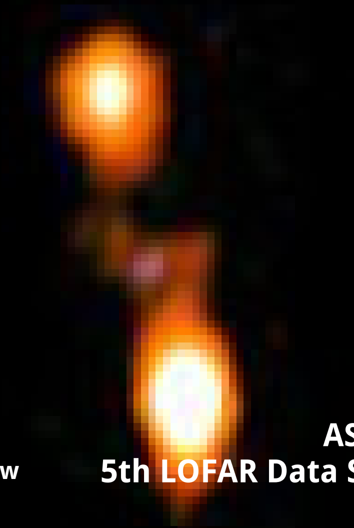
Long Baseline imaging with LOFAR
aka what is VLBI and how does it apply here?



Dr. Leah Morabito
Millard and Lee Alexander Fellow

ASTRON
5th LOFAR Data School

Outline

- Very Long Baseline Interferometry (VLBI)
- LOFAR-VLBI: making the most of the full ILT
- Science applications
- Phase and delay errors
- Techniques for handling delay errors
- Long Baseline Calibrator Survey
- Calibration strategies for LOFAR-VLBI

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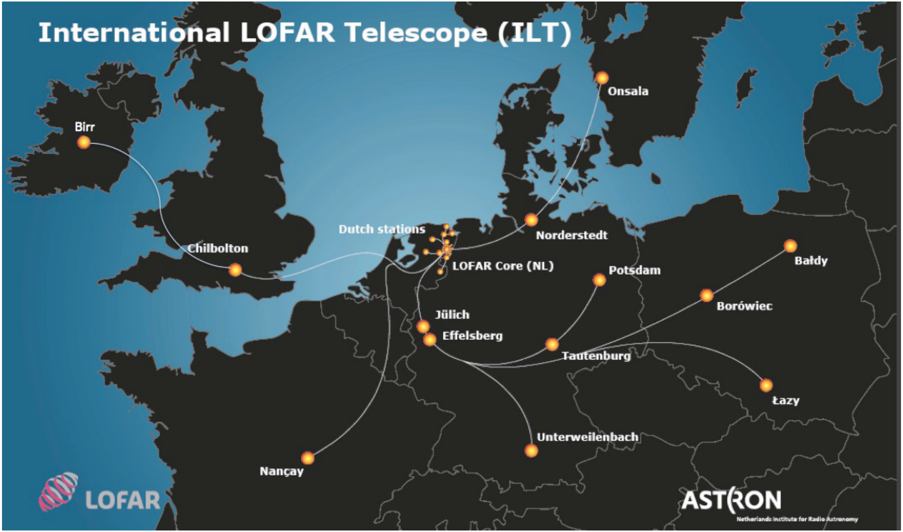
The benefit ... much higher resolution!

LOFAR-VLBI



International LOFAR Telescope (ILT)
Onsala
Birr
Dutch stations
Norderstedt
Chilbolton
LOFAR Core (NL)
Potsdam
Bałdy
Borówiec
Jülich
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Tautenburg
Łazy
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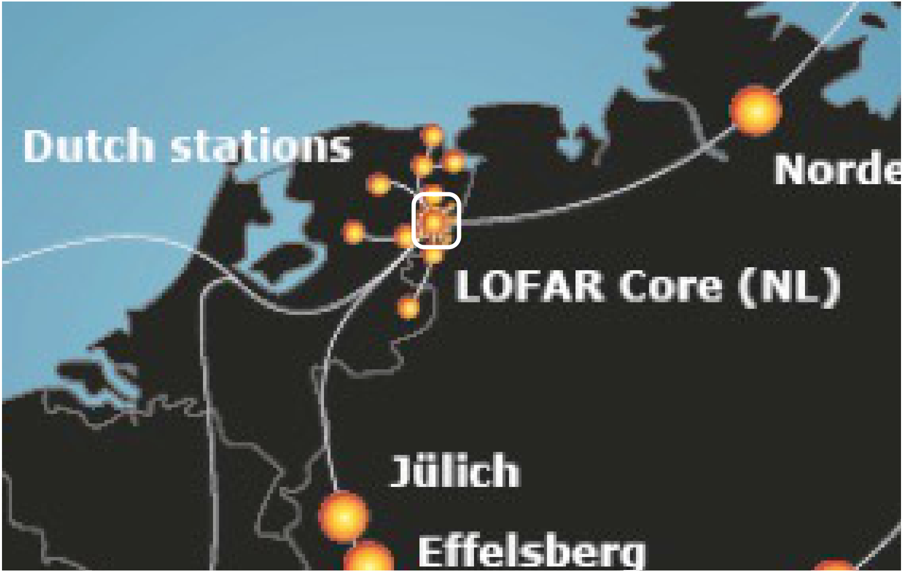
LOFAR
ASTRON
Netherlands Institute for Radio Astronomy

LOFAR-VLBI



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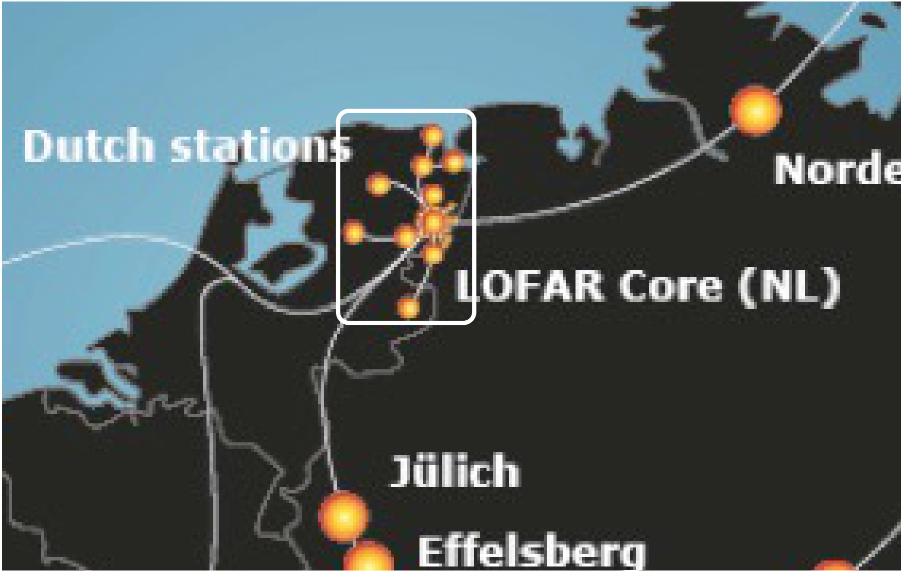

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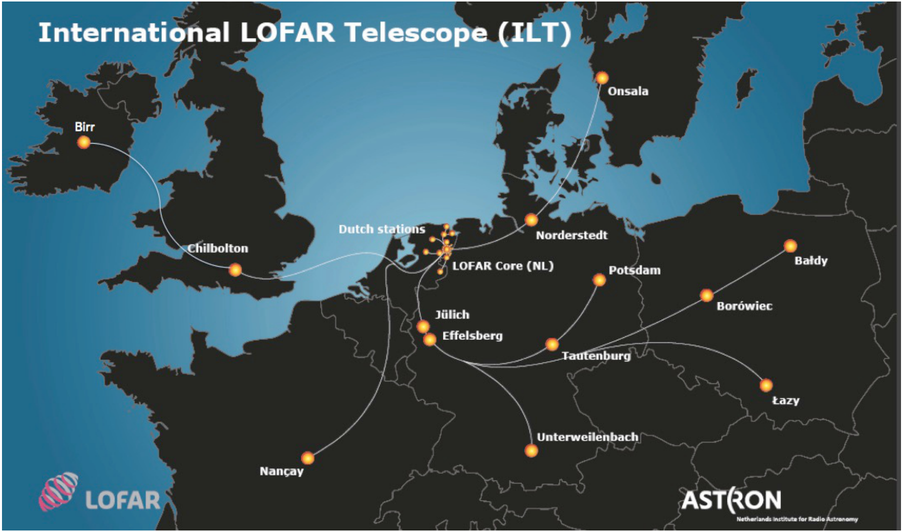

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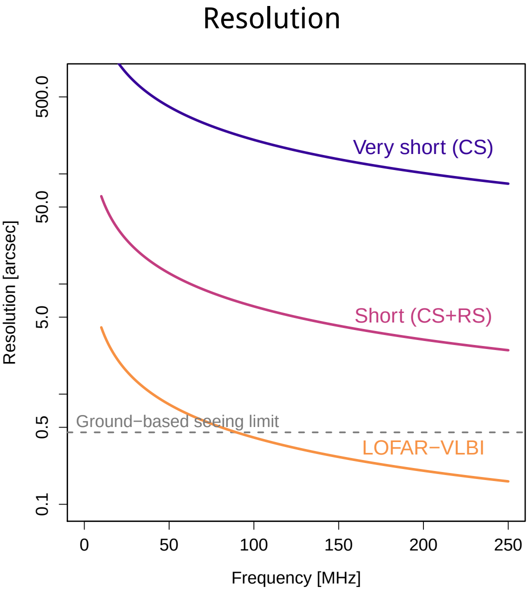
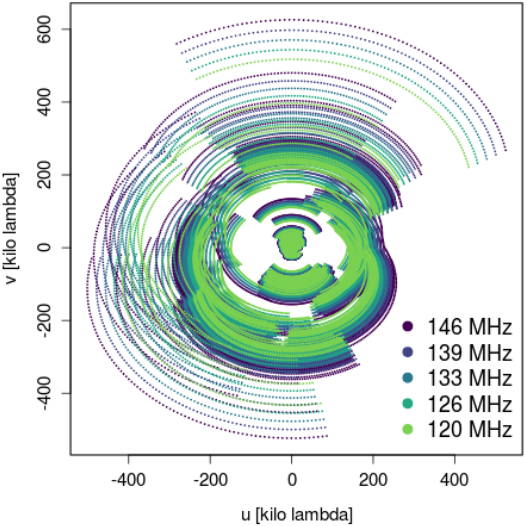


Resolution
Very short (CS)
Short (CS+RS)
LOFAR−VLBI
Ground−based seeing limit
Resolution [arcsec]
500.0
50.0
5.0
0.5
0.1
Frequency [MHz]
0
50
100
150
200
250

LOFAR-VLBI

However, it’s not that simple ... large gaps in u-v coverage



LOFAR-VLBI

Other main points to keep in mind

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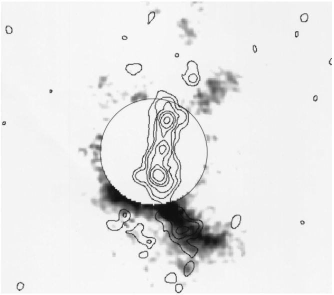
4. Bandwidth and time smearing will be worse
   - $\rightarrow$ Smaller field of view

Science Applications

Matched resolution with optical provides vast potential!



Capetti et al. (1995)

- Image: Hubble Space Telescope
- Radio countours: MERLIN

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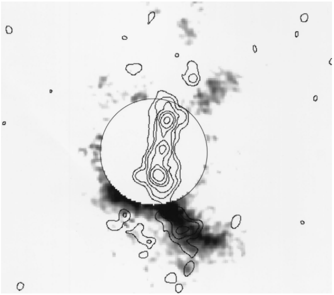
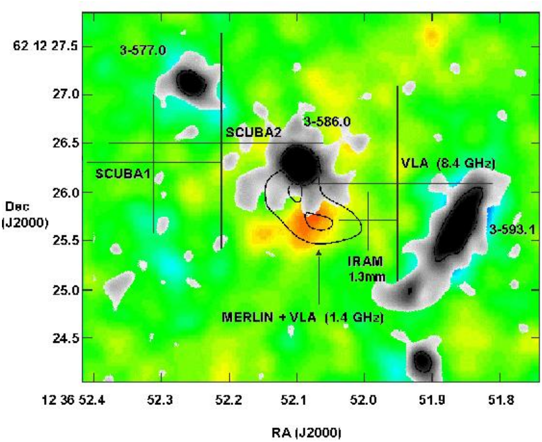


Capetti et al. (1995)

- Image: Hubble Space Telescope
- Radio countours: MERLIN
- Central part of a Seyfert galaxy
- Optical jet is made by expansion of hot material around radio jet

Science Applications

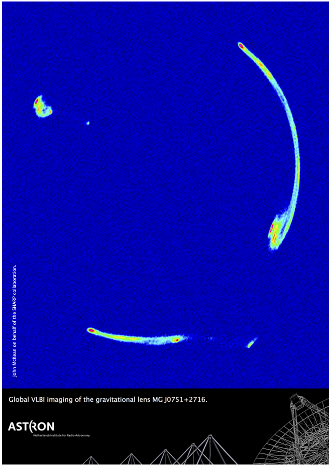
Accurate identification of host galaxy



Muxlow et al. (2005)

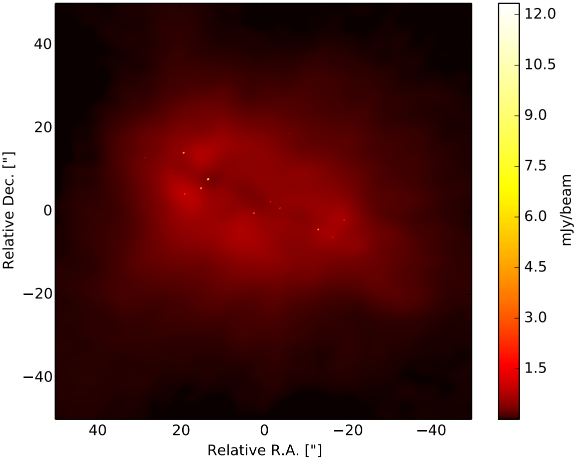
Science Applications

Gravitational lenses



Science Applications

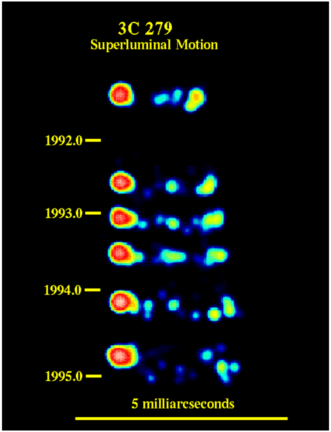
Star-forming galaxies + supernovae!

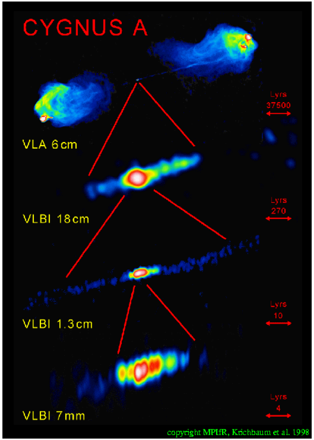


Varenius et al. (2015)

Science Applications

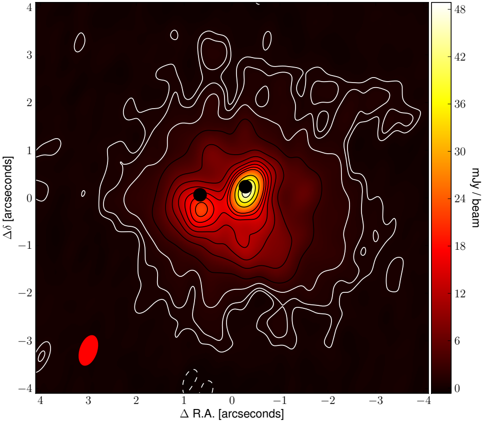
Active galactic nuclei: jetted





Science Applications

Active galactic nuclei: Arp 220

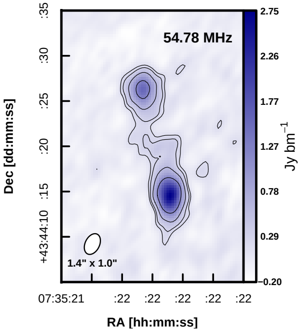


Varenius et al. (2016)

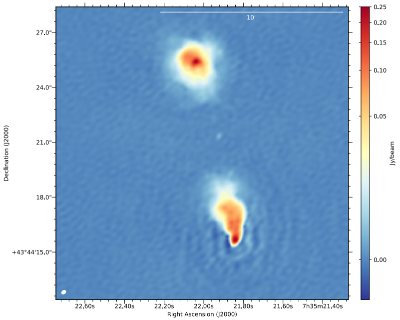
Science Applications

Resolving distant sources: 4C 43.15
enables spectral modelling

LBA



HBA



Morabito et al. (2016)

F. Sweijen, in prep.

How do we get from collected data to science-ready images?

Phase errors

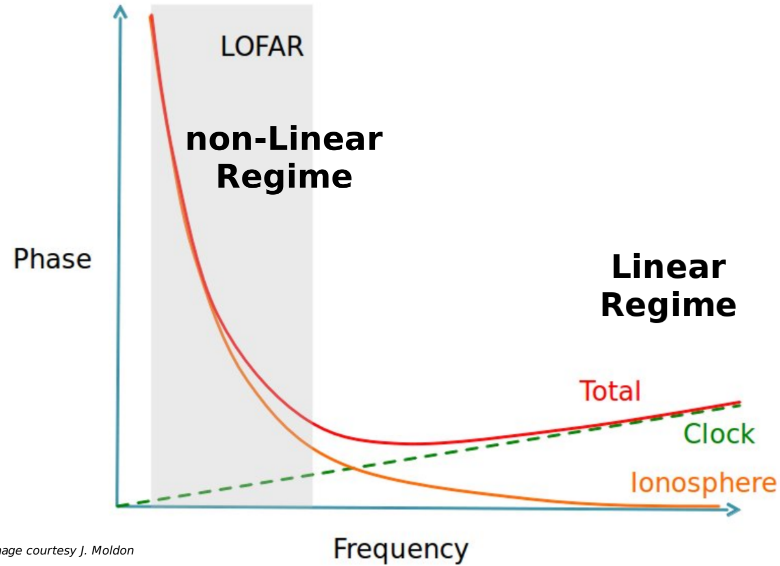


Image courtesy J. Moldon

Phase errors

Take the relation between phase and delay:

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1st order expansion shows:

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$\phi_0 \equiv$ 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

Phase errors

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

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

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

$\frac{\delta\phi}{\delta t} \equiv$ how that phase changes with *time*

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Normal phase calibration only estimates ϕ_0. **Fringe-fitting** is any process that also estimates the *delays* and *rates*.

Summary of delay errors

$$\tau = \tau_{ion} + \tau_{tropo} + \tau_{cl} + \tau_{inst} + \tau_{geo} + \tau_{source}$$

Table 22–1. Terms of a VLBI Geometric Model [a]

Item	Approx max Magnitude [b]	Time scale
Zero order geometry.	6000 km	1 day
Nutation	$\sim 20''$	< 18.6 yr
Precession	~ 0.5 arcmin/yr	years
Annual aberration	$20''$	1 year
Retarded baseline	20 m	1 day
Gravitational delay	4 mas @ 90° from sun	1 year
Tectonic motion	10 cm/yr	years
Solid Earth Tide	50 cm	12 hr
Pole Tide	2 cm	$\sim$1 yr
Ocean Loading	2 cm	12 hr
Atmospheric Loading	2 cm	weeks
Post-glacial Rebound	several mm/yr	years
Polar motion	$0.5''$	~ 1.2 years
UT1 (Earth rotation)	Random at several mas	Various
Ionosphere	~ 2 m at 2 GHz	seconds to years
Dry Troposphere	2.3 m at zenith	hours to days
Wet Troposphere	0 – 30 cm at zenith	seconds to seasonal
Antenna structure	<10 m. 1cm thermal	—
Parallactic angle	0.5 turn	hours
Station clocks	few microsec	hours
Source structure	5 cm	years

[a] Adapted from Sovers, Fanselow, & Jacobs 1998

[b] For an 8000 km baseline, 1 mas $\leftrightarrow$ 3.9 cm. $\leftrightarrow$ 130ps

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and into 2 different regimes:

- Slowly changing (e.g., dry troposphere)
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but this requires enough signal to noise in a single *coherence time*

Coherence time

Fact 1: $\phi \propto \tau$

Fact 2: for waves, $\phi = 2\pi = 4pi = \ldots$

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Typical Coherence Times

Freq	**Good**	**Bad**
150 MHz	3 min	15 sec
408 MHz	10 min	45 sec
2 GHz	45 min	3 min
5 GHz	40 min	10 min
22 GHz	3 min	10 sec
200 GHz	30 sec	1 sec

FRINGE-FITTING AND OTHER TECHNIQUES TO FIND DELAYS

Closure Phase and amplitude

Regardless of antenna based errors, source information is preserved in the **closure phase** and **closure amplitude**

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For any 3 antennas with antenna-based errors ϵ:

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For any 4 antennas with errors J:

$$\left| \frac{V_{ij}^{obs} V_{kl}^{obs}}{V_{jk}^{obs} V_{jl}^{obs}} \right| = \left| \frac{J_i J_j V_{ij} J_k J_l V_{kl}}{J_j J_k V_{jk} J_j J_l V_{jl}} \right| = \left| \frac{V_{ij} V_{kl}}{V_{jk} V_{jl}} \right|$$

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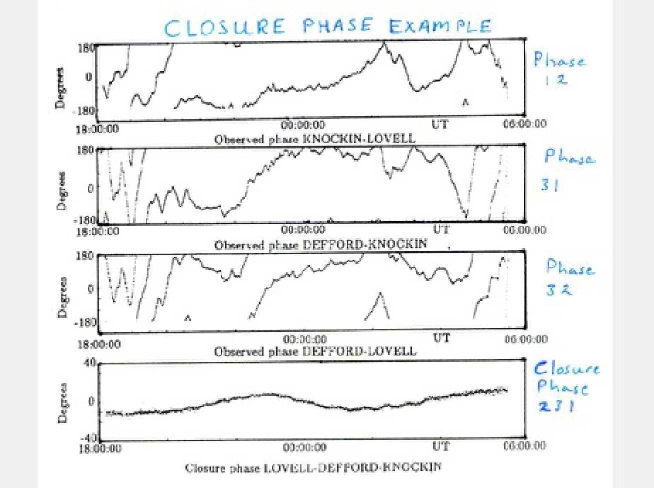
Good check at end of calibration that closure phase is the same as at beginning!

Closure Phase



Tim Cornwell

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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The disadvantages of this method are: (1) that the source must be detected all baselines and (2) antenna-based quantities are not conserved ...

Baseline-based + closure constraints

Remember closure phase and amplitude?

For any 3 antennas:

$$\phi_{cl,ijk} \equiv \phi_{ij}^{obs} + \phi_{jk}^{obs} + \phi_{ki}^{obs} = \phi_{ij} + \phi_{jk} + \phi_{ki}$$

For any 4 antennas:

$$V_{cl,ijkl} \equiv \left| \frac{V_{ij}^{obs} V_{kl}^{obs}}{V_{jk}^{obs} V_{jl}^{obs}} \right| = \left| \frac{V_{ij} V_{kl}}{V_{jk} V_{jl}} \right|$$

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Using both baseline-based fringe-fitting and closure phase + amplitude can preserve the antenna-based quantities! But this doesn't solve the problem that the source must be detected on some, if not all, baselines ...

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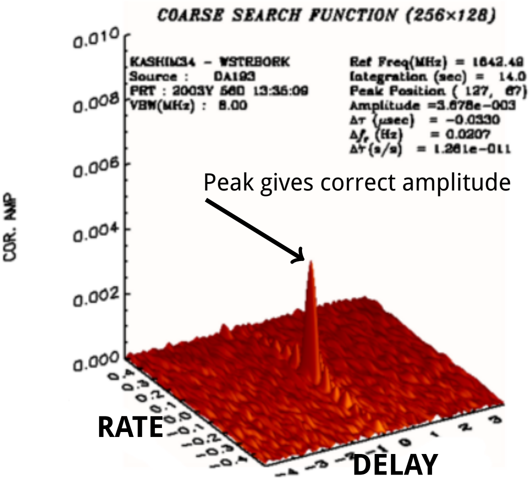
The big advantage here is that even if an antenna doesn't see a source on every baseline it is in, the antenna-based solutions *can still be found!* This is necessary for weak sources.

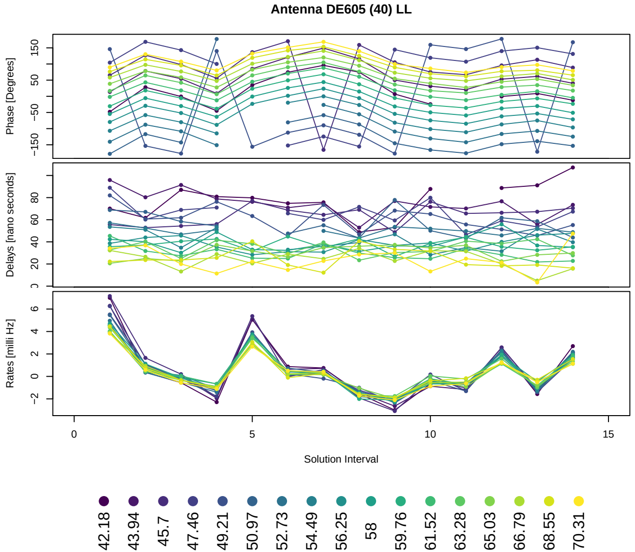
Fringe-fitting in practice

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



Global Fringe-fitting

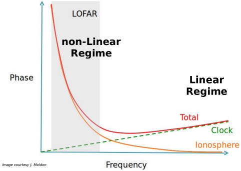
An example from LOFAR



Another way to calculate delays

Clock/TEC fitting in solution space

- Solve for phases using a solution interval less than the coherence time
- Use the different frequency dependence of clocks and ionosphere (TEC) to separate them



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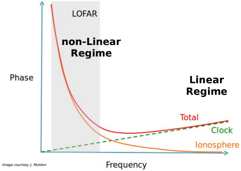
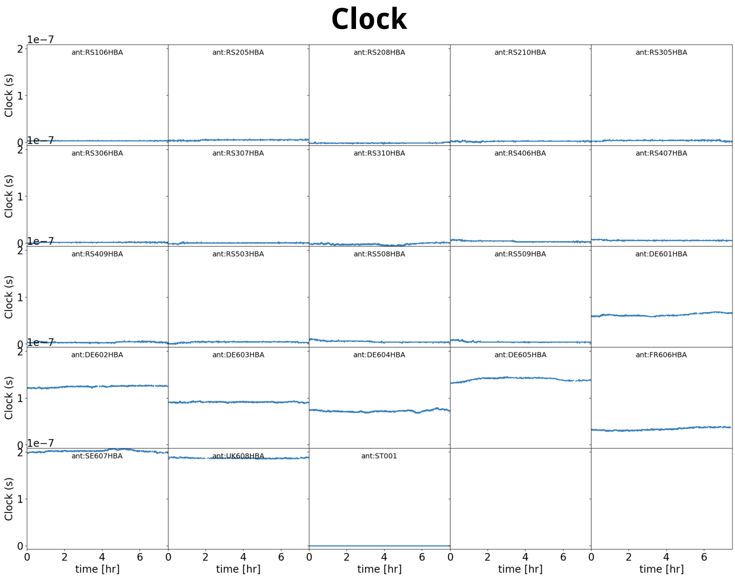


+ Using entire bandwidth, increases signal to noise
- Does not solve for rates (this is OK as long as solution interval $<$ coherence time)

Another way to calculate delays



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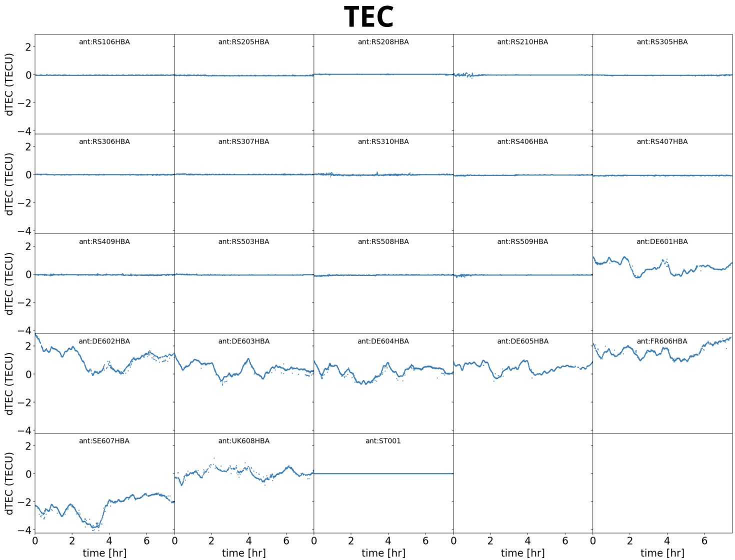
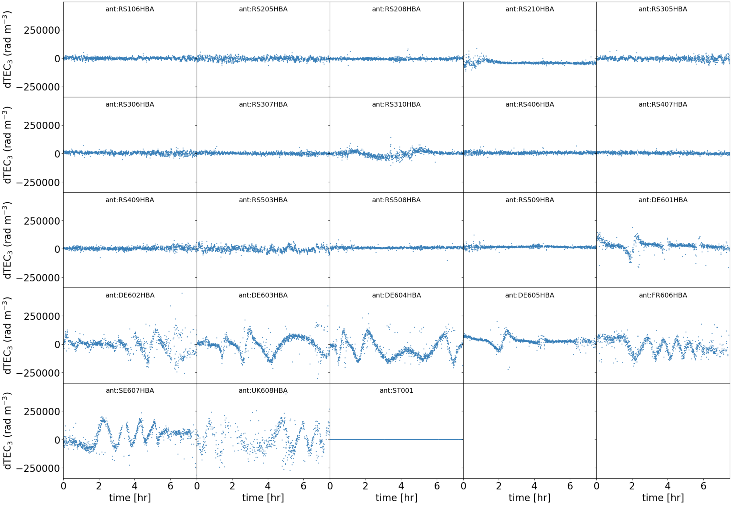
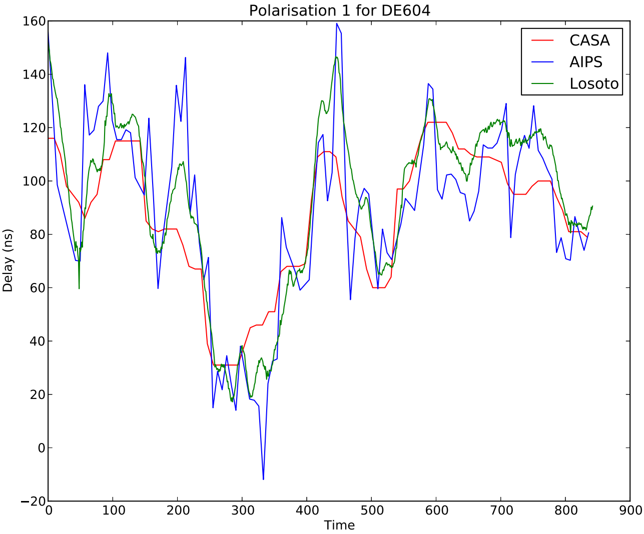


Another way to calculate delays

3rd Order TEC (aka source structure in this case)

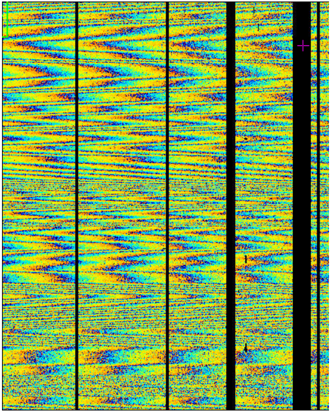


Comparison of methods

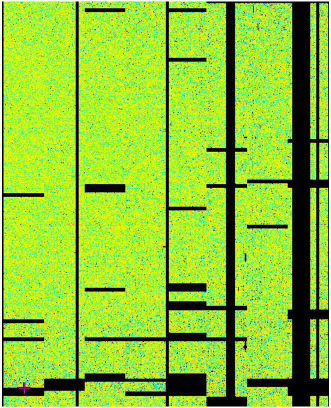


Correcting for delays

Whichever way you choose, this is what happens:

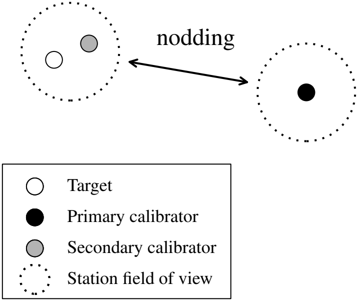


uncorrected



corrected

Phase referencing



- Find phases on nearby calibrator source
- “Reference” phases for target to calibrator phases (i.e., apply calibrator phases to target)
- Use a fainter, secondary calibrator in the target field to check/correct phase residuals

Long Baseline Calibrator Survey

Ongoing survey to identify LOFAR-VLBI calibrator sources
Jackson et al. (2016); Moldon et al. (2015)

Source selection:

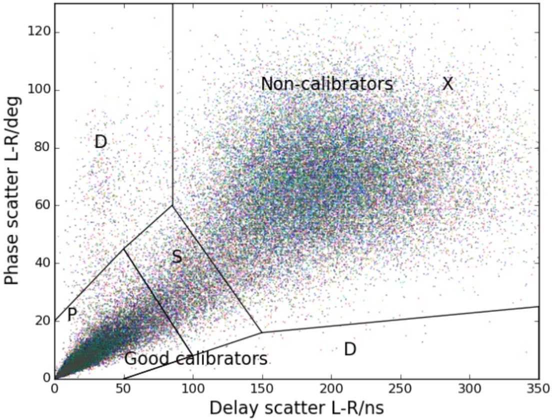
- compact in WENSS (above 30°N) or
- compact in NVSS (below 30°N)
- also detected by VLSSr or MSSS (or TGSS)
- VLBA calibrators

Typical predictors of compact structure:

- have flat low-frequency spectral indices
- have high total WENSS flux density

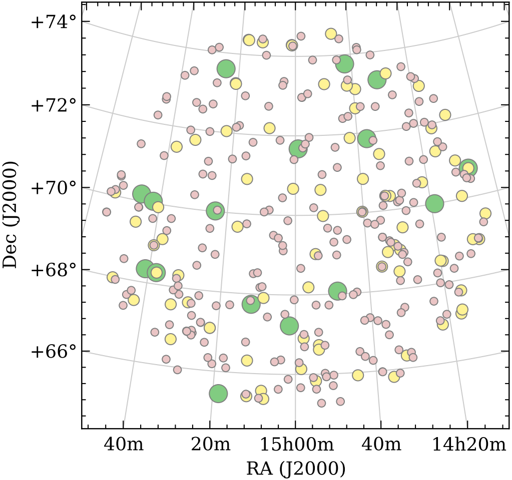
Long Baseline Calibrator Survey

- 3 minutes long with 3 MHz of bandwidth
- Proccessed with LBCS pipeline (uses fringe-fitting)



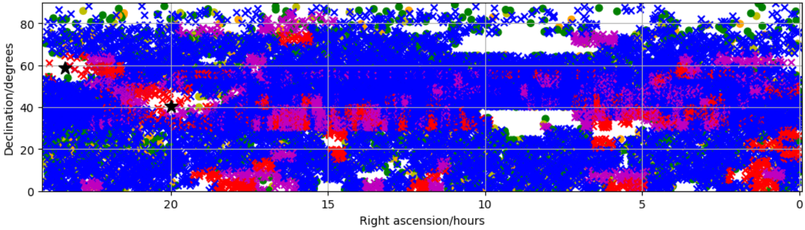
Long Baseline Calibrator Survey

Density of about 1 good calibrator per square degree



Long Baseline Calibrator Survey

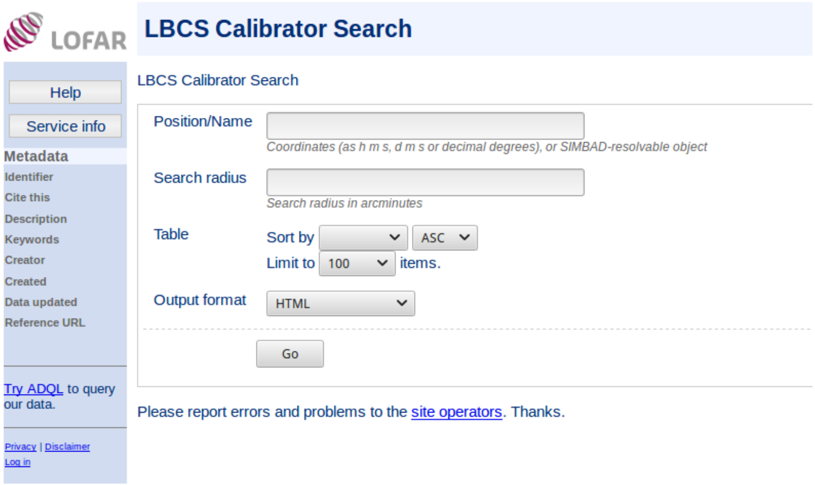
LBCS nearing completion!



Long Baseline Calibrator Survey

Database of LBCS calibrators on ASTRON Virtual Observatory

`https://vo.astron.nl/lbcs/lobos/cone/form`



CALIBRATION STRATEGIES FOR LOFAR-VLBI

Challenges at low frequencies

What are some of the issues?

Sensitivity	LBA especially has poor signal to noise
Clocks	Connected, but only core stations (very short baselines) are on the same clock
Correlator Model	Baselines up to 2000 km lead to geometric errors/delays
Ionosphere	Can be wildly varying, larger impact on longer baselines
Calibrators	Need to use compact (sub-arcsec), bright sources

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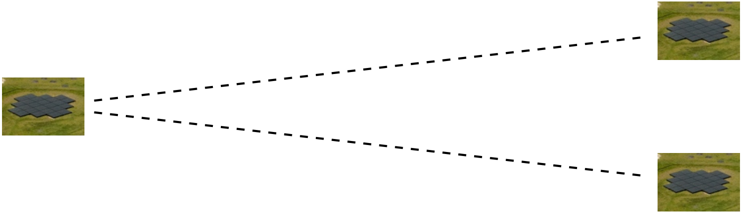
These issues are the same as traditional VLBI!
We use the same techniques to solve for them

(with some extra work)

Some of the extra work ...

Data sizes with just the Dutch stations are $\sim$2TB/observation.

Including *all* stations, a single observation can be up to 20 TB!

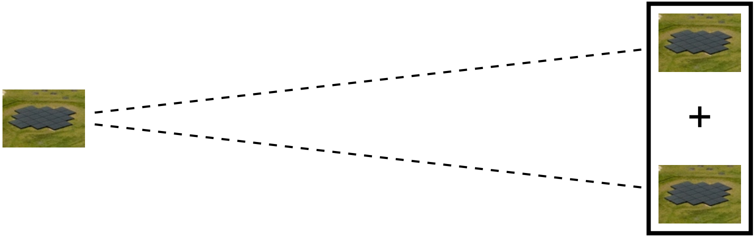


Some of the extra work ...

Data sizes with just the Dutch stations are ~2TB/observation.

Including *all* stations, a single observation can be up to 20 TB!

To make the data smaller, we combine the core stations



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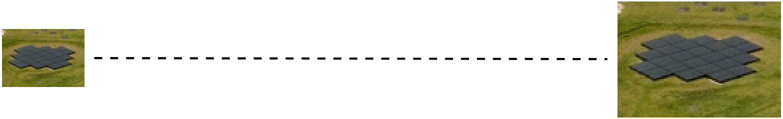
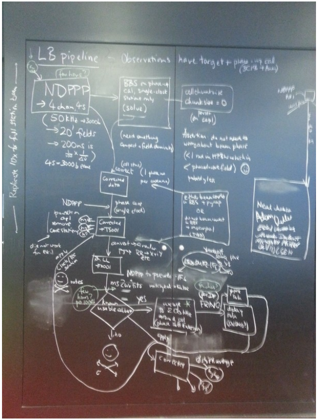
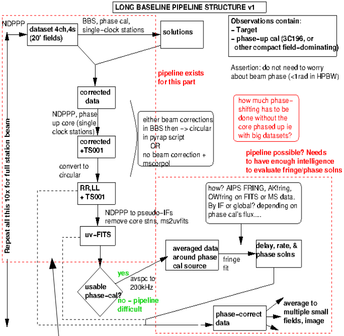


This also helps calibration, because now you have a bigger, more sensitive station at the center of the array!

Long Baseline Pipeline

Long Baseline Working Group has been building a pipeline using the same framework as prefactor





Now in official pipeline

Long Baseline Pipeline

It’s simple really ...

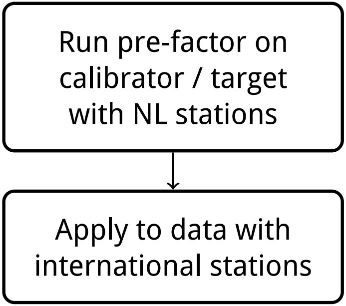
Long Baseline Pipeline

It’s simple really ...

Run pre-factor on
calibrator / target
with NL stations

Long Baseline Pipeline

It’s simple really ...



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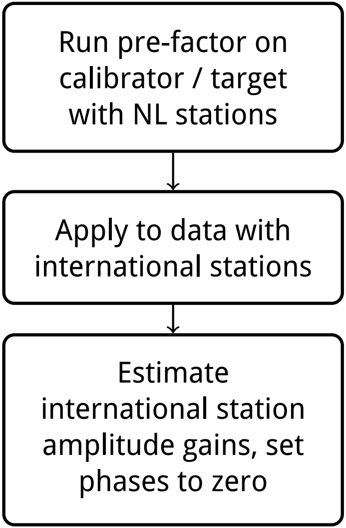

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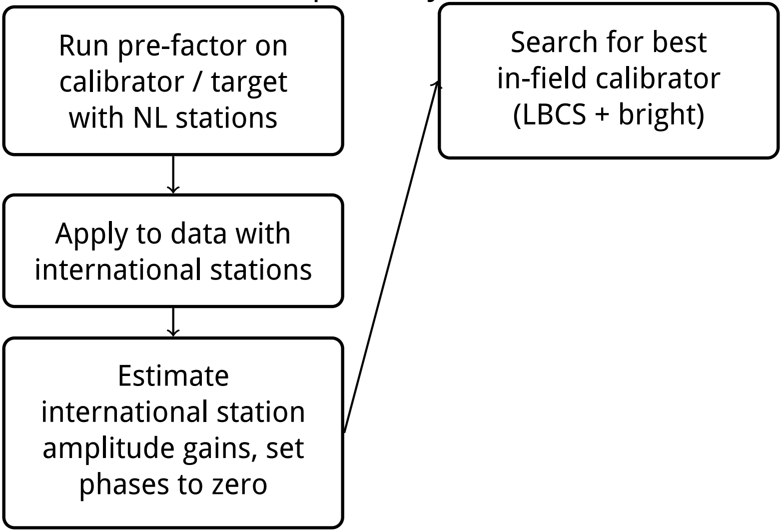

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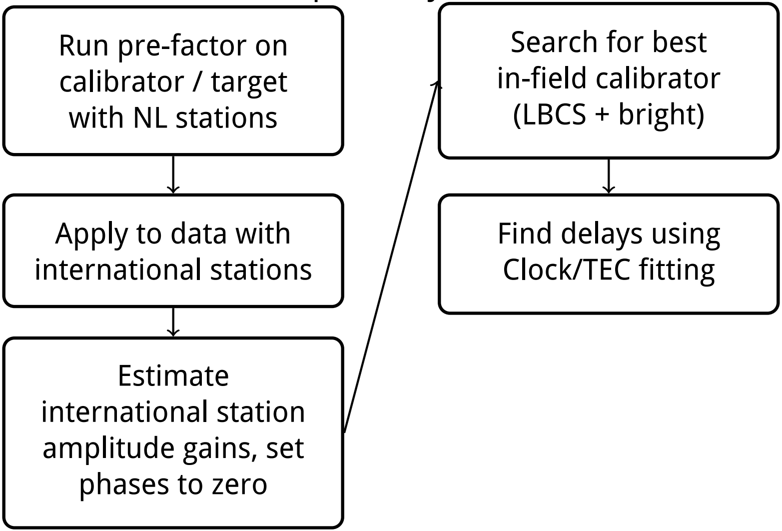

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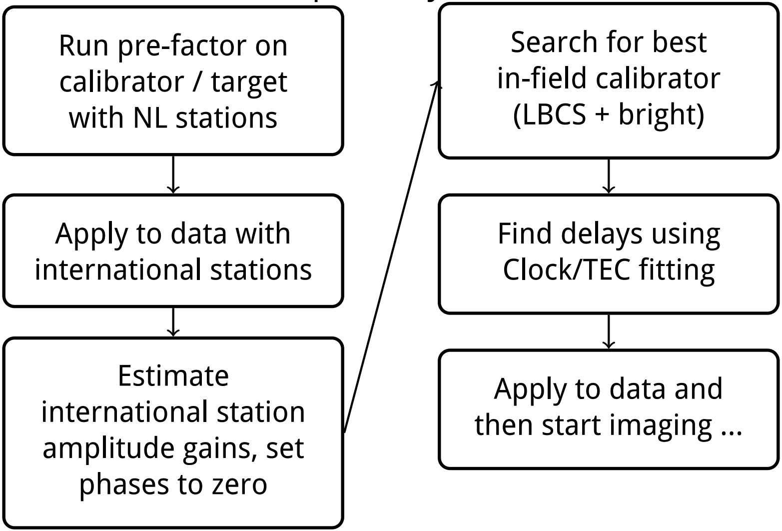


Long Baseline Pipeline

It's simple really ...

Run pre-factor on calibrator / target with NL stations

Search for best in-field calibrator (LBCS + bright)

A
int

ys using
C fitting

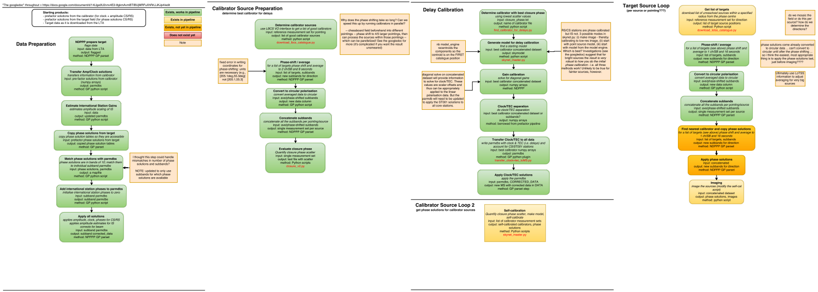
If you have a pointed observation for your target with a nearby LBCS calibrator ($\lesssim$1 deg) this is all you need (plus your favourite self-cal + imaging software)

Estimate international station amplitude gains, set phases to zero

Apply to data and then start imaging ...

Long Baseline Pipeline

but in practice there are a lot more steps ...



Long Baseline Pipeline

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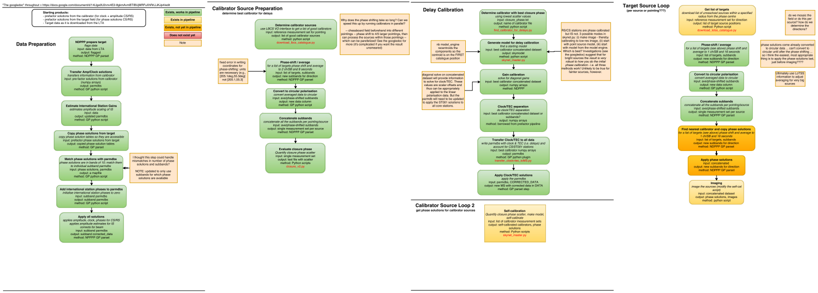
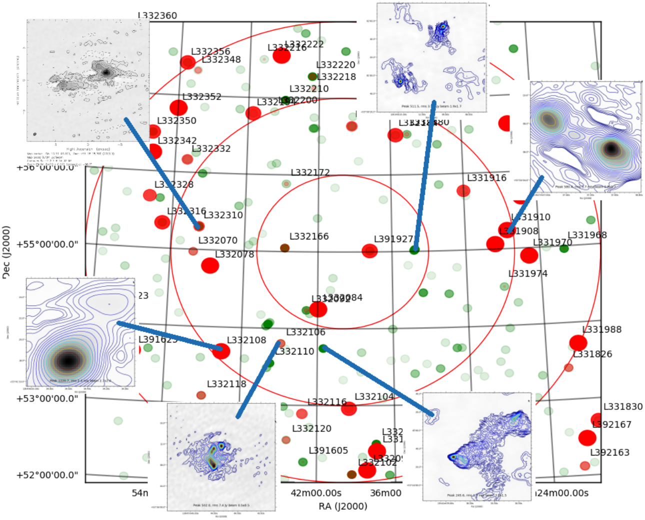


but don't panic! We are here to guide you through a tutorial tomorrow

Long Baseline Pipeline

The (near) future: wide-field VLBI

LoTSS pointing P205+55



Long Baseline Pipeline

Many thanks to ...

Alexander Drabent, Evita Vavilina, Gatis Gaigals, Carole Roskowinski, Rachael Ainsworth, Sean Mooney, Tim Shimwell, Leah Morabito, Neal Jackson, Alexander Kappes, Marco Iacobelli (Not pictured: Shruti Badole, Frits Sweijen, Samira Rezaei, Javier Moldon, Wendy Williams, John McKean, Adam Deller, Eskil Varenius + more)

Summary

- Very Long Baseline Interferometry (VLBI)
- LOFAR-VLBI: making the most of the full ILT
- Science applications
- Phase and delay errors
- Techniques for handling delay errors
- Long Baseline Calibrator Survey
- Calibration strategies for LOFAR-VLBI

QUESTIONS?