VLBI With LOFAR

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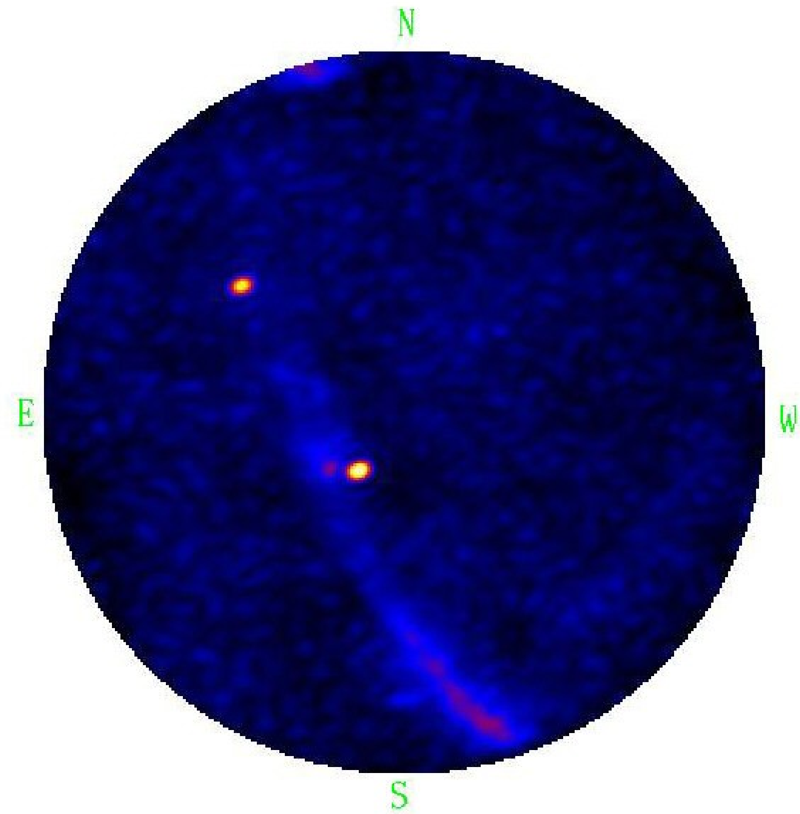


On behalf of the LOFAR collaboration

Max-Planck-Institut
für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

Acknowledgements

- Much of the processing of long baseline LOFAR data has been done by **Olaf Wucknitz**
  - Olaf cannot be here today, so I am giving this talk instead of him
  - Many of the plots in this presentation were prepared by Olaf, and credit should go to him for that work
- The LOFAR Long Baseline Working Group (LLBWG) is a collection of people working toward making long baseline observations with LOFAR available for the masses
  - Cross-Key Science Project group, as the requirements for high angular- resolution measurements are found in many of the KSPs
- New people who can contribute time/resources to commissioning LOFAR are welcome to join the LLBWG
  - Some members of the German DFG Magnetism group, especially the Bonn students will be especially "encouraged" to participate

Warning!

- I will probably be blunt and say things some people would not like to hear
  - Sometimes I am just not a good team player
  - Sometimes some things just need to be said
- I'm really stressed out right now, so I would like to apologize for being in a bad mood right now

This Talk Does **Not** Explain VLBI

- I assume that you are already familiar with the basic concepts of very long baseline interferometry (VLBI) as practiced by the cm-wave VLBI community
- If not, I suggest that you read through some of the NRAO Synthesis Imaging Summer School talk on VLBI
  - http://www.aoc.nrao.edu/events/synthesis/2010/ http://www.aoc.nrao.edu/events/synthesis/2008/ http://www.aoc.nrao.edu/events/synthesis/2006/
- Or visit one of the German LOFAR interferometry school sites
  - http://www.astro.rub.de/glow_school_2010 http://www.lofar.org/operations/doku.php?id=public:meetings:glowbi2008&s[]=glo
- And then sit down with a VLBI expert for a week or more and reduce a much easier cm-wave dataset before going through this material

Wait for Some of the Audience to Leave

- No, really. If you don't know what fringe tracking, fringe finding, time-average smearing, oscillator coherence time, or delay/rate plots are, you would probably be better off going outside to read up on VLBI, go over the hands-on session from yesterday, or read your e-mail
- I know that the school web pages says that, “Familiarity with the concepts of radio interferometry...will be useful but not required”, but I don't have time in 45 minutes to explain VLBI and to explain how to analyze long baseline LOFAR data

VLBI Analysis of LOFAR

All† LOFAR Interferometry is VLBI

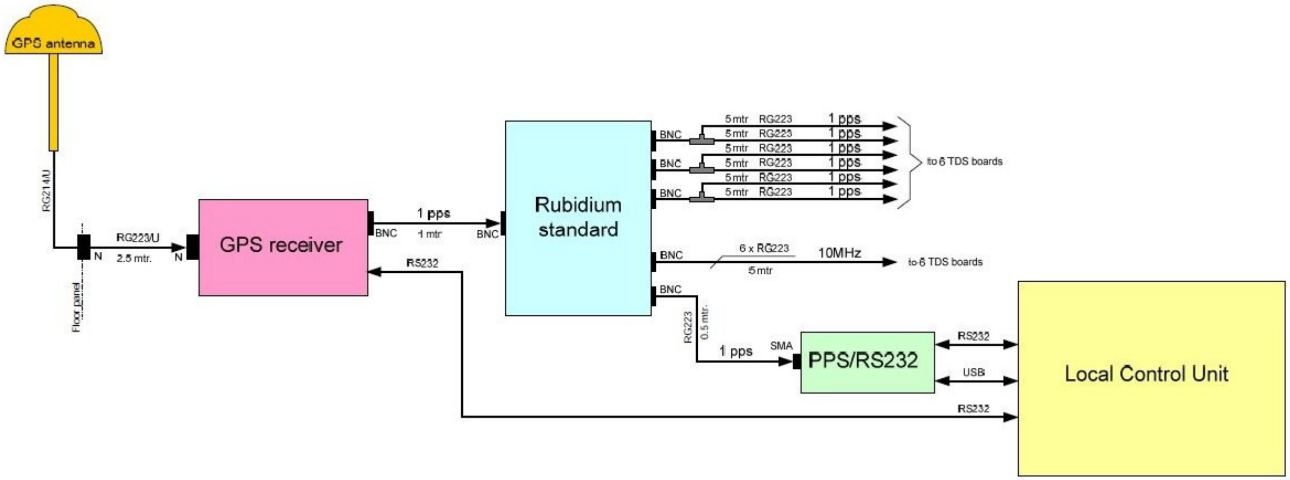
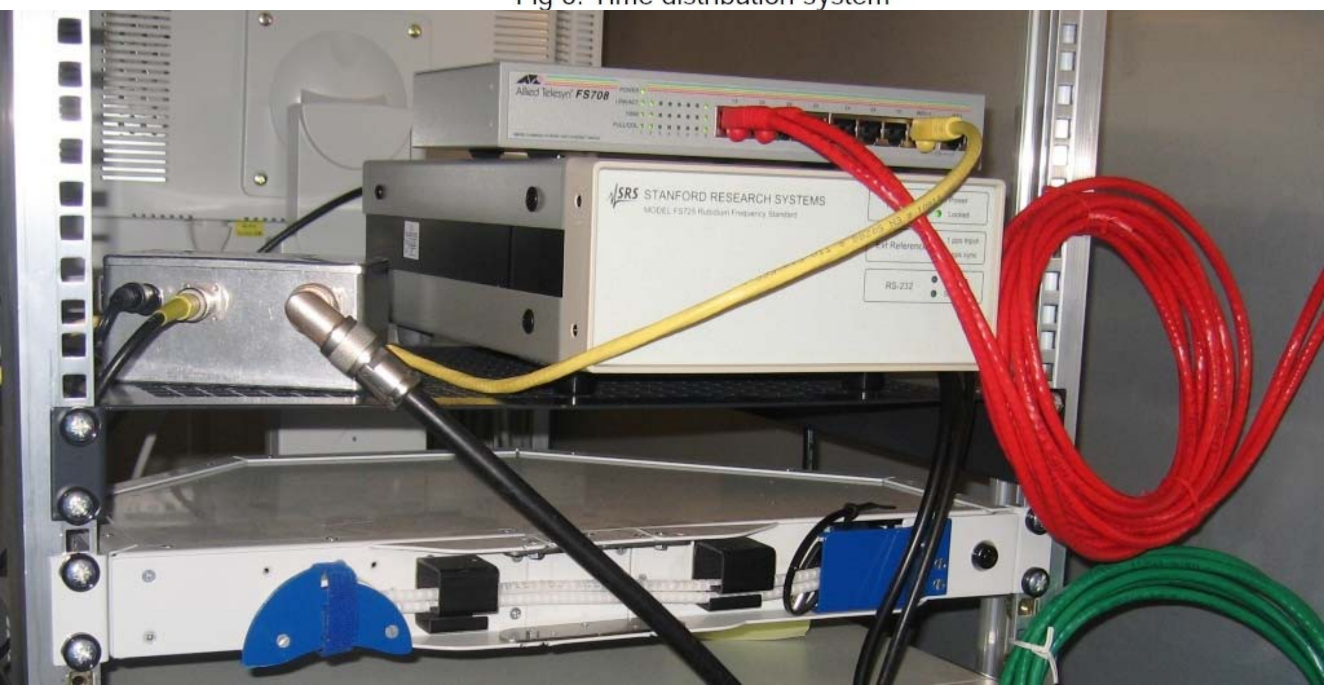


Fig 6: Time distribution system



LOFAR Station User Manual

- The defining characteristic of VLBI is not the length of the baseline, but rather the use of independent clocks at the different stations
- Each LOFAR station has its own rubidium maser clock system, bounded by a GPS time receiver
- †The superterp clock distribution system is a special case which I will ignore for this discussion since it only involves a small number of the LOFAR stations

So Why Aren't We Doing VLBI Analysis of All LOFAR Interferometry Data?

- Good question. Maybe we would learn more about the working of the LOFAR system if we did
- GPS-driven rubidium masers within a few km of one another usually manage to not drift too radically from one another
  - So the clocks often stay close enough to each other that you don't have to worry about delays and can just calibrate phases
  - Plenty of S/N on the sources being looked at on km baselines to get phases per subband or channel
  - Result: BBS and MeqTrees can give you a calibration which yields a reasonable-looking image, as long as you don't pay attention to the details of the calibration values
- The masers do not stay close to one another on baselines of several hundred km, so we have to do VLBI analysis for long baseline LOFAR
  - I have been predicting for many years that the Remote baselines (>~ 30 km) will suffer in the same way

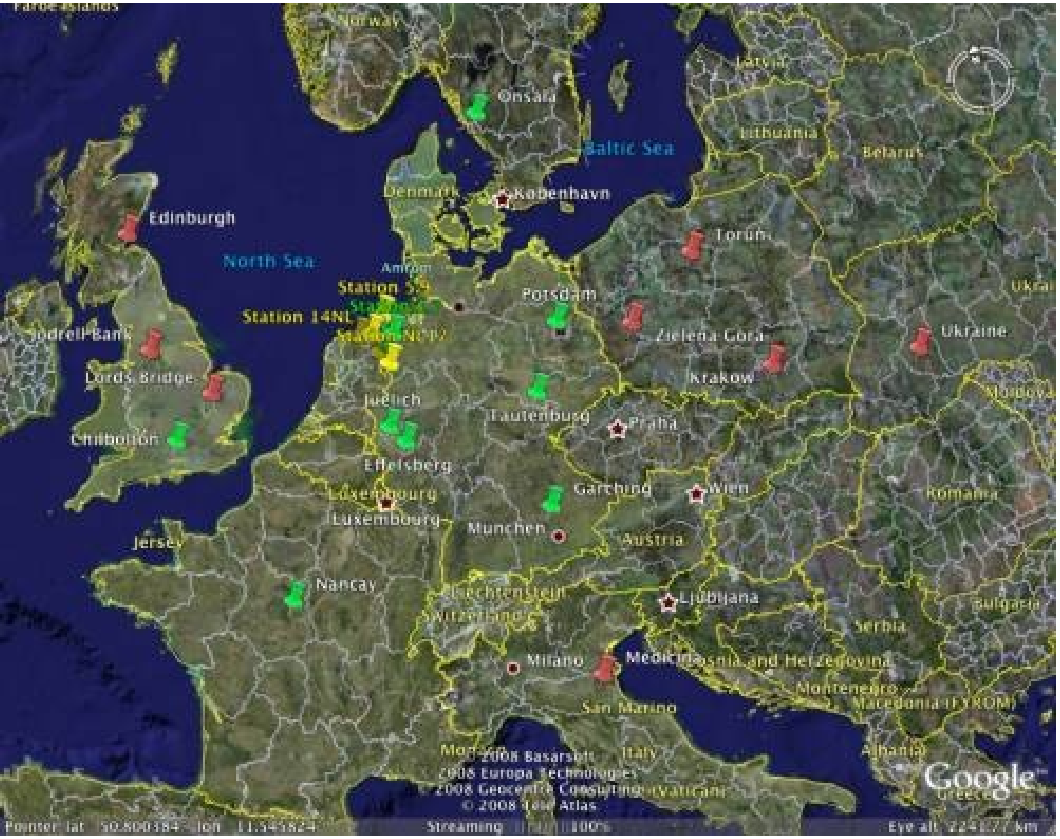
So Why Aren't We Doing VLBI Analysis of All LOFAR Interferometry Data?: 2

- Some people are more interested in getting pretty pictures and doing science rather than actually commissioning the telescope
- There are no standard tools available for dealing with fringe-fitting and ionospheric delays for the LOFAR instrument
  - This is the main problem at the moment
  - Real VLBI analysis for LOFAR requires
    - non-frequency averaged channel data
    - many, many subbands simultaneously used for deriving calibration
    - delay model including ionospheric component
    - Faraday rotation
    - dealing with linear feeds
  - This will probably **not** go into BBS within the next 6—12 months

Effelsberg and LOFAR

Review of LOFAR Hardware

LOFAR:
The Low Frequency Array



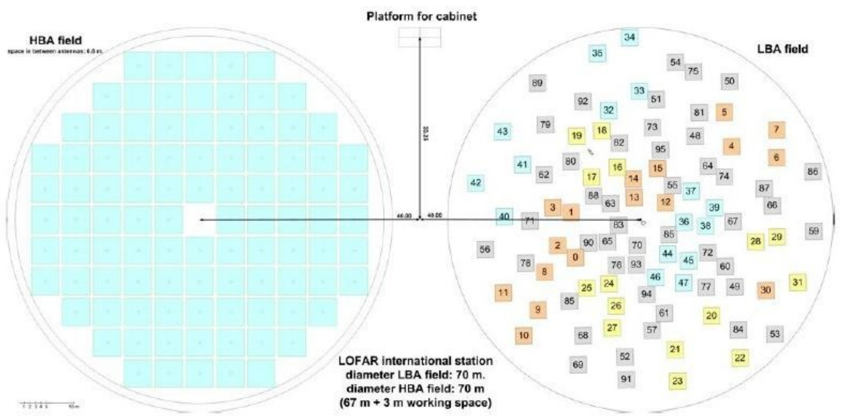
- Aperture array technology
  - digital processing
- Low Band (LBA)
  - normally 30 to 80 MHz
  - can do 10 to 80 MHz
- High Band (HBA)
  - 110 to 260 MHz
- 3rd input
  - open at International stations
  - extra LBA inputs for Dutch stations (better performance < 30 MHz)

- Core (2 km diameter)
- Remote (inside NL)
- International (outside NL)

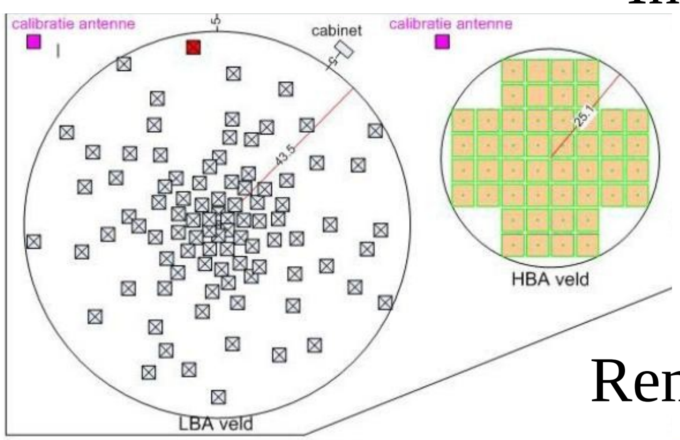
Orginal LOFAR

Current LOFAR

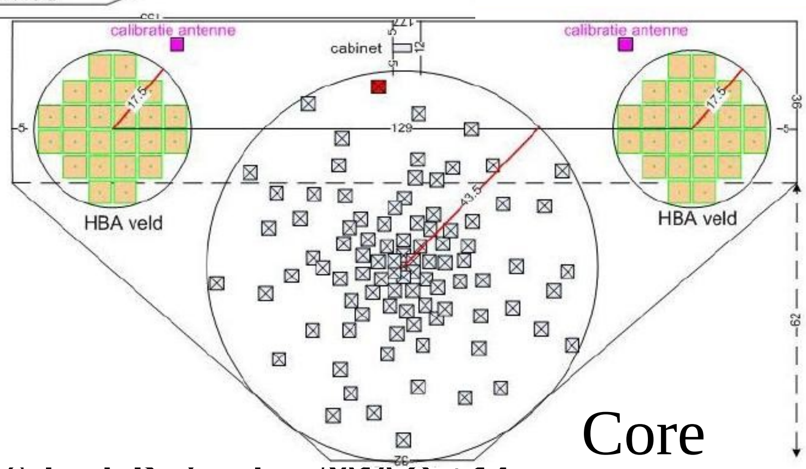
LOFAR Station Type Comparison



International



Remote



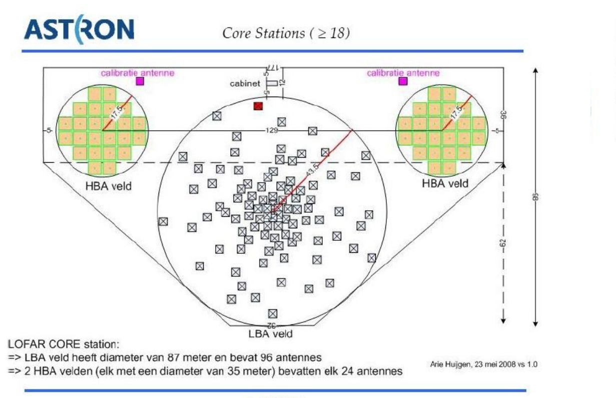
Core

- International LOFAR stations have **96** usable receiver elements, compared to **48** for the Dutch Core and Remote stations
- International stations twice as sensitive as Dutch stations
  - But nearly all sources are resolved on long baselines, so the visibility amplitudes are down by often orders of magnitude
- Vastly different station beams, but VLBI black-belts are used to this

Core

- 2 km diameter
- Micky Mouse design
- Station Beam FWHM
  - 8.7 6.6 5.3 2.6°
  - 30 75 120 240 MHz
- Synthesized beam
  - 800 300 200 100”
  - 30 75 120 240 MHz

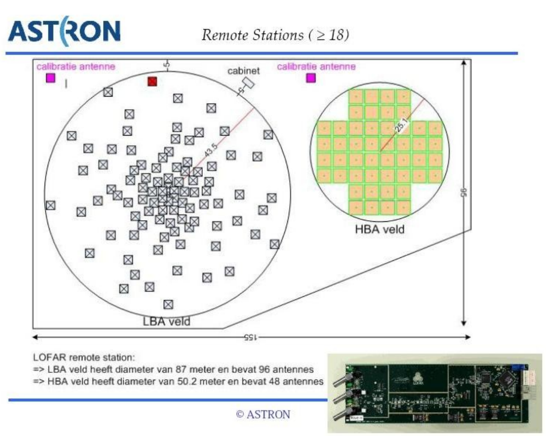
- Core area will be a nature reserve
- 96 LBA antennas (48 observing at a time) & 2 x 24 HBA tiles



Remote

- Up to 130 km baselines
- Circular-pair half-design
- Station Beam FWHM
  - 8.7 6.6 3.7 1.9°
  - 30 75 120 240 MHz
- Synthesized beam
  - 20 8 5 3”
  - 30 75 120 240 MHz

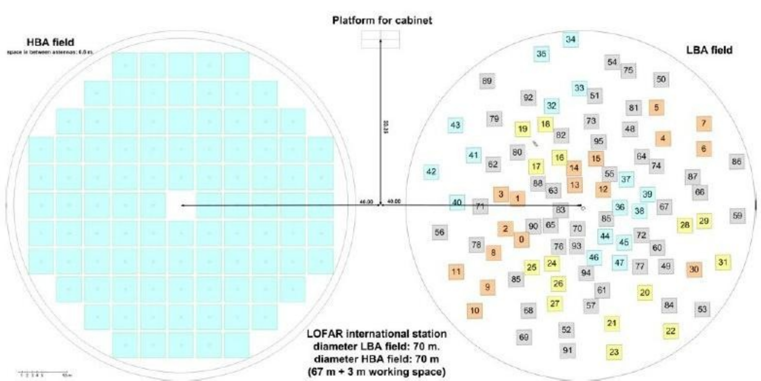
- 48 HBA tiles & 96 LBA (only 48 at a time used for observation)
- Station field rotation as well



International

- ~1000 km baselines
- Original station design
- Station Beam FWHM
  - 9.9 4.0 2.5 1.2°
  - 30 75 120 240 MHz
- Synthesized beam
  - 1.7 0.7 0.4 0.2”
  - 30 75 120 240 MHz

- 96 LBA and 96 HBA tiles
- Station rotation also applied

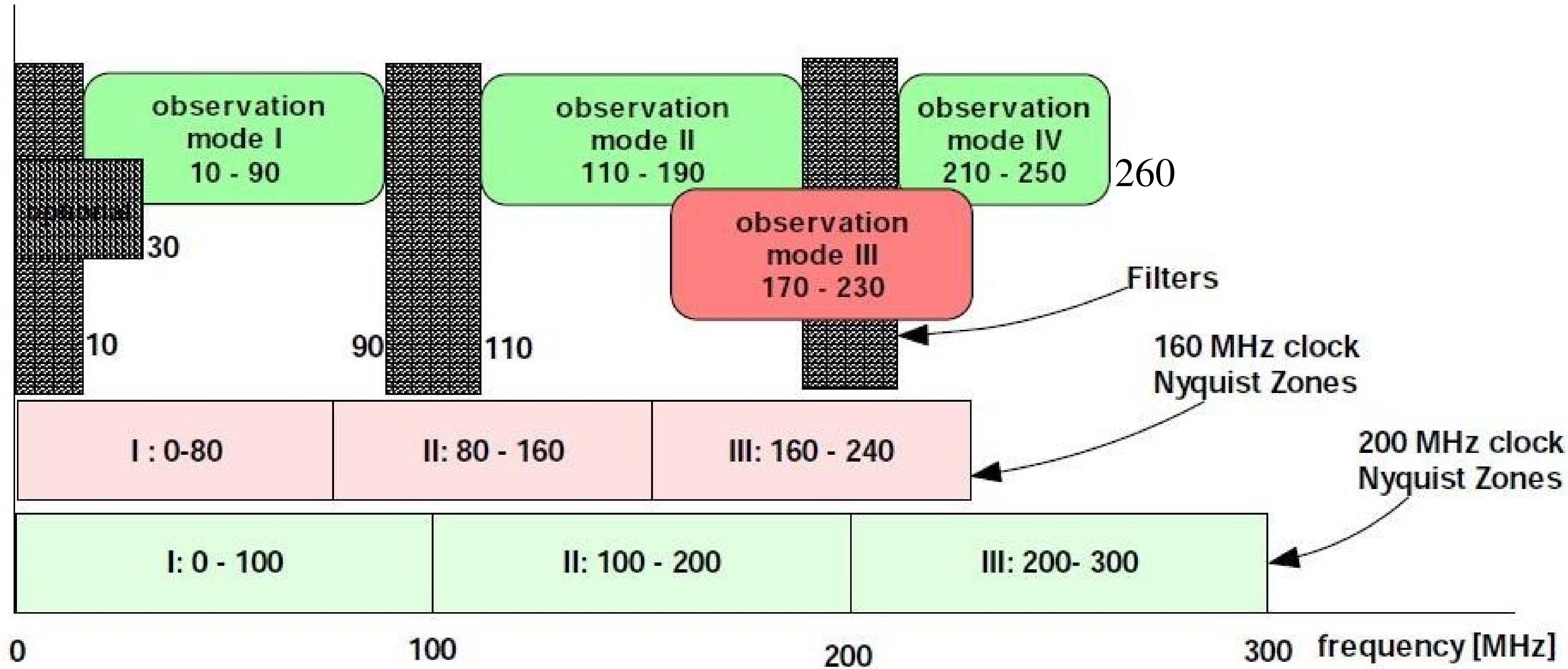


Update on International LOFAR

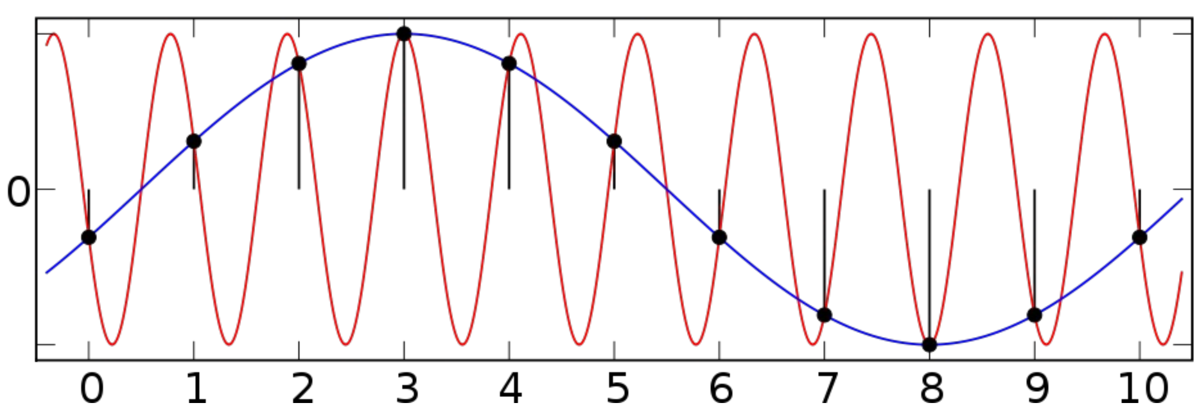
- Joint EISCAT/LOFAR group in Finland will install a station in NW Finland
- Will only be a Remote-class station (48 receivers), so reduced sensitivity compared to other International stations
- Really long baseline, with no short baselines to the station
  - All sources will be very weak
  - Pain in the **** to calibrate properly
  - Probably of limited value unless more LOFAR stations go into northern Scandanavia

LOFAR Frequency Selection Reminder

LOFAR Band Selection



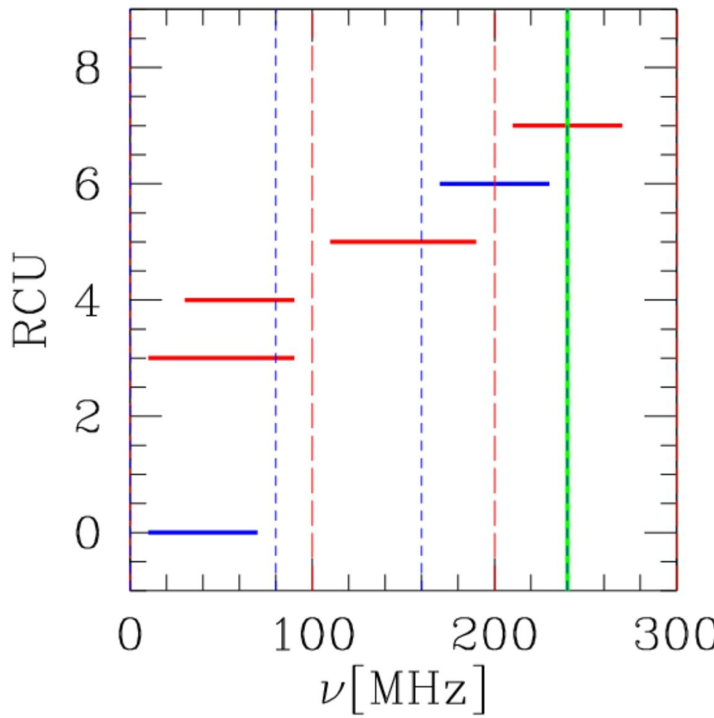
Gunst



Wikipedia

Station Electronics: Gory Details 1

- Bandpass filter
  - 10—90 MHz
  - 30—90 MHz
  - 110—190 MHz
  - 170—230 MHz
  - 210—270 MHz

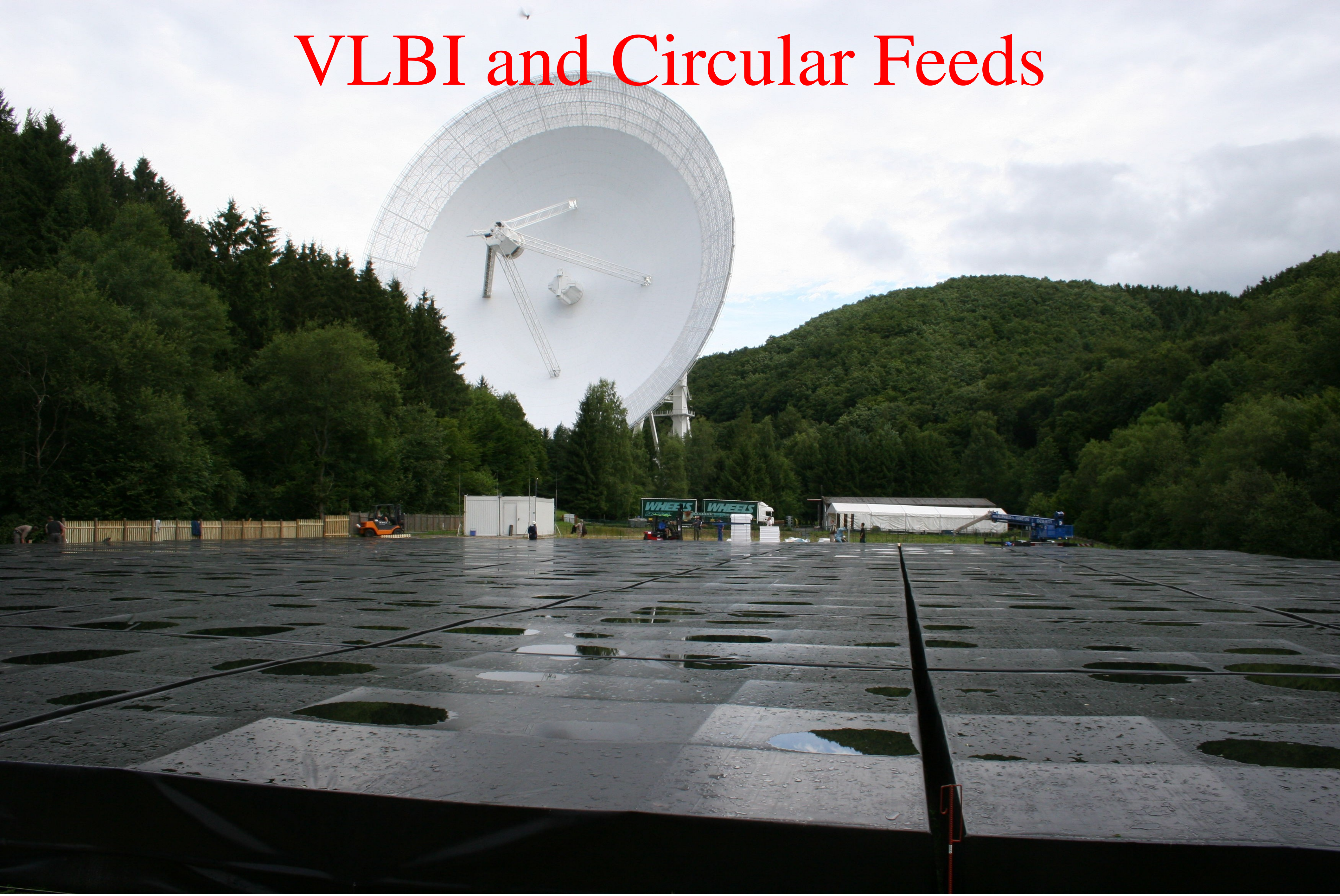


- 12 bit A/D converter
  - 200 MHz or 160 MHz clock
  - Forms 100 MHz or 80 MHz bands
- RCU modes: common combinations of antenna inputs, bandpass filters, and clock rates assigned special RCU codes
  - But LOFAR can observe with any antenna input, bandpass filter, and clock rate combination
    - Low band observations with 160 MHz clock potentially important for full frequency coverage for RM synthesis and spectral line work
  - Each antenna/polarization input can chose own antenna and bandpass
    - Must use the same clock frequency

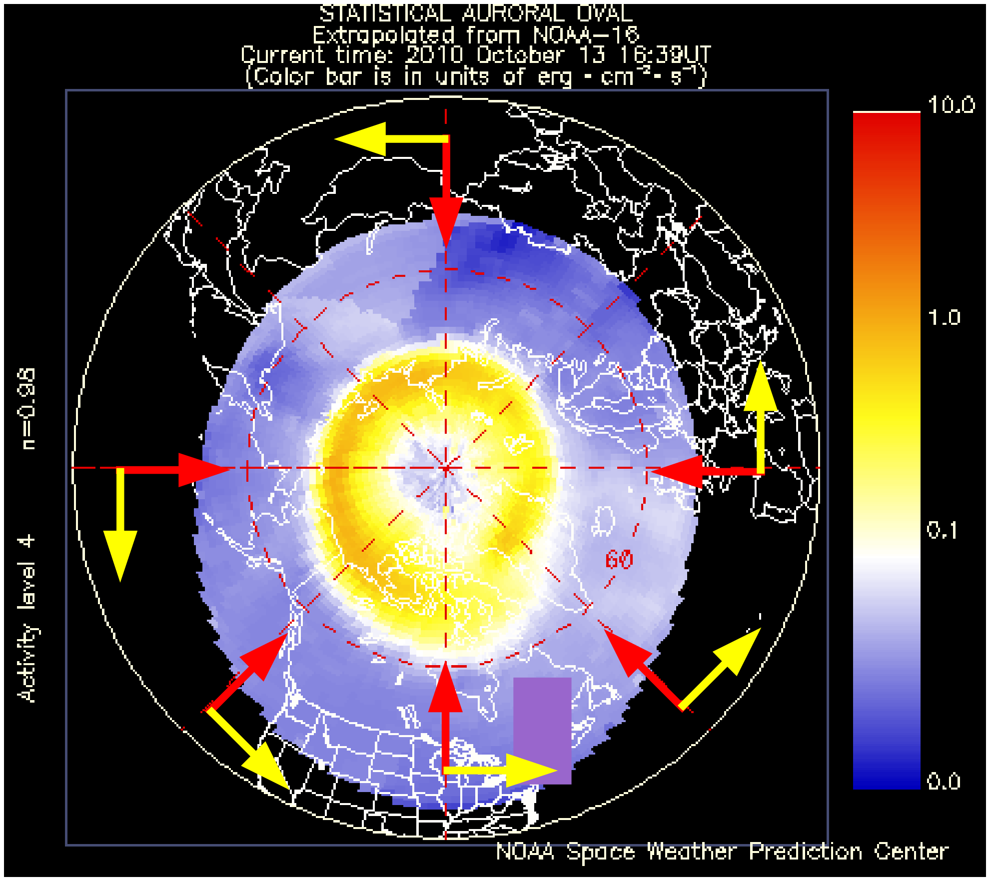
Station Electronics: Gory Details 2

- Polyphase filterbank converts the time series data from each dipole/tile into 512 (513) frequency subbands
  - 195.3125 kHz subbands for 200 MHz clock
  - 156.2500 kHz subbands for 160 MHz clock
  - 16 bit complex number (16 bit real, 16 bit imaginary) for each subband every 5.12 μs (200 MHz) or 6.40 μs (160 MHz clock)
- Beamformer hardware processes up to 248 (244, 183) beamlets
  - A beamlet is one subband beamformed for a specific direction
  - 248 beamlets determine maximum bandwidth available to beamformer
    - 48.4375 MHz for 200 MHz clock
    - 38.7500 MHz for 160 MHz clock
  - **Arbitrary** subband selection by astronomer
  - **Frequency coverage** not required to be contiguous
  - Calibration will work best in full production system with wide **frequency coverage**

VLBI and Circular Feeds



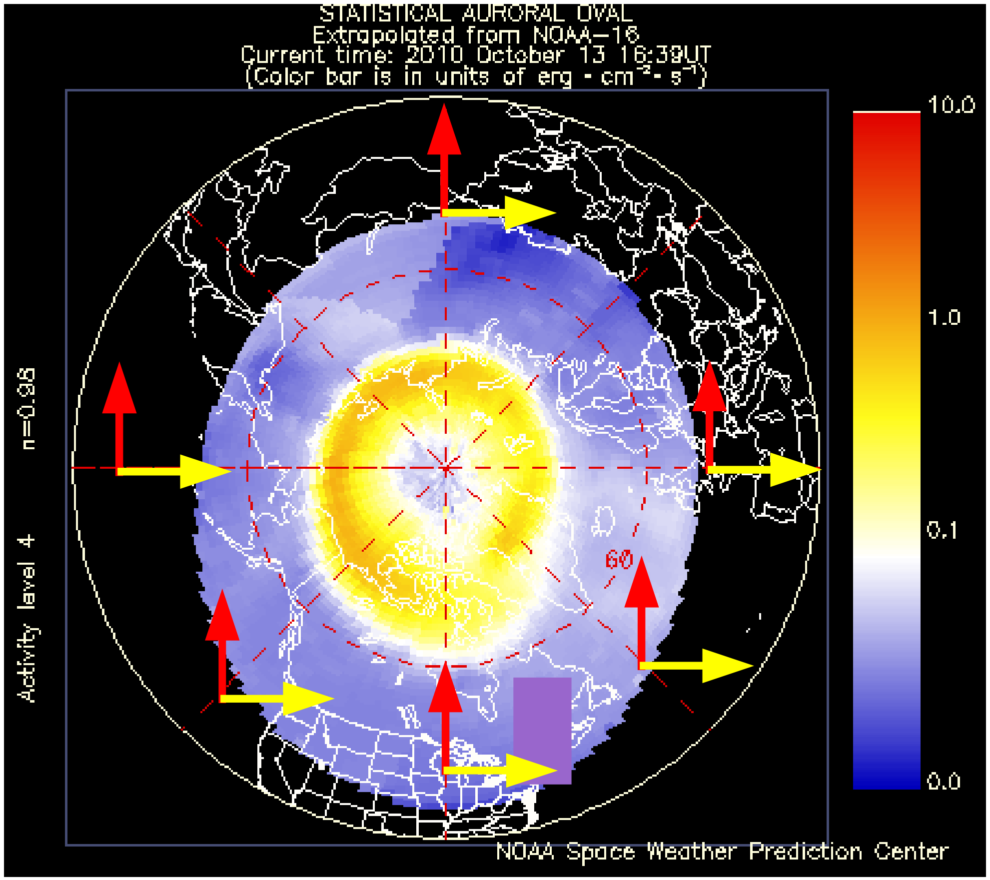
Geometry



NOAA

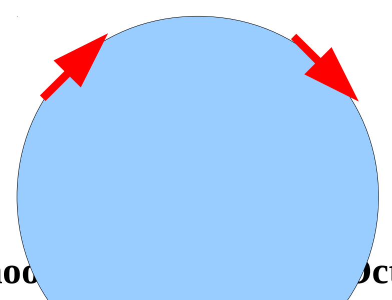
- Linear feeds have a problem in that the orientation of the feed is different as viewed by a celestial source for different locations on the Earth
- Suppose that you align your X and Y dipoles so that Y points toward the North
- Then X linear polarization from a source at the North Celestial Pole is seen as Y polarization at some stations

Geometry: 2

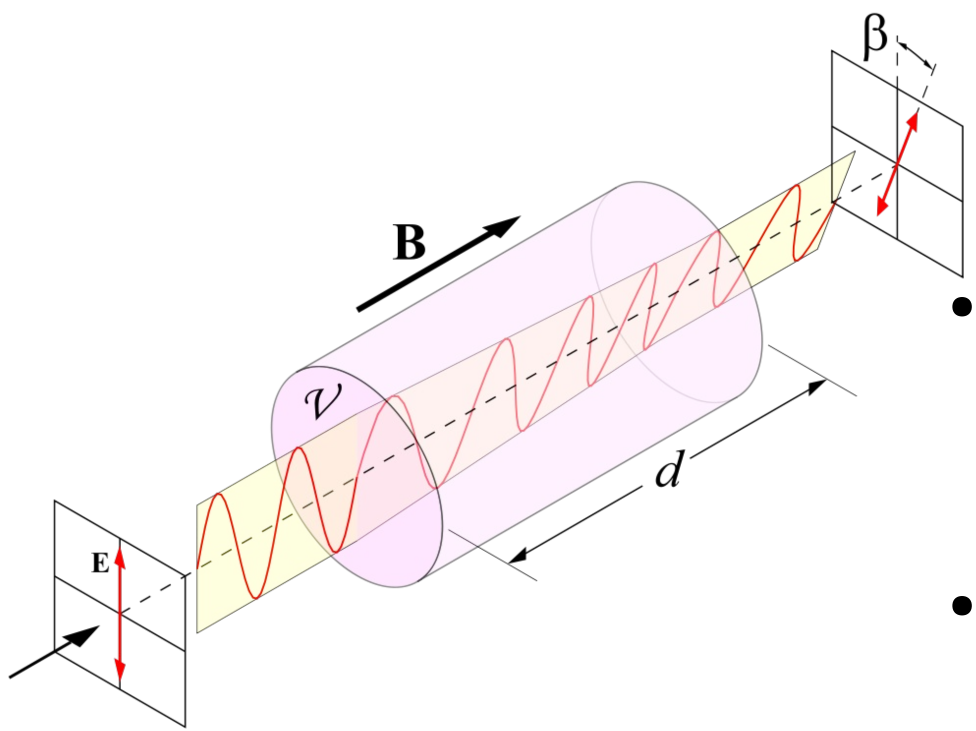


NOAA

- Aligning the dipoles to a common reference plane, as was done for LOFAR, helps to reduce the problem
- But the solution is only valid for one direction on the sky
- For a source at 0 degrees declination above Europe, the **Y** dipoles of the US and Russian stations are still orthogonal
- Using circular feeds fixes the problem, **R** is always **R**



Faraday Rotation



Wikipedia

- Differential Faraday rotation, such as the Faraday rotation caused by looking through different patches of ionosphere for LOFAR stations, causes differential rotation of the polarization plane for radio waves
- This affects all of the emission, not just the Stokes Q and U components
- So some of what is **X** at one station is partially in **Y** at another station, or even **-X** at another station

Faraday Rotation: 2

- For circular feeds, Faraday rotation is just a differential delay between **R** and **L**
- So **R** stays **R**, and **L** stays **L**, so there is no amplitude change between the different Stokes correlation visibilities
- Easier for software to deal with the problem
- Easier for the poor astronomers' brains to see what is going on when looking at data
- But you have to be careful to not lose the information by not paying attention to the fringe-fitting results

τ

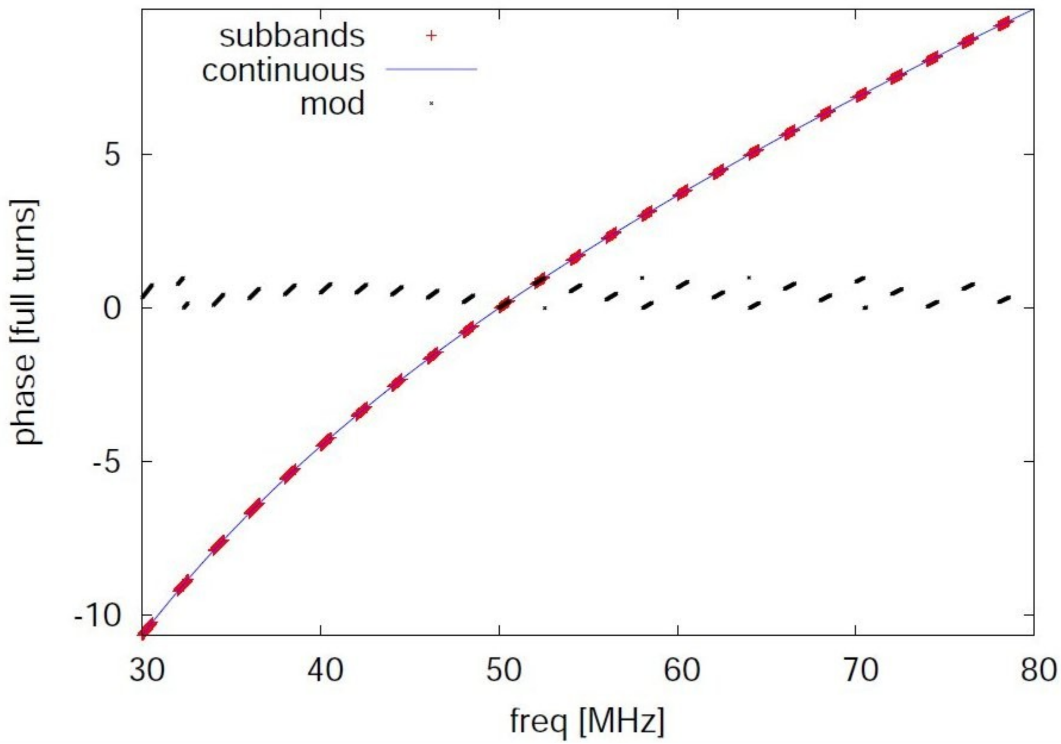
Delay, Not Phase

- For VLBI, you have to get used to thinking about delay, rather than phase, for your interferometry measurements
- For standard connected-element interferometry in the past, you could get away with fitting phase rather than delay
    - Delays not too large because there is only one clock
    - Small relative bandwidths
    - Often just a single visibility per band
- But physically, nearly everything which is causing a phase change is really a delay change
    - Important when the delays are large, such as when you have different clocks
    - Requires visibility measurements at multiple frequency points (channels)
    - Useful to include visibilities at different times
    - Important issue when you have large fractional bandwidths
    - Useful when there is not enough S/N in individual channels to make measurements, but integrating over bandwidth does provide sufficient S/N

Basic Delay/Rate Information

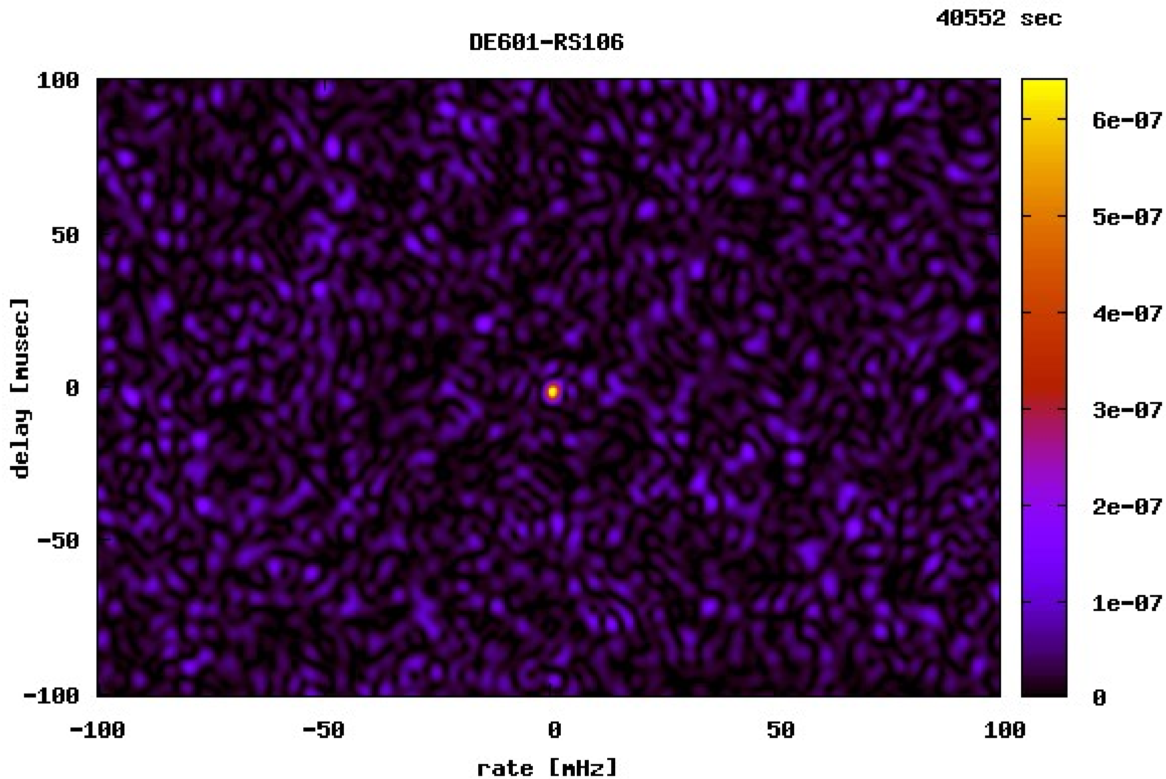
- Delay $$\tau = \frac{1}{2\pi} \frac{\partial \phi}{\partial \nu}$$
- Rate $$r = \frac{1}{2\pi} \frac{\partial \phi}{\partial t}$$
- Non-dispersive delay (clock, troposphere, etc.) $\tau_{nd}(t)$
- Dispersive delay (ionosphere) $\tau_{iono}(t)\left(\frac{\nu_0}{\nu}\right)^2$

Measuring Instantaneous Delay



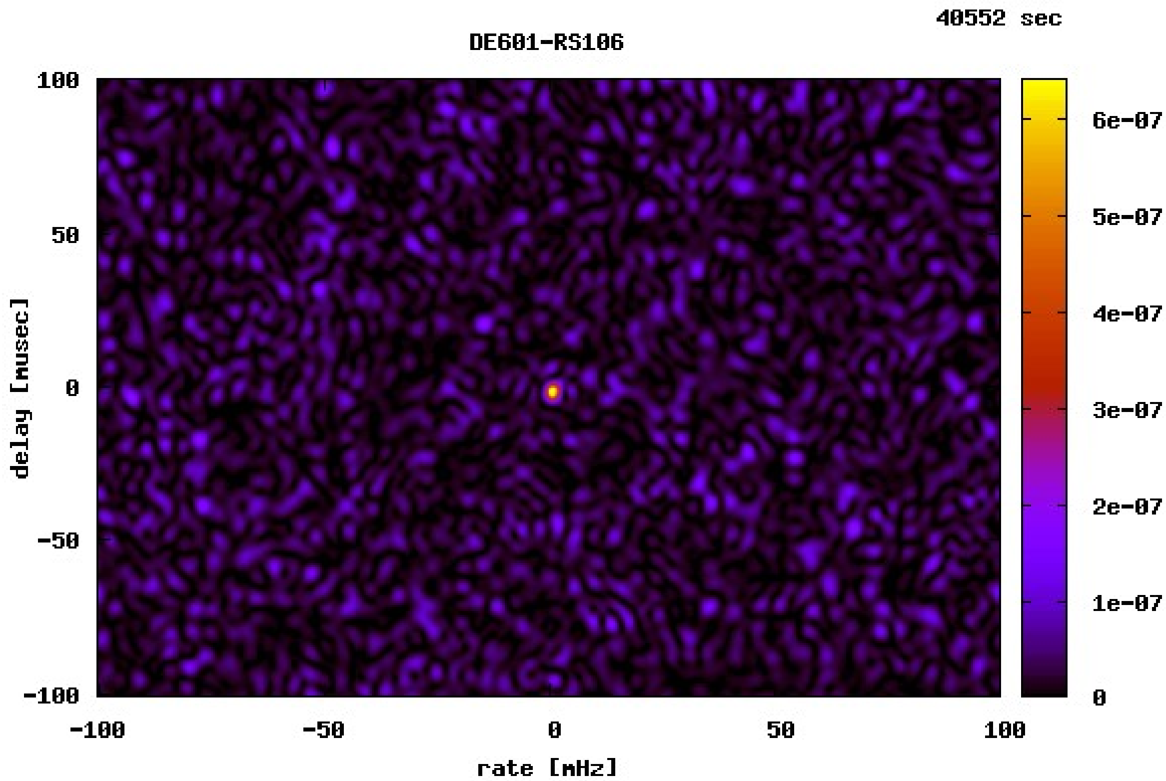
- Visibilities from multiple subbands provide phase information at the black dots
- Phases are modulo 2π
- In principle, one can adjust the phases by multiples of 2π in order to fit a curve with a dispersive and non-dispersive behavior

Delay/Rate Data



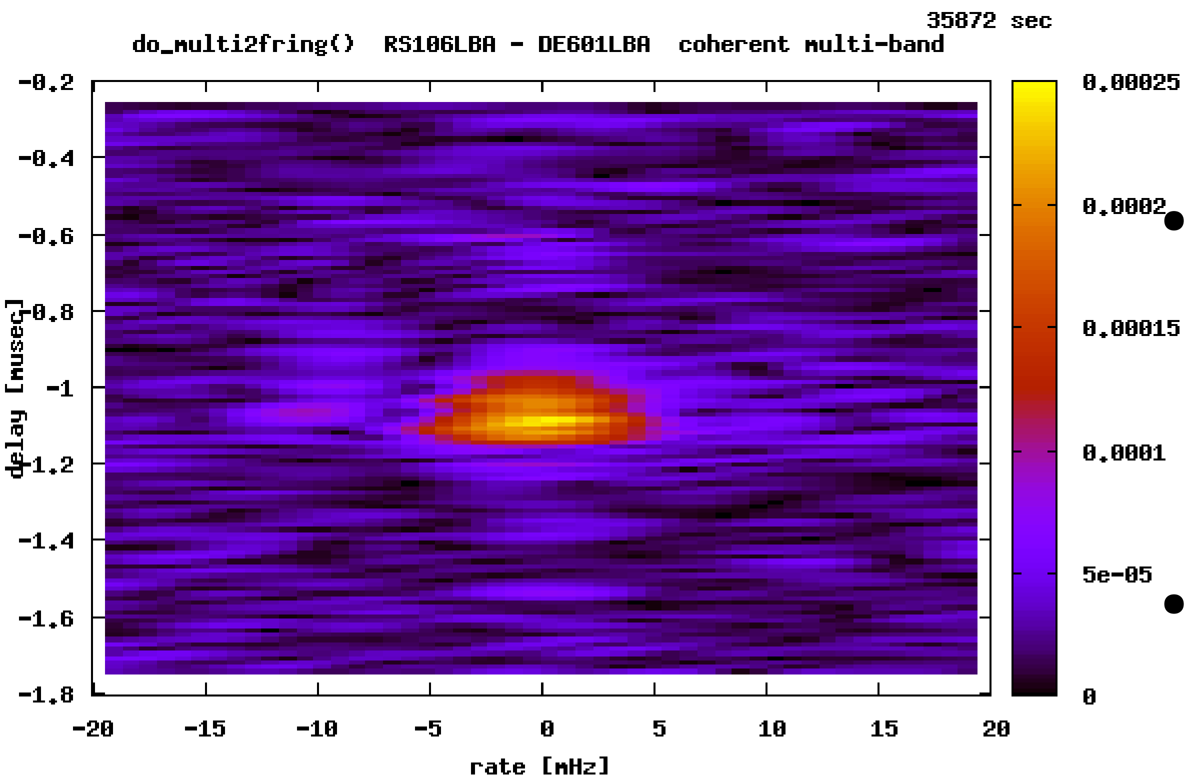
- Fourier transform the visibility data from frequency,time space to delay,rate space
- For a point source you should end up with a single bright peak
- The location of the peak indicates the calibration values for your instrument
- Works well for non-dispersive delays, but not for strong ionosphere

Single Subband Delay/Rate Data



- The movie here shows the delay/rate information for a single subband
- Note the units of μs and mHz, and the poor precision available with single LOFAR subband data

Multiple Subband Delay/Rate Data

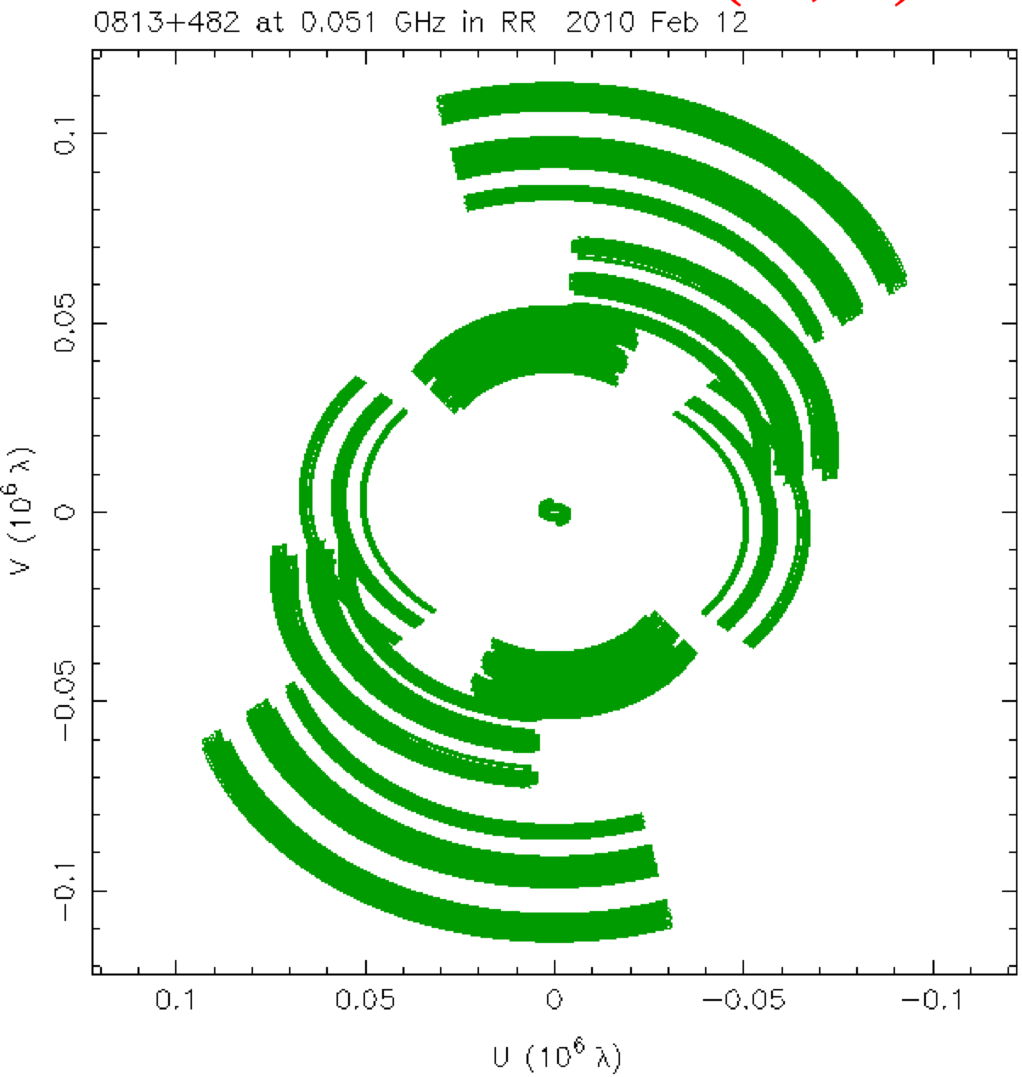


- The movie here shows the delay/rate information for multiple subbands
- Note the dramatic improvement in delay precision (about 0.05 μs here)
- The precision in rate remains about the same, as that is limited by the coherence time, typically of the ionosphere

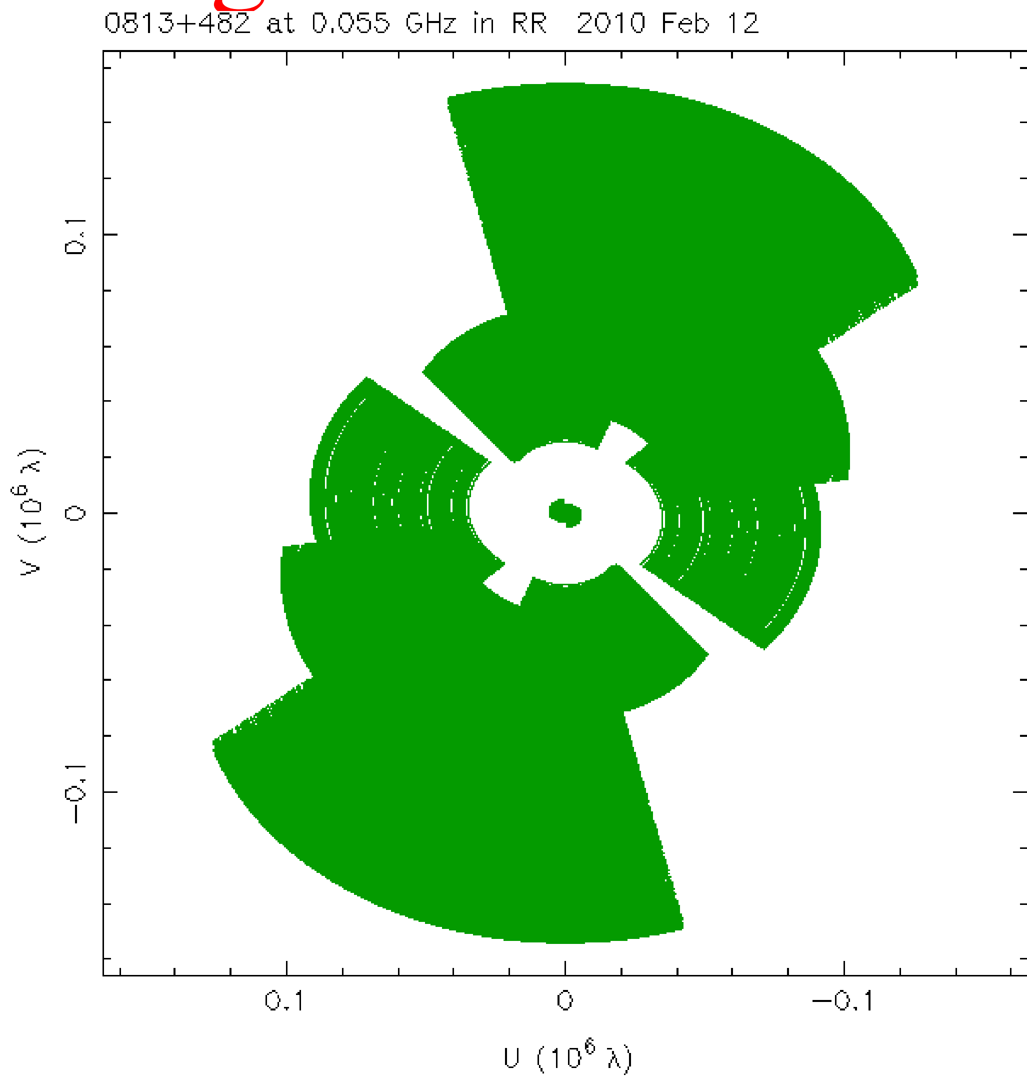
Processing Example: 3C196

- 3C196, LBA, 31 / 160 subbands, 44–59 / 30–80 MHz (ripple!)
- bandwidth 6 MHz / 48 MHz
- D2010 16704 6 h on 12/13 Feb 2010
- 5 NL + 3 DE stations (Effelsberg, Unterweilenbach, Tautenburg)
- corrected for 1 μsec and 17 μsec constant delays
  - 1 μs delay causes a 1.2 rad phase change across a single subband
  - 17 μs delay causes a 21 radian phase change across a single subband
- RR and LL from XX/XY/YX/YY using geometric model
- (self-)calibrated and imaged LL/RR in difmap
- MFS with/without spectral index correction

(u,v) Coverage

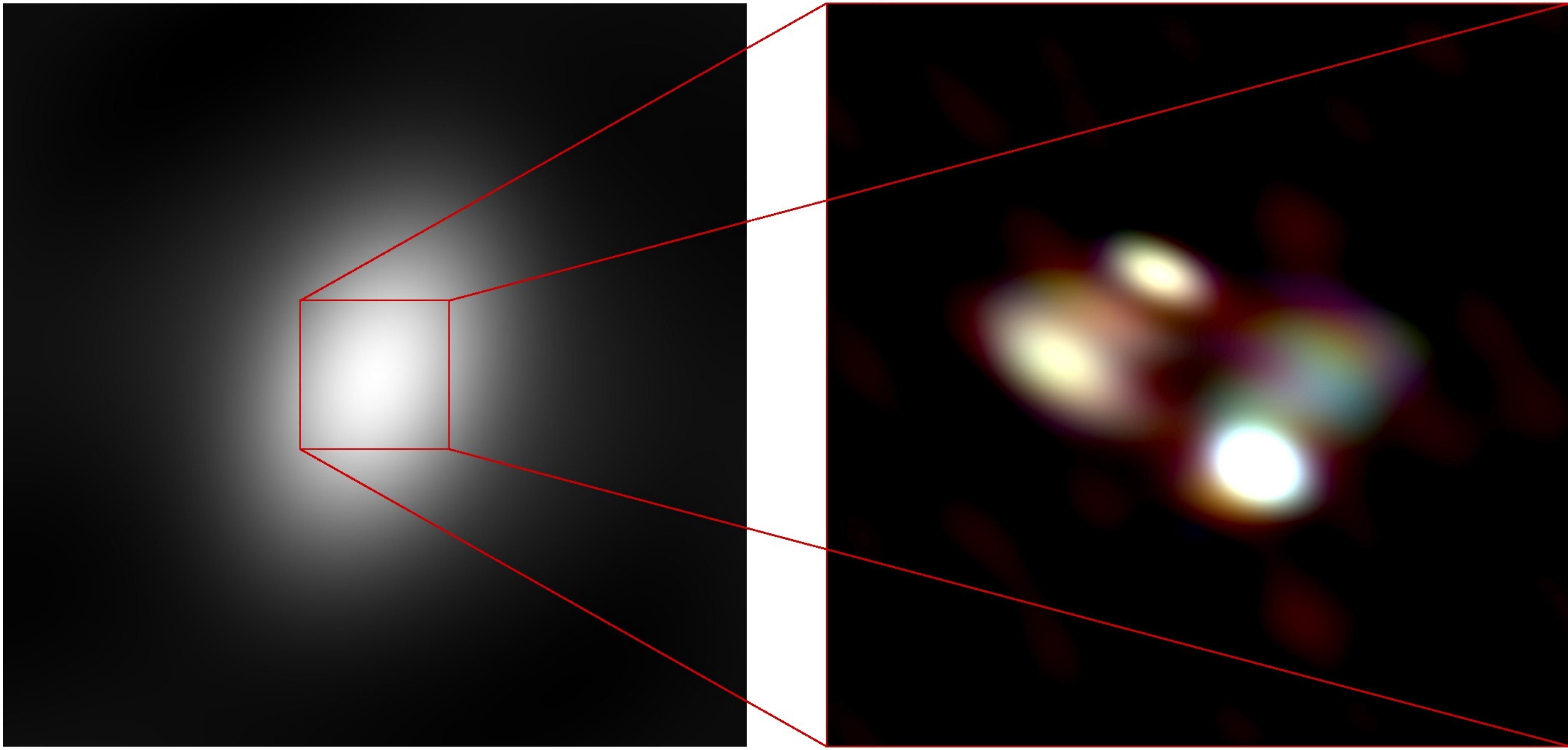


3 subbands



All subbands

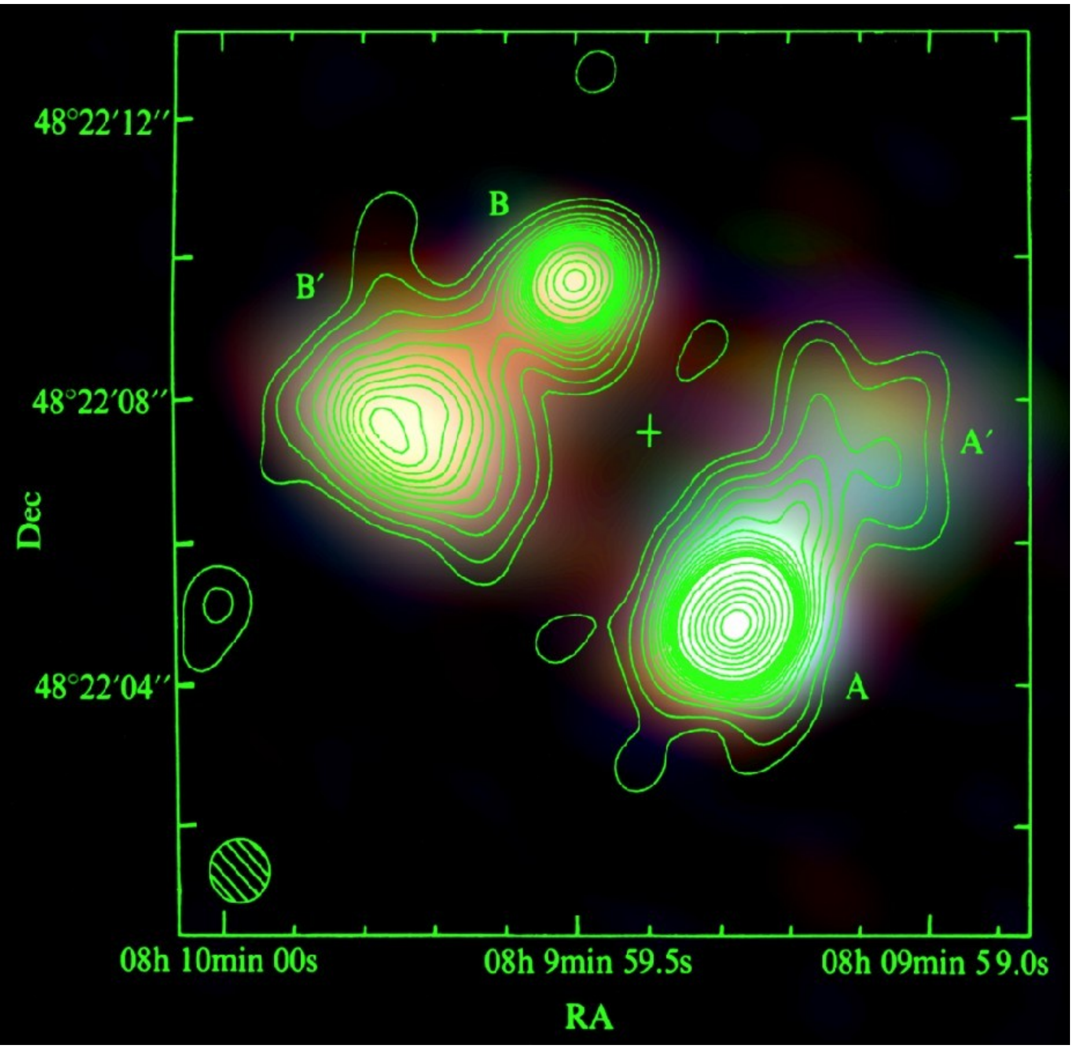
3C196



Dutch baselines only

Including international baselines

Comparison To MERLIN Data

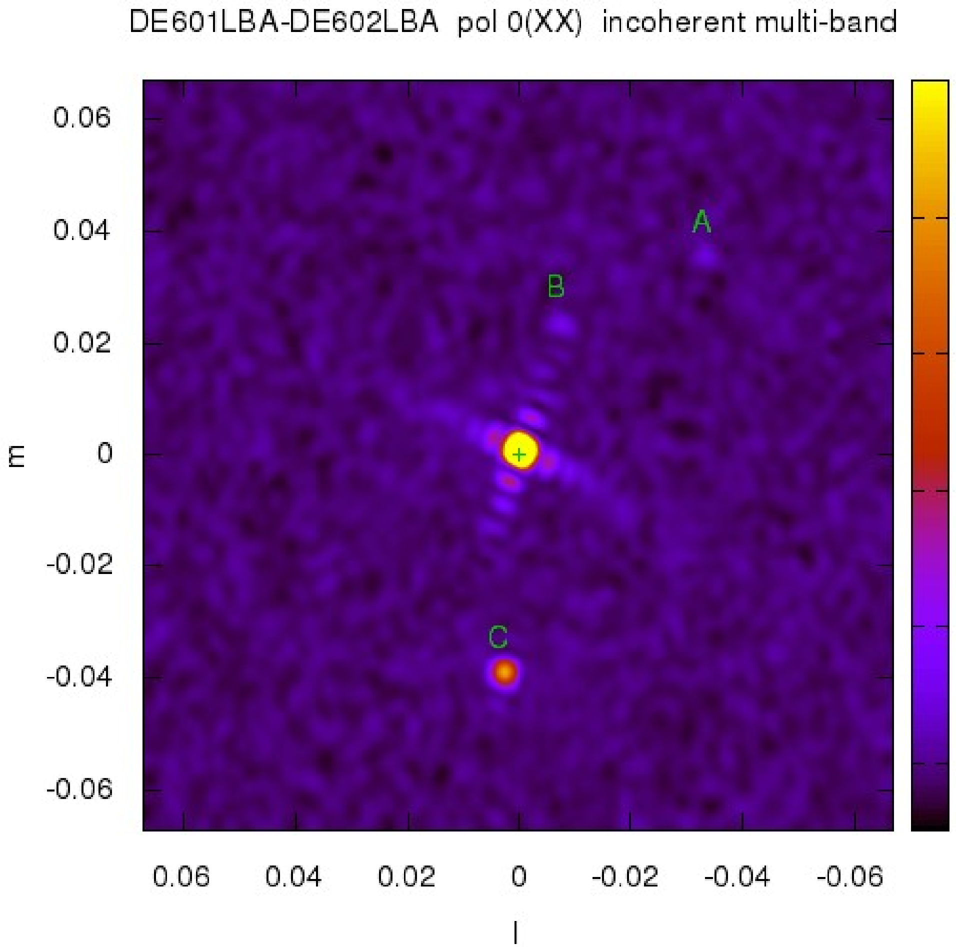


- 408 MHz MERLIN contours
  - Lonsdale & Morison (1980)
- LOFAR LBA image
- Change in brightness of the various components between the different frequencies

Technical Details

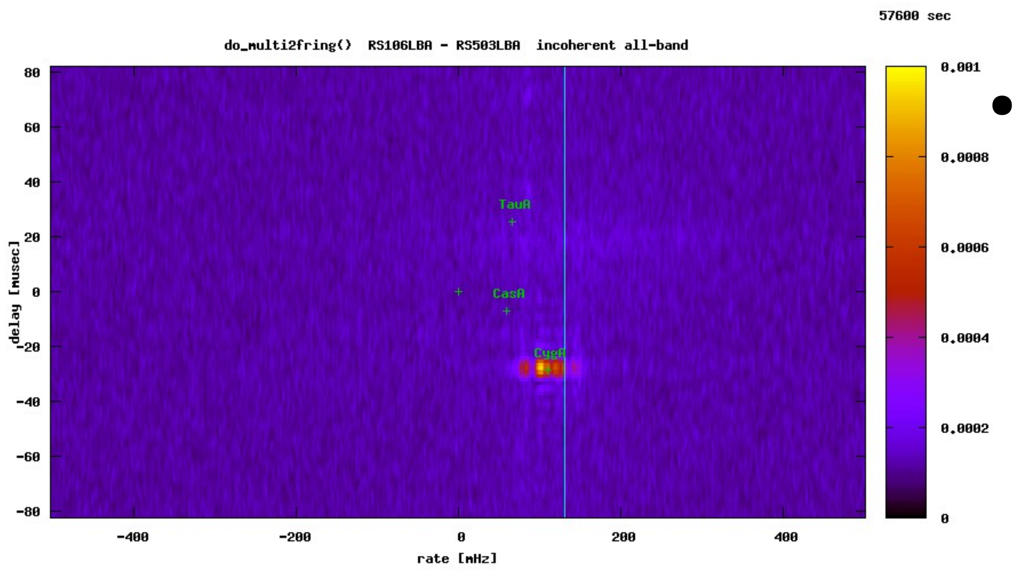
- Fringe-fitting performed using least-squares minimization following an initial Fourier transform to delay/rate space
- Multi-subband optimization
- Allows for dispersive and non-dispersive delays and rates
- Talk with Olaf if you want more details

Delay/Rate Image and Other Sources



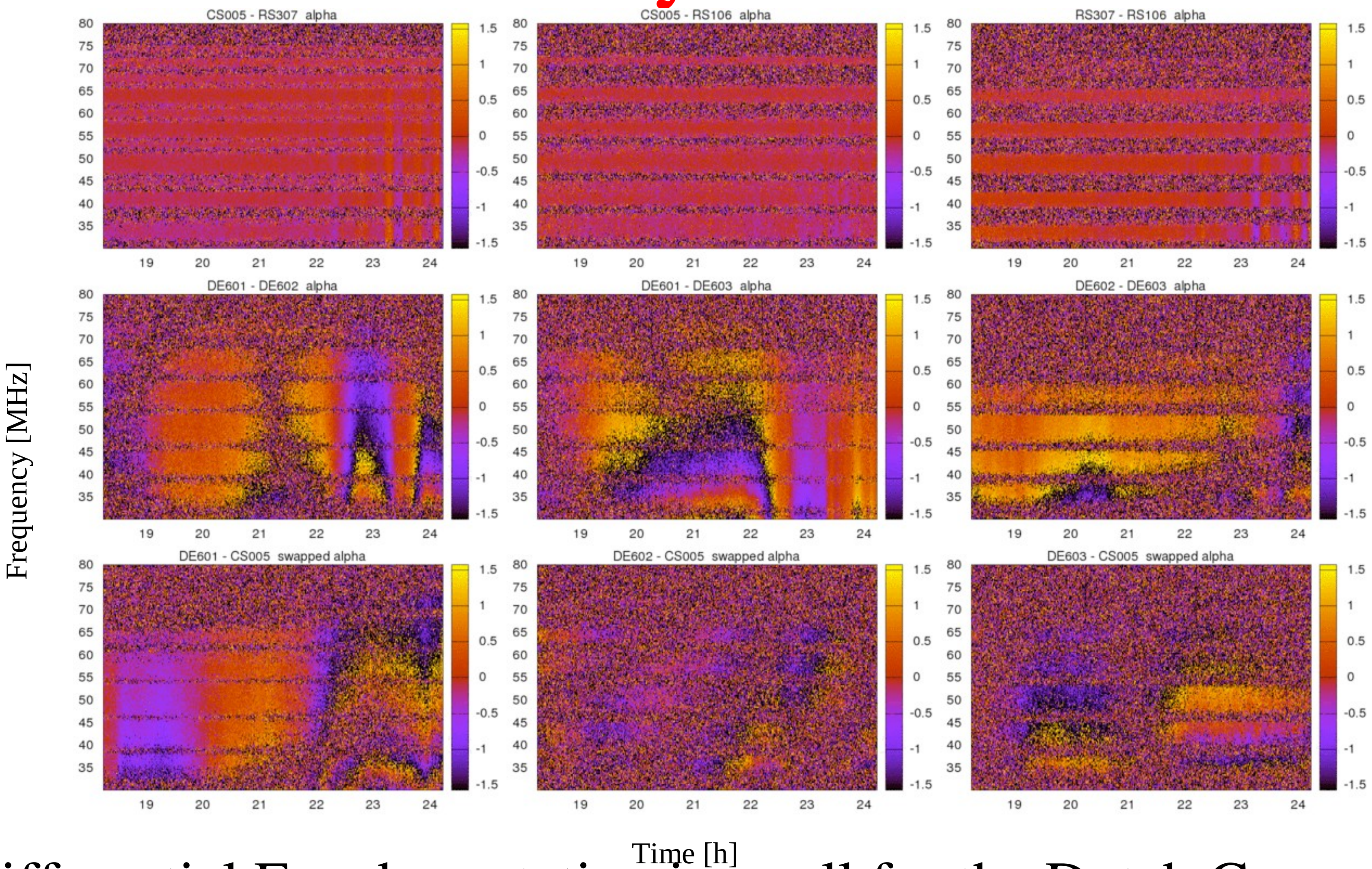
- Combining multiple subbands in the delay/rate plot increases the S/N
- In this image, 3C196 is at the center
- The other visible sources can be identified from their positions in the delay/rate plot with VLSS sources with flux densities of 19 (A), 6 (B) and 17 Jy (C) at 74 MHz

The A-Team in Delay/Rate Space



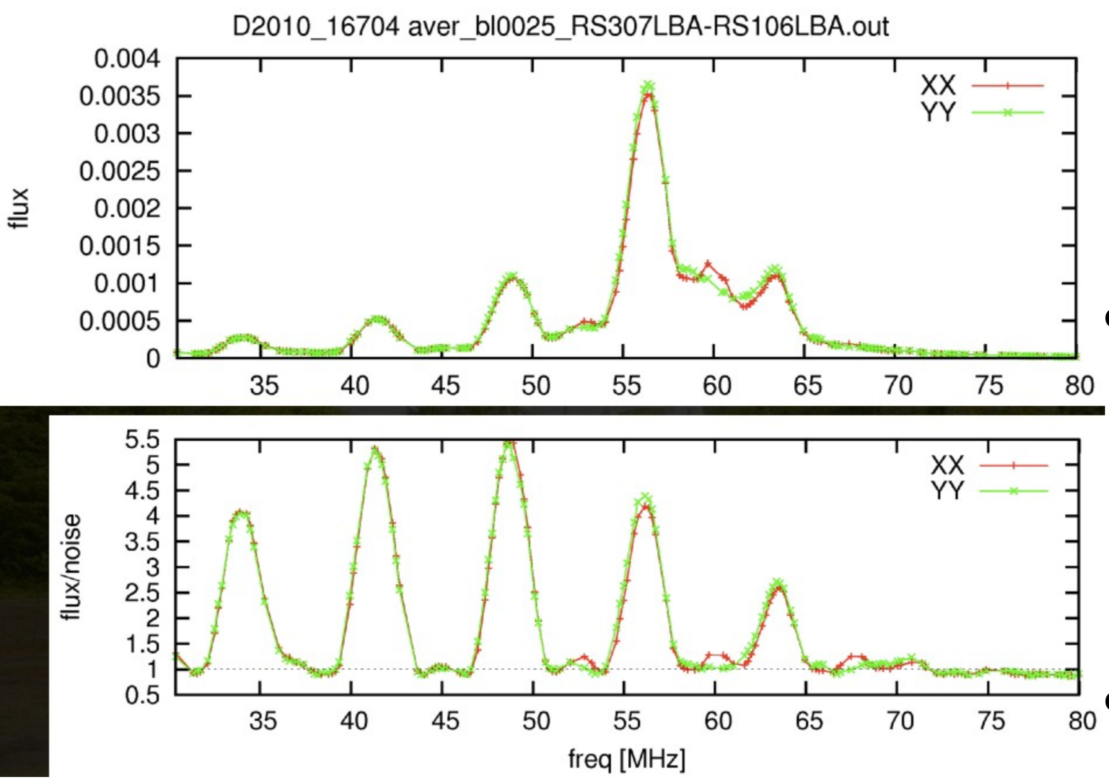
- Expanding the delay/rate space to larger values, one can see bright sources such as Cas A, Cyg A, Tau A, …
- On short (Dutch) baselines, the A-Team sources are brighter than the target source, even though they are > 60 degrees away from the station beam center
- Flagging of A-Team in delay/rate space possible, but expensive

Faraday Rotation



- Differential Faraday rotation is small for the Dutch Core baselines (top row)
- Long baselines (bottom rows) show variations

Instrument Gain Problems



- The 3C196 observations for the first long baseline image had severe gain problems as a function of frequency
- Problem eventually tracked down to the cable delays in the beamserver being turned off
- Unclear as to why no-one else noticed this earlier
  - Are people not checking that the gain solutions from BBS or MeqTrees make sense?

Additional Issues

- For 3C196 dataset
  - LBA polarizations swapped in Dutch stations
  - Significant data dropouts
    - Seem to be RSP board based, as the dropouts are always in contiguous 25% chunks of the subbands
- HBAs
  - Station beam calibration required for International stations to be useful for HBA observations
  - So we have not really done any long baseline observations since 2010 early spring (just twiddling our thumbs)
- Weird hardware issues
  - Sudden > 10 mHz rate jumps, apparently for different RSP boards on the same station

Source Issues

- S/N issues for single subbands are already a problem for the brightest sources in the sky on long baselines
  - Multiple-subband calibration required
- Source structure complicated at high resolution

Software Issues

- BBS not expected to have fringe-fitting for at least 6—12 months, if ever
  - If the reason why the International stations have large clock offsets and rates can be solved, this becomes less of an issue
- Olaf's software only runs on his cluster in Bonn, and only Olaf knows how to run it
- No feedback from Olaf's software back to the standard LOFAR software

Future Development

- Bonn will port Olaf's software from Olaf's cluster to the MPIfR VLBI cluster
  - Try to make Olaf's software more portable, installable at other locations
  - Modify Olaf's software so that it can be run by other people
    - Testing on the Bonn DFG students
- Python code to transfer the calibration values from Olaf's software to the original LOFAR datasets
  - Allow rest of the LOFAR software to process long baseline data, testing out the imager software, and so on, for long baseline observations

Bonn Processing Cluster

- Groningen cluster already busy, running out of disk space
  - Problem will only get worse as more stations come on-line and the pipeline processing advances before, during, and after MS^3
- In the process of obtaining storage system for commissioning long baseline observations in Bonn
  - Will have > 100 TB for LOFAR processing combined for MPIfR and AIfA
- Already have large processing cluster in Bonn, available part-time for processing LOFAR data
- Require fast data transfer from Groningen (10 GE LOFAR network connection)

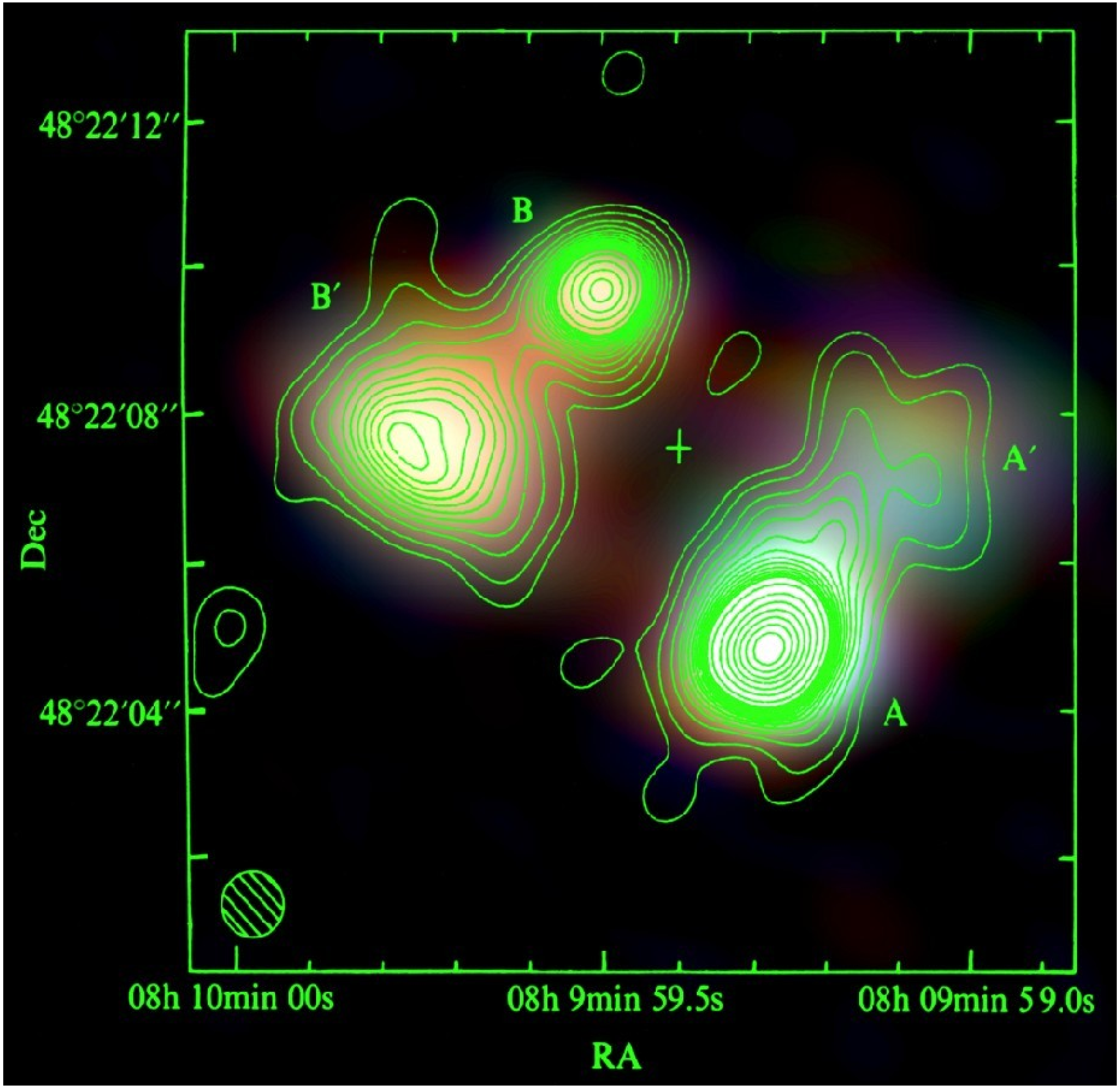
Commissioners

- Need more people to commission and develop long baseline LOFAR!
- Olaf and myself hope to continue working on long-baseline data
- DFG Magnetism group adds several new people in Bonn, plus Bochum and Tautenburg who are supposed to work on commissioning including long baseline data
- Other interested parties in the international community, if the right software can be made available for use on LOFAR

Conclusions

- 8 International stations available by ~end of 2010
- Huge amount of development and commissioning work yet to be done
- But also hopefully very interesting results for this unexplored imaging resolution for these frequencies

The End



48°22′12″
48°22′08″
48°22′04″
Dec
B
B′
A
A′
08h 10min 00s
08h 9min 59.5s
08h 09min 59.0s
RA