LOFAR: history, lessons, status & results

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++ LOFAR team, EoR project team

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LOFAR: some array design and data processing issues

- A bit of history, descope and upgrades
- Configuration, stations, uv-coverage, maximum baseline
- Frequency range, resolution and RFI mitigation issues
- FOV stations, (multi-) beaming
- Data processing and data products
- Foregrounds (total intensity, polarization)
- Ionospheric effects and calibration
- Some LOFAR and EoR results
LOFAR rescope and upgrades
LOFAR changes/evolution in configuration/specs

Important changes: for good or bad

Sep 2007: rescope from 32 CS + 45 RS \(\rightarrow\) 18x2 CS + 18 RS array
NL stations from 96 tiles/RCUs \(\rightarrow\) 48 tiles/RCU’s
\(\rightarrow\) barely complete uv-coverage (worries for EoR)
\(\rightarrow\) loss in sensitivity factor 3.5 !!

Losses for EoR / surveys somewhat compensated by larger FOV

2009
BlueGene correlation bandwidth: 32 MHz \(\rightarrow\) 48 MHz
2 RS \(\rightarrow\) 2 split CS

2010
4 additional CoreStations 24x2 CS + 16 RS

Oct 2012:
16-bit \(\rightarrow\) 8-bit data transport: 48 \(\rightarrow\) 96 MHz bandwidth !!

Oct 2012:
all core stations time-aligned on a single clock
LOFAR station configuration aspects, uv-coverage etc
The LOFAR observatory: brief overview

**LBA**  (10) 30 - 90 MHz
isolated dipoles

**HBA**  115 - 240 MHz
tiles (4x4 dipoles)

Core      2 km       24 stations
NL        80 km      14(16) stations
Europe   > 1000 km   8+ stations

A station has 24 - 48 - 96 antennas / tiles

Principle of **Aperture Synthesis**
Array resolution: sub-arcsec to degrees

Pulsars: 128 coherent tied-array(s), (in)coherent sums

Bandwidth (8-bit mode): 96 MHz !!
Sensitivity (after 8 h, 60 MHz, ~ 60 stations)  @ 150 MHz  ~ 100 μJy (achieved!)
Locations of 16 Remote Stations (13 operational 2013.2)

- Latest additions:
  - RS305  Nov 2012
  - RS407  Dec 1
  - RS409  Dec 20
  - RS310  Dec 20
  - RS210  May 2013
  - RS404  2013/2014
  - RS410  2013/2014
LOFAR core configuration - ‘tailored’ to EoR project

Core dimension
2 x 2.5 km

the ‘superterp’
diameter ~ 350 m
6 stations
(more are possible !)
1st LOFAR station (May 2009) 48 HBA tiles \(\rightarrow\) 2x24
Layout of 24-tile and 48-tile HBA-stations

All CS and RS have a unique rotation ..... to lower interferometric sidelobes

Physical area: 600 m²

SEFD (150 MHz, zenith) ~ 2600 Jy

Physical area: 1200 m²

SEFD (150 MHz, zenith) ~ 1300 Jy
3C196: 11 or 13 Remote Stations 6h vs 8h synthesis

11 Stations 13

← 6h →

← 8h →
LOFAR uv-coverage with 48 CS + 13 RS

3C196 8h ‘EoR-windows’ NCP 12h
LOFAR core uv-coverage at Dec $+48^\circ$ after 6$^h$

Complete uv-coverage is essential for the EoR

EoR signals are detectable on short baselines only (less than (say) 2 km)

$\rightarrow$ resolution (PSF) 3-5 ’

Long LOFAR baselines (10-60 km) are used for modeling, station calibration, confusion removal, and ionospheric calibration.
Inner uv-coverage at dec +90°

NCP +90°

Elevation 53° !!

Great field!
Alas, not at SKA sites

12h synthesis
Frequency coverage, spectral resolution, receiver modes & RFI mitigation
LOFAR frequency coverage and resolution

Two 12-bit ADC sampling modes: 200 MHz and 160 MHz clock

Frequency filtering done in two digital (Poly-Phase-Filter) stages:
- at station ⇒ 512 subbands (either 156 or 195 kHz)
- at CEP (BG/P) ⇒ 256 channels for each of 488 subbands split over N beams

Oct 2012: 96 MHz total bandwidth → 124,928 channels of 0.76 kHz!
RFI mitigation, algorithms and research

Work by Andre Offringa:

Thesis defense: 22 Jun 2012
University of Groningen

Products:
- AO-flagger
- Low-pass filtering approaches
- The LOFAR radio environment
- Spatial distribution of RFI sources
LOFAR radio RFI environment


LBA 24h (1s, 0.76 kHz)
Only 1.8% RFI
33 stations 9 Oct 2011

HBA 24h (1s, 0.76 kHz)
Only 3.2% RFI
13 stations 27 Dec 2010
A day in the life of LOFAR: HBA RFI-occupancy

Figure 9. The dynamic spectrum of RFI occupancy during the HBA survey

Offringa et al, 2013
Multi-beaming aspects in LOFAR
LOFAR has a very wide Field-of-View

HBA tile beam

LBA dipole beam

(analog beamformer, 5-bit delay)

digitally formed station beam

~22°

~100°
The future of radio astronomy: multi-beaming !

For imaging LOFAR has up to 8 digital beams (currently) also expressed as 488 beamlets (beam - subbands)

This has many, many advantages:

- great flexibility (e.g. EoR observations have 1x72 MHz + 6x4 MHz)
- survey speed
- imaging large areas (limited by LOFAR analog tile beam, 20-25° HPBW)
- inside-beam calibration transfer
- ionospheric calibration (tomography, with extended ground array)
- simultaneous programs (timing pulsars, TOO,... multiple users)

Expandable in the future when processing cheaper
(# digital beams ≈ # dipoles in station)

SKA AA-low must have multi-beaming !?
Dataprocessing & data products
LOFAR EoR data volume, products and formats

- Measurement Sets: raw, data format 64ch-2s \(45 \text{ TB/night}\)

- Processed data sets/formats: now accumulated \(\sim 0.5 \text{ PB}\)
  15ch - 2s \((\text{NB: } 12\text{kHz} = 24 \text{ km/s velocity resolution at } 150 \text{ MHz})\)
  3ch - 2s
  1ch - 10s

- Imagecubes: small, large,
  20x20 deg, 2” pixels, 6” PSF \(36k \times 36k \times 370 \ (488) \rightarrow \sim 1 \text{ TB total (Stokes I)}\)
  restored, apparent flux \(\rightarrow\) science analysis
  6x6 deg, 40” pixels, 3’ PSF \(512 \times 512 \times 370) \ (488) \rightarrow \sim 1 \text{ GB (IQUV)}\)

- Residual visibilities in ‘stripped’ format (gridded?)
  to use in ML inversion
  to use in Foreground Fitting
  to use in PS estimation
Lofar Eor Diagnostic DataBase  

Martinez-Rubi et al, ADASS, 2012, arXiv

dedicated 32 nodes for 3C196 and 32 nodes for NCP
Visualizing instrumental complex gains: 3C196

9/10 Jan '13  48 CS + 13 RS  8h at 10s  38/370 subbands

Oscar Martinez-Rubi & Cyril Tasse
Visualizing instrumental complex gains: 3C196

9/10 Jan ‘13  48 CS + 13 RS  8h at 10s  zoom 129-136 MHz

t=0.0, Freqs=[128.7, 135.9]MHz, RefStation=CS001HBA0

Oscar Mar2nez-Rubi & Cyril Tasse
SAGEcal: NCP beam amplitude solutions (20m snapshot)

Data from 2012 December: beam amplitude 145 MHz 10 deg. FOV
SAGEcal: NCP beam phase solutions (20m snapshot)

Beam Estimation

Data from 2012 December: beam phase (rad) 145 MHz 10 deg. FOV
Ionospheric effects, polarization
Faraday rotation, tomography,..
3C196  WSRT 139 MHz  nonisoplanaticity in 3 km array!

3C196
80 Jy

3 sources 6 - 8 Jy

Sources need to be ‘peeled’ for DDE’s

de Bruyn et al, 2009
Bernardi et al, 2010
3C196  WSRT selfcal phase solutions for 6x12h nights

Note the very different ionospheres!

However, these hardly affect the quality of the Q,U images.

6 x12h

LOFAR & SKA-low: history, lessons, status & results
Observation with strong variable Differential Faraday rotation (DFR)

20 km baseline and strong associated amplitude decorrelation
3C196  117 MHz  4 Feb 2011

Amplitude

10m at 2s resolution

Phase

10m at 2s resolution

DFR ~ 0.2 rad in 100s  →  DPD ~ 20 radians phase
Quantitative understanding of the effects of DFR

DFR converts (unpolarized) signals into circularly polarized signals visible in XY and YX. DFR arises when we encounter large TEC gradients. Let us look at this quantitatively.

(Absolute) Ionospheric Phase Delay:
\[ \Delta \phi = -50 \text{ TEC} \left( \frac{\lambda}{2m} \right) \text{ radians} \]
where TEC is in TECU (=1x10^{12} \text{ el/cm}^2)

(Absolute) Faraday Rotation of polarisation angle:
\[ \Delta \theta = \text{RM.} \, \lambda^2 = 0.81 \times 10^6 \, B_// \, n_e \, dl \, \lambda^2 \text{ radians} \]
where \( B_// \) in Gauss and \( dl \) in pc

Differential Phase Delay (DPD) between two stations i and j:
\[ \Delta_{ij}(\Delta \phi) = -50 \, \Delta_{ij}(\text{TEC}) \left( \frac{\lambda}{2m} \right) \text{ radians} \]

Differential Faraday Rotation (DFR) between two stations i and j:
\[ \Delta_{ij}(\Delta \theta) \sim 1.04 \, B_// \, \Delta_{ij}(\text{TEC}) \left( \frac{\lambda}{2m} \right)^2 \]

Hence:
\[ \text{DPD/DFR} \sim 48 \left( B_// \cdot \frac{\lambda}{2m} \right)^{-1} \quad \text{independent of the } \Delta(\text{TEC}) \]

For a typical \( B_// \sim 0.4 \text{ Gauss} \) and a frequency of 122 MHz
\[ \Rightarrow \text{DPD/DFR} \sim 100 \]

A DFR of 0.1 radian (as observed on ~ 25 km baselines) therefore also implies large ionospheric phase differences (~ 10 radians or \( \Delta \text{TEC} \sim 0.2 \text{ TECU} \))!! On the previous slides one can see that this occurs quite often !! If ionospheric phase rates are very fast (say within 10s) they also cause amplitude decorrelation !
Differential Faraday rotation between two stations (28 km apart) rotates the signal from the parallel-hand ($XX$, $YY$) to the cross-hand ($XY$, $YX$) correlations.

This scales as $\lambda^2$ at 31 MHz ~ $90^\circ$ rotation!
(Galactic) foregrounds
Locations of calibrators: 3C147, 3C380, 3C295 and 3C196

Haslam et al, 1981
Full-sky high-frequency polarized images of our Galaxy

22.8 GHz  WMAP image

The FAN region

1.4 GHz  Reich et al

(more sensitive, but depolarization effects visible)

Fig. 2. The WMAP 22.8 GHz all-sky polarized intensity map (upper panel) and the 1.4 GHz all-sky polarized intensity map.
Range

-2, 20 mJy
Residual image after subtracting sources down to 20 mJy and smoothed to 5'.
Polarized intensity distributions of the FAN

RM = -5 rad/m²

RM = -2 rad/m²

Variable polarized intensity at Faraday depths from -6 to +2 rad/m²

Integrated about 10 K peak brightness!
Correcting for time-variable Faraday rotation

Elais N1 field: ionospheric RM correction

See also Sotomayor et al 2013 (arXiv)
Correcting for time-variable station beams: AW-imager

One frame from RM-cube of Elais-N1 field

few K signals!

Some LOFAR and EoR-KSP results
Oct 2012

celebrating start of NCP observing
Preparing for the LOFAR EoR project: overview '05-'12

LOFAR-EoR experiment: end-to-end pipeline

R. Thomas
PhD thesis

V. Jelić
PhD thesis

A. Offringa
PhD thesis

P. Lambropoulos
PhD thesis

Cosmological 21cm signal

Extracted cosmological 21cm signal

Galactic and extragalactic foregrounds

Extraction

Inversion

Ionosphere

Calibration

RFIs

Instrumental response and noise

Mix

Mock datasets

Jelic et al 2008
Harker et al 2009, 2010

Yatawatta et al 2009, 2013
Kazemi et al 2011, 2013
3C196 window: the full picture 45” PSF

Pandey et al
3C196 average of 2x8h 15” PSF
3C196: zoom-view with 15” PSF (30 km taper)

3C196 removed almost perfectly

Still awaiting 1000 km baseline data
Ultra-deep imaging on the NCP

Effect of Far Away Sources

3C390.3, 11 degrees away from the NCP, before and after SAGECal

Serod Yatawatta
Ultra-deep imaging on the NCP

Sarod Yatawatta

80 h on NCP
(5 x 15-16h)

Centered on NCP
0.7° x 0.7°
(1% of image)

PSF 6”x6”
rms 30 μJy
Giant radio galaxy  MSSS  \(\rightarrow\)  LOFAR  Global Sky Model

Presented by George Heald at Dalfsen LOFAR meeting (19-20 March 2013)

See also Heald

AJDI, 20 March 2013
Conclusions

LOFAR works very well, once station beams were calibrated

RFI not an issue (30-80 and 115-200 MHz)

New developments in (fast) calibration and imaging were needed

Direction dependent calibration essential (100+ directions)

6” PSF widefield imaging: very large images needed 36k x36k pixels (2”)

Very high DR (>60 dB) → requires ~ 500 km baselines (3C196, 3C295)!

Image noise scales as 1/ (B t)½ (up to B=60 MHz and t=100h !)

Multi-beaming great asset
EoR and recombination line contamination

EoR and Galactic hydrogen recombination lines:

- In Galactic plane: $\sim 100 - 500$ mK (at 325 MHz, e.g. Roshi et al, 2001)
- Out of plane: probably less than 50 mK

Fluctuations on 3-10’ scale probably an order of magnitude smaller still
Lines around 150 MHz probably weaker

NB: IF recomb lines are detected they will be helpful for fidelity checks.
Lines can easily be excised:
(~20 kHz / ~1 MHz or ~2% of spectrum)

de Bruyn, COSMO’05, Groningen