Long Baseline Imaging with LOFAR

Putting the International into International LOFAR Telescope

Javier Moldón

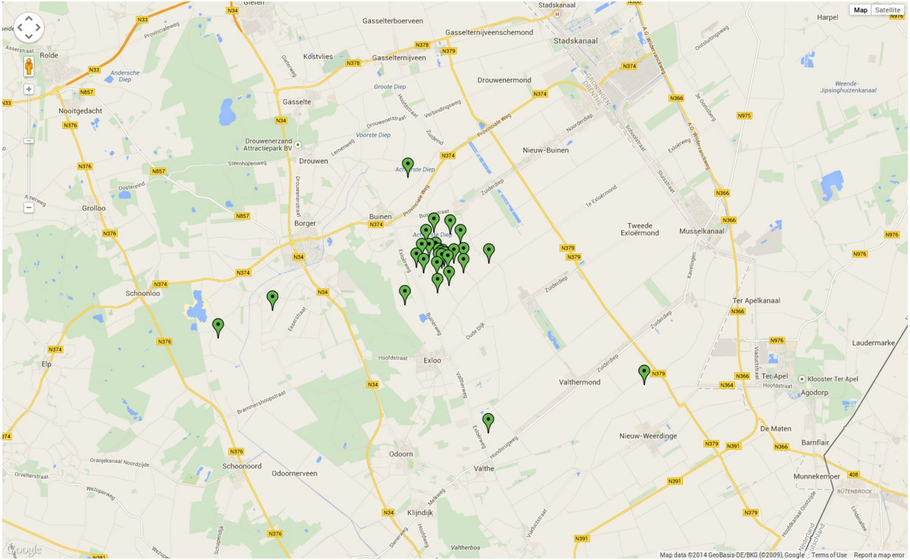
ASTRON Netherlands Institute for Radio Astronomy

3rd LOFAR Data Processing School
Dwingeloo, November 20, 2014

Outline

- What is LOFAR VLBI?
- Resolution!
- Differences between short and long baselines
- Calibration
- Practical considerations

Very short baselines (CS)



Intermediate baselines (CS+RS)

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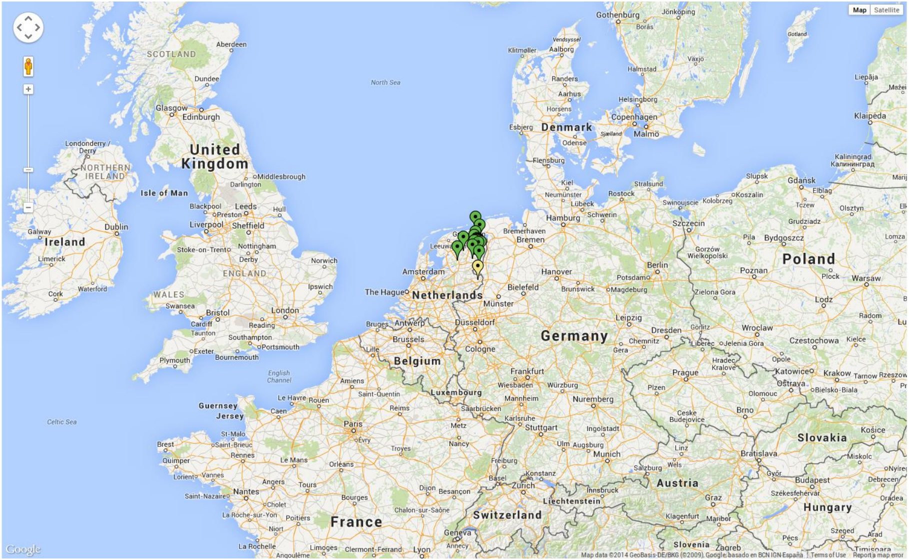
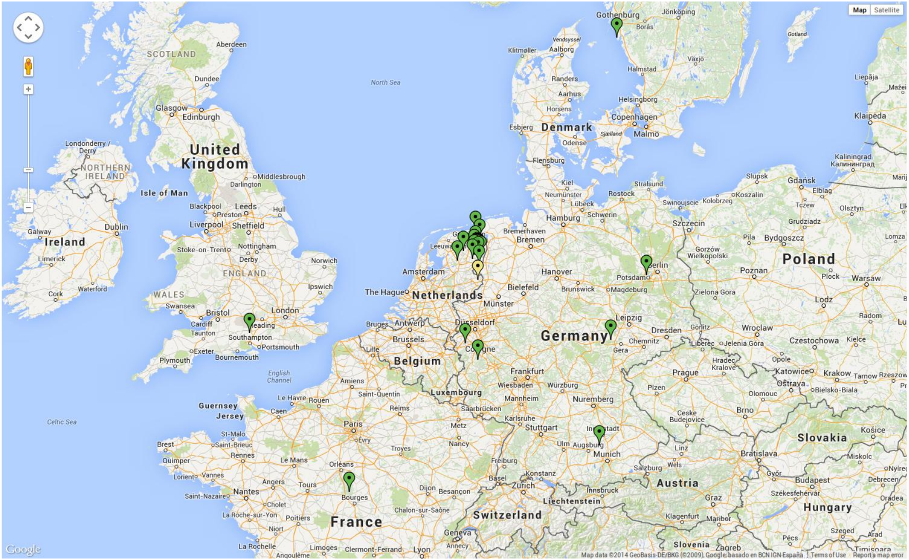
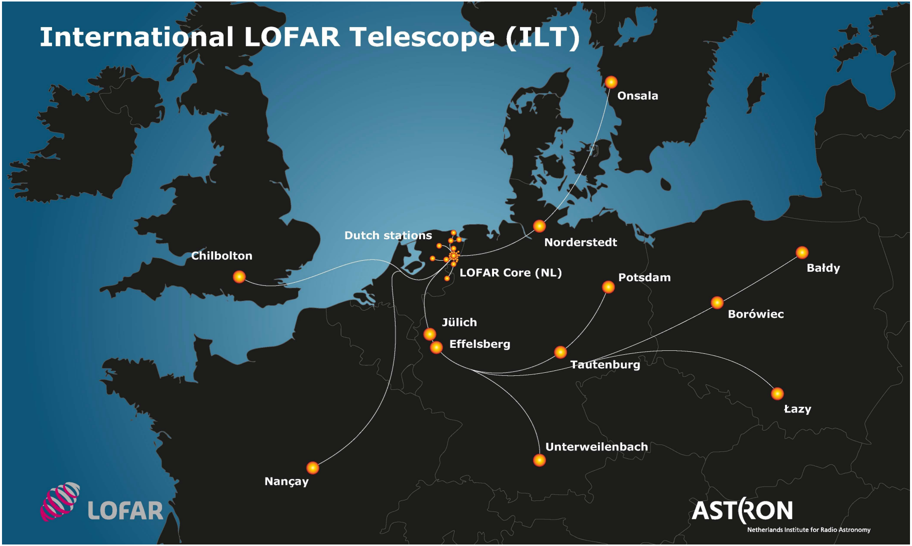


International LOFAR



International LOFAR

Future International LOFAR



Baselines between international stations

	CS001	DE601	DE602	DE603	DE604	DE605	FR606	SE607	UK608
CS001	0	266	581	396	419	226	700	594	602
DE601	266	0	390	344	476	53	490	833	590
DE602	581	390	0	277	455	440	690	990	959
DE603	396	344	277	0	186	372	800	714	920
DE604	419	476	455	186	0	487	957	556	1005
DE605	226	53	440	372	487	0	498	807	552
FR606	700	490	690	800	957	498	0	1292	495
SE607	594	833	990	714	556	807	1292	0	1110
UK608	602	590	959	920	1005	552	495	1110	0

$$\left[\frac{\theta}{\mathrm{rad}}\right] \approx \frac{\lambda}{B}$$

$$\left[\frac{\theta}{\mathrm{arcsec}}\right] \approx 206.3 \left[\frac{B_{\mathrm{max}}}{\mathrm{k}\lambda}\right]^{-1}$$

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International LOFAR resolution

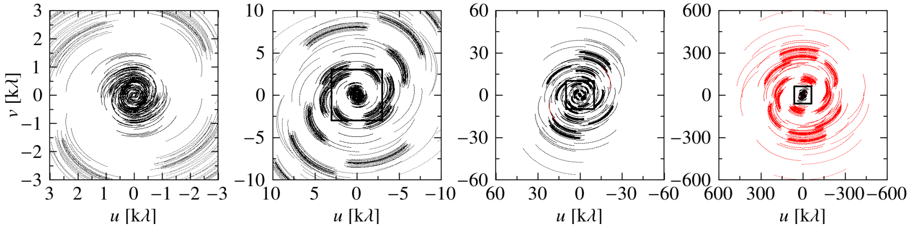


Figure : uv coverage for a typical 4-hr observation of a source at declination $+48°$ with a single subband centred at 140 MHz. Only one visibility every 160 seconds is shown. The rectangles in the last three panels show the area covered by the previous panel. Visibilities corresponding to baselines with international stations are plotted in red.

International LOFAR resolution

International station Beam and LOFAR synthesized beam (FWHM) as a function of frequency.

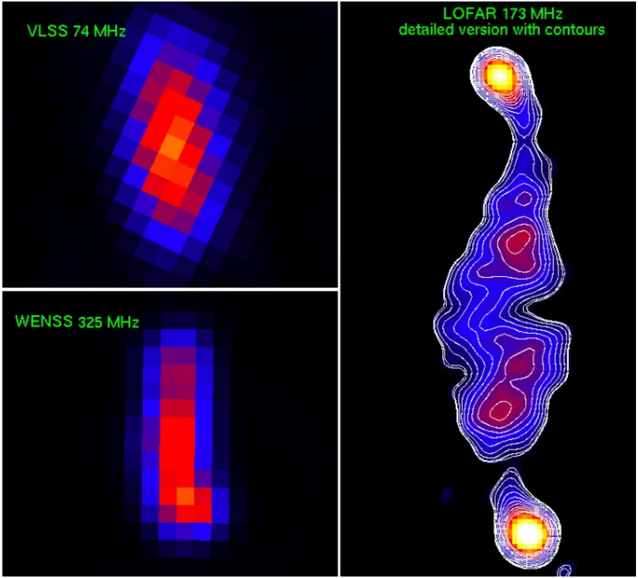
Freq. (MHz)	λ (m)	St. Beam (deg)	PSF ($''$)
15	20.0	19.4	3.30
30	10.0	9.7	1.65
60	5.0	4.8	0.82
120	2.5	2.6	0.41
150	2.0	2.1	0.33
200	1.5	1.6	0.25
240	1.2	1.3	0.21

Why high angular resolution?

3C61.1

80″

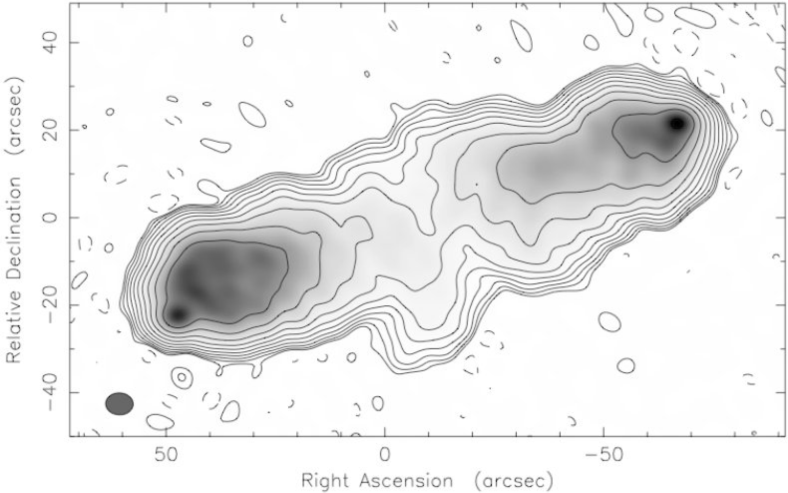
54″



$9.7'' \times 9.4''$

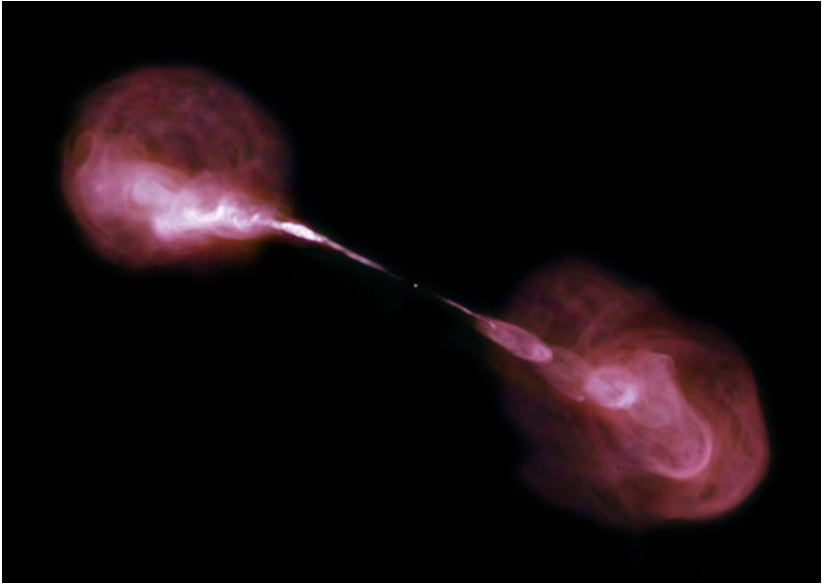
Why high angular resolution?

Cygnus A (240 MHz)



$6.3'' \times 5.01''$

Why high angular resolution?



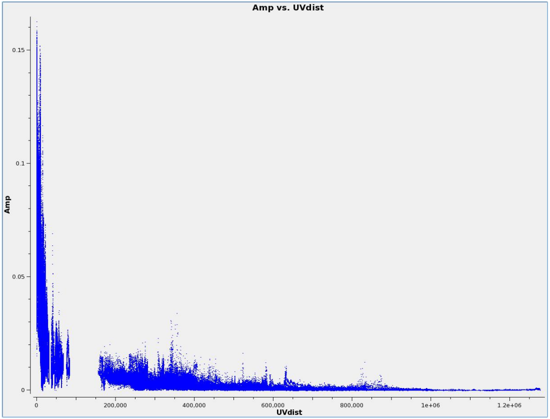
The curse of resolution

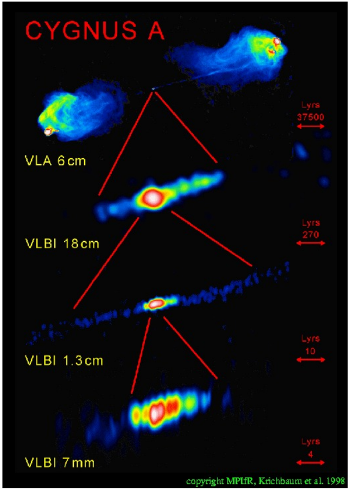
- If the object is larger than your synthesized beam, emission from different regions will interfere destructively and the source will be "resolved out".
- The surface brightness sensitivity is very low (array filling factor is low)

Long baselines are only sensitive to very compact structures.

LOFAR covers a huge range of uv-distances. Short baselines sample different "sources" than long baselines (different calibration).

The curse of resolution





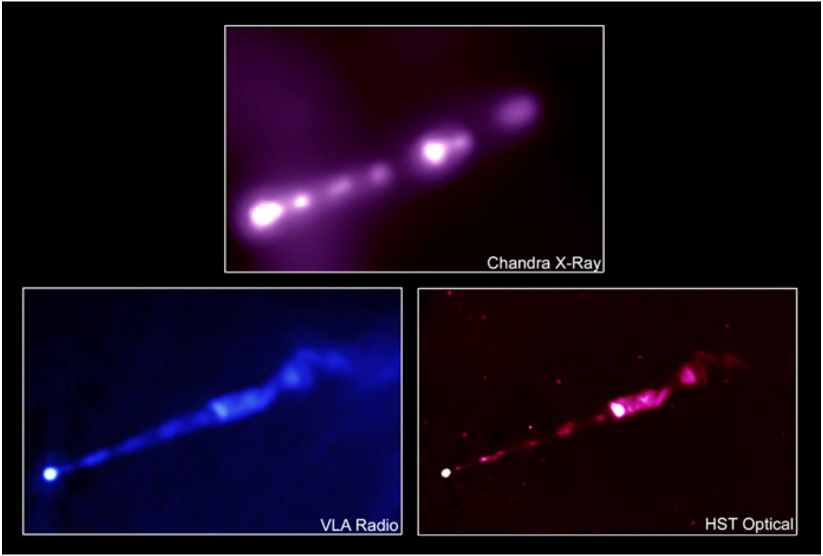
Matching resolution with other instruments

Matching with other instruments. 0.7arcsec resolution corresponds to:

- 3 km baselines @ 45 GHz (VLA C array)
- 9 km baselines @ 15 GHz (VLA B array)
- 27 km baselines @ 4.5 GHz (VLA A array)
- 100 km baselines @ 1.4 GHz (E-MERLIN)
- 1200 km baselines @ 120 MHz (Intl. LOFAR)

For each resolution we are sensitive to different parts of the source, so matching resolutions are needed for spectral analysis.

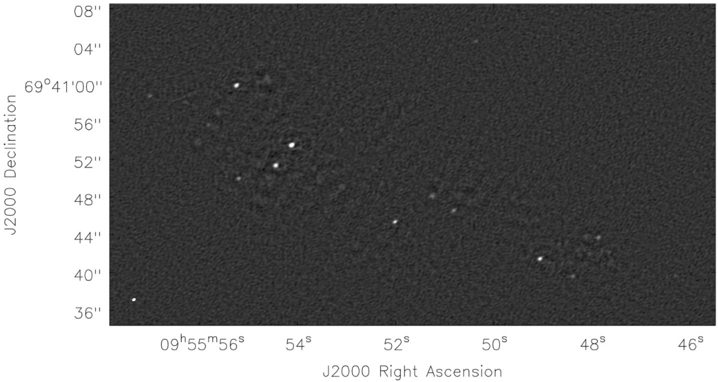
Matching resolution at other energy ranges



LOFAR Long Baselines are already here!

M82: Varenius et al.

- Observations with International LOFAR at 118 MHz and 154 MHz.
- Resolutions of about 0.35 and 0.3 arcsec.
- Close to thermal noise: 0.30 mJy/beam and 0.15 mJy/beam.



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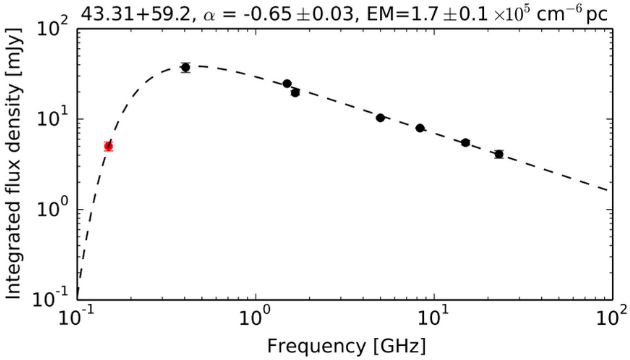
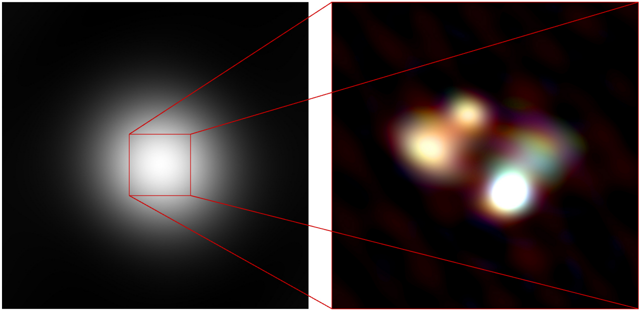


3C196 at 30–80 MHz

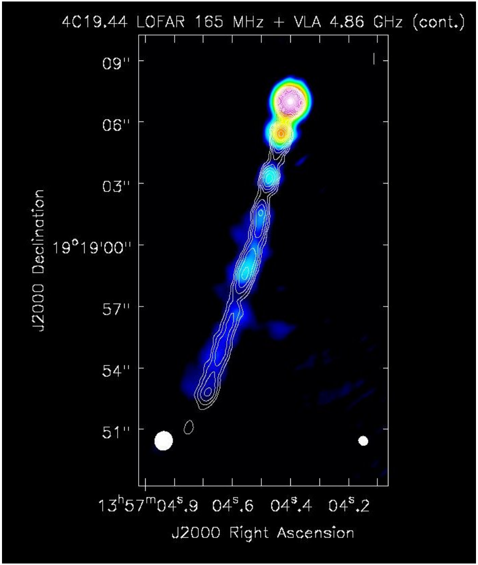
- High resolution images also possible below 100 MHz.
- Calibration of long-baselines LBA data is complicated.
- Dutch stations: 30″.
- When including just 3 International Stations: 1.5″



Olaf Wucknitz, 2010

Jet acceleration in 4C19.44

- Preliminary image done with only 3 MHz (1/16 of total)
- Similar resolution as VLA and *Chandra* observations.
- Testing the IC/CMB Model for X-ray Emission on knots along the quasar jet.



kpc structure of 4C55.16

- It is a radio galaxy at the centre of a cool core cluster of galaxies.
- Monitored in the MOJAVE project.
- Study of the source morphology at kpc scales and jet bending.

Do you want to see it? Oh well, then do the image yourself.
This is the source for Tutorial 4.

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Phases, delays, et al.

Long- vs short-baseline observations

There are not fundamental differences between long- and short-baseline data. Everything is interferometric data. Differences:

- Very different ionosphere. Fast and uncorrelated phase changes.
- Different electronics. Clocks.

To track the phase changes we have two basic magnitudes:

- Phase delay: phase slope with frequency [ns]

$$\tau = \frac{1}{2\pi}\frac{\partial\phi}{\partial\nu}$$

- Phase rate: phase slope with time [mHz]

$$r = \frac{\partial\phi}{\partial t}$$

Phase delay

$$\tau = \tau_{\rm geom} + \tau_{\rm source} + \tau_{\rm troposphere} + \tau_{\rm ionosphere} + \tau_{\rm instrumental} + \epsilon$$

- $\tau_{\rm geom}$: Source and station positions. Earth Orientation Parameters.
- $\tau_{\rm source}$: Source structure.
- $\tau_{\rm troposphere}$: Non-dispersive. Low impact for LOFAR
- $\tau_{\rm ionosphere}$: Dispersive. Main contribution for LOFAR!
- $\tau_{\rm instrumental}$: Clocks. Instrumental noise.

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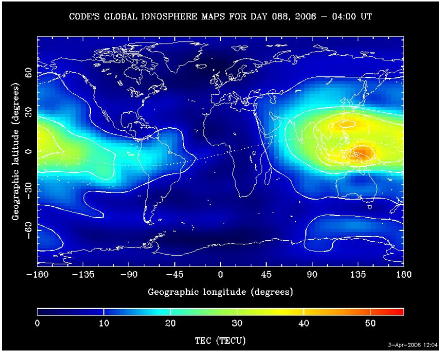
Ionospheric delay

- The Total Electron Content (TEC) is measured in TEC Units (10^{16} electrons m^{-2}).
- $\tau_{\mathrm{ion}} = \frac{c^2 r_{\mathrm{e}}}{2\pi\nu^2} \times \mathrm{TEC}$
- $\Delta\phi = 2\pi\nu\Delta\tau$

  $\Delta\phi = c^2 r_{\mathrm{e}} \frac{1}{\nu} \Delta\mathrm{TEC}$
- 1 $\mathrm{TECU} = \frac{1.34}{\nu_{[\mathrm{GHz}]}}$ cycles



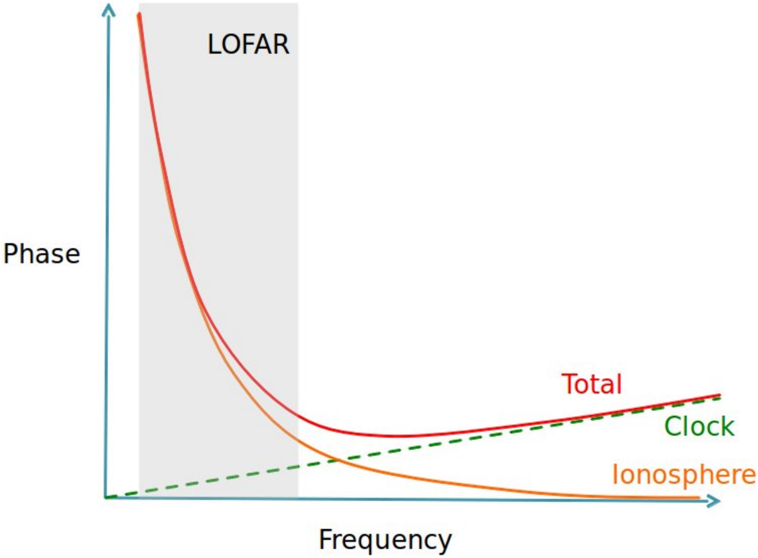
Phase delay

Why is the phase delay so important:

Table : Approximate delay contributions at 140 MHz to a 700 km baseline.

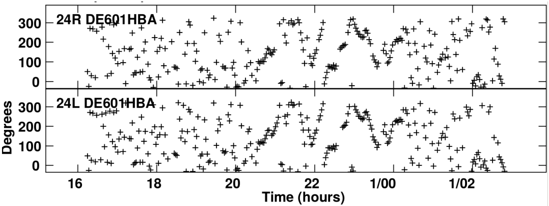
Effect	Delay	Time scale
	Non-Dispersive	
Correlator model error	~ 75 ns	24h (periodic)
Station clocks	~ 20 ns	$\sim$20 min
Source position offset (1.5″)	~ 15 ns	–
	Dispersive	
Slowly varying ionosphere	~ 300 ns	$\sim$hours
Rapidly varying ionosphere	$\gtrsim$10 ns	~ 10 min
Differential ionosphere (source elevation 60 deg)	5 ns/deg sep.	–

Phase calibration



Phases go wild!

- $\tau = \frac{1}{2\pi}\frac{\partial\phi}{\partial\nu} = 300\mathrm{ns} \implies \phi$ changes by 2π in ~ 3 MHz bandwidth.
- $r = \frac{\partial\phi}{\partial t} = 5\mathrm{mHz} \implies \phi$ changes by 2π in ~ 3 min.



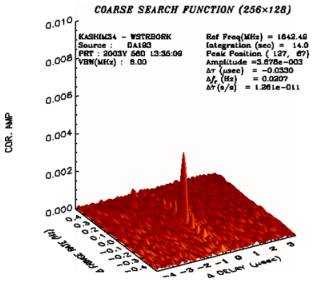
Difficulty:

- Phase calibration need narrow solution intervals: bright calibrator
- Differential directional delay: close calibrator

LOFAR Long Baselines calibration

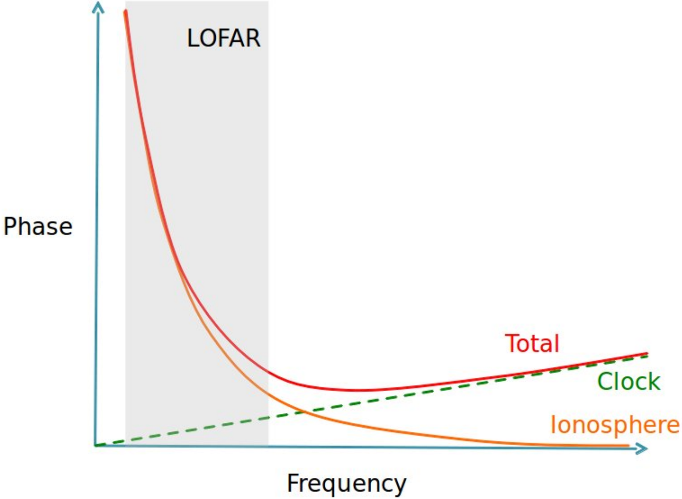
Phase calibration

- Time-variable delay offsets at each station.
- Solving directly for phases would require short time, narrow bandwidth: bad sensitivity.
- We can use "VLBI" tools to coherently combine more data: delay/rate search.
- We need to solve for [phase, phase delay, phase rate] simultaneously for each [station, time range, frequency range].



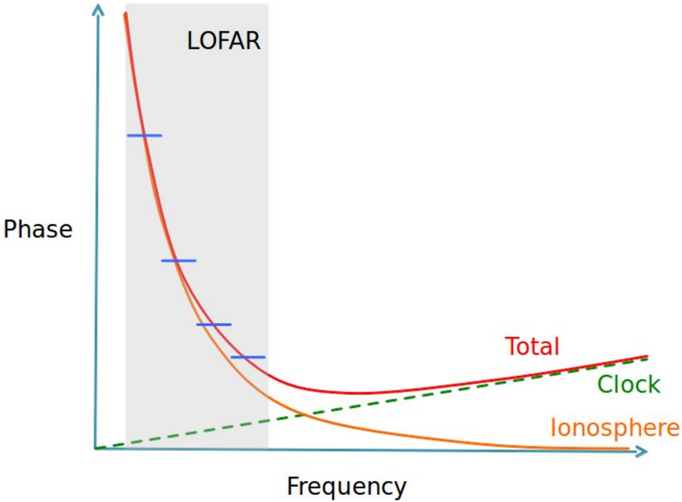
Phase calibration

- The phases change very fast because of the high delays at low nu.
- The ionospheric delay is dispersive, depends on the frequency.



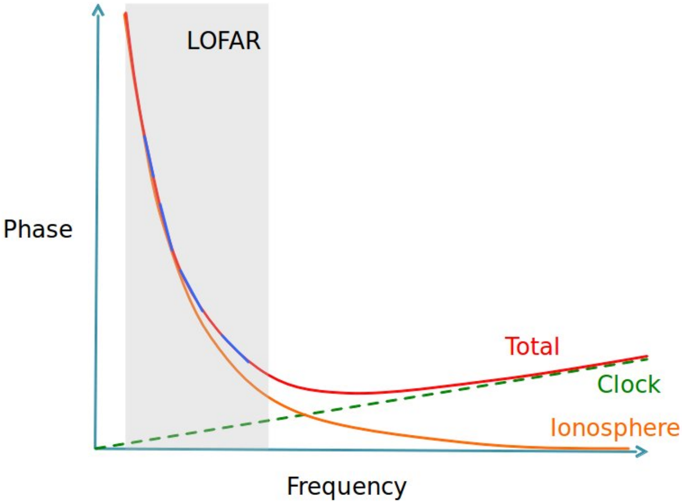
Phase calibration

- Standard phase calibration does not include changes across the band.
- Strong decorrelation occurs as more bandwitdh is added.



Phase calibration in AIPS

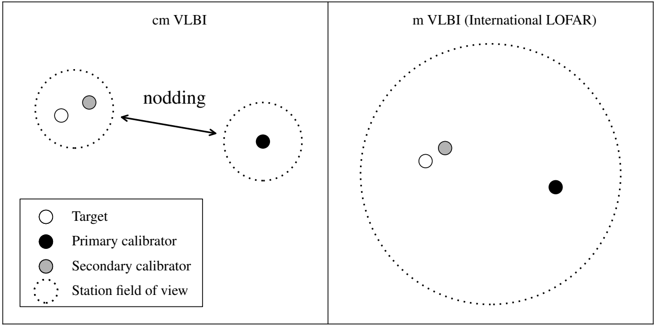
- Solving for non-dispersive delay we can include more bandwidth.
- Solving for dispersive delay for an even wider band is not possible yet.



Calibration strategy

We need different types of calibrators:

- Dutch array calibrator. Calibrate short baselines (and form combined station).
- Primary calibrator. To solve for stations delay.
- Secondary calibrator. Closer to target, to refine phase solution.



Calibration strategy

We need different types of calibrators:

- Dutch array calibrator.
  - Very bright and well-known sources. 3C196, 3C84.
  - Known flux density to set scale.
  - Can be several degrees away.
  - Apply normal LOFAR calibration techniques (BBS, NDPPP).
- Primary calibrator.
  - Compact source.
  - Moderately bright (above 50 mJy on the longest baselines).
  - Separations of $\sim$degrees.
  - Fringe-fitting in AIPS (non-dispersive delay, using $\sim$3 MHz 'subbands').
  - We determined that there is ~ 1 suitable primary calibrator per square degree.
- Secondary calibrator.
  - Relatively faint source (5–10 mJy).
  - Close to target $\sim$ arcmin.
  - Normal phase calibration (residual delays are small).

Amplitude calibration

- What we need:
  - Compact source.
  - Has to be bright.
  - With known and stable flux density.
- What we have:
  - Low-resolution catalogues provide flux density at very different scales.
  - Most sources are resolved, and we don't know its structure.
  - No catalogue of compact sources.
  - Compact and bright regions of potential calibrators, usually AGN, are expected to change with time.
- What to do?
  - Instrumental gains within LOFAR could be tracked with time. This option is currently being commissioning with the COBALT correlator.
  - Self-calibrate a bright calibrator to find its small-scale structure, and bootstrap its flux density between the short and long baselines
  - Good compact sources are pulsars, which should show the same flux density at short and long baselines (link).

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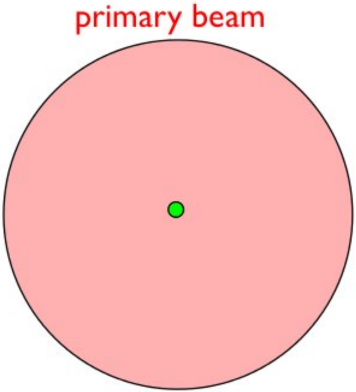
Practical considerations

Limited Field of View

- Time smearing and bandwidth smearing are intense because of high fringe rate.
- Even if correlator can make necessary visibility dataset, it will be HUGE.

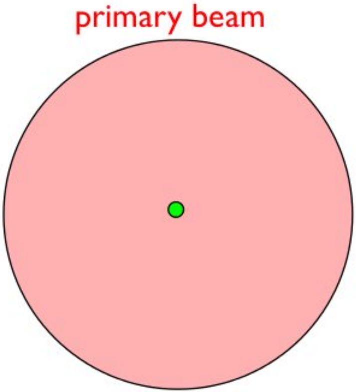


Limited Field of View

- International station beam:
  $\theta \sim \frac{\lambda}{D} \sim 2$ deg at 140 MHz.

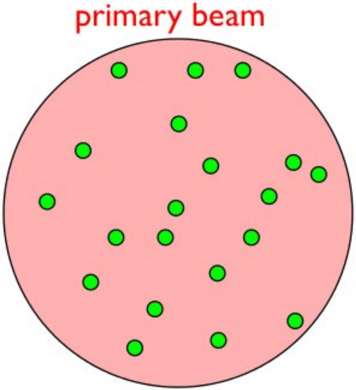
- Synthesized beam:
  $\Theta \sim \frac{\lambda}{B_{\max}} \sim 0.3$ arcsec.

- Number of pixels:
  $M^2 = (\frac{L}{D})^2 \sim 10$ Gigapixels.



Limited Field of View

- Postage-stamp approach: only map small regions of interest.
- Multiple small output datasets centered on sources of interest.
- We need to know where interesting sources are:
- We can use a low-resolution image with the same data, or some catalogue: MSSS, VLSS, WENSS.
- Operation can be done easily in NDPPP by setting the coordinates of new phase centers.



Distributing bandwidth on different sources

- General LOFAR feature, not specific of long baselines.
- It is useful to obseve target + calibrator. But even better...

- Fast search of calibrators:
  - For example one can generate 30 beams to observe simultaneously 30 sources with 3 MHz bandwith
  - No need for shifting. Averaged data.
  - Computationally inexpensive.

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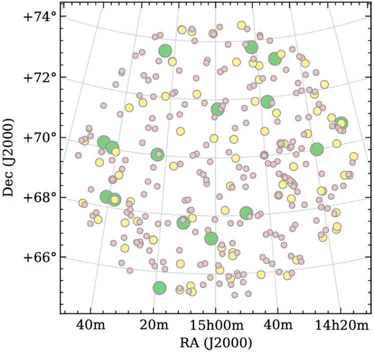
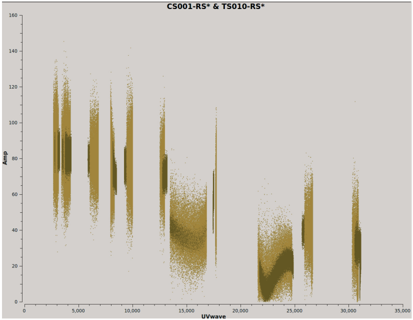


Form a combined super-station

- When studying the compact structure of a source, the shortest baselines do not add too much information.
- They can make calibration much difficult. Much greater sky region, brighter sources, diffuse sources.
- The core stations can be added to form a coherent “tied station” (TS001) that keeps the core sensitivity and the long baselines to the international stations.



Form a combined super-station

- Multiple benefits!
  - Significantly reduce the data volume. $\sim 1000 \implies 250$ baselines.
  - Very sensitive stations Ideal for calibration.
  - Very small FoV. (Very attenuated sidelobes).
  - Core stations are not lost, can be used anyway.
- How to form a tied station:
  - Core stations share the same clock and are under similar atmospheric conditions. No need to fring-fitting.
  - We have to observe a bright primary calibrator once every ~ 1 hr.
  - NDPPP task "StationAdder"
  - Core-Core baselines can be discarded using the NDPPP task "Filter".

Linear to circular polarization

- Differential Faraday rotation introduces rapid phase changes into linear polarization data on long baselines.
- The disturbances are coupled in amplitude and phase.
- Differential Faraday rotation does not mix R and L polarizations.
- Standard VLBI techniques like fringe fitting work in a circular (R,L) polarization basis.
- How to covert X-Y to R-L:
  - The station beam should be calibrated with BBS before converting the data
  - Using the Table Query Language (TAQL).

```
update <filename.ms> set DATA = mscal.stokes(DATA,'circ')
update <filename.ms>/POLARIZATION set CORR\_TYPE=[5,6,7,8]
```

Convert to UVFITS

- AIPS understands the UVFITS-format, but not Measurement Sets.
- You may use the tool ms2uvfits available at the LOFAR cluster.

```
ms2uvfits in=[input-MS] out=[output-FITS] writesyscal=False
```

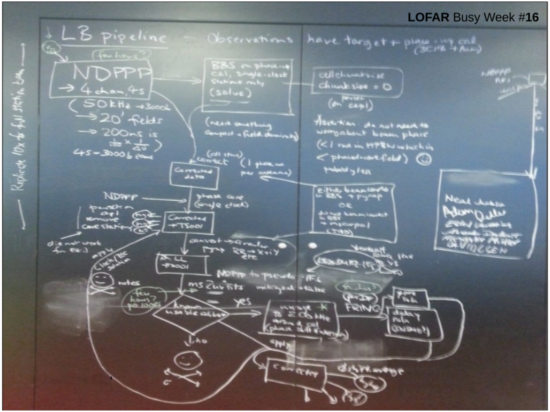
- Or the function “exportuvfits” in CASA.
- UVFITS requires that the data are contiguous in frequency. If there is no contiguous subband coverage in frequency, it is possible to insert fake data.

Opening International LOFAR to not specialized observers

Long baseline group

- Calibrating long-baseline data requires special procedures and techniques.
- The long-baseline group has been working to understand the data, the calibration approach and the instrument.

John Conway
Adam Deller
Alexander Drabent
Tobias Carozzi
Neal Jackson
Anna Kapinska
John McKean
Javier Moldon
Leah Morabito
Eskil Varenius
Olaf Wucknitz
Philippe Zarka



Making long-baseline observations possible

- Testing and developing calibration and imaging strategies.
- Finding primary calibrators for long baseline observations.
  - The LOFAR long baseline snapshot calibrator survey.
  - LOBOS: the LOFAR Long-Basline calibratOr Survey.
- Developing the long-baseline pipeline.
  - Provide a FITS file that can be directly processed in AIPS.
  - Calibrate and phase-up the core stations, filter stations, convert to circular polarization, shifting to different phase centers, combining subbands and forming FITS file.
  - Saves PI from dealing with 10+ TB datasets
- Future.
  - Go to lower frequencies.
  - Supercharged calibration, using all available bandwidth simultaneously to solve for dispersive delay and dispersive delay rate.

International LOFAR Telescope (ILT)

hopefully no mystery any more soon ...

Thank you for your attention!