Long Baseline Imaging with LOFAR

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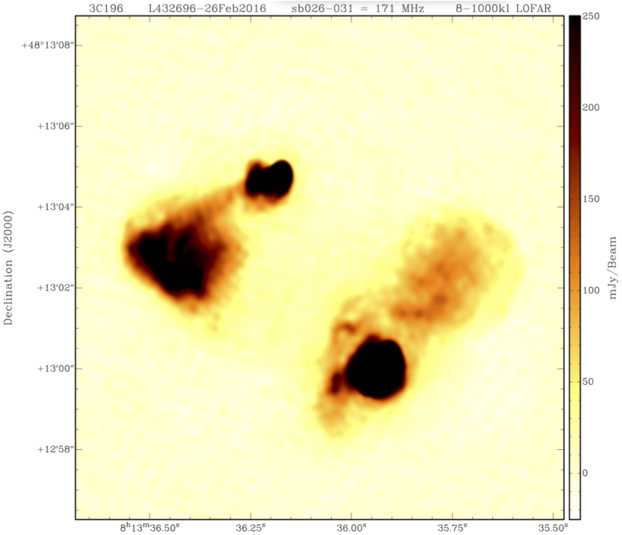
Jodrell Bank Centre for Astrophysics - The University of Manchester

4th LOFAR Data Processing School
Dwingeloo, September 8, 2016

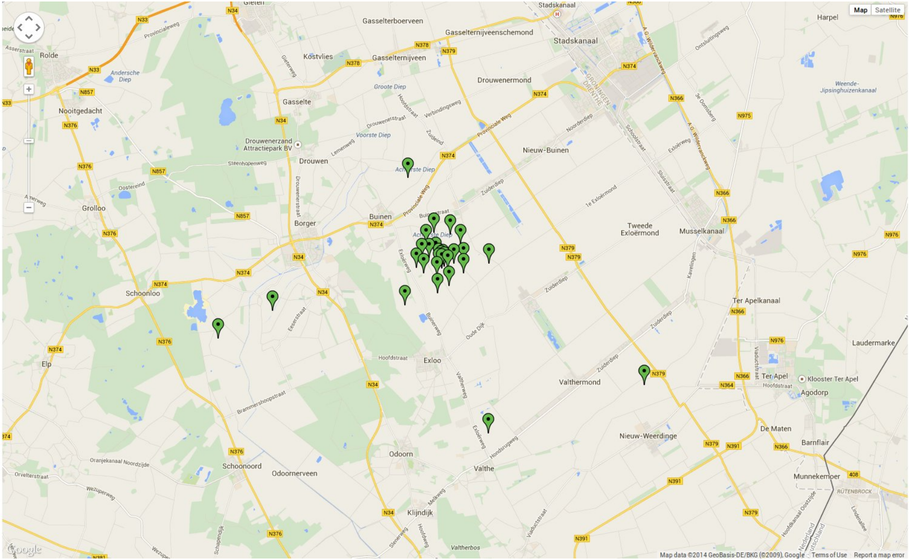
3C196 (Ger de Bruyn)



Outline

- What is LOFAR VLBI?
- Resolution!
- Challenges
- Calibration
- Practical considerations

Very short baselines (CS)



Intermediate baselines (CS+RS)

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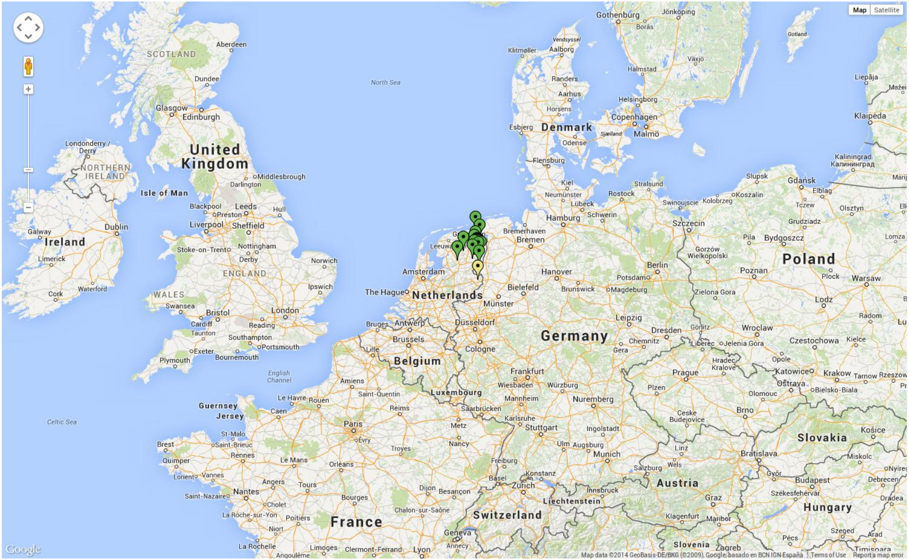
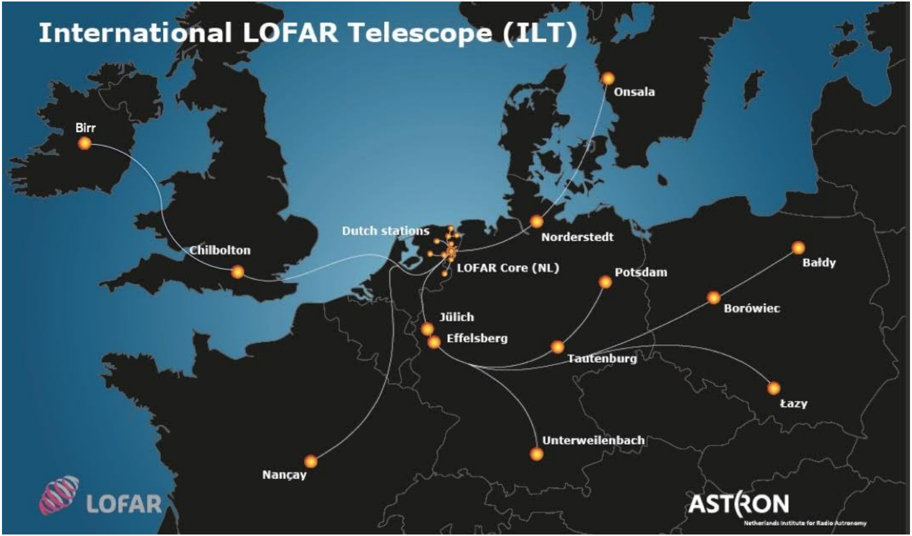


International LOFAR



Baselines between international stations

	DE601	DE602	DE603	DE604	DE605	DE609	FR606	PL610	PL611	PL612	SE607	UK608
DE601	0	390	344	476	53	412	490	734	970	997	833	590
DE602	390	0	277	455	440	585	690	587	689	862	990	959
DE603	344	277	0	186	372	325	800	398	633	671	714	920
DE604	476	455	186	0	487	248	957	277	590	524	556	1005
DE605	53	440	372	487	0	394	498	753	1002	1010	807	552
DE609	412	585	325	248	394	0	892	502	834	701	430	825
FR606	490	690	800	957	498	892	0	1197	1372	1468	1292	495
PL610	734	587	398	277	753	502	1197	0	351	278	658	1280
PL611	970	689	633	590	1002	834	1372	351	0	404	1000	1550
PL612	997	862	671	524	1010	701	1468	278	404	0	691	1515
SE607	833	990	714	556	807	430	1292	658	1000	691	0	1110
UK608	590	959	920	1005	552	825	495	1280	1550	1515	1110	0

$$\left[\frac{\theta}{\mathrm{rad}}\right] \propto \frac{\lambda}{B} \qquad\qquad \theta_{150\ \mathrm{MHz}} \approx \frac{400}{B_{\mathrm{max,\ km}}}\ \mathrm{arcsec}$$

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International LOFAR resolution

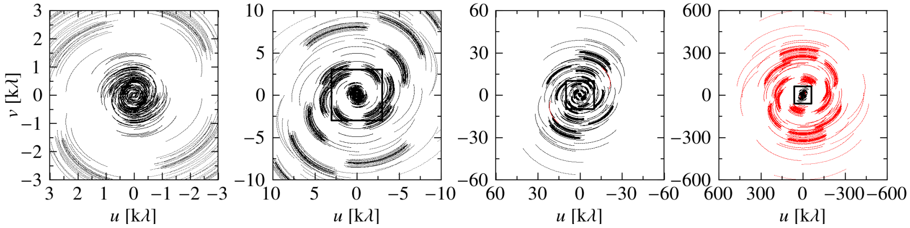


Figure : uv coverage for a typical 4-hr observation of a source at declination $+48°$ with a single subband centred at 140 MHz. Only one visibility every 160 seconds is shown. The rectangles in the last three panels show the area covered by the previous panel. Visibilities corresponding to baselines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

International LOFAR resolution

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

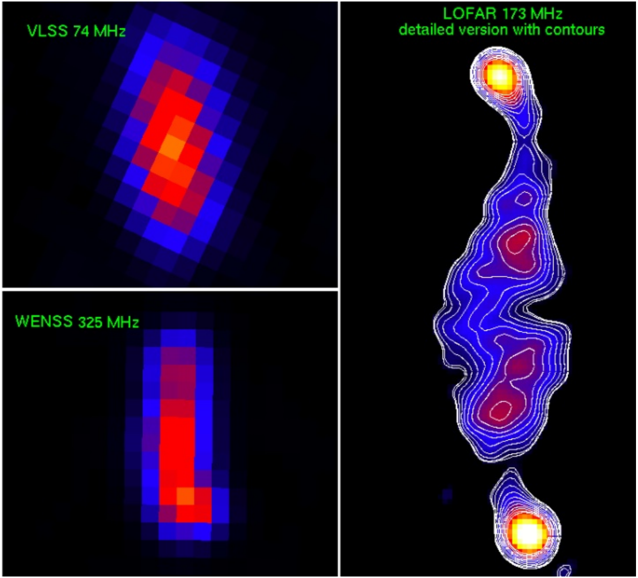
Freq. (MHz)	λ (m)	St. Beam (deg)	PSF ($''$)
15	20.0	19.4	2.6
30	10.0	9.7	1.3
60	5.0	4.8	0.6
120	2.5	2.6	0.32
150	2.0	2.1	0.26
200	1.5	1.6	0.19
240	1.2	1.3	0.16

Why high angular resolution?

3C61.1

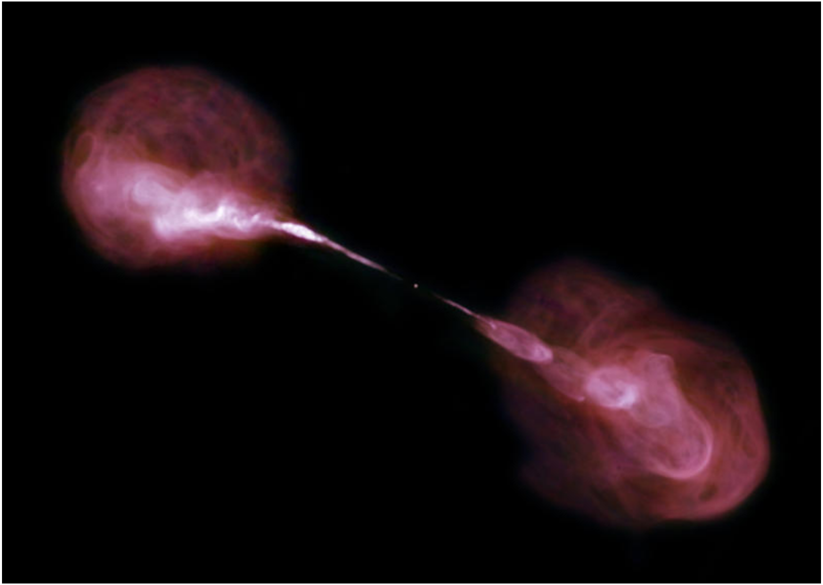
80″

54″

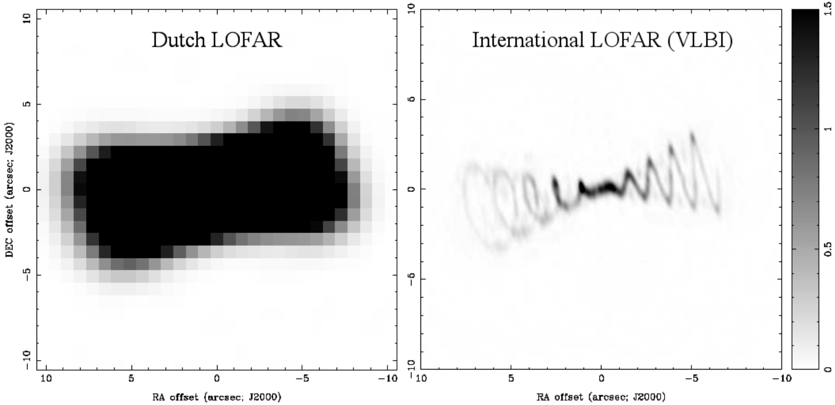


$9.7'' \times 9.4''$

Multiple scales



Going LOFAR VLBI



Simulation of the capacity to resolve the jet in the archetypal binary jet source SS433 of the Dutch array (top) and the whole array using VLBI techniques (bottom).

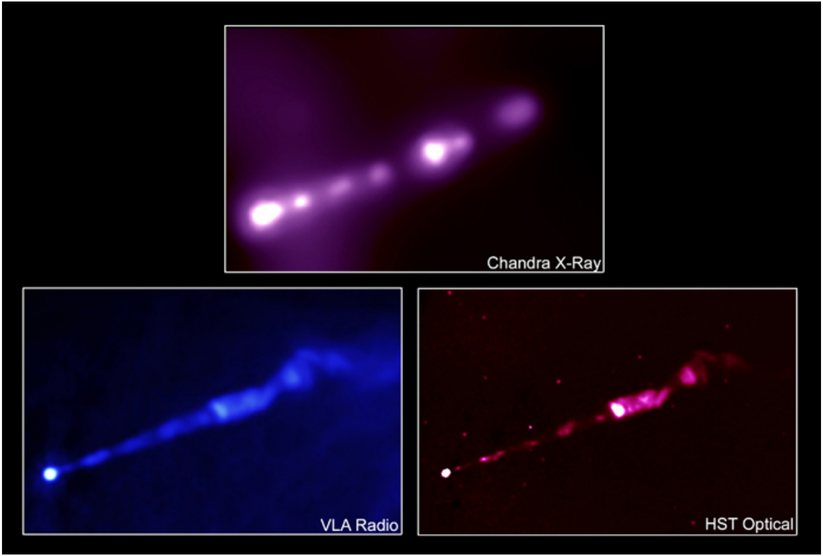
Matching resolution with other instruments

Matching with other instruments. 0.7arcsec resolution corresponds to:

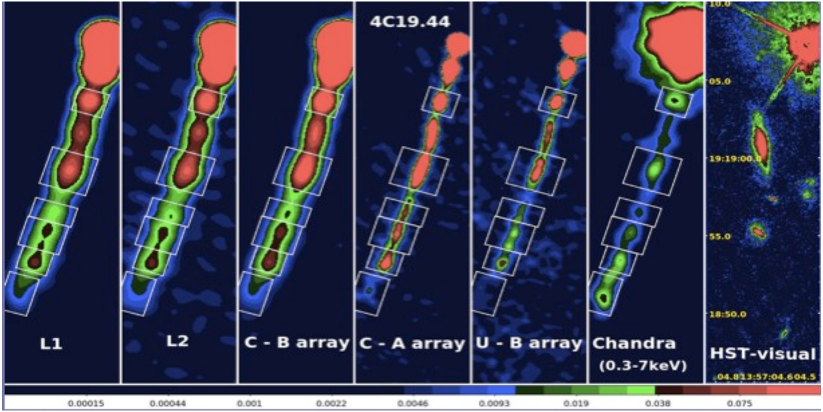
- 3 km baselines @ 45 GHz (VLA C array)
- 9 km baselines @ 15 GHz (VLA B array)
- 27 km baselines @ 4.5 GHz (VLA A array)
- 100 km baselines @ 1.4 GHz (e-MERLIN)
- 1200 km baselines @ 120 MHz (Intl. LOFAR)

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

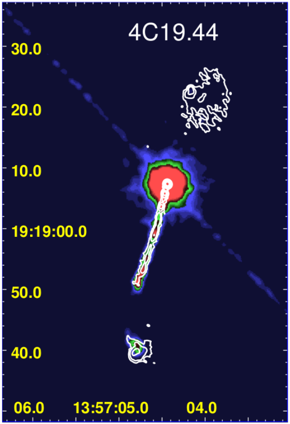


Jet acceleration in 4C19.44

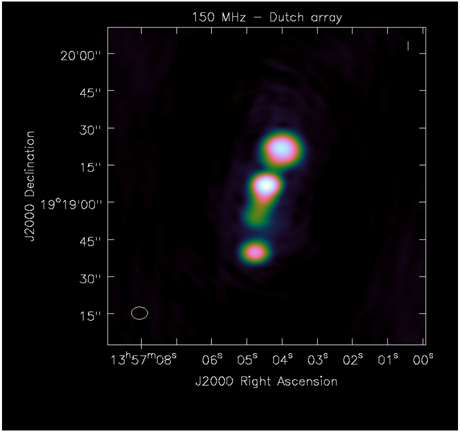


- This source has a long jet providing many resolution elements with Chandra's arcsec resolution.
- VLA maps at L, C, and U bands, and 180 ks with *Chandra*.

Jet acceleration in 4C19.44



VLA + Chandra

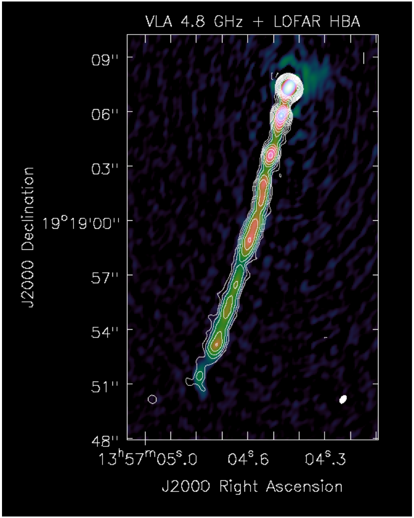


LOFAR (Dutch array)

LOFAR Long Baselines are already here!

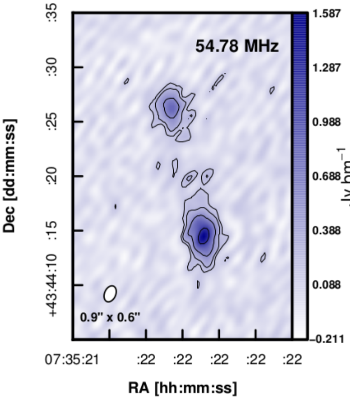
Jet acceleration in 4C19.44 (J. Moldon)

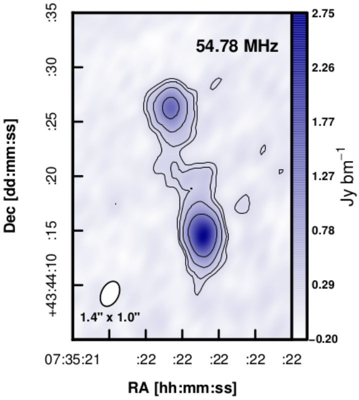
- Resolution is $0.5'' \times 0.3''$.
- Image rms is 85 μJy/beam (140 μJy/beam at the core).
- Dynamic range is about 10 000:1.



LOFAR LB at LBA 55 MHz! (L. Morabito)

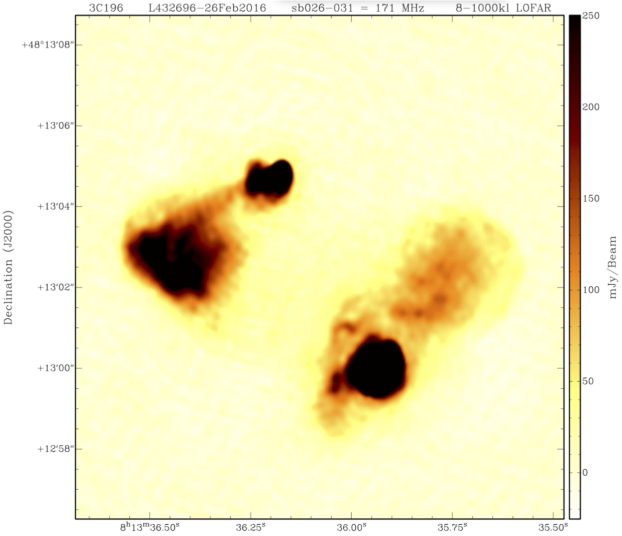
- 4C 43.15, a radio galaxy at $z = 2.4$.
- Resolution: 0.9 and 0.6 arcsec.
- Noise level: 60 mJy/beam.
- Morabito, L. K. et al. 2016, MNRAS, 461, 2676.





3C196 (Ger de Bruyn)

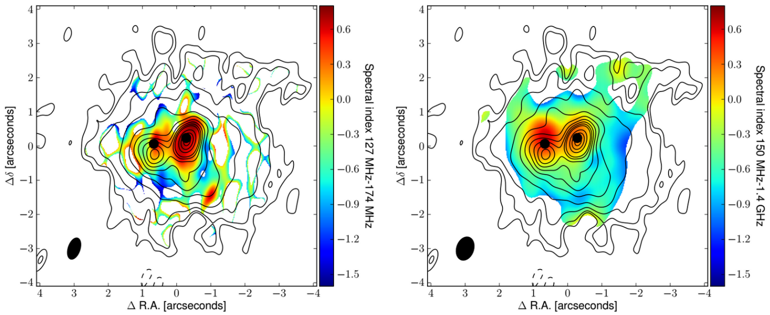
- Resolution: 0.2 and 0.3 arcsec. 5 subbands.



Arp 220 (E. Varenius)

- Arp 220 is an ultra luminous infrared galaxy (ULIRG).
- Resolution: 0.65 and 0.35 arcsec.
- Noise level: 0.15 mJy/beam.
- Varenius, E., Conway, J. E., et al. 2016, arXiv:1607.02761.

E. Varenius et al.: Subarcsecond international LOFAR radio images of Arp 220 at 150 MHz



(a) LOFAR in-band α, 127-174 MHz

(b) 150 MHz-1.4 GHz

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

kpc structure of 4C55.16

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Long Baseline challenges I:
Flux density

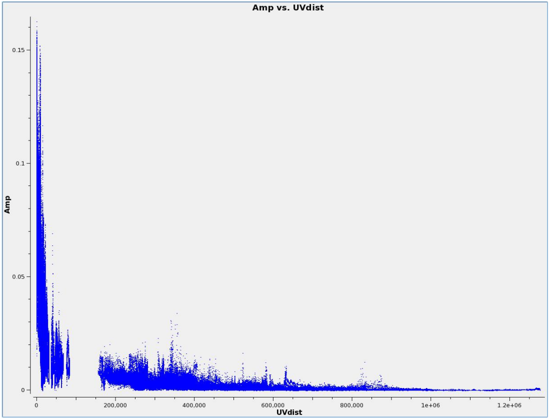
The curse of resolution

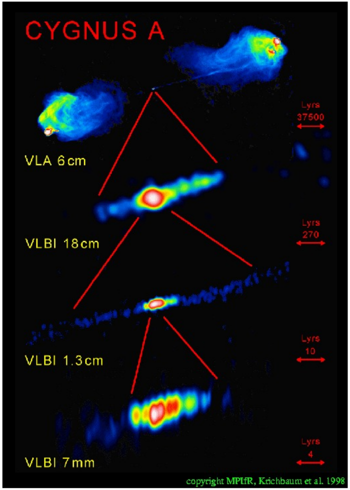
- If the object is larger than your synthesized beam, emission from different regions will interfere destructively and the source will be "resolved out".
- The surface brightness sensitivity is very low (array filling factor is low)

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





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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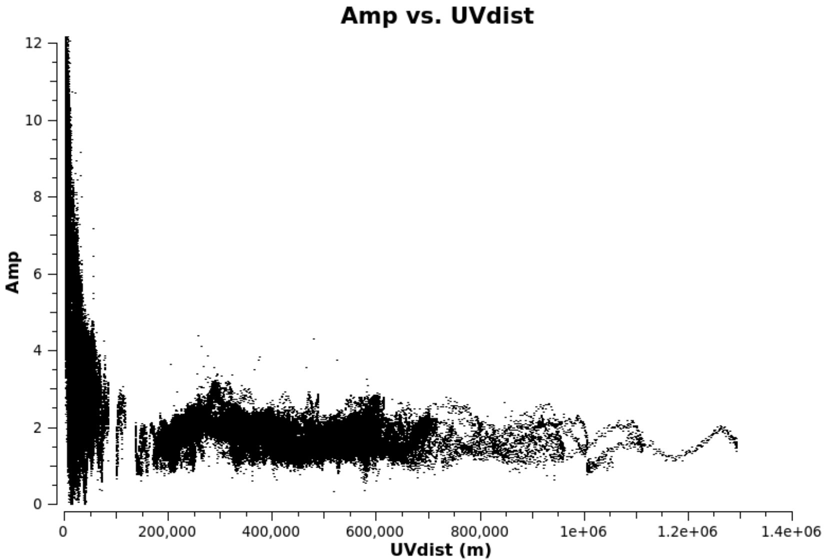
Calibration with long baselines



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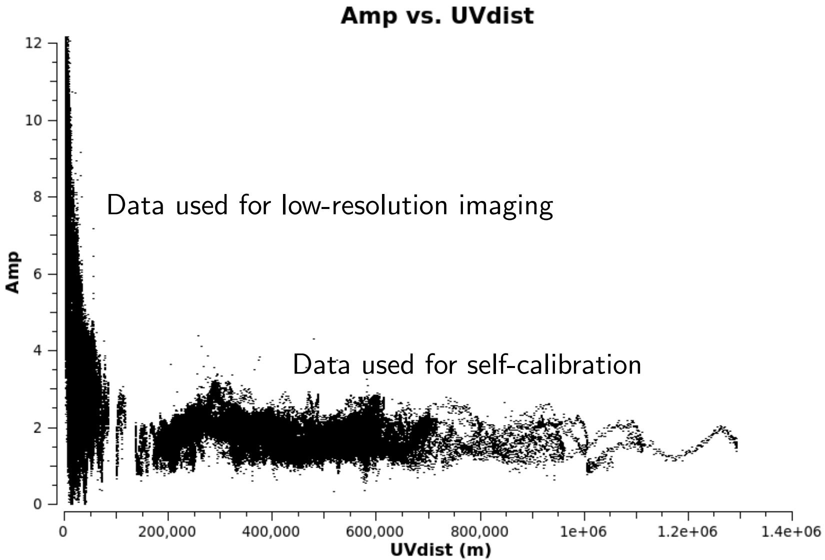
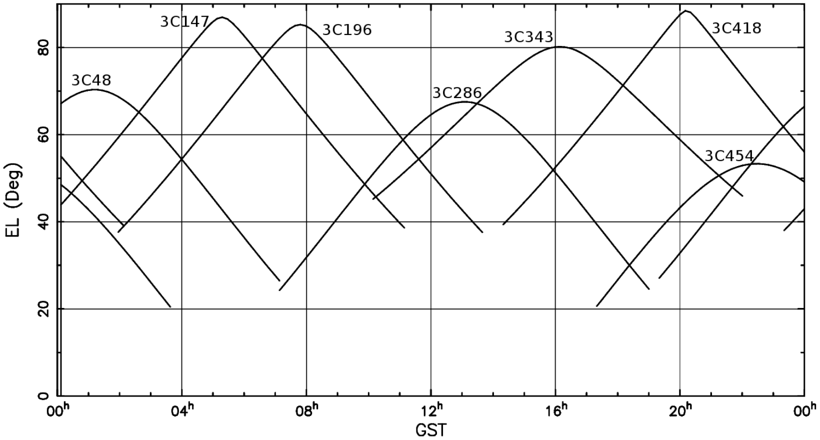


Flux calibration using source models

- Mapping the kpc-scale structure of Compact Steep Spectrum sources at 150 MHz. (PI: Adam Deller)



Long Baseline challenges II:
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

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

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

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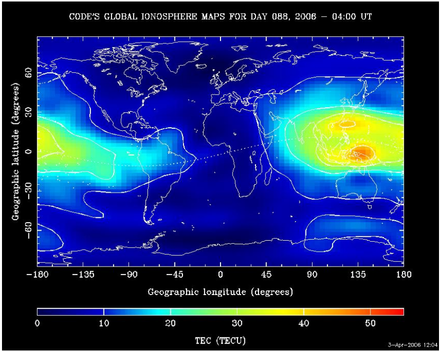
Ionospheric delay

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

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



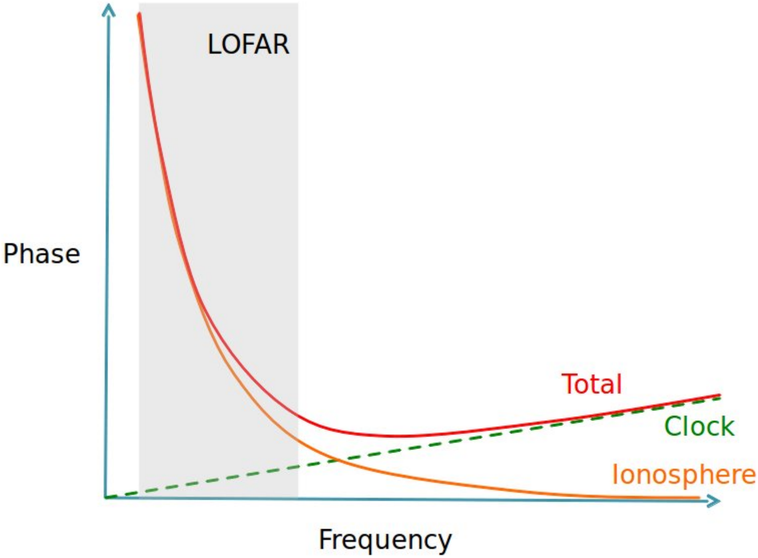
Phase delay

Why is the phase delay so important:

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

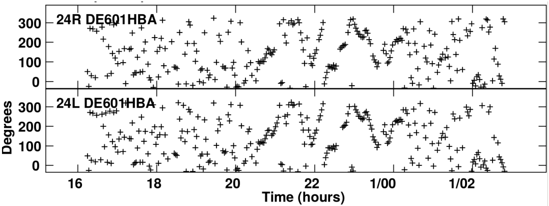
Effect	Delay	Time scale
Non-Dispersive		
Correlator model error	~ 75 ns	24h (periodic)
Station clocks	~ 20 ns	$\sim$20 min
Source position offset (1.5″)	~ 15 ns	–
Dispersive		
Slowly varying ionosphere	~ 300 ns	$\sim$hours
Rapidly varying ionosphere	$\gtrsim$10 ns	~ 10 min
Differential ionosphere (source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

Phase calibration



Phases go wild!

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



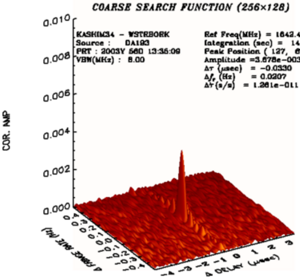
Difficulty:

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

LOFAR Long Baselines calibration

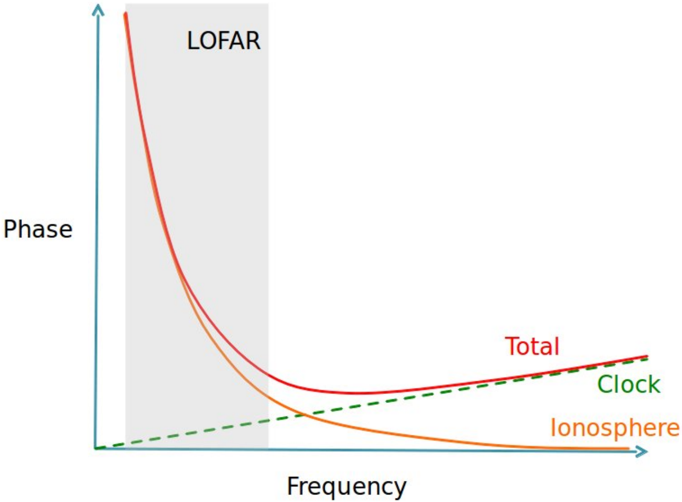
Phase calibration

- 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].



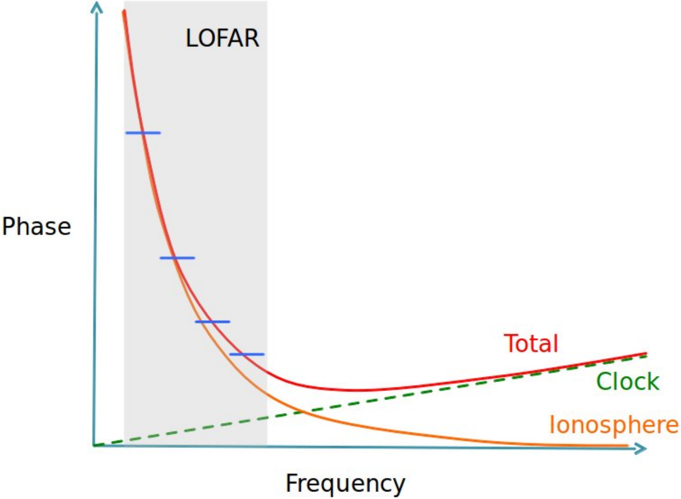
Phase calibration

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



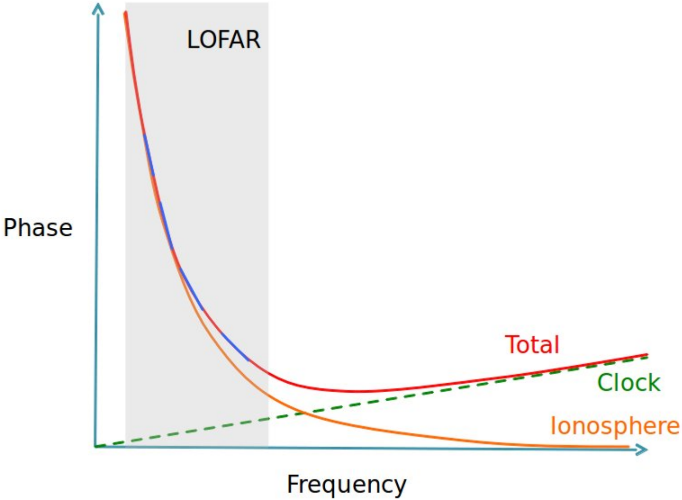
Phase calibration

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



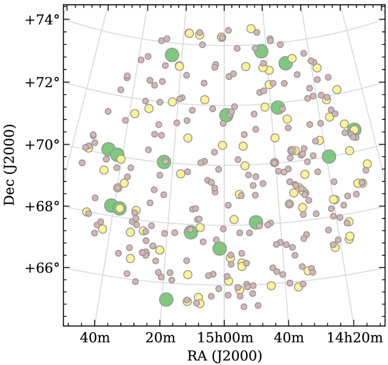
Phase calibration in AIPS

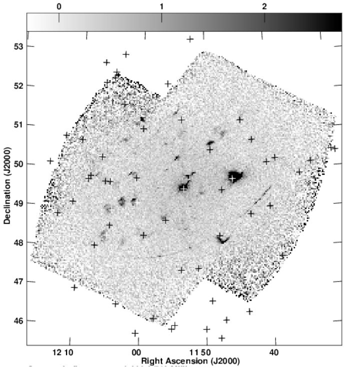
- Solving for non-dispersive delay we can include more bandwidth.
- Solving for dispersive delay for an even wider band is not possible yet.



Complete calibrator survey

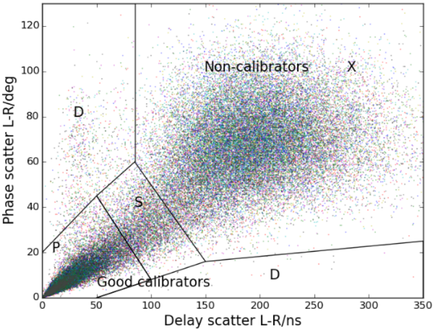
- The LOFAR long baseline snapshot calibrator survey. [Moldón et al. 2015, A&A 574, A73]
- LOBOS: the LOFAR Long-Baseline calibrator Survey [Jackson et al. 2016, A&A, arXiv:1608.02133]

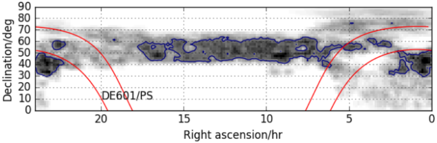




LOBOS (LBCS)

- The LOFAR Long-Baseline Calibrator Survey.
- Correlated flux densities $> 50 - 100$ mJy.
- 15 000 sources observed (published).
- Aiming for 30 000 sources covering the whole Northen sky.
- Our statistics show that there are $\sim$1 suitable calibrator/deg^2.





LBCS VO

http://vo.astron.nl/lobos/lobos/cone/form

vo.astron.nl

The VO @ ASTRON

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Please check out our site help.

Services available here

By Title | By Subject

L...

- LOBOS Calibrator Search
  LOBOS Calibrator Search
- [P] LOFARTIER 1 Image Archive
  The LOFAR HBA Tier-1 preliminary data release contains images and catalogs that characterise the low-frequency radio emission in the region of the HETDEX Spring Field. In excess of 40,000 sources are detected in the images that cover an area of over 350 square degrees, have a resolution of 25 arcsec, and typical noise levels of less than 0.5 mJy/beam.
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- [P] LOFARTIER 1 Source Catalogue
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M...

- [P] MSSS catalogue
  The Multifrequency Snapshot Sky Survey (MSSS) is the first major observing program to be carried out with LOFAR during its ongoing commissioning phase. This service queries the unified source catalogue database for the MSSS survey.
- [P] MSSS Image Archive
  The Multifrequency Snapshot Sky Survey (MSSS) is the first major observing program to be carried out with LOFAR during its ongoing commissioning phase. This service queries the archive of both LBA and HBA images.
- MSSS Verification Field Images
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LBCS VO

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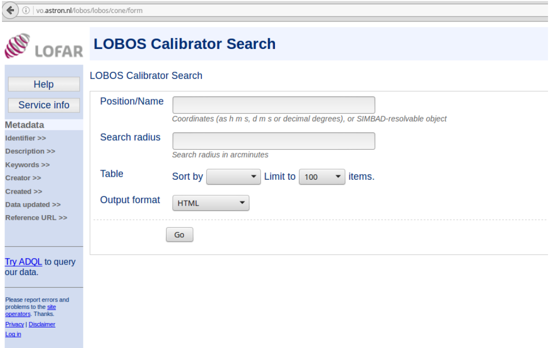

LBCS VO

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LOFAR

LOBOS Calibrator Search

Help

Service info

Metadata

Identifier >>

Description >>

Keywords >>

Creator >>

Created >>

Data updated >>

Reference URL >>

Try ADQL to query our data.

Please report errors and problems to the site operators. Thanks.

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Log in

Parameters

- Position/Name: 10.0, 50.0
- Search radius: 200.0

Result

Matched: 32

Send via SAMP | Quick Plot

Obs ID	RA [deg]	DEC [deg]	Date	Time	Baselines	Quality
L269411	7.02658333333	47.4528330556	2457086.5	12:32:02	PPP-PXPP	15
L269427	7.11454166667	48.4912219444	2457086.5	12:32:02	SXS-SXXXX	15
L270531	10.851625	47.2768330556	2457086.5	13:08:02	PPPPPPSPP	18
L269475	8.904125	48.1846938889	2457086.5	12:32:02	XXXXPXXXX	15
L270507	12.07725	47.8831388889	2457086.5	13:08:02	XXX-XXXXX	18
L270499	12.7472083333	47.8523061111	2457086.5	13:08:02	PPP-PPPXP	18
L269419	6.12158333333	48.9246388889	2457086.5	12:32:02	XXX-XXXXX	15
L269435	5.90283333333	49.3154438889	2457086.5	12:32:02	XXXXXXXXX	15
L269463	5.96441666667	49.5296669444	2457086.5	12:32:02	PPPXPXXXX	15
L269447	7.68079166667	48.7041669444	2457086.5	12:32:02	PPXPPSXPP	15
L269439	7.22045833333	48.9561938889	2457086.5	12:32:02	XXXXPXXXX	15
L269451	7.36020833333	48.9793888889	2457086.5	12:32:02	PPPPPPPPP	15
L269815	5.50725	50.0916938889	2457086.5	12:44:02	XXXXXXXXX	16
L269499	7.97754166667	49.9350830556	2457086.5	12:32:02	XXXXXXXXX	15
L269795	8.11095833333	50.2109719444	2457086.5	12:44:02	XXXXXXXXX	16
L269779	6.045375	51.1315280556	2457086.5	12:44:02	XXX-XXXXX	16
L269767	6.60825	52.4260280556	2457086.5	12:44:02	XXX-XXXXP	16
L323782	6.60825	52.4260280556	2457099.5	12:02:04	PXX-XXXXP	1
L270579	9.69970833333	48.8063888889	2457086.5	13:08:02	XXXXSXXXX	18
L269479	8.447375	49.1839719444	2457086.5	12:32:02	XXXXXXXXX	15
L270575	9.94583333333	49.00925	2457086.5	13:08:02	PPPPPPPPP	18
L270547	10.439125	48.3728330556	2457086.5	13:08:02	XXXXXXXXX	18
L270555	10.3294583333	48.502	2457086.5	13:08:02	XXXXSXXXX	18

Calibration strategy

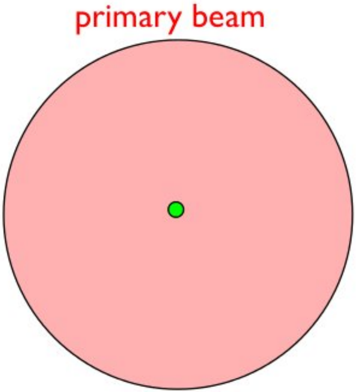
We need different types of calibrators:

- 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 ∼degrees.
  - Fringe-fitting in AIPS (non-dispersive delay, using ∼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).

Practical considerations

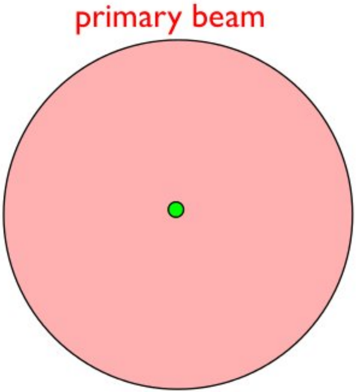
Limited Field of View

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



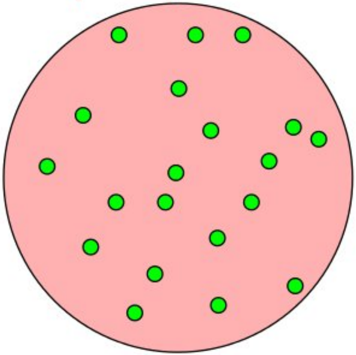
Limited Field of View

- 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.
- Time and frequency smearing isolates interesting sources

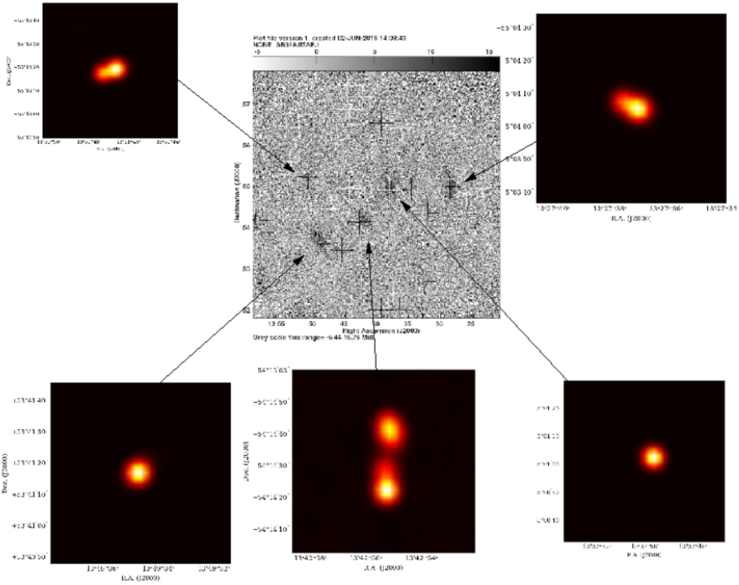


Limited Field of View

- 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.

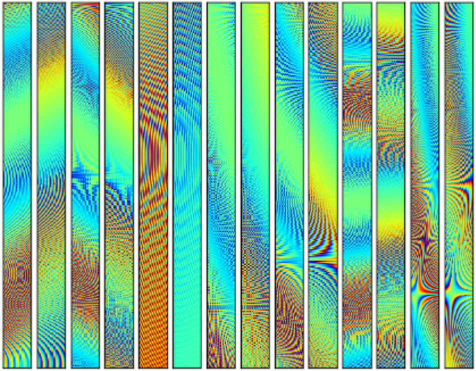


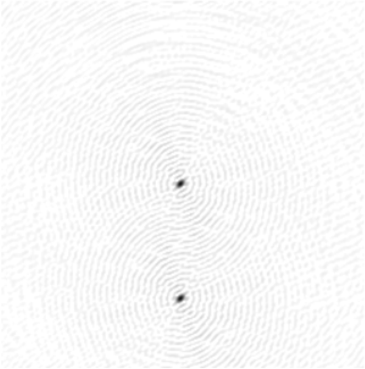
Fringe-rate mapping



Differential smoothing of data

- To reduce the field of view we need to smooth in time/frequency.
- This unfortunately needs a smoothing that is dependent on baseline.





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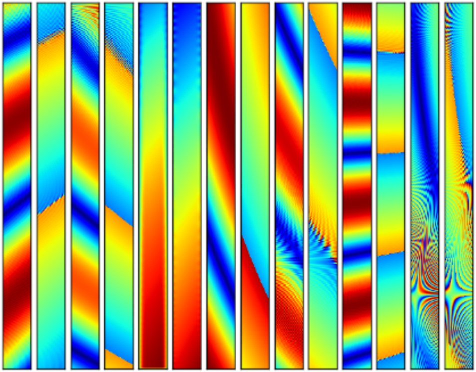
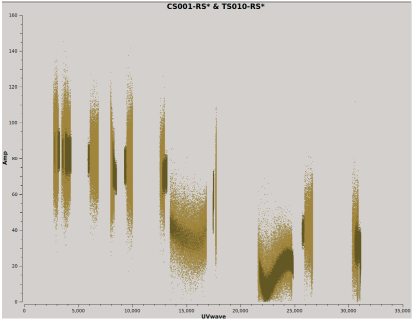


Form a combined super-station

- 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 convert 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.

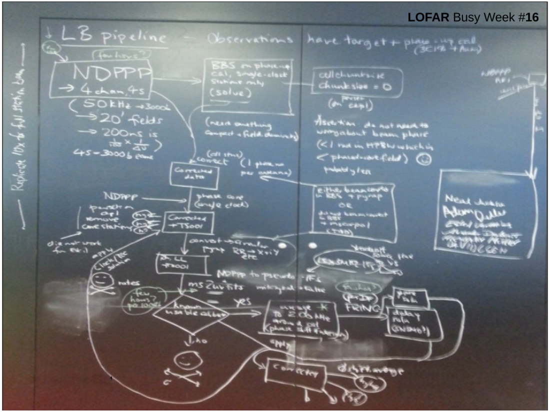
Processing summary

Step	Resource	Implementation
Data flagging	NDPPP	locapi.py/RO pipeline
Data averaging	NDPPP	locapi.py/RO pipeline
Obtain A&P calibration dutch array	NDPPP/BBS	locapi.py/RO pipeline
Apply A&P calibration dutch array	NDPPP/BBS	locapi.py/RO pipeline
uv shift	NDPPP	locapi.py
Form tied station ΣCS $\rightarrow$TS001	NDPPP	locapi.py/RO pipeline
Linear $\rightarrow$ circular polarization	TAQL	simple2circ.py
	pyrap	mscorpol.py (incl. beam)
Concatenation (Σsubbands $\rightarrow$ IF)	NDPPP	locapi.py/RO pipeline
MS $\rightarrow$ UVFITS	ms2uvfits	–
Load/indexing	AIPS	lofipi.py
Fix Weights	AIPS	lofipi.py
Fringe fitting	AIPS	lofipi.py
UVFITS $\rightarrow$ MS	CASA+TAQL	–
Low-resolution imaging	AIPS/CASA/WSclean	–
High-resolution imaging	AIPS/CASA/Difmap	–
Self-calibration	AIPS/CASA	–

Long baseline working group

- The long-baseline group has been working to understand the data, the calibration approach and the instrument.
- longbaselinelofar'@'astron.nl

Adam Deller
Alexander Drabent
Tobias Carozzi
Neal Jackson
Javier Moldon
Leah Morabito
Eskil Varenius
Stephen Bourke
Colm Coughlan
...



Putting the 'I' into the ILT