Initial Observations with the LOFAR Effelsberg—Exloo Baseline

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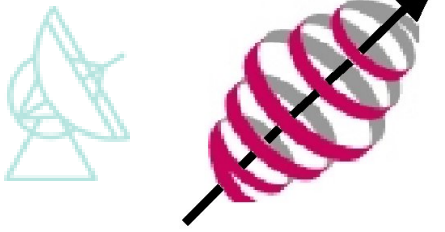


LOFAR

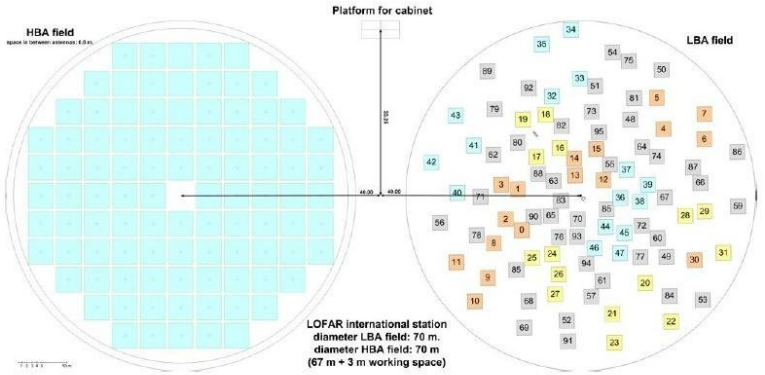
MAX-PLANCK-GESELLSCHAFT

Short Overview

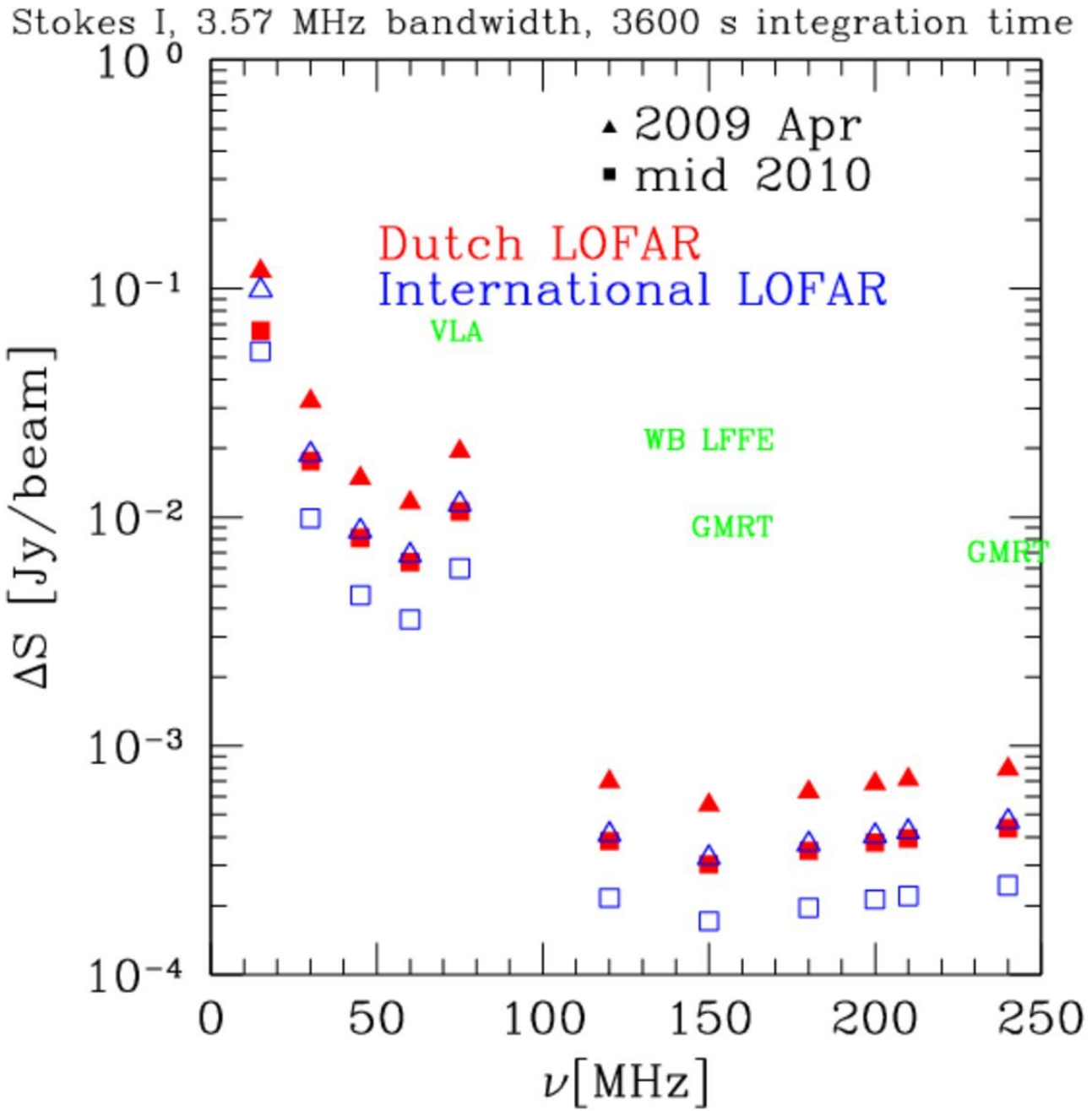
- We have not seen a fringe on a long baseline yet
- But we are very confident we will see one soon
- And there is a lot of building, development, commissioning, and observing to be done in the next few months and years
  - Long baseline, low frequency region little explored
  - Great exploratory science, if you can put up with the working conditions

Long Baseline LOFAR: International Stations

- ~ 1000 km baselines
- ~ Original station design
  - 96 antennas/tiles
- 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



Long Baseline Sensitivity: *I*



- Full (international) LOFAR about 2 times better than NL LOFAR
- HBA sensitivity roughly flat
- LBA system peaks around 56 MHz
- Noise increases rapidly to low frequencies

Long Story

- Effelsberg station (LBA only) operational 2007 Oct
  - But no network connection at that time
- Longish baseline test observations in 2007 Nov failed
  - Exloo to Dwingeloo
  - No fringe detected, but system very noisy (few antennas, sheep fence)
- Disk-based recording possible at Effelsberg since 2008 spring
- Two experiments to detect Jupiter bursts failed in 2008 Apr
  - Computer clocks set to different times, ...
- Effelsberg network link to Groningen finished, but no connection to Blue Gene
- Ex—Ef test observations of Cyg A and the Crab Pulsar made end 2008 spring
  - But Blue Gene not available for correlation

Well, I'll Just Write My Own Correlator...

- DiFX software correlator (Adam Deller) for VLBI available
- Bonn already has a cluster for processing VLBI data with DiFX
- GLOW wants to have a correlator for independent operation of German LOFAR stations anyway
  - For times when Blue Gene is busy with NL-only LOFAR observations
  - Useful for single-station observations as well
  - Britain also wants to have their own operations
  - Would be useful for observations with Nançay, the Northern Cross, ...
- DiFX already proven to work on long baselines
  - VLBI delay model, fringe rotation, and so on
- It shouldn't be that hard, right???

Changes Needed:1 --- Complex Data

- LOFAR data comes as a complex datastream out of the stations
- Many new instruments (aperture arrays, phased arrays) will produce complex datastreams
  - Might as well tackle this now, and have DiFX as capable as possible to deal with new instruments in the future
- Complex data: N samples
- Real-valued data: 2N samples

Changes Needed: 2 --- Timekeeping

- LOFAR 200 MHz clock breaks DiFX assumption that samples do not cross second time boundaries
- LOFAR beamformed datastreams do not fall on ns timesteps
- LWA scans starting at ~ 10 ms boundaries
- Major pain in the rear given the current DiFX code
- Times currently defined as seconds, nanoseconds
- DiFX scans start at second boundaries
- Times also defined as the number of samples since some time.
  - This becomes difficult with complex and real data
- I have implemented an FxTime class
  - Currently 2 doubles (seconds, fractional seconds)
  - Could be transparently changed to two 64-bit integers
    - Seconds and femtoseconds?

Changes Needed: 3 --- Bandwidth

- Standard VLBI assumption that bandwidth is 2^N MHz
- LOFAR beaks this assumption
  - Polyphase filter takes 200 MHz or 160 MHz sampled data and divides this into 512 subbands
- Code has scattered assumptions about relationship between bandwidth in MHz and delays in microseconds

Changes Needed: 4 --- Multiple Beams

- Different station pointing directions
  - Antenna/tile datastreams combined to point station in different directions
  - LOFAR will have up to 32 pointing beams per station
  - Pointing beams can have different subsets of antennas/tiles
    - End up with different coordinates for (u,v,w) calculations, delay calculations
- Different correlation directions
  - 1 or more correlation directions per pointing beam
  - Correlation direction different from pointing direction
    - Need to keep track of pointing direction for later processing
- Subarrays
  - Stations/beams may go away and come back
- Different configurations
  - Different integration times, overlapping scans, different channels

Changes Needed: 5 --- Subbands

- LOFAR can have up to 864 subbands (or perhaps 832?) per station
  - Minimum number of channels per subband is 256
  - Always correlate full cross-polarization
  - ~ 7 MB per baseline
  - 10 stations with autocorrelations ~ 400 MB
  - May have ~ 5 visibility buffers in array to fit in 2 GB
  - LOFAR will have ~ 62 HBA "stations" by end 2009
- LOFAR post-correlator software expects each subband
  - Suggests breaking correlation down into manageable numbers of subbands
  - Write out each subband separately?
    - May be able to write to separate locations for each subband (write to the machine which will process the subband)
- Moved visibility writing to new FxWriter object/process

Changes Needed: 6 --- Other Things

- LWA plans to change sources on 10 ms timescales
- Station hardware creates delay breaks every 1 s as the pointing model updates
- Ionospheric corrections
  - Very large for low frequencies
  - May need to be fed into CALC/VTD
    - Also ionospheric effects on (u,v,w)s
  - Different delay for each subband
  - Different (u,v,w) for each subband
    - Up to 20% change at 20 MHz, 20 degrees elevation
  - Implement these later
- Scan/source information
  - Many places in code that need to access source ID and so on
  - Change to indicate when not on source, optimize time search

Changes Needed: 7 --- Other Things

- Multiple beams handled by separate FxManager processes
- New FxBoss process created
  - Relatively stupid --- only knows about start and stop time of experiment and a list of Cores
  - Assigns Cores to FxManagers in time order, keeping telescope access ordered in time
  - Each FxManager can have different integration times, number of channels, start/stop times, and so on
- Last integration of scan has modified integration time
- Beginning to allow T_{sys} to be different for each subband
- Visibility weights
- Large number of bits (up to 32 bits per sample for LOFAR)
- ...

Future Development for LOFAR DiFX

- Blue=directly LOFAR related, Green=peripherally LOFAR
-
- Finish development to get LOFAR working
- Put the polyphase filter back in
- Write DiFX to HDF5 converter
- Deal with multiple polarizations (Nançay)
- Deal with different bandwidths (perhaps Nançay, Northern Cross, Westerbork Mark5, LWA, ...)
- Correlate different frequencies (A. Roy)
- Investigate DiFX operation at Jülich
- Realtime correlation from network stream (?)

Current Status

- 2nd DiFX Correlator Workshop held last week in Bonn
  - 10 people in a room writing and debugging code, SVN pages, web pages, and so on
  - Support for most of the changes necessary for LOFAR
- LOFAR DiFX producing visibilities soon
  - 1—2 weeks if I don't have any more meetings to attend
- Blue Gene/P in Groningen now working
- Network connection in Groningen for Effelsberg in ≤ 1 month
  - Andre Gunst agreed to increase priority last Thursday
- Complementary ASTRON (Blue Gene) and MPIfR (DiFX) efforts should yield results soon
  - Will have to do initial clock and ionosphere search
  - S/N for single subband low (about 4 or 8), but combining subbands should give reliable result

- Exloo LBA
- Effelsberg LBA
- Unterweilenbach LBA system ready ~ end Oct
- Tautenburg LBA system ready in Nov?
- NL central stations begin end Dec
- Other stations continue after that
- HBA systems added to existing stations later

LLBWG

- LOFAR Long Baseline Working Group
- Headed by Corina Vogt and myself
  - Involvement from quite a few other busy people too
- A science case for long baseline LOFAR exists
  - Workshop organized in 2006, report edited by Vogt
  - ~ Arcsecond resolution key for many different science goals
  - Long baseline measurements planned for many KSP projects
  - New ideas continue to be explored
- Long baselines bring additional challenges which require special attention
- LLBWG formed to address the long baseline issues
  - Special attention to development and commissioning (mostly imaging mode)
  - Bring in expertise from the long baseline community

LLBWG Projects Before MS^3

- 2S^3 (2 Source Starting Survey)
  - Crab Pulsar and Cyg A
  - Detect first fringe
  - Initial system performance tests and ionospheric studies
  - Now through 2008 December
- HS^3 (Hundred Source Surface Survey)
  - 3C catalog and Jupiter
  - Calibrator survey for LOFAR
    - Find good calibration sources for MS^3 and future LOFAR projects (clocks, ionosphere)
    - Amplitude dependence on (u,v) and frequency
    - Polarization present?
  - Test multiple beam operation
  - Ionospheric behavior and calibration techniques
  - 2008 Nov/Dec through 2009 Apr (and beyond)

MS^3 and Long Baseline Observations

- Million Source Shallow Survey
- Long baselines will be included during MS^3 observations
  - Full sky survey with LBA and HBA
  - ~ 20 + NL stations and ~ 7 International stations
  - Starting 2009 Apr and continuing for probably a few months
- Populate the LOFAR Global Sky Model at high resolution
- Continued long baseline commissioning

Press Gang Instructions for LLBWG

- Set anchor in a harbor city where VLBIers are congregating
- VLBIers have reputations for drinking heavily in seedy bars
- Block exits to bar, to prevent VLBIers from escaping
- Enter bar and identify the people with VLBI experience
- Abduct the VLBIers
  - Some may come willingly
  - Some may come with proper offer of daily rations (food and alcohol)
  - Handcuffs may be used for the kinky ones
  - Knock the unruly ones unconscious
- Take them back to the home institution
- Train them to operate the new LOFAR software
- Sail off to search the high resolution universe

"Make Long-Baseline LOFAR Work" Night

- Thursday evening at 18:00
- In an international pub just down the street
  - Guinness available for those of you who don't like proper Bier
- Corina Vogt and I will discuss details of LLBWG plans
  - Can discuss LOFAR long baseline technical details
  - Observation plans
  - Development and commissioning needs
- LLBWG needs people for development and commissioning work starting this year
- Thursday night intended for people who can commit to working on initial LOFAR long baseline analysis, or can commit other people to such analysis
  - **Great initial science possible, but it will not be easy!**

End

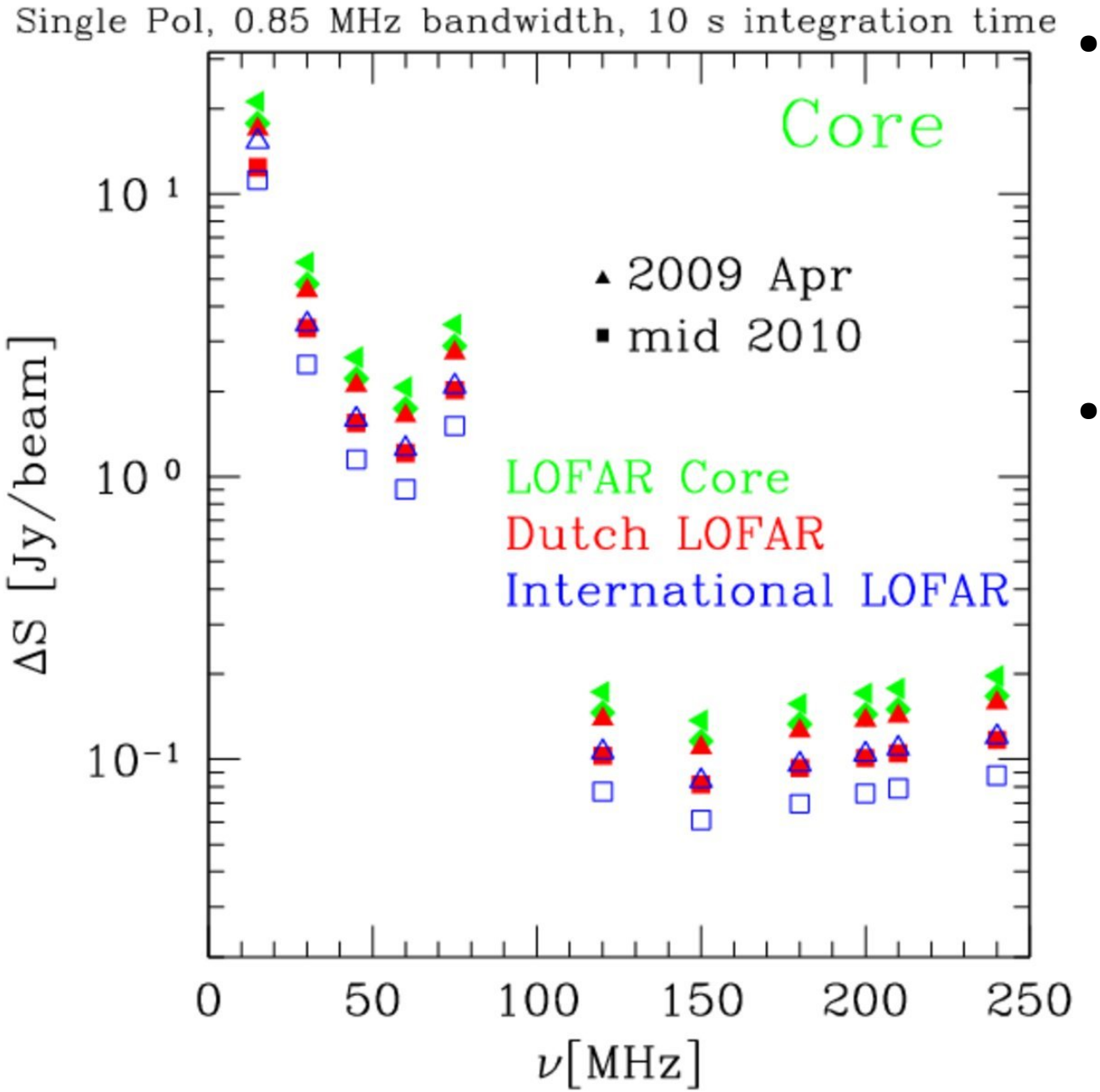
- Lots of gory details available now if you insist
- We won't have a projector at the bar for you to look at the slides, so ask now, or download the PDF of this presentation and continue reading past this page

Long Baseline Details

Data Rates And Processing

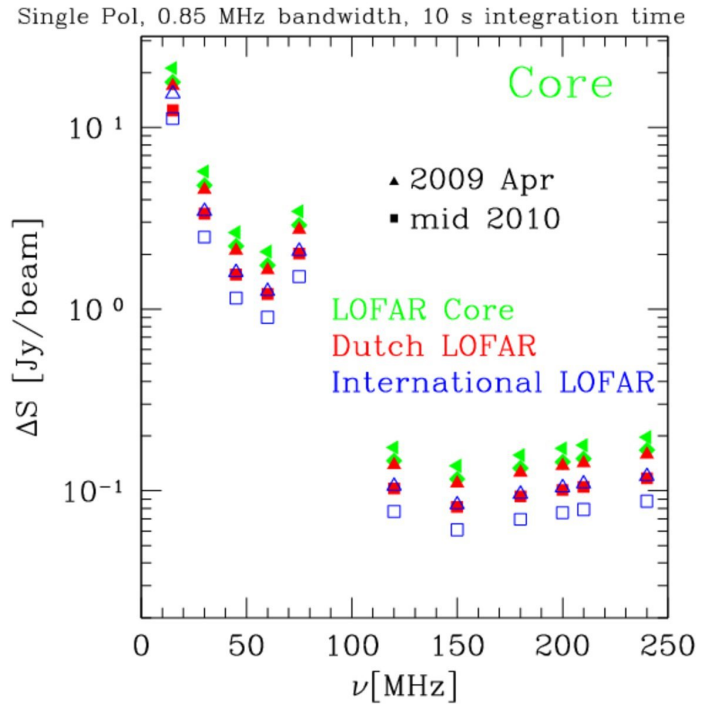
- Blue Gene correlator can already handle the integration times and frequency resolution required for long baseline LOFAR
- Theoretical data rate out of correlator (full processing) in GB/s for the standard 16 bit sample mode
  - Baselines Dutch International
  - LBA **1** **9**
  - HBA **3** **17**
- Data rates would grow by a factor of 4 for the 4 bit sample mode if LOFAR can deal with the data rate
- Correlating sources independently does not lower data rates
  - RFI and ionosphere require high time and frequency resolution
- Currently each subband is processed semi-independently
  - Requirements for processing cluster size need to be examined

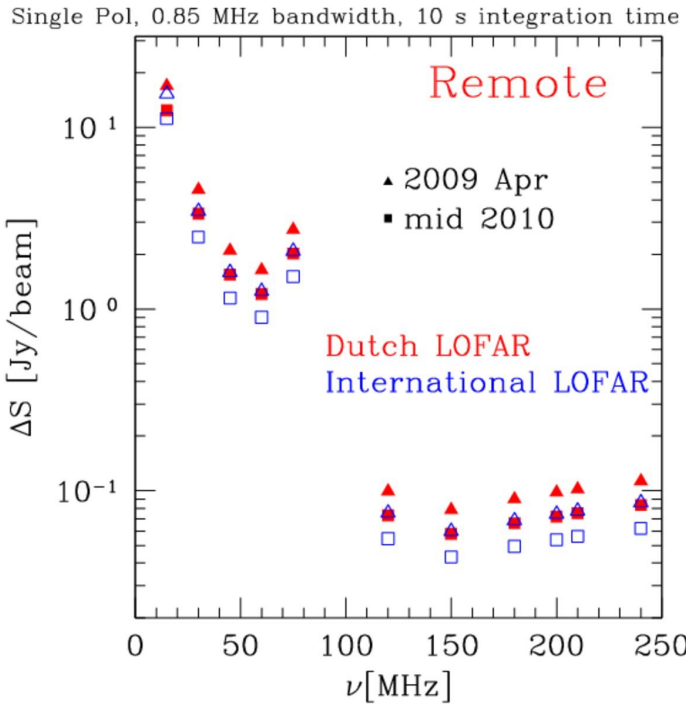
Single Pol Selfcal Noise Level

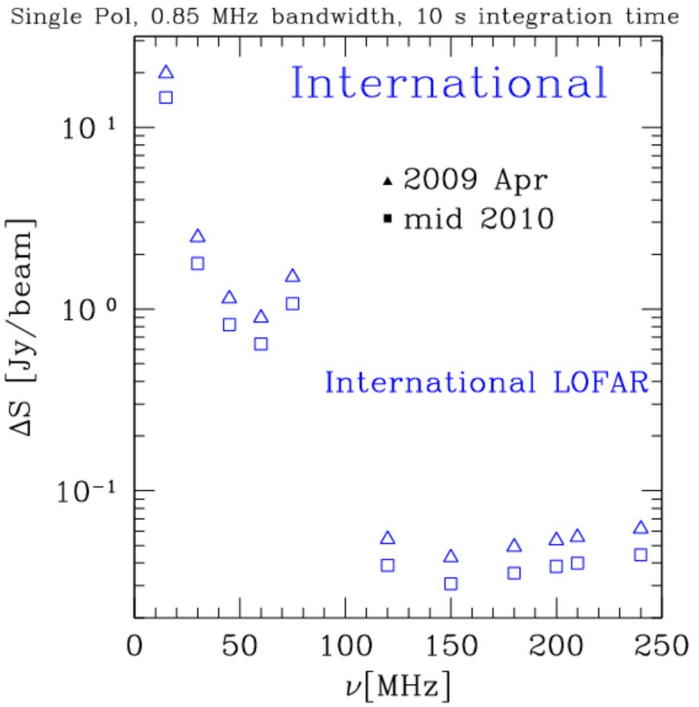


- Selfcal equivalent flux density for a single station (ear) naturally larger than image sensitivity
- Inclusion of longer baselines assumes that sufficient flux density can be found at high resolution

Selfcal for Different LOFAR Stations (Ears)







- Noise level (generally) decreases going to the more distant stations, as they have more collecting area
- But flux density rapidly drops off for long baselines
- LBA system (< 100 MHz) difficult to calibrate for 1000 km baselines
  - Very few ~several Jy sources at that resolution
  - Need many short baselines to every International LOFAR station

Calibration Details (Future Development)

- Clock offsets (1 param)
  - LOFAR is a VLBI instrument
- Ionospheric Terms
  - Ionospheric delay (MIM)
  - Faraday refraction (MIM)
  - Ionospheric absorption (derived)
  - Ionospheric refraction (derived)
    - Also changes station position for (u,v,w) calculation depending on frequency
- Troposphere
  - Delay (standard model or MIM)
  - Pressure information from station weather data may be good enough for modeling, but must be calculated over wide-field
- Station position offsets (3 param)
  - Weather fronts, ocean loading, and so on produce significant station position offsets even on Dutch baselines
- Instrumental terms
  - Complex station/tile/dipole gains (several param + model)
  - Beamformer sawtooth
  - Beamformer delays
  - Dipole/Tile/Station delay and phase offsets
  - Reception location depends on incidence angle (extra station position shift)

Commissioning Details: 1

- Correlator Output
  - Understand phases and amplitudes
  - Check N bit operation
  - Check multiple phase center operation
  - Multiple beam correlation
  - Weights and S/N
  - Check that fringe detection gives same delays and rates for Blue Gene and DiFX correlation
  - Pulsar binning
- Delay Model
  - Implement and check a proper long baseline delay model
  - Compare Blue Gene and DiFX delay calculations at integration centers
  - Compare (u,v,w) calculations
  - Check ionospheric delay calculation for individual subbands
  - Delay as a function of distance from Sun
  - Near field calculations (Jupiter and the Sun)

Commissioning Details: 2

- Ionosphere
  - Measure delays for individual stations
  - Check delay as a function of frequency
  - Analyze ionospheric variability
    - TEC amplitude, timescale, dependence on baseline length, time of day, time of year, solar cycle, azimuth and elevation
  - Check multiple beam measurement sand modeling
    - Check modeling for beams far apart and for beams close together on sky
- Sources
  - Measure *I* as a function of (u,v) and frequency
    - Will initially require individual station calibration to ge approximate amplitude calibration (How does T_{sys} for a single beam relate to the full-sky calibration?)
  - Measure source structure as more stations come on-line
  - Measure approximate relative sky positions
  - Geodetic-type observations when many stations are available (needs good ionospheric model)
  - Comparison of source structure with higher frequencies (What do we see? Are they good calibrators?)
  - Variability studies --- calibrators should not vary much intrinsically, or because of ISM, IPM, ionosphere

Commissioning Details: 3

- Polarization
  - Find sources with significant polarization for calibration
    - Need linear and circular polarization for commissioning
    - Start with 3C catalog and Jupiter ASAP, then add 4C and pulsars as sensitivity improves
  - Measure dependence on (u,v) and frequency
  - Test dipole/antenna/tile/station beam models
  - Check software production of rotation measure synthesis cubes
  - Check polarization calibration software
    - Ionospheric delay, Faraday rotation, using rotation measure data
- Imaging Software
  - Test operation for long baselines/high resolution
  - Test polarization output
  - Check w-correction operation and optimization for long baselines
  - Check imaging of fields far from correlation center
    - Position shifts and other effects, check against direct correlation at target position
  - Check imager and calibration operations properly deal with delays, rates, and Faraday rotation
  - Delay and (u,v,w) model software incorporated into calibration and imaging software (especially important for distant sources, including far sidelobe source removal)

Commissioning Details: 4

- Station Performance
  - Measure clock stability
  - Check RFI environment (go through all frequencies, full day)
  - Check system noise level
  - Check polarization angles
  - Check station position
  - Measure station position movement (during geodetic-type observations)
  - Measure network performance
- Ionosphere
  - Compare measurements with GPS measurements
  - MIDAS model comparison
  - Check MIDAS input into correlator model
  - Check LOFAR-derived ionospheric model input into correlator
  - Check refraction and refraction-based delay, and (u,v,w) changes

Commissioning Details: 5

- Fringe Fitting
  - Get it implemented
  - Make it work
  - Compare results with other software (AIPS)
  - Check performance measuring ionospheric frequency dependence
  - Check polarization and Faraday rotation performance
  - Check path length changes with ionosphere (refraction)
  -
- Pulsars
  - Need sensitive instrument before starting pulsar search
    - ISM scatter broadening expected to be significant
  - Measure amplitude as function of (u,v), frequency, time
  - Polarization and pulsars as calibrators
    - Do we need pulsar binning
    - Measure polarization, strength, possible pulse phase dependence, time stability
  - Measure short-term variability
    - How long does LOFAR have to average before polarization reliable?

Commissioning Details: 6

- Correlator
  - Check data rates
    - Cannot really test until we have nearly all stations
  - Check multiple correlation direction operation within a single beam
  - Check operation of different integration times for different baseline lengths (if implemented)
- Software Systems
  - Long baseline specific development
  - Long baseline analysis tools proposed
  - Development, installing, commissioning, and using the software
- Doppler Shift
  - Check Doppler shift correction operation in correlator
  - Calibration software operation for line emission
  - Other processing software
  - Initially can use Jupiter burst observations to test