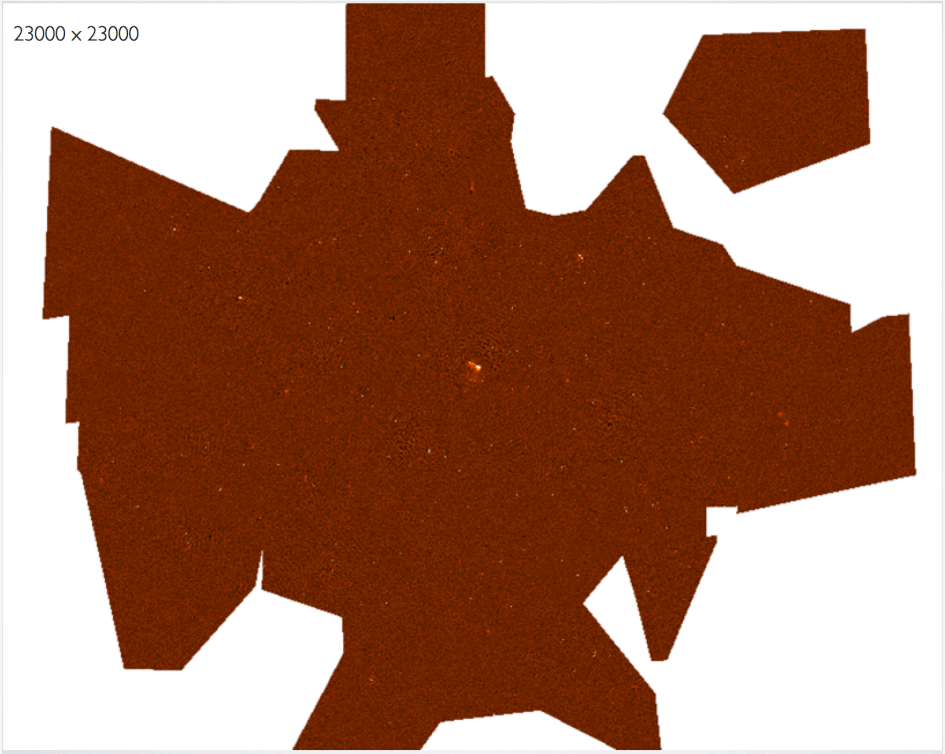
The LOFAR Tier-1 survey

Timothy Shimwell

Leiden

The observational aims of the Tier-1 HBA survey

- ≈5" resolution
- ≈100μJy/beam sensitivity
- 48 MHz bandwidth (from 120 MHz to 168 MHz) towards each pointing
- 3200 pointings to cover the northern sky (pointings separated by 2.6° and beam FWHM from 3.35° to 4.75°)



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).

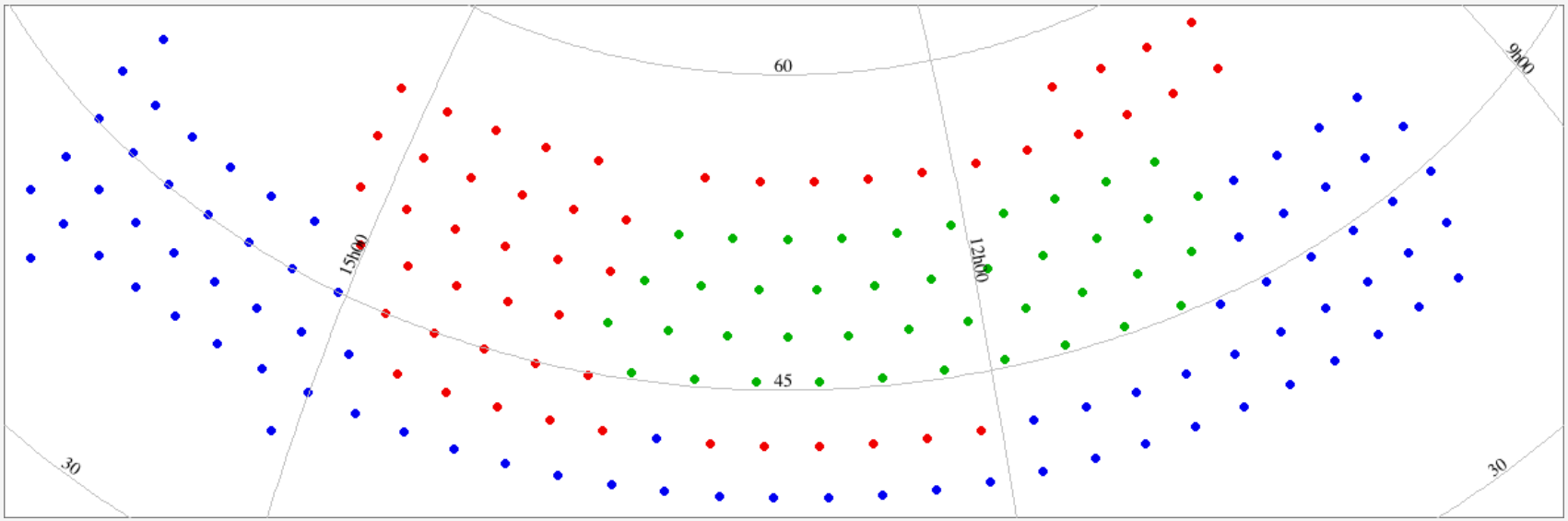
The scientific aims of the Tier-1 survey

- 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
- 164 members from 54 institutions.

Outline

Completed and ongoing observations

- Observations began June 2014
- $\approx 100 \times 8\,\mathrm{hr}$ pointings have been observed and 80 are scheduled.
- 48 MHz bandwidth (from 120 MHz to 168 MHz) towards each pointing
- Always using core and remote stations (40 m to 120 km) in HBA-dual-inner mode and ≈50% of the time also using the international stations.



Cycle 2 (green) and cycle 3 (red) and cycle 4 (blue) pointings.

Reduction strategy

Assess data quality

- Manual inspection of LOFAR observatory validation plots
- A rapid calibration and imaging of 2 MHz bandwidth

Deep imaging

- Calibrate, image and self calibrate 2 MHz data chunks
- Combine calibrated data to 8MHz bandwidth for deeper and wider-band cleaning
- Stack 7 8 MHz images in the image plane to produce final image

Advanced calibration

- Wide-field direction dependent calibration.
- Studying individual interesting objects.
- Rapidly removing bright sources from data

Our current reduction - computational requirements

Approximate reduction time for each pointing (all 48 MHz bandwidth) on 24 processors.

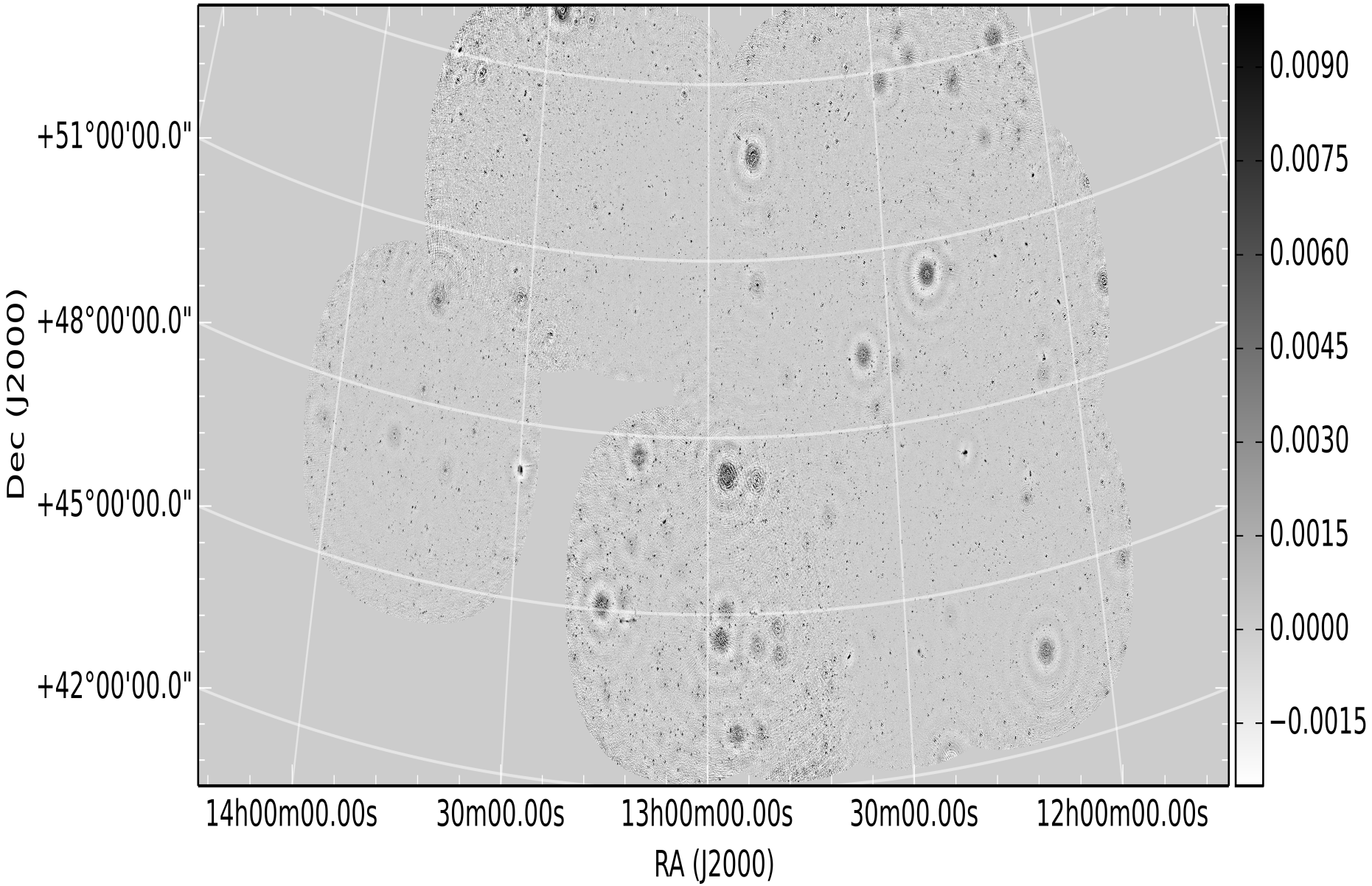
- Downloading the data – 12hr
- Calibrating the calibrator – 5hrs
- Flux calibrating the field and removing “Ateam" source – 20hrs
- Phase calibrating the field off the GSM – 12hrs

Final deep imaging of 8 MHz chunks – 12hrs
Total time to reduce one field ≈3days

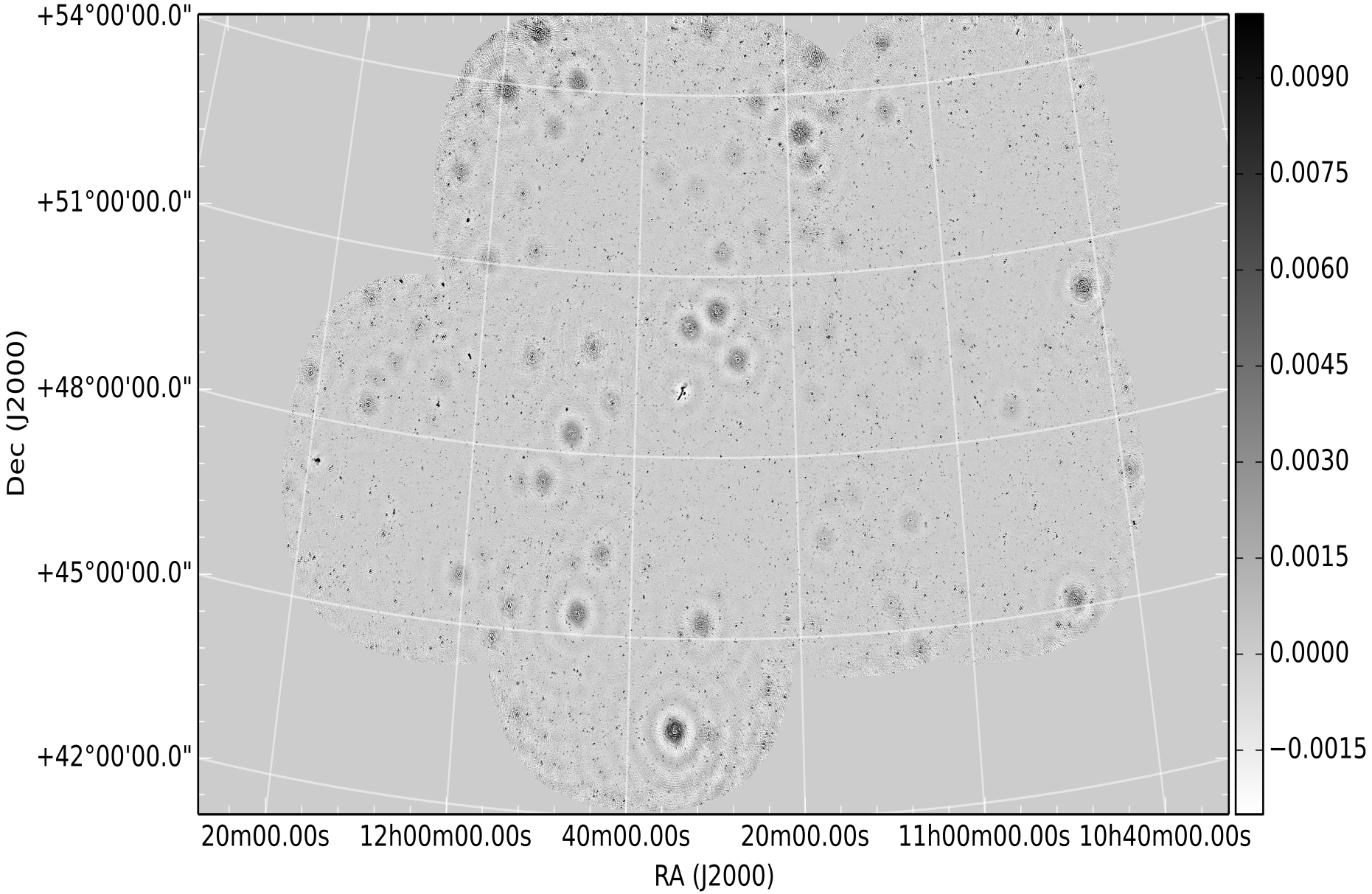
Approximate storage for full 48 MHz.

- Raw data min: $244 \times 12\text{GB (field)} + 244 \times 250\text{MB (cal)} = 3\text{TB}$
- Raw data max: $244 \times 64\text{GB (field)} + 244 \times 1.3\text{GB (cal)} = 16\text{TB}$
- Final data products: $24 \times 24\text{GB (field)} = 580\text{GB}$

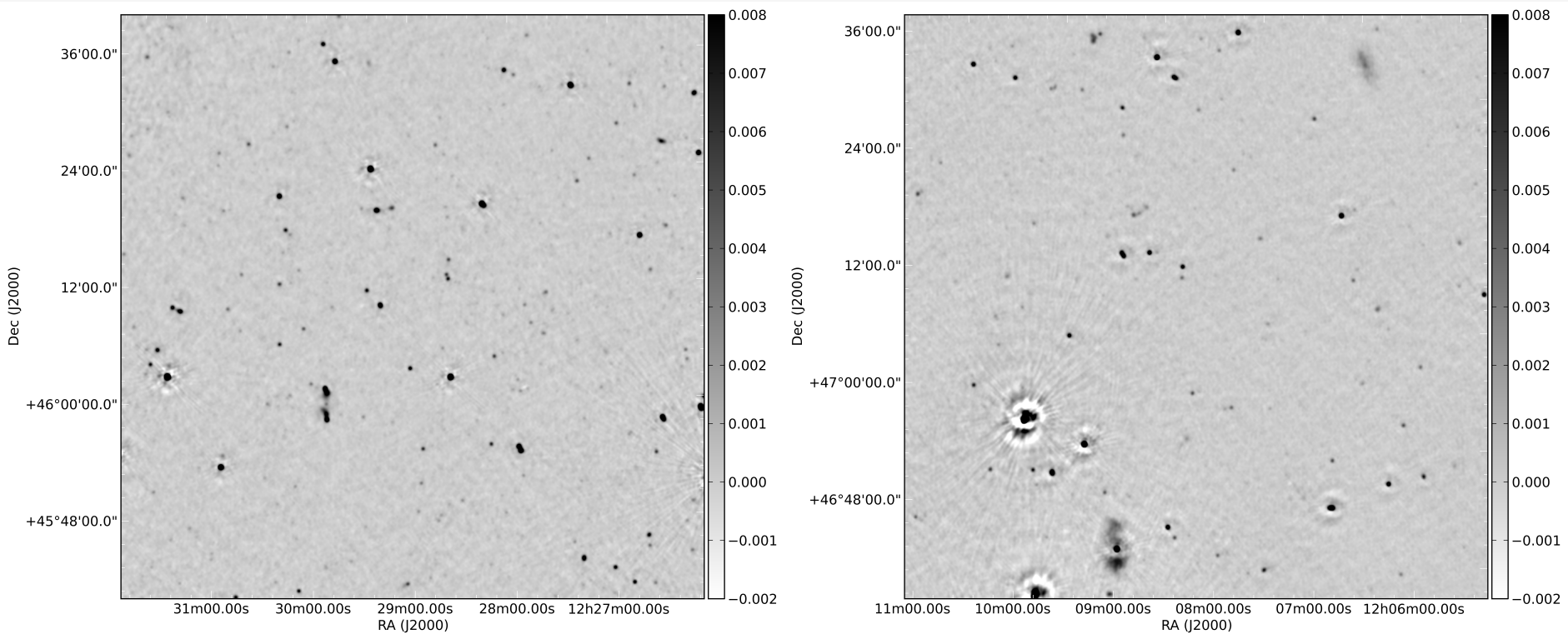
Our current reduction – mosaic



Our current reduction – mosaic

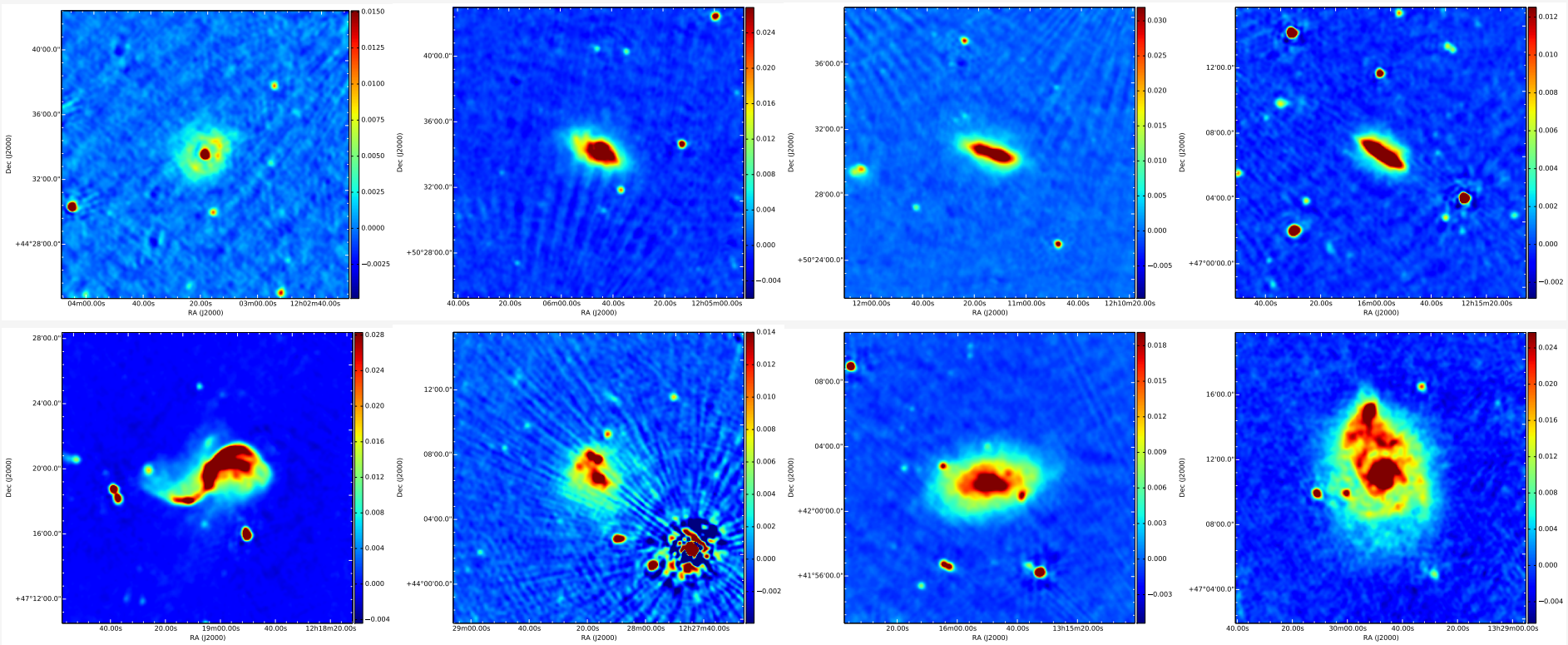


Our current reduction – images



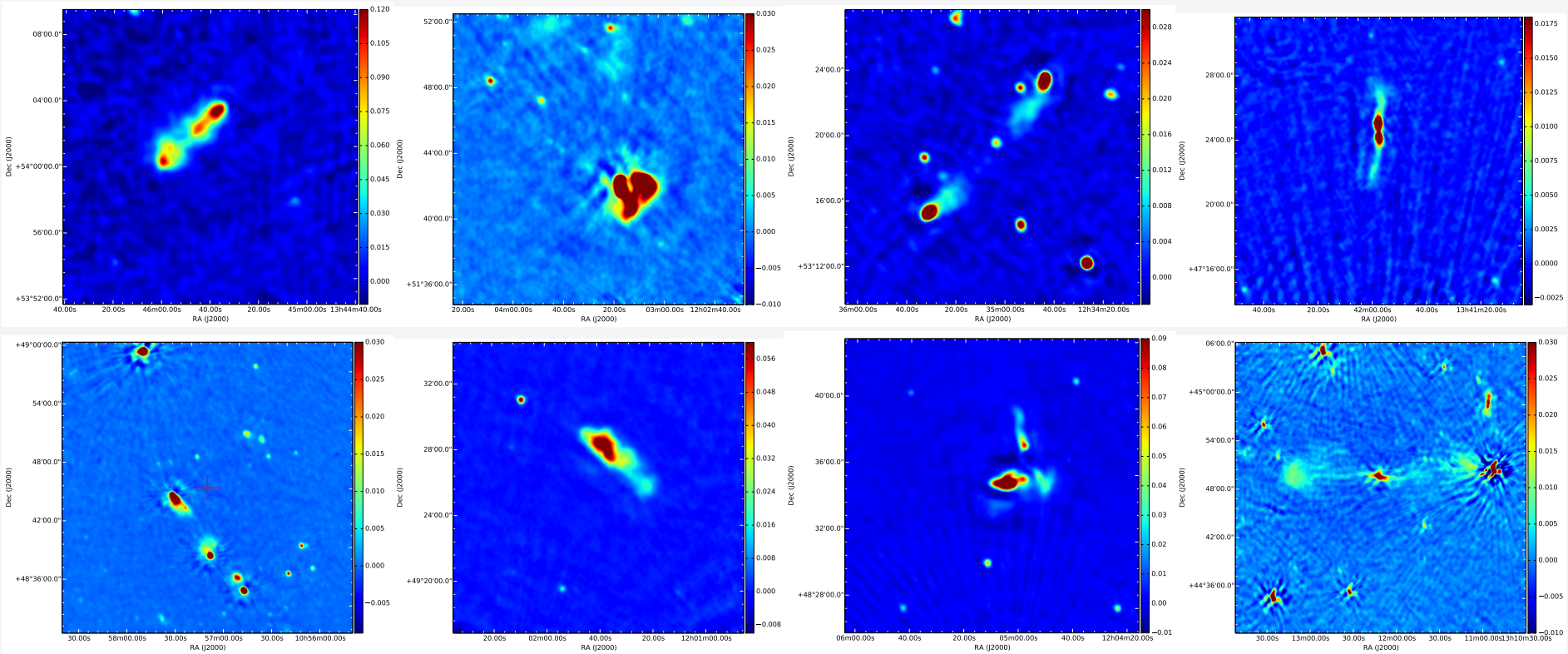
Two example degree square regions from the mosaiced image.

Our current reduction – galaxies



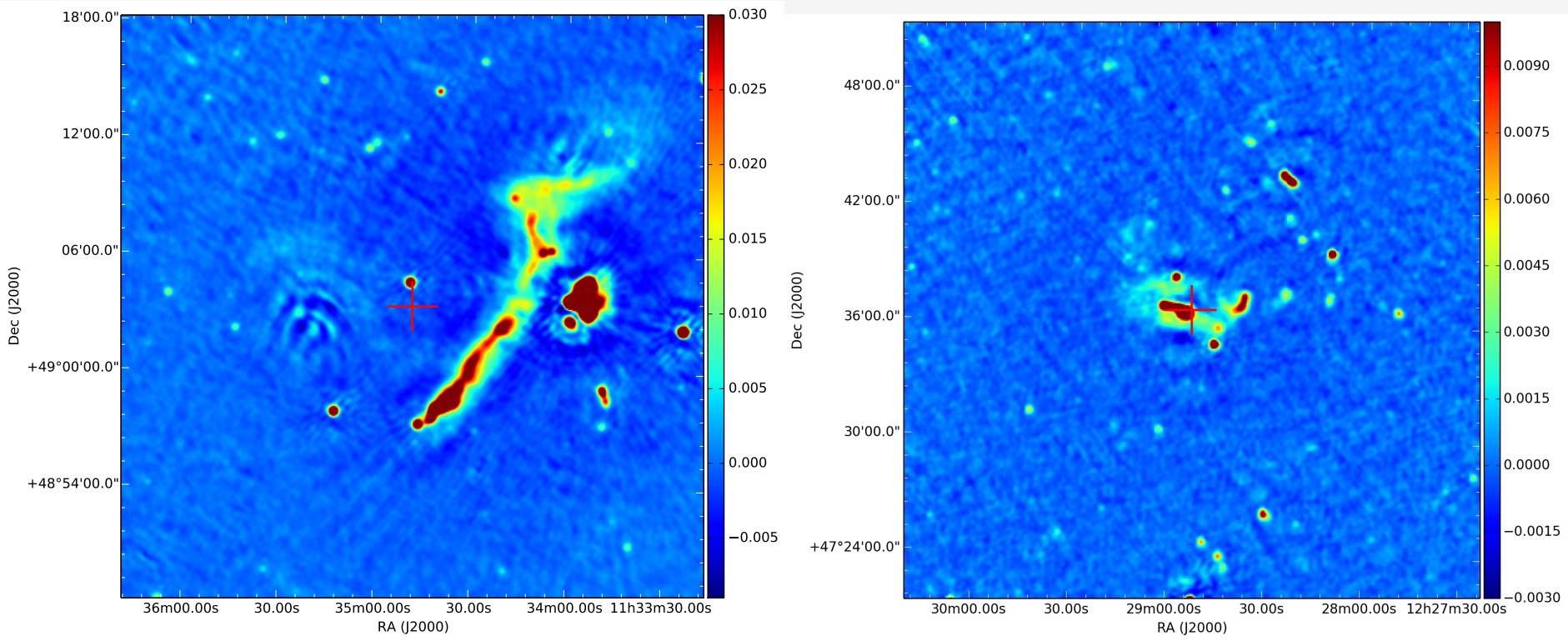
NGC 4051, 4088, 4157, 4217, 4258, 4449, 5055, 5194

Our current reduction – jets



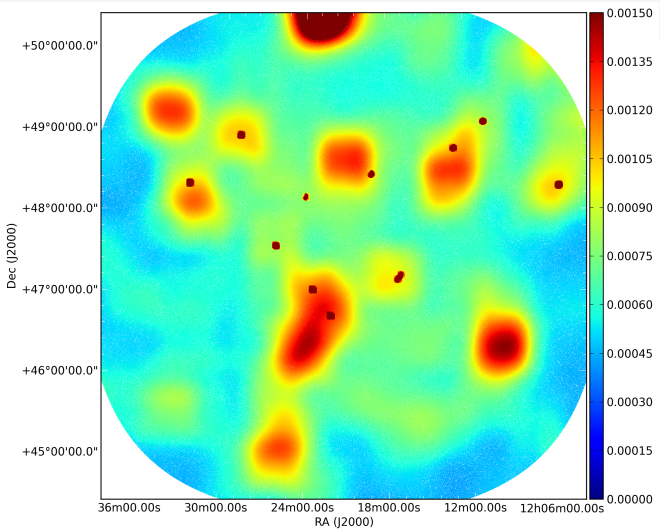
NGC 4051, 4088, 4157, 4217, 4258, 4449, 5055, 5194

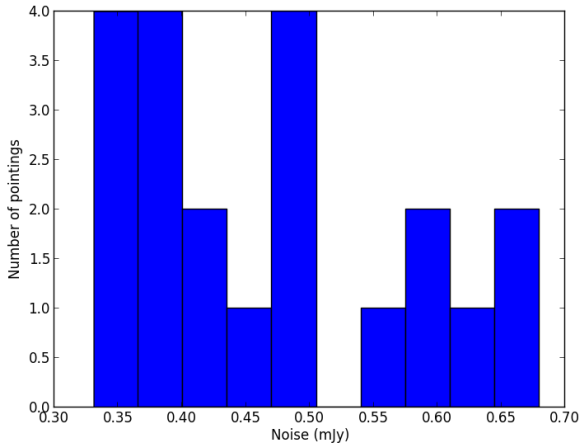
Our current reduction – clusters

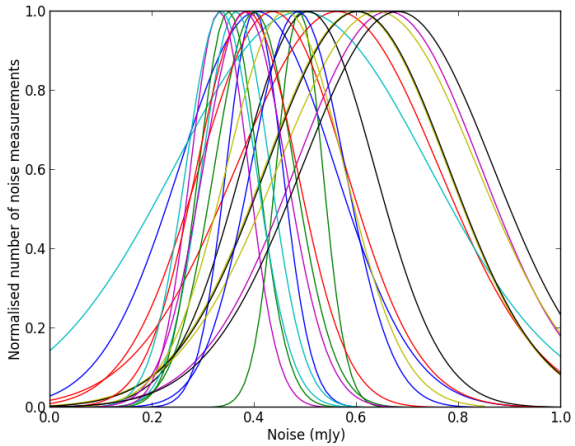


Abell 1314 and Planck 133.60+69.04

Our current reduction – noise levels







The noise on the images varies significantly with position but 70% have average noise levels below 500μJy.

Advanced calibration – introduction

Facet calibration

- By calibrating in many (20-100) directions using peeling solutions the ionospheric effects can be minimised and a high resolution and high sensitivity image can be produced.
- The procedure is very time consuming (weeks to months) but is becoming less manual.
- This calibration scheme is being tested on 9 fields.

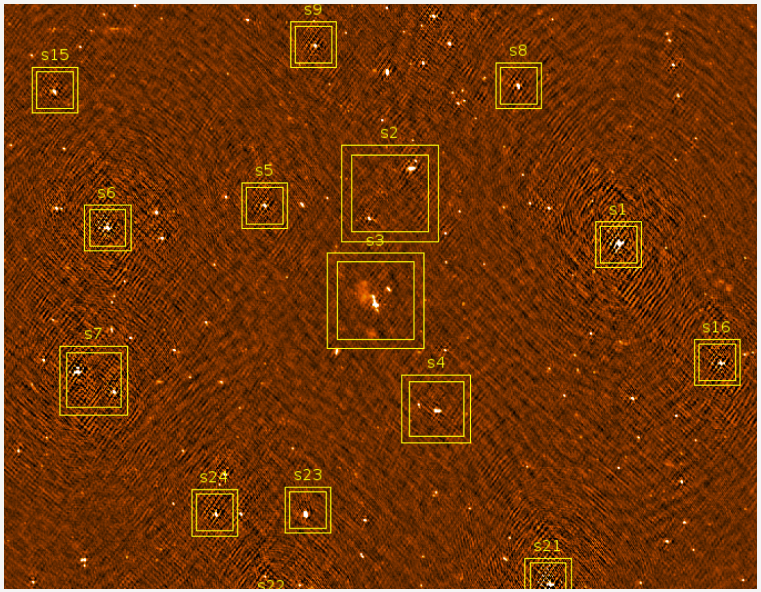
Studying individual objects

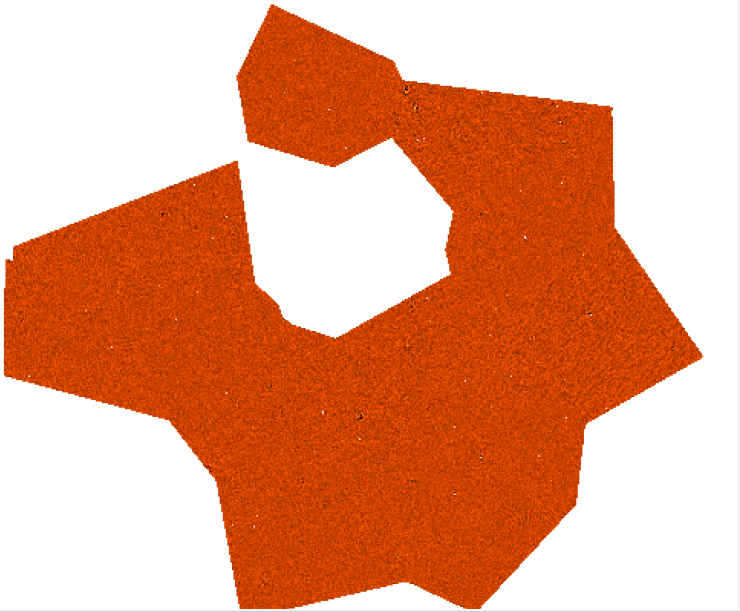
- By subtracting the rest of the field the target object (or a nearby simple and bright object) can be used to self calibrate to high resolution and frequency like above.
- This procedure can be fast depending on the complexity of the field.

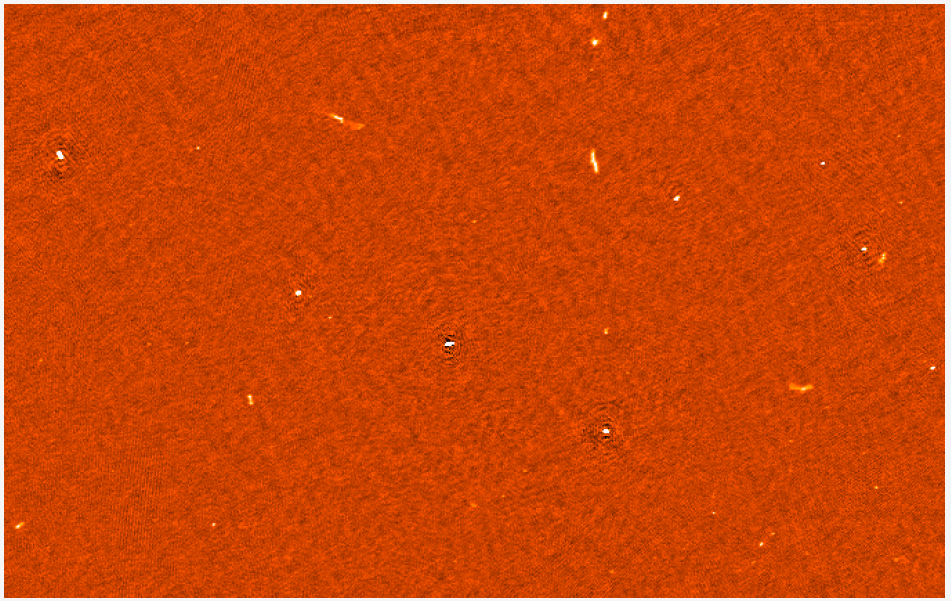
Remove bright sources from the Tier-1 survey images

- Direction dependent calibration tools such as Killms (Cyril Tasse) or Sagecal (Sarod Yatawatta) can be used to rapidly remove contaminating bright sources and decrease the noise.

Advanced calibration - facet calibration on Abell 2034

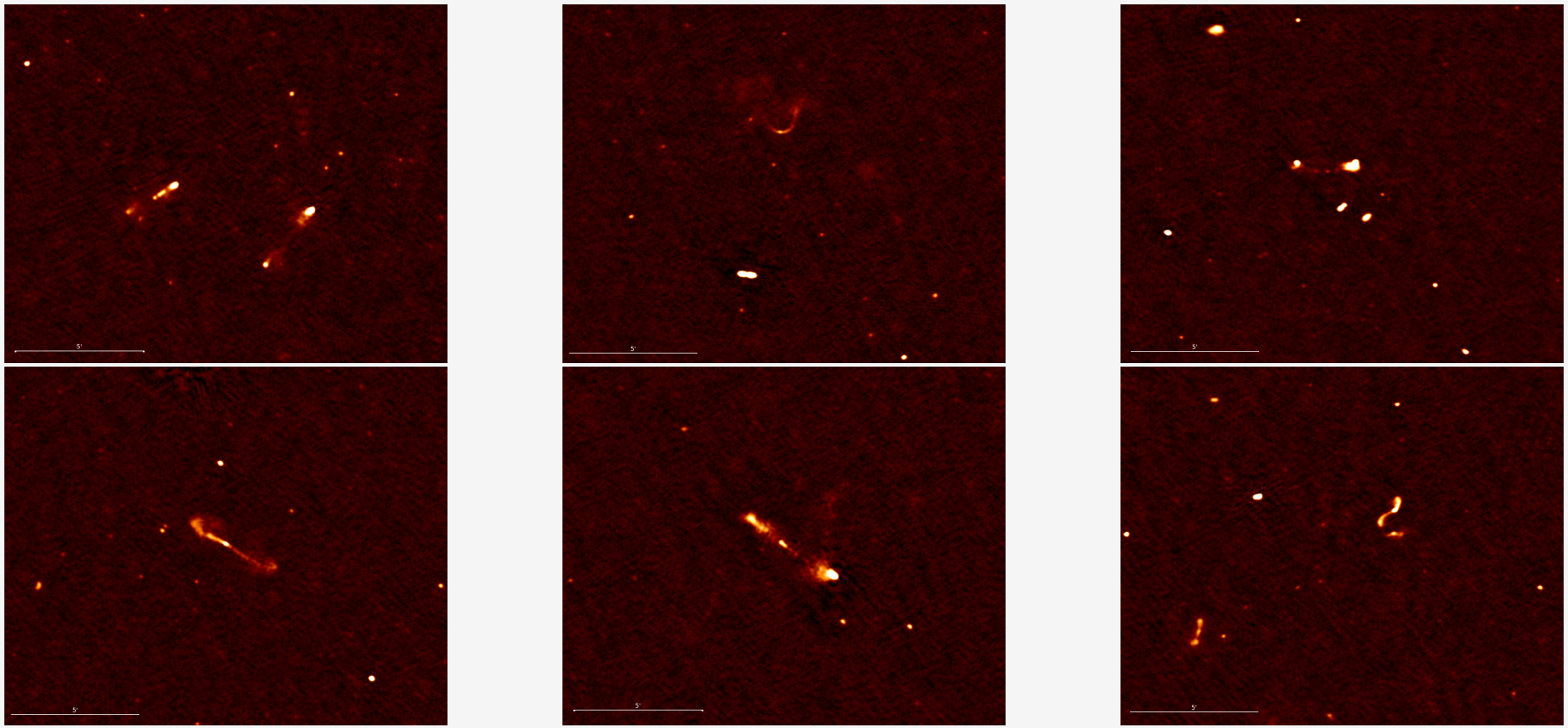






Facet calibration of the Abell 2034 cluster field.
Improvements and speed ups are constantly being made.

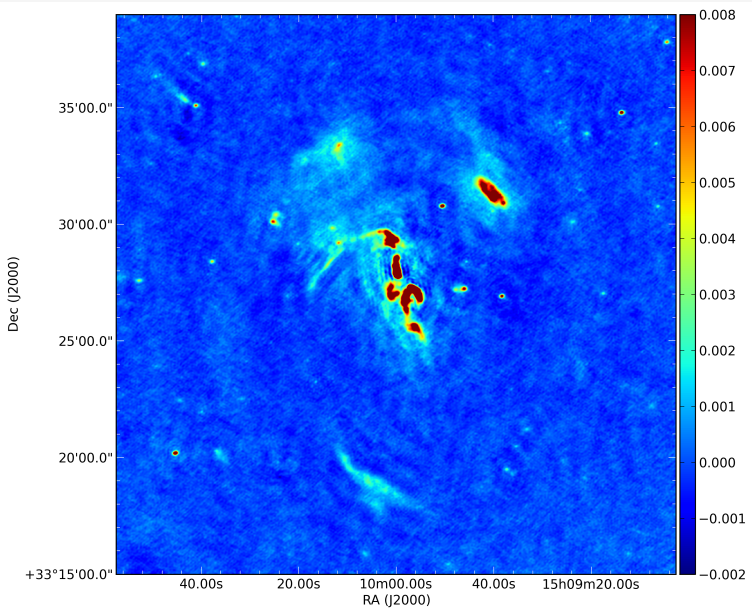
Advanced calibration - facet calibration on Bootes by Wendy Williams

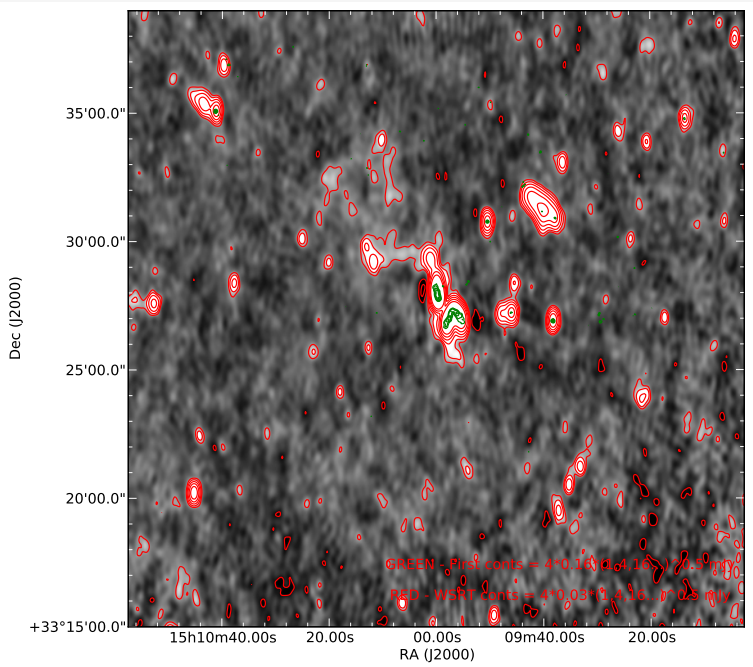


120μJy and 5x7arcsec resolution.

Advanced calibration - studying interesting objects in the survey

The surveyed volume is sufficient to contain e.g. 5 $z > 6$ radio galaxies, 25 Planck clusters and 800 NGC galaxies. High resolution and sensitive images can be made by subtracting all other sources besides the target and self calibrating.

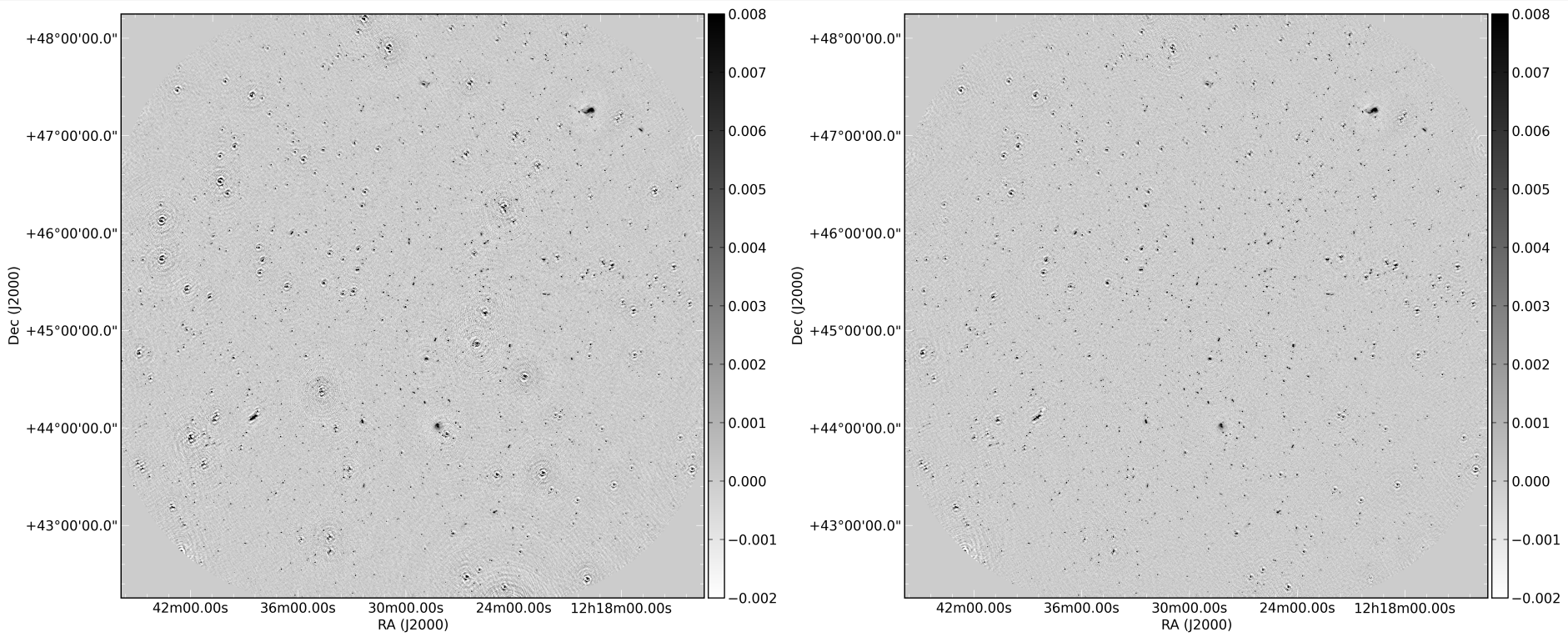




Left: A 30 MHz bandwidth LOFAR image of A2034 (rms ≈190μJy at 8"). Right: 21cm WSRT image of A2034 (rms 30μJy).

Advanced calibration – subtracting bright sources

The artefacts around bright sources increase the noise and reduce the image quality.



Left: Standard survey reduction. Right: The same data after direction dependent calibration and subtraction of bright sources using Cyril Tasse's killms software.

Next cycles

- Over the next few cycles we aim to complete a 4200 deg^2 region (568 pointings) that overlaps with both the FIRST and SDSS surveys (7.5 $<$ RA $<$ 17.5 hrs, 25 $<$ Dec $<$ 65 deg)
- This volume is sufficient to contain e.g. 25 $z > 6$ radio galaxies, 125 Planck clusters, 4000 NGC galaxies and 4000 lensed radio sources.
- All pointings will be observed for $\approx$8 hrs ($\approx$100μJy/beam)
- The LBA Tier-1 survey will be started in cycle 4 with 24 pointings in the HETDEX region.
- Continue to work closely with other groups to maximise the potential science output (e.g. international baselines for long baseline working group and increase the frequency resolution for spectral work).

Upcoming events

- September 14th to 16th LOFAR surveys team meeting in Leiden and registration is open.
  https://www.strw.leidenuniv.nl/cms/web/2015/20150914/info.php3?wsid=44
- We can start doing science with these survey images and the Bootes field. Interested team members who have some time can visit Leiden to access images, data and discuss science – email shimwell@strw.leidenuniv.nl

Conclusions

- We have HBA Tier-1 survey data on ≈100 pointings and another 80 are scheduled.
- Fast reductions of each observation show that the data quality is good – see http://lofar.strw.leidenuniv.nl/wiki/doku.php?id=current_progress
- Our current reduction strategy of the entire band produces 20" resolution images and a noise level of 200-500μJy. These scripts are operational on several clusters.
- Facet calibration allows for thermal noise limited (≈100μJy for our datasets) images at full resolution (5") and is being applied to 9 fields (2 completed).
- Direction dependent calibration routines are being experimented with to e.g. remove the contamination from bright sources.