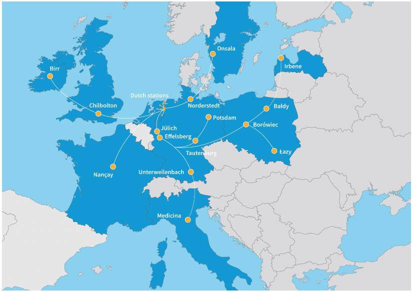
Long baseline calibration

(and why we should stop saying "long baselines")

6th LOFAR Data School

March 2021



Science and Technology Facilities Council

Durham University

Leah Morabito

UKRI Future Leaders Fellow

Durham University

LOFAR

What does *long baseline* mean?

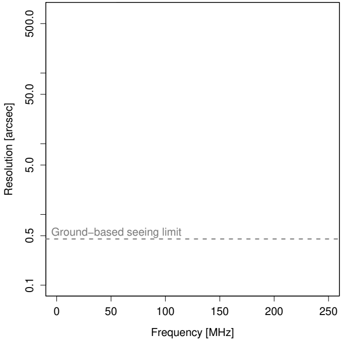
Outline

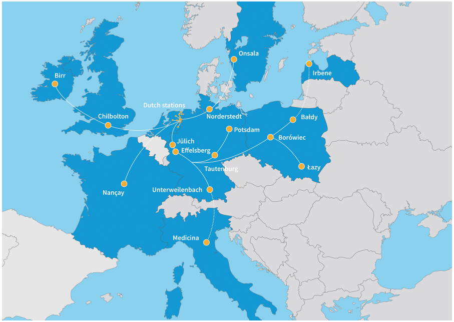
- The different resolutions of LOFAR
- Introduction to Very Long Baseline Interferometry (VLBI)
- LOFAR-specific challenges
- The LOFAR-VLBI pipeline
  - A demonstration with a typical field
- Setting up an observation
- Current / future work

The different resolutions of LOFAR

Flexible angular resolution dependent on stations used

Standard options:





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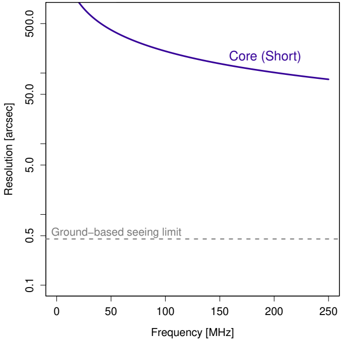

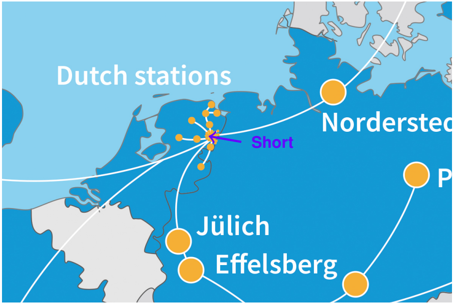

Core stations: 3′ at 150 MHz (max baseline 3.7 km)

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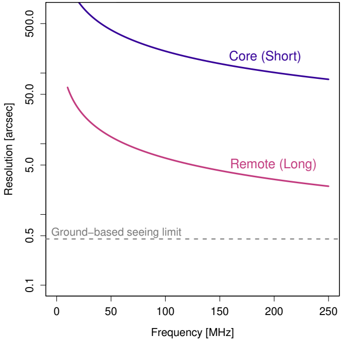

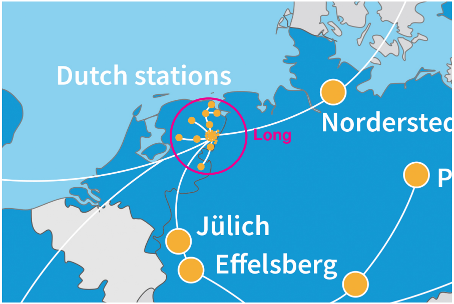

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Remote stations: 5″at 150 MHz (max baseline 120 km)

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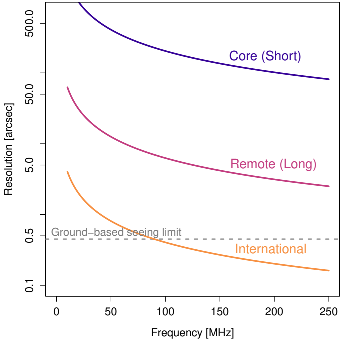
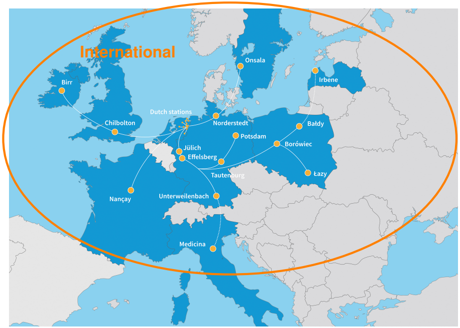




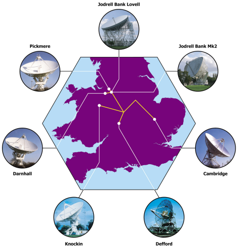
Core stations: $3'$ at 150 MHz (max baseline 3.7 km)

Remote stations: $5''$at 150 MHz (max baseline 120 km)

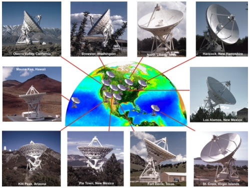
International stations: $0.2''$at 150 MHz (max baseline 1989 km)

Why do I need sub-arcsecond resolution?

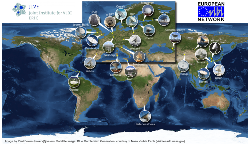
Very Long Baseline Interferometry: Arrays



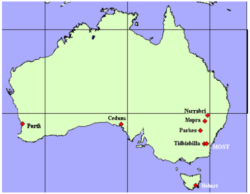
e-MERLIN



VLBA

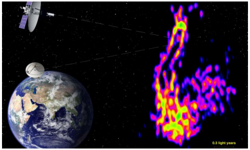


EVN



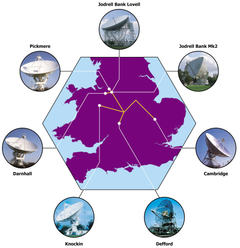
LBA

Tanami



RadioASTRON

Very Long Baseline Interferometry: Arrays



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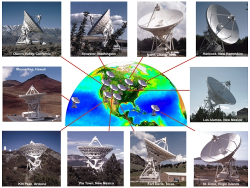

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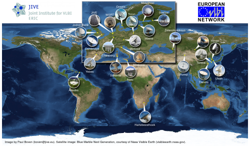

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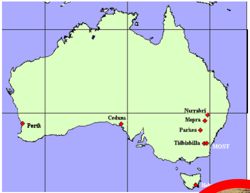

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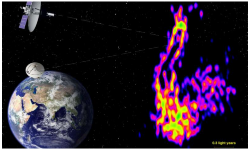

RadioASTRON

Very Long Baseline Interferometry: Arrays

	Frequencies	**Resolution**
e-MERLIN	1.5, 5, 22 GHz	150, 40, 12 mas
VLBA	0.3 - 80 GHz	22 - 0.12 mas
EVN	1.6 - 22 GHz	5 - 0.15 mas
LBA	1.4 - 22 GHz	22 - 1.4 mas
Tanami	8.4, 22 GHz	1.5, 0.7 mas
RadioASTRON	0.3 - 22 GHz	0.53 - 0.007 mas
LOFAR	*0.055, 0.120 GHz*	*900 - 250 mas*

Very Long Baseline Interferometry

Common element: stations are so far apart that they require separate (non-distributed) clocks

This drives:

- Non-(near)-real time correlation
- Clock / delay correction required
- Lower tolerance for errors in geometric model of array
- Having to cope with resolved sources

What part does resolution play?

baseline sensitivity: $$S_{ij} = \sqrt{\frac{S_{sys,i}}{\sqrt{2\Delta\nu\Delta t}} \frac{S_{sys,j}}{\sqrt{2\Delta\nu\Delta t}}}$$

note there is no dependence on baseline length!

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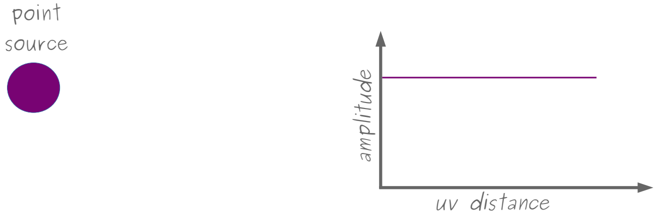

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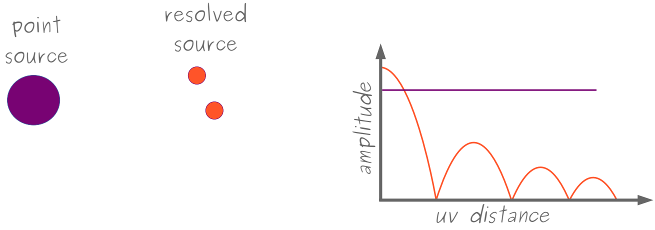

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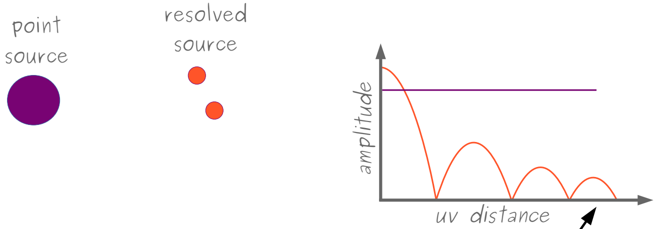

smaller signal on longer baselines

How might we improve signal to noise?

type a short answer in the Zoom chat

VLBI: The foundation

Take the relation between phase and delay:

$$\phi_{\nu,t} = 2\pi\nu\tau_t$$

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1st order expansion shows:

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

VLBI: the foundation

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

$\phi_0 \equiv$ the **phase** error at t_0, ν_0

$\frac{\delta\phi}{\delta\nu} \equiv$ **delay** or delay residual

$\frac{\delta\phi}{\delta t} \equiv$ **rate**, delay rate, or delay residual

The foundation

$$\Delta\phi_{\nu,t} = \phi_0 + \left(\frac{\delta\phi}{\delta\nu}\Delta\nu + \frac{\delta\phi}{\delta t}\Delta t\right)$$

$\phi_0 \equiv$ phase error a single time and frequency

$\frac{\delta\phi}{\delta\nu} \equiv$ how that phase changes with *frequency*

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Normal phase calibration only estimates ϕ_0

Fringe-fitting is any process that also estimates *delays* and *rates*

Effectively increases SNR by increasing solution interval

Baseline-based fringe-fitting

This equation can be described in terms of individual baselines, containing antennas i, j:

$$\Delta\phi_{ij} = \phi_{i,0} - \phi_{j,0} + \left(\left[\frac{\delta\phi_i}{\delta\nu} - \frac{\delta\phi_j}{\delta\nu} \right] \Delta\nu + \left[\frac{\delta\phi_i}{\delta t} - \frac{\delta\phi_j}{\delta t} \right] \Delta t \right)$$

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Construct this equation for each pair of baselines and solve for all baseline phases, delays, and rates.

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Disadvantages:

(1) that the source must be detected all baselines

(2) antenna-based quantities are not conserved

Global Fringe-fitting

Global Fringe-fitting is generally what people mean when they say *fringe-fitting*. Again we use:

$$\Delta\phi_{ij} = \phi_{i,0} - \phi_{j,0} + \left(\left[\frac{\delta\phi_i}{\delta\nu} - \frac{\delta\phi_j}{\delta\nu} \right] \Delta\nu + \left[\frac{\delta\phi_i}{\delta t} - \frac{\delta\phi_j}{\delta t} \right] \Delta t \right)$$

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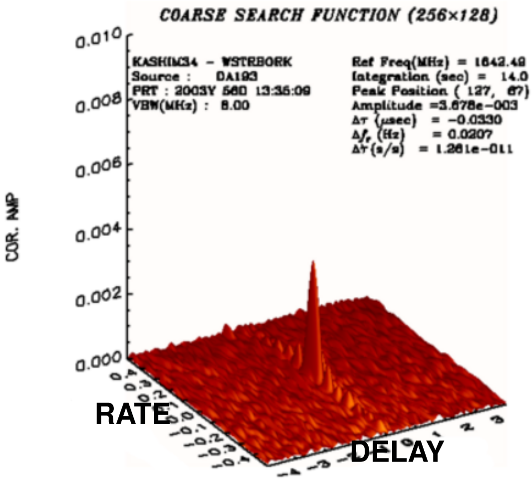
Major advantage:

Even if an antenna doesn't see a source on every baseline it is in, the antenna-based solutions *can still be found!* This is necessary for weak sources.

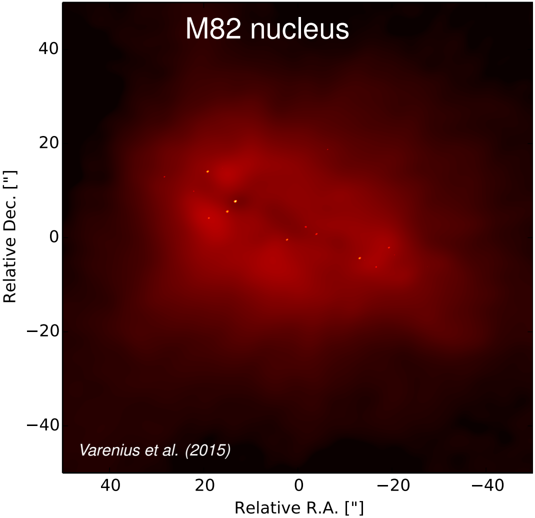
Fringe-fitting in practice

In practice, to make our lives easier we Fourier transform the data into the delay-fringe rate domain.



How does this work for LOFAR?

Fringe-fitting is implemented in AIPS*, used successfully for LOFAR



- HBA data
- converted to RR and LL
- channels of 5.3 MHz
- used only international stations

typical delays 100-300 ns
typical rates 1-3 mHz

now also in CASA! Not yet well tested with LOFAR data.

LOFAR specific challenges

Common VLBI challenges

Clocks	independent station clocks have to be synchronized
Correlator model	baselines up to 2000 km mean lower tolerance for errors
Source structure	not everything is a point source

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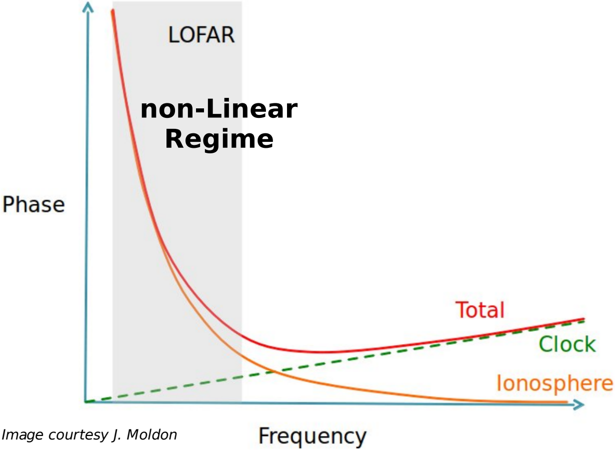
LOFAR specific challenges

Data Volume	typical observations are 4 - 20 TB
Ionopshere	causes dispersive delay
Sensitivity	only international stations use all 96 dipoles
Calibrators	need ‘Goldilocks’ calibrators: compact and bright enough
Wide field of view	FoV is $\sim$5 deg^2

LOFAR specific challenges

dispersive delay from the ionosphere

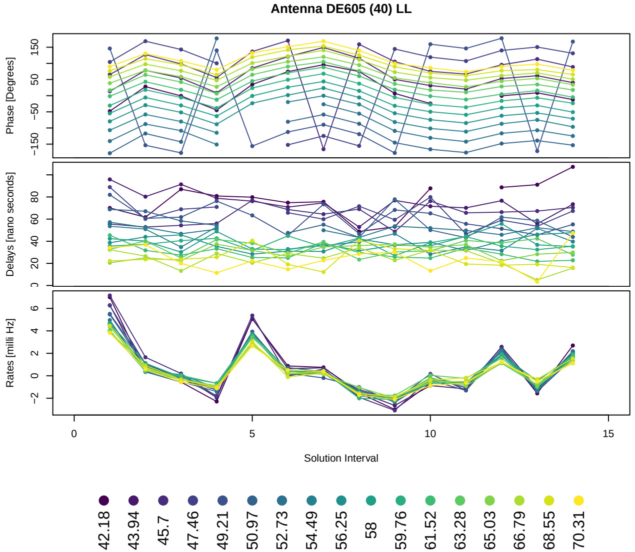


dispersive-delay fringe-fitting has only recently become available in CASA

LOFAR specific challenges

LOFAR LBA example

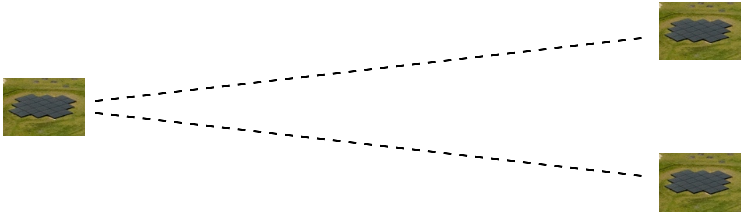
fringe-fitting in channels and fitting multi-channel delay after



LOFAR specific challenges

<u>combination of core stations:</u>

- increase sensitivity in centre of array
- reduce data volume by up to 80%



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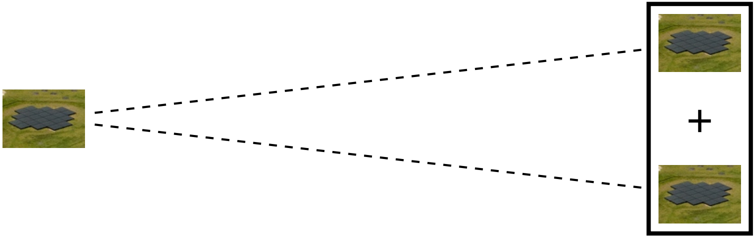

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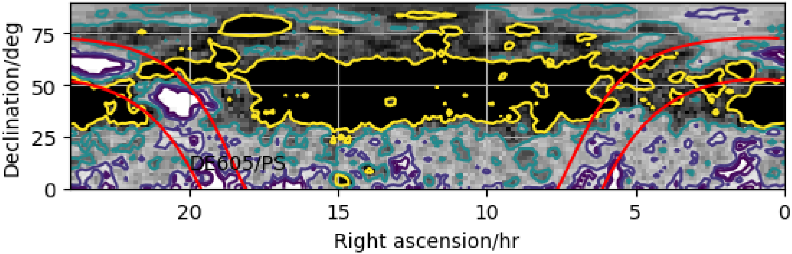
LOFAR specific challenges

Long Baseline Calibrator Survey (LBCS)

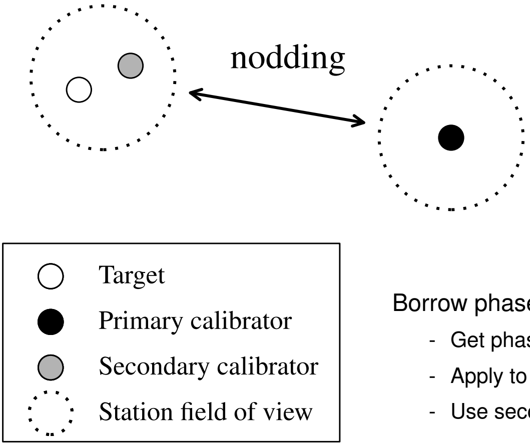
Jackson+ (submitted), Jackson+ 2016, Moldon+ 2014



- Selection: bright at low ν, flat low-ν spectral index
- Multibeaming: groups of 30 with 3 MHz bandwidth, 3 minutes each
- Now finished $\sim$30,000 sources!
- Covers all Northern sky except around Cas A / Cyg A
- Coherence statistics to baselines of $\sim$2000 km
- **About one good calibrator per square degree**

LOFAR specific challenges

wide field of view



Borrow phase referencing from VLBI:

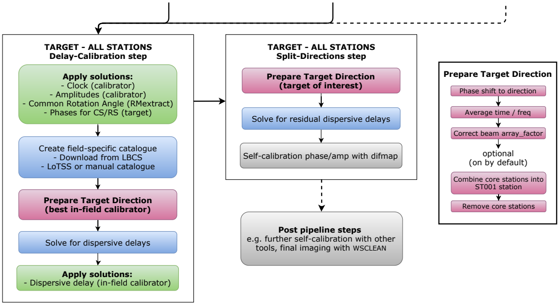
- Get phases on nearby calibrator
- Apply to target
- Use secondary calibrator to check

Okay! We're ready ... let's review

The LOFAR-VLBI pipeline

We developed a calibration strategy for high resolution imaging at < 200 MHz, building on some VLBI techniques

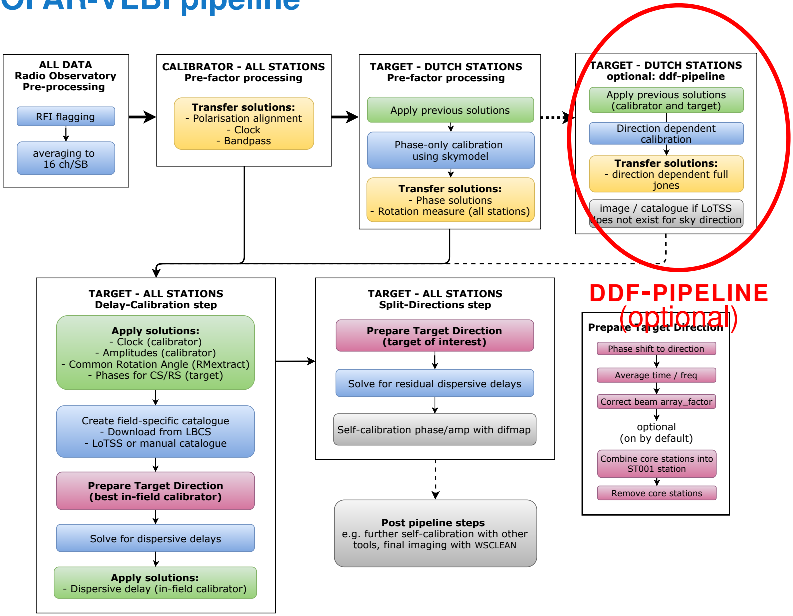
designed as extension of LoTSS calibration



LOFAR-VLBI pipeline (stable software release June 2020)

pipeline available at: `https://github.com/lmorabit/lofar-vlbi`
documentation at: `https://lofar-vlbi.readthedocs.io/`
description and demonstration in: Morabito+ (submitted)

The LOFAR-VLBI pipeline



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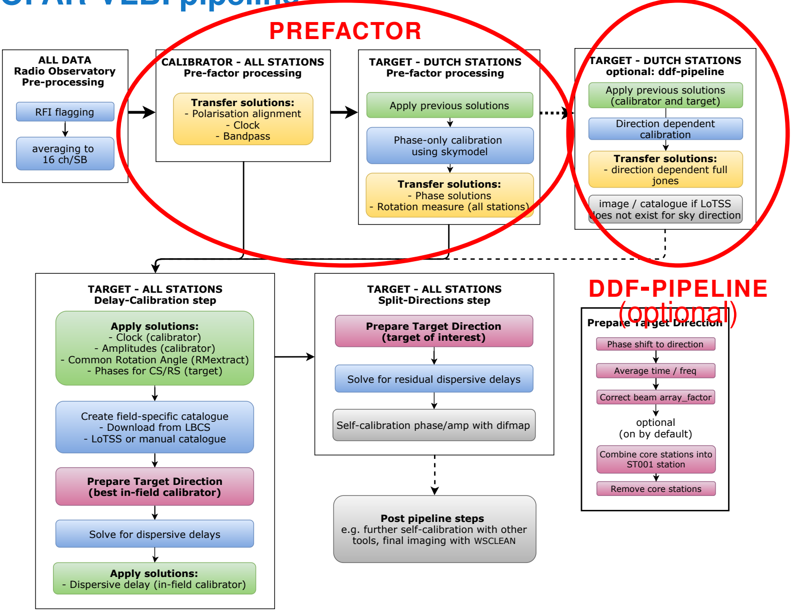
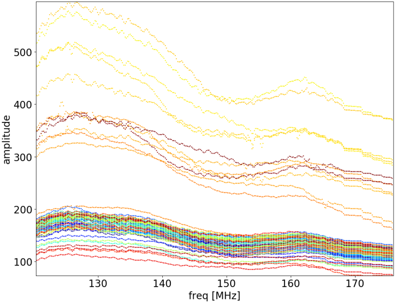
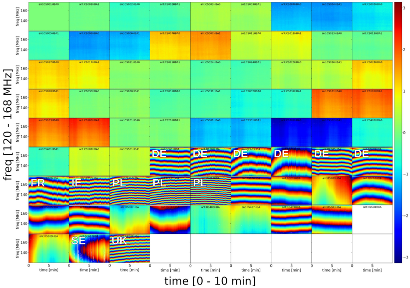


Pre-Facet-Calibrator

Run including international stations

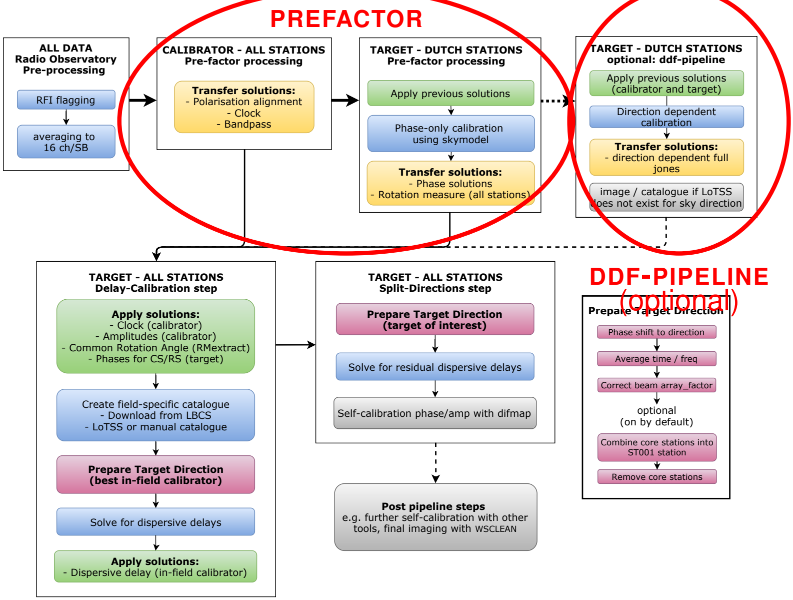




Only recently have we incorporated high resolution models
most compact to least: 3C 48, 3C 147, 3C 295, 3C 196

solutions above for 3C 147

The LOFAR-VLBI pipeline



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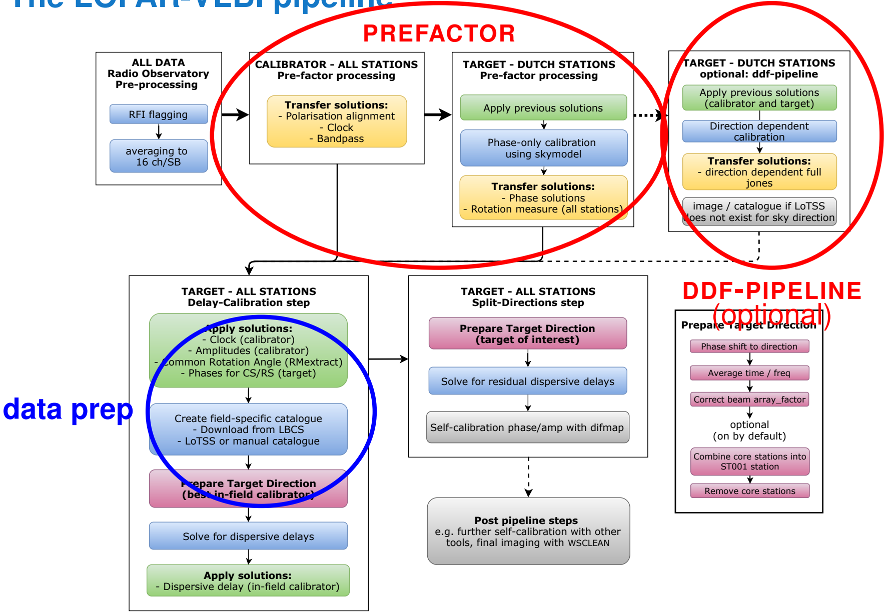
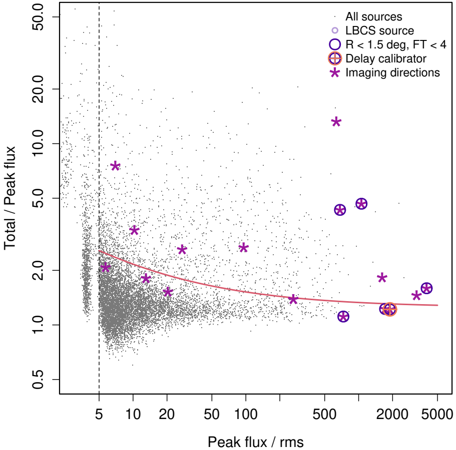


The LOFAR-VLBI pipeline: Data preparation

1. Apply Prefactor solutions
2. Get 6′′/ LBCS information
3. Identify Delay calibrator



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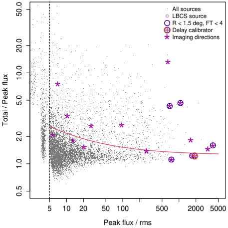
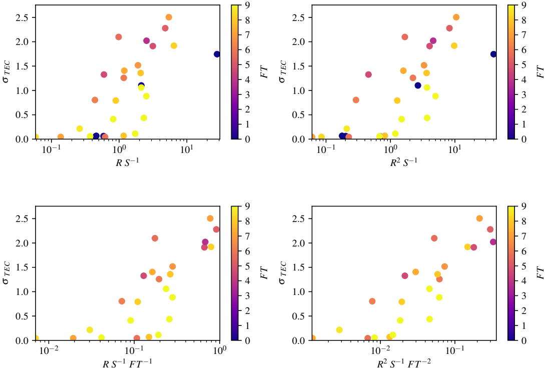
using information from LBCS and LoTSS





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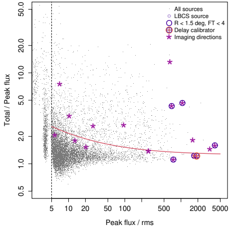
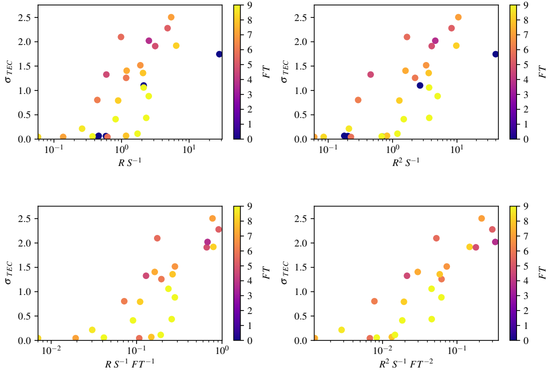
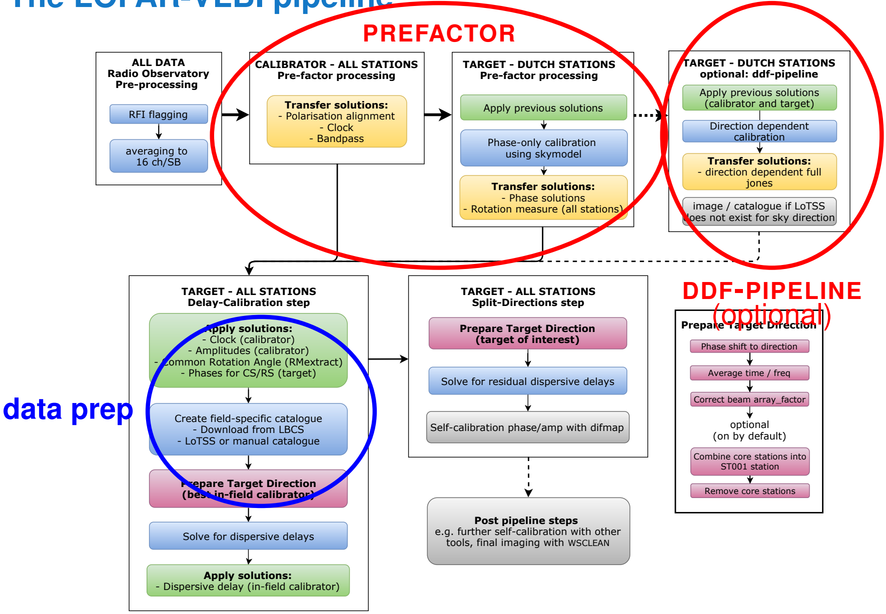




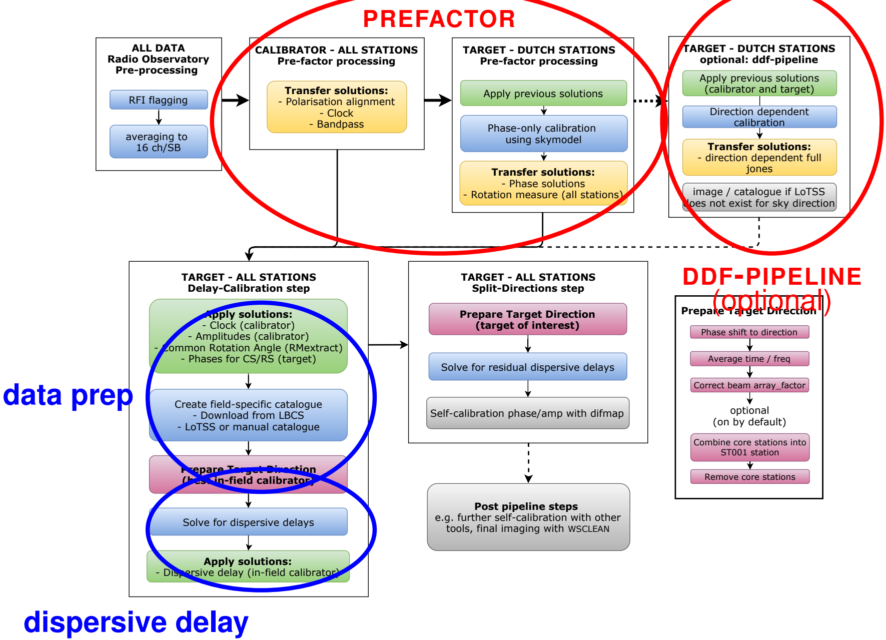
Splitting out sources

1. Phase-shift to source
2. Make super-station, remove core stations
3. Average down (10s of GB!)

The LOFAR-VLBI pipeline



The LOFAR-VLBI pipeline



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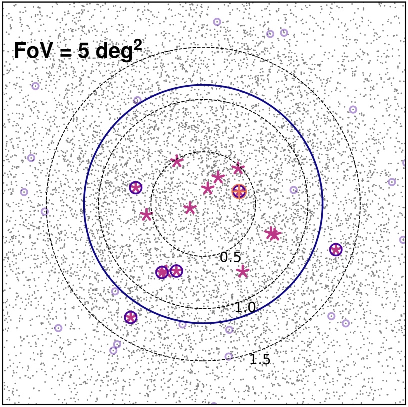
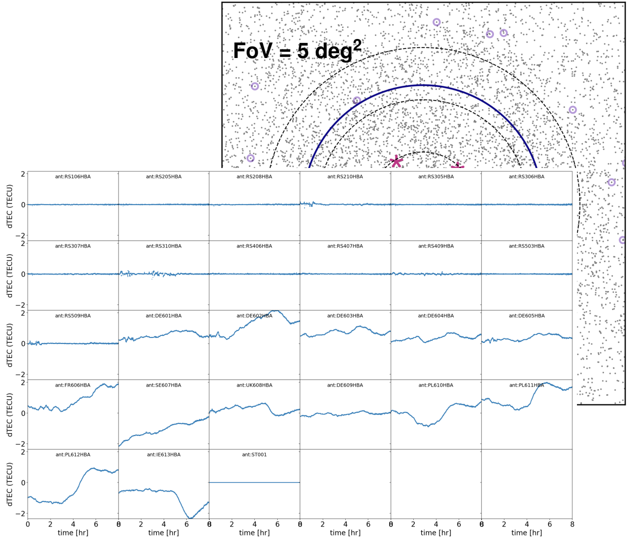


Morabito+ (submitted)

The LOFAR-VLBI pipeline



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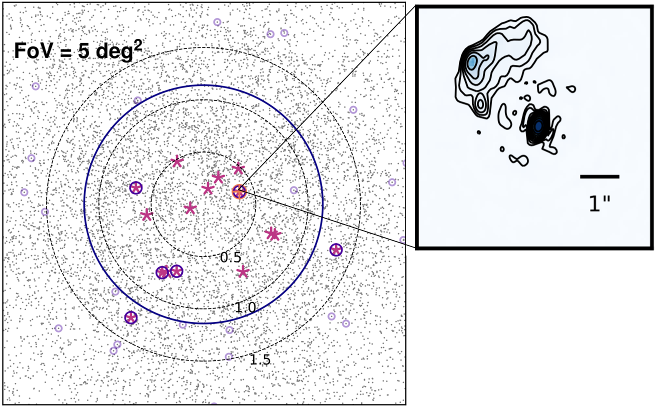
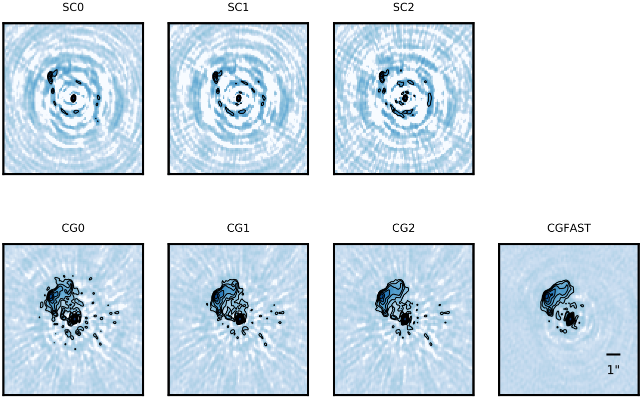


Morabito+ (submitted)

The LOFAR-VLBI pipeline

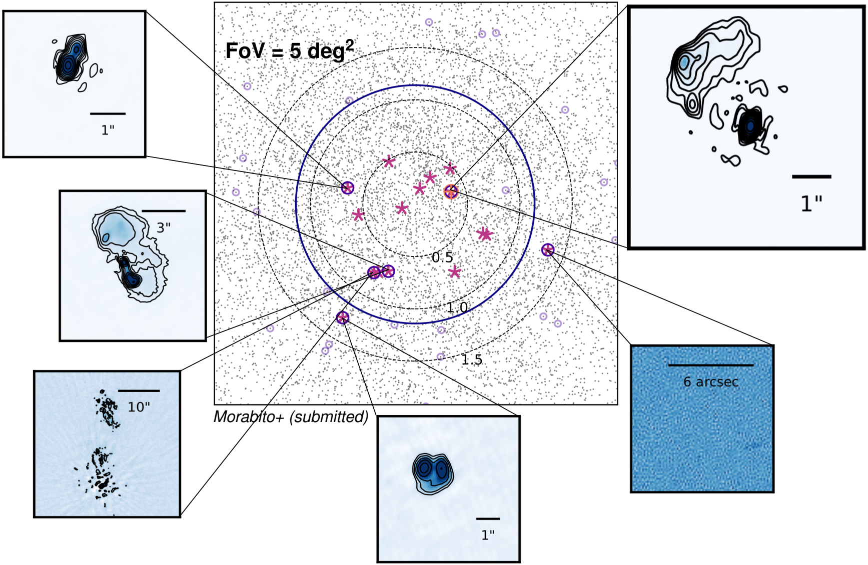
Self-calibration of delay calibrator

1. Solve for dTEC (i.e. dispsersive delay)
2. Self-calibrate phases / amplitudes in difmap
   (quick but only one solution per $\Delta\nu$)
3. Self-calibrate slow-varying ampltitudes with NDPPP
4. Apply solutions to data



The LOFAR-VLBI pipeline

LBCS calibrators

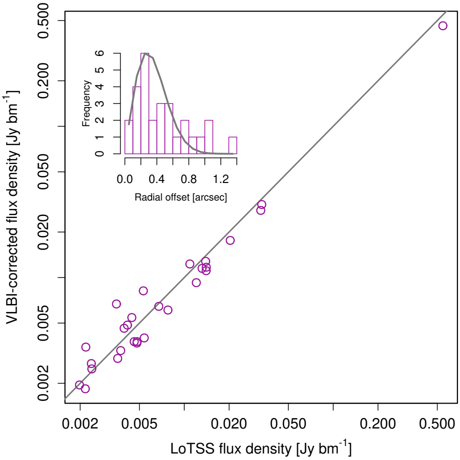


Morabito+ (submitted)

The LOFAR-VLBI pipeline

Checking the fluxscale and astrometry using 6″ imaging

apply solutions to dataset with core stations, image with Dutch stations only



Using the delay calibrator

scatter is ∼14% when using point sources only

astrometric accuracy ∼0.28″

The LOFAR-VLBI pipeline

In how many directions can we image?

Source_id	LBCS	$S_{\rm int}$ [mJy]	$S_{\rm peak}$ [mJy]	radius [$^\circ$]	distance to cal [$^\circ$]	noise [μJy bm^{-1}]	beam [arcsec]
ILTJ1349+5341		2514.99	1727.51	1.82	2.17	315	0.34×0.23
ILTJ1344+5503	Y	1761.70	1105.76	0.66	0.99	120	0.26×0.19
ILTJ1342+5414	Y	1472.67	341.66	0.76	1.07	99	0.29×0.21
ILTJ1345+5332		1423.88	107.53	1.57	1.87	216	0.34×0.23
ILTJ1331+5344		1315.70	720.10	1.78	1.62	176.41	0.34×0.24
ILTJ1331+5426	Y	936.36	200.90	1.34	1.08	138	0.31×0.23
ILTJ1337+5501	Y	667.33	547.63	0.36	0.00	92	0.25×0.18
ILTJ1344+5348	Y	496.94	405.78	1.29	1.59	230	0.31×0.24
ILTJ1341+5415	Y	429.82	386.32	0.69	0.97	100	0.27×0.19
ILTJ1340+5505		90.06	64.94	0.20	0.42	86	0.27×0.19
ILTJ1339+5512		20.03	7.49	0.33	0.29	86	–
ILTJ1339+5502		5.31	0.70	0.16	0.30	84	–
ILTJ1335+5436		5.10	1.95	0.70	0.50	90	0.28×0.20
ILTJ1337+5514		2.71	0.81	0.48	0.22	87	–
ILTJ1341+5451		2.19	1.43	0.13	0.50	84	0.27×0.19
ILTJ1335+5435		1.73	0.96	0.74	0.53	90	–
ILTJ1339+5509		0.81	0.39	0.29	0.24	87	–

12 / 17 sources are detected; 70% detection rate!

can depend on flux density and distance to phase centre / distance to calibrator

How do I set up a successful observation?

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1. Select a good standard calibrator
   - Typically the most compact is best, but consider sky position too
   - Most to least compact: 3C 48, 3C 147, 3C 295, 3C 196
   - Bookend, and possibly try to get two different calibrators

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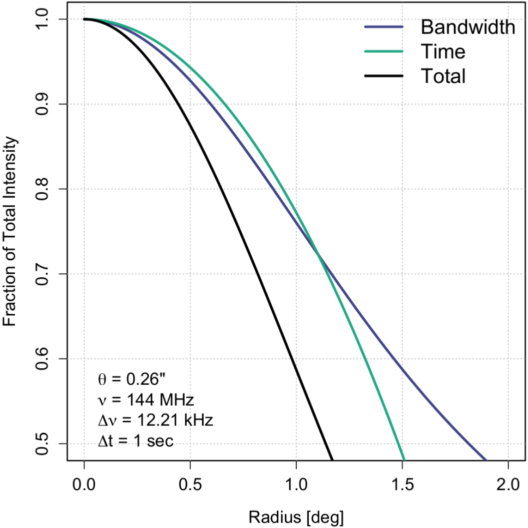
4. Consider your data averaging
   - Bandwidth and time smearing will cause intensity losses
   - International station beams limit FoV to $\sim$1.25°

How do I set up a successful observation?

recommendation: 1 sec / 16 channels



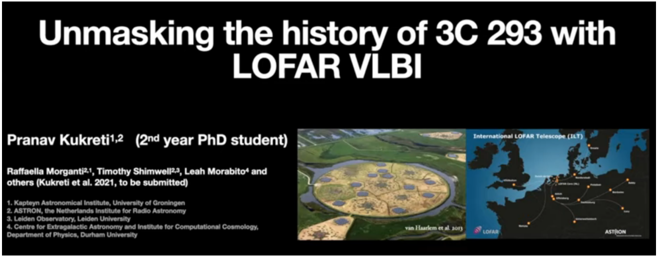
Current work: highlights

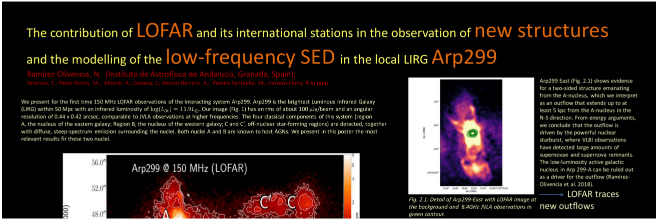
Upcoming paper splash in A&A with 2 technical + 9 science papers

Using the LOFAR-VLBI pipeline to process individual science targets

1 accepted, 4 submitted, 6 in prep.

Pranav Kukreti

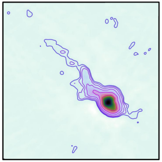


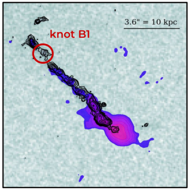


Naím Ramirez-Olivenicia

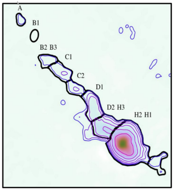
Current work: highlights

Jets: 3C 273 *S. Mooney, J. Harwood*


LOFAR (image, contours)

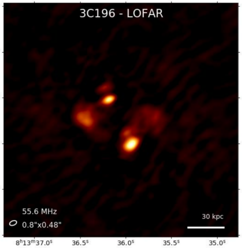


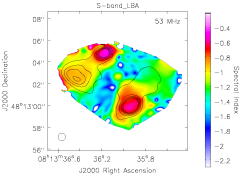
HST (image, contours), LOFAR (filled contours)



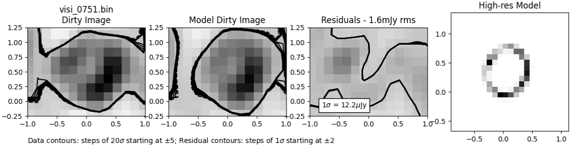
LOFAR image with knots marked

3C sources with LBA
C. Groeneveld





Gravitational Lenses: 0751 *S. Badole, N. Jackson*

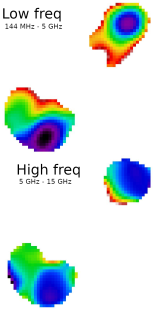


Data contours: steps of 20σ starting at ±5; Residual contours: steps of 1σ starting at ±2

Current work: highlights

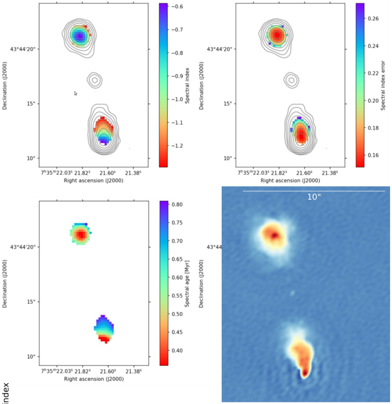
Spectral properties of 3C 295

E. Bonnassieux



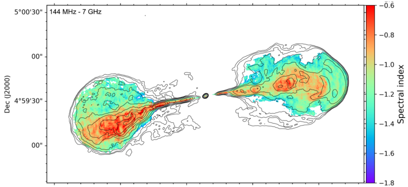
Spectral modelling of HzRG

F. Sweijen (accepted)

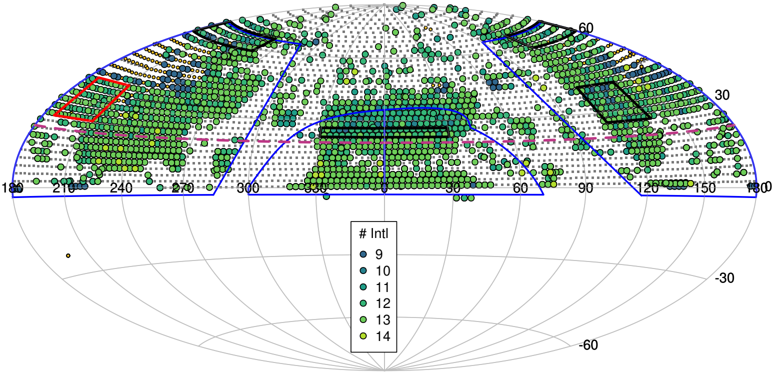


Hercules A

R. Timmerman

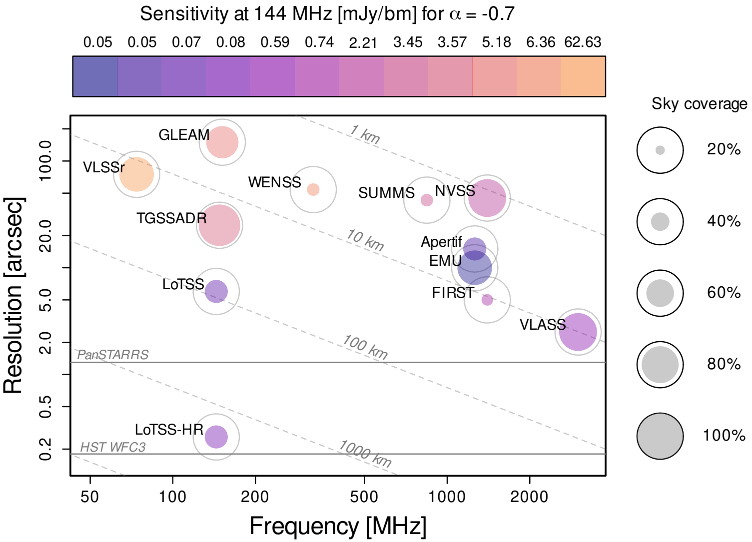


Current / future work: LoTSS-High Resolution (LoTSS-HR)



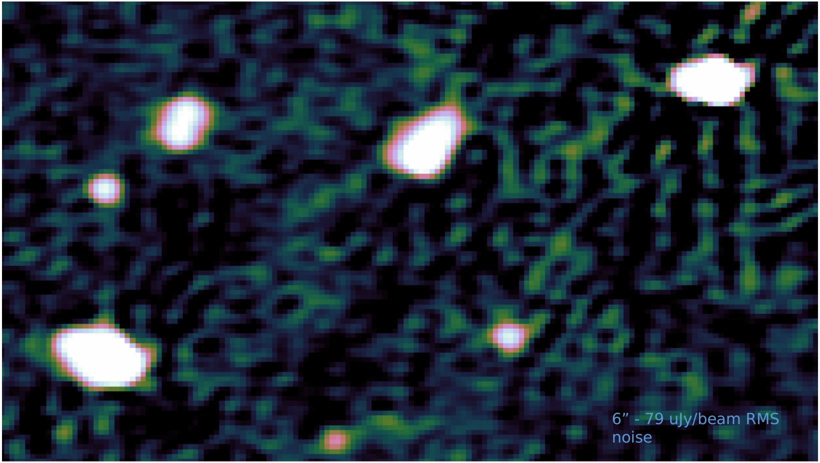
LoTSS data is recorded with international stations
starting to process in North of H-ATLAS field

Current / future work: LoTSS-High Resolution (LoTSS-HR)



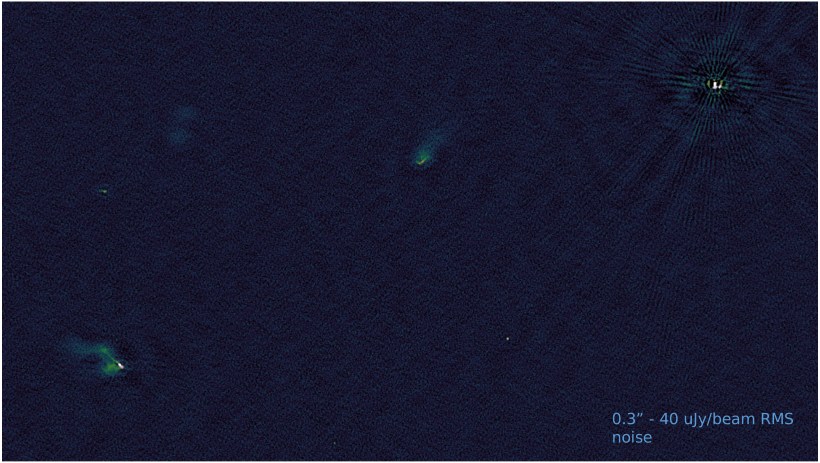
Based on P205+55, expect $>$ 3 million sources in LoTSS-HR

Current / future work: LoTSS Deep Fields – wide-field VLBI



Lockman Hole *(F. Sweijen)*

Current / future work: LoTSS Deep Fields – wide-field VLBI



Lockman Hole *(F. Sweijen)*

- 0.3″imaging over full ∼5 deg^2 field of view
- Single 8 hour observation required 250,000 cpu hours

Summary

- The different resolutions of LOFAR
- Introduction to Very Long Baseline Interferometry (VLBI)
- LOFAR-specific challenges
- The LOFAR-VLBI pipeline
  - A demonstration with a typical field
- Setting up an observation
- Current / future work

Thanks to many people!

Busy week ASTRON 2018

Busy week Durham 2019

N. Jackson, A. Drabent, S. Mooney, F. Sweijen, S. Badole, E. Bonnasieux, D. Venkattu, M. Iacobelli, O. Wucknitz, A. Deller, M. Hardcastle, T. Shimwell, J. Croston, A. Kappes, A. Tagore, J. Moldón, M. Brentjens, T. Carozzi, G. Gaigals, C. Roskowinski, ASTRON support scientists + others