German LOFAR – a new era in radio astronomy

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Outline

• Why LOFAR?
• What is happening with LOFAR?
• Why LOFAR in Germany?
• Outlook
10^{23}-10^{20} \text{ Hz} \\
Compton Gamma-Ray Observatory

10^{19}-10^{17} \text{ Hz} \\
ROSAT

\text{Gamma Ray} >100\text{MeV CGRO/EGRET} \\
\text{X-Ray} 0.25, 0.75, 1.5 \text{ KeV ROSAT/PSPC}
$10^{16}-10^{15} \text{ Hz}$

Extreme Ultraviolet Explorer

$10^{14} \text{ Hz}$

Hubble Space Telescope
$10^{13}-10^{12}$ Hz

Infrared Astronomical Satellite

$10^{11}-10^{10}$ Hz

Wilkinson Microwave Anisotropy Probe
$10^9 - 10^8$ Hz

Radio

$10^8 - 10^7$ Hz

Low-frequency
Why is the low-frequency regime still unexplored?

- RFI mitigation
- Ionospheric transients
History of the Universe
(condensed version)

Cosmological Redshift - Hydrogen line is seen at:

Big Bang
Opaqueness
Quark Soup
Big Freeze Out
Protons
Hydrogen
First Stars
Sun & Earth
Modern Universe
Now

LOFAR

0 - 10^{-32} Sec.
1 Second
300,000 Years
1 Billion Years
12-15 Billion Years

1.4 MHz  14 MHz  140 MHz  1.4 GHz
Neutral IGM

“Dark Ages”

Redshift

Galactic synchrotron emission

Clusters

10

10

3

First UV sources

Galaxies

Ionized IGM

Proto-galaxies

Faint radio-loud quasars

Time

3 \times 10^5 y

5 \times 10^8 y

13 \times 10^9 y

Foregrounds

Galactic synchrotron emission

LOFAR

Proto-galaxies
Re-Ionization of the Universe

• A key science goal of LOFAR is to map the epoch of re-ionization
• After the big bang and recombination of elements the universe was neutral
• Stars and quasars must have started to re-ionize the universe
• We expect clumpy neutral hydrogen emission from primordial matter at z~6-12.
• 21cm line shifted to 200 MHz

Gnedin (1999)
LOFAR – the next generation radio telescope

- Telescope the size of the Netherlands plus Germany
- Frequencies: 30 - 240 MHz
- Replace a few big expensive antennas by many cheap ones
- No moving parts: purely electronic beam steering
- Current Funding: 74 M€
Extreme Flexibility: Electronic Beamforming

**Principles:**

a) E is detected, interference can be performed (off-line) in computer
b) No quantum shot noise: extra copies of the signal are free!

**Consequences:**

a) Can replace mechanical beam forming by electronic signal processing
b) Put the technology of radio telescopes on favorable cost curve
c) Also: multiple, independent beams become possible
Lo-Band Antenna (30-80 MHz)
# LOFAR Correlator

## List of Top 500 Supercomputer Sites

<table>
<thead>
<tr>
<th>Rank</th>
<th>Site Name</th>
<th>Country/Year</th>
<th>Computer/Processors</th>
<th>$R_{\text{max}}$</th>
<th>$R_{\text{peak}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DOE/NASA/LLNL</td>
<td>United States/2005</td>
<td>BlueGene/L eServer Blue Gene Solution / 65536 IBM</td>
<td>136800</td>
<td>183500</td>
</tr>
<tr>
<td>2</td>
<td>IBM Thomas J. Watson Research Center</td>
<td>United States/2005</td>
<td>BGW eServer Blue Gene Solution / 40960 IBM</td>
<td>91290</td>
<td>114688</td>
</tr>
<tr>
<td>3</td>
<td>NASA Ames Research Center/NAG</td>
<td>United States/2004</td>
<td>Columbia SGI Altix 1.5 GHz, Voltaire Infiniband / 10160 SGI</td>
<td>51870</td>
<td>60960</td>
</tr>
<tr>
<td>4</td>
<td>The Earth Simulator Center</td>
<td>Japan/2002</td>
<td>Earth-Simulator / 5120 NEC</td>
<td>35660</td>
<td>40960</td>
</tr>
<tr>
<td>5</td>
<td>Barcelona Supercomputer Center</td>
<td>Spain/2005</td>
<td>MareNostrum JS20 Cluster, PPC 970, 2.2 GHz, 1408</td>
<td>27910</td>
<td>42144</td>
</tr>
<tr>
<td>6</td>
<td>ASTRON/University Groningen</td>
<td>Netherlands/2005</td>
<td>eServer Blue Gene Solution / 12288 IBM</td>
<td>27450</td>
<td>34406.4</td>
</tr>
</tbody>
</table>
LOFAR Configuration
LOFAR Planning

- Design & engineering
- Procurement
- Rollout and Integration

Connection Core Blue-Gene/L CDR Initial Operation Core Inner ring Ring 2 Ultimate Operation

Jan 2004 2005 2006 2007 2008 2009 2010 2020
LOFAR Performance

LOFAR Angular Resolution
(≤ 500 km baselines)

LOFAR Sensitivity
(1 square km @15 MHz, 8 hrs, Δν~3 MHz)

3 orders of magnitude!
The EoR with LOFAR

LOFAR will measure, with ~ 3’ resolution, several data-cubes with ~10°x10° spatial dimensions and one frequency dimension (redshift ~6-11.5).

The main scientific goals are:

• The global EoR signal
• Statistical analysis will be used in order to extract the principal structural measures of the reionisation signal from the noisy and foreground contaminated data
• EoR map reconstruction: The ultimate goal is to reconstruct a large-sky maps of the EoR signal.
LOFAR expected response

\[ L20 @ z \sim 14.5 \ (\sim 90 \text{ MHz}) \]

- Instrument sampling
- Gaussian noise
- Convolution with a Gaussian beam (\( \sigma = 3 \text{ arcmin} \))

It will be possible to map the reionization history, especially its latest stages

\[ S5 @ z \sim 10 \ (\sim 130 \text{ MHz}) \]

Courtesy of Benedetta Ciardi (MPA)
Transient Sources

- **X-ray Binaries** (stellar mass black holes)
- AGN (supermassive black holes)
- Pulsars (neutron stars)
- CV’s/Flare Stars
- LIGO Events (merging neutron stars)
- Supernovae
- Jupiter-like Planets
- **Gamma-Ray Bursts** (prompt emission and afterglows)
- Cosmic Rays & Neutrinos
- Meterorites
- … New sources …
  - Aliens, Airplanes, etc.
The fossil Universe: Radio relics and halos

Hoeft, Brüggen, Yepes 2003
Radio Relic Luminosity Function

![Graph showing the radio relic luminosity function with logarithmic scales on both axes. The x-axis represents flux in Jy at 151 MHz, and the y-axis represents the number of relics per sky area. The graph includes a histogram and several curves representing different luminosity functions.]
LOFAR Studies of the Solar System: Space Weather

Solar Wind
observed via Radio Source Scintillation
Other LOFAR Science Drivers

• Structure and Evolution of Galaxies (cosmic rays, magnetic fields)

• Evolution of AGN, Jets & Radio Lobes

• Galactic astronomy (magnetic field, ISM, SNR, surveys)

• Astroparticle physics (neutrinos, cosmic rays)
European Expansion ...
The White Paper describes a German participation in LOFAR.
German contribution

• Six LOFAR remote stations in Phase I (2006-2009)
  planned locations: Bremen, Effelsberg-Bonn, Garching, Hamburg, Jülich, Tremsdorf-Potsdam, and possibly Göttingen
• LOFAR Science network
• Another six stations in Phase II (2009-2012)
Key benefit of German contribution: **long baselines** (> 100 km)
Science Network

Based on the existing expertise in Germany, the foci of the science network could be the following areas:

- Galaxies
- Polarization, Galactic astronomy, AGNs
- Large-scale structures
- Cosmology & Epoch of Reionisation
- Surveys
- Solar physics
## Development Paths in Radio Astronomy

<table>
<thead>
<tr>
<th>Improvements</th>
<th>Telescopes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1) Resolution.</strong></td>
<td><strong>2006-2010: LOFAR</strong></td>
</tr>
<tr>
<td></td>
<td>- &quot;new&quot; frequency windows</td>
</tr>
<tr>
<td></td>
<td>- 100 times more resolution</td>
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<tr>
<td></td>
<td>- 100 times more sensitivity</td>
</tr>
<tr>
<td></td>
<td>- very flexible digital beam forming</td>
</tr>
<tr>
<td><strong>2) Sensitivity.</strong></td>
<td><strong>2007-2011: ALMA</strong></td>
</tr>
<tr>
<td></td>
<td>- new frequency window</td>
</tr>
<tr>
<td></td>
<td>- 10-100 times more sensitivity</td>
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<td>- 10-100 times more resolution</td>
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<td><strong>3) Frequency.</strong></td>
<td><strong>2012-2015: SKA</strong></td>
</tr>
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<td>- 100 times more sensitive</td>
</tr>
<tr>
<td></td>
<td>- very flexible beam forming</td>
</tr>
<tr>
<td></td>
<td>- extreme frequency agility</td>
</tr>
<tr>
<td><strong>4) Flexibility!</strong></td>
<td><strong>NOW: → eVLBI</strong></td>
</tr>
</tbody>
</table>

Factor 100 improvement in all areas within a decade over 5 decades of frequency! This will be the largest step radio astronomy has ever made.
Conclusions

• LOFAR is a novel radio telescope that will observe a largely unexplored part of the spectrum

• As a result exciting new discoveries loom in the low frequency regime

• LOFAR is the first instrument to map the re-ionisation of the Universe

• Almost all branches of astronomy are served by LOFAR

• A German participation with the provision of long baselines is essential
# LOFAR Performance

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$A_{\text{eff}}$ (m$^2$)</th>
<th>$T_{\text{sys}}$ (in K)</th>
<th>$\delta S$ in 1s (mJy)</th>
<th>$\delta S$ in 10h (mJy)</th>
<th>$\delta S$ in 100h (mJy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$3.3 \times 10^5$</td>
<td>23k</td>
<td>68</td>
<td>0.35</td>
<td>0.11</td>
</tr>
<tr>
<td>75</td>
<td>$5.2 \times 10^4$</td>
<td>2450</td>
<td>46</td>
<td>0.24</td>
<td>0.07</td>
</tr>
<tr>
<td>120</td>
<td>$3.3 \times 10^5$</td>
<td>820</td>
<td>2.4</td>
<td>0.013</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Approximate sensitivity per beam, with 4 MHz BW and for a single polarization.
LOFAR Key Science Programmes

• Cosmology
  – Epoch of Reionization

• All-Sky Surveys
  – Star forming galaxies, AGN, Clusters, etc.

• Transient detection
  – Everything that bursts and varies

• Astroparticle Physics
  – Direct detection of cosmic rays
  – Cosmic rays & neutrinos impacting the moon
Costs for 2006-2009 (Phase I)

Initial investment per station € 686,000
Two engineers to be in charge of the six station € 100,000/year

*Excluding the costs for the data connection and land we envisage for a period of 3 years a total investment of ~ € 5 Million.*