Long baseline experiments with LOFAR

- LOFAR
- long baseline issues, fringe-fitting
- first long-baseline fringes
- first long-baseline images
- The Sun!
LOFAR

- **LOw Frequency ARray**
- low frequencies
  - LBA: \(~30(10)–80~\text{MHz}\)
  - HBA: \(~110–250~\text{MHz}\)
- \(~40~\text{stations in Netherlands}\)
- additional stations in Germany, France, England, Sweden, Italy?, Poland?, . . .
- wide field of view, several beams
- good survey speed
- full synthesis imaging at low frequencies with high resolution
- long baselines: subarcsec resolution, useful for lens surveys
LOFAR resolution

fringe-spacing $\theta = \lambda/L \approx \text{resolution}$

<table>
<thead>
<tr>
<th>$\lambda$/m</th>
<th>freq/MHz</th>
<th>1 km</th>
<th>30 km</th>
<th>300 km</th>
<th>1000 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>10</td>
<td>1.7&quot;</td>
<td>3.4&quot;</td>
<td>21&quot;</td>
<td>6.2&quot;</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>34'</td>
<td>1.1'</td>
<td>6.9&quot;</td>
<td>2.1&quot;</td>
</tr>
<tr>
<td>3.8</td>
<td>80</td>
<td>13'</td>
<td>26&quot;</td>
<td>2.6&quot;</td>
<td>0.77&quot;</td>
</tr>
<tr>
<td>2.5</td>
<td>120</td>
<td>8.6'</td>
<td>17&quot;</td>
<td>1.7&quot;</td>
<td>0.52&quot;</td>
</tr>
<tr>
<td>1.9</td>
<td>160</td>
<td>6.4'</td>
<td>13&quot;</td>
<td>1.3&quot;</td>
<td>0.39&quot;</td>
</tr>
<tr>
<td>1.4</td>
<td>220</td>
<td>4.7'</td>
<td>9.4&quot;</td>
<td>0.94&quot;</td>
<td>0.28&quot;</td>
</tr>
</tbody>
</table>
German LOFAR stations
LBA details at Unterweilenbach
HBA + LBA in Tautenburg
VLBI methods for LOFAR

- Long baselines require VLBI techniques
- meaning of long depends on circumstances ($\lambda$)
- unstable phases, short coherence times
- weak signal: have to average in time and frequency
- solve for delays
  \[ \tau = \frac{1}{2\pi} \frac{\partial \phi}{\partial \nu} \]
- solve for rates
  \[ r = \frac{1}{2\pi} \frac{\partial \phi}{\partial t} = \frac{\partial \tau}{\partial t} \]
- non-dispersive
  \[ \tau = \tau_0 \]
- dispersive
  \[ \tau = \tau_0 \left( \frac{\nu_0}{\nu} \right)^2 \]
Fringe-fitting for LOFAR

- either for single subbands (BW $\sim 200$ kHz, $\Delta \tau \propto 5 \mu$sec)
- or coherent multi-band (BW $\sim 48$ MHz, $\Delta \tau \propto 0.02 \mu$sec)
- beware of multiple peaks in delay/rate
- produce 2-d delay/rate spectra
- simultaneously ‘fit’ for four parameters
- dispersive/nondispersive delays/rates
Coherently averaged over time intervals, then FFTed in frequency, then incoherently averaged over 1 h.
Fringes in delay/rate space (single subband)
Delays and phases

![Graph showing phase vs. frequency for subbands with continuous and modulated lines.](image)
Multi-band: more sensitivity and higher resolution delay
‘Results’ of fringe analysis

- long baseline fringes found
- clock offsets in some stations ✓
- confusion in LBA polarisation labels ✓
- strong 8 MHz ripple ✓
- 63 MHz LBA resonance
- strong differential Faraday rotation ✓
- time for imaging!
LBA long-baseline map: some details

- 3C196, LBA, 31 / 160 subbands, 44–59 / 30–80 MHz (ripple!)
- bandwidth 6 MHz / 48 MHz
- D2010_16704 6 h on 12/13 Feb 2010
- 5 NL + 3 DE stations (Effelsberg, Unterweilenbach, Tautenburg)
- corrected for 1 µsec and 17 µsec constant delays
- RR and LL from XX/XY/YX/YY using geometric model
- (self-)calibrated and imaged LL/RR in difmap
- MFS with/without spectral index correction
UV coverage with long and short baselines
MTRLI (MERLIN) observations of 3C196 at 408 MHz

[ Lonsdale & Morison (1980) ]
LOFAR maps of 3C196 (LBA: 30-80 MHz)

NL only, $35'' \times 22''$ beam

NL+DE, $1''5 \times 0''9$ beam
LOFAR LBA vs. MERLIN 408 MHz

[Wucknitz + Lonsdale & Morison (1980)]
First interferometric Solar observations

- initiated by J. Anderson, F. Breitling, G. Mann, A. Polatidis, C. Vocks, O. Wucknitz (alphabetical order)
- 8 ten-minute scans on 9th June 2010, 9:48 – 15:50 UT
- 4 with LBA and HBA each
- phase/pointing centre near Sun and calibrator sources
- LBA
  - difficult, other sources dominating: 3C123, CygA, CasA, . . .
  - situation unclear
- HBA
  - much clearer signal, Sun dominating on short baselines
  - self-calibration possible because of compact component
- only short baselines used!
The very first map
Variability: 30 sec in 1 sec steps (8 subbands)
Summary

• long baseline LOFAR works!

• but no pipeline yet

• fringe analysis revealed a number of technical problems (mostly solved now)

• Sun can be observed and resolved with LOFAR!

• to do
  ★ full fringe-fitting and calibration
  ★ not independent of polarisation calibration (differential Faraday rotation)
  ★ Sun as function of time and frequency
Additional material

- International LOFAR stations
- Multi-band delay fitting (details)
- Delay/rate map of 3C196
- Expectations: 3C196 at 5 GHz
- Very first LBA long-baseline imaging attempts
- First HBA long-baseline imaging attempt
- Dynamic spectra of the Sun
- 10 min movie of the Sun
The International LOFAR Telescope (ILT)

http://www.astron.nl/~heald/lofarStatusMap.html
Delay fitting

- do not fit phases directly
  - only know phase modulo $2\pi$
  - data are noisy

- equivalent (but better!): maximise the corrected signal

- measured and original visibility
  \[ V(\nu) = e^{2\pi i \nu \tau(\nu)} V_0(\nu) \]

- hope that $V_0(\nu) = \text{const}$ and correct for delay

- find maximum of

\[ \left| \int d\nu \, e^{-2\pi i \nu \tau(\nu)} V(\nu) \right|^2 \]

- this is Fourier transform if $\tau = \text{const}$
Multi-band delay fitting

- delay almost constant within subbands
- apply FFT for all subbands
- combine the results incoherently
- combine the results coherently

\[
 f_i(\tau_i) = \int d\nu \, e^{-2\pi i (\nu - \nu_i) \tau_i} V(\nu) \quad \text{with coarse FFT}
\]

\[
 F[\tau] = \sum_i e^{-2\pi i \nu_i \tau(\nu_i)} f_i(\tau(\nu_i)) \quad \text{on fine grid, interpolation}
\]

- \( \tau \) arbitrary function of frequency (non-/dispersive)
Include fringe rates

- have to integrate in time to increase $S/N$
- take into account rates (time-derivatives)
- do not use phase rates but delay rates
- $r = \frac{\partial \tau}{\partial t}$ dispersive/non-dispersive

$$f_i(\tau_i, r_i) = \int d\nu e^{-2\pi i(\nu - \nu_i)\tau_i} \int dt e^{-2\pi i(t-t_0)r_i} V(\nu, t)$$

$$F[\tau, r] = \sum_i e^{-2\pi i\nu_i\tau(\nu_i)} f_i(\tau(\nu_i), r(\nu_i))$$

- all phase rates are frequency-dependent
Delay/rate map of field around 3C196

VLSS (74 MHz):
A 19 Jy
B 6 Jy
C 17 Jy
3C196 140 Jy
VLSS vs. LOFAR map of field around 3C196
3C196 on long baselines: expectations

Cambridge 5km at 5 GHz

[ Pooley & Henbest (1974) ]
First long baseline maps of 3C196
HBA observations of 3C196: some details

- 3C196, HBA, 120 / 244 subbands, 131–155 MHz
- bandwidth 24 MHz
- L2010_07608 12 h, 22nd May 2010
- 7 NL + 2 DE stations (Effelsberg, Tautenburg)
- corrected for 8 µsec in superterp, . . .
- (self-)calibrated and imaged YY in difmap
- phase jumps, rates, inconsistent delays (in freq)
- low S/N in German stations most of the time

- imaging very tough, details not reliable yet
HBA observations: uv coverage, dirty beam

beam size $1'.0 \times 0'.5$
LBA + HBA images of 3C196
LBA + HBA images of 3C196 with contours
Dynamic spectra of the Sun

Significant variability as function of time and frequency!
Variability: 10 min in 10 sec steps (1 subband)
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