LOFAR Calibration of the Ionosphere and Other Fun Things

James M Anderson
anderson@mpifr-bonn.mpg.de

LIONS
(LOFAR IONospheric Simulations)
http://www.strw.leidenuniv.nl/LofarWiki/doku.php?id=lions
bemmel@strw.leidenuniv.nl

LOFAR Long Baseline Working Group (Vogt & Anderson)
Effelsberg LOFAR Station Manager (with W Reich)
LOFAR Cosmic Magnetism KSP (R Beck)
LIONS

Max-Planck-Institut für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

LOFAR IONospheric Simulations

Leiden: Niruj Mohan Ramanujam, Aleksander Usov, Amitesh Omar, **Huib Intema**, **Ilse van Bemmel**, Mamta Pandey, Huub Röttgering, Reinout van Weeren, Sridharan Rengaswamy

ASTRON: **Jan Noordam,, Oleg Smirnov,** Ronald Nijboer, Ger de Bruyn, ...

Groningen: **Maaijke Mevius**

MPIfR Bonn: **James M Anderson**

TU Delft: Bas van der Tol, Hans van der Marel

Oxford: Hans Kloeckner, Steve Rawlings, Ian Heywood, ...

RAL Bath: Ian McCrea, Cathryn Mitchell, Paul Spencer

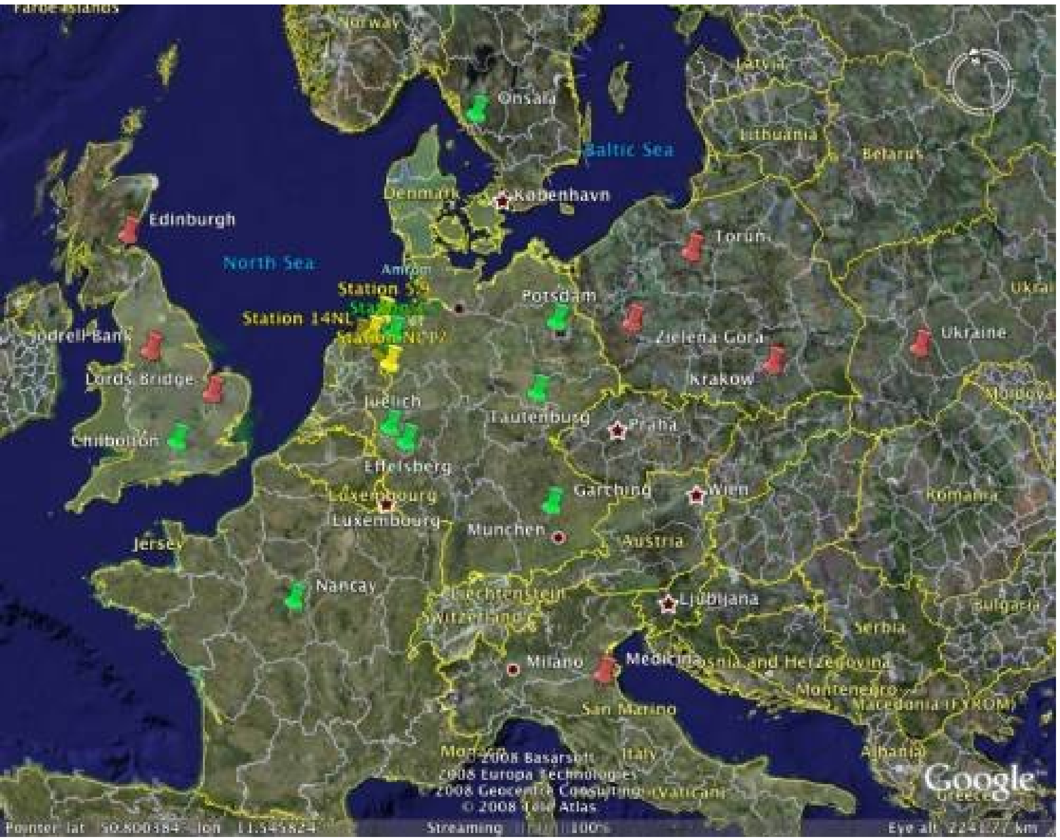
Aberystwyth: Richard Fallows, Manuel Grande

Cambridge: **Software Postdoc TBD**

Outline: LOFAR (Ionospheric) Calibration

- LOFAR hardware review
- LOFAR processing software
- Sensitivity and sources
- SPAM to MIM (and more calibration terms)
- Refraction

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)
  - 120 to 240 MHz
- 3rd input unused

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

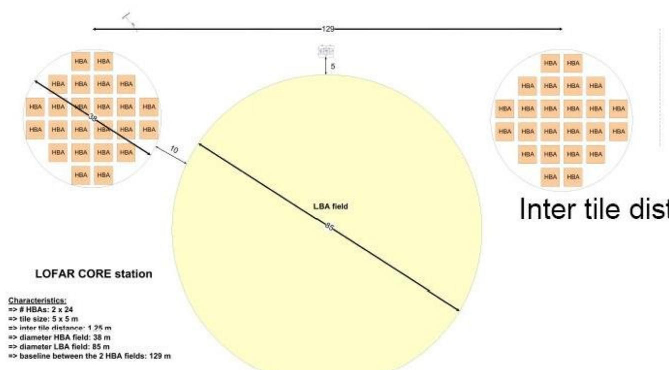
Orginal LOFAR

Current LOFAR

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

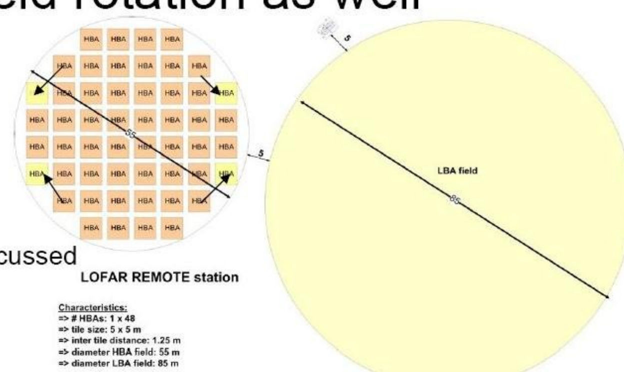


Inter tile distance: 0.6 m

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

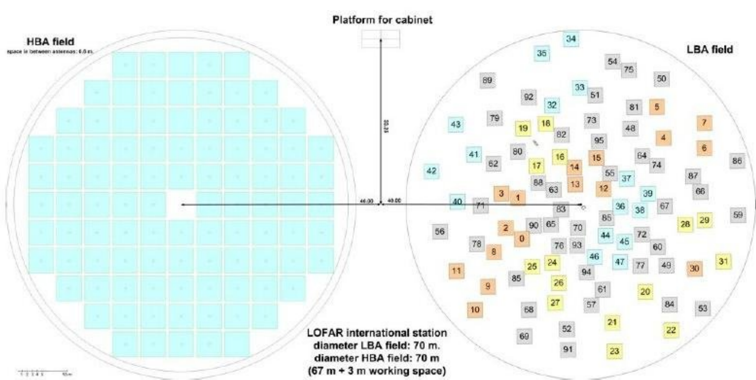


Final HBA distribution discussed

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



Rollout

- 2008 Jun: BlueGene L replaced with BlueGene P
- 2008 Jul: Remote station installation began
- 2008 Aug—Sep: Intl. station installation begins
- 2008 Oct: Core station installation begins
- 2009 Apr: LOFAR Phase 1, major commissioning phase
  - 13 Core, 7 Remote, 7 International LOFAR stations
  - Global Sky Model observations (coordinate reference system)
  - Million Source Shallow Survey (all-sky < 3 months)
  - LOFAR Long Baseline Working Group astrometry survey
  - Tied-array mode, CR, etc.
  - Magnetism KSP commissioning and initial science?
- 2010 Mid: LOFAR Phase 2, all antennas in place
- >~ 2010: E-LOFAR (???)

Frequency Selection

- Station A/D converters form 100 MHz or 80 MHz bands
- These are divided into 512 subbands (IFs) of about 200 kHz
- Station beams can send back an arbitrary subset of these subbands
  - Frequency coverage not required to be contiguous
  - Calibration will work best in full production system with wide frequency coverage
- Up to 8 (16, 32) beams, for 16 (8, 4) bit samples, with a combined bandwidth of up to 32 (64, 128) MHz
  - But some fraction of that will be taken up by calibration beams
- Correlator creates 256 channels within each subband, so final channel resolution is < 1 kHz

Data Rates And Processing

- Theoretical data rate out of correlator (full processing) in GB/s for the standard 16 bit sample mode

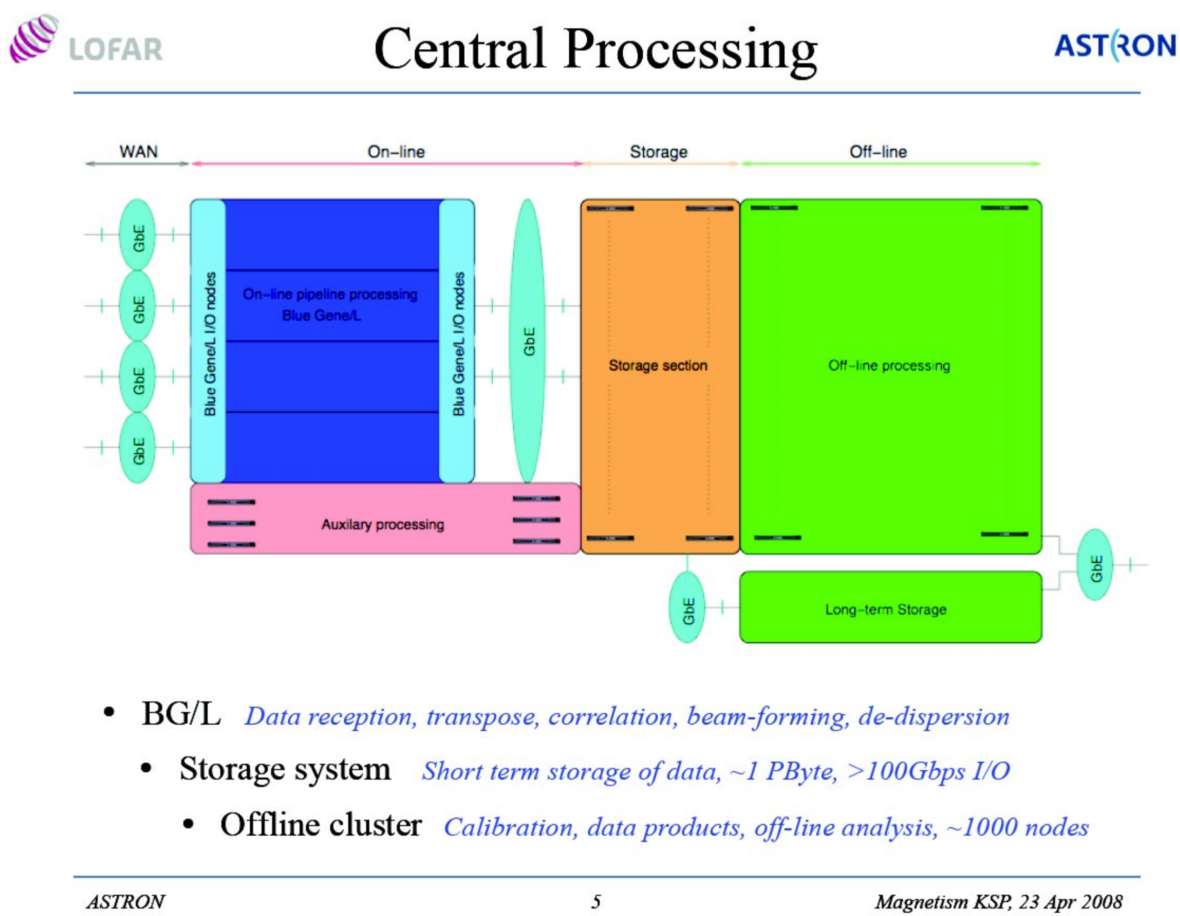
Baselines	Dutch	International
LBA	**1**	**9**
HBA	**3**	**17**

- Data rates would grow by a factor of 4 for the 4 bit sample mode if LOFAR can deal with the data rate
- Currently each subband (IF) is processed semi-independently
  - RFI flagging and coarse calibration
  - Possible frequency averaging to lower effective data rate during calibration

Outline: LOFAR (Ionospheric) Calibration

- LOFAR hardware review
- LOFAR processing software
- Sensitivity and sources
- SPAM to MIM (and more calibration terms)
- Refraction

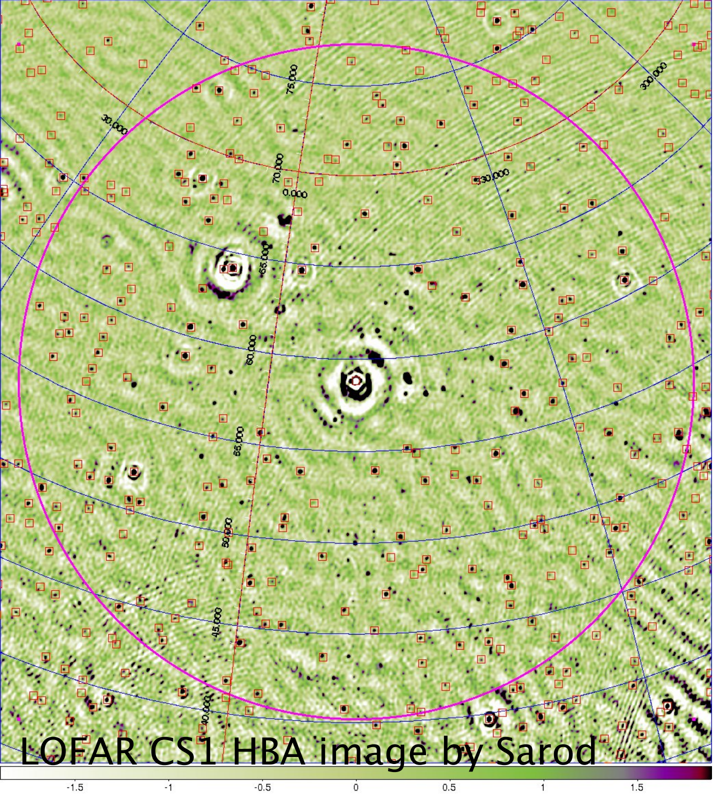
Interferometry Processing Path

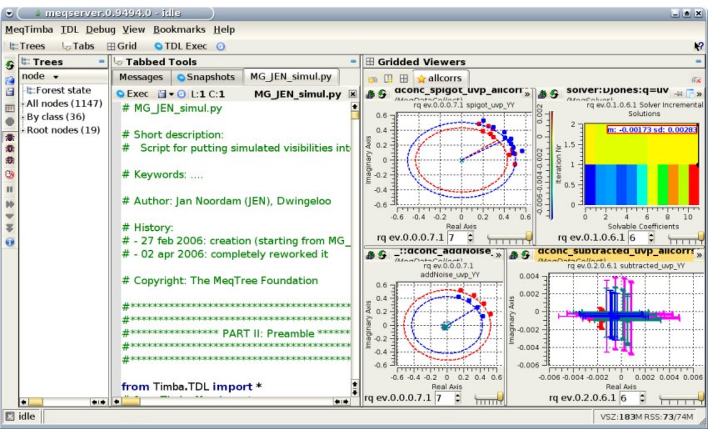


LAD presentation by M. Wise

- Current pipeline system for imaging working in Groningen
- Can already deal with modestly large number of bselines
- Current software really only works (tested) for baselines < 2 km
- Huge amount of work to be done by April next year for new stations

MeqTrees


LOFAR CS1 HBA image by Sarod



- Not officially part of LOFAR
- But being used for much of the LOFAR development and commissioning
- Ease of installation now greatly improved
- Rapidly expanding userbase
- CasaCore and Python
- Used in CA and NL for focal-plane array calibration
- Heavily used for SKA simulations

http://www.astron.nl/meqwiki

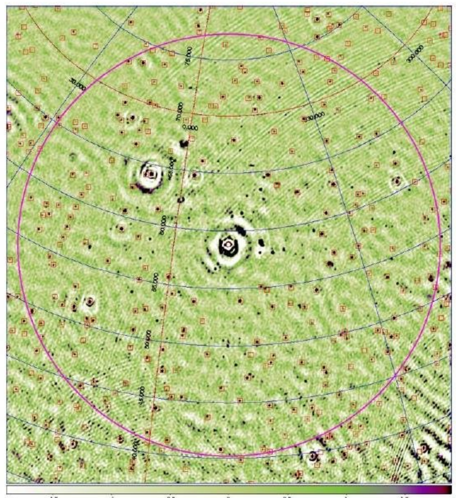
Bonn MeqTrees Seminar presentations available at
http://usg.lofar.org/wiki/doku.php?id=documents:minutes:2008:2008-05-26_meqtrees_seminar

BBS (Blackboard Selfcal)

Standard Imaging

Recent progress
- Distributed BBS available
- Solution based flagging
- BBS ported to RuG cluster
- First version of CIMAGER Release of PyBDSM package

Next quarter
- BBS global solver complete
- GSM implementation design
- MIM implementation design
- Mosaicing designValidation of CIMAGER
- HDF5 data cube format

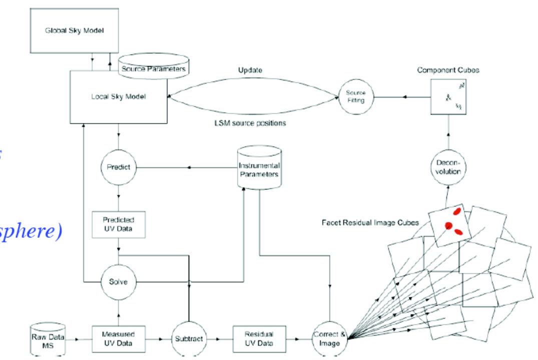


4 HBA tiles, 24 hrs, 36 subbands, 125-175 MHz

GLOW presentation by Vogt

BBS SelfCal

- Solving for:
  - *Instrumental parameters*
  - *Direction-dependent sky parameters (beam, ionosphere)*
  - *Source parameters (point and gaussian)*
- Subtract sources
- Apply corrections for instrumental parameters
- Distributed; can solve globally (almost done)
- Multi-threaded



ASTRON 12 *Magnetism KSP, 23 Apr 2008*

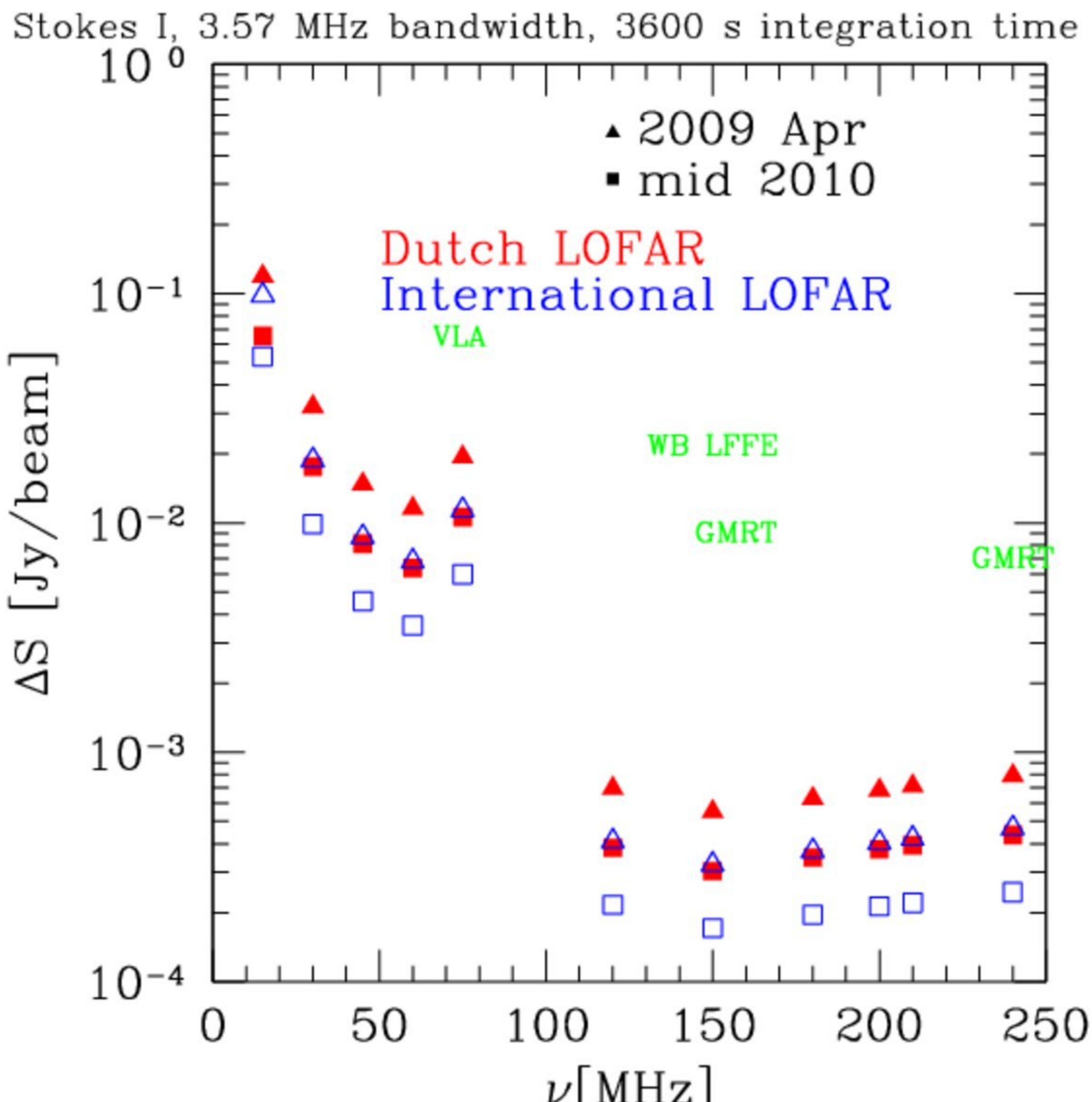
LAD presentation by M. Wise

- Main LOFAR pipeline software
- C++ and Python, casacore based (eventually)
- CImager runs in parallel environment
- Cluster calibration software --- fits calibration terms using information from many subbands (IFs) simultaneously

Outline: LOFAR (Ionospheric) Calibration

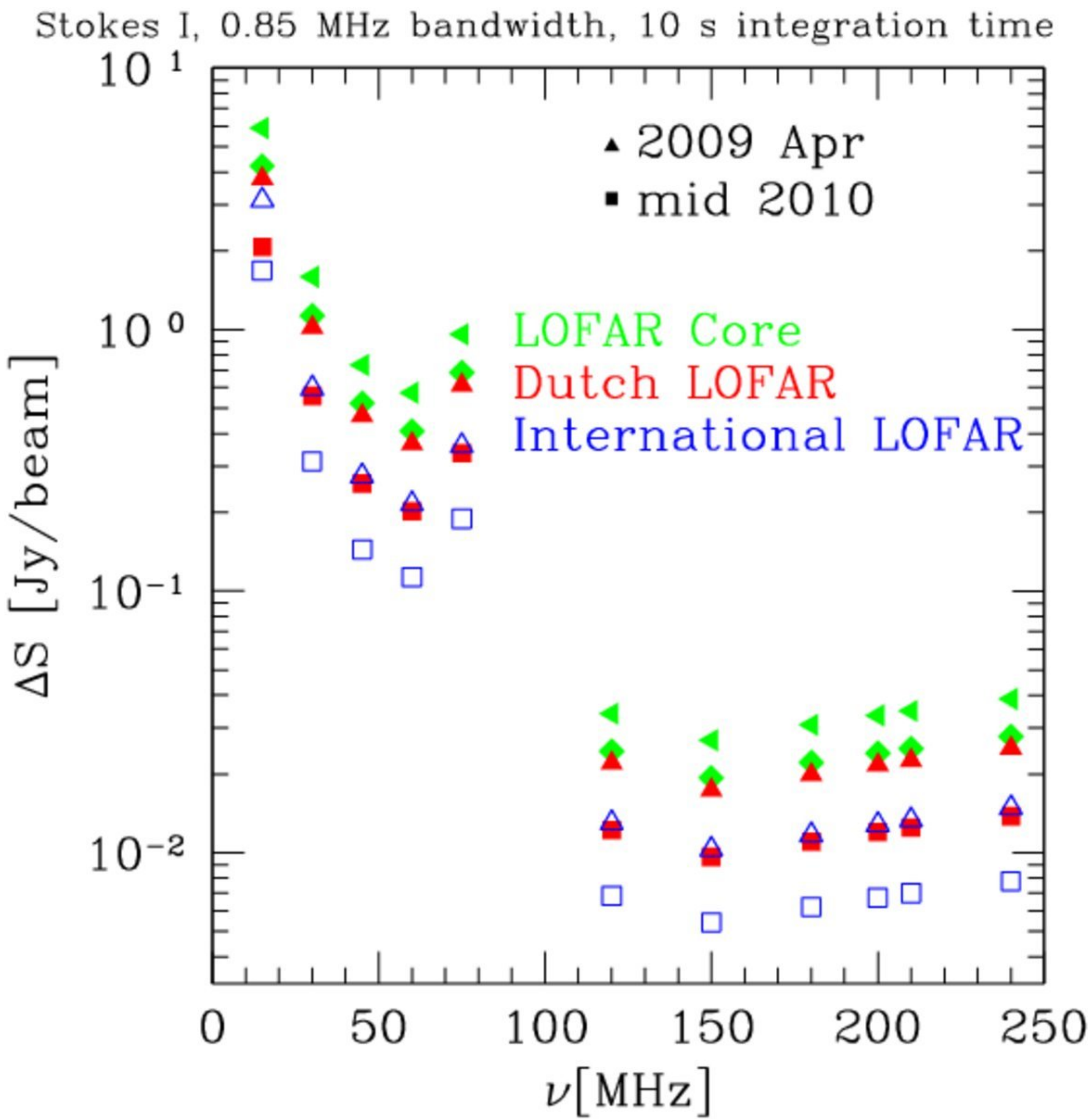
- LOFAR hardware review
- LOFAR processing software
- Sensitivity and sources
- SPAM to MIM (and more calibration terms)
- Refraction

User Sensitivity: *I*



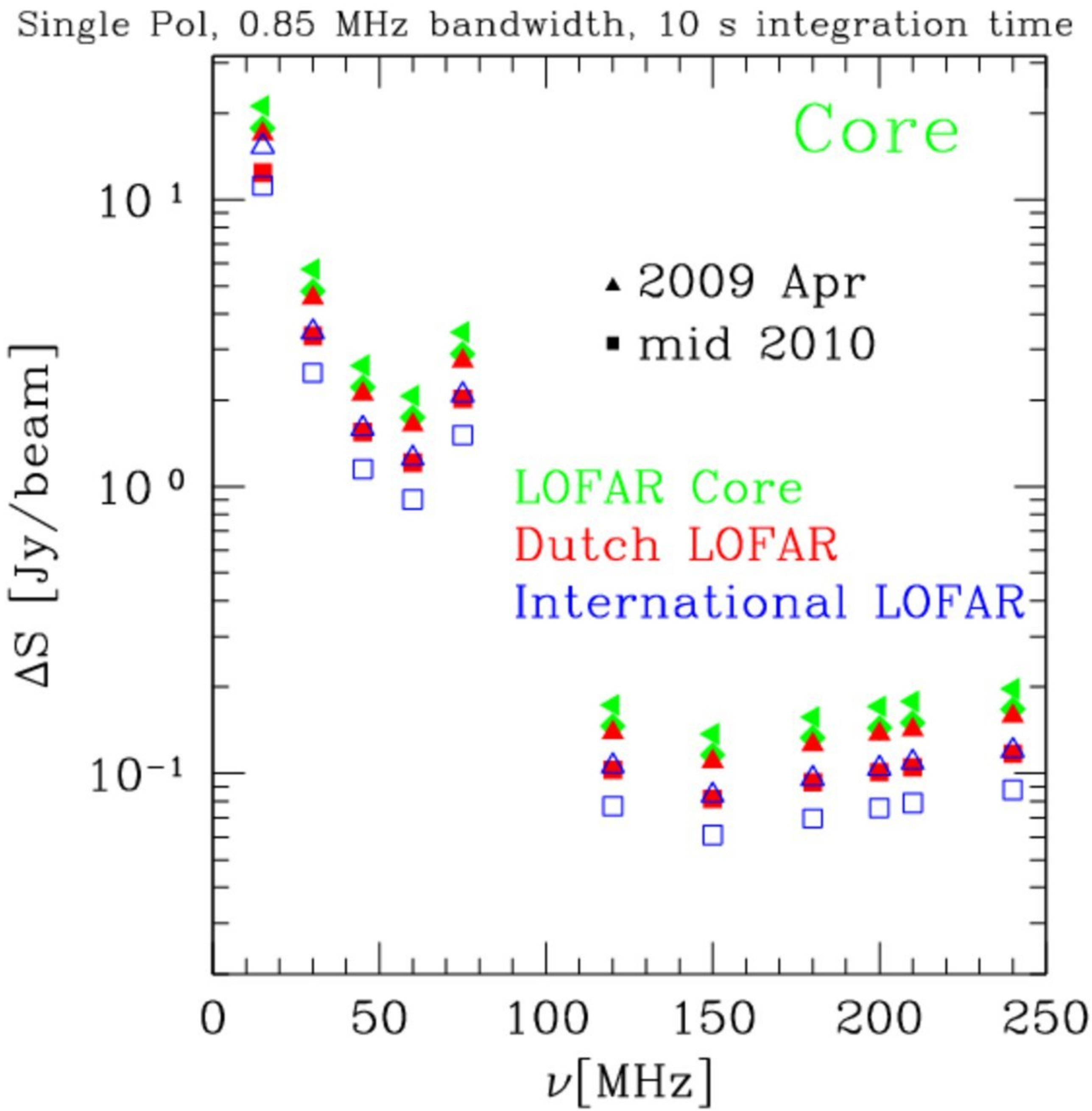
- Full (international) LOFAR about 2 times better than NL LOFAR
- HBA sensitivity roughly flat
- LBA system peaks around 56 MHz
- Noise increases rapidly to low frequencies

Calibration Sensitivity: *I*



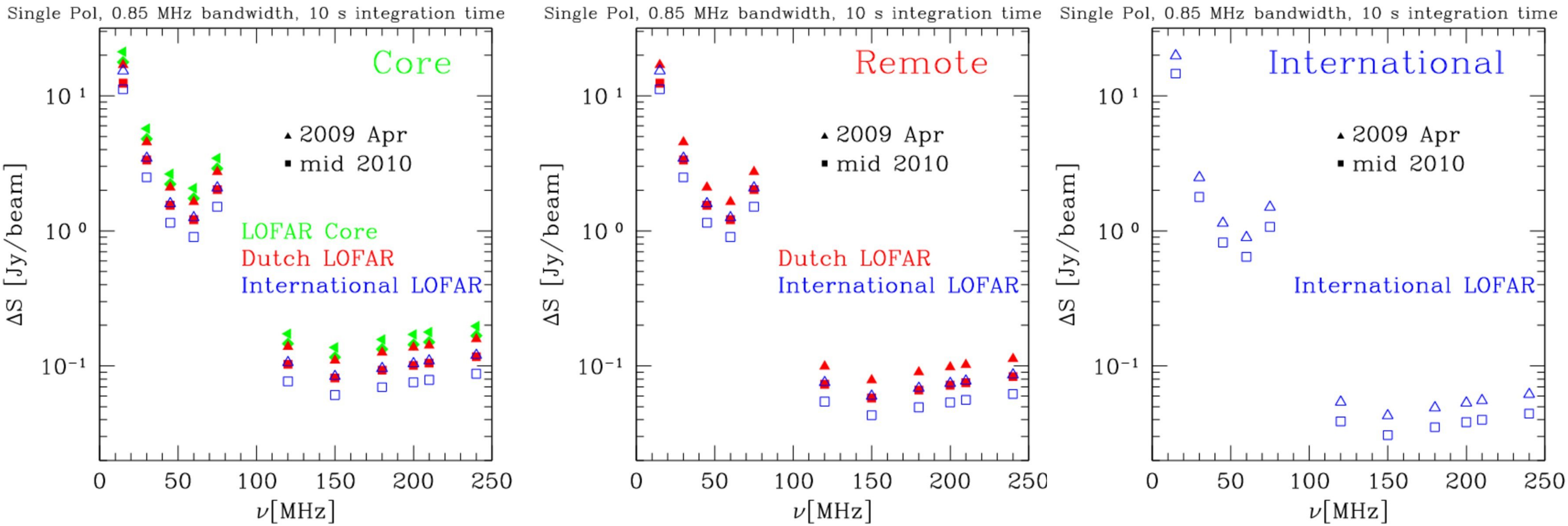
- 10 s is approximate timescale for ionospheric changes
- Several beams, MHz of bandwidth dedicated to calibration observations
- HBA sensitivity roughly flat
- LBA system peaks around 56 MHz
- Noise increases rapidly to low frequencies
  - But so may flux density ...

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

Global Sky Model

- LOFAR calibration will not be performed using isolated point sources
  - At most resolutions calibrators will be resolved
  - Fields of view are huge, with strong, distant sidelobes, so there are no isolated sources
- LOFAR Global Sky Model
  - Catalog of > millions of sources
  - Brightness, shape, polarization, rotation measure, ...
  - Coordinate reference system
- Calibration uses a subset of the Global Sky Model with many sources in the primary beam and sidelobes
  - More flux density for calibration
  - More lines of sight through ionosphere

Outline: LOFAR (Ionospheric) Calibration

- LOFAR hardware review
- LOFAR processing software
- Sensitivity and sources
- SPAM to MIM (and more calibration terms)
- Refraction

SPAM: Source Peeling & Atmospheric Modeling

(generalized selfcal © Jan Noordam)

© Monty Python

Recipe:

- Obtain ionospheric phase info through peeling
- Model fit ionospheric phases with thin screen at fixed height
- Predict ionospheric phases for arbitrary viewing directions while imaging

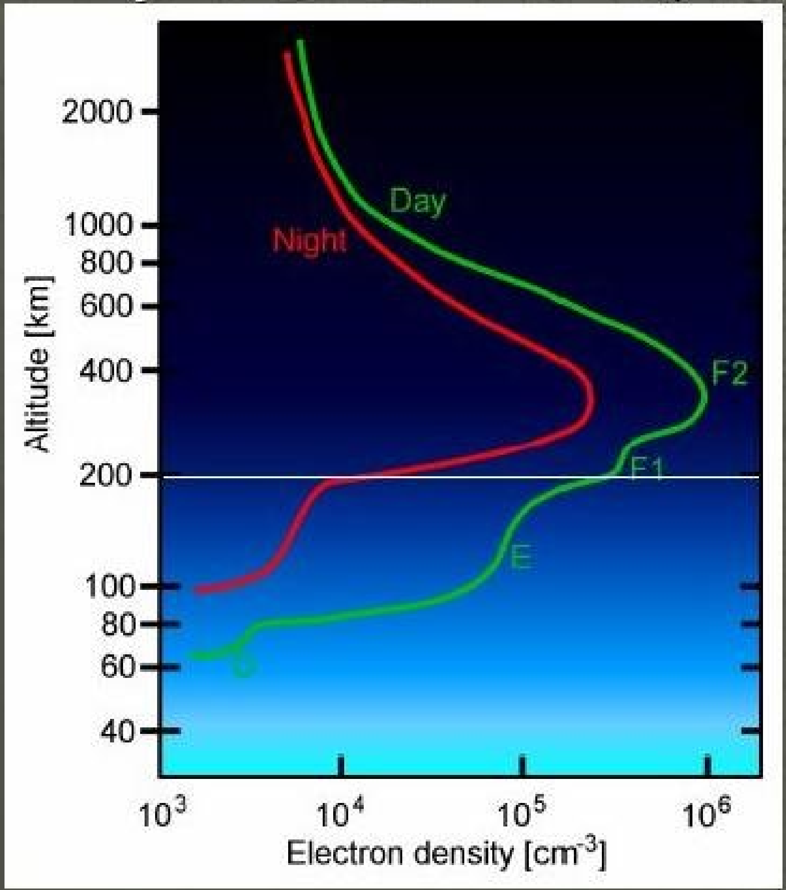
Repeat if necessary

SPAM is the PhD dissertation work of Huib Intema, Leiden

Slides taken from Huib's 2008 May LIONS presentation

(II) Fit ionospheric phases with thin screen at fixed height

- Thin layer phase screen at 200 km heigth
- Kolmogorov turbulent medium with $\left\langle \left[\phi(\vec{x}) - \phi(\vec{x}+\vec{r})\right]^2 \right\rangle_{\vec{x}} \sim r^{5/3}$
- Optimised set of Karhunen-Loève base "functions" (van der Tol et al., 2007, IEEE proceedings)



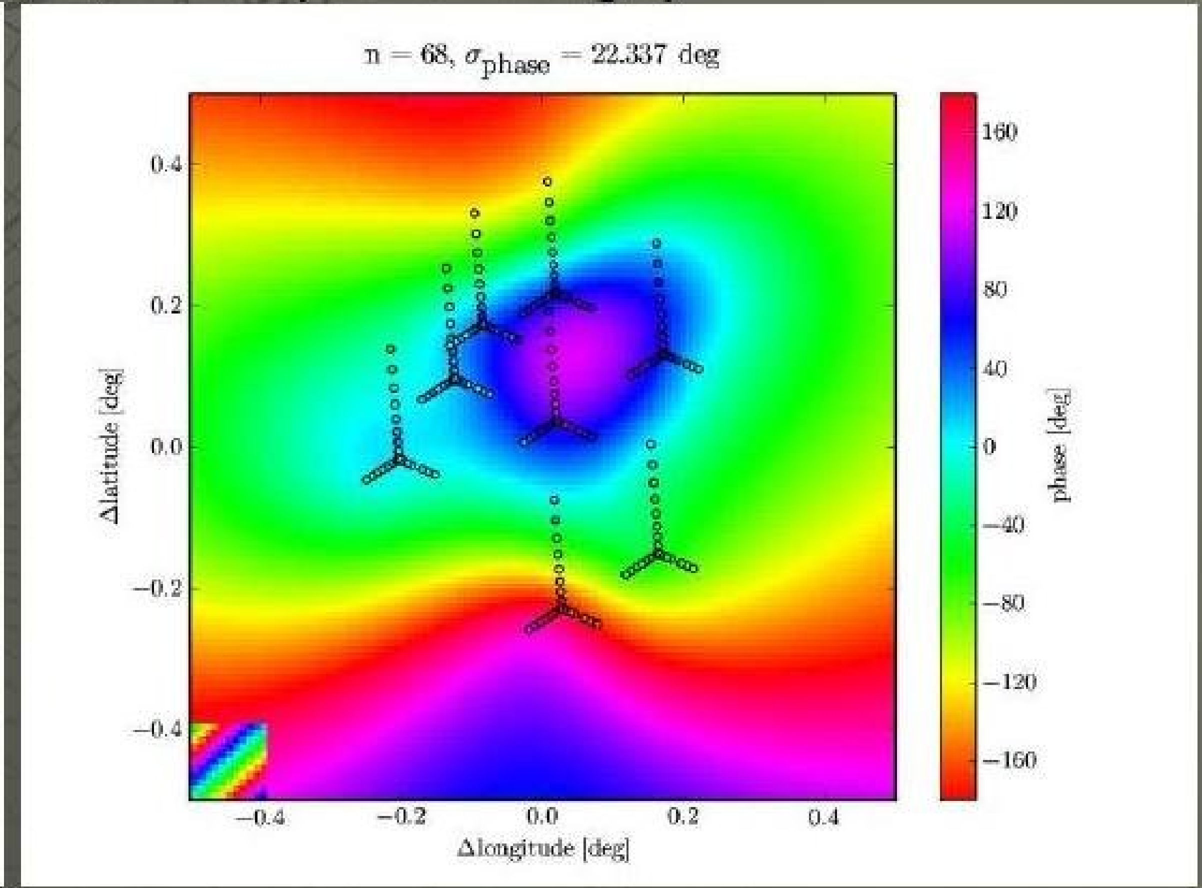
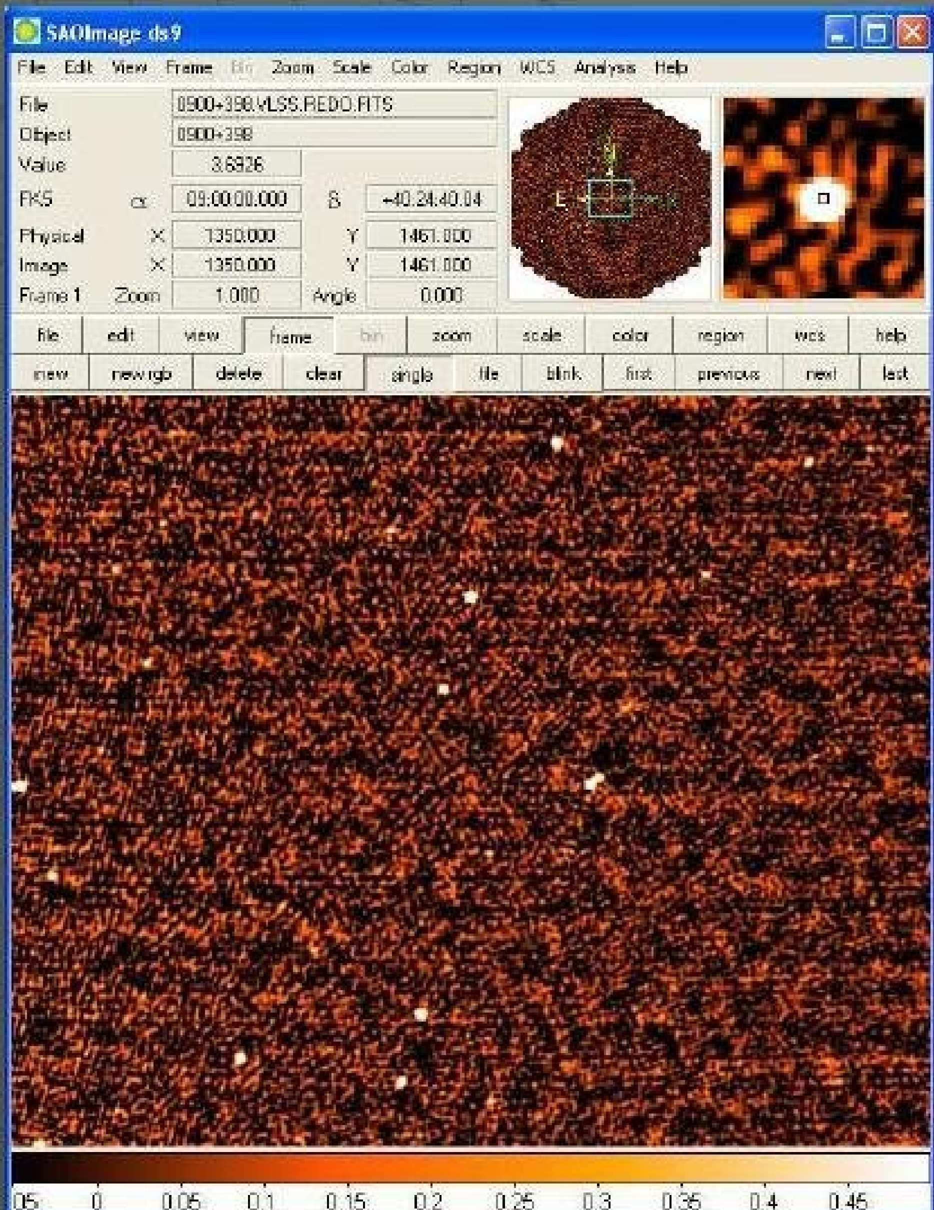
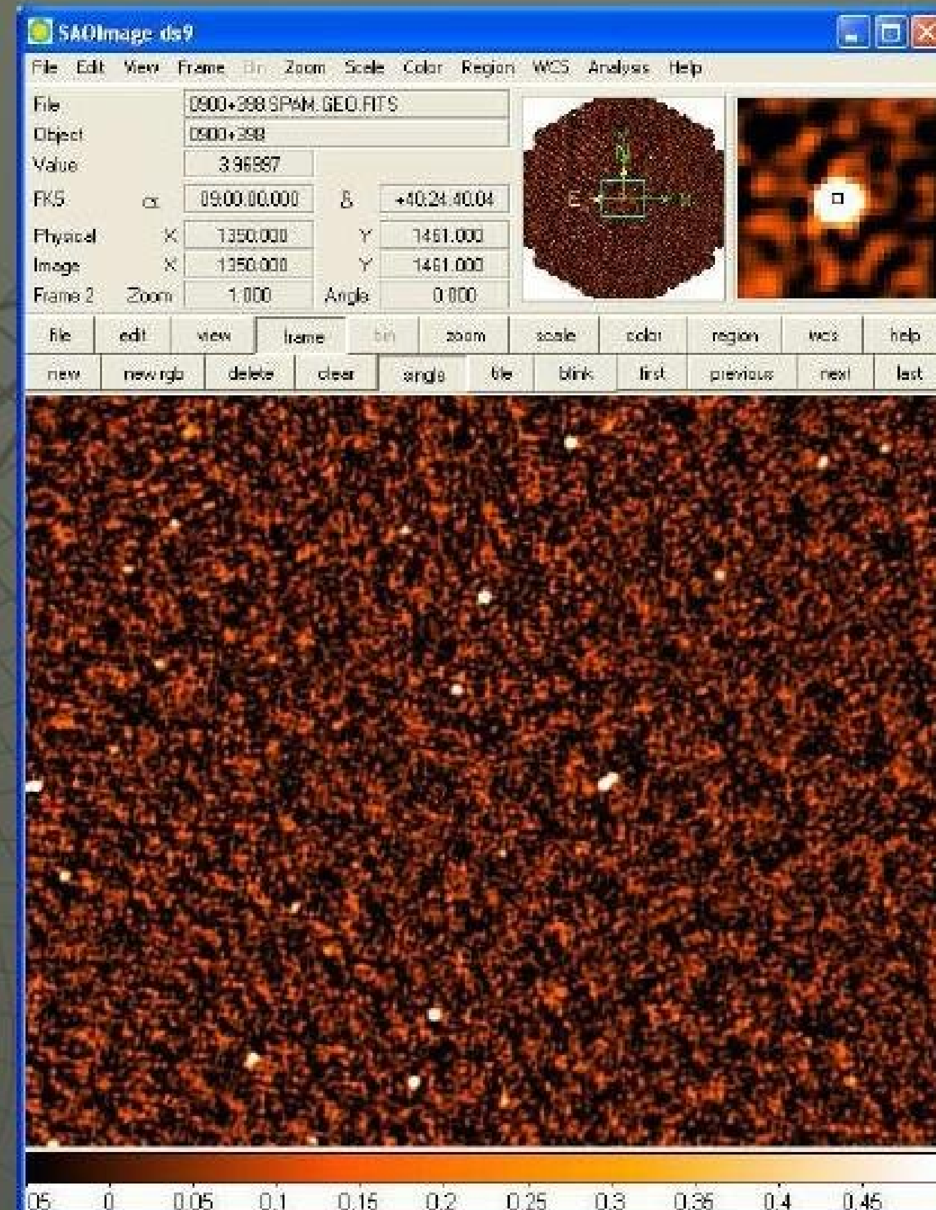


Image analysis: quiet ionosphere

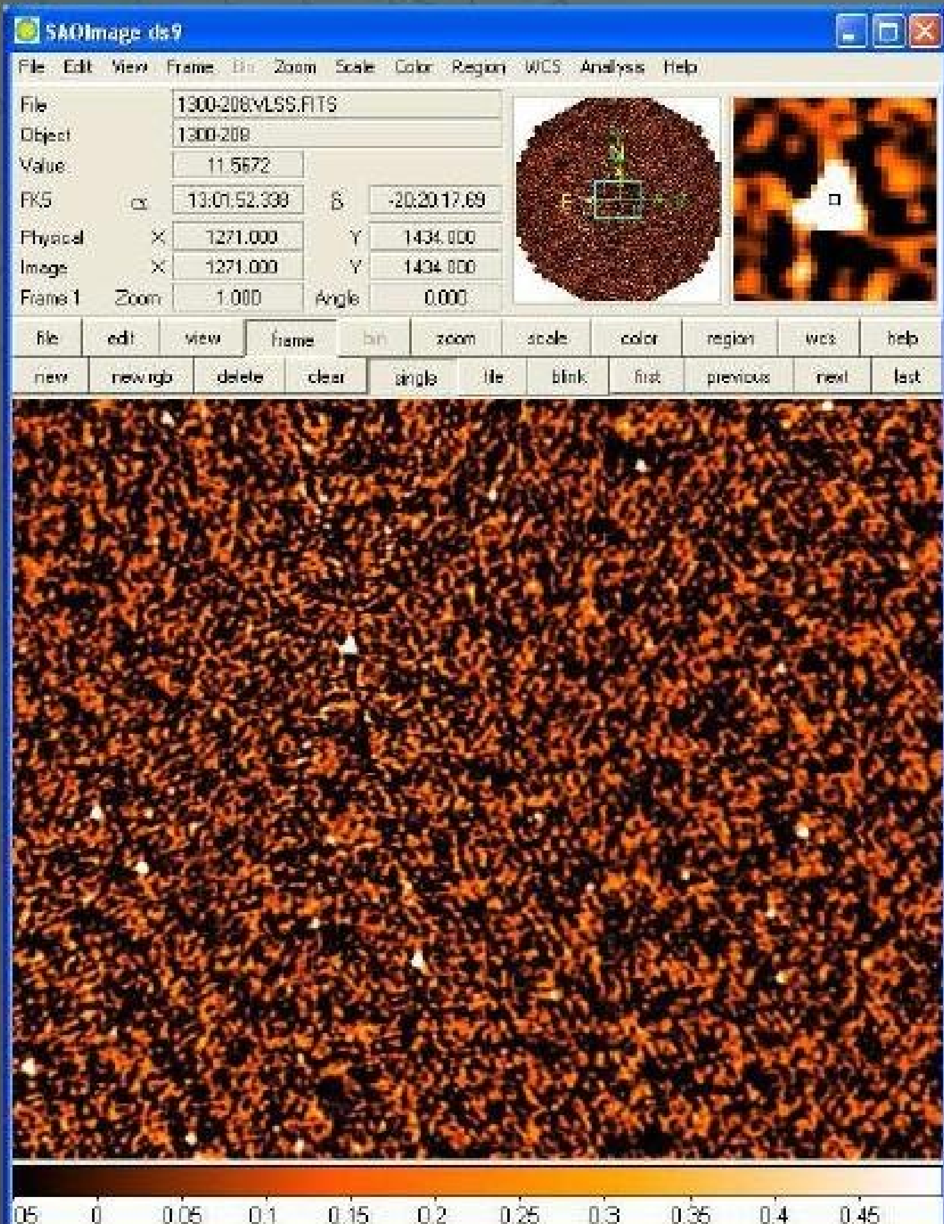


FBC

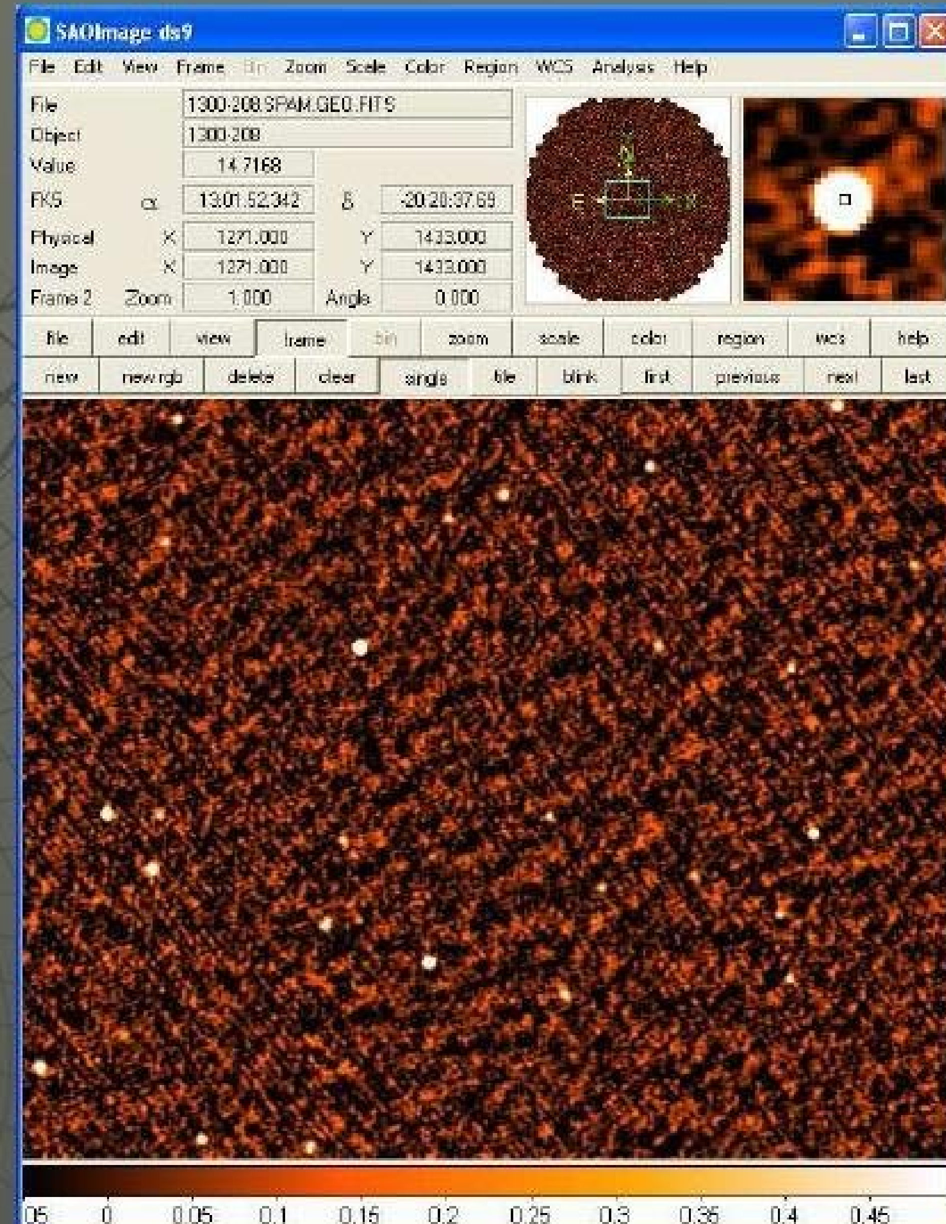


SPAM

Image analysis: worse ionosphere



FBC



SPAM

BBS Calibration Development Stages

- Currently implementing SPAM in BBS
  - 2-D ionosphere model now, fits phases
  - Easily extended to 3-D model (extra ~ 2 weeks of development time)
  - LOFAR use of SPAM intended as temporary solution to get LOFAR going while more complicated algorithms are coded
  - SPAM requires initial calibration from somewhere ...
- Long-term algorithm development will fit ionospheric TEC directly to observations
- Minimum Ionosphere Model (MIM, Noordam et al.)
  - Telescope-based MIM of Noordam fully generalized, and easy to transform results for application of calibration
  - 3-D ionosphere-based MIM of Anderson more complicated to apply to observations, but easier to apply ionospheric physics

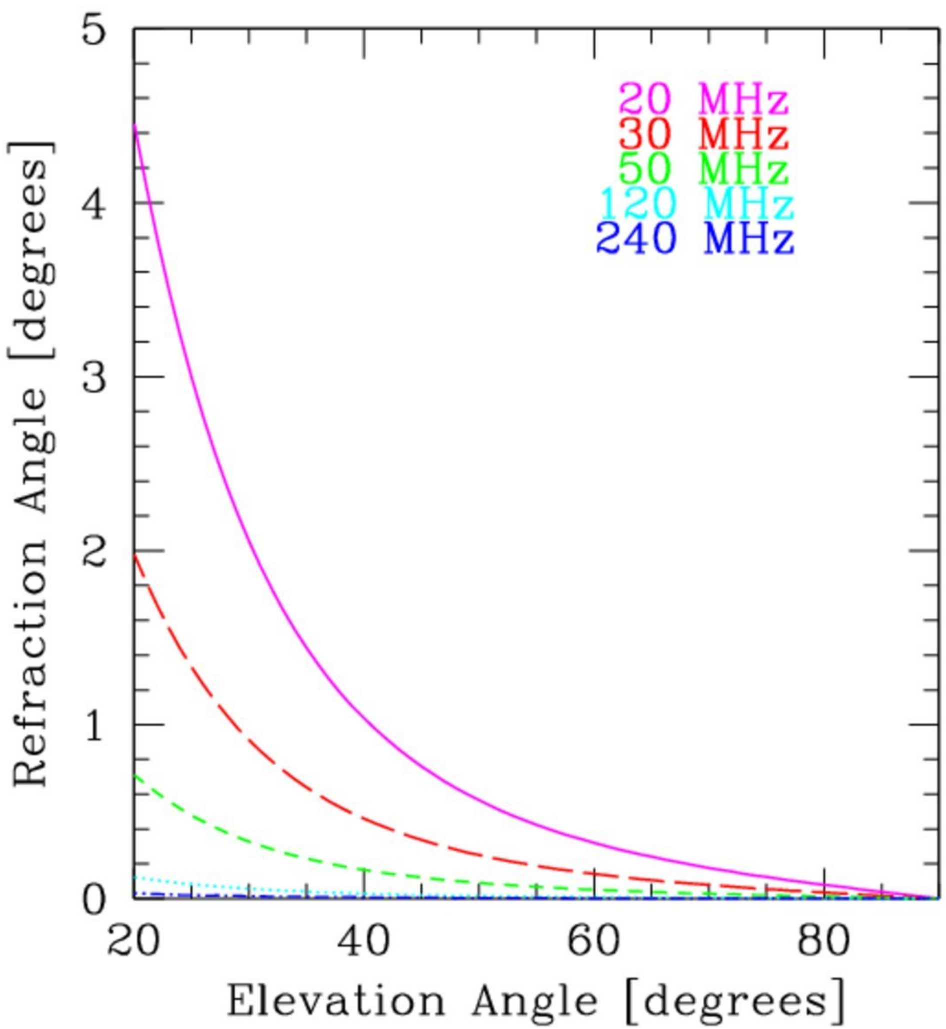
Calibration Details (Future Development)

- 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)

Outline: LOFAR (Ionospheric) Calibration

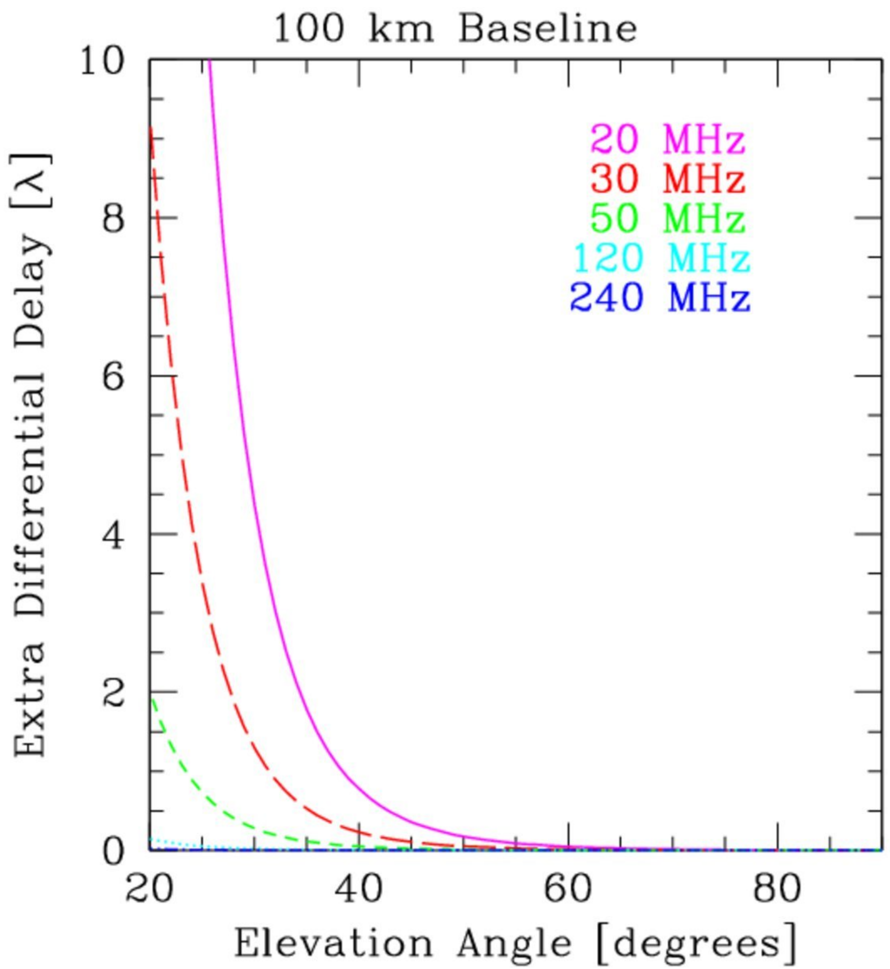
- LOFAR hardware review
- LOFAR processing software
- Sensitivity and sources
- SPAM to MIM (and more calibration terms)
- Refraction

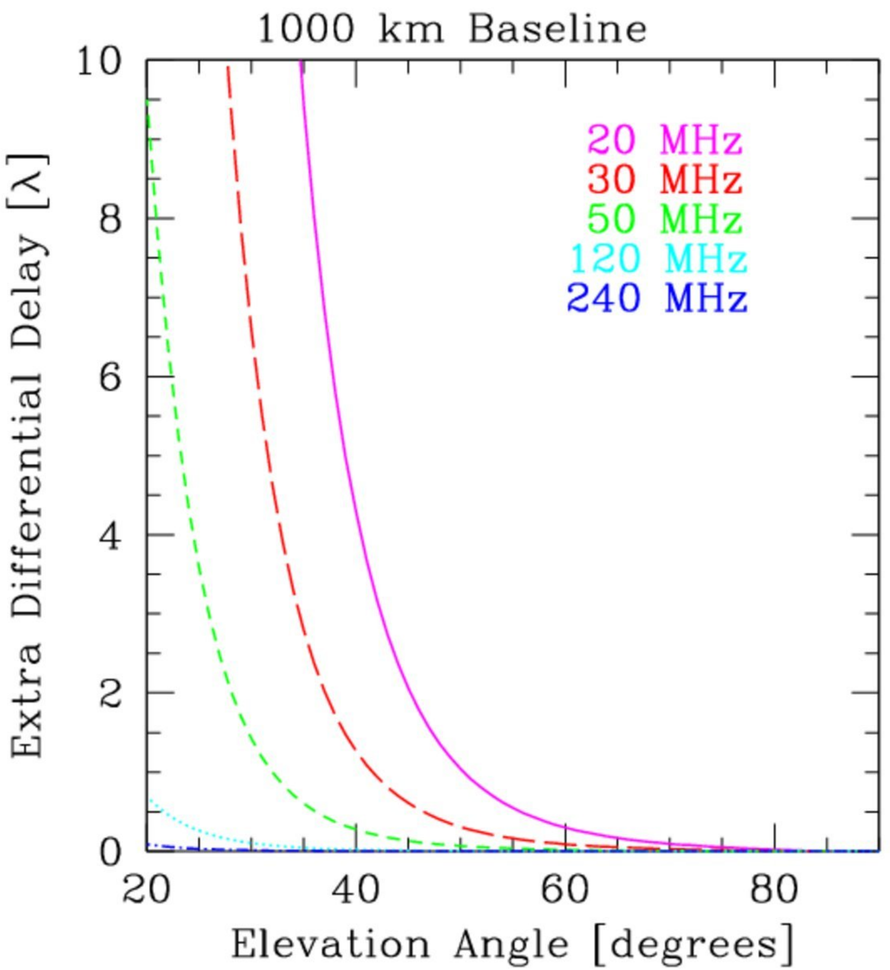
Ionospheric Refraction



- In addition to ionospheric delay and Faraday rotation, refraction is important at low frequencies
- Strongly increases toward lower frequencies
- Substantial fraction of beam FWHM at low elevations
  - Can have a significant impact on gain calibration
- To first order interferometer delays are insensitive to this, but ...

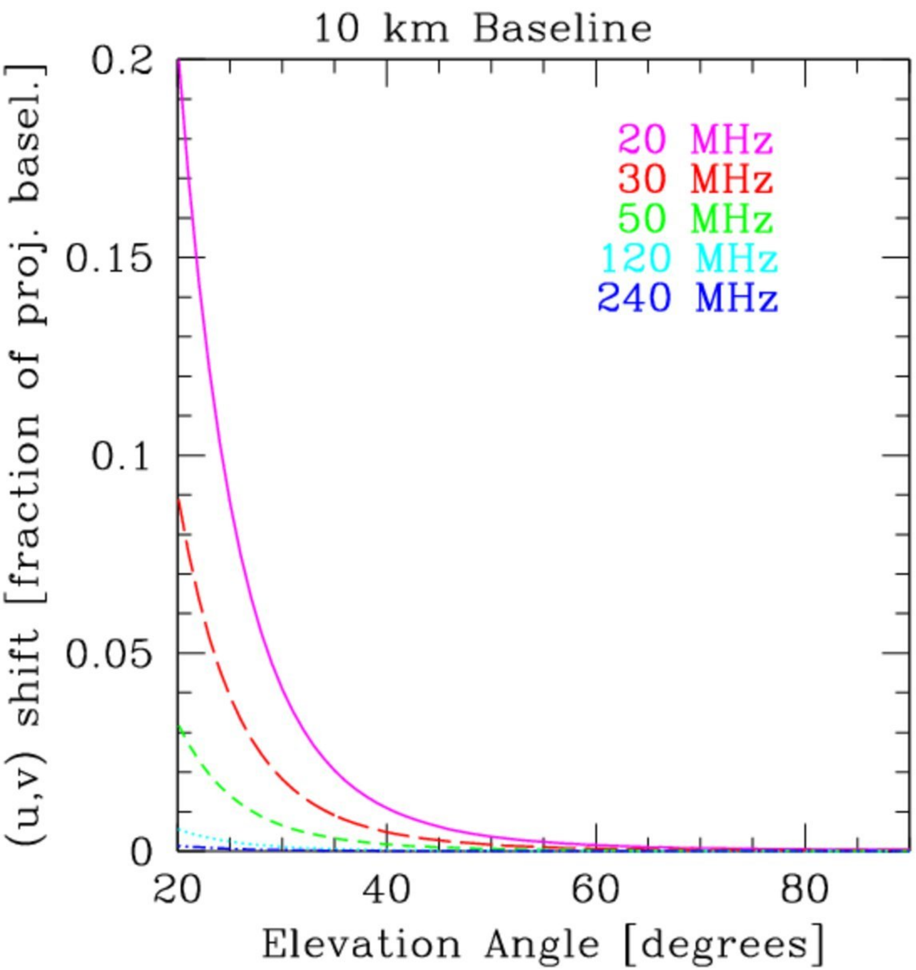
Extra Delay from Refraction

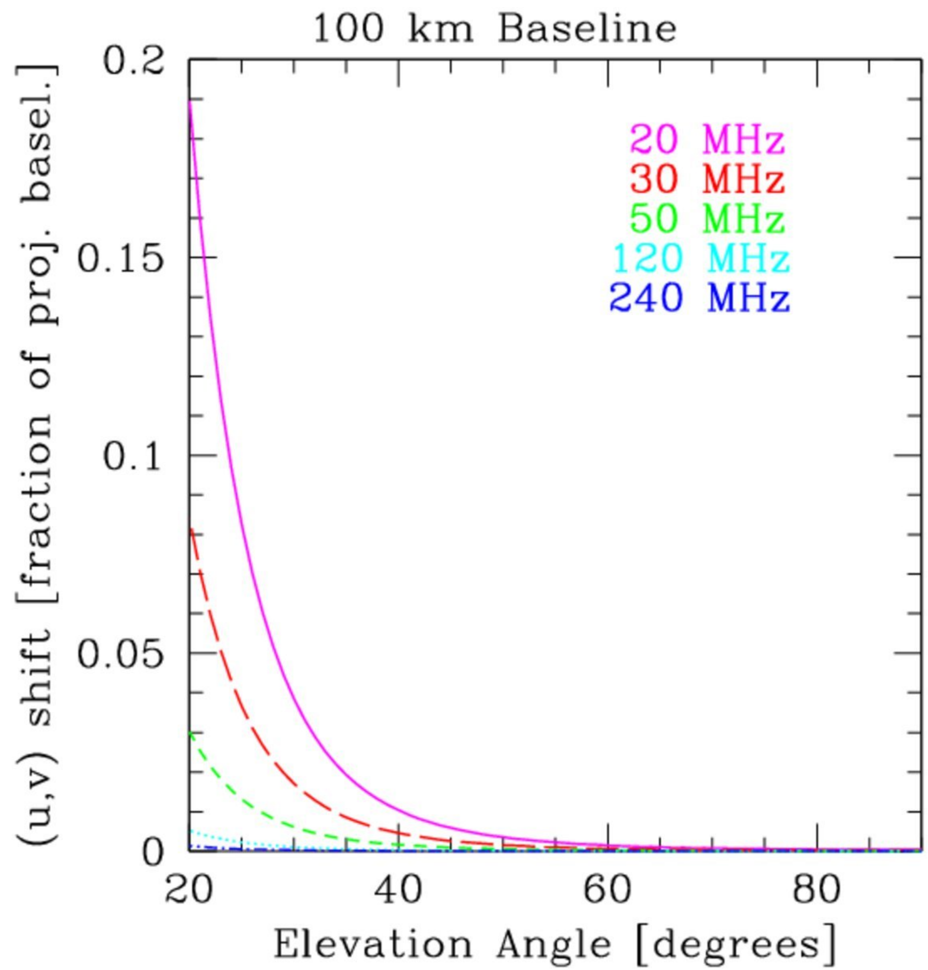




- To higher order, ionospheric refraction is important
- Bent path delay does not follow standard ionospheric path delay ν^{-2} relationship --- extra calibration challenge

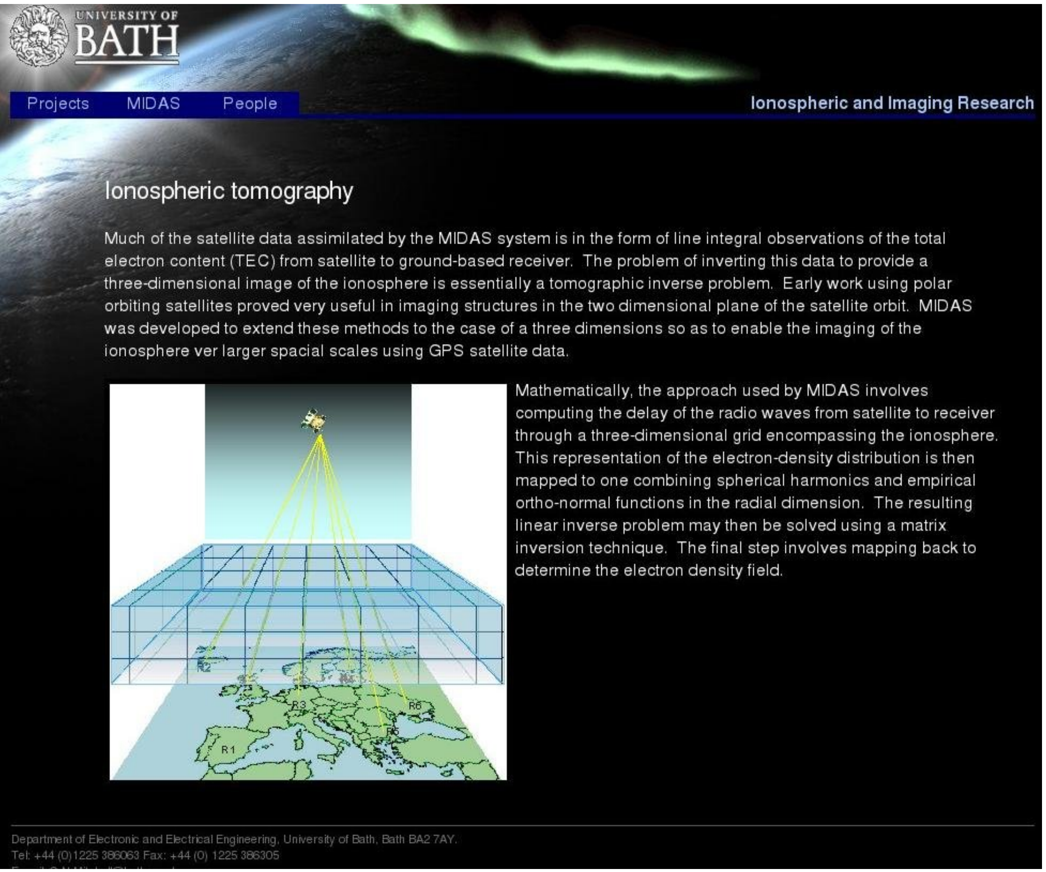
Station Position Shift by Refraction





- Ray path outside of Earth's atmosphere is different
- (u,v) coordinates are different from simple geometric prediction
- Fractional (u,v) difference can be many percent, even on short baselines

Need to Bring In Ionospheric Scientists



- More work here than we can deal with
- Need help inverting measurements to electron content
  - Refraction, absorption, etc.
- LIONS working with different ionospheric groups
  - LOFAR calibration will eventually use realtime GPS-based 3-D ionosphere models from MIDAS
- Special joint session at URSI GA on Thursday afternoon

Final Thoughts
(Or, Other Random Topics for Discussion)

- Adopting common terminology useful
- What software packages are being used?
  - Any hope of adopting common basic libraries (casacore)?
- File formats
  - FITS-IDI needs some updating for aperture arrays (phased arrays and focal-plane arrays). Please contact me if you are interested in working out some of the details.
  - LOFAR also re-examining our image storage format
  - LOFAR will probably use HDF5 internally, not FITS or aips++ measurement sets.
    - But we are aiming to adhere to a common information content, and will be able to produce standard (FITS?) files
- Astrophysics with E-LOFAR, Hamburg, 2008 Sep 15--19