The LOFAR Tier-1 HBA Survey

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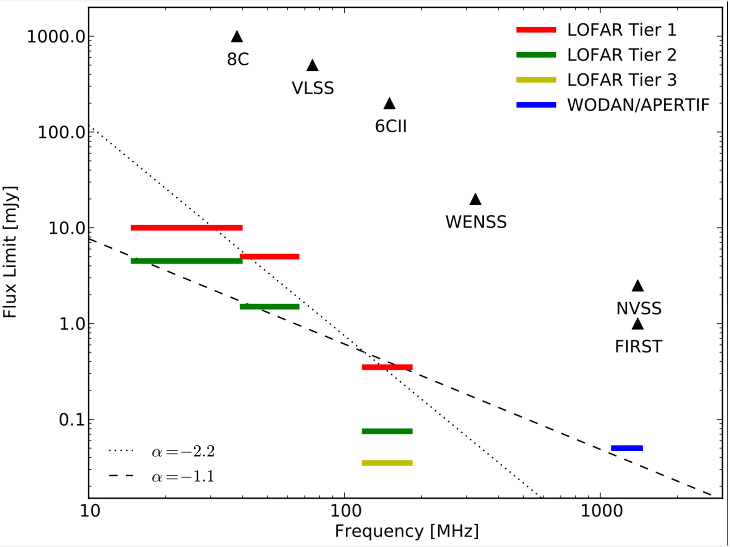
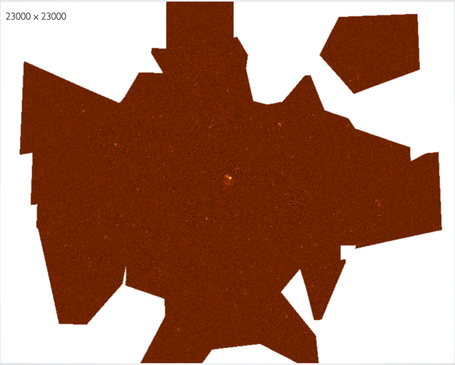
Why do a low frequency survey?



Outline

The observational aims of the Tier-1 HBA survey

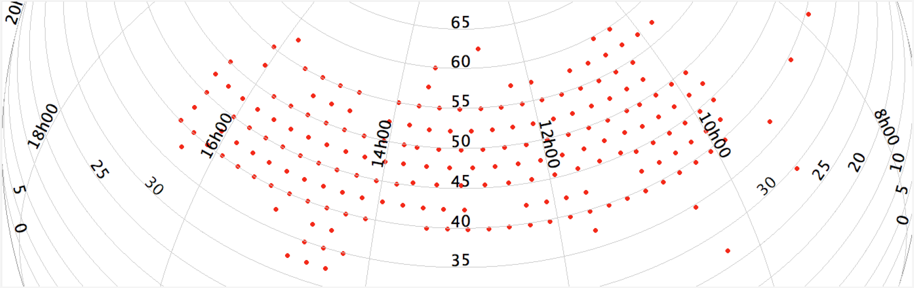
- ≈5” resolution
- ≈100μJy/beam sensitivity in 8hrs
- 48 MHz bandwidth (from 120 MHz to 168 MHz) towards each pointing
- 3500 8hr pointings to cover the northern sky (14,000 hrs observing with 8-bit mode)



Demonstrating the LOFAR capabilities with a 10 hr observation of a cluster field. The image noise level is 100μJy/beam and the resolution is 5" (by Reinout van Weeren).

Status of observations

- ≈1000hrs HBA observations so far (cycles 2, 3, 4 and 5).
- 210 × 8 hr Tier-1 pointings with 48 MHz bandwidth have now been observed (3500 are required to cover the northern sky).



Some major challenges of the HBA Tier-1 survey

- Increasing the observing speed
- Data retrieval
- Routine science quality imaging
- Scientific exploitation

Increasing the observing speed

The Tier-1 HBA survey contains 3500 pointings. We hope to increase the rate of observations from our current average ~50 pointings per cycle.

- Co-observing with the surveys ksp – new for cycle 6+. We will perform a direction independent calibration of your target data if you use some of your spare bandwidth to place a beam on a Tier-1 surveys pointing.
- 4-bit mode if working well this will half the amount of time required to complete the survey (7,000hrs rather than 14,000hrs).

Data retrieval – working at the archive

The surveys datasets are 16Tb per 8hr pointing to facilitate e.g. spectral line studies and international baseline imaging. Staging and downloading from the LTA takes ≈1month per pointing. We have a new pipeline to significantly speed this up for 5” imaging:

- We have obtained 200,000 CPU hrs and 160Tb of storage at SURFsara (PI: Oonk).
- For the main Tier-1 survey aims we only need 4ch/sb and 4 sec resolution to avoid significant smearing (the data are recorded at 16ch/sb and 1sec for other studies and legacy value).
- Simple NDPPP flagging, averaging, demixing and compressing can be performed on SURFsara.
- This allows us to decrease the data size by at least a fact of 8 and the products be downloaded in less than a day.

Routine science quality imaging

Three strategies:

- Correct field for the average ionospheric phase effects in the field
- Use the facet calibration technique to correct field with ≈30 ionospheric corrections for a different directions in the field
- Wirtinger direction dependent calibration and DDFacet imaging

Images after average ionospheric correction

Calibrating and imaging data with a single calibration off a sky model of the field is a fast ($\approx$ 3 days per pointing) process that can produce images which will allow the Tier-1 surveys to complete many of its scientific aims.

- This calibration is an intermediate step for our direction dependent calibration strategies
- About 70 fields reduced using this procedure
- Images produced at 20" resolution have a sensitivity of typically 200-500μJy/beam about 75% of the time.

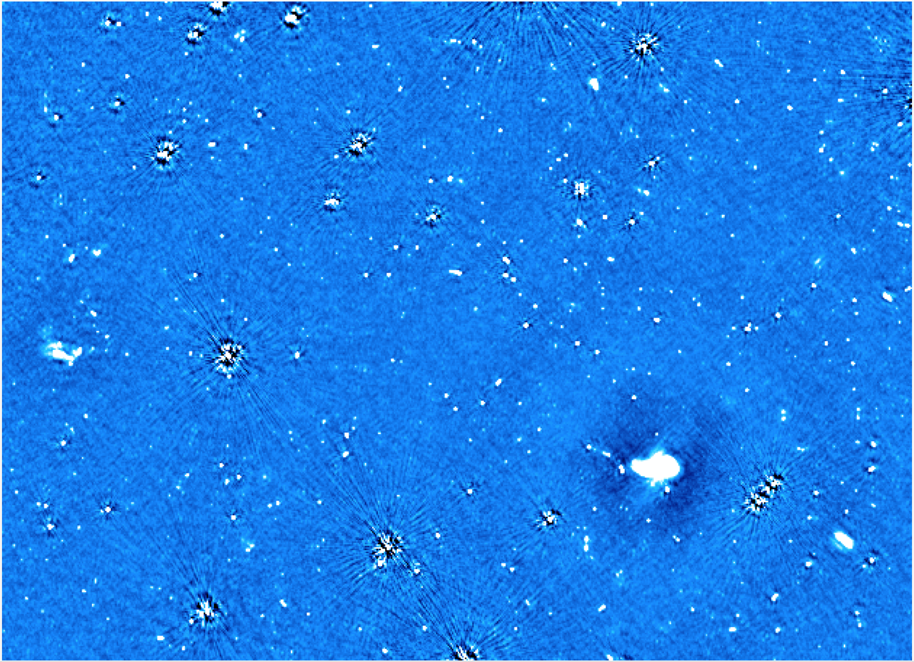
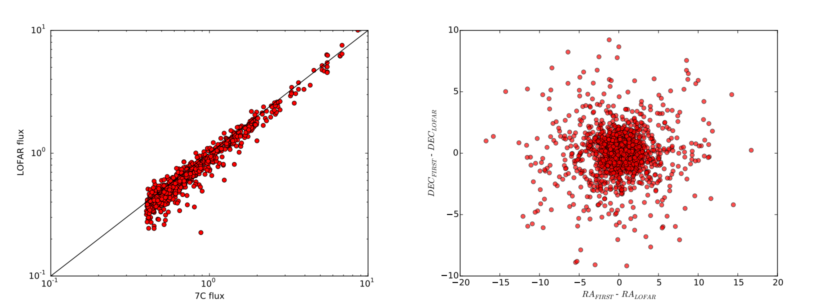


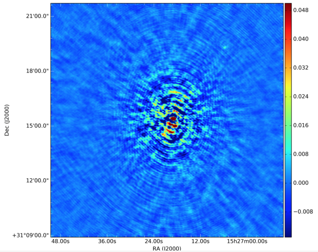
Image quality after average ionospheric correction

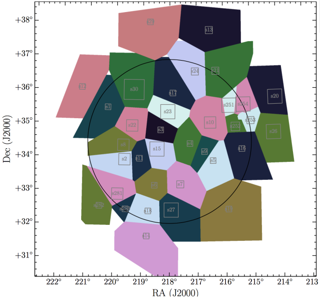


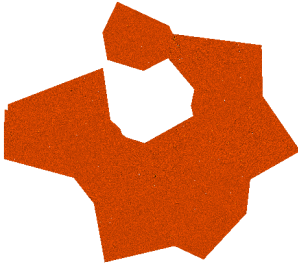
About 200 sources in each field can be matched with 7C sources. The LOFAR fluxes in our direction independent calibration of point-like sources are typically within 10% of the 7C measured flux. About 1500 sources in each field can be matched with FIRST sources. The LOFAR source positions are typically within 5arcsec but there is a systematic offset that varies from pointing to pointing.

Facet calibration

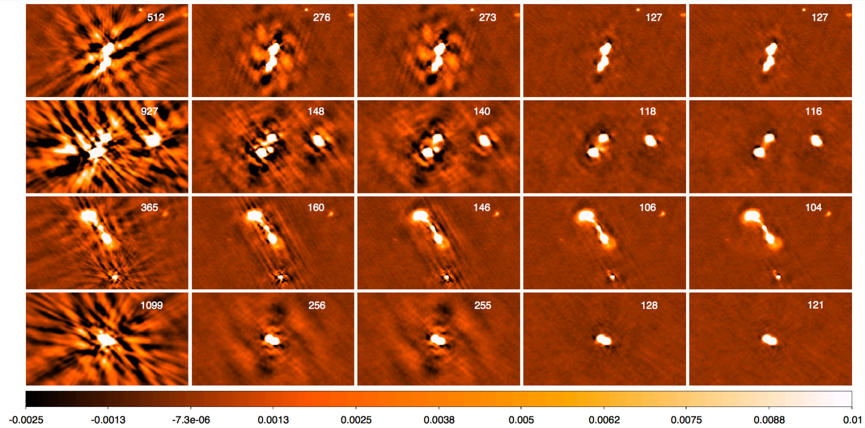
The facet calibration scheme is described in van Weeren R. J., et al., 2016, ApJS, 223, 2 and Williams et al., MNRAS submitted.



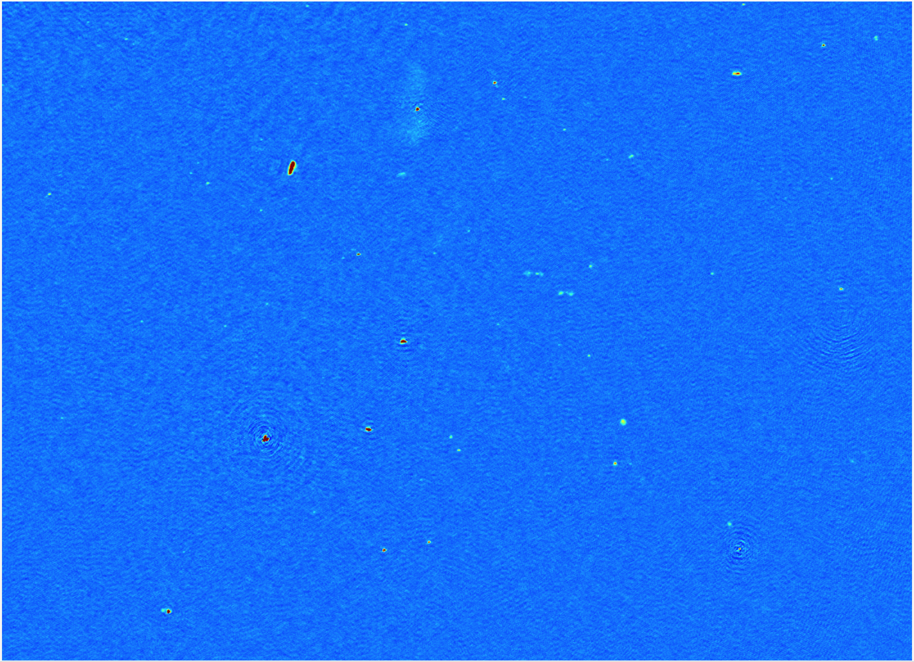




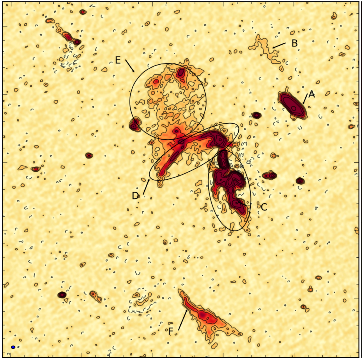
Facet calibration

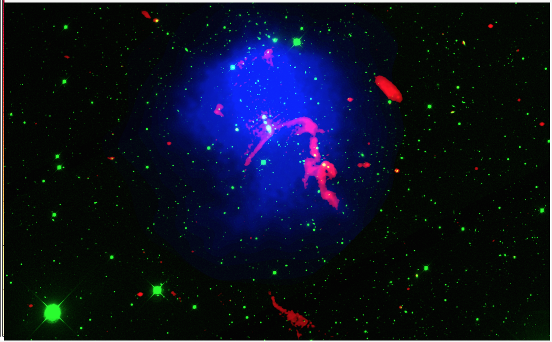


Demonstrating direction dependent calibration (van Weeren R. J., et al., 2016, ApJS, 223, 2)



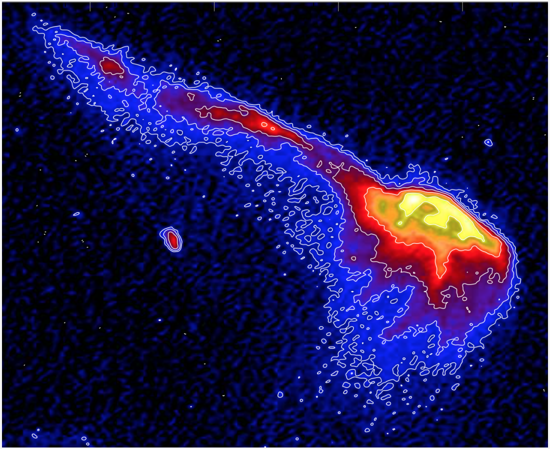
Facet calibration





Thermal noise limited images at 5" resolution. Abell 2034 (Shimwell T. W., et al., 2016, MNRAS accepted – arXiv:1603.06591).

Facet calibration



Thermal noise limited images at 5" resolution. The toothbrush cluster (van Weeren R. J., et al., 2016, ApJ, 818, 204).

Facet calibration

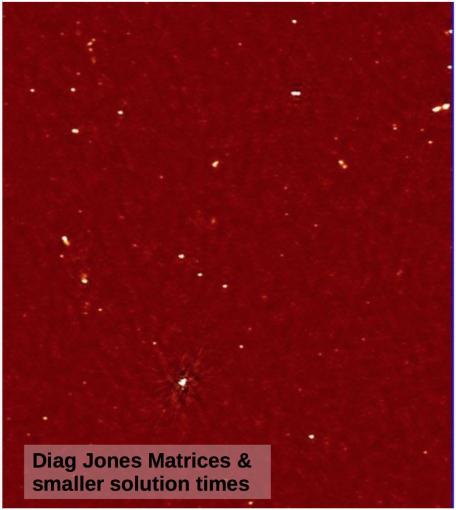
- By calibrating in $\approx$30 directions the ionospheric effects and beam errors can be significantly reduced.
- This calibration scheme has been successfully run on about 10 fields (reaching approximately thermal noise) and is being tested on a further 20+
- Without any software improvements the runtime will be $\sim$1month for a Tier-1 survey pointing.
- Completely automated scripts have been developed and are in the final stages of commissioning (see Andreas talk).
- Preparations are beginning to routinely perform facet calibration on Tier-1 survey datasets (Tim, David, Andreas, Reinout, Wendy, Martin, Sarrvesh, Pepe).

Wirtinger calibration and DDFacet imaging

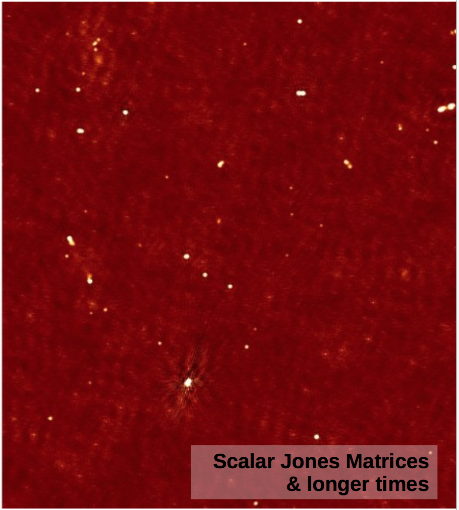
Cyril Tasse developed direction dependent calibration and imaging procedure.

- Create initial sky model from direction independent image (or external model).
- Calibrate with Wirtinger calibration which performs rapid simultaneous N-directional solving
- Apply calibration solutions during in the imaging with DDFacet

Bootes field (Facet-based vs Wirtinger)



Facet-based calibration (Wendy+Reinout)



DDFacet + Wirtinger-Kalman filter

Wirtinger Calibration : speed ?

How long does it take ?

- **A good machine :**
  - 20 cores – 40 threads
  - 2.6 GHz
  - 256 Gb RAM
- **Calibration :**
  - ~100 directions (>10.000 sources in the SkyModel)
  - XX/YY (Amp+Phase)
  - Small memory consumption
  - **~60-100 minutes/10 SubBands** (24-40 hours for 240 SB)
- **Imaging :**
  - 20.000 x 20.000 pixel image
  - Using ~100 Gb at peak consumption for imaging
  - Full-pol correction
  - **~12 hours (100 SubBands - 11 major cycles)**

Scientific exploitation – The scientific aims of the survey

- PI: Huub Röttgering
- Highest redshift radio sources: George Miley
- Clusters and cluster halo sources: Gianfranco Brunetti & Marcus Brügen
- Starforming galaxies at moderate and high redshifts: Peter Barthel & Matt Lehnert
- AGN at moderate redshift: Philip Best
- Detailed studies of low-redshift AGN: Raffaella Morganti
- Nearby Galaxies: Krzysztof Chyzy & John Conway
- Gravitational lensing: Neal Jackson
- Galactic radio sources: Glenn White
- Cosmological studies: Matt Jarvis

Scientific exploitation – WEAVE-LOFAR

- WEAVE is a new multi-object spectrograph to be installed on the WHT in 2018.
- WEAVE will be the primary source of spectroscopic information for the LOFAR surveys.
- It has a 2 degree field of view and can obtain 1000 spectral in a single exposure.
- *http://star.herts.ac.uk/~dsmith/Dan_Smiths_Website/Home.html*

Scientific exploitation – Making the data accessible to the surveys KSP

Products will be accessible with a TGSS style web interface – http://tgssadr.strw.leidenuniv.nl/doku.php

A paper detailing the Tier-1 survey and some early results is in preparation.

Entering production mode

Presently we observe ∼50 pointings every 6 months and the Tier-1 surveys is preparing to enter production mode to build up large areas of the sky imaged at 5" and 100μJy/beam.

- Downloading the data has been reduced to less than a day by utilising SURFsara
- A full facet calibration takes a month – pipelines with minimal human interaction are nearly fully commissioned (Wirtinger calibration about 10 times faster and is being tested).
- We have access to many computers and with just 40 simultaneous reductions we could keep up with the rate at which we could download the data from SURFsara.
- We hope to begin the early stages of production mode within approx 6 months.

Conclusions

- We have surveyed about 10% of the northern sky
- Our pipelines for data retrieval and routinely producing science quality images are in the final stages of commissioning.
- We hope to shortly enter into production mode and we will be able to process data at a much faster rate then we have currently been observing (to date we are averaging about 50 pointings observed per cycle).
- We have a large team of $\sim$200 scientists from over 50 institutions ready to exploit our Tier-1 HBA datasets.