Very Long Baseline Interferometry
with the International LOFAR Telescope (ILT)

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Frontend research at low radio frequency

April 2023

UK Research and Innovation
Durham University

Outline

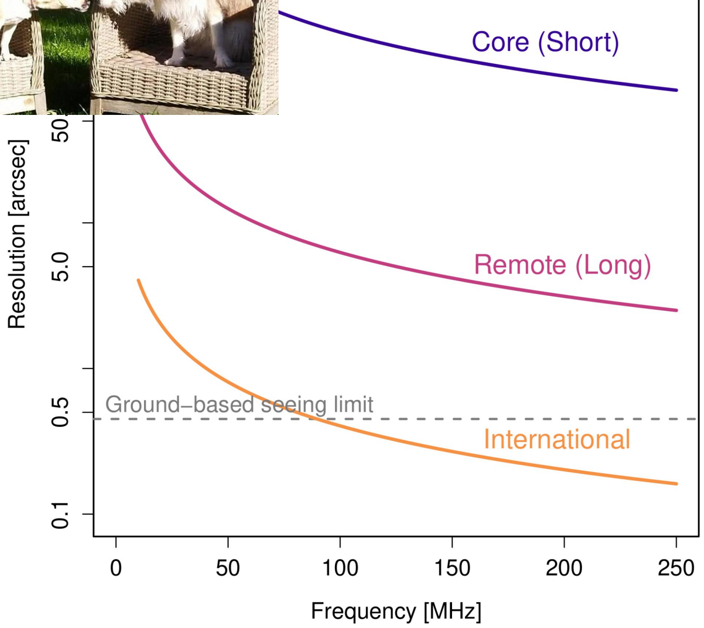
- Very Long Baseline Interferometry (VLBI)
- VLBI with LOFAR
- Data calibration challenges
- Calibration strategies for LOFAR-VLBI
    - Long Baseline Calibrator Survey
    - Calibration strategy / demonstration

What is Very Long Baseline Interferometry (VLBI)?

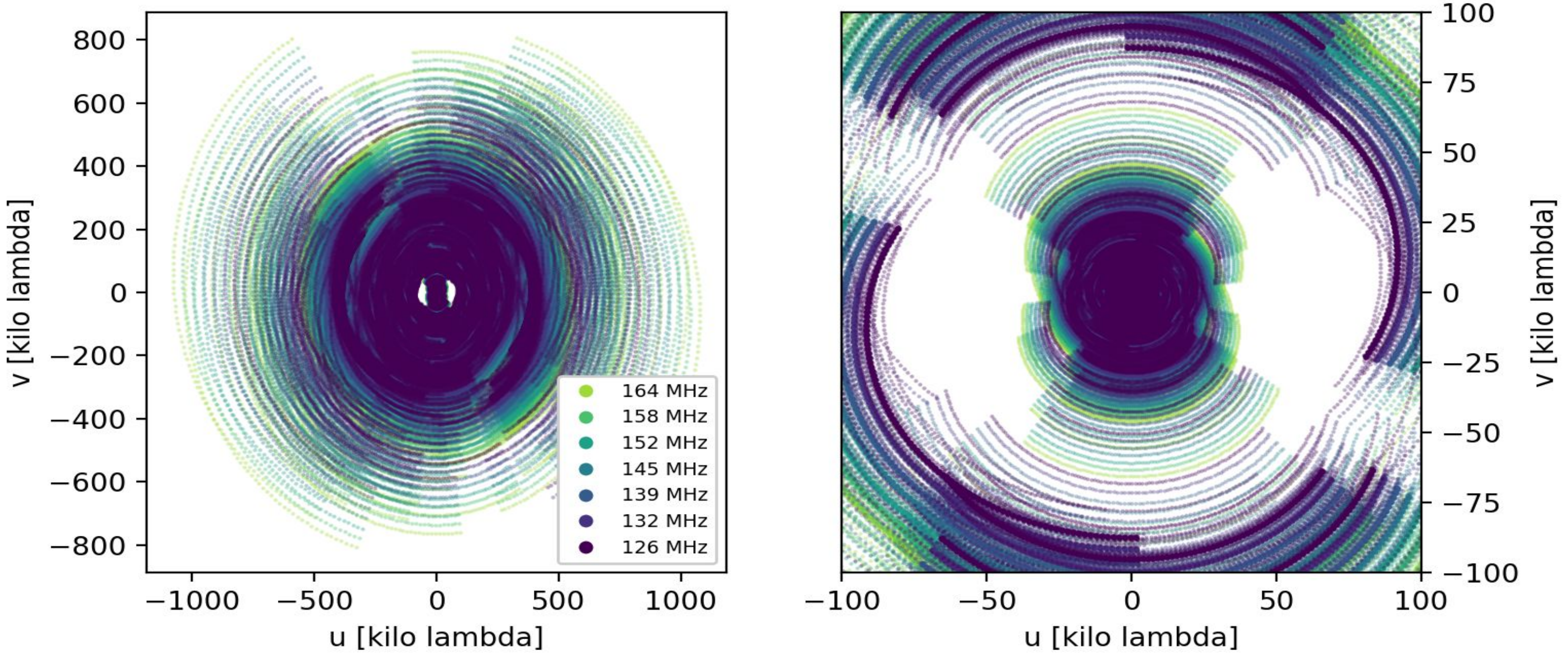
- **Longer baselines:** geometric correction needs to be more precise
- **Non-connected interferometry:** clocks are not synchronised through the same local oscillator (historically data recorded separately and shipped to correlator)
- **Different atmospheric conditions:** the longer the baseline, the more different the atmosphere above the antennas
- **Sparser *u*-*v* coverage:** antennas are fewer and further between
- **Field of view limited:** maximum field of view depends on aperture size, complicates calibration

The payoff: higher resolution!

VLBI with LOFAR



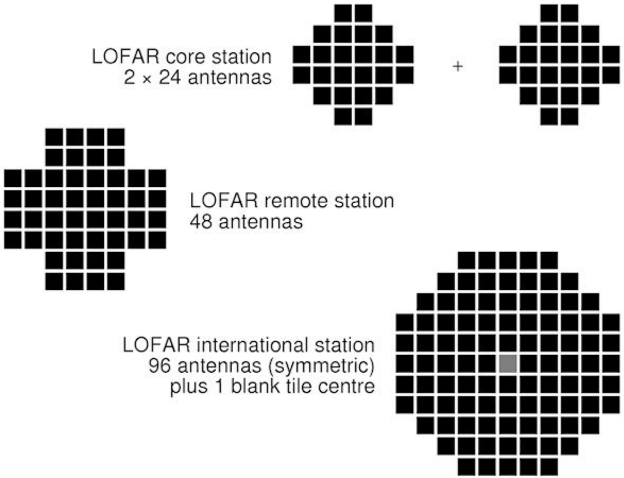
VLBI with LOFAR - *u-v* coverage

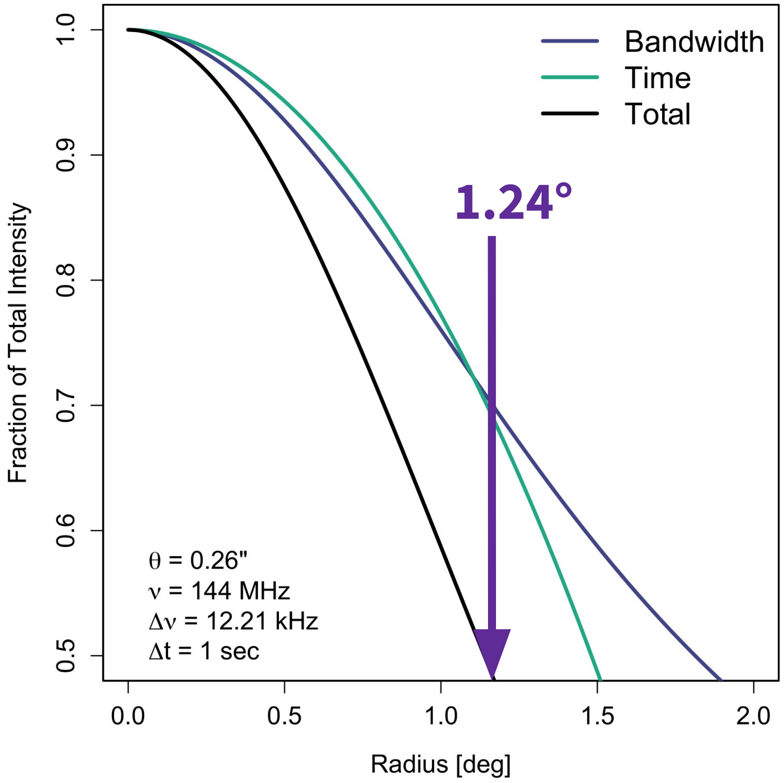


VLBI with LOFAR - Field of View (FoV)

Limited by:

- Station beam of international stations
- Smearing (bandwidth and time)





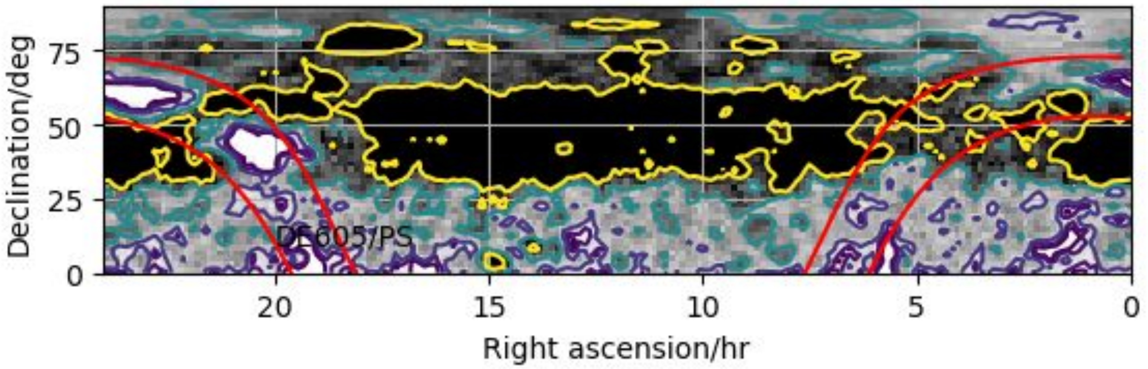
Data calibration challenges

- **Calibrators:** need ‘Goldilocks’ calibrators for resolution / frequency
- **Ionosphere:** requires directional dependent calibration
- **Data volume:** datasets are 4-20TB per observation
- **Clocks:** remote and international stations on individual clocks
- **Source characteristics:** low-frequency absorption, source structure

Long Baseline Calibrator Survey (LBCS)

Covers entire Northern sky for HBA *(Jackson et al, 2022, 2016)*

- Multi-beaming with 3 MHz, 3 min observations of calibrator candidates
- ~30,000 sources in final catalogue, about 1 good calibrator per square degree

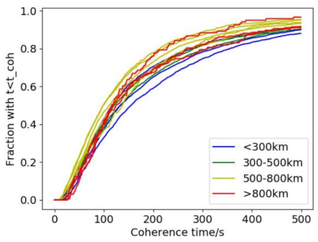


- Accepted commissioning proposal to extend to LBA (PI: Jackson)

Long Baseline Calibrator Survey (LBCS)

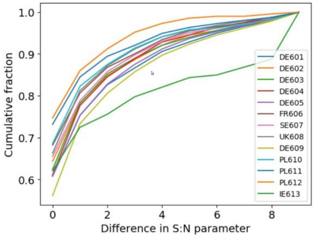
Quality indicators / metrics

Atmospheric coherence statistics



Coherence time is worse on longer baselines, but the effect is not huge

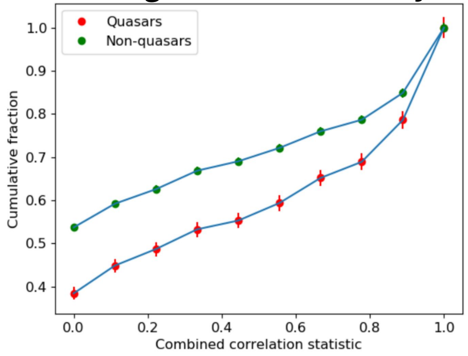
Reproducibility



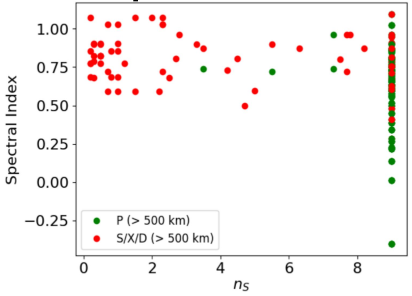
Sources observed more than once: results very similar for all baselines

Science with LBCS

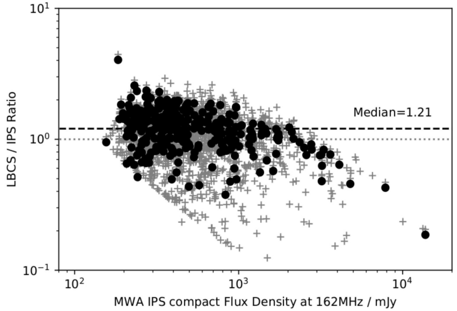
Testing Unification Theory



Compact sources are flat



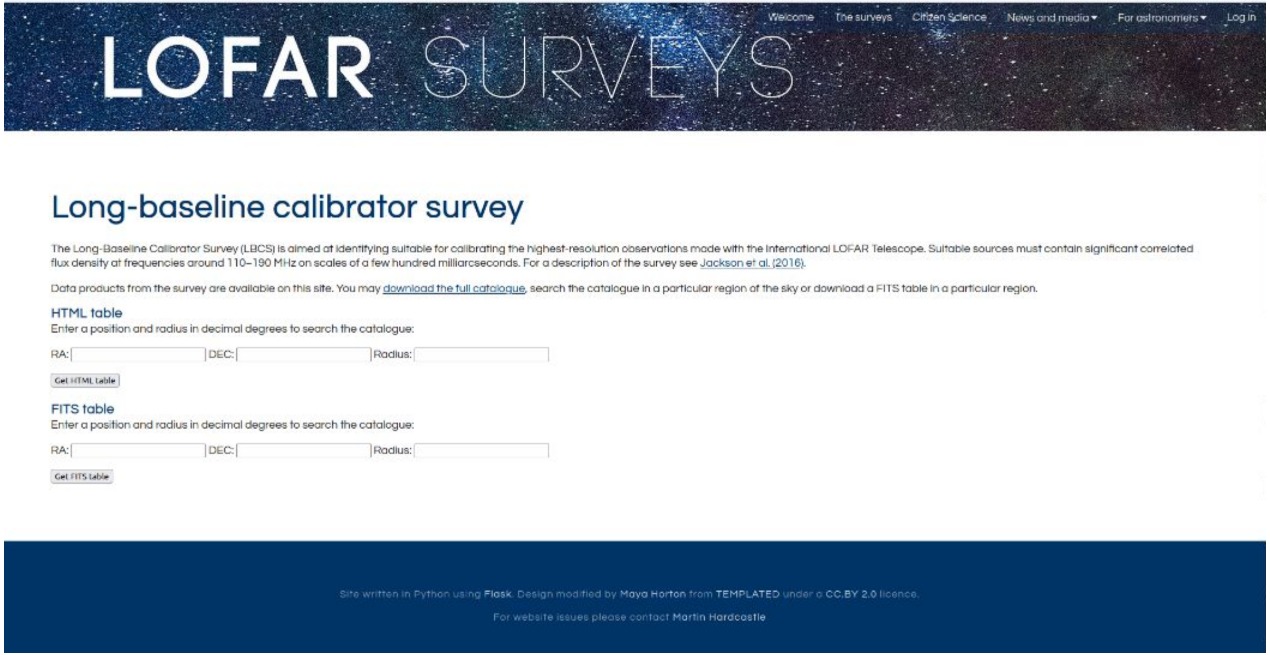
Interplanetary Scintillation



In conjunction with MWA; J. Morgan

Long Baseline Calibrator Survey (LBCS)

https://lofar-surveys.org/lbcs.html



Data calibration challenges

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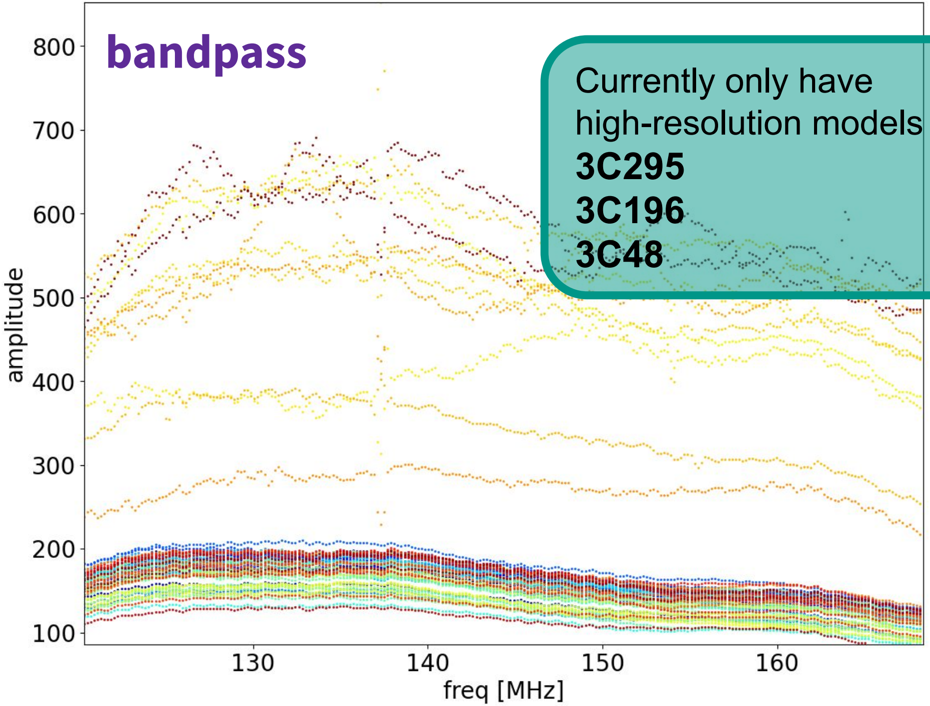
Developing a calibration strategy

LoTSS processing
Full array – instrumental effects
Dutch array – phases

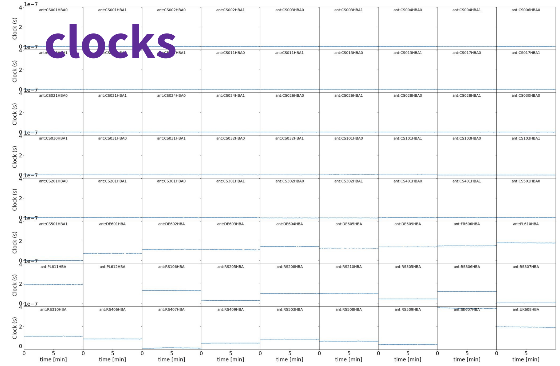
de Gasperin et al. 2019

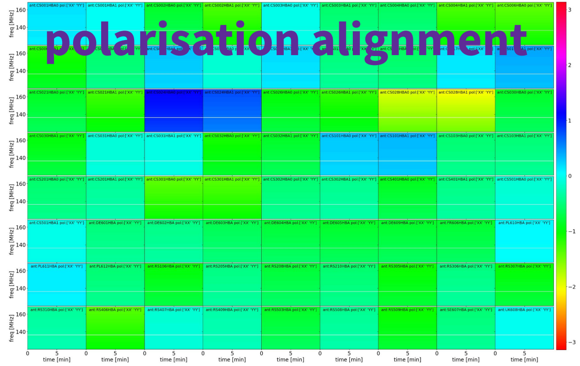
Developing a calibration strategy

LINC calibrator – provides instrumental effects



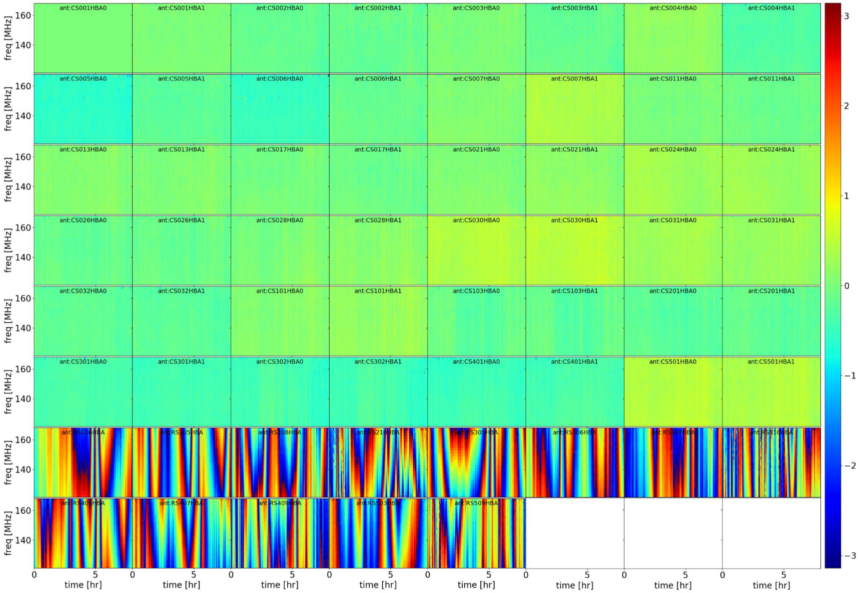
Currently only have high-resolution models for:
3C295
3C196
3C48



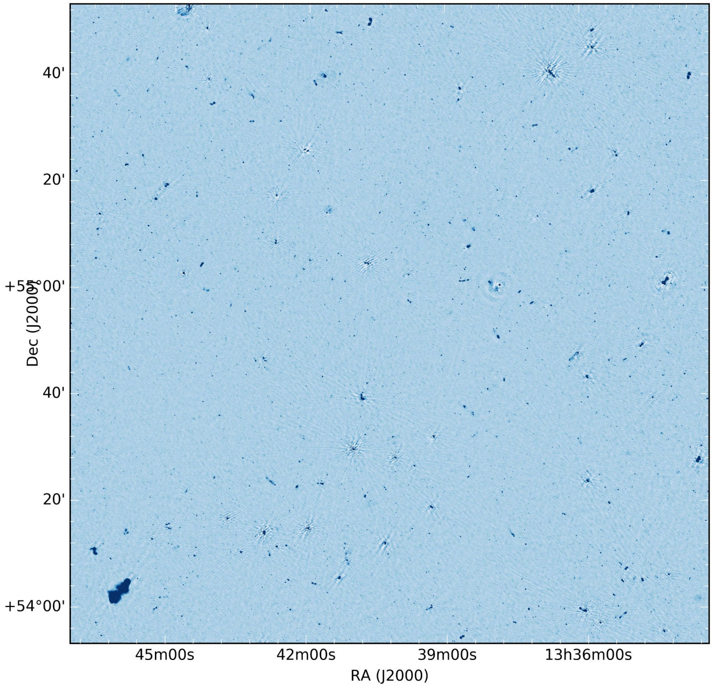


Developing a calibration strategy

LINC target – provides Dutch station direction-independent phases



ddf-pipeline – provides Dutch station direction-dependent phases & final catalogue



Developing a calibration strategy

LoTSS processing
Full array – instrumental effects
Dutch array – phases

de Gasperin et al. 2019

LOFAR-VLBI pipeline
Dispersive delay
Phase calibration

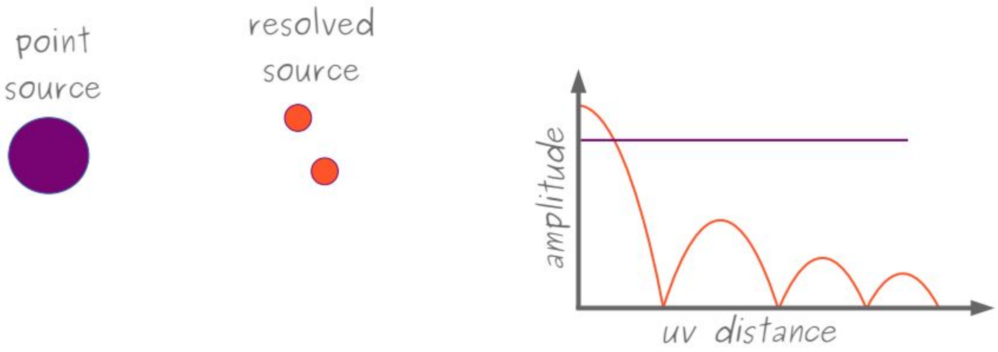
Techniques
- Combine core stations
- Solve directly for TEC
- Phase-shift & average to reduce FOV

Morabito et al. 2022

Calibration uses LOFAR-native tools but borrowing from VLBI techniques

Developing a calibration strategy

Calibration at high resolution has to handle lower signal to noise on long baselines

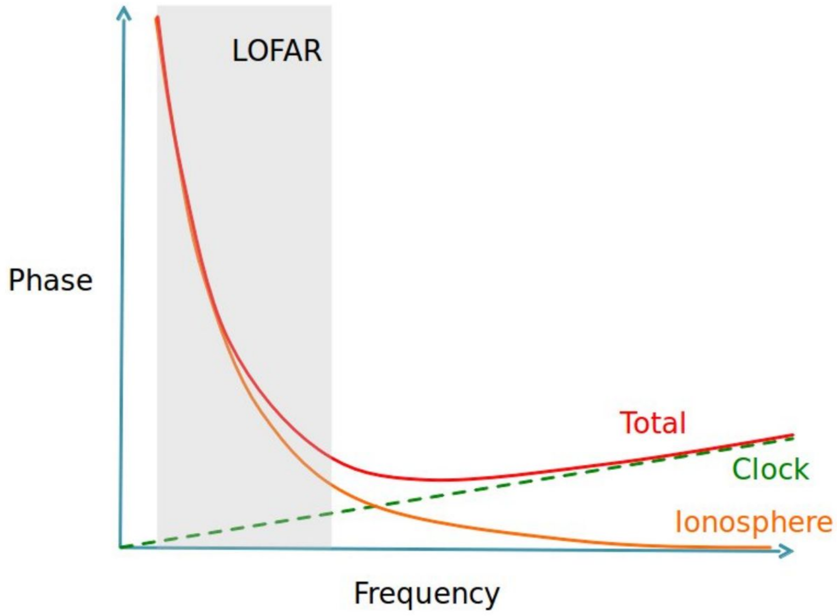


To cope with this a technique called ***fringe-fitting*** was developed to increase the solution intervals by solving for *delays* and *rates* in addition to a phase offset:

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

Developing a calibration strategy

Fringe-fitting algorithms have, until very recently, only been able to cope with *non-dispersive delays* (i.e., phase is linear with frequency)

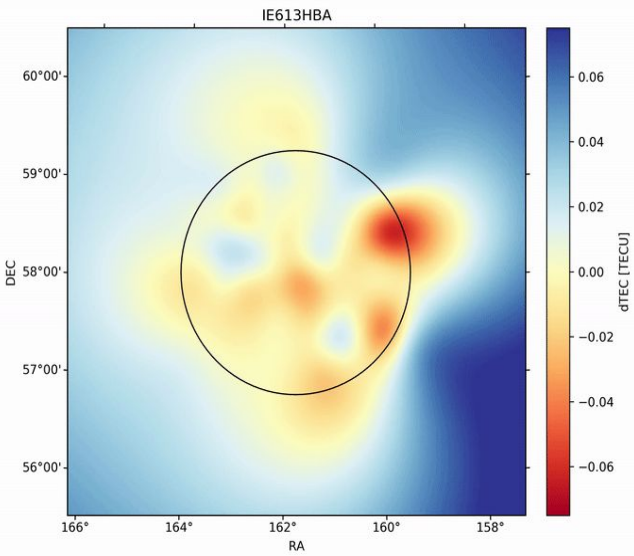


LOFAR is dominated by ***dispersive delays*** due to the ionosphere

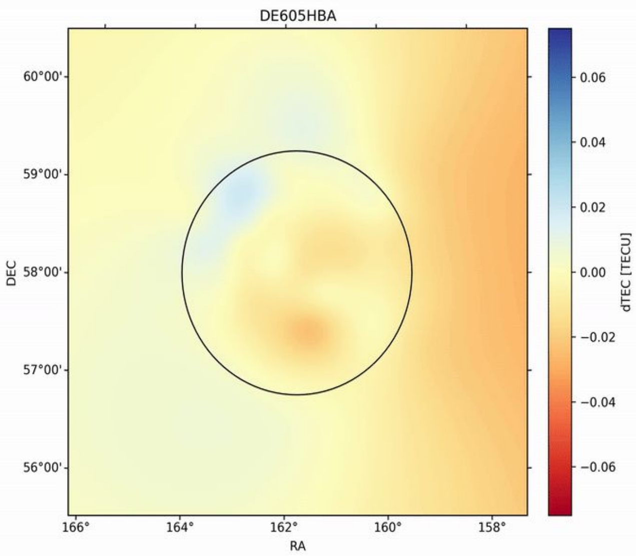
Image courtesy J. Moldón

VLBI with LOFAR - ionosphere

Irish station



German station



dTEC (differential Total Electron Content) seen in Lockman Hole, courtesy F. Sweijen

Developing a calibration strategy

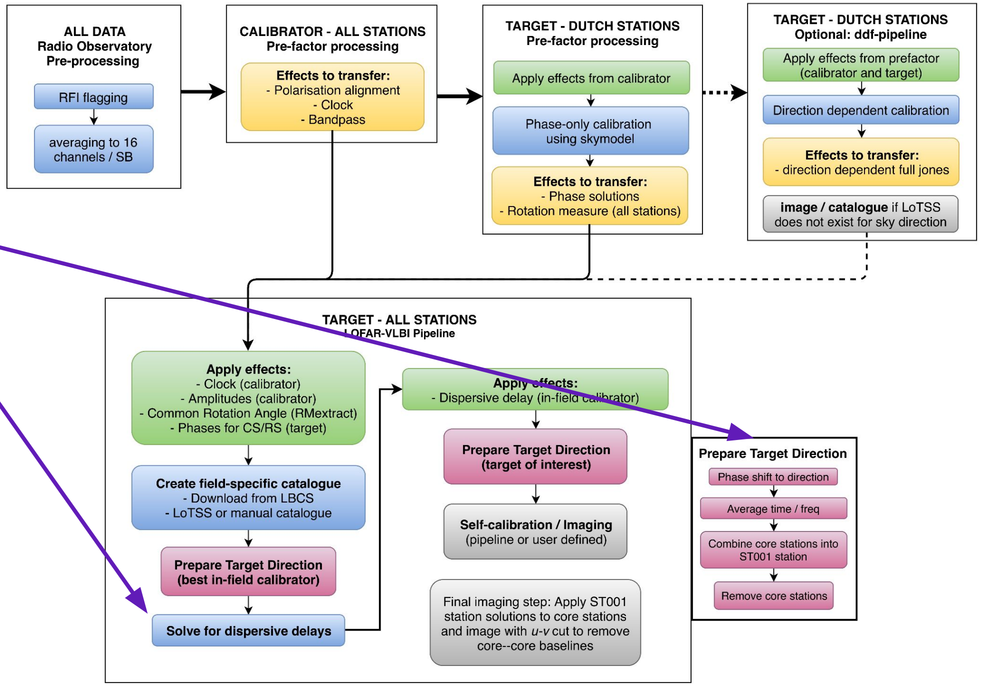
Use LOFAR-native tools to:

- Correct clock offsets
- Solve directly for dispersive delay
- Combine core stations into a ‘super-station’ to help anchor calibration and reduce data volume

Publicly available on github *(Morabito et al. 2022)*

Built as an extension to the processing for the LOFAR Two-metre Sky Survey *(Shimwell et al. 2017,2019,2022)*

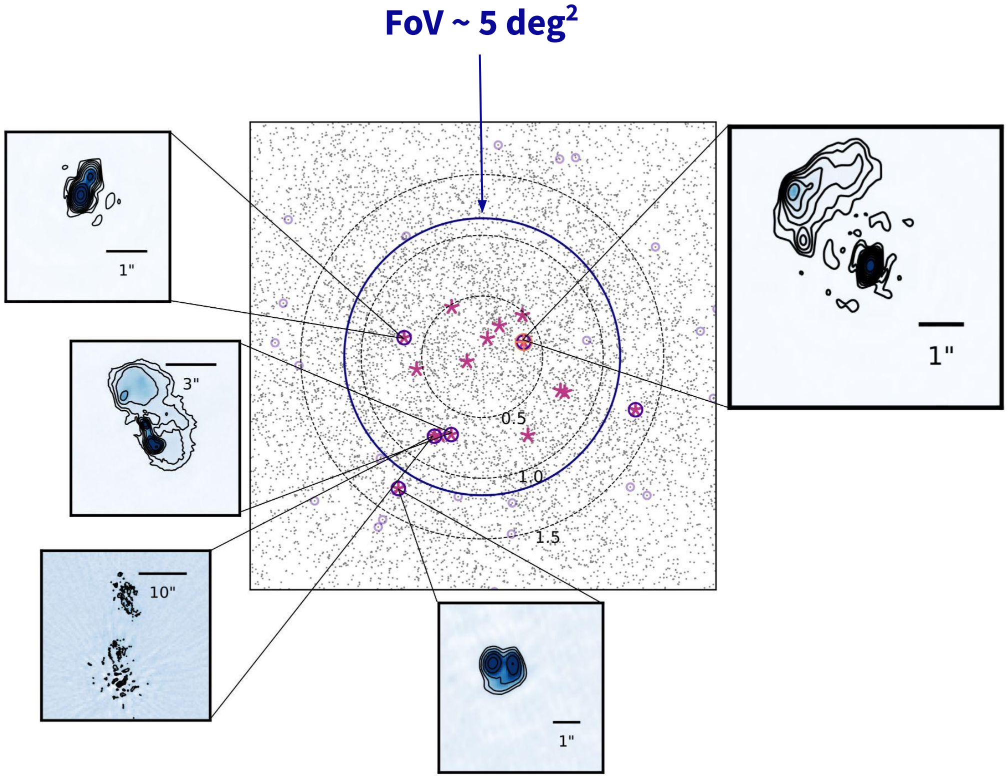
Self-calibration has been replaced by with lofar_facet_selfcal *(van Weeren et al. 2021)*



Demonstration: P205+55

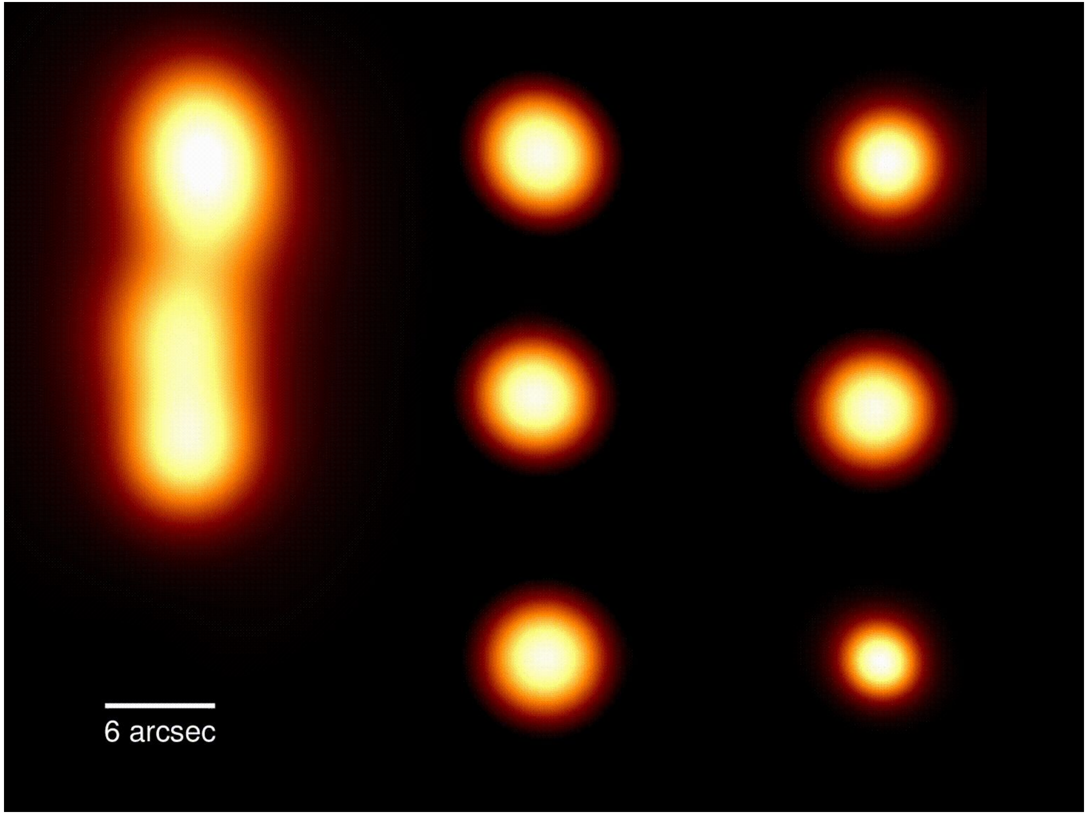
Field of view limited to 1.25° radius
(by smearing and station beams)

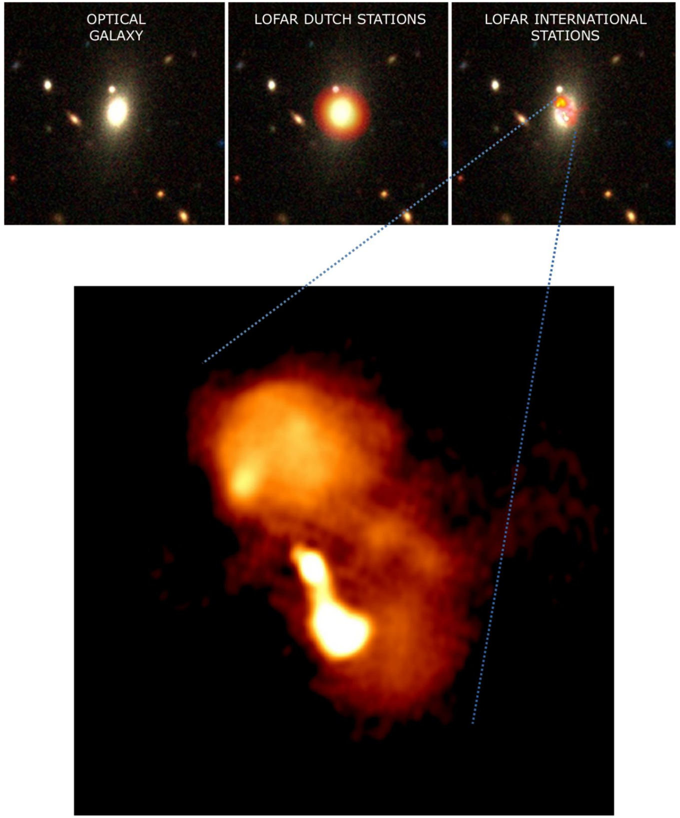
1. Find dispersive delays on best LBCS in-field calibrator
2. Transfer to other LBCS calibrators
3. Propagate phase-referencing around the field



Full demonstration: Morabito et al. (2022)

Demonstration: P205+55





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de Gasperin et al. 2019

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LOFAR-VLBI pipeline
Dispersive delay
Phase calibration

<u>Techniques</u>
- Combine core stations
- Solve directly for TEC
- Phase-shift & average to reduce FOV

Morabito et al. 2022

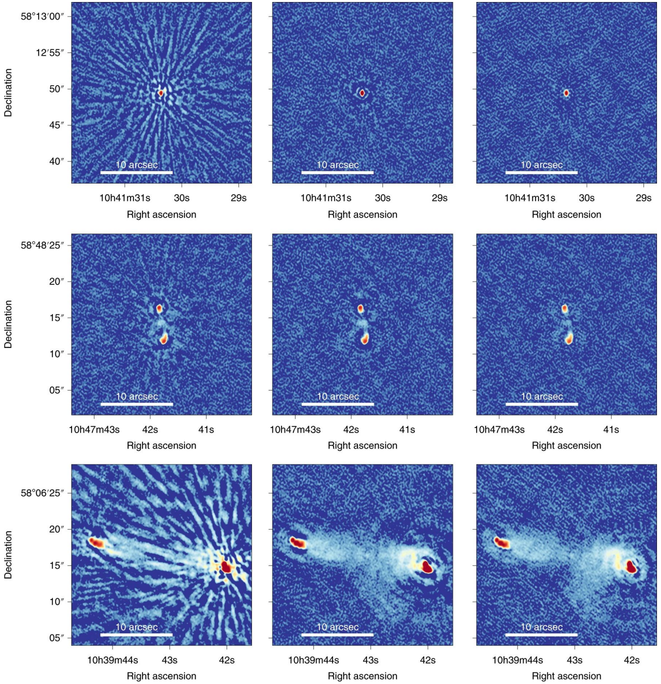
Widefield LOFAR-VLBI
Residual delay across field
Directional phase / amplitude self-cal

<u>Techniques</u>
- Facet-based imaging
- Combine facets for final image

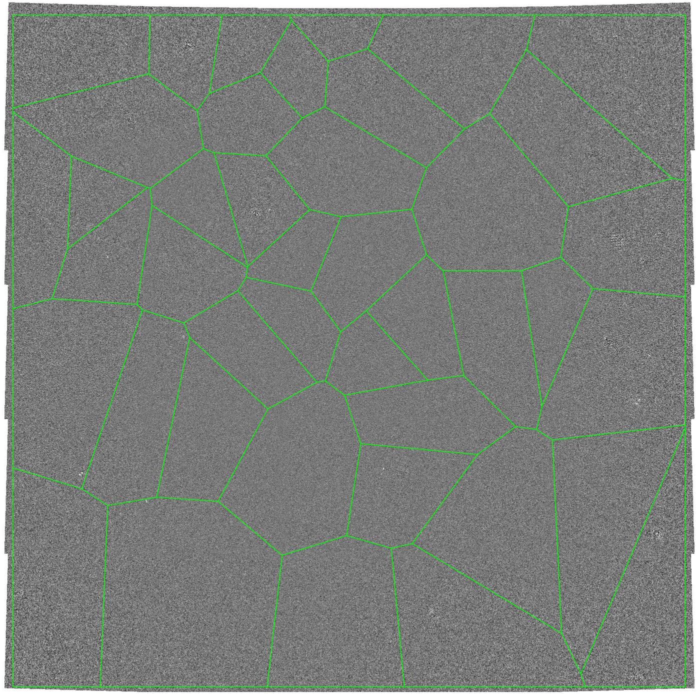
Sweijen et al. 2022

Demonstration: Lockman Hole

direction-dependent self-calibration



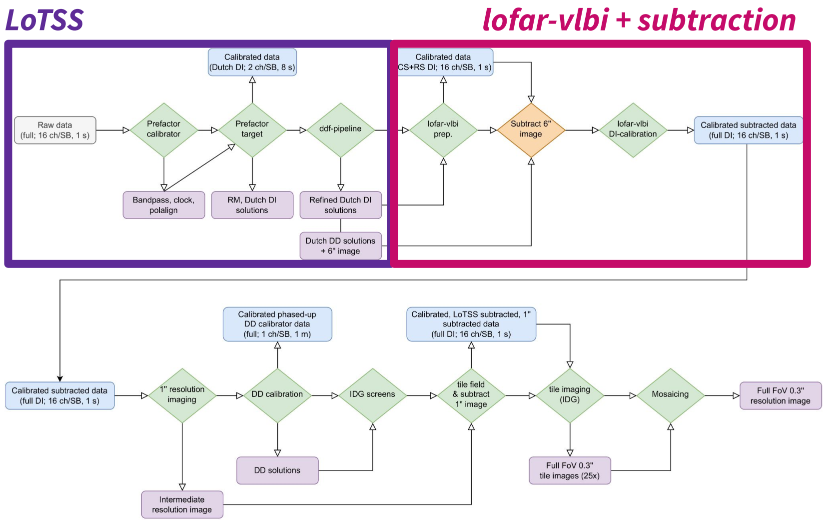
faceting over the field

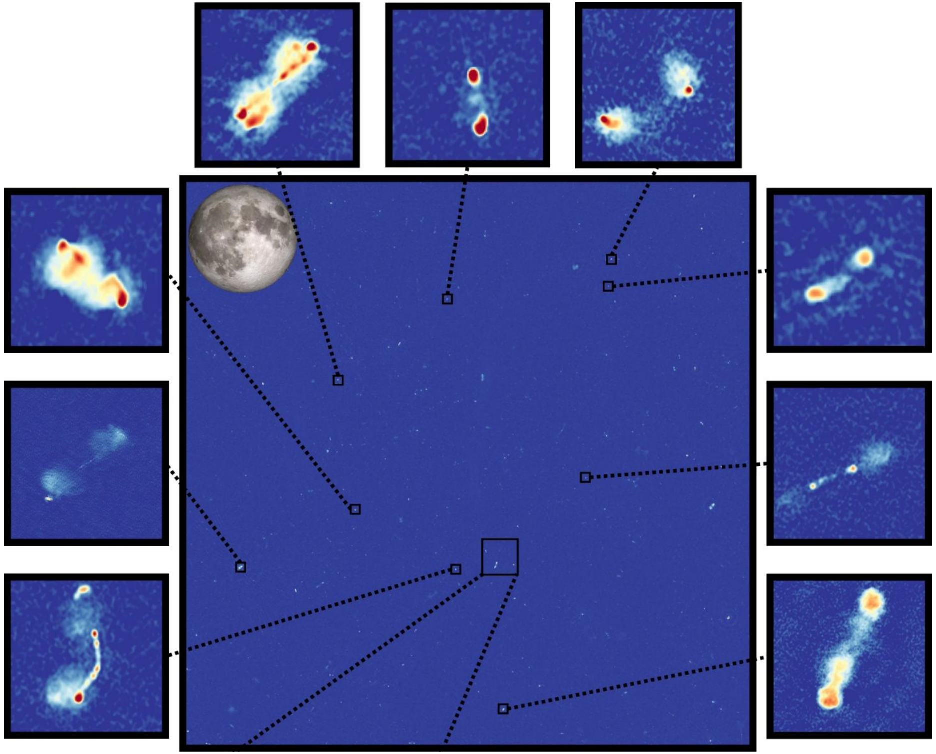


Sweijen et al., 2023

Demonstration: Lockman Hole

- 8 hour observation
- 250,000 CPU hours
- 36 μJy/beam median noise
- Field of View - 6.6 deg2
- 2,214 sources



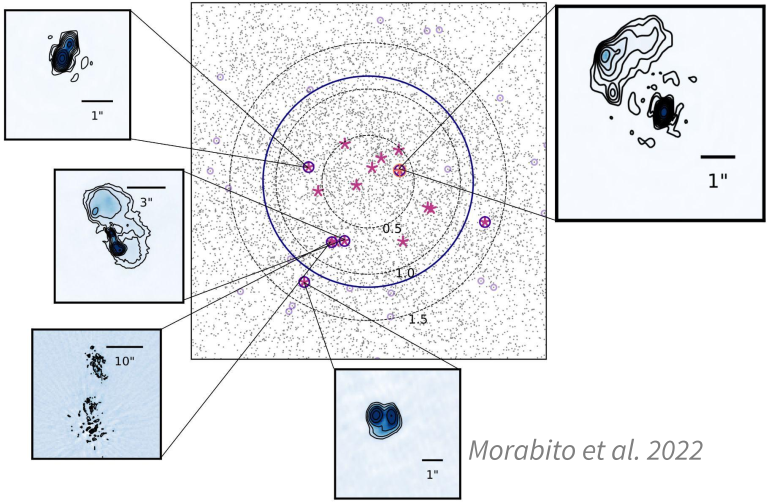


Sweijen et al. 2022

Wide-field VLBI with LOFAR

LOFAR-VLBI pipeline

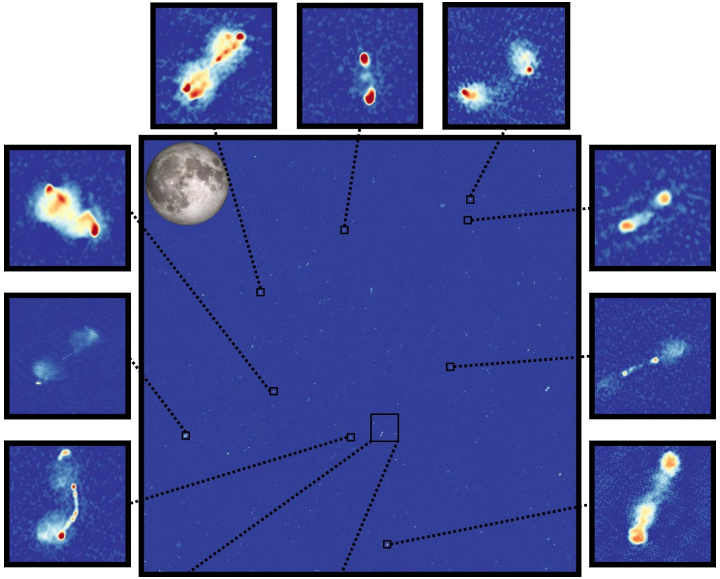
Application: wide area surveys



Morabito et al. 2022

Widefield LOFAR-VLBI

Application: deep field surveys



Sweijen et al. 2022

Summary

- LOFAR is a Very Long Baseline Interferometry (VLBI) instrument

- Although challenging, we have a calibration strategy

- Becoming more user-friendly
  - publicly available pipeline (currently being converted to CWL)
  - Long Baseline Working Group – telecons and Slack workspace

    → contact *leah.k.morabito@durham.ac.uk*

Extra slides

Developing a calibration strategy

james script for bootes

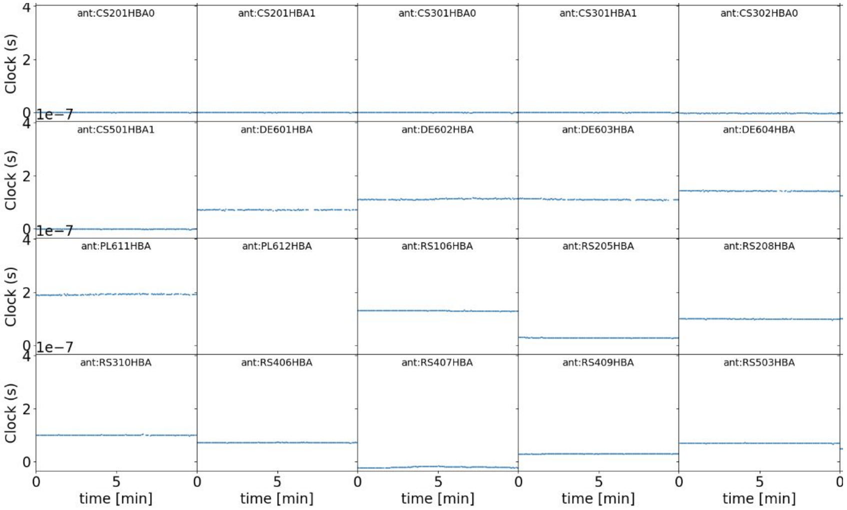
show emmy nice calibrator

facetselfcal citation / github

VLBI with LOFAR - Clocks

Different clocks for non-core stations

solve for clock offsets on flux calibrator



leftover: clock "drifts" during observation