LOFAR APPROACHING THE CRITICAL DESIGN REVIEW

Jaap D. Bregman

ASTRON, P.O.Box 2, 7990 Dwingeloo, The Netherlands, Bregman@ASTRON.nl

ABSTRACT

Located in the North-Eastern part of The Netherlands the Low Frequency Array (LOFAR) will initially consist of 77 stations separated up to 100 km, each with 2 sets of 100 dual-polarized sky noise limited antennas. These cover the 10-80 MHz band with all-sky viewing short dipoles and the 110-230 MHz band with a 16 element phased array tile. Early delivery of Blue Gene/L, Europe's biggest supercomputing machine (43 Tflop) by IBM, which forms the heart of the software radio telescope, creates opportunities for dedicated observations using small sets of second phase prototype hardware. We summarize the technical status of the LOFAR project and address imaging and deep integration issues that need further research. A proposal is made to extend the initial test station to a core test array for experimental validation of the key science program need in 2006 prior to full scale operation planned for 2008.

INTRODUCTION

The scientific drivers for a new generation of radio telescopes argue for roughly two orders of magnitude increased sensitivity, which can only be achieved by increasing the total flux collecting area, together with correspondingly increased angular resolution. At the 10 to 230 MHz operating frequencies of the Low Frequency Array (LOFAR) radio telescope it is feasible to employ very large numbers of simple, all-sky antennas with wide-band early digitization. This means that almost the full signal processing chain can be realized in (embedded) software. This approach makes it possible to deal with earth-based radio signals in effective and novel ways and to open a previously largely unexplored frequency domain for challenging radio-astronomical research.

The LOFAR project status [1] summarizes the science goals, the system design, calibration and operations issues and the project time line as of early 2004. Here we summarize some key figures as they have evolved during the development process. The LOFAR band is covered by two antenna types (10-80 MHz and 110-230 MHz respectively, avoiding the FM band). LOFAR will consist of 77 stations each with 100 dual-polarized antennas of both types. Antenna signals are combined in phased array mode, forming beams (116 Top/s) at one or many directions on the sky. Signals are transported over a glass fiber network (0.8 Tb/s) to central processing systems (43 Tflop/s), where the phased array beams can be combined in several ways. For imaging, stations are combined through correlation, thus forming an aperture synthesis array.

The combination of very large data rates, high levels of man-made interference and severe phase distortions due to ionospheric turbulence puts extreme challenges on the signal processing and calibration of LOFAR. The very large data rates force LOFAR to calibrate data in a streaming processing model. This requires new programming models, an increased focus on signal integrity and the introduction of system health management concepts.

The paradigm shift has been extended further by positioning LOFAR as a Wide Area Sensor Network, allowing the processing concepts and infrastructure to be reused by other applications. Geophysical sensors and sensors for research in precision agriculture have been added to the RF-sensors for astronomy. LOFAR as a multi-disciplinary research infrastructure passed its Preliminary Design Review (PDR) at the end of 2003, and is scheduled for completion in 2008, with initial operations starting in 2006.

The Critical Design Review (CDR) is planned by the end of 2005 and we summarize the optimizations in system design and expected performance that match LOFAR with budgetary constrains, site acquisition and procurement progress and scientific requirement evolution. From a summary of the key science areas we derive a set of issues that should be addressed with shortly available hard- and software prototypes to guide the final development process.

We discuss array and station configuration options for a test array in the compact core in relation to the architectures for station based beam forming and array based cross-correlation imaging and pay special attention to the scientific possibilities in 2006

DEVELOPMENT STATUS

The PDR has provided a suite of papers referenced in an overview [2] and proving the feasibility of the LOFAR concepts. A subsequent set of hard- and software prototypes have been developed, validated and presented [3, 4, 5, 6, 7]. We summarize the main results in terms of sensitivity and available range and skip technical details.

Low frequency antenna

The marginal linearity of the current-feedback designs used for the 40 – 80 MHz band of LOPES and the 10 – 40 MHz band of the Initial Test Station (ITS) has been succeeded by a design without resonance peak and larger bandwidth that should handle the 30 – 80 MHz band with a single antenna adding less than 20 % to the sky noise and reduced performance for 10 – 30 MHz band.

High Band Tile

The first four prototype tiles form a mini station that is evaluated using the low frequency receiver system [3] at the Westerbork Synthesis Radio Telescope. The current low noise amplifiers add about 250 K to the sky noise, but an improved design promises less than 100 K.

Receiver

A direct conversion system [4] uses Nyquist filters for the first, second and third zone of a 12-bit ADC that operates at a clock of 200 MHz to cover the bands 10 – 80 MHz, 110 – 190 MHz and 210 – 270 MHz. respectively. The lowest band has a 20 MHz wide guard band from the half clock frequency to avoid aliasing of strong FM signals in the 88 - 108 MHz band. In order to cover the 190 – 210 MHz gap a separate filter covering 170 – 230 MHz is available requiring the ADC clock to operate at 160 MHz.. All filters have out-of-band levels of -80 dB and -40 dB at the clock frequency and its sub harmonics. When a full swing signal is present at the ADC the digitization noise level is raised by 6 to 15 dB limiting its dynamic range to 11 bit in the first and 10 bit in the second Nyquist zone. This is sufficient to do all required spectral filtering operations in the digital domain. After evaluation of the combination of receivers and antennas at actual sites, final decisions on the frequencies of the 3 dB point will be taken as well as on the system gain that defines the sky noise level at the ADC.

Digital Beam Former

Embedded Station processing use poly-phase filter-banks with very high out-of-band suppression such that all the sky noise and RFI from a whole 80 MHz band that is aliased into a single 195 kHz sub band is less than 10 % of the sky noise in that band. A distributed beam forming architecture [4] uses ring links where the element signals are co added at each passed node.

Data Transport

Fibre connections are available from the central core site to the processing centre at the University in Groningen where the IBM BlueGene supercomputer is operational since April 2004. Already one fibre pair of the 77 is illuminated with a 1 G/bs Ethernet link. Another pair will be illuminated before end 2005 to provide 8 channels of 1GbE in CWDM mode, which would allow the 60 receiver Initial Test Station (ITS) to observe with 10 % integration efficiency using a fraction of BlueGene/L as correlator.

Central Processing

Complex cross-correlation processing on a 32 node section of BlueGene/L has been demonstrated to use 85% of the available multiplying power. A critical issue is the optimisation of the external GbE links that limit the throughput, which is the product of stations, beams per station, bit depth and sample rate per input signal.

Monitoring & Control

Multi node control software that tailors the commercial PVSS-II package has been demonstrated to control both beam former nodes on a dedicated hardware platform together with correlation nodes on a general purpose cluster.

Station Calibration

The ITS has 60 antennas placed at exponentially increasing distances along 5 spiral arms spanning 200m diameter and produces confusion limited all sky images using 86 snapshots each having 6.7 sec integration time per 9.77 kHz channel [5]. Radio Frequency Interference detection techniques have been developed that allow to identify those frequency channels that are sky source dominated such that multi-source self-calibration could be used successfully.

Array Calibration

The peeling process [6] has been demonstrated successfully and a mathematical proof of its soundness has been given.

RFI mitigation

The main strategy has been defined as excision of intermittent interference and spatial filtering of time-continuous interference [7]. In principle the algorithms will be implemented at the central processor where the station sub-bands are divided in channels of 1 kHz width and will be aggregated to 10 kHz wide RFI-free channels.

Site acquisition

Locations for 32 station sites are available in the central core and acquisition for the 45 remote stations is in progress. This would allow erecting a Core Test Array (CTA).

SCIENCE GOALS

The five key areas of astrophysical science driving the design of the LOFAR radio telescope are the following.

High Redshift Universe

Deep surveys at radio frequencies lower than conventional radio telescopes record promise to reveal populations of objects in the early Universe that are luminous enough to permit detailed study. At later cosmological epochs one expects to encounter important populations of fossil radio sources.

Epoch of Re-ionization.

The first luminous objects that formed in the early Universe must have re-ionized the surrounding neutral medium. This universal phase change marks the last completely unexplored cosmological epoch. The detection of its global signature and the mapping of its structures are thought best to be done at radio frequencies in the LOFAR band. The telescope is therefore being designed to attempt its detection.

Particle astrophysics

The origin and distribution of cosmic rays in galaxies and the physical mechanisms responsible for their acceleration to exceedingly high energies are important astrophysical questions to be addressed by LOFAR. Low and medium energy cosmic ray electrons can be mapped for the first time in 3D in our Galaxy, while ultra-high energy particles impinging on the Earth can be detected and studied through the Askaryan effect (producing Giga-Jansky radio pulses that are readily detected by LOFAR antennas).

Bursting and Transient Universe

The LOFAR signal processing chain is conceived to enable surveys and long term study of variable and transient phenomena: bursts from Jupiter-like planets, merging and interacting compact objects, pulsars and so on.

Solar-Terrestrial Relationships

LOFAR will generate excellent maps of the solar wind using interplanetary scintillation of background radio sources, and of coronal mass ejections. It promises to provide essential information on magnetic fields frozen in the plasma, which is of prime importance to the strengths of the geomagnetic storms they can cause. Additional research in this category includes ionospheric tomography and the physics of the outer solar atmosphere.

ISSUES TO BE RESOLVED

To meet its science goals LOFAR does not only need its sensitivity and resolution, but foremost appropriate calibration and imaging procedures. The calibration is under control, but the imaging has not yet received appropriate attention.

All sky imaging

We must realize that low frequency imaging is all-sky imaging, since both the antenna stations as well as the array have low spatial resolution compared with the spectral resolution and the time resolution of a snapshot image. The result is that there is no bandwidth or integration time smearing that effectively limits the field of view of the array. The main reason however are the high station side lobes of order $(\lambda/D)^2$ for a dense array of diameter D and even worse 1/N for a sparse array with only N receptors. This means that an array with only a single antenna element at each station and viewing the whole sky will see the same whole sky with the same sensitivity as a synthesis array with stations having 100 elements, but without station pattern structure. The sky noise as well as all instrumental cross talk is the same also in the main beam of such an N element station however the sources are a factor N stronger. Nevertheless we still need to subtract all the sky sources in the station side lobes which could give array side lobes and grating responses in the main beam that are higher than the noise floor. This is a problem for the Epoch of Re-ionisation observations with the compact core of LOFAR where 150 kHz channels at 150 MHz give a spectral resolution of 10^{-3} while the same temporal resolution is reached after 15 seconds integration, which are both low compared with the 2 10^{-3} spatial resolution of a 1 km diameter core array.

Deep integration

The basic principle to reach low noise is averaging. In a single snapshot of a two dimensional array we can subtract [5,7] not only the strong sky sources but also RFI from terrestrial or satellite sources such that their side and grating lobes are below the noise floor of that snapshot. By averaging more snapshots the sky sources remain, but the noise floor decreases with the square root of the number of snapshots. Also the residuals of non sky sources decrease, but linear with integration time since we rotate our snapshot images to track the sky, which smears objects that move faster or slower than the sky. If we now repeat the imaging the next day, many effects might repeat exactly, except for the Sun and the Moon which have different positions then and for intermittent interference. It is important to prove that our subtraction algorithms leave no systematic residuals at a level which is a factor ten below the noise floor of a 24 hour synthesis observation such that they could build up in repeated observations.

This proof needs only an array of sufficient size to avoid confusion, but the stations need only a single receptor. This proof, that repeating an observation a hundred times indeed gives a factor ten lower noise floor, is crucial for the first two key science areas. We have to prove even more, namely that our spectral dynamic range is about a million in real observing conditions. Secondly we need to prove that the ripples in the pass band of a station can be calibrated to that same one-in-a-million level for spectral channels that are about 0.5 MHz wide. There is no fast simulation track, we just need the receivers and the correlator, integrate for a day and repeat for a hundred days. Just working with one receiver per station is a worst case situation. Nothing like a phase switching system is planned so we need experimental evidence that such a system is indeed not needed at all.

Imaging procedures
Aperture synthesis imaging records spatial frequency information with interferometers and constructs an image by inversion. This procedure assumes that the object to be imaged is stationary, which is not the case since the station side lobes see a part of the sky rising while another part is setting.
A second problem is that the polarization response of sky objects depends on their position within the antenna pattern of the individual receptors in a station. A correction should be applied, but not on the individual spatial frequencies but on each individual snapshot image. The final sky image is then a summation of the corrected and properly de-rotated hemispheric snapshot images. This suggests that our imaging procedures need to be structured accordingly.
Such a multi-snapshot imaging procedure needs a fast transformation of a limited set of spatial frequencies into a large set of image points. To facilitate such a fast kernel based on a fast Fourier transform it could be important that our compact core array is a truly planar one to avoid additional image position dependent phase corrections to be handled. Alternatively we need sufficient processing power to make proper two dimensional images with a three dimensional array. Especially for the epoch of re-ionisation we need very high precision in removing all discrete sources as well as the polarized galactic foreground, without introducing any calibration artefact.

PROPOSED TEST CONFIGURATIONS AND OBSERVATIONS

A compact core test array with only 32 dual polarisation receptors working at 150 MHz would have 50 K brightness sensitivity after 24 h integration of a 150 kHz channel. With rotation measure synthesis we could increase our effective bandwidth to at least 15 MHz providing 5 K sensitivity, which would be sufficient to image the polarized galactic foreground polarisation.
The point source sensitivity of such a single channel is 0.1 Jy reaching just the confusion level, and allows comparing images integrated over more channels with single channel images after many days of integration.
A second step would be to replace the single dipoles by a single tile with 16 elements. We do not even need a steering beam former but fixed wiring to point at the North Celestial Pole would be sufficient to demonstrate that we can use the sky model obtained with the single elements to subtract all residuals of that model that would give responses in the main beam of the tile.

CONCLUSIONS AND RECOMMENDATIONS

Since the Preliminary Design Review progress has been made such that the developed hard- and software prototypes could form the basis for final production designs, that will provide a LOFAR meeting its science goals.
To validate that the developed concepts reach a factor ten lower noise levels after repeating observation more than a hundred times and to guide the detailed implementation of calibration, RFI mitigation and imaging procedures, appropriate actual data has to be provided by a Core Test Array composed of available hardware prototypes. At the same time we want to make intermediate observational steps towards our scientific goals.

REFERENCES

[1] H.R. Butcher, "LOFAR: First of a New Generation of Radio Telescopes," *Proc. SPIE*, vol. 5489, p 537, 2004
[2] J.D. Bregman, "The designing of LOFAR a HF-VHF Radio Telescope," *Tijdschrift van het NERG*, vol.3, 2004
[3] J. van der Marel, "Low Frequency Receivers for the WSRT a Window of Opportunity," *URSI-GA*, 2005
[4] A.W. Gunst, "Signal Processing and Transport in LOFAR," *URSI-GA*, 2005
[5] S.J. Wijnholds, "Confusion Limited all Sky Imaging with LOFAR's Initial Test Station applying wide field calibration techniques," *URSI-GA*, 2005
[6] J.E. Noordam, "MeqTrees: Prototype calibration package for LOFAR," *URSI-GA*, 2005
[7] A.J. Boonstra, A.W. Gunst, S.J. Wijnholds, "LOFAR interference mitigation strategy, considerations and tradeoffs," *URSI-GA*, 2005