Concept for a LOFAR "Super" Station

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General context

The LOFAR project[1], led by ASTRON in the Netherlands, is presently at a crucial stage of its development, with two important events occurring in parallel : (1) an ongoing "rescope plan" that implies a redefinition of the number of stations, distribution of antennas, performances of backend…, and (2) increasing participation throughout Europe which becomes effective with several stations in Germany[2], UK[3], soon a French LOFAR station in Nançay[4], and further contacts in several other countries[5]. The official decision for funding the French station has been taken by CNRS and Observatoire de Paris, with about 40% of the funding already secured.

LOFAR stations

One LOFAR station consists of several sets of antennas (LBH = low-band-high antennas 30-80 MHz ; HBA = high-band antenna tiles 120-240 MHz ; possibly in the future LBL = low-band-low antennas 10-30 MHz), connected to receiver units (RCU) that digitize and process the signals. In the current LOFAR design[6] having 77 stations concentrated in the Netherlands (LOFAR77), there are 96 dual-polarization antennas (or tiles) per set, connected to 96 pairs of RCU[7]. The back-end cabinet - containing the RCU, clocks, power supplies… - is connected via a Gbit network link (1 to 10 Gb/s - tbd) to the central processor (Blue Gene, in Groningen, The Netherlands). LBH do presently exist. HBA should exist in a near-future. LBL are still an option for a more distant future, although the present redesign may affect that possibility in the Dutch stations. Each RCU has 3 input channels : LBL, LBH and HBA, that differ only by their input filters, and between which it can switch. Thus LBL, LBH or HBA measurements cannot be made simultaneously but must share time.

Modes of operation

We will keep referring here to the LOFAR77 design, since the ongoing redesign of LOFAR Phase 1 is not yet finalized. In this design, all stations are identical, 32 of them are grouped in a central area a few km in diameter (the core) and 45 are distributed in rings up to 100 km from the core (outer stations). Core stations can be used with or without outer stations. When used alone (Radio Sky Monitor mode), they can perform a multibeam survey of the whole sky with moderate angular resolution (a few arcmin.), over a maximum bandwidth of 120 MHz. A mode using core stations only will be heavily used for the EoR (Epoch of Reionization) key project.

When core+outer stations are used together, they provide the maximal angular resolution of the LOFAR77 interferometer (of the order of 10") and allow to build visibility maps (so-called (u,v) maps) and then images of parts of the sky over a maximum bandwidth of 32 MHz.

Other possible modes of operation include the use of core stations + possibly some outer stations as a single phased array, coherently synthesizing an instantaneous pencil beam, or the incoherent

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[1] http://www.lofar.org/

[2] http://lofar.mpa-garching.mpg.de/glow.html

[3] http://www.lofar-uk.org/

[4] http://www.lesia.obspm.fr/plasma/LOFAR2006/FLOW_Science_Case.pdf

[5] http://www.lofar.org/workshop/

[6] see information and links at http://www.lesia.obspm.fr/plasma/LOFAR2006/atelier-eng.html

[7] in the following, we simply write "antennas" and "RCU" for "dual-polarization antennas" and "pairs of RCU"

addition of the same stations to synthesize a broad instantaneous beam, both over a maximum bandwidth of 32 to 120 MHz.
The ongoing LOFAR rescope may lead to a reduced number of Dutch stations and/or fewer antennas per station.

European distant stations
In parallel, European countries have started installing additional LOFAR stations (Extended LOFAR) at distances up to ~1000 km from the core, adding longer baselines to the (u,v) plane (but with limited coverage) and thus eventually increasing by a factor ~10 the angular resolution in interferometric mode[8]. In France, one LOFAR station will be installed in Nançay, ~700 km from the Dutch core. Standard European distant stations will increase only moderately the sensitivity of the LOFAR array (unless the LOFAR Phase 1 redesign severely impacts the instrument's sensitivity). A significant increase would imply to multiply the number of stations, hence their cost and the data volume to be processed.

"Super" station concept
We propose here the concept of a LOFAR "Super" Station (LSS). The aim is to increase significantly its sensitivity and thus its "weight" in the correlation with Dutch stations (by ~1 order of magnitude), without increasing much its cost (by a factor <2). The basic idea is to add to a standard LOFAR station a set of 96 antennas, that will feed the 96 RCU, each of these antennas being itself a (dense ?) phased array of N elementary antennas (with N~10). Phasing of these sub-arrays of N antennas will be done in an analog way (delay lines or other tbd method…), and identical for all sub-arrays, so that each one will finally be connected to one RCU input. LSS sensitivity will thus be increased by a factor ~N at the cost of the new set of antennas + their phasing (and control/command) system.
These antennas could be identical to LBH antennas or specific (e.g. LBL or intermediate : 20-70 MHz or other tbd). Note that although existing LBH have already been used below 30 MHz by bypassing the high-pass filter at LBH input, the expected normal operation of LBH will stop at 30 MHz. Super-station antennas more sensitive below 30 MHz would expand the band of interest of LOFAR. These antennas could use the available LBL channel of the RCU (with an input filter adapted to the spectral band of the antennas). Thus, the RCU will be able, without any design change, to switch between standard LBH or HBA (standard station mode) or the above sub-arrays (LSS mode).

Preliminary discussion
Below is a preliminary discussion of the advantages and constraints of the LSS concept. It is intended to start a broader discussion involving all interested parties, from scientific users to engineers…

- In all cases, LSS will include all the functionalities of a standard (distant) station when switched to its standard LBA or HBA antennas.
- In LSS mode (i.e. switched to sub-array input), one may distinguish between standard and non-standard use. Standard use implies to consider the LSS as part of the LOFAR array, but with possibly different antenna bandwidth, response, polarization, FoV (+ impact on data bandwidth?)… that should be taken into account in the processing and correlation with all other LOFAR stations. Correlation of signals from inhomogeneous stations (here LSS versus standard stations) is done routinely in VLBI observations, and may already be necessary in the rescoped LOFAR. It should thus not be a drawback.
- The field of view of LSS will be reduced compared to that of a standard station, implying constraints for the standard use of LSS. But LSS will provide high-sensitivity visibility measurements for long baselines in the (u,v) plane.

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[8] http://www.lofar.org/conference_meetings/LOFAR_LOBAS_Science.pdf

• Due to higher sensitivity, LSS should allow to detect instantaneously more faint point sources with higher S/N (albeit within a smaller FoV - tbd) and may thus improve ionospheric calibration. This would be especially useful early in the project (first 2 years ?) when ionospheric calibration over the whole field (up to 1000 km from core) will not yet be possible. If ionospheric conditions are poor (and of course decorrelated above distant LOFAR stations), then correlation fringes drift fast, so that short integration times allowed by a more sensitive stations are better (in VLBI, large antennas remain usable when small ones are not).

• One expects strong competition for the use of LOFAR observation time, and since several modes of operation do not involve all stations, there should be a significant fraction of the time during which outer (and distant) stations can be used in non-standard mode.

• One non-standard use consists, when the core is used alone (e.g. for EoR observations), in correlating together separately the outer + distant stations, with LSS providing core-like high-sensitivity visibility measurements for long baselines in the (u,v) plane. Although this should be checked for a specific design and operating mode, we have indications that the Blue Gene computer (or its successor) should in principle be able to handle sub-arrays of stations from LOFAR. We note that the German LOFAR consortium is interested in doing correlations (possibly at Jülich) independent of Groningen at times.

• A second core-like station (the LSS) will be useful for coincidence observations of bursts (and thus better transients detection efficiency and robustness).

• More generally, the possibility to correlate the signals by synthesizing 2 large sub-arrays of stations with comparable sensitivity (one including the core, the other including ≥1 LSS) should also help confirm the detection of weak sources (e.g. exoplanets), thanks to decorrelated ionospheric perturbations, RFI, and instrumental effects at the 2 sub-arrays. One can also think, for weak sources or transients, to correlate all stations together, and only process the subset of stations which were free of RFI or ionospheric decorrelation based on an examination of the data.

• Various full array and sub-arrays schemes including a LSS may also improve high-resolution astrometry.

• When not taking part in correlations with other LOFAR stations, LSS can be used in standalone mode. With an effective area 3-4 times that of the Nançay decameter array, it will have the sensitivity for detecting and studying strong radiosources such as Jupiter, the Sun, some pulsars, etc. Standalone use is especially adapted to student training purposes. It implies the ability to extract locally the data output from the LOFAR back-end.

• Further discussion should address :

- the scientific interest of LSS : impact for Key Science Projects ? for new KSPs *(e.g. the magnetism KSP will find high resolution extremely useful for studying polarization at low frequencies to avoid beam depolarization. This may extend even as far as being necessary for polarization calibration. In LOFAR Phase 1 frame, a LSS will approach the sensitivity of the Dutch core, helping to weight the (u,v) sensitivity toward longer baselines, making the imaging easier)* ?
- impact for high-resolution studies ? new scientific objectives ?
  in summary → why we want them at all ??
- open technical questions : type and characteristics of LSS antennas (bandwidth, beam…) ? instrument simulations ? advantages and inconvenience of LSS versus several colocated standard stations ? etc.
- the interest for several LSS in Europe ? (a few LSS operated together in a frequency range covering both LBL and LBA ranges might offer new perspectives) …