Figure 1). Each FIR filter is a 16-tap band pass filter. The incoming samples are round-robin distributed over the FIR filters; the outputs are fourier transformed. To achieve optimal performance, both the FIR filter and the FFT are implemented in assembly (although we maintain an equivalent C++ version for debugging and portability purposes).

After the subbands are split into narrow channels, the remainder of the delays are compensated, by shifting the phase of each sample. The correction factor depends on time and frequency. The delays are computed exactly for the beginning and ending of each integration period (typically: one second), and interpolated both in time and (channel) frequency such that the phase of each sample is corrected by an accurate factor.

The PPF implicitly converts the 16-bit complex number to 32-bit floating-point numbers, since the BG/L performs floating point computations faster than integer operations. Also, the phase correction and the correlations are done in floating point.

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Maybe this paragraph should be moved to the IEEE Computer paper. An example that illustrates the benefits of a flexible software solution was the ease with which we could move the second-stage PolyPhase Filter, which was originally designed to run on FPGAs at the stations, to the Blue Gene/L. Once we saw that we could obtain really high performance from the BG/L in practice and recognized that sufficient computational power was left, a considerable cost reduction was achieved by removing the PPF FPGAs from the station design.

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Although the BG/L is computationally very efficient, streaming the station data into the machine at the required data rates turned out to be a major problem, despite the BG/L's atypical high number of I/O interfaces. For each 16 BG/L compute cores, there is one *I/O node* that has one external gigabit-Ethernet interface and transparently handles all I/O calls initiated by its associated compute cores (see Figure **??**). We found that the stock network system software was not particularly optimized for high-throughput I/O, and that the obtained bandwidths were far from what theoretically should be achievable.

The dissatisfaction about the performance and about the I/O model in general led to a joint effort to redesign the entire network software infrastructure, and resulted in a new environment called *ZOID* [3]. ZOID does not only yield better performance, but it is much more flexible, since it allows application code to be run on the I/O node. With ZOID, we were able to move the receipt of the station data from the input cluster nodes to the BG/L I/O nodes, so that the station data are sent directly through the WAN into the BG/L. Not having to build a separate input cluster results in an estimated cost saving of €700,000.

IV. Central Processing: Calibration

The processing of LOFAR data has to deal with a number of challenges [4], [5]. First of all, the data volumes are huge and being able to process the data in finite time dictates the design of the data processing chain. Second, compared to traditional steel dishes, the phased array station beams are far more variable (in time, in frequency, as well as over the different stations), they yield a higher degree of instrumental polarization, and they have relatively high sidelobes. All these issues complicate the processing of the data. Especially, since a high dynamic range must be reached. The third category of challenges lies in the sky itself. At the low frequencies where LOFAR will observe there will be very bright sources so that a high dynamic range and, hence, a high accuracy is needed to see the faint background sources. The sky will also be filled with a large number of sources, giving rise to confusion. Finally, the Earths ionosphere seriously defocusses the images.

With LOFAR we enter a new regime in radio astronomical data processing. The challenges imply that for LOFAR we have to reconsider exisiting processing strategies and algorithms and develop new strategies and algorithms. The processing therefore remains a work in progress of which we give an overview of the current status.

A. Processing large data volumes

The total amount of data that is produced is detemined by the total number of stations that are used in the observation. This number is still uncertain and will be different in the Low Band and the High Band, since the High Band stations in the Core will be split in 2 half stations. Using 20 Core stations and 20 Remote stations as a working example this generates between 0.28 Gbyte/s for the LBA Core Array in 200 MHz sampling mode and 3.1 Gbyte/s for the HBA Full Array in 160 MHz sampling mode. After a typical observation of 4 hours between 3.3 Tbyte and 35 Tbyte will be collected.

Since a permanent data storage is not part of the LOFAR telescope these data volumes have to be processed near real time. Fortunately, not all LOFAR applications are so data intense, so that for every 1 hour of observation we may have up to, say, 4 hours to further process the data. With this in mind data I/O becomes a serious problem. Obviously the data needs to be processed in a parallelized and distributed way minimizing the I/O that is needed [6], [7].

Data can be distributed over a large number of processing nodes in a number of ways. Distribution over baselines is not very suitable for imaging, where data from all baselines must be combined to produce an image. Distribution over time has the disadvantage that up to sevaral Gbytes/s have to be sent to a single processing node. Frequency, therefore, seems to be the best way. This distribution scheme matches with the design of the correlator. It is also a convenient scheme for the imager, where images are created per (combined) frequency channel.

A consequence of distribution over frequency is that in the self-calibration step solver equations from different compute nodes may need to be combined. The combining of solver equations, however, involves far less data then the underlying visibility data.

Even though the processing of the data will be done on a large cluster of computers, the total amount of data can be such that we expect the quality of the final result to be processing limited. This means that for all the algorithms we have to weight accuracy against the amount of Flops needed. It also means that the LOFAR instrument can be improved by upgrading the processing cluster in the future.

B. *Processing steps*

LOFAR calibration is a joint estimation problem for both instrumental parameters and source parameters. At its heart lies the "Measurement Equation" that is used to model the observed data [8]. A signal processing data model and a Cramer-Rao lower bound analysis are given in [9]. The latter paper also provides a good introduction to the signal processing aspects of LOFAR Self-Calibration.

The final LOFAR calibration strategy is still under development. However, we foresee that the following steps and iterations will be part of it. The first step consists of removing bad data points, which are due to e.g. Radio Frequency Interference (RFI). After this step the contaminating contribution of a couple of very strong sources (like CasA, CygA, TauA, VirA) that enter through the station beam sidelobes needs to be removed. Since modelling the station beam sidelobes is infeasible due to the large number of parameters involved, the combined effect of the sources and the instrumental effects has to be estimated and subtracted from the data.

Once the interfering signals are removed from the data, the data may be further integrated. The high resolution in frequency is only needed for removing RFI. The final resolution is determined by bandwidth smearing requirements [10]. In the frequency direction the data may be reduced by a factor of 3 to 10, depending on the size of the array used for the observation **CHECK**. In principle the data may also be integrated along the time axis. Here, however, we have to make sure that the effect of the ionosphere remains constant over a time sample. The maximal reduction factor determined by time-average smearing ranges from 3 tot 10, again depending on array size **CHECK**.

Next an iterative loop, dubbed the "Major Cycle", is entered where we first estimate instrumental and source parameters using the visibility data, then image the data, and finally refine the estimation of the source parameters using image data. Since the estimation algoritms are also iterative in nature, this loop will be traversed a number of times [5].

After initial operation of the LOFAR instrument the parameters for the strongest sources will be known. From then on the strongest sources can be used in every observation to estimate ionospheric parameters, instrumental parameters, and to refine the estimate for the station beams that is available from the station calibration. Using these estimates the contributions from the strongest sources are removed from the data. The remaining residual visibility data is then corrected and imaged.

The sky image is the Fourier transform of the visibility domain. Due to the fact that the visibility domain is only discretely sampled, sources in the sky image are convolved with a Point Spread Function (PSF). The contribution from sources that generate PSF far sidelobes that are higher than the image noise level should be subtracted from the visibility data.

One visibility sample is the summation of contributions from all sources in the sky. Since LOFAR has a large Field of View (FoV), the contribution from different sources is distorted by different ionospheric and beam effects. When imaging the visibility data, however, it is only possible to correct the data for one direction in the sky. This would mean that the image would be sharp for the direction of correction and the image quality would degrade outwards. To overcome this problem LOFAR images will be made in facets, where we can correct the data for the center of each facet.

Facet imaging is a well known technique to overcome the problem related to the so-called "w-term", which are due to the fact that the baselines are non-coplanar [10]. However, the non-coplanar baseline problem is better solved by the w-projection algorithm [11]. Therefore, we will apply the w-projection technique per facet and the facet size will only be determined by the variability of the station beam and the ionosphere.

Since we correct the data per facet, this means multiplying the total amount of data with the number of facets. Fortunately, the facet size will be far smaller then the total FoV. This allows us to shift the data to the center of the facet and then integrate the data in both time and frequency. Hence, the total amount of data will be more or less the same.

Once the image is produced, source finding and extraction algorithms may be used to estimate source parameters. This would then lead to an updated source model and we are ready to enter a new cycle of the Major Cycle.

By sampling the data in each iteration of the Major Cycle, doubling the sampling density in every cycle, and using only the full resolution data in the last cycle, we effectively have not more then twice the I/O that is needed for the full resolution data. We expect that will seriously inprove the total speed of the processing.

V. Current State and Roll-out Planning

Currently [12], four partially-built stations are functional: 3 stations with 16 LBAs and 1 station with 48 LBAs. To create more baselines and achieve better UV coverage, the stations each can be split into four *microstations*. This yields 16 microstations, which are treated the same as real stations in the online and offline processing pipelines.

A consequence of quadrupling the number of stations is that the bandwidth is reduced to 36 subbands of 195 KHz or 48 subbands of 156 KHz. Alternatively, the station with

48 LBA can be split into 12 microstations, so that together with the other 3×4 microstations a total of 24 microstations can be formed, but WAN restrictions limit the bandwidth to 12 resp. 16 subbands. The HBA units are currently being commissioned. A full LBA station in Effelsberg, Germany is also operational, and will soon be connected via a dedicated wide-area link to the Central Processor.

In the course of this year 18 full stations (13 core + 5 remote) will be produced and installed in the field. Also the WAN infrastructure and Central Processor facility will be ready in the end of 2008 to handle the data of the 18 full stations and a couple of international stations as well. In the year thereafter another 18 stations will be produced and installed in the field.

Construction of the full stations is planned as follows. ***"station" should be consistent with HBA-core "double station"*** The first 18 full stations (13 core + 5 remote) ***to be confirmed*** including the WAN links to the Central Processor will be operational by the end of 2008, and the remaining 18 stations will be built in the course of 2009. Meanwhile, construction of international stations will continue. The Blue Gene/L is capable of handling all foreseen future data rates.

VI. Conclusion

The conclusion goes here.

VII.
Acknowledgment

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