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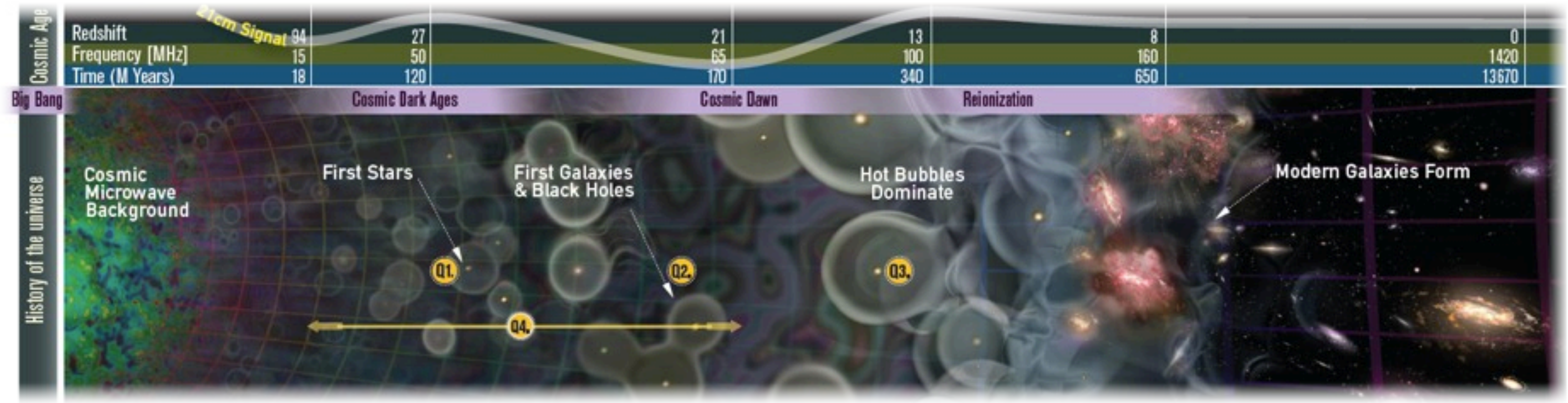
kapteyn instituut

Total Power Experiments with LOFAR

Using its full hierarchy and why it might be necessary.



Léon Koopmans
(Kapteyn Astronomical Institute)

CAASTRO EoR Global Signal Workshop - Nov 19, 2012

Current Team[s]:

Leon Koopmans, Harish Vedantham, Stefan Wijnholds, Benedetta Ciardi, Ger de Bruyn, Michiel Brentjens, ...	LOfar Cosmic-Dawn Search: LOCOS
Ralph Wijers John Swinbank [New PhD Student]	AARTFAAC
Philippe Zarka, Michel Tagger, Simon Prunet, Gilles Theureau, Julien Girard, Laurent Denis, Benoit Semelin	LSS

General Outline

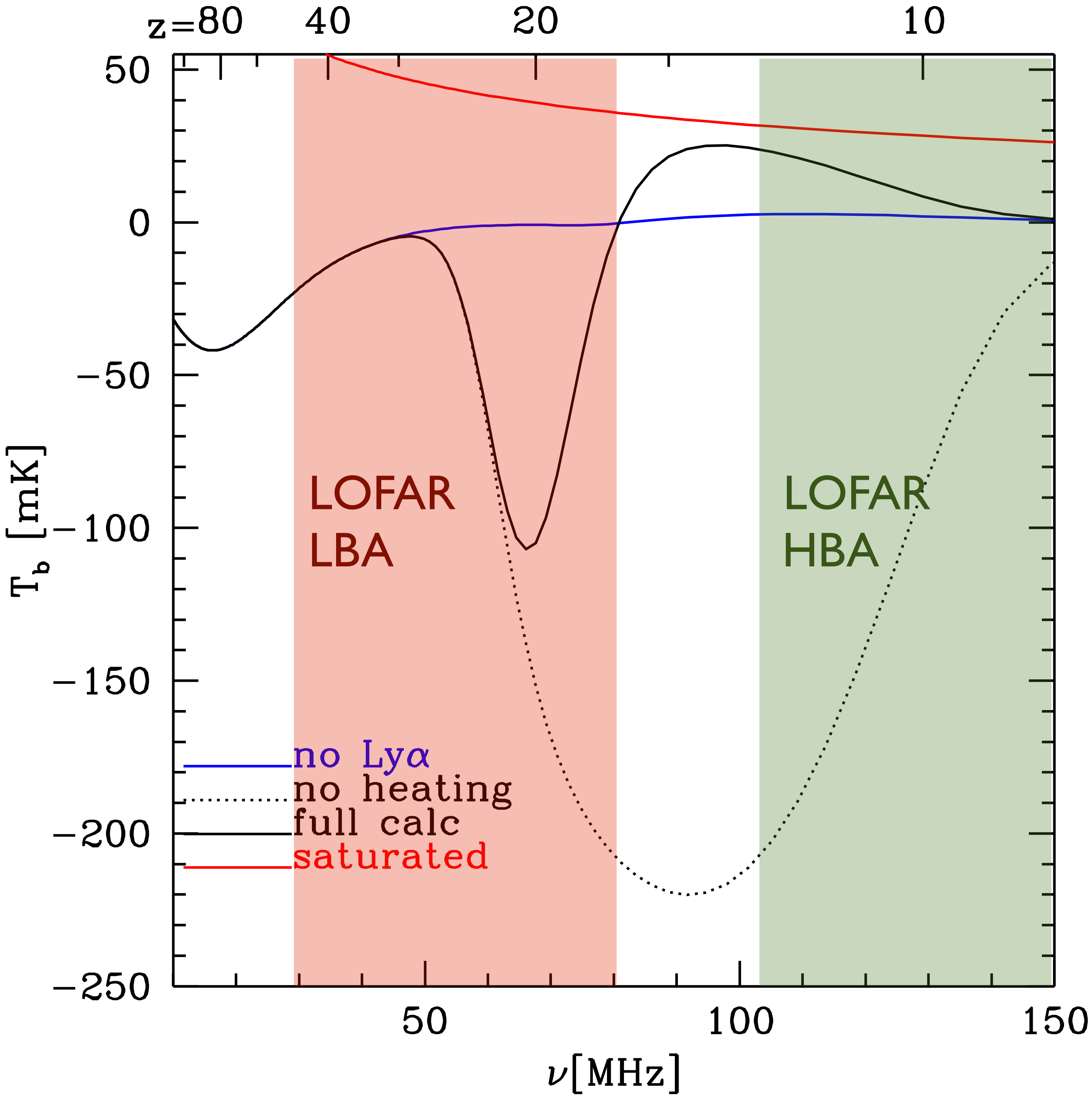
- General Goals of the

  LOfar COsmic-dawn Search
- The Low-Frequency Array (LOFAR)
- Many Challenges:

  Sky/RFI/Ionosphere/Instrument
- LOFAR - A Hierarchical Instrument
- LOCOS - Observational Goals & Strategy

  - Pilot results/Data/Lessons Learned
- LOFAR Superterp (AARTFAAC)
- LOFAR Super Station (LSS)
- Future developments

The Global Signal of Neutral Hydrogen



The physical processes during the Dark Ages, Cosmic Dawn and EoR are poorly known.

Whereas LOFAR-HBA can study the EoR, the Cosmic Dawn can only be studied with the LOFAR-LBA or other instruments

Adapted from Pritchard

General Goals of LOfar COsmic-dawn Search

- Chart all observational, data processing, calibration and signal-extraction issues associated with global HI-signal measurements using LOFAR and its extensions (i.e. AARTFAAC and LSS).

- Measure/constrain the shape of the redshifted 21-cm line intensity as function of frequency/redshift from $z{\sim}6$ to $z{\sim}45$ (ν=200-30 MHz).

- Compare this "spectrum" to theoretical models during the [Dark Ages], Cosmic Dawn & EoR.

- Constrain the (astro)physics of the first stars/BHs, test effects of bulk-flows at recombination, test cosmological models and particle/dark-matter physics.

LOFAR/LOCOS - Challenges

- Signal-to-noise from z=6 to z=30
- Radio Frequency Interference [Internal+External] (see talk Offringa)
- Chromatic sky (spectrum varies with position) (see talk Vedantham)
- Ionospheric refraction and diffraction (see talk Vedantham)
- Chromatic beam (see talk Vedantham)
- Mutual Coupling
- Time-varying instrument - Receiver gains/beams?
- Time-varying sky - Rotation/Variable sources
- Receiver gain - Bandpass calibration
- Receiver temperature - Noise mimicking signal

The Low-Frequency Array

The Low Frequency Array

LOFAR is a fully European radio telescope with its core in the Netherlands
(i.e. Netherlands, Germany, UK, France & Sweden; interests in Italy, Poland, Spain, Austria+Ukraine)

Core	2 km	2x24 stations
NL	80 km	14 stations
Europe	>1000 km	8+ stations

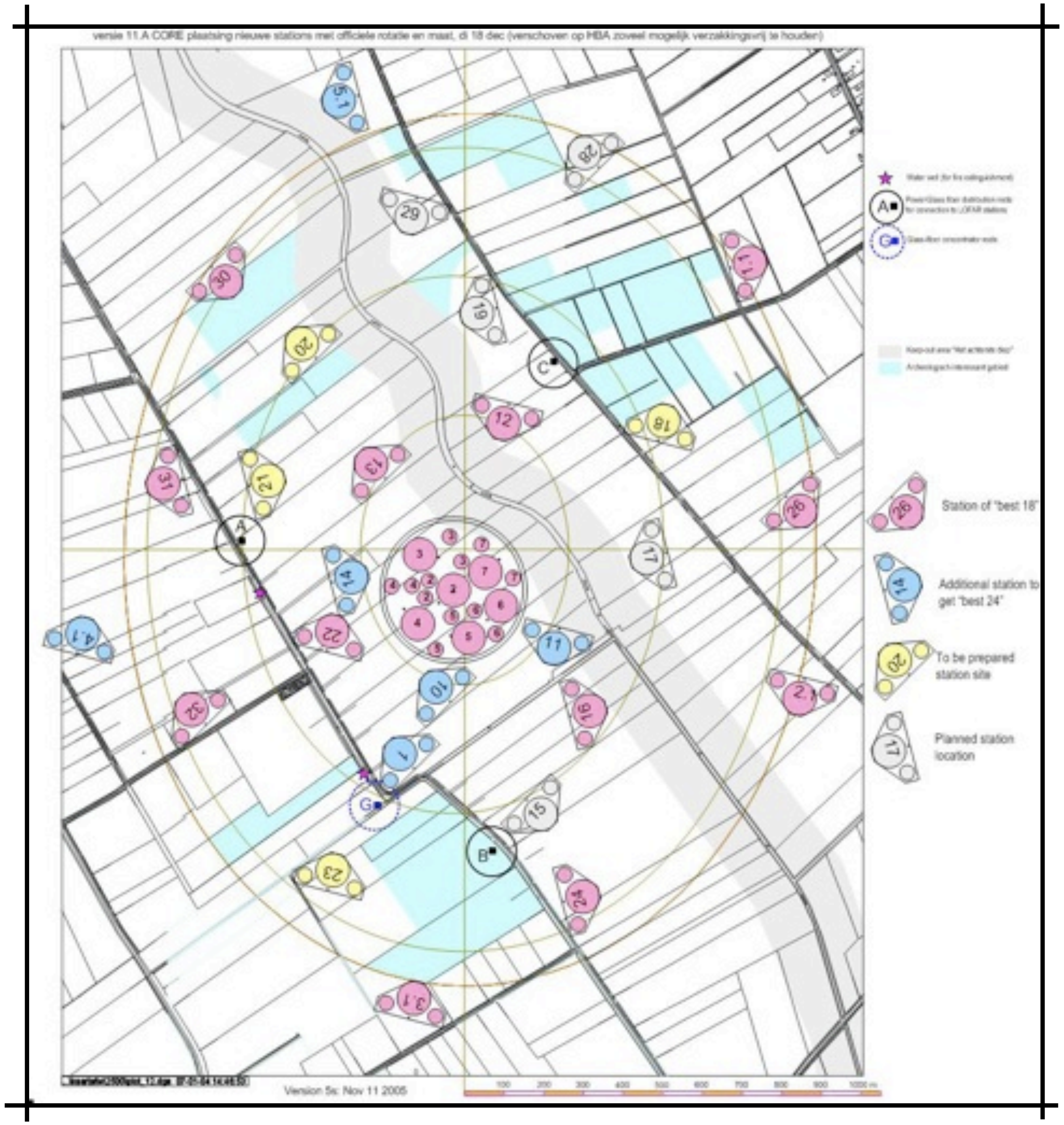
Stations have 24 – 48 – 96 antennas/tiles

Principle of Aperture Synthesis
Array resolution: sub-arcsec to degrees

Pulsars: tied-array(s), (in)coherent sums

Sensitivity (after 12h, 48 MHz)
@ 60 MHz ~ 3 mJy (LBA)
@ 150 MHz ~ 0.1 mJy (HBA)

The Low Frequency Array



Core area - 2 km near Exloo

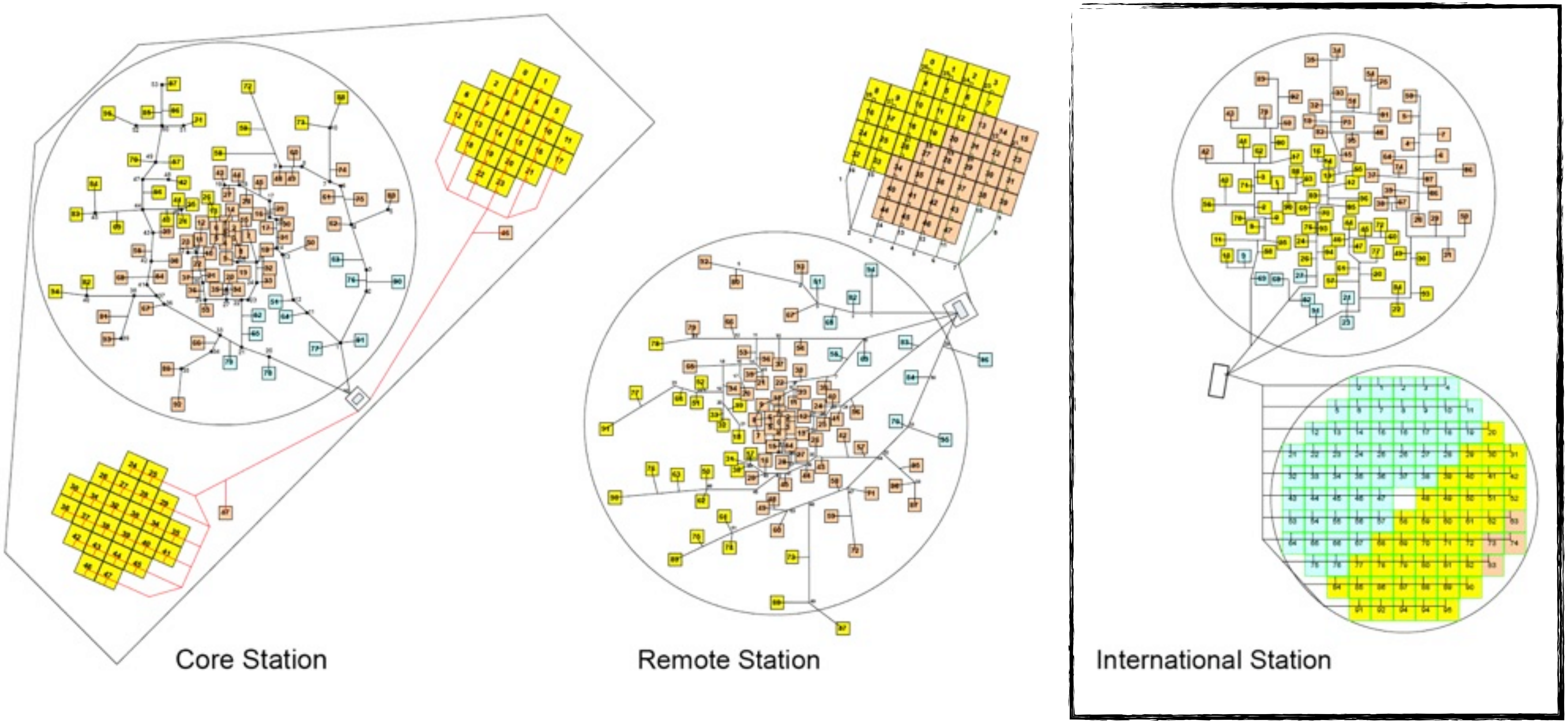
– 24 stations while preparing for more (note HBA stations are split in two micro-stations)

- Goal is to have dense UV-coverage to probe all scales on the sky with few arcmin to few degree resolution at 150 MHz.

- Genetic Algorithms were use to optimize UV coverage under pre-conditions.

- Area will become nature-reserve.

The Low Frequency Array



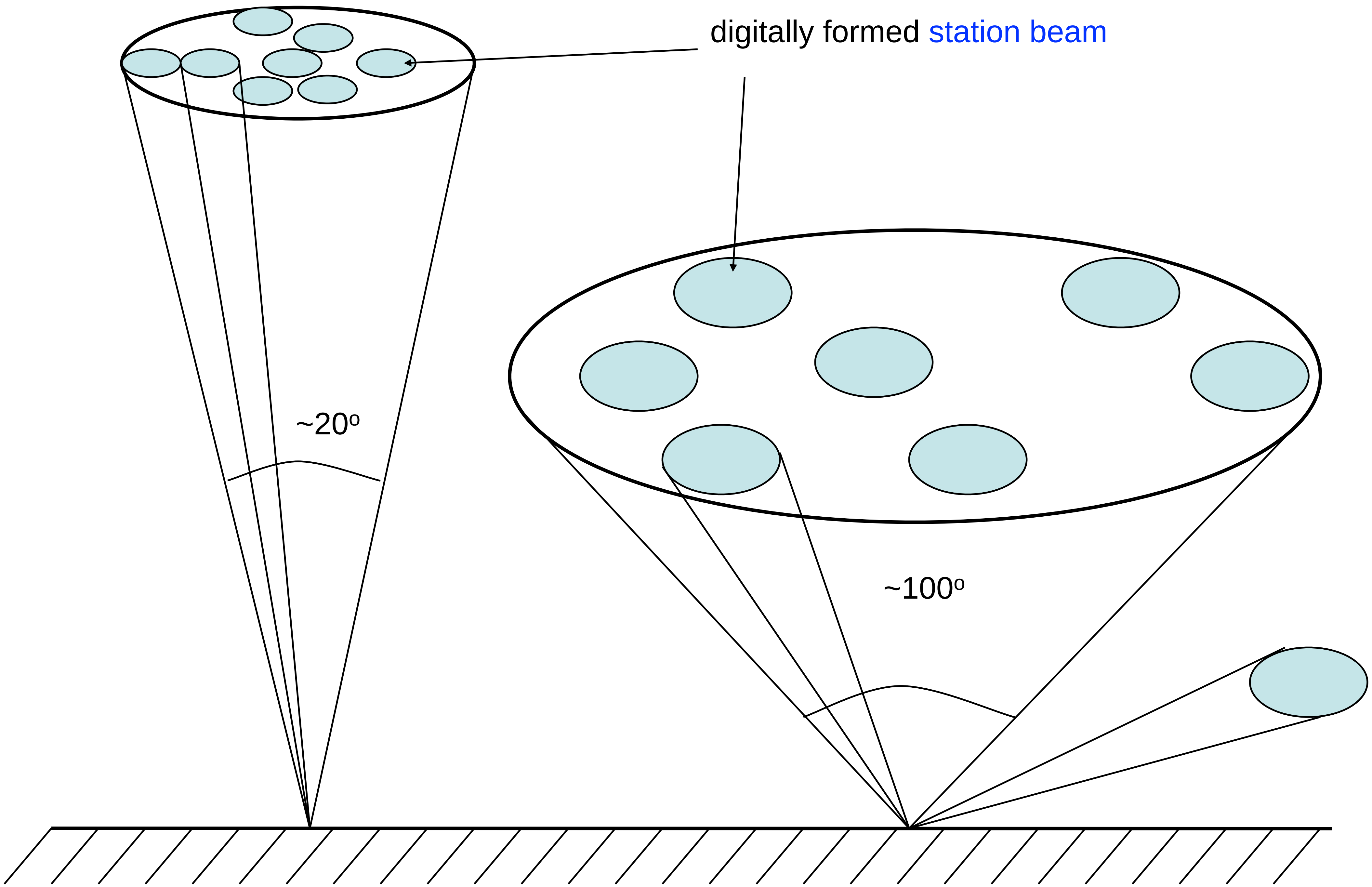
Low Band Antenna

- (10) 30MHz - 80 MHz
- 96 dipoles per station
- within NL only 48 can be used at a time

High Band Antenna

- 115 MHz - 240 MHz
- 1 tile = 4 x 4 antennas
- 48 tiles per station (within NL) or 96 tiles

The Low Frequency Array

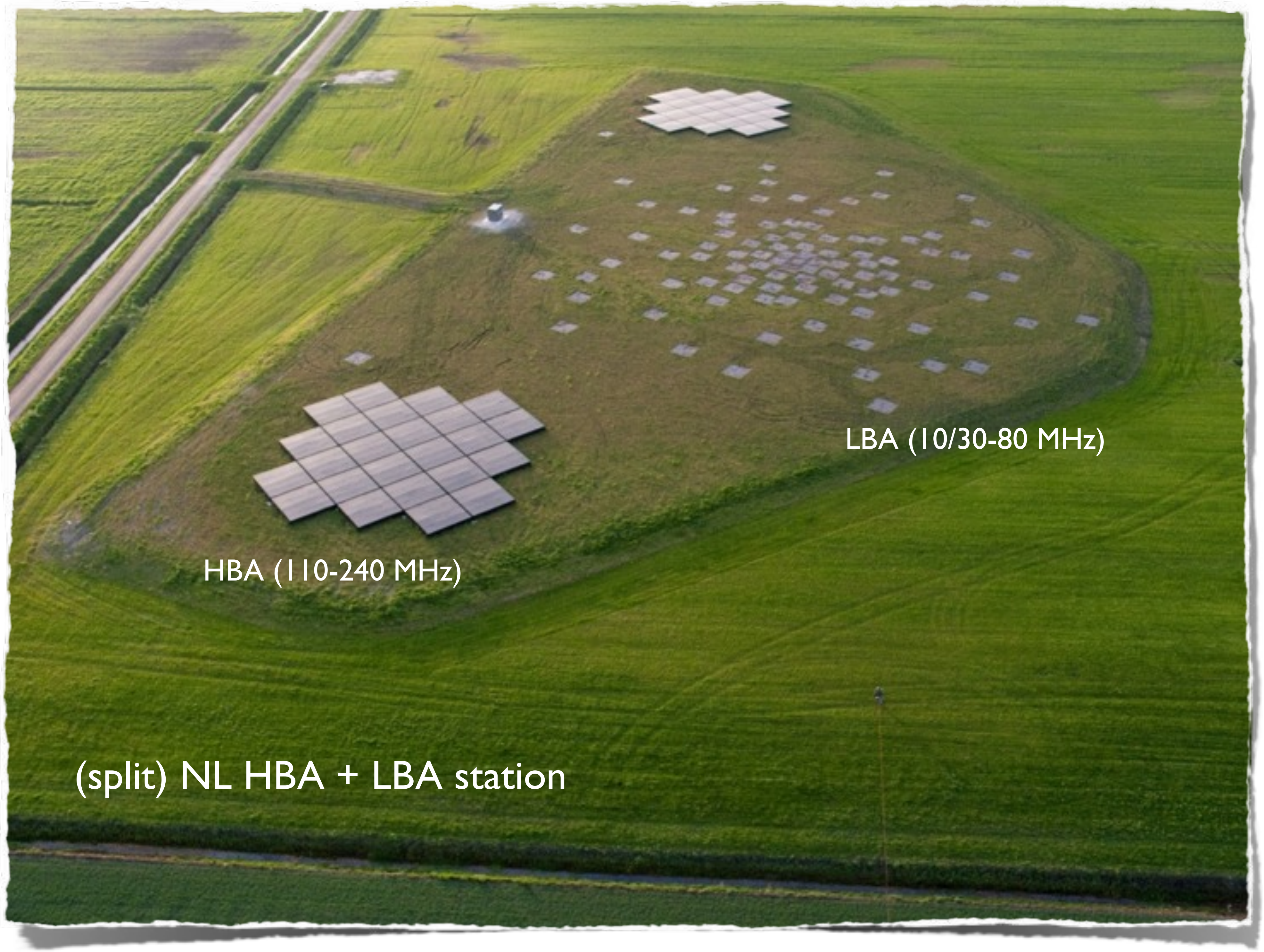


HBA tile beam

(analog beamformer, 5-bit delay)

LBA dipole beam

The Low Frequency Array



The Low Frequency Array

“Superterp” aka “Six-pack”
6 densely packed stations

Current Status of LOFAR and of the LOFAR EoR Key Science Project

The LOFAR EoR Key Science Project

Current status LOFAR-HBA imaging mode

- 48 Core + 12(+4) Dutch Remote + 8 EU Remote Stations ready
- 96 MHz*Beams (8-bits); e.g. 2x48MHz beams, 3x32MHz beams, etc
- New synoptics boards: improved phasing (2xS/N) + common clock core

- Current sensitivity (Nov. 2012): ~50 μJy/beam/48MHz (core+remote)
  [12hrs] ~100 μJy/beam/48MHz (core)
  ~ 700 μJy/beam/1MHz (core)
  ~ 700 mK/beam/1MHz (core)

- Data volume: 50-100 TB/12hrs; (semi)real-time processing needed!

The LOFAR EoR Key Science Project

Before continuing with LOCOS, and update on the LOFAR EoR-KSP
[LOCOS is under the KSP umbrella]

Current status EoR KSP:

- Use full Dutch array at 1sec-0.76KHz resolution: 50-100 TB/12hrs
- Real-time correlation w/IBM BlueGene supercomputer
- Flagging+Preprocessing using CEP Offline Cluster (data-averaging)
- Data-transport via LTA to dedicated EoR CPU-GPU/Cluster
  (I/O: 20 GBit/sec; 160GPUs=160 TFlops; 640 CPUs= 5Tflops 0.5PB HD; 1TB mem)
- Processing 2x12hrs in ~ 3 days on 2x30 out of 80 nodes:
  full directionally-dependent calibration [~500 directions]
  for 240 subbands [200 KHz each]
- Extension of cluster planned in 2013 w/latest GPUs [8.5x faster]

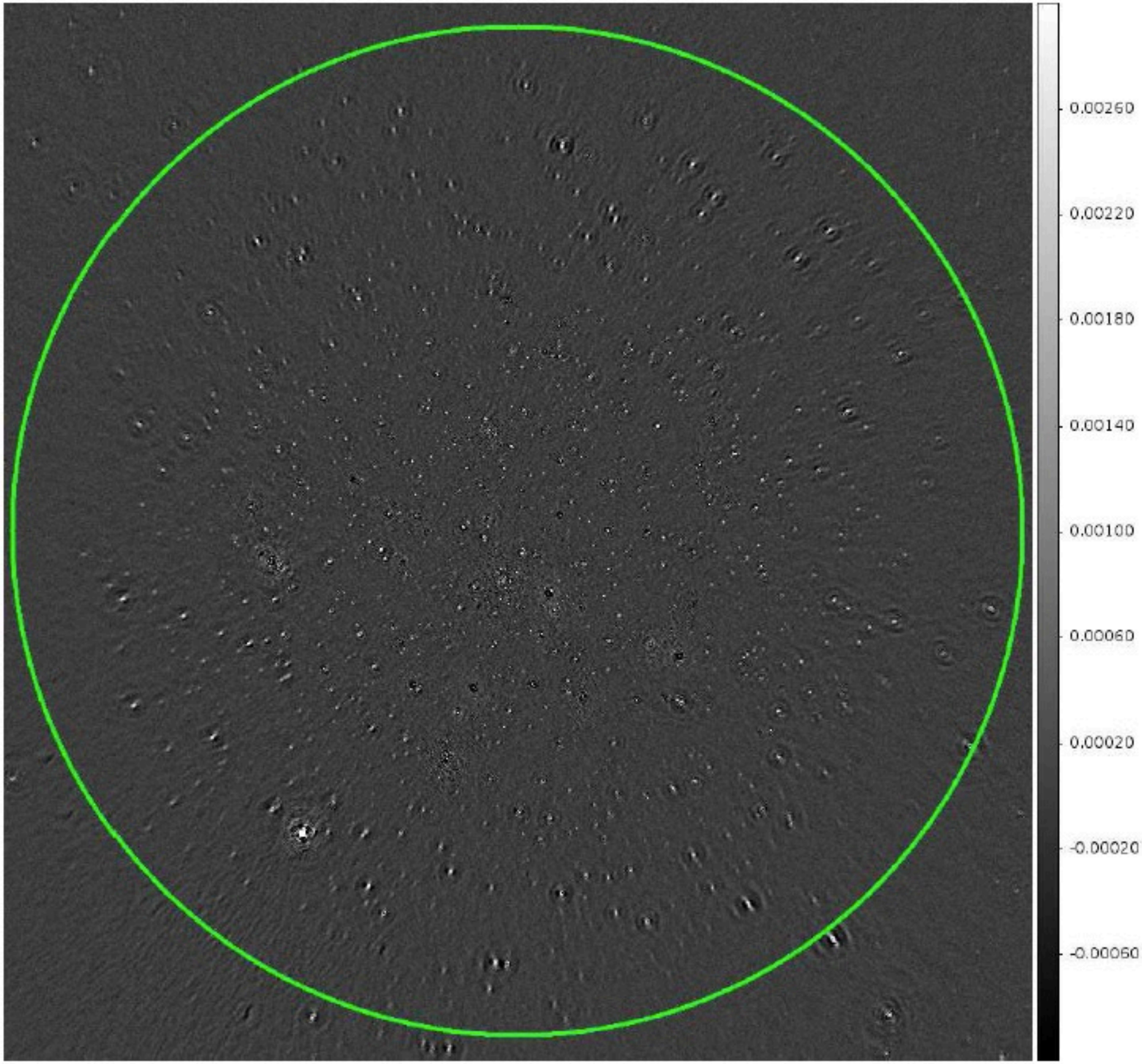


Fig. 9. The NCP image after multi-directional calibration and source subtraction using `SAGECal`. The skymodel is restored onto the image. The circle indicates an area of diameter 10 degrees. The image has 12000 × 12000 pixels of size $4''$ and the noise level is about 100 μJy. Due to frequency smearing, the sources at the edge of the image appear 'attracted' towards the center. The colourbar units are in Jy/PSF.

NCP with all Dutch baselines included and DD calibration for several hundred directions

Yattawatta et al. 2012, submitted

The LOFAR EoR Key Science Project

Current Observational Status EoR KSP:

- Cycle 0 - KSP started observing in Oct. 2012
- Requested 800hrs; currently approved ~600hrs
- Depth ~200 muJy/beam for core; half that for full array

  [current array is ~2x better due to improved beam forming]

Based on current depth and very conservative scaling, we expect at k=0.1, 150MHz, dk=k per 1MHz per 12hr:

$$\Delta^2_{21} \sim \frac{10^4 \ \mathrm{mK}^2}{B_{\mathrm{MHz}}\, \tau_{\mathrm{12hr}}}$$

- After 600 hr we should should reach <20 mk^2, well below the theoretically expected signal at z=10 in single beam/field.

Challenges for (non)Global HI Detection Experiments

Sky, Beam, RFI, Mutual Coupling, [Ionosphere]

Signal-to-noise @ z=20

$$\boxed{t_{\rm int} = 17\ {\rm hr} \times f_{\rm rec}^{-2} \left(\frac{\nu}{70\ {\rm MHz}}\right)^{-5.1} \left(\frac{\Delta\nu}{1\ {\rm MHz}}\right)^{-1} \left(\frac{\delta T}{10\ {\rm mK}}\right)^{-2}}$$

This eqn provides the required integration time to reach a given brightness temperature error at a given frequency, for a given bandwidth and receiver filling factor. This temperature is valid for the receiver beam area (i.e. large for a dipoles, much smaller for the stations or a sparse array)

f=1.0	for LBA dipole
f~0.06	for LBA station
f~0.03	for LBA superterp
f~0.005	for LBA core

Using more-filled beams increases S/N, but might make calibration harder!

Dilemma! Hierarchical strategy is needed.

The RFI Environment

RFI - environment: A problem?

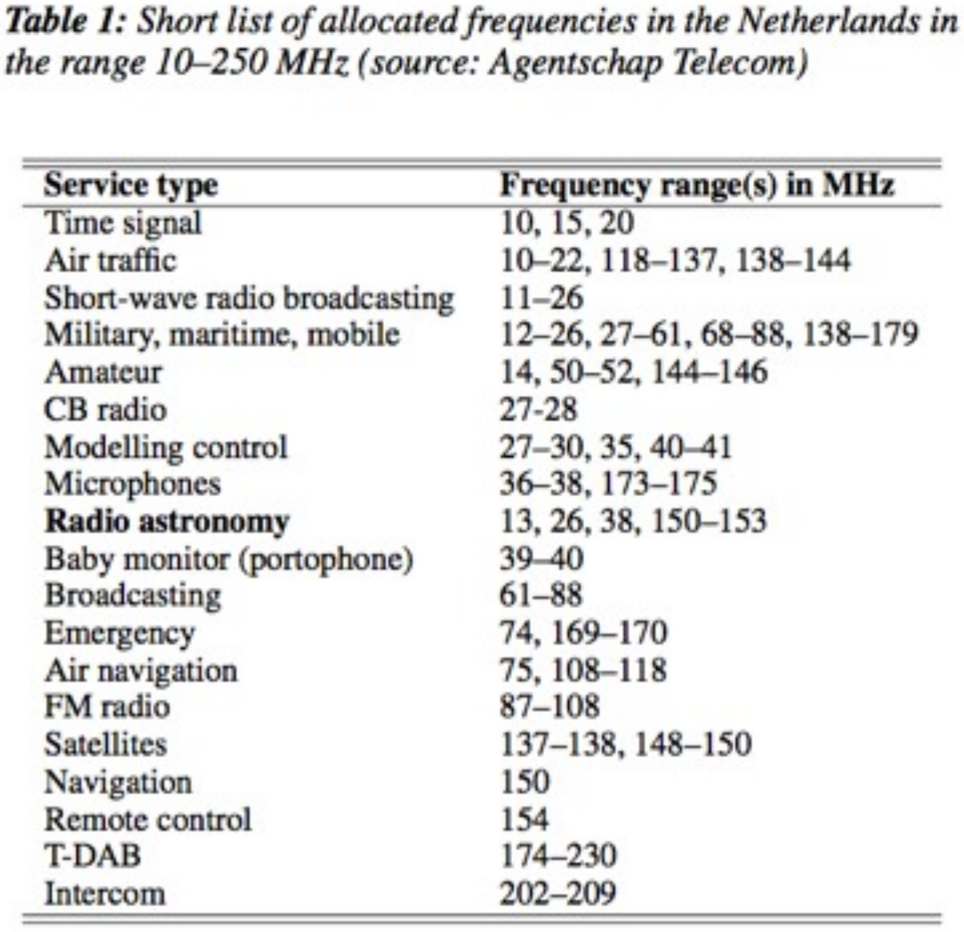


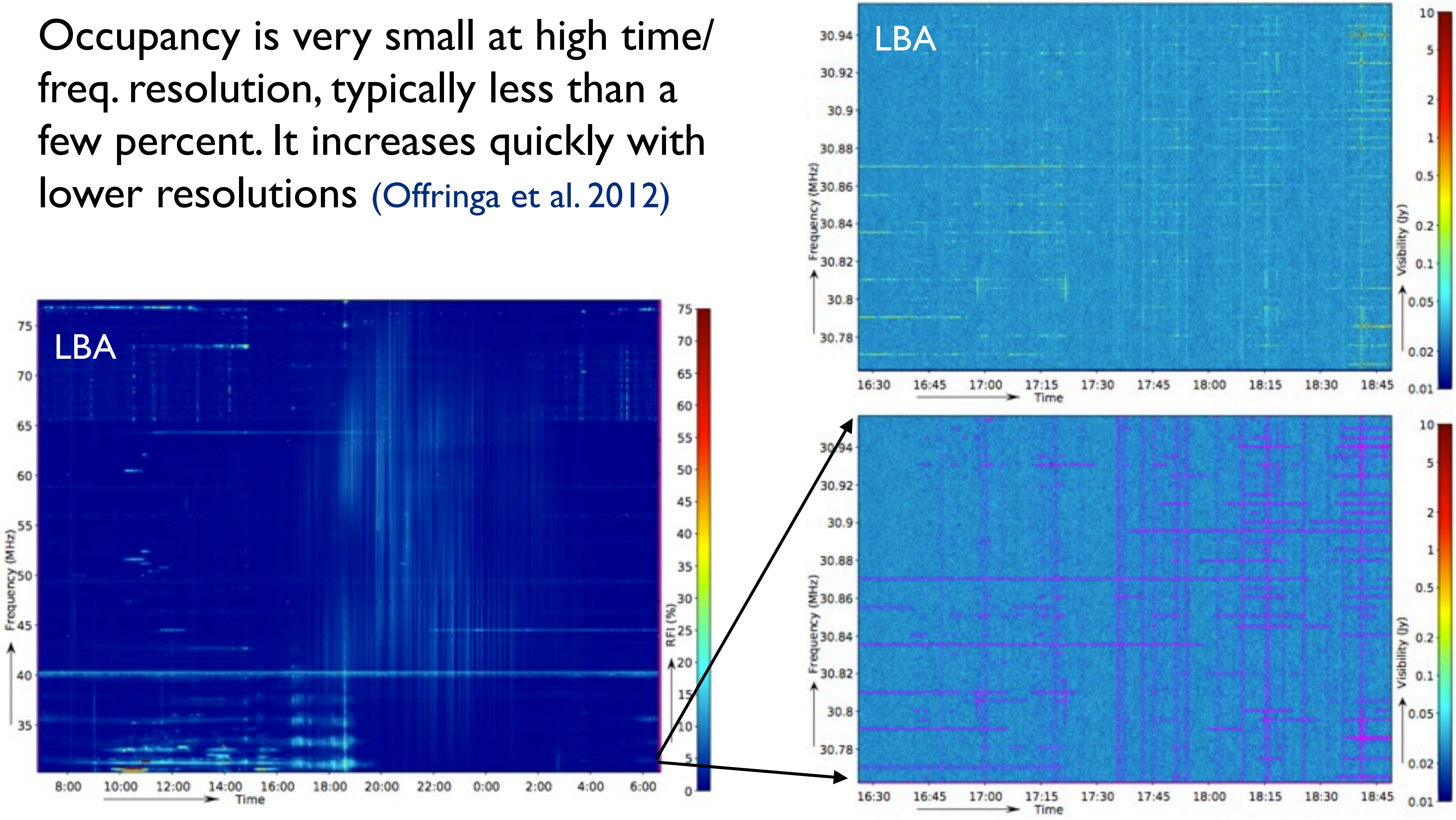
Table 1: Short list of allocated frequencies in the Netherlands in the range 10–250 MHz (source: Agentschap Telecom)

Service type	Frequency range(s) in MHz
Time signal	10, 15, 20
Air traffic	10–22, 118–137, 138–144
Short-wave radio broadcasting	11–26
Military, maritime, mobile	12–26, 27–61, 68–88, 138–179
Amateur	14, 50–52, 144–146
CB radio	27-28
Modelling control	27–30, 35, 40–41
Microphones	36–38, 173–175
Radio astronomy	13, 26, 38, 150–153
Baby monitor (portophone)	39–40
Broadcasting	61–88
Emergency	74, 169–170
Air navigation	75, 108–118
FM radio	87–108
Satellites	137–138, 148–150
Navigation	150
Remote control	154
T-DAB	174–230
Intercom	202–209

Offringa et al. (2012)

The RFI Environment

Occupancy is very small at high time/freq. resolution, typically less than a few percent. It increases quickly with lower resolutions (Offringa et al. 2012)



The RFI Environment

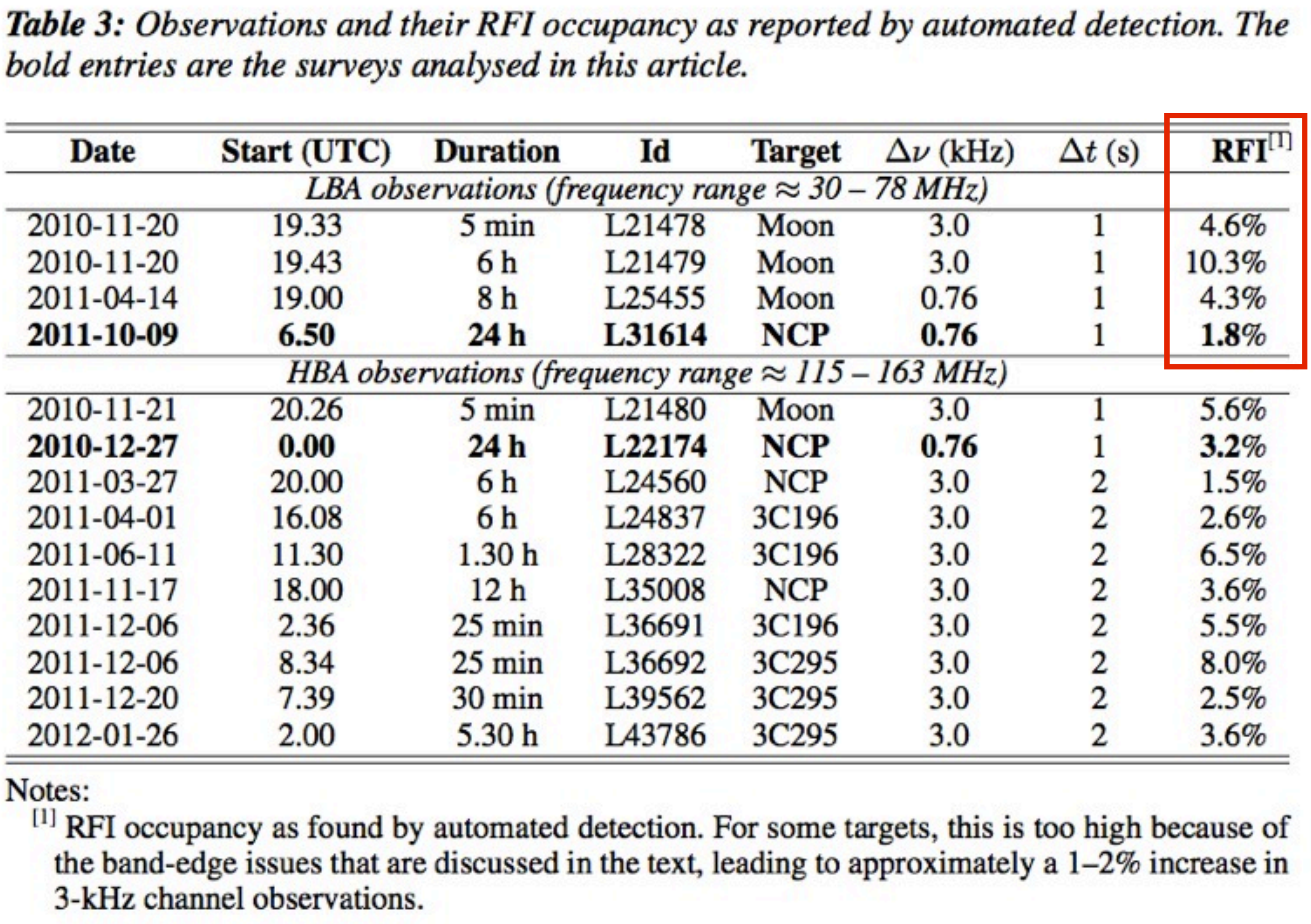


Table 3: *Observations and their RFI occupancy as reported by automated detection. The bold entries are the surveys analysed in this article.*

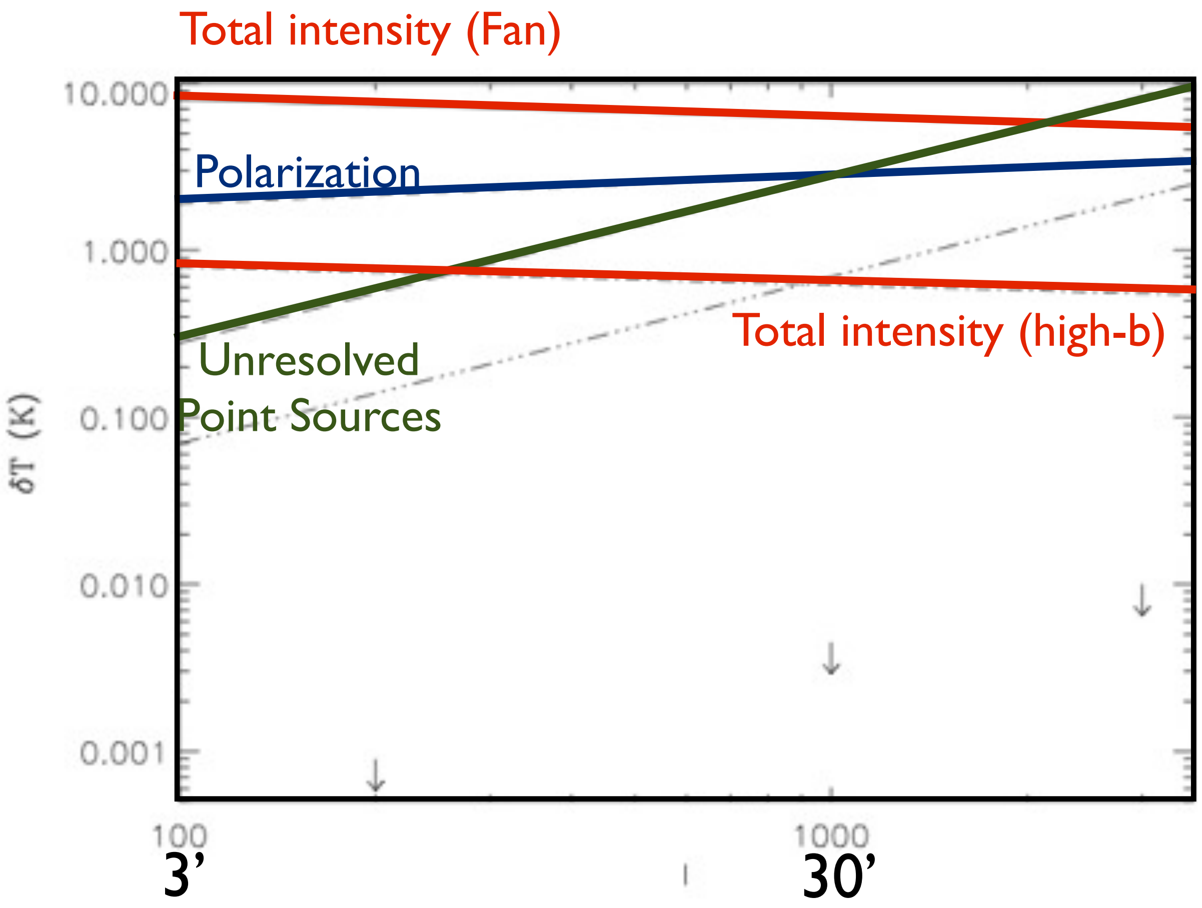
Date	Start (UTC)	Duration	Id	Target	$\Delta\nu$ (kHz)	Δt (s)	RFI[1]
LBA observations (frequency range ≈ 30 – 78 MHz)							
2010-11-20	19.33	5 min	L21478	Moon	3.0	1	4.6%
2010-11-20	19.43	6 h	L21479	Moon	3.0	1	10.3%
2011-04-14	19.00	8 h	L25455	Moon	0.76	1	4.3%
2011-10-09	**6.50**	**24 h**	**L31614**	**NCP**	**0.76**	1	**1.8%**
HBA observations (frequency range ≈ 115 – 163 MHz)							
2010-11-21	20.26	5 min	L21480	Moon	3.0	1	5.6%
2010-12-27	**0.00**	**24 h**	**L22174**	**NCP**	**0.76**	1	**3.2%**
2011-03-27	20.00	6 h	L24560	NCP	3.0	2	1.5%
2011-04-01	16.08	6 h	L24837	3C196	3.0	2	2.6%
2011-06-11	11.30	1.30 h	L28322	3C196	3.0	2	6.5%
2011-11-17	18.00	12 h	L35008	NCP	3.0	2	3.6%
2011-12-06	2.36	25 min	L36691	3C196	3.0	2	5.5%
2011-12-06	8.34	25 min	L36692	3C295	3.0	2	8.0%
2011-12-20	7.39	30 min	L39562	3C295	3.0	2	2.5%
2012-01-26	2.00	5.30 h	L43786	3C295	3.0	2	3.6%

Notes:

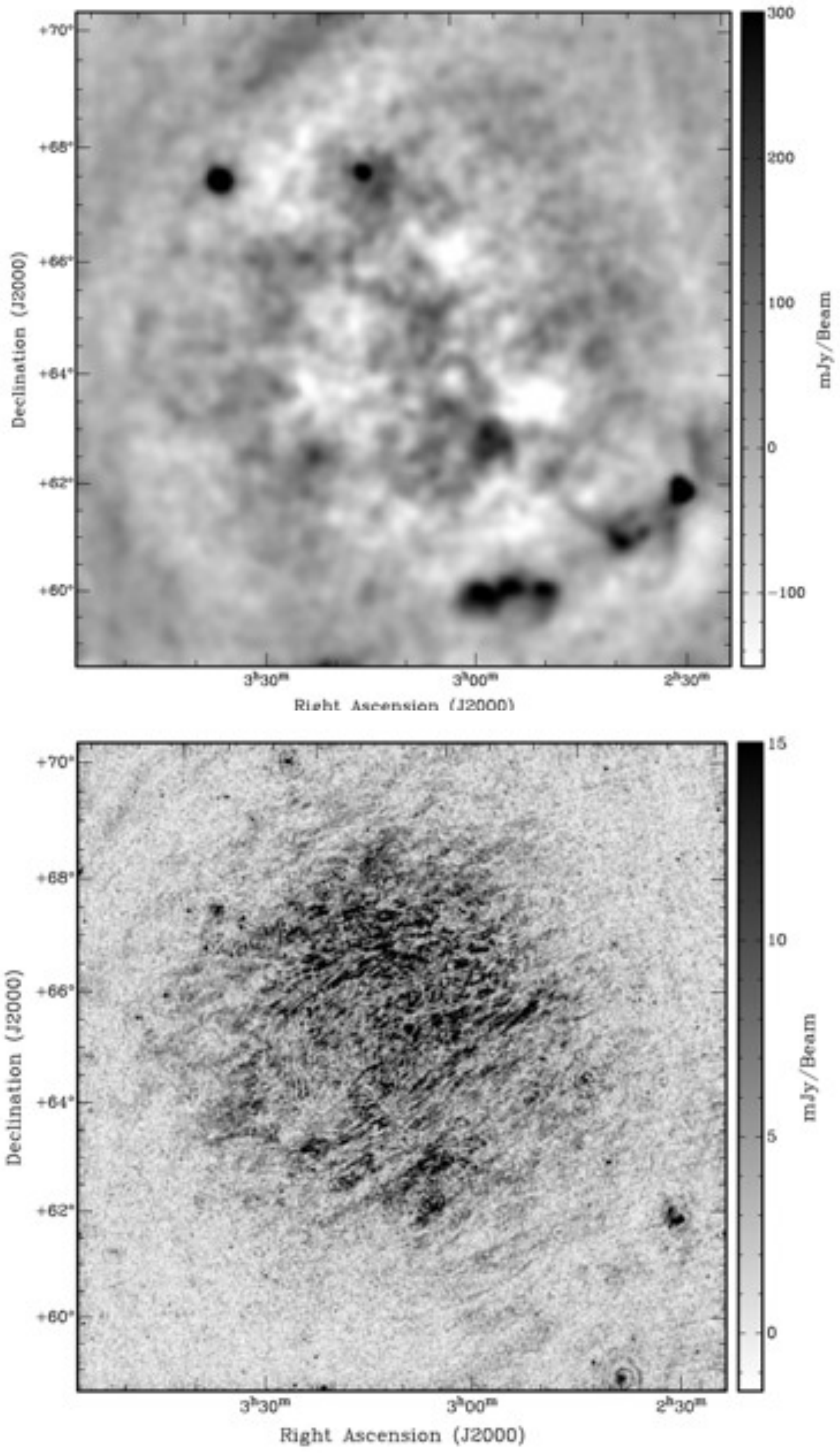
[1] RFI occupancy as found by automated detection. For some targets, this is too high because of the band-edge issues that are discussed in the text, leading to approximately a 1–2% increase in 3-kHz channel observations.

A Chromatic Sky

Galactic FGs have dT~0.1-few K spatial fluctuations on scales of 3'. This structure is stronger in polarization. They mix in Stokes if the instrument is polarized but also mix in time and frequency in the dynamic spectrum



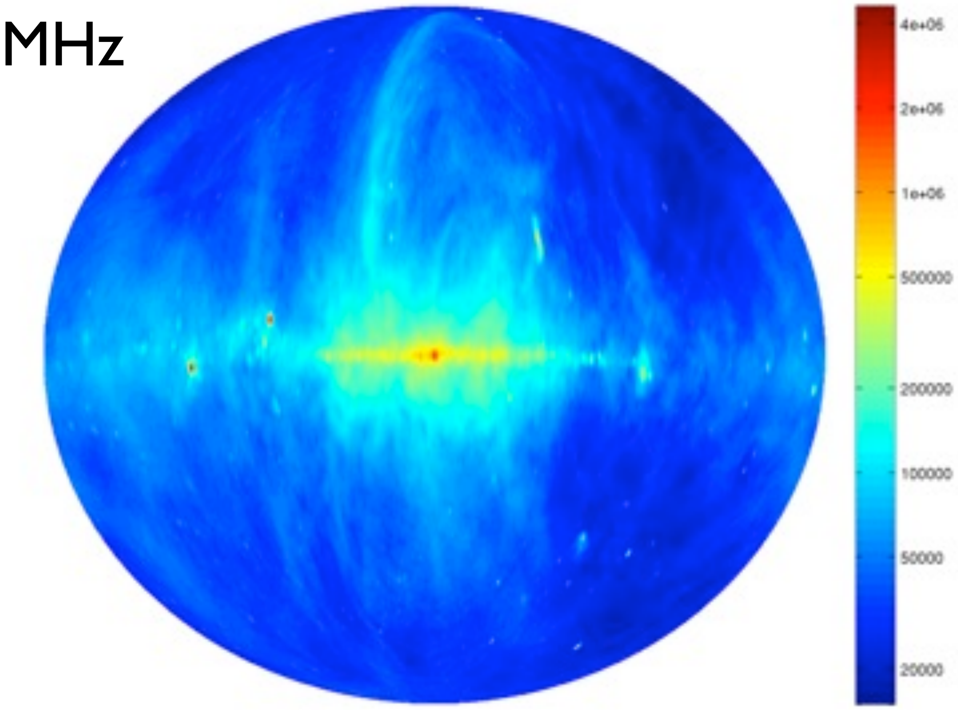
1mJy ~ 1 K



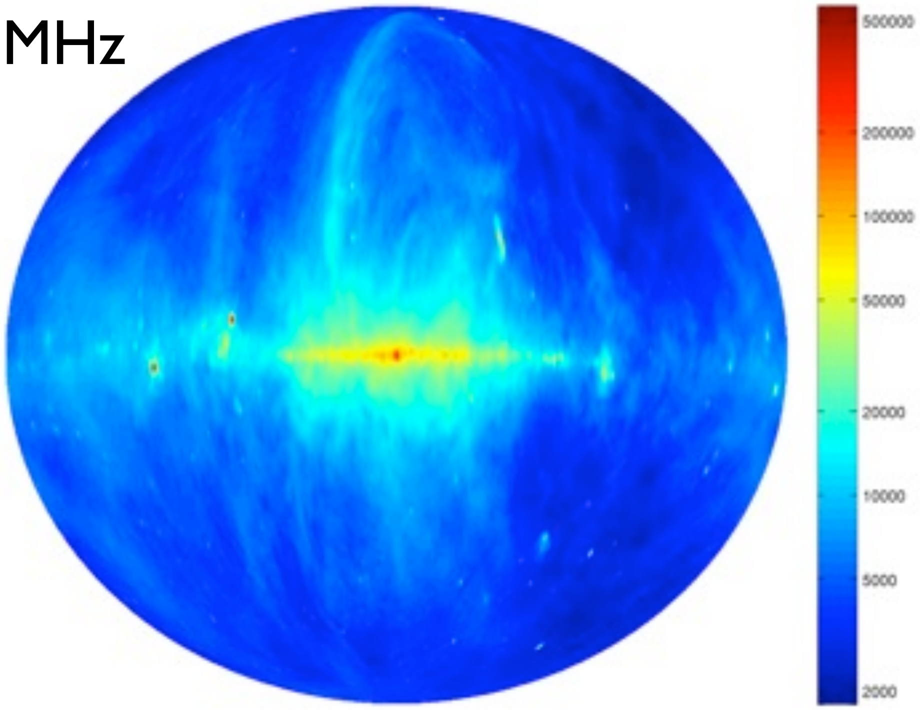
Bernardi et al. (2010)

A Chromatic Sky

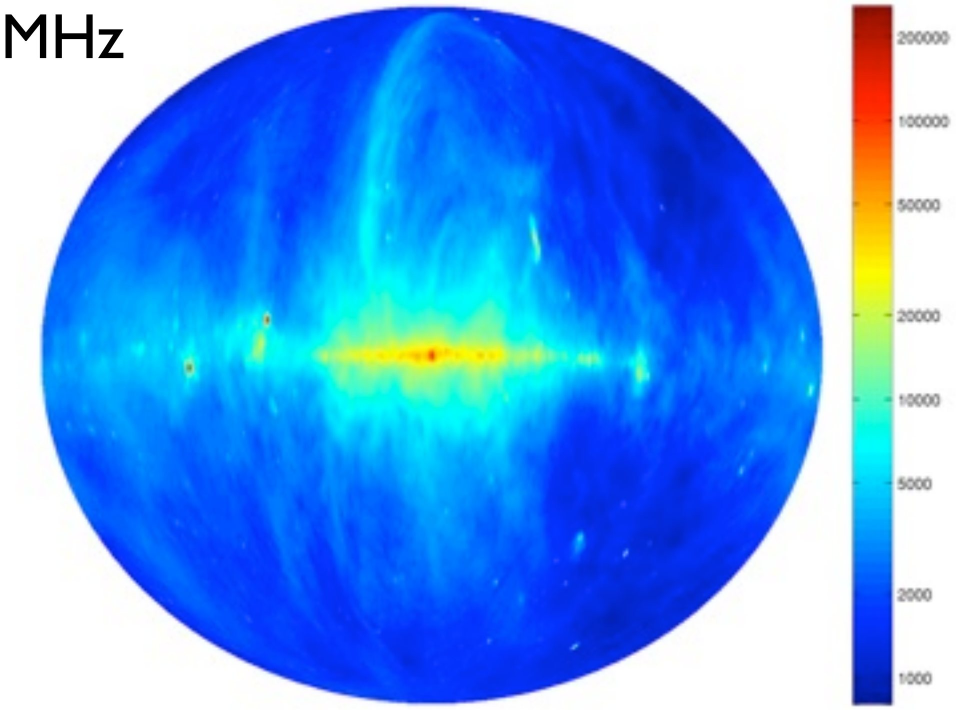
20 MHz



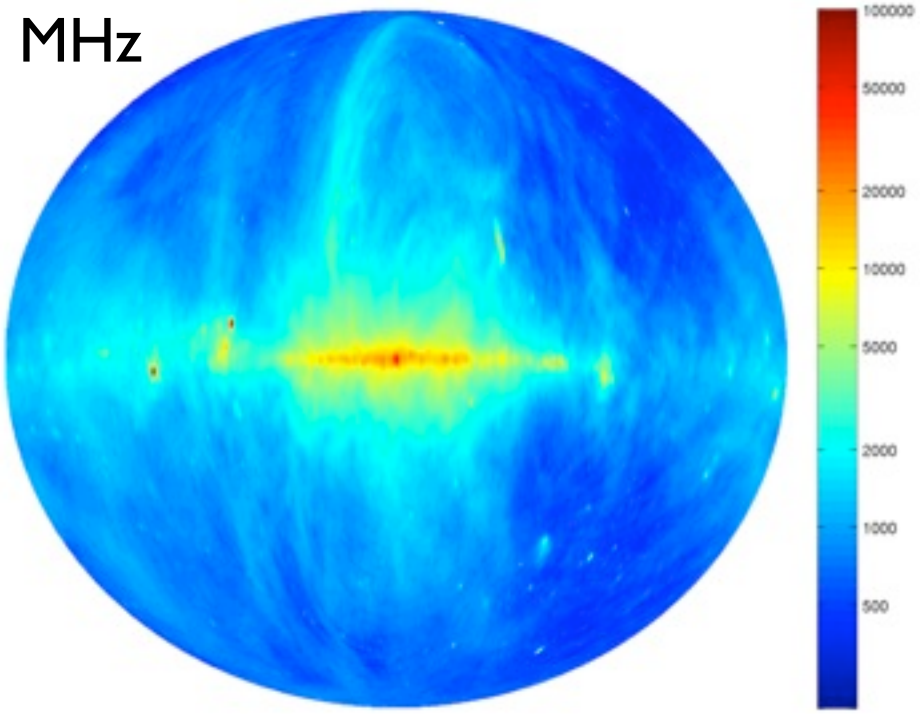
50 MHz



70 MHz

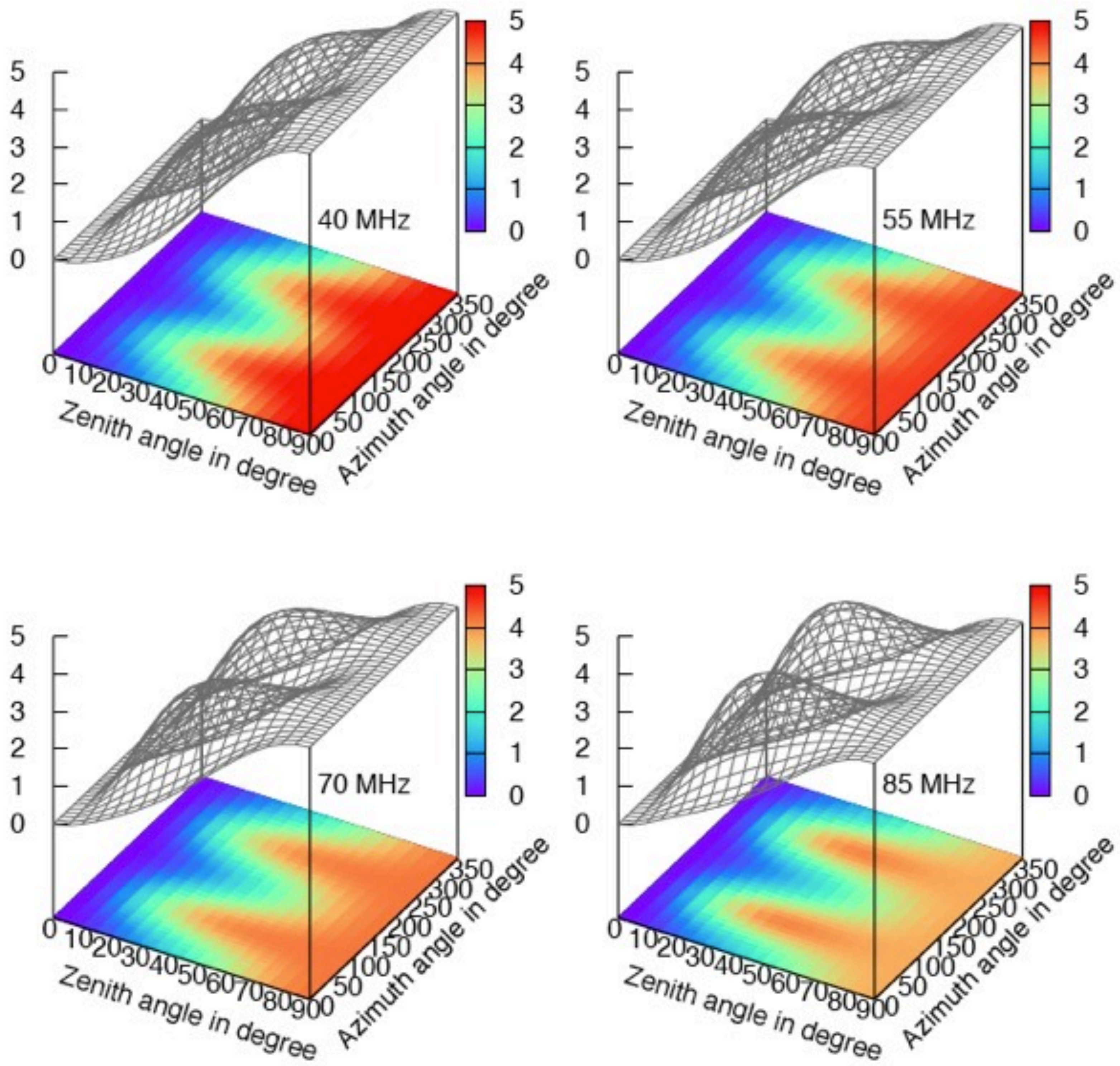


100 MHz



de Oliveira-Costa (2008)

A Chromatic Beam



EM simulations of the LBA beam
(courtesy: Stefan Wijnholds)

LOFAR-LBA dipoles beams depend quite strongly on frequency.

Consequence:

At each frequency a different beam sees a different sky.

Additional fluctuations in the spectrum are the result.

Larger beams cause slower freq. variations but suffer more from ionosphere and all-sky effects and might be harder to calibrate. Narrow-beam from an array would would be best but have low filling factors.

(see talk Vedantham)

Meeting these challenges w/LOFAR - Using its hierarchy/flexibility

- LOFAR is a massively hierarchical instrument

  - ✓ Dipoles are combined in tiles
  - ✓ Tiles/Dipoles are combined in stations
  - ✓ Stations are combined in an array/superterp
  - ✓ Multiple beams can be formed at the station/array.

- Total power can be obtained for dipole/tiles, from the station beams (multiple per station) and from the complete array/Superterp (in)coherent beams (multiple).

- Auto and cross-correlation can be obtained simultaneously and the latter can be used for cross-check/calibration purposes and to reduce chromatic effects (see later)

LOFAR - hierarchy/flexibility

LOFAR-LBA can observe in many modes and data can be processed and stored in many different ways:

Dipole data - 48/96 x (24+12[+4]+8) ~ 4000 dipoles providing a total power measurement
Station data - 24 (+12[+4]+8) ~ 48 stations each providing a (a few) beam-formed total-power measurement
Superterp data - provides (multiple) beam with each total-power data
Full Array Data - can provide multiple beams each providing total-power data

LOFAR - hierarchy/flexibility

Scenarios:

(1) Dipole/tile-level: Obtain auto-correlations per sub-band/sec for all 48/96 dipoles/tiles and cross-correlations one sub-band per time-unit. Use cross-correlations to calibrate/cross-check the auto-correlation data. These data can be obtain all the time for all stations in piggyback mode.

Near future: AARTFAAC: full auto/cross-correlation data per second per 24KHz for all 288 dipole/tiles in the superterp (inner 300 meters). LSS: full auto/cross-correlation data per second per 28KHz for 96 mini-stations (19 dipoles) in Nançay.

(2) Station-level: Includes -1- for all stations, but adds station (multi)beam-formed data which is cross/auto-correlated centrally (Groningen/BlueGene). The (multiple) beam(s) is/are one resolution element in the sky as seen by the dipoles/tiles. Chromatic effects can be controlled that way and weights on the tiles/dipoles can used to lessen the chromatic beam effects.

(3) Array-level - Includes -1- and -2-, but coherent beams can be formed at different levels (full array or Superterp [pulsar mode]). These can also provide auto-correlations.

Although calibration becomes easier as one goes from 1 to 3, the filling factor decreases, so S/N in brightness temperature decreases rapidly. This can be compensated by the large number of stations/dipoles/tiles.

LOfar COsmic-Dawn Search

Pilot Program with LOFAR-DE602

The Unterweilenbach Station

LOCOS uses the DE602 station in Germany

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The Unterweilenbach Station

LOCOS uses the DE602 station in Germany

LOCOS Data Flow/Processing in the LOFAR Hierarchy

- LBA/HBA Station correlators (200 kHz/1-sec):

- Provides all sub-band auto-correlations per second
- Provides one sub-band cross-correlation per sec.
  (either the same of cycling through a set)
- Data is locally stored for all stations and can
  be transferred via ftp protocol.

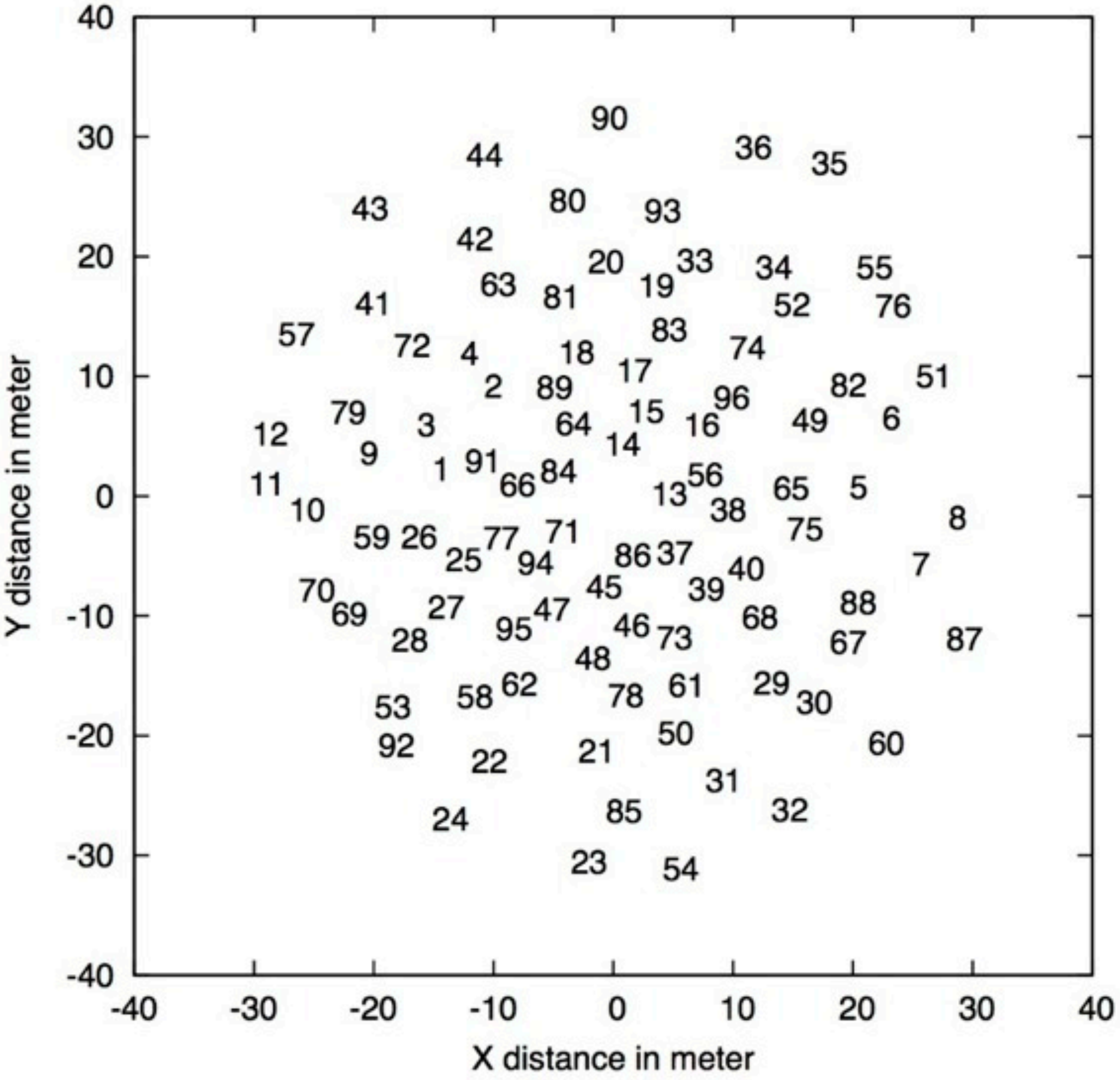
- LBA Data volume per station (24 core + 8 remote):

For a Dutch LOFAR station (96 receivers), the first results in
96 RCUs * 512 subbands * 8 bytes * 3600 s/h * 12 h = 15.8 GB of data per station

For a Dutch LOFAR station, the second results in
96 RCUs * 96 RCUS * 16 bytes * 3600 s/h * 12 h = 5.9 GB of data per station

The total amount of data per station thus amounts to about 21.7 GB per station.

The Unterweilenbach LBA Station



Station Specifications

96 dipoles (x & y pol), relatively uniformly distributed within a D~60m station. Station FoV ~5d (@60MHz). Dipole FoV ~ all sky. Freq. coverage (10)30-80MHz with 0.2 MHz sub-bands. Station-based correlator: all auto-correlations per integration time, but only one sub-band (either the same or cycling through a list). Stand-alone data is locally stored and transported via ftp.

The Raw LBA-Station Data

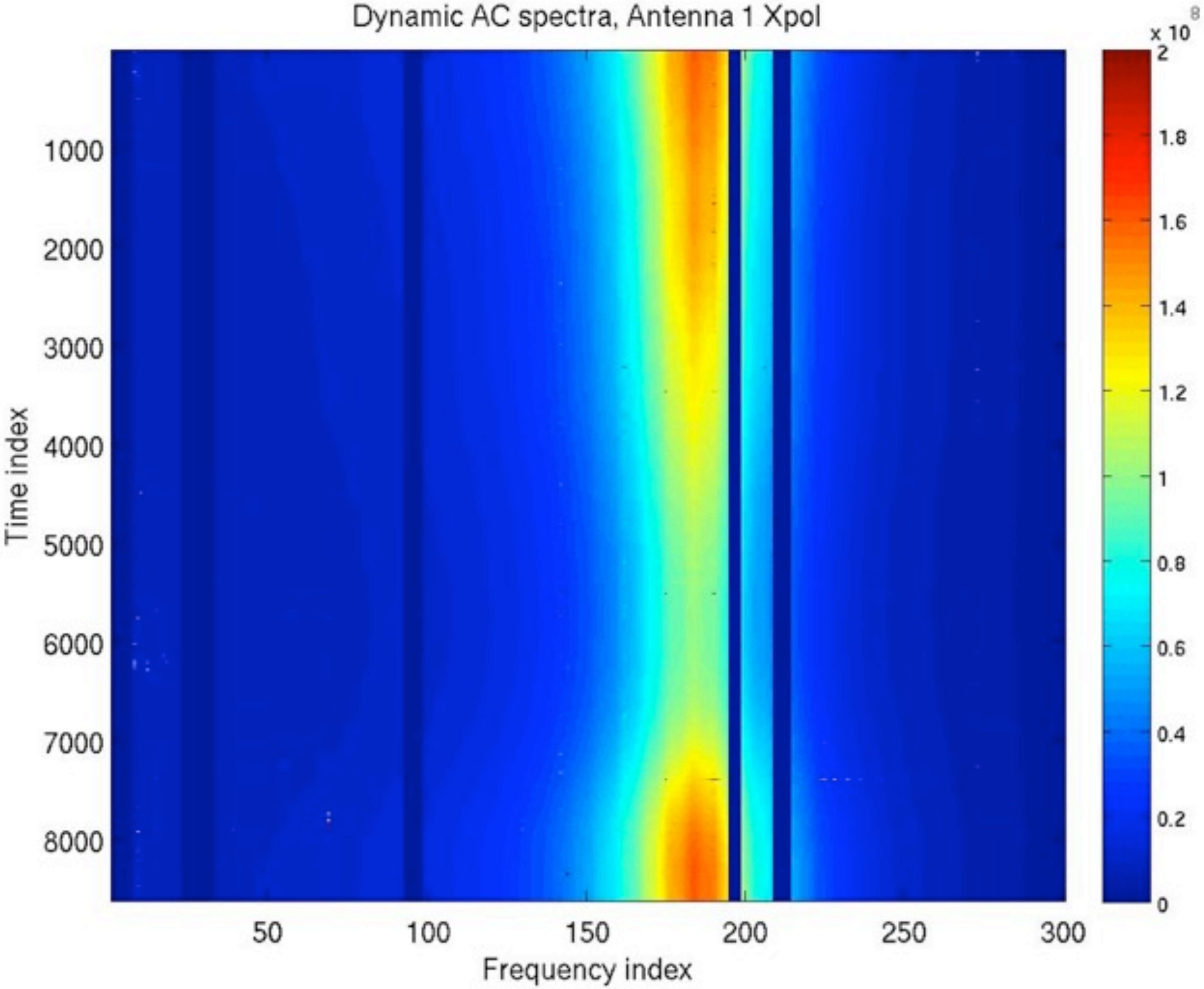
Capacity of the station-correlator is limited

(1) Cross-correlations: At the station-level data are obtained only for one 200-KHz sub-band per n-sec time-slice for all cross-correlations. Hence sky-maps/uv-data per sub-band are obtained every 512 seconds (~8.5 min for n=1) or less if fewer sub-bands are used.

(2) Auto-correlations: data are obtained for all sub-bands per n-sec time-slice for all 96 auto-correlations.

This is currently the major limitation at the station level, but could be resolved with a better station correlator (Oxford effort). Note that this is no issue when (part of) the full LOFAR-array is used with CEP (or AARTFAAC). Future includes also the French LSS and other efforts.

The Raw LBA-Station Data



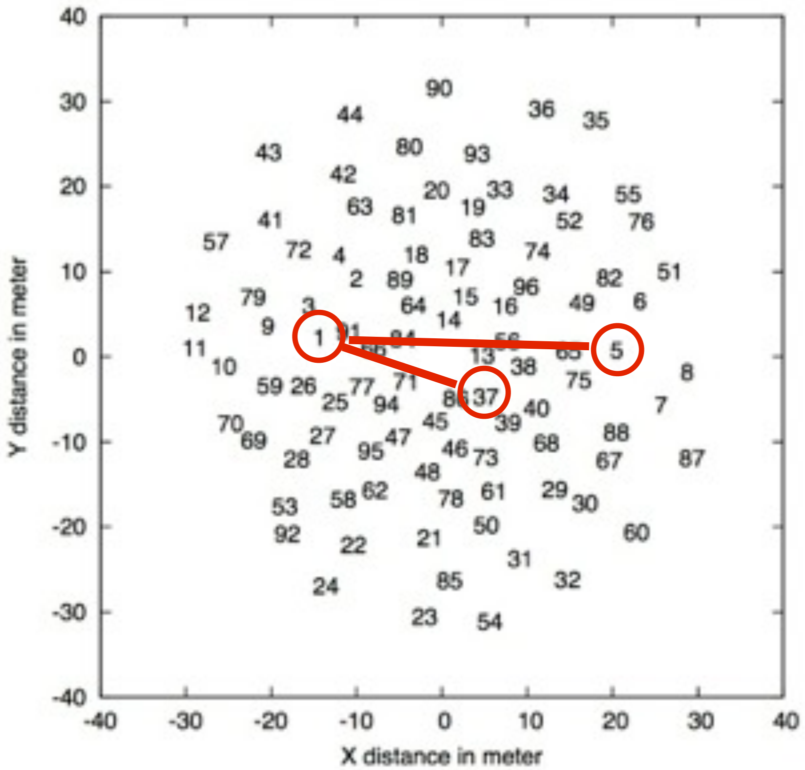
Auto-correlation data:

24hr/10sec time-slices
300 sub-bands (BW: 60MHz)
Rough flagging

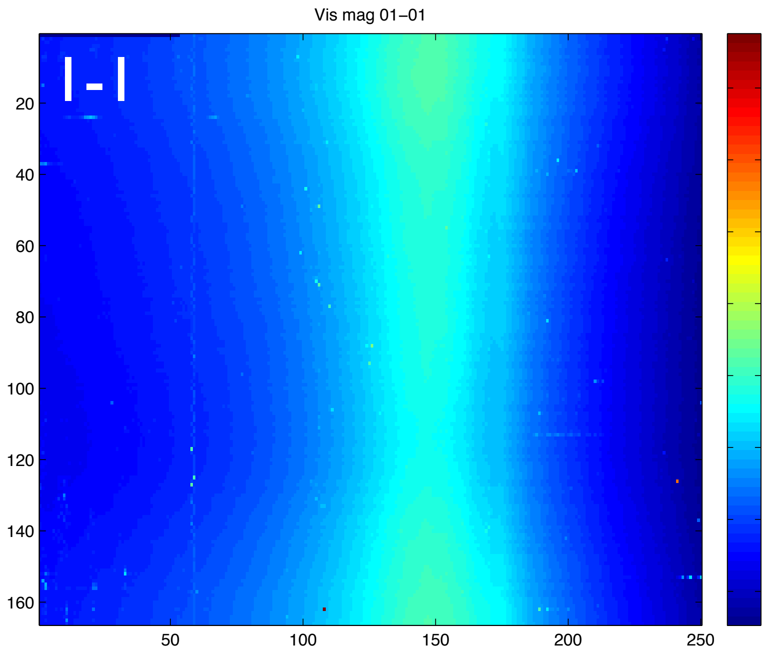
Main features:

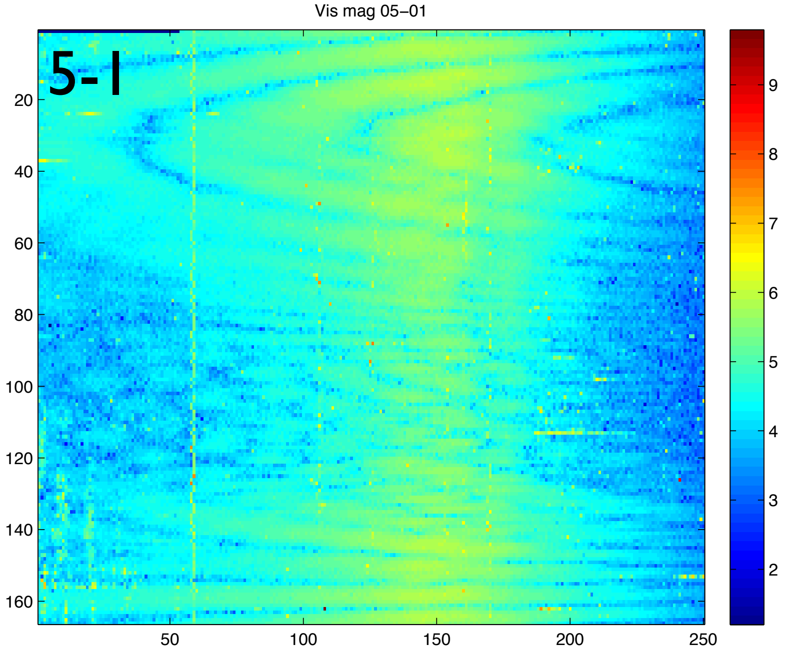
Max sensitivity around 60 MHz
Main contributors to the power are the MW and CygA and CasA. Strong variation over 24hr cycle.

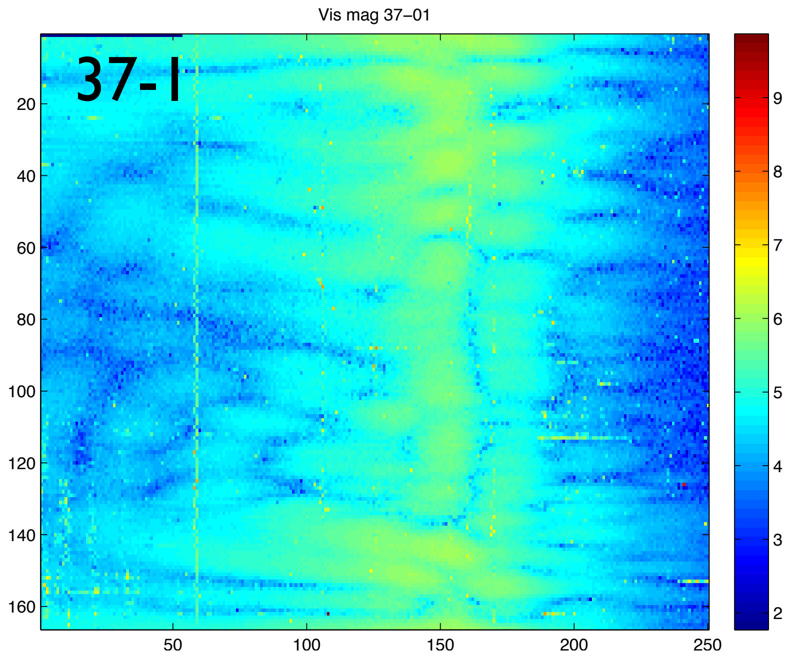
The Raw LBA-Station Data



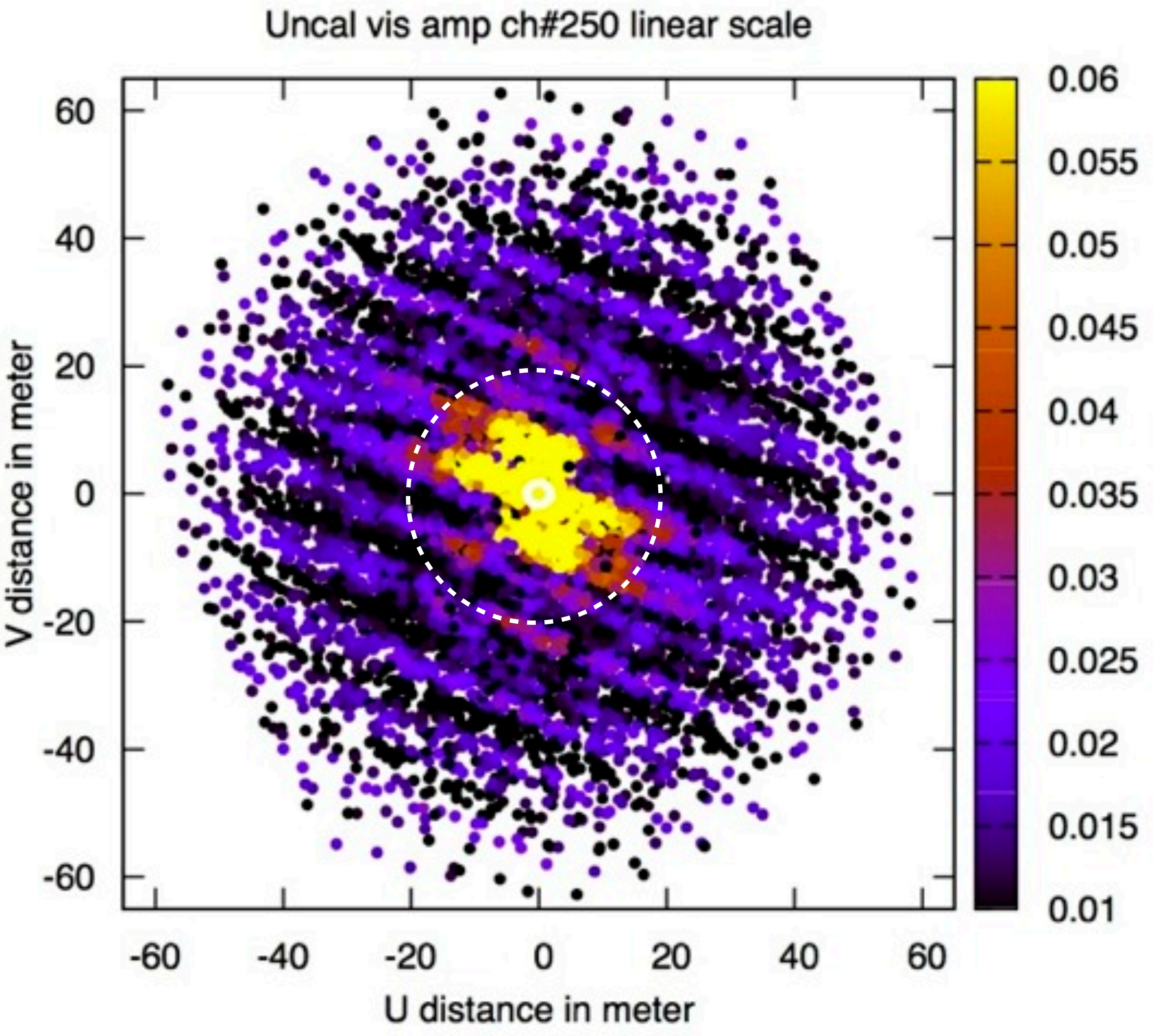
Besides a strong auto-correlation signal, all baselines show structure due to a time-freq. dependent sky. The main features are the MW on short baselines and CygA and CasA on longer baselines (>4λ)







The Raw LBA-Station Data

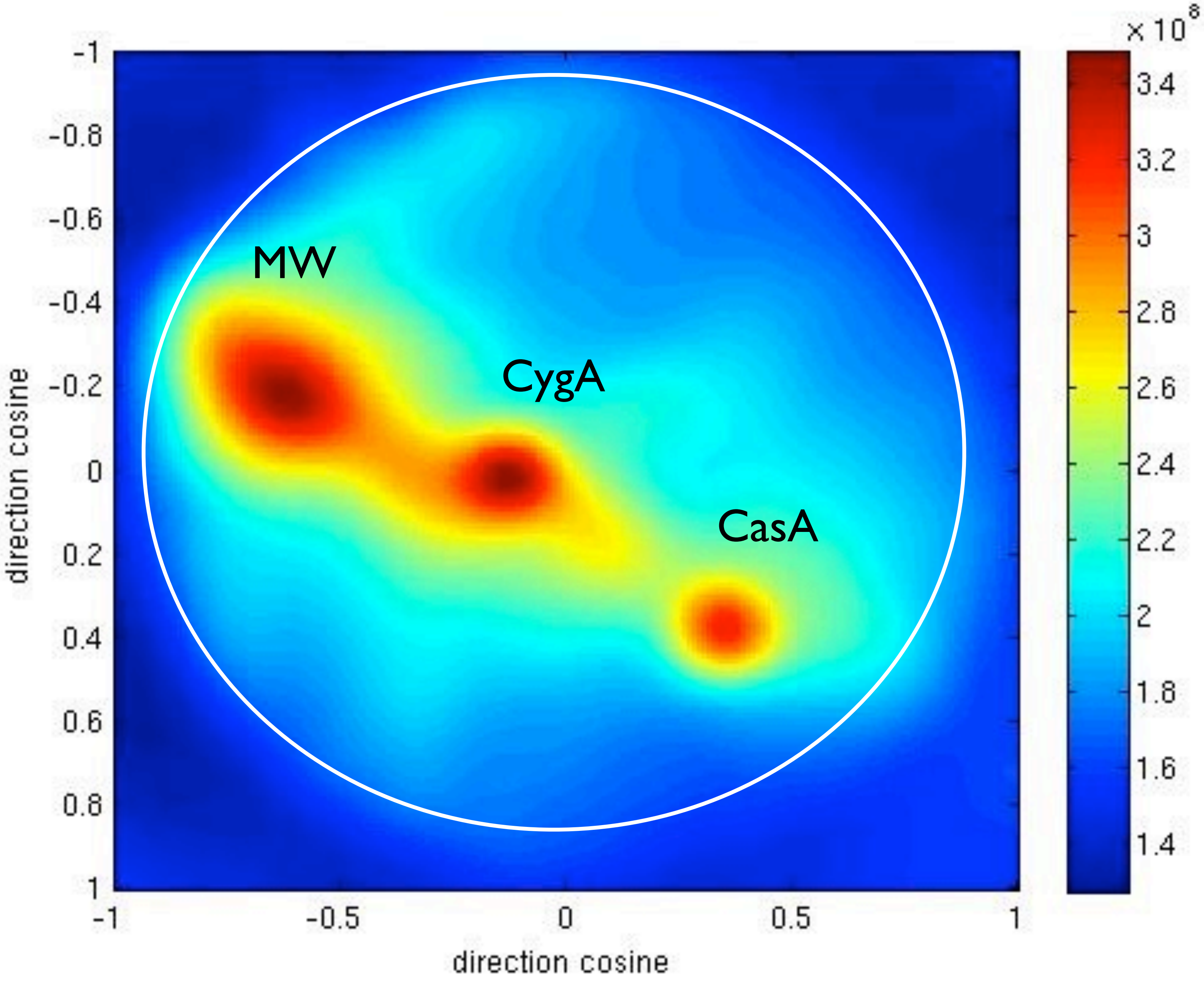


Instantaneous UV-snapshot

Short baselines dominate the signal: *Milky Way*

All baselines show the beating between *CygA and CasA* which dominates beyond 4λ

The Raw LBA-Station Data



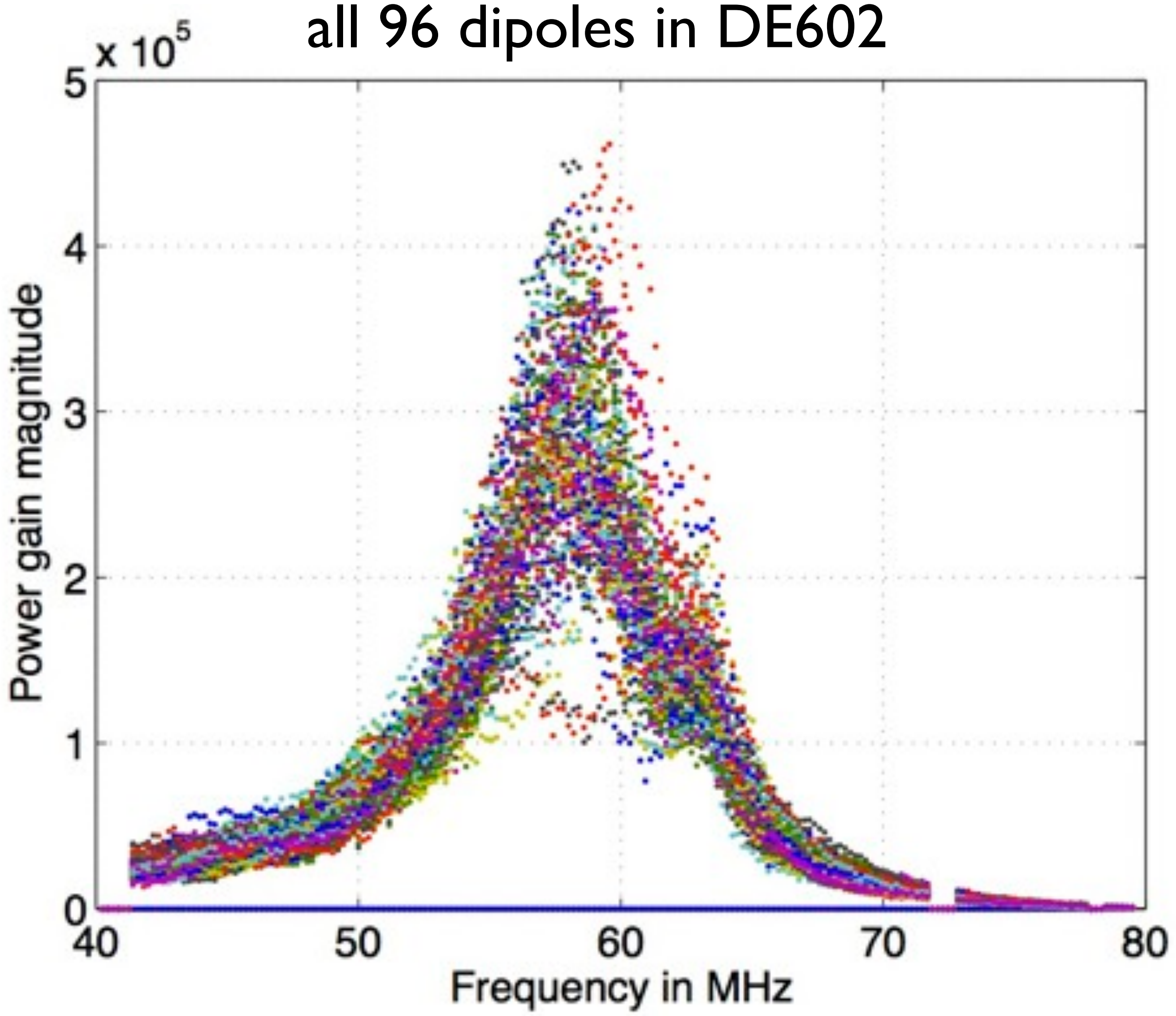
A single time-stamp and sub-band (10s-200KHz) data-set already provides an all-sky images clearly showing the MW, CasA and CygA.

A good sky model could be critical for calibration. Simply assuming CasA/CygA on longer baselines is not sufficient.

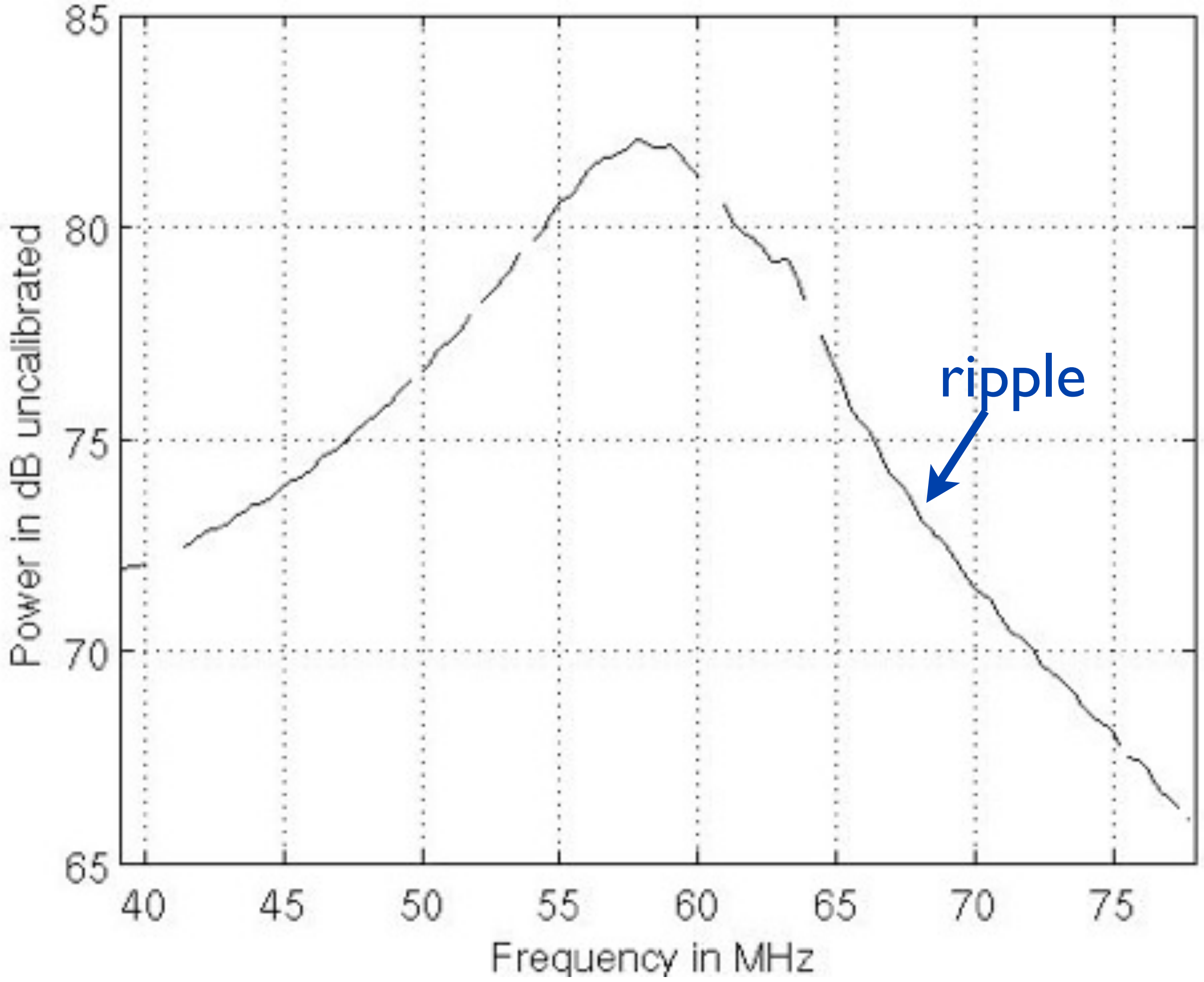
Bandpass Gains

The band-pass of the LOFAR station is highly structured and varies between dipoles (mutual coupling?). It has a peak around 60MHz (filters + dipole size), but also a ripple(!)

all 96 dipoles in DE602

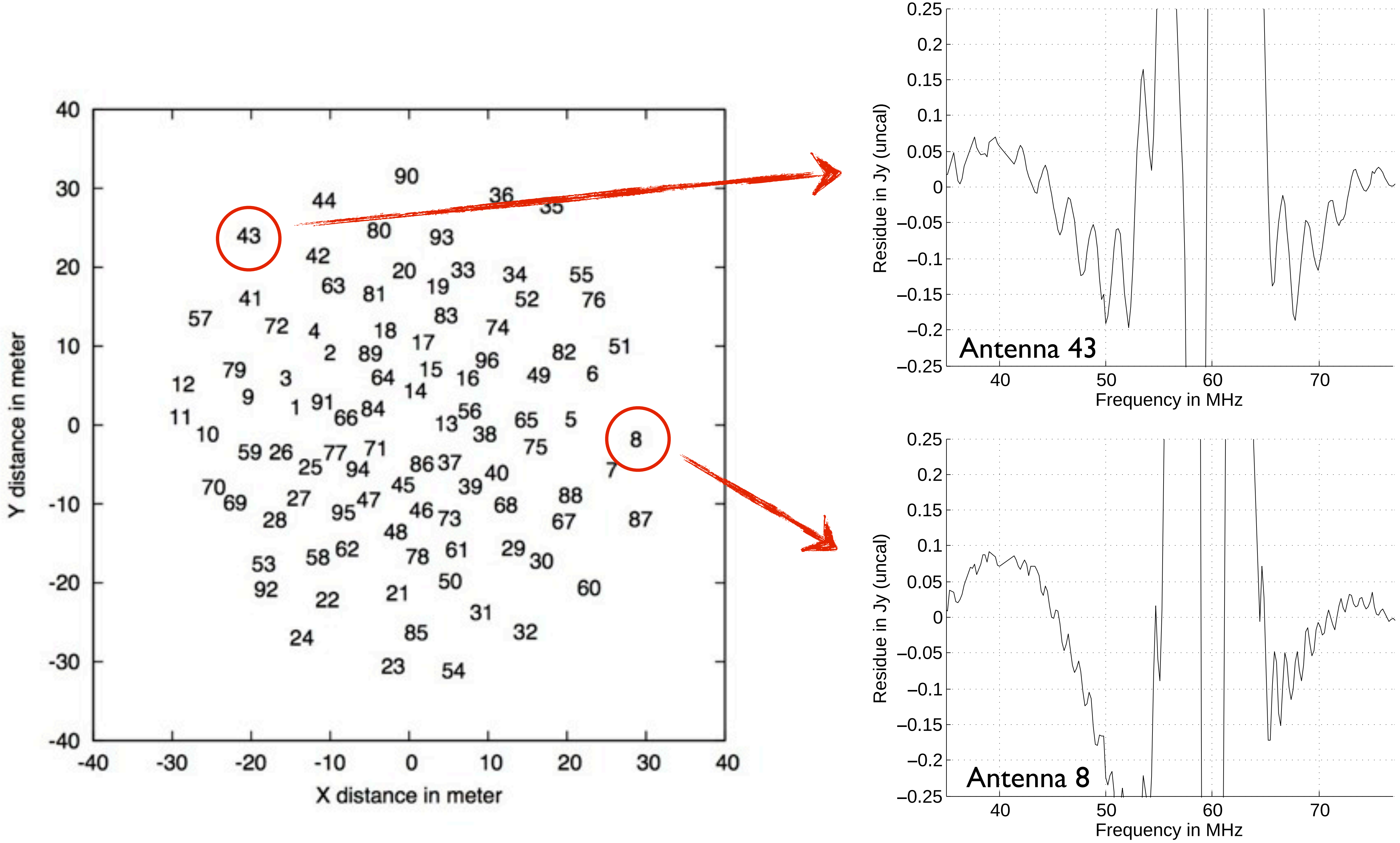


averaged gain DE602



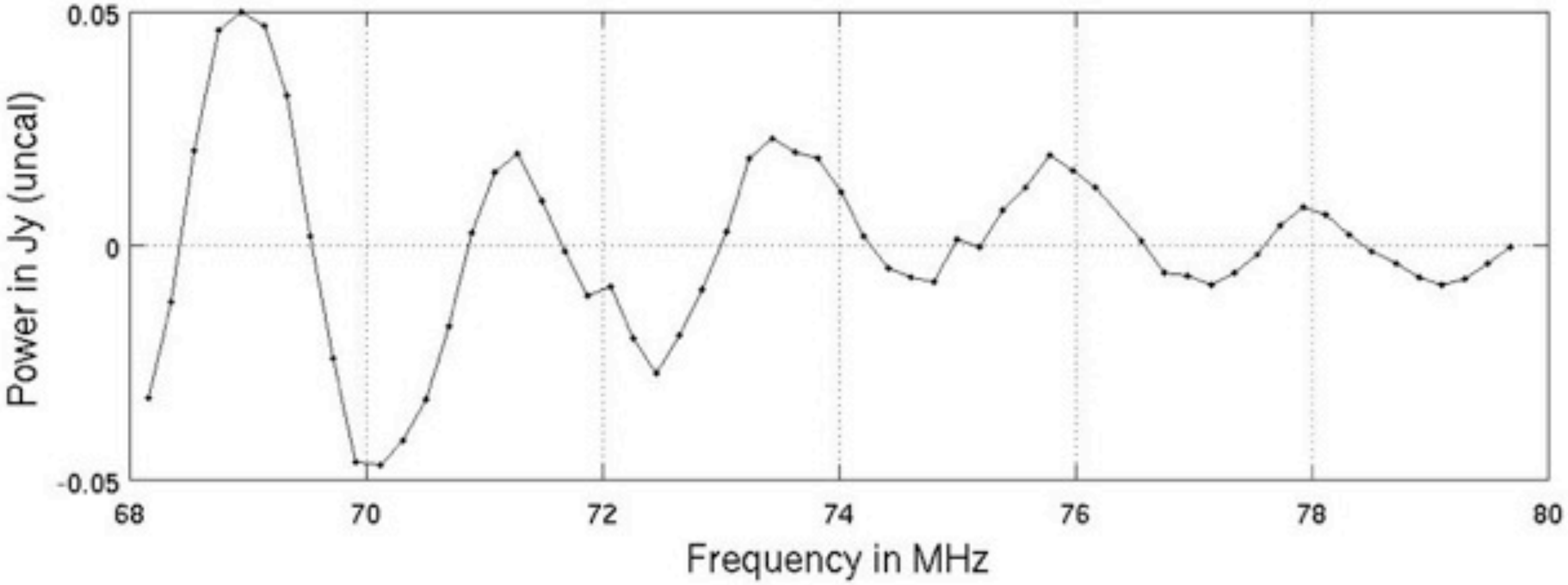
Bandpass Gains

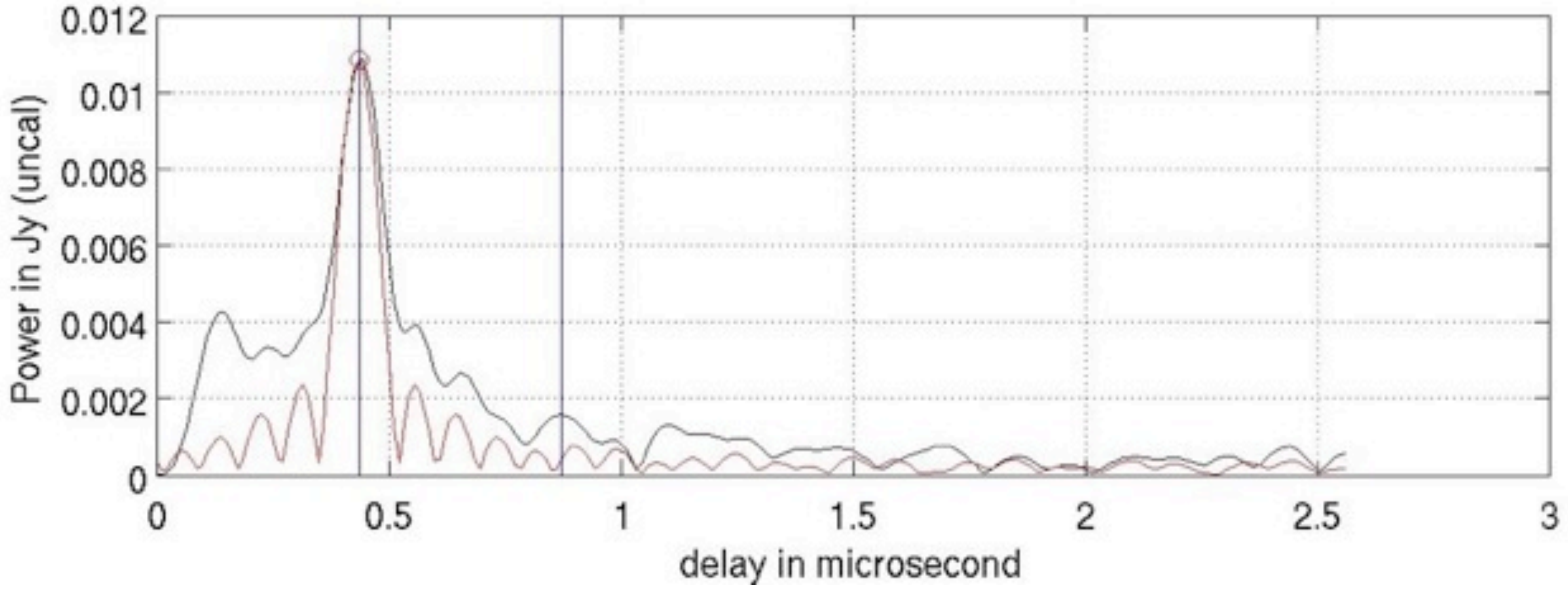
Subtracting a simple fit from the bandpass brings out the ripple very clearly for each station. Amplitude/wave-length are different.



Bandpass Gains

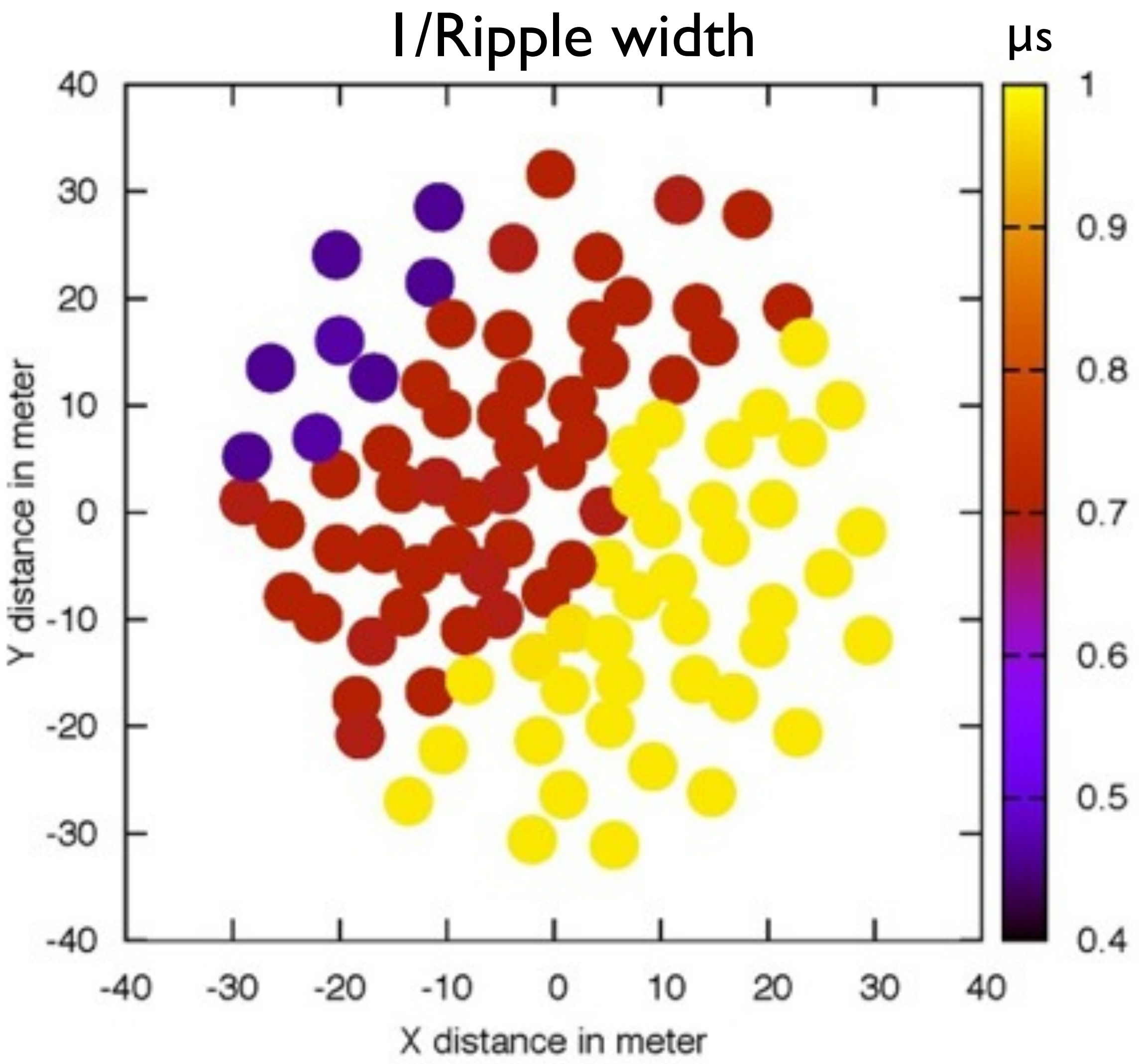
A power spectrum analysis of a part of the data where the average can properly subtracted yield a delay in the cable due to standing waves, causing the ripple.

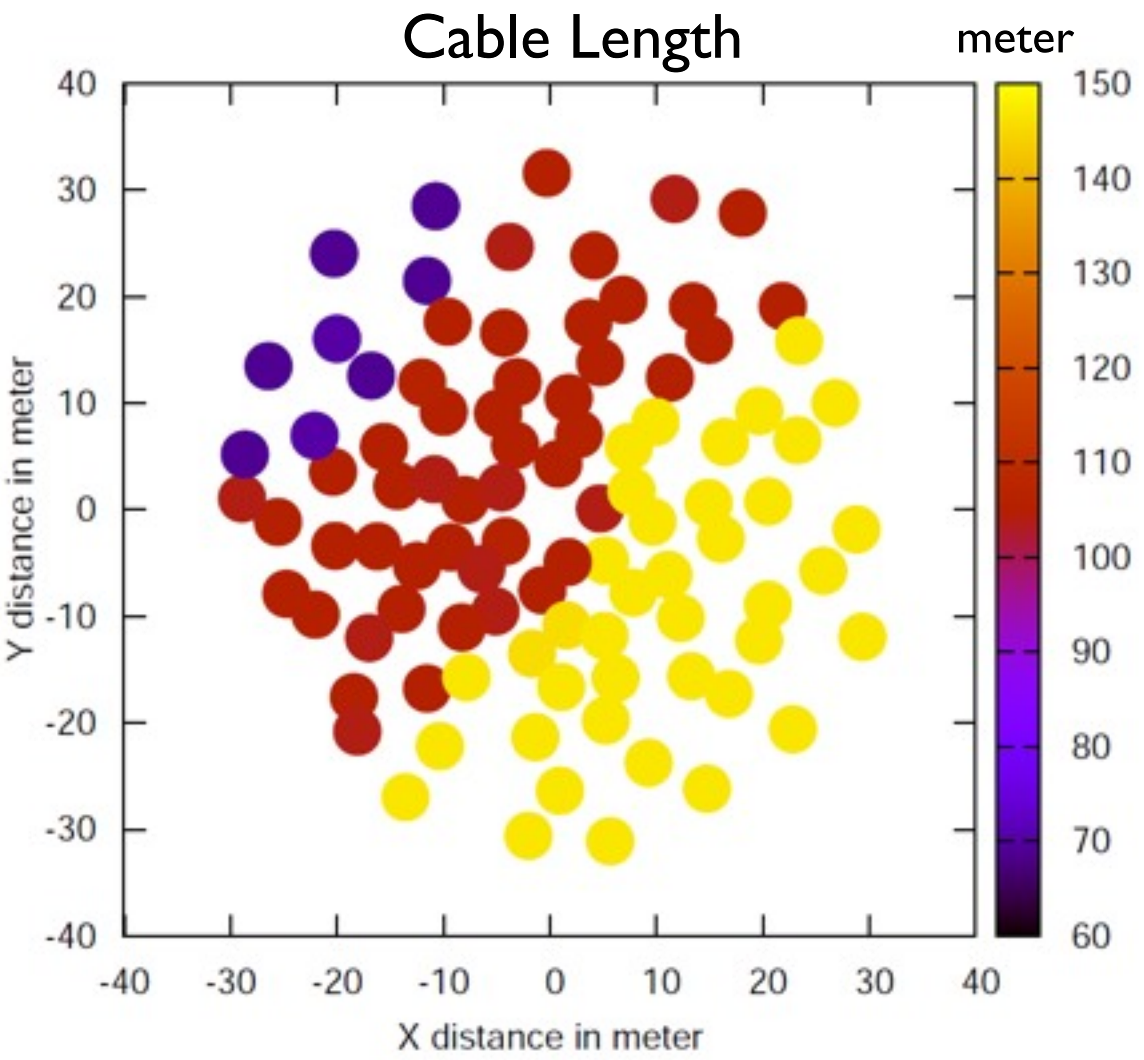




Bandpass Gains

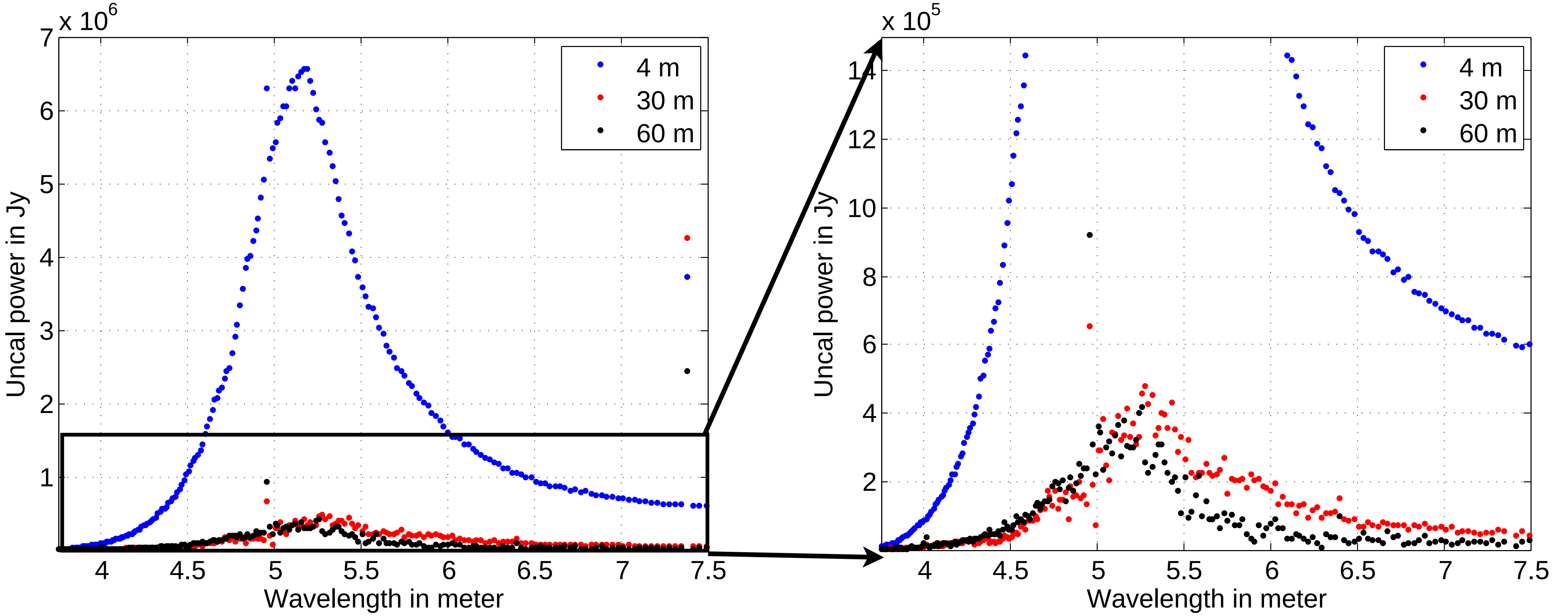
The frequency-scale of the ripple corresponds to a time-delay (1/width). When plotting this for each dipole, a pattern emerges. It correlates one-to-one with the cable length, which are not in units of λ.


1/Ripple width


Cable Length

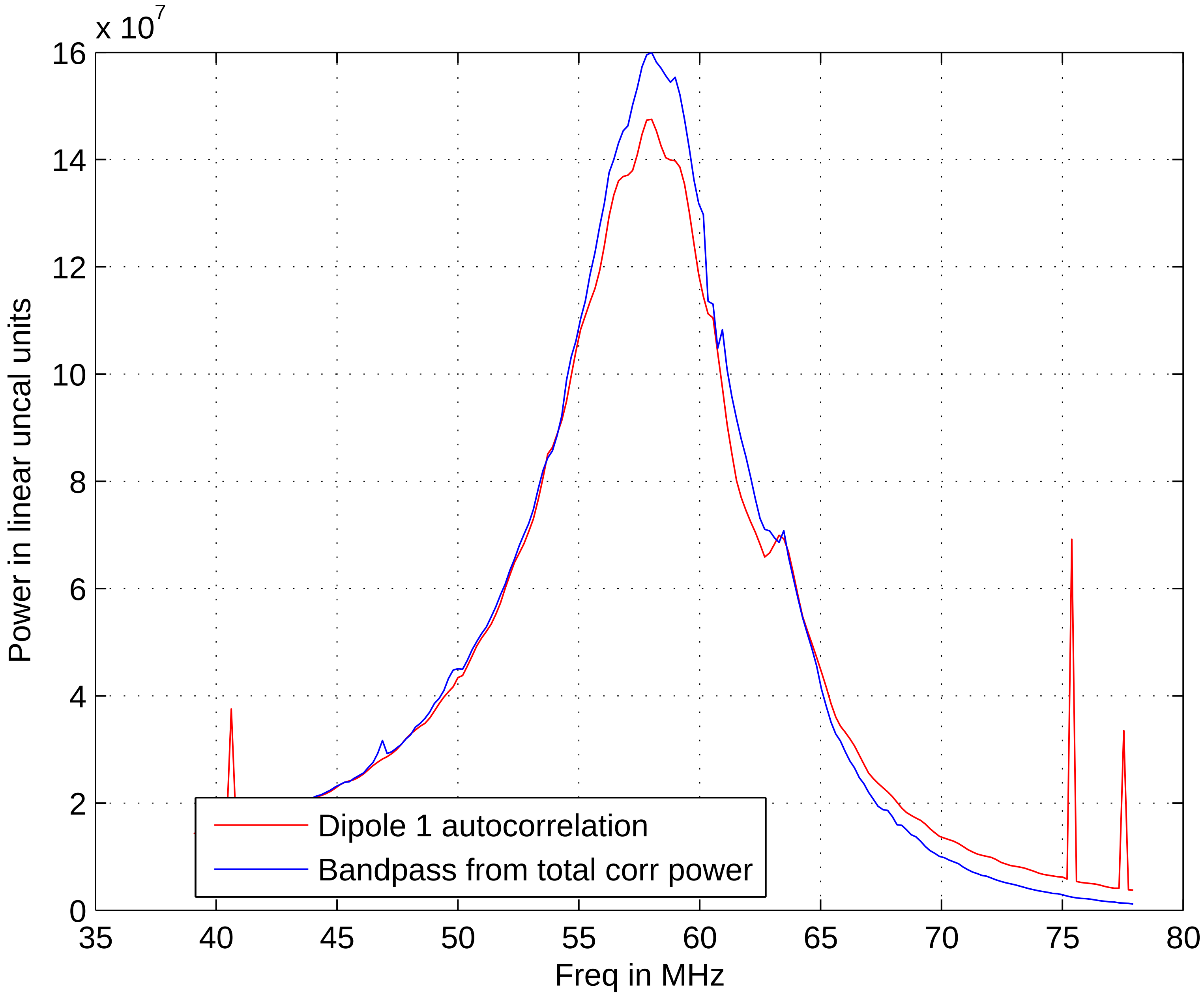
Bandpass Gains

Can the band-pass for the auto-correlations be properly determined from the cross-correlations, assuming the sky is spectrally smooth overall?



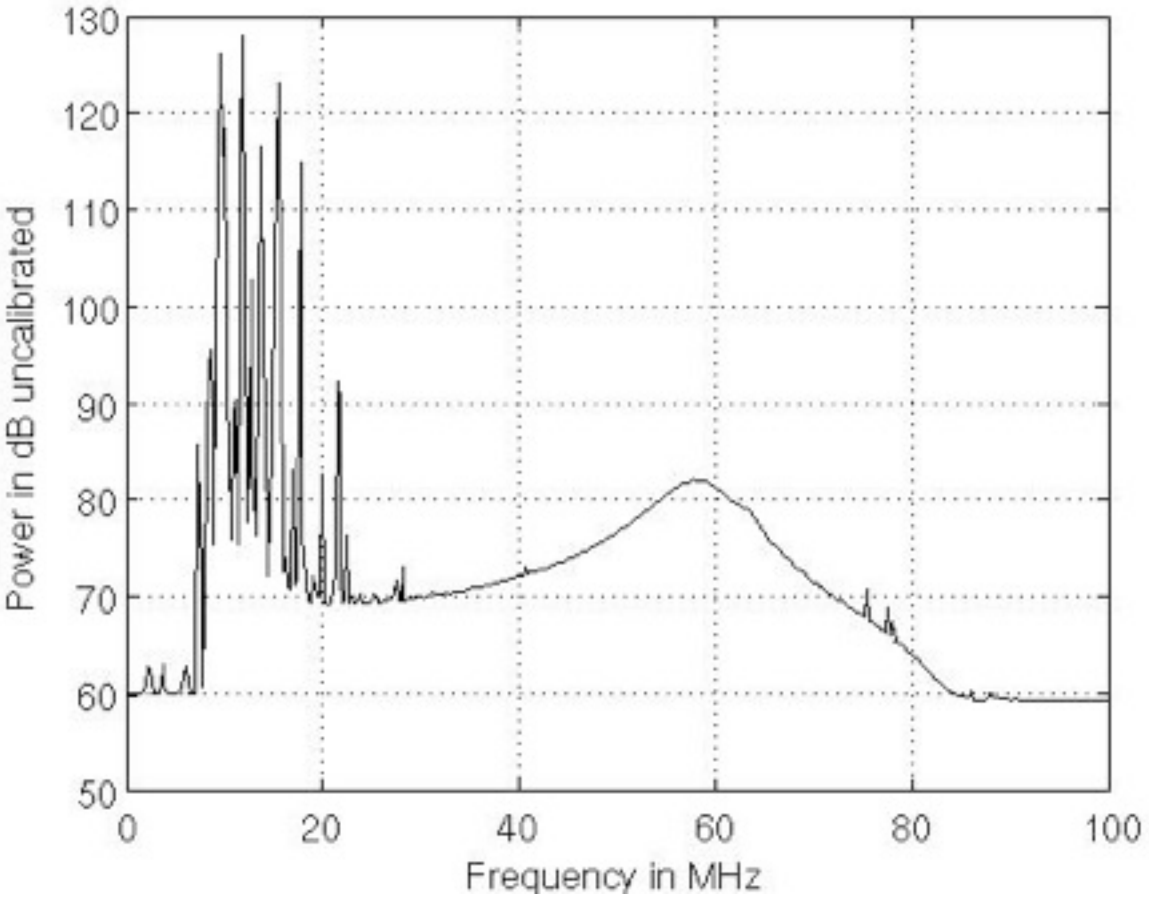
Bandpass Gains

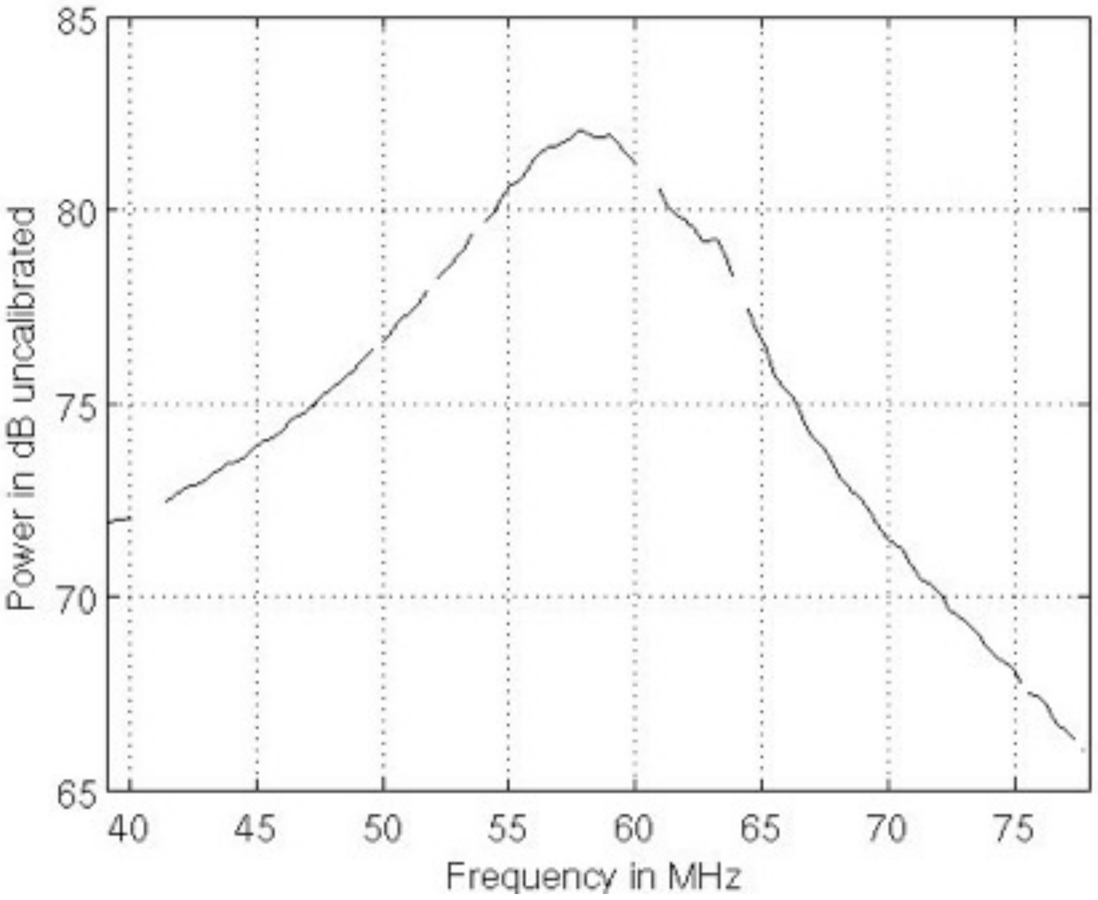
Short baselines have a BP shape similar the autocorrelations. But this is unlikely to be sufficient and a full-sky model is most likely needed for BP calibration



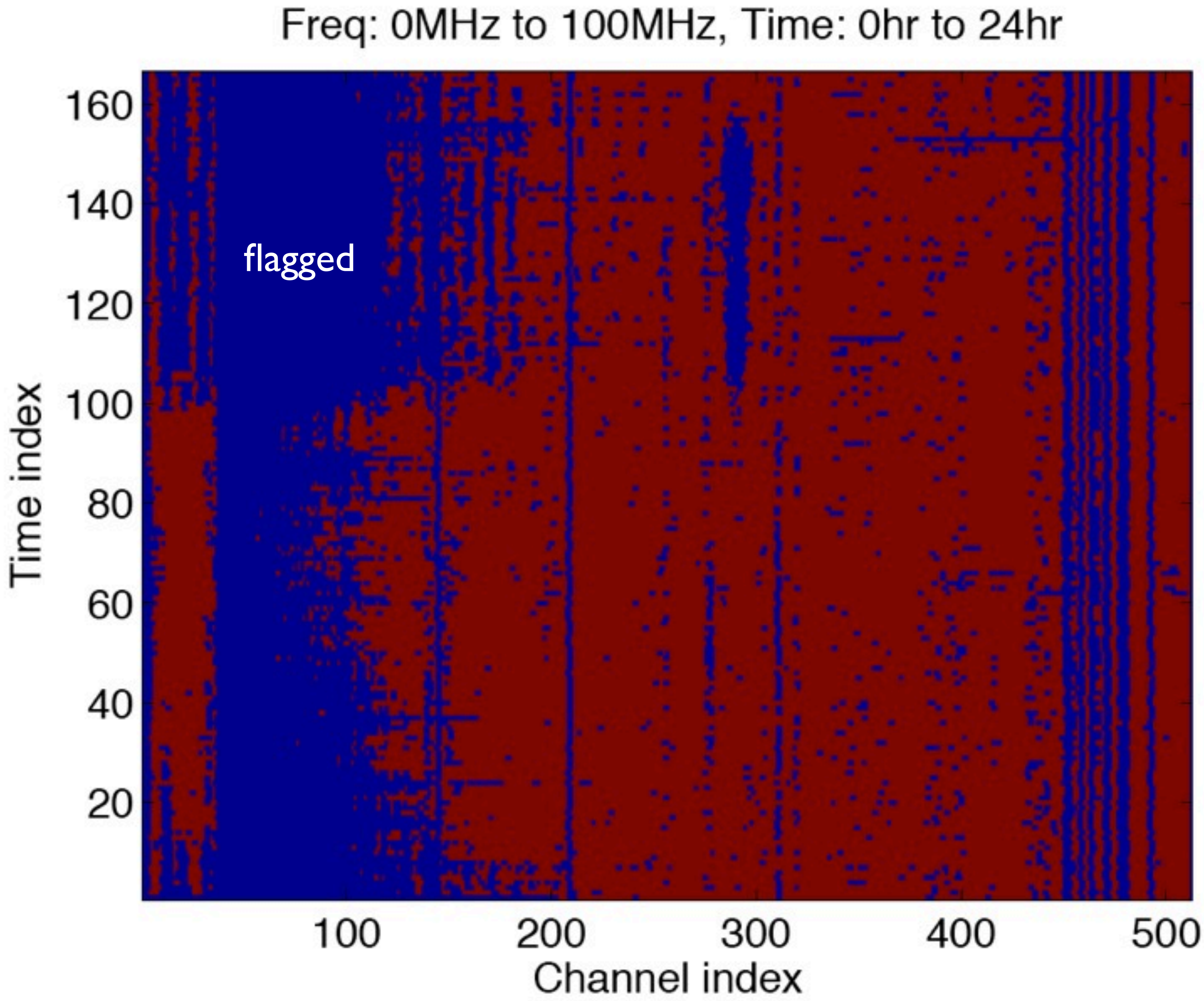
Radio-Frequency Interference

RFI is severe below 20-30MHz where most of the spectrum is lost. But the spectrum can be cleaned quite well although at the station level quite some data is lost (note that this is not the case when cross-correlating stations where RFI is independent).



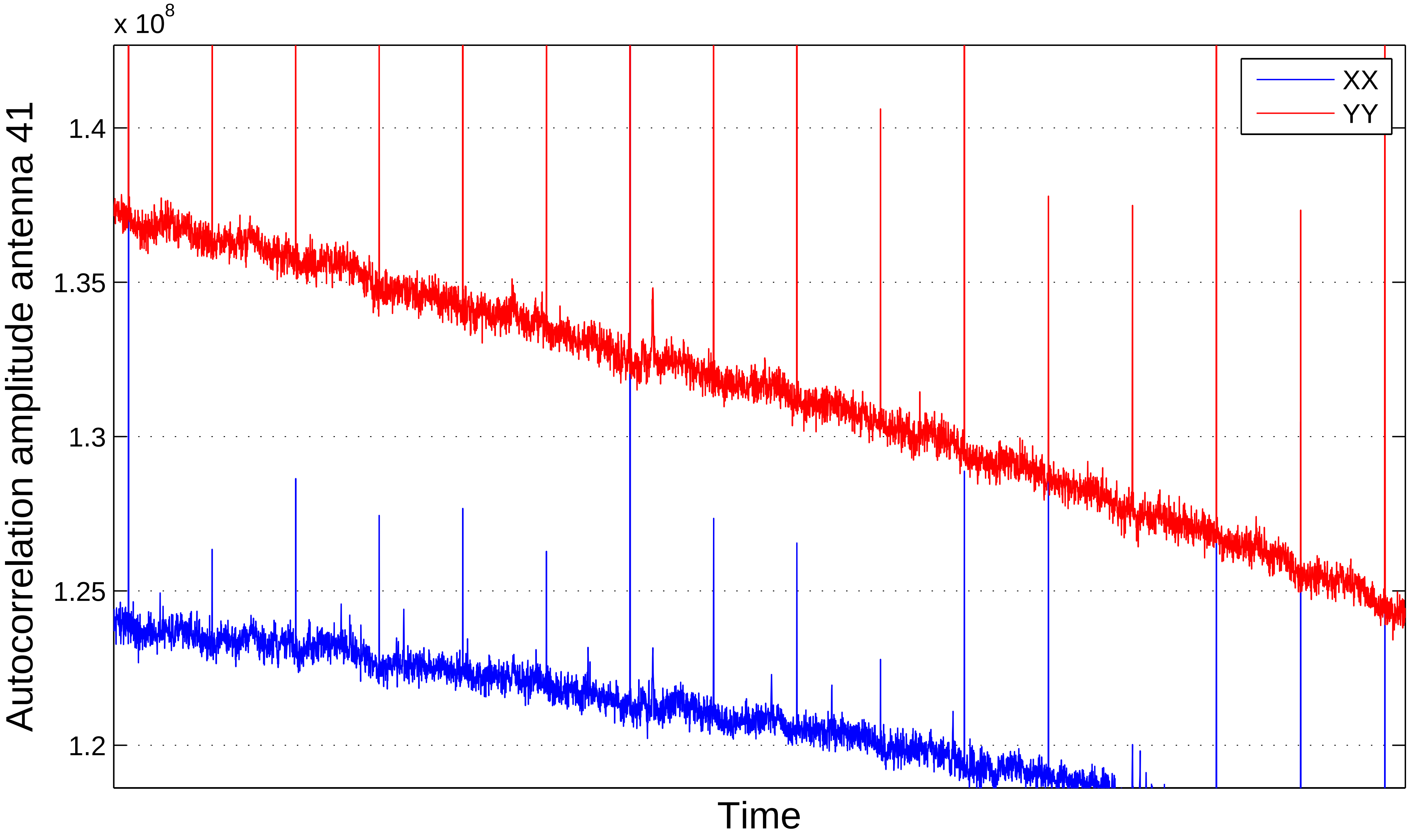


Radio-Frequency Interference



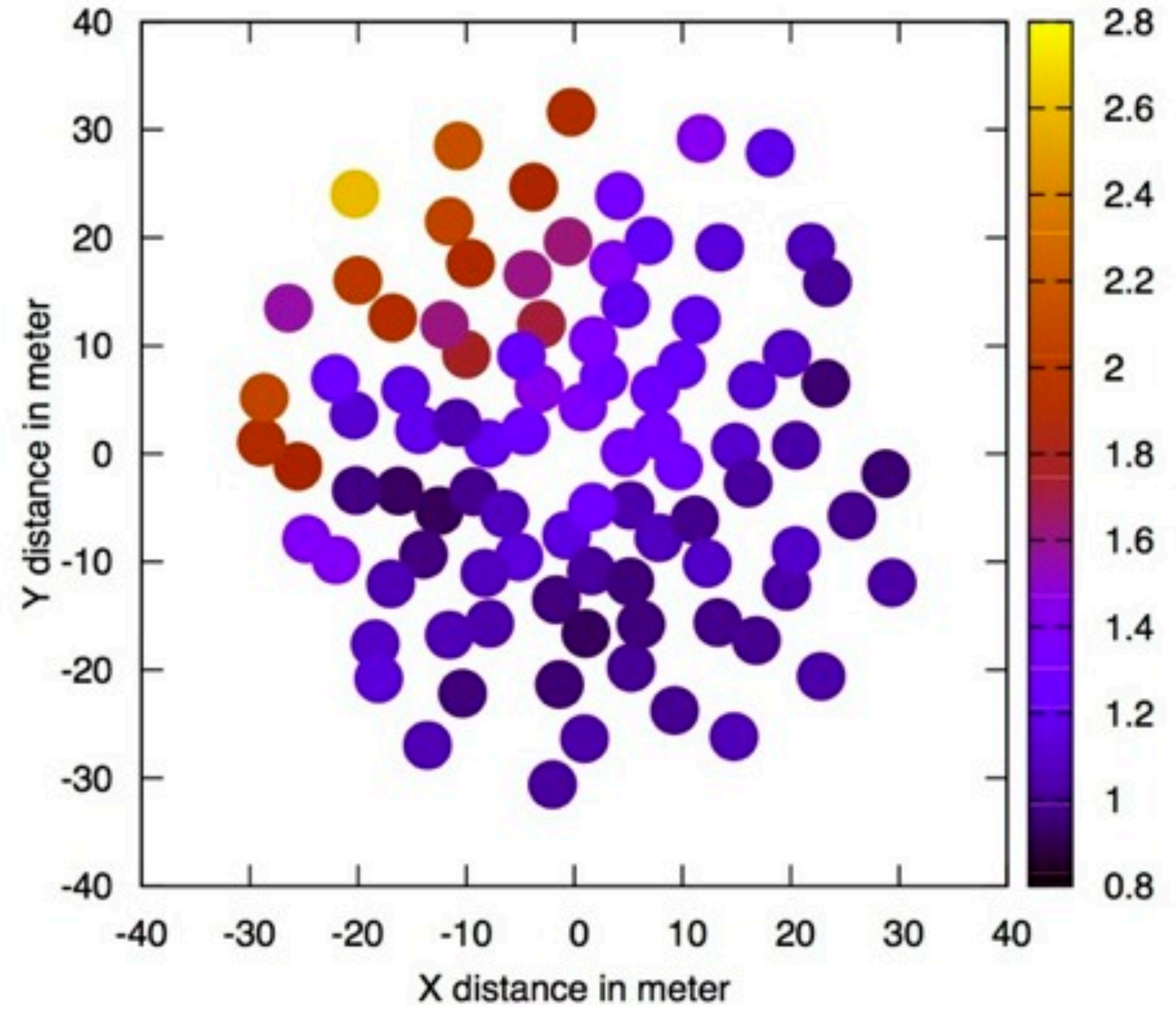
Radio-Frequency Interference

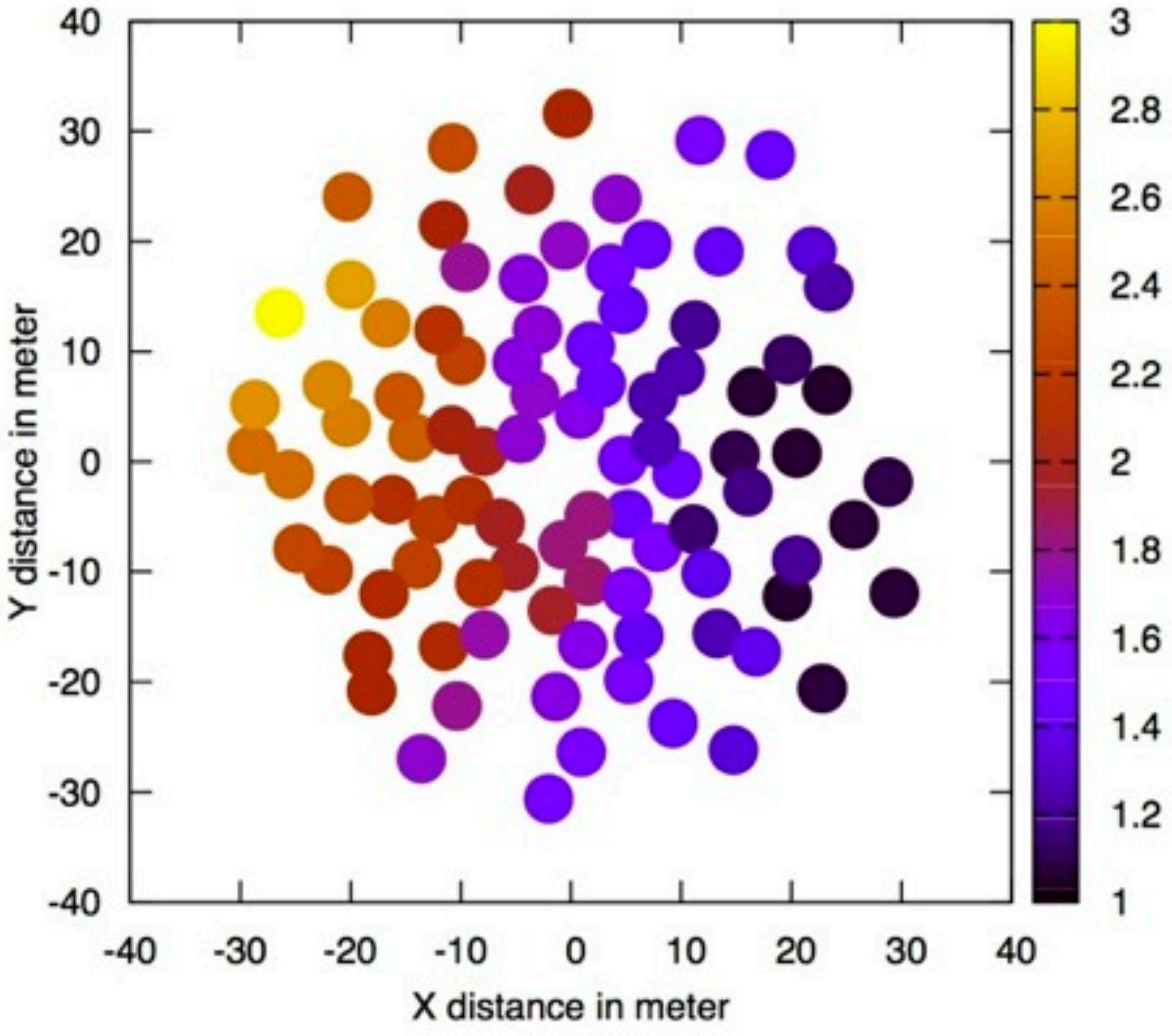
Some repetitive RFI is found in sub-band 300
that seems to leak out of the cabinet



Radio-Frequency Interference

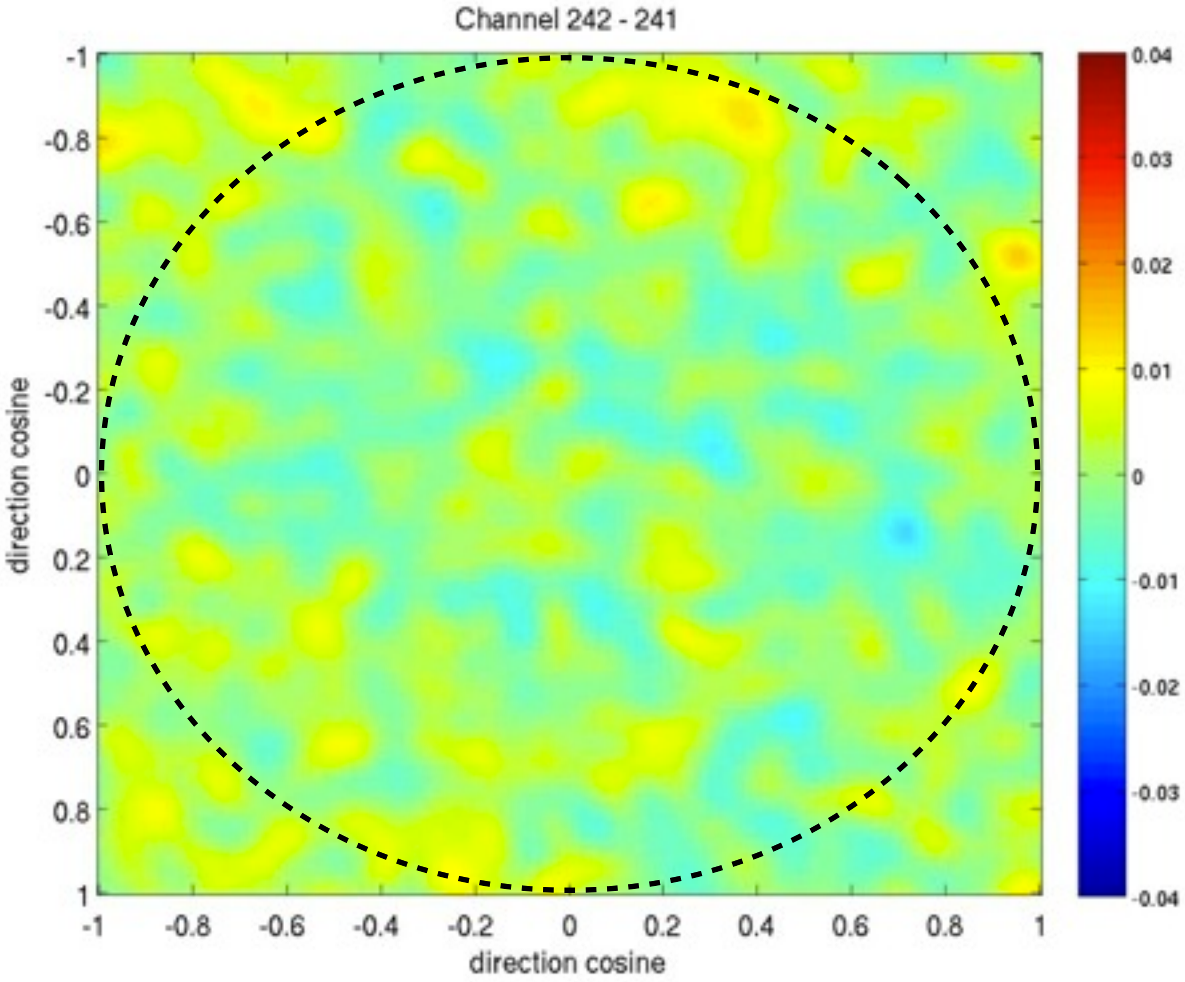
RFI levels show a distinct pattern over the DE602 array for sub-band 300 (repetitive signal) in both xx and yy, pointing in the direction of the electronics cabinet. Maybe RFI shielding is not a strong enough or internal RFI (electronics to electronic?). No issues for station correlations, but it could be for total-power measurements.

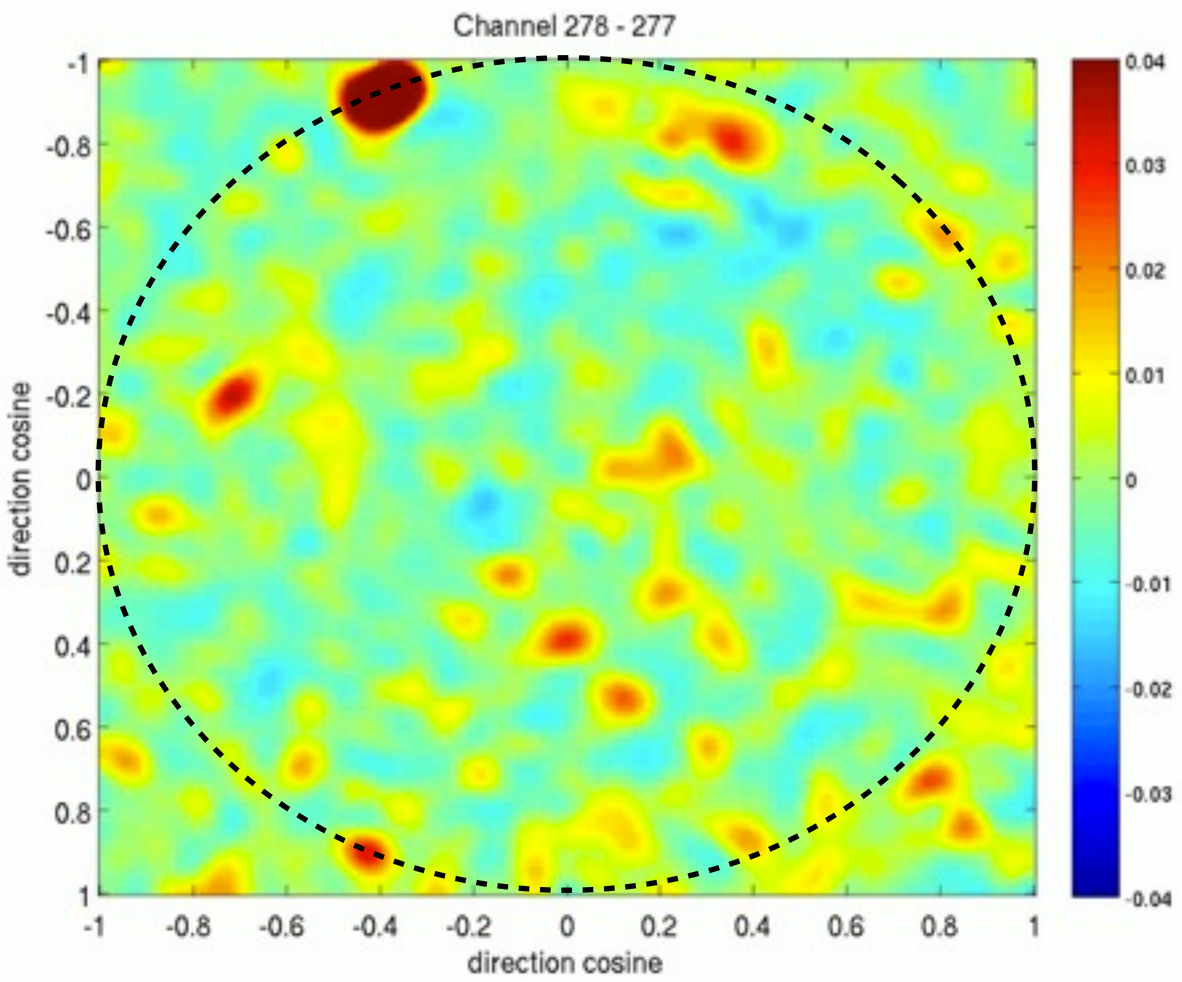




Radio-Frequency Interference

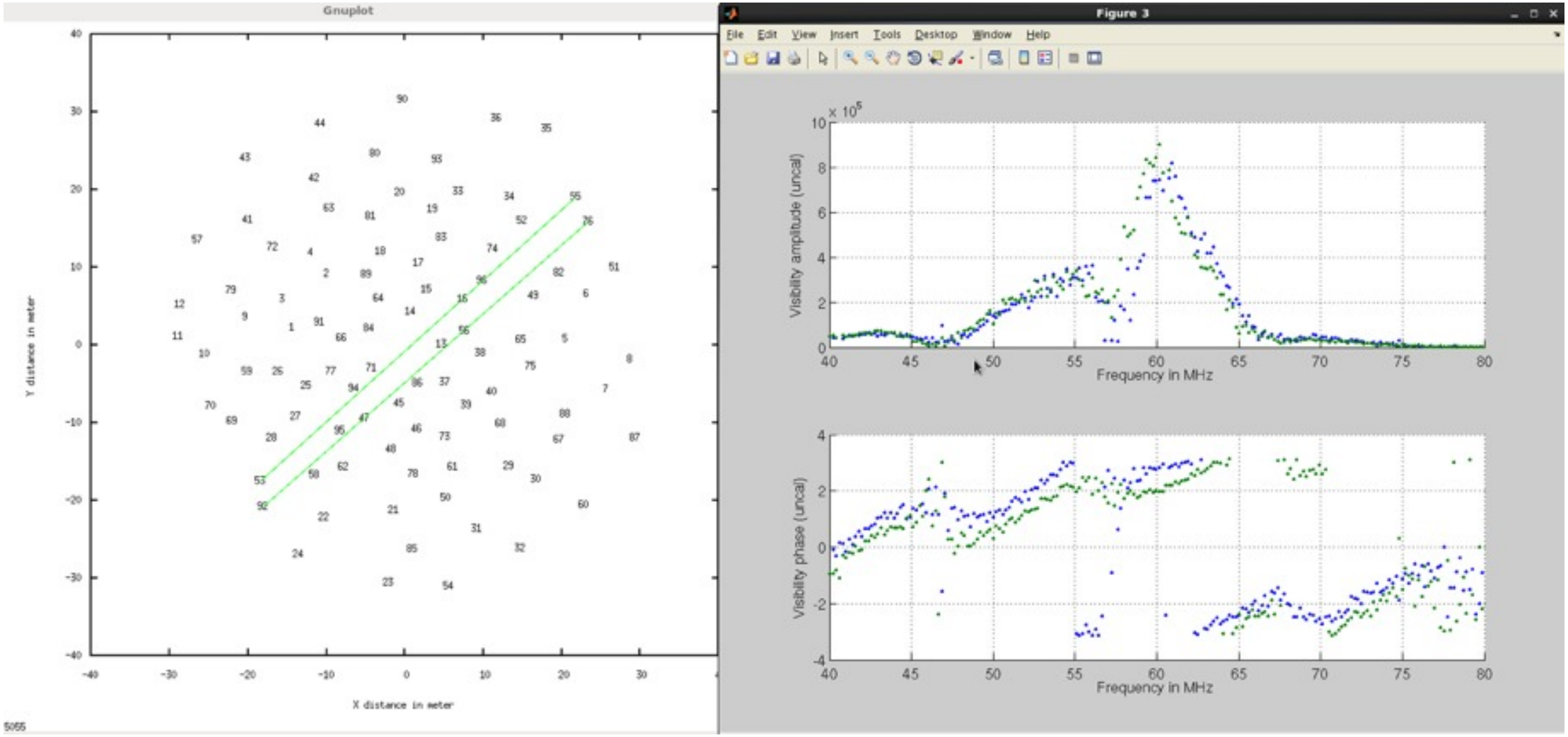
To asses the quality of the data further and if there are RFI source in the near/far-field (sky or surroundings), it's easiest to make difference maps after or even w/o gain calibration (varies slowly).





Redundancy Calibration

Calibration if very hard w/o a good model, but the 96-dipole station has a lot of redundancy that can be use for calibration. Similar baselines show different amplitudes/gains. With enough common pairs this allows (relative) calibration of the array



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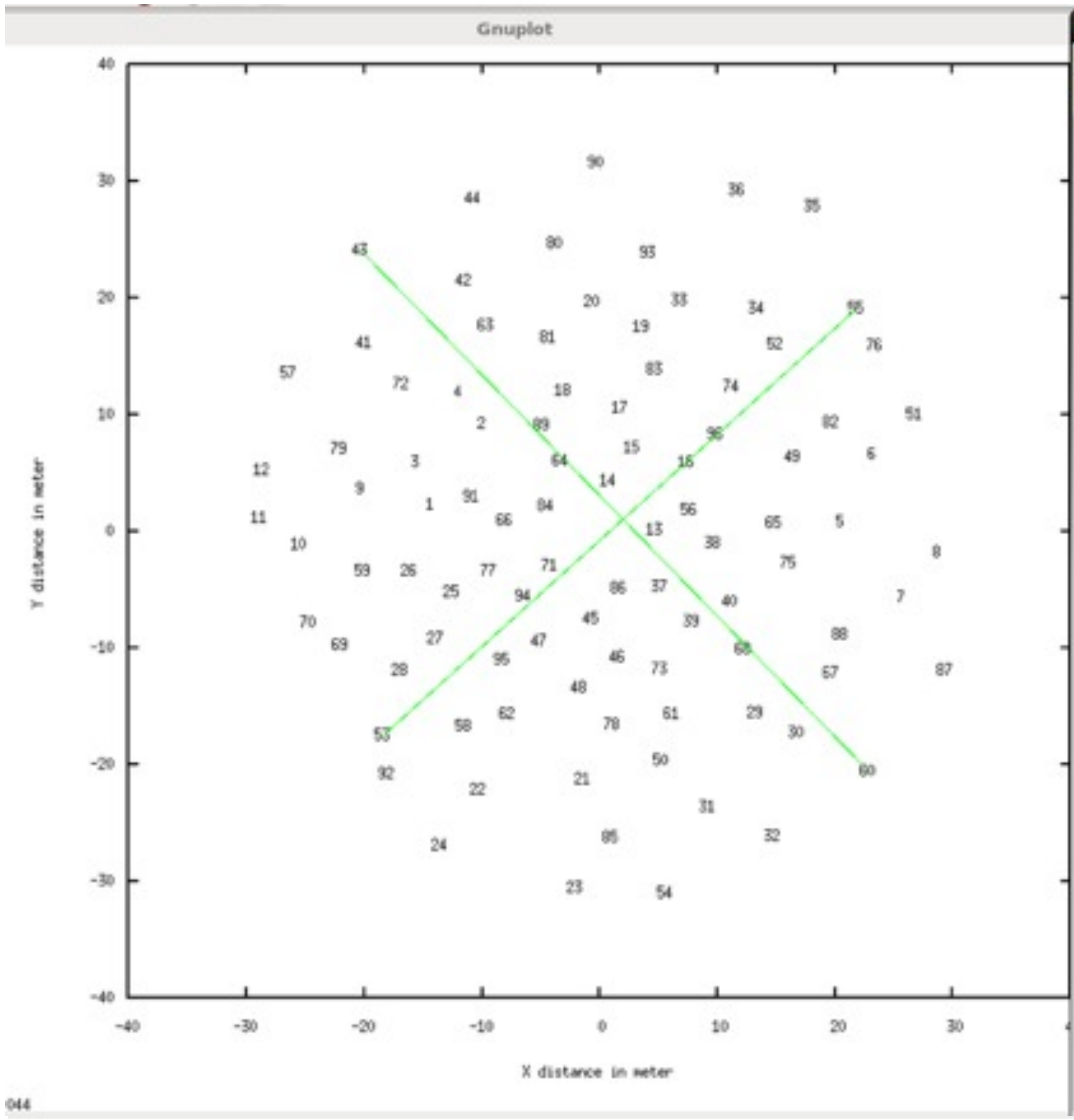

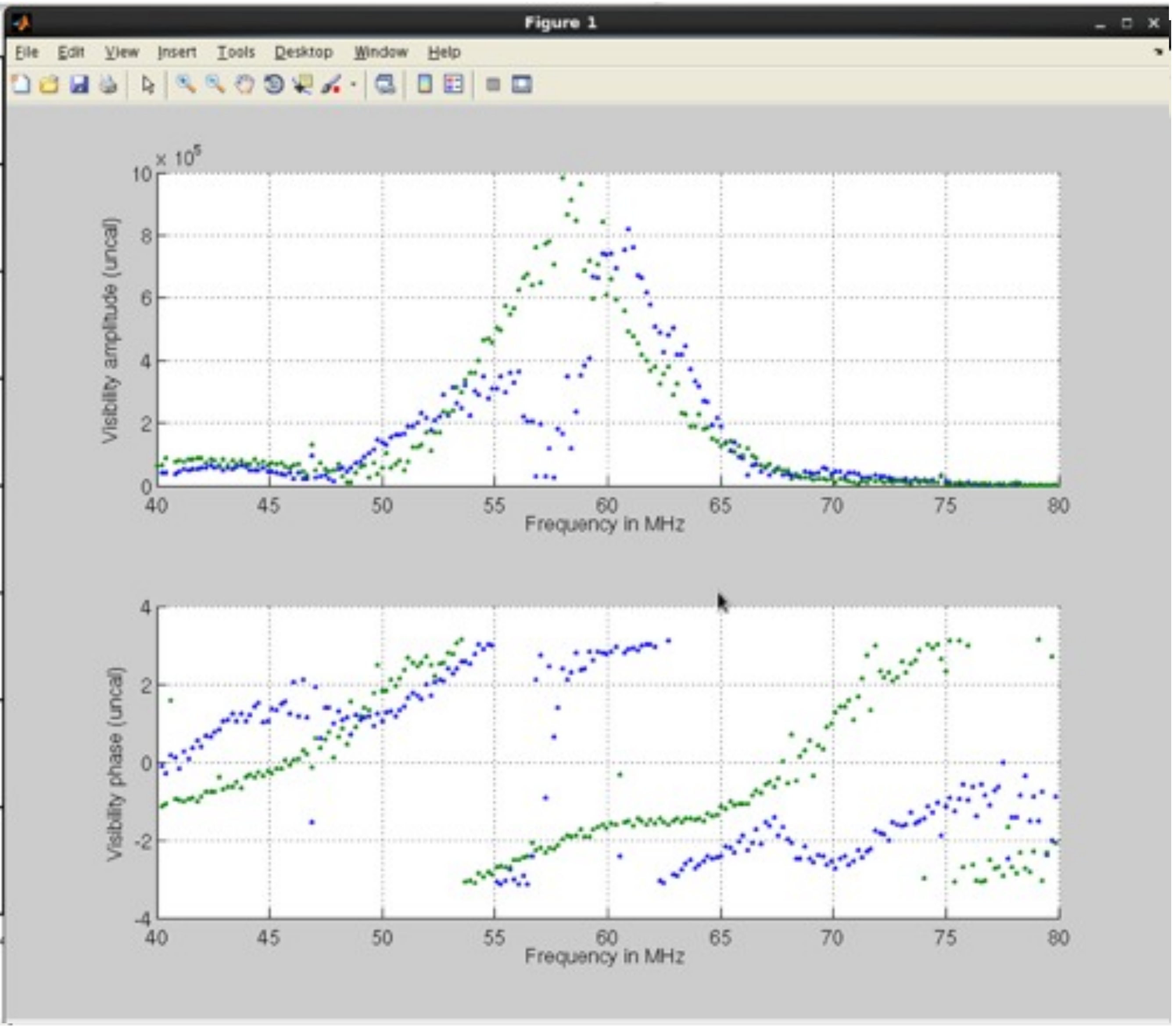

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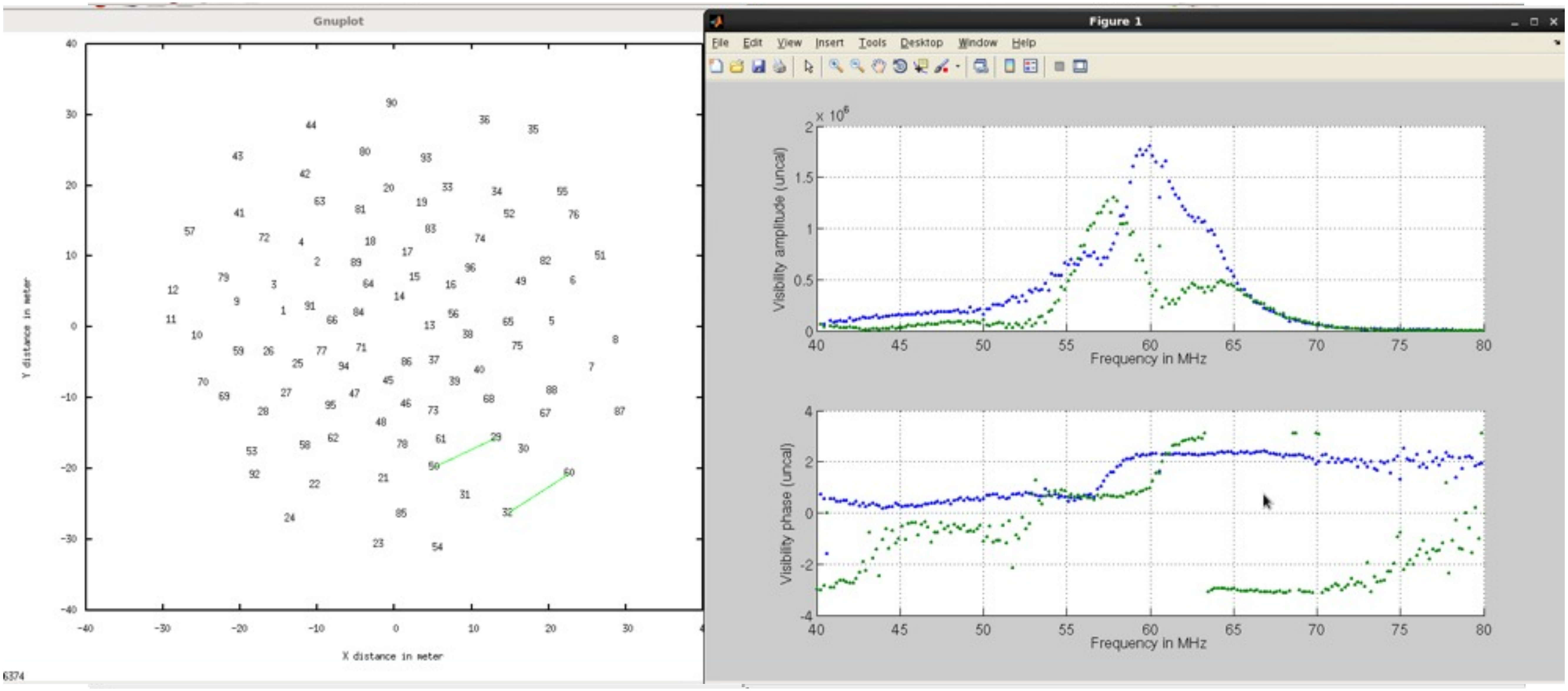

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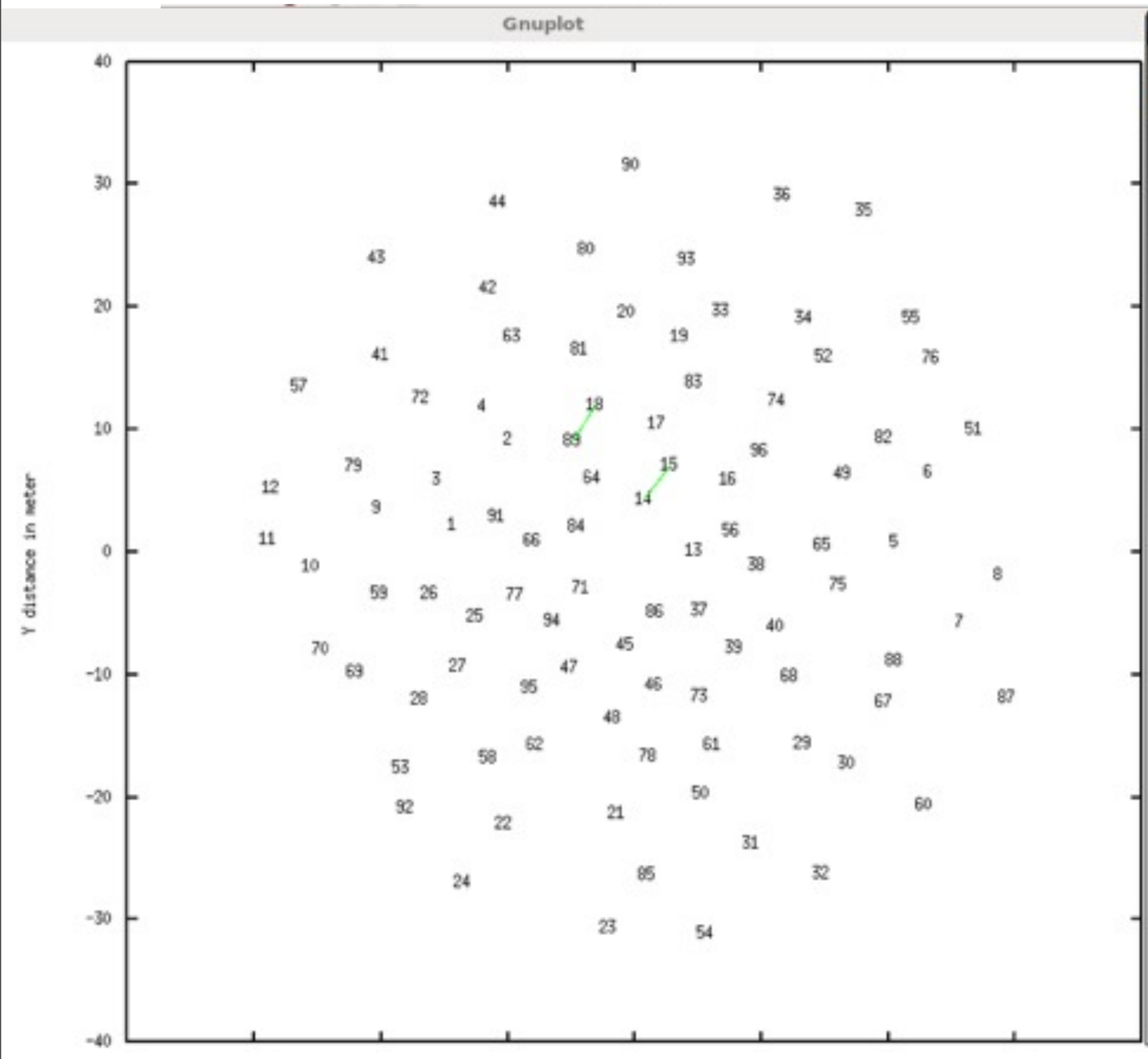
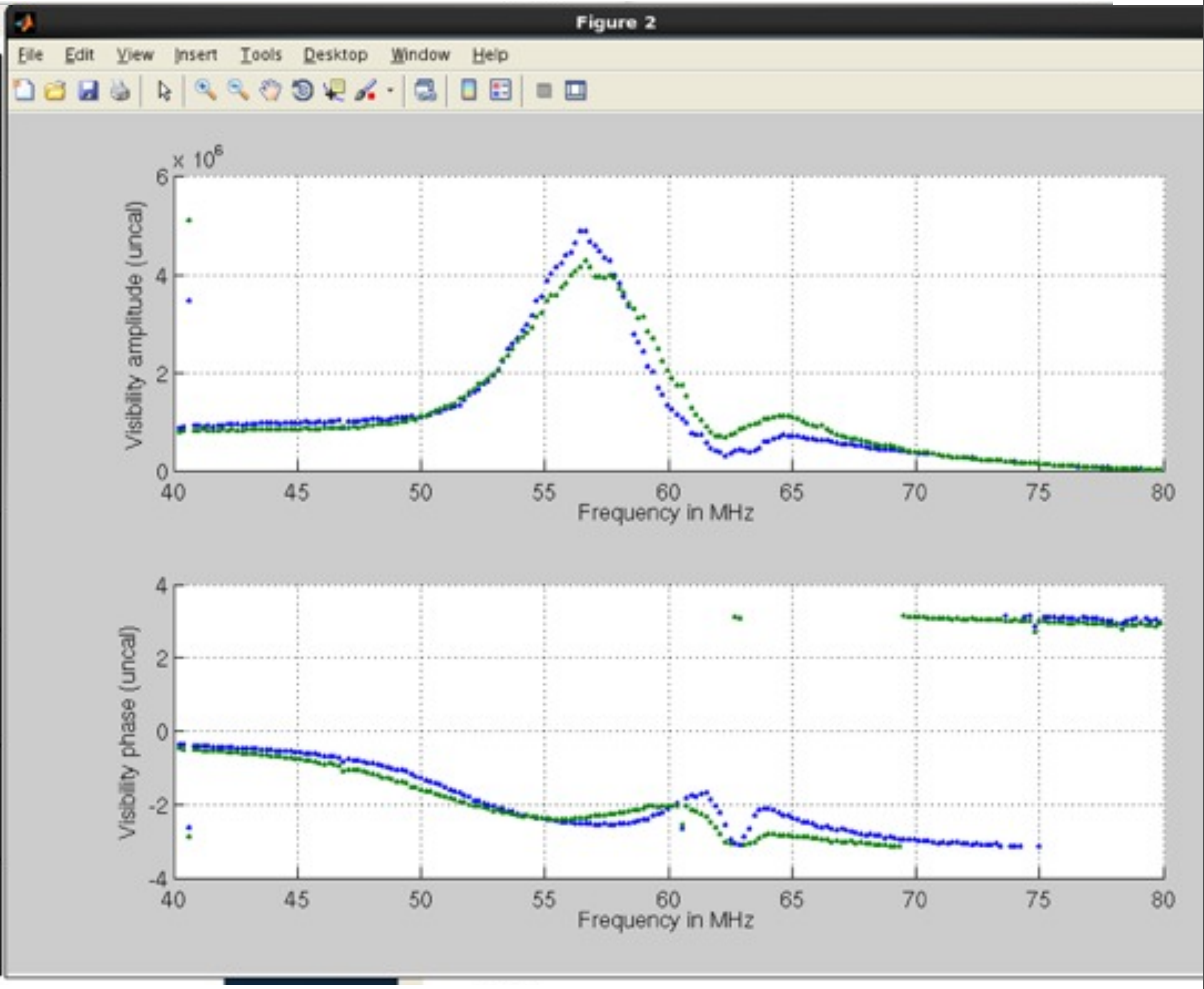
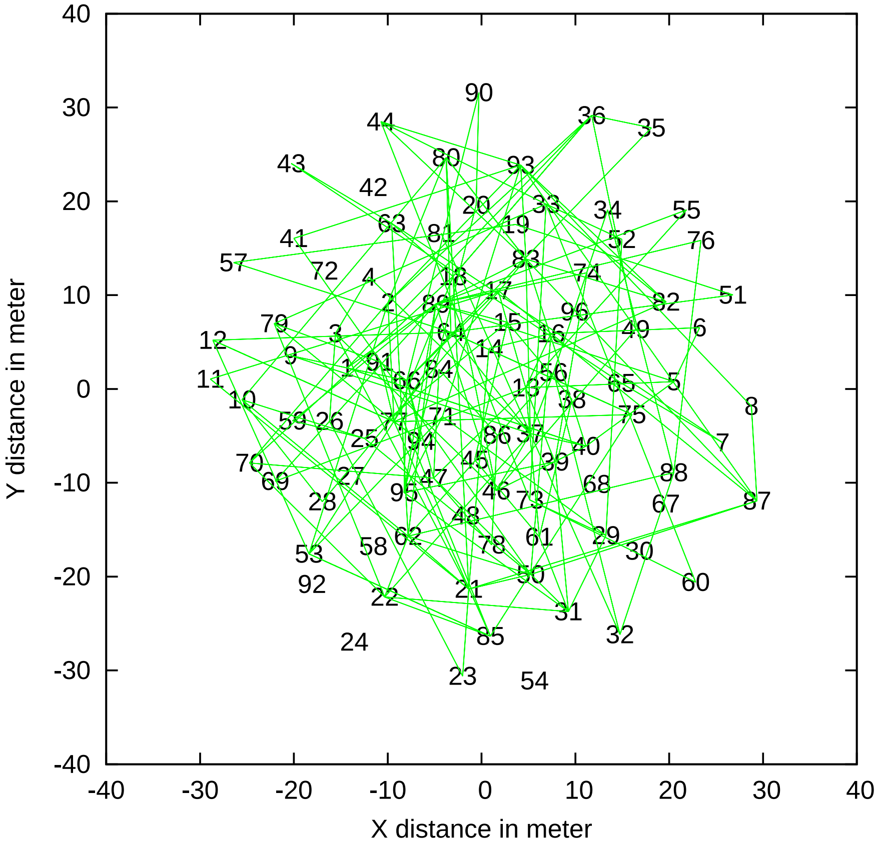




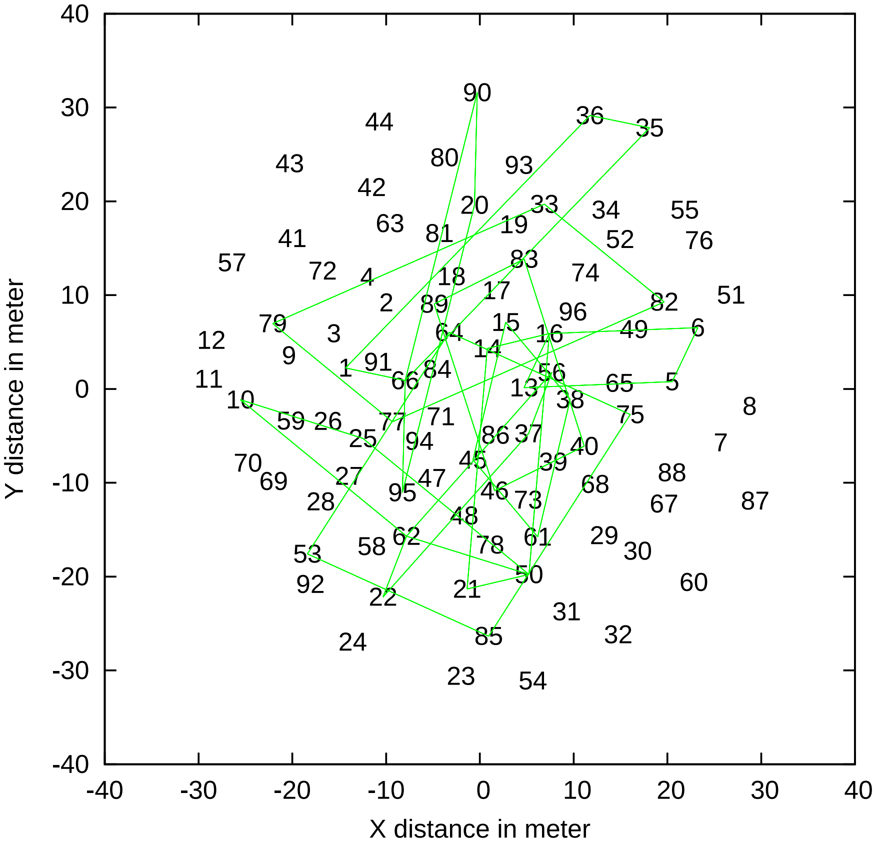
Redundancy Calibration

Calibration of the data needs to be done using either a sky-model that is obtained from the data or through redundancy calibration. Are there enough redundant baselines inside an LBA station?

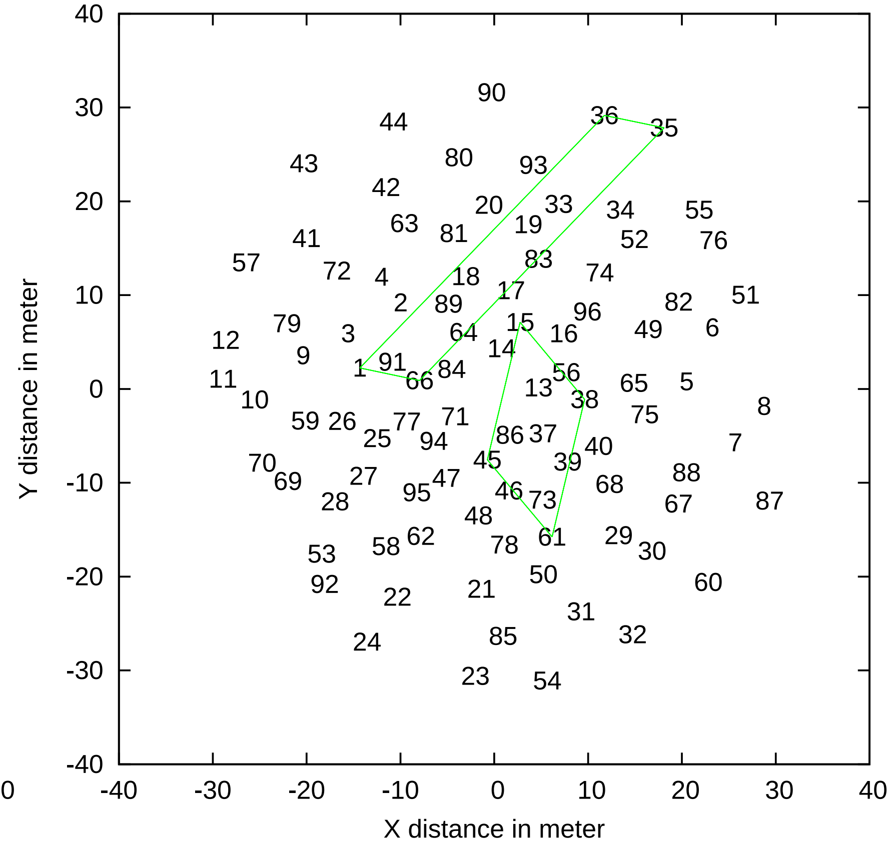
0.1λ



0.05λ



0.01λ



There are many <0.1 λ baselines that can be used. But enough?

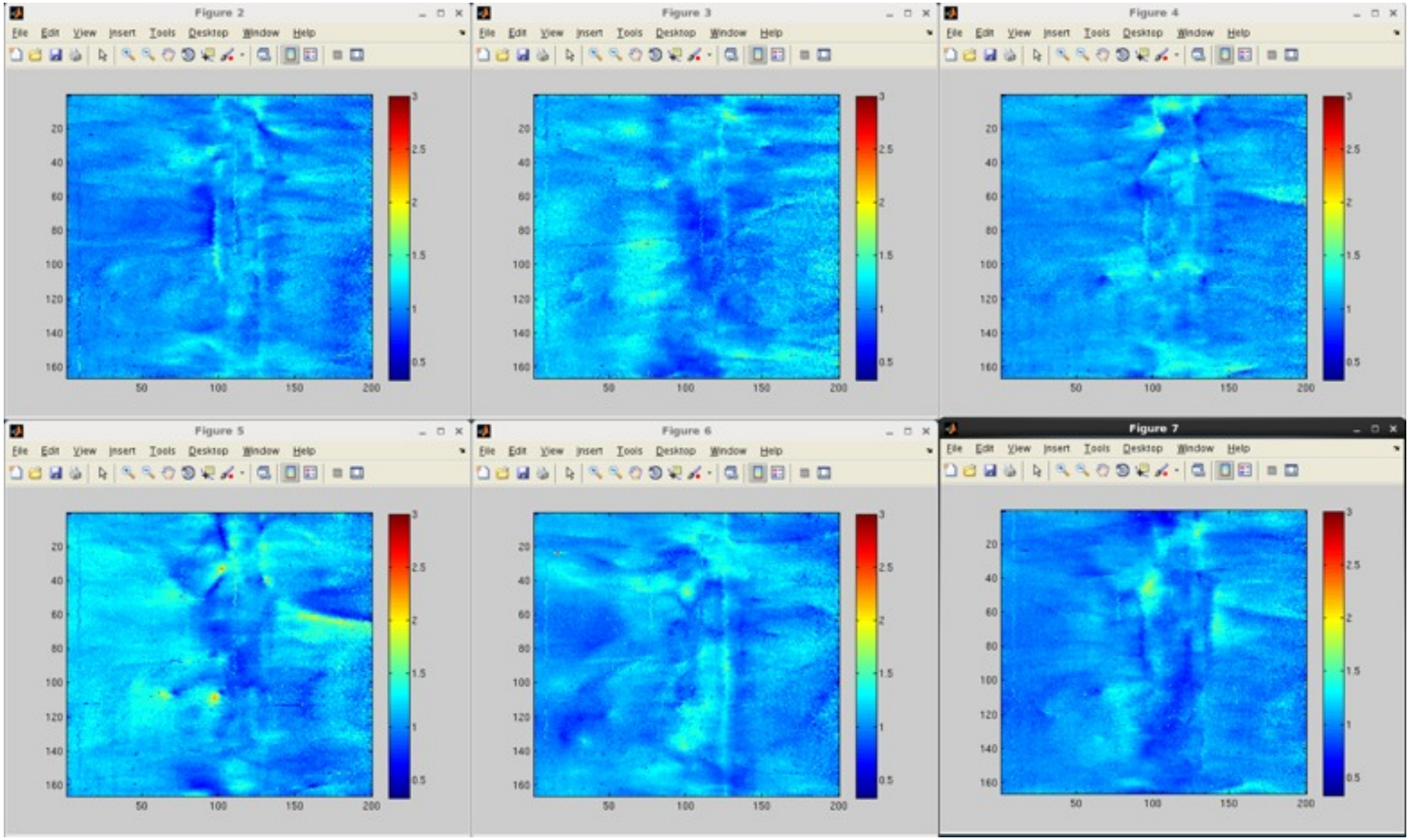
Redundancy Calibration

Gain-solutions show considerable structure: beam, ionosphere?

SNR is good, so promising road to calibrate the system.

Gain-solution amplitudes

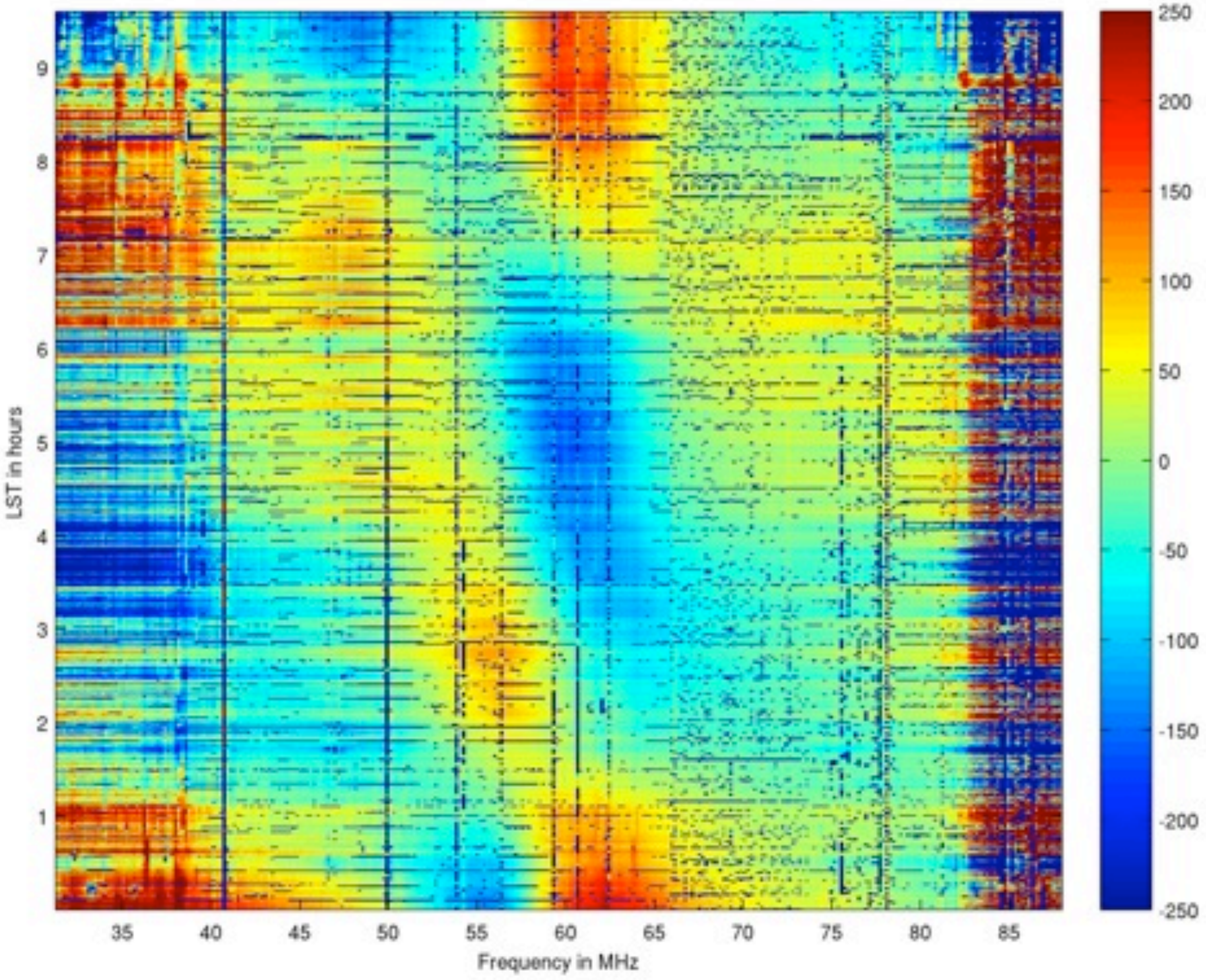
6 dipoles
24hr x (40-70MHz)



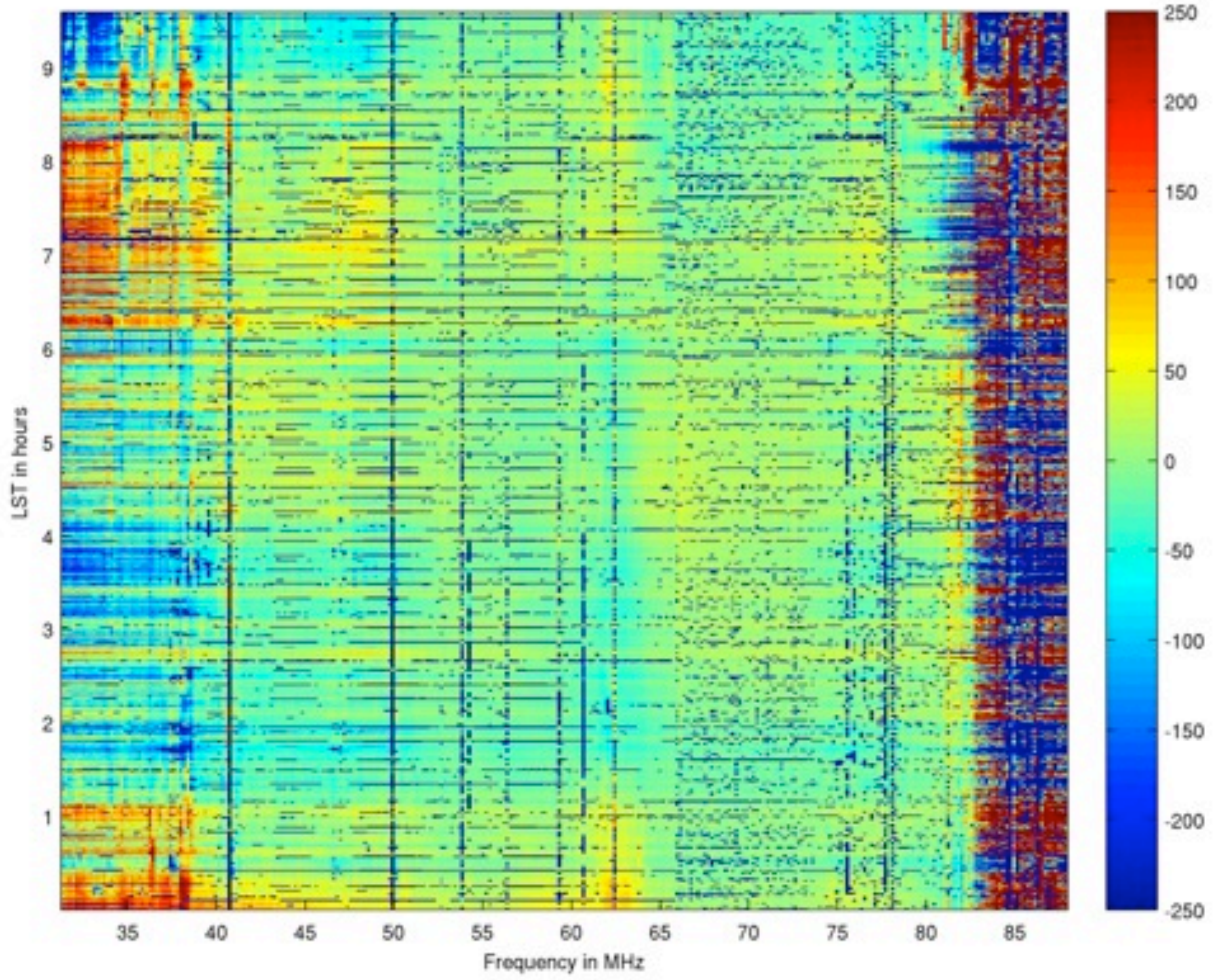
Mutual Coupling

The sky will show mutual coupling, but the EoR will not.

Embedded Dipole

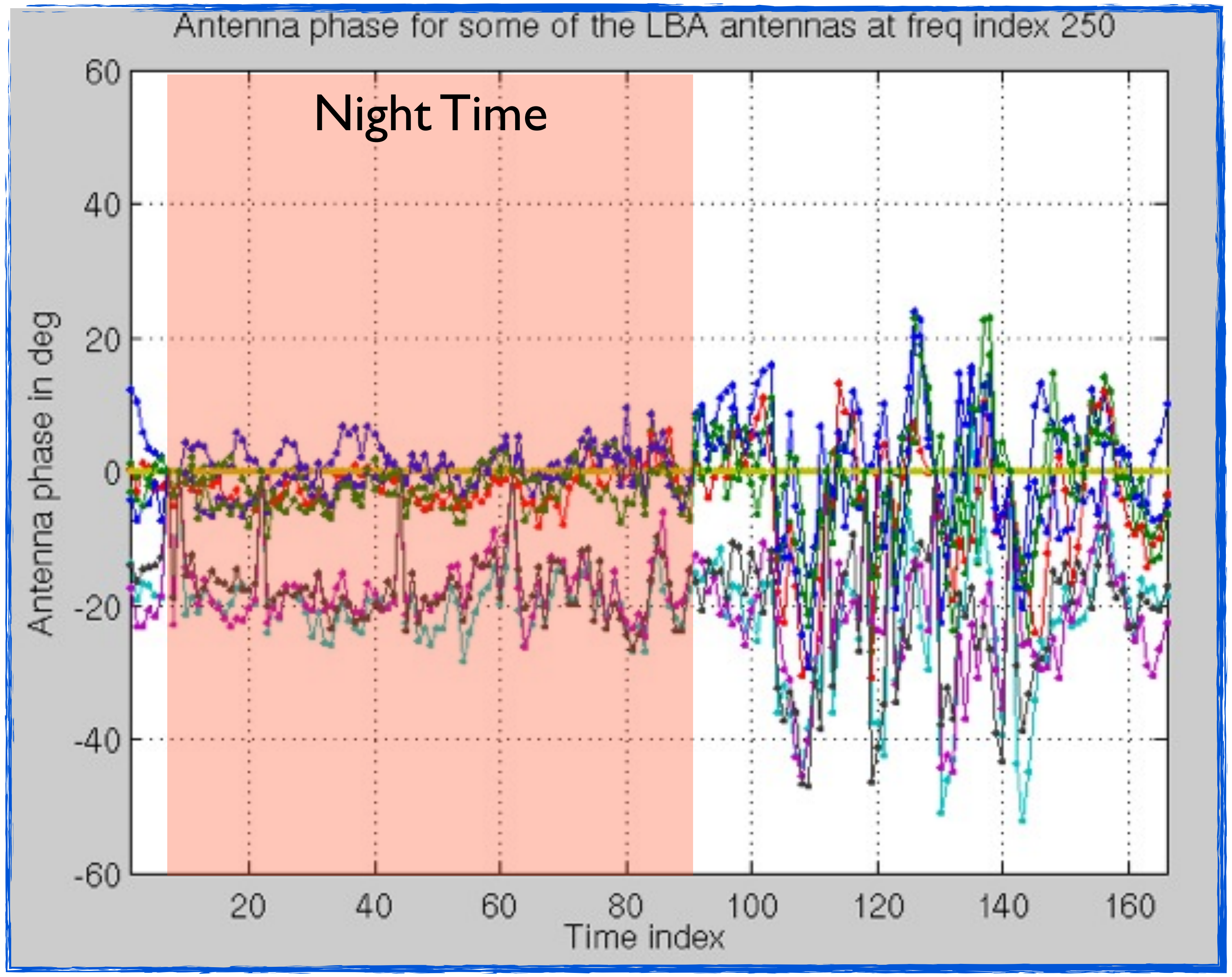


“Isolated” Dipole



Ionospheric Effects

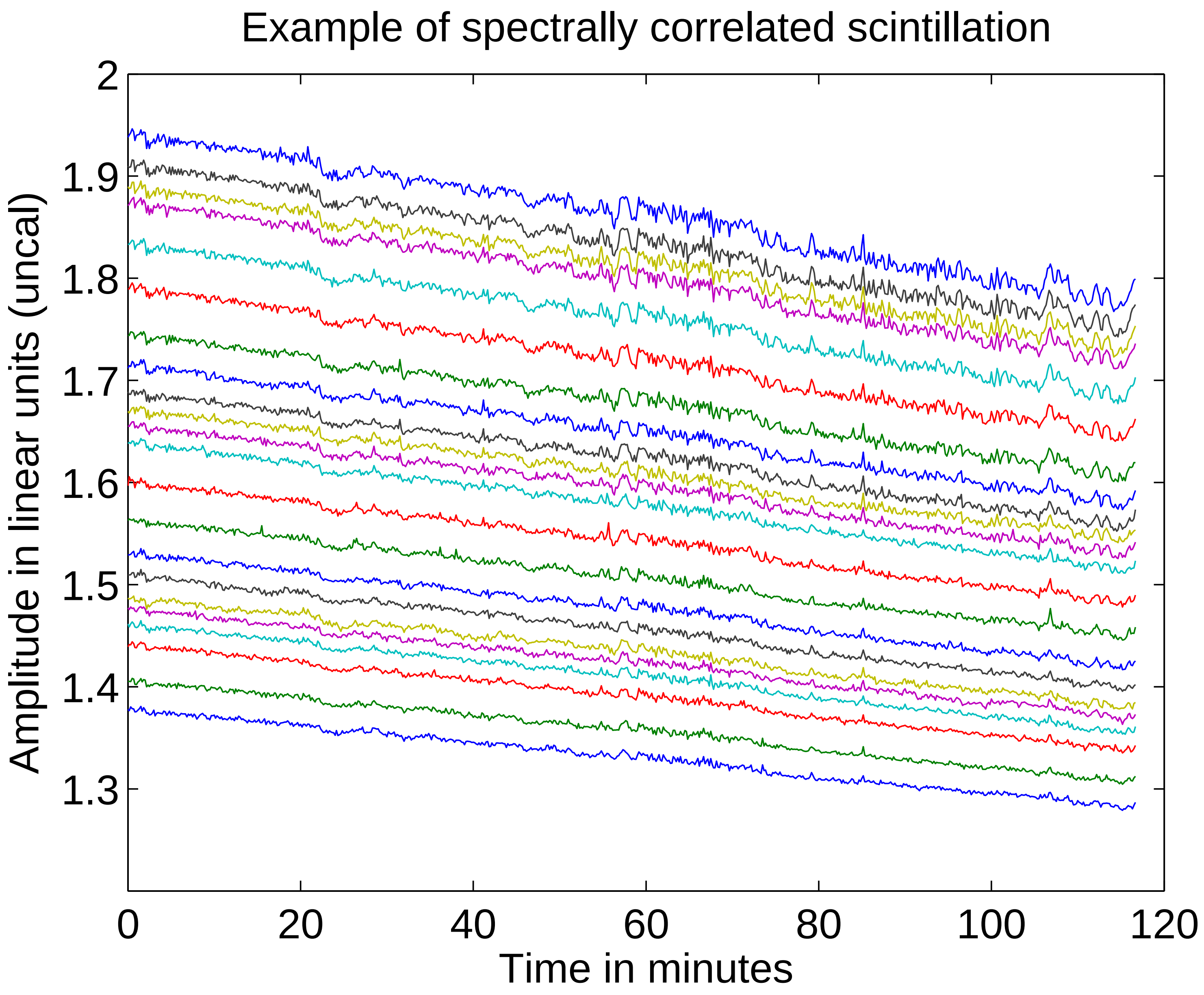
Night-Day Time effects on the dipole phases.



Phase solutions on long baselines show strong and correlated corrections due to the ionosphere *(possibly the lack of the sun in the sky model is still an option).*

These waves are very large (100s of km) and cause phase-gradient over a station beam, but also directionally-dependent effects for the dipole beam

Ionospheric Effects



Total power for all dipoles flickers (few%) on time-scales of minutes, is spectrally relatively smooth and correlates between all dipoles.

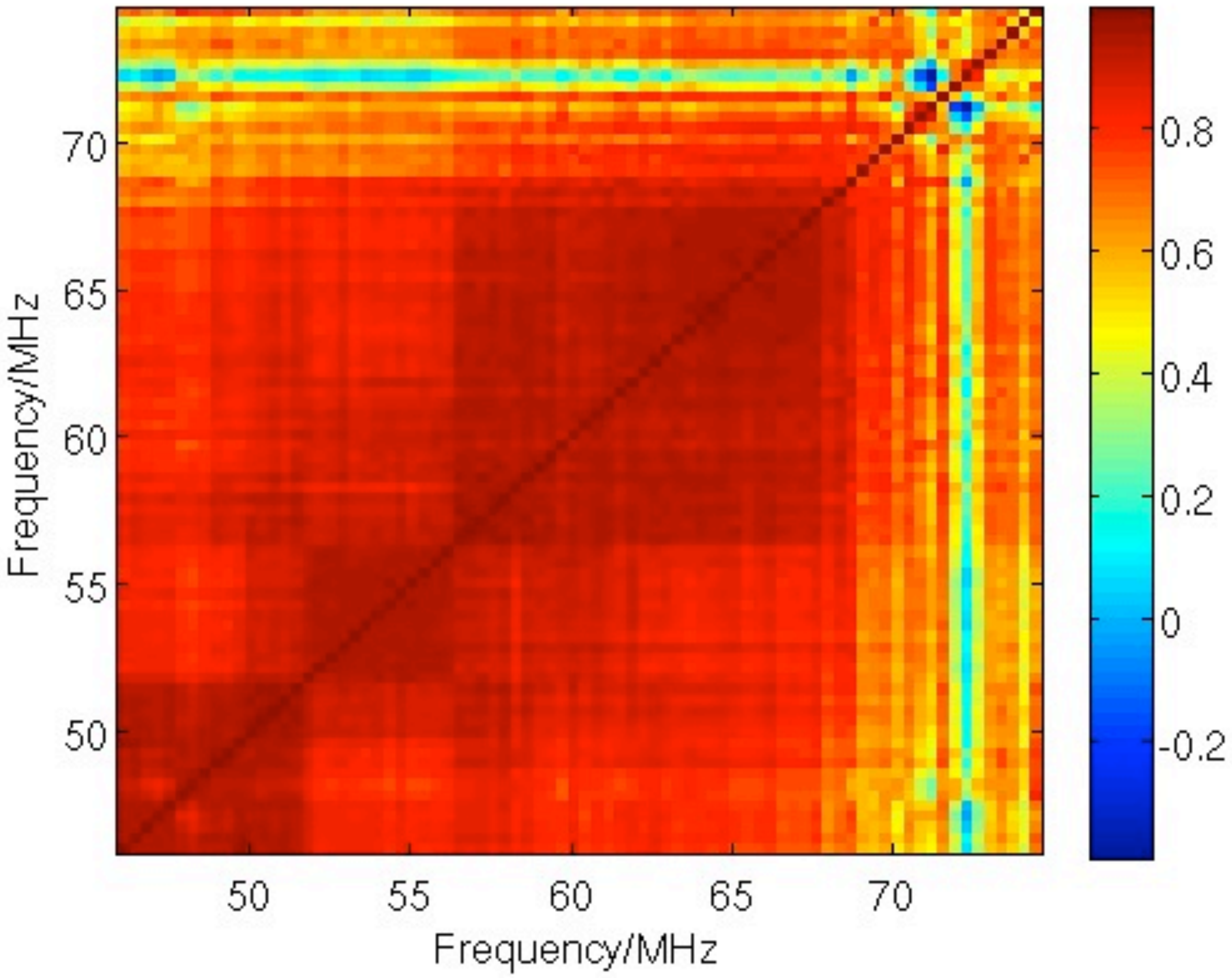
Ionospheric Scintillation
(refraction or diffraction)?
Ionospheric Absorption?

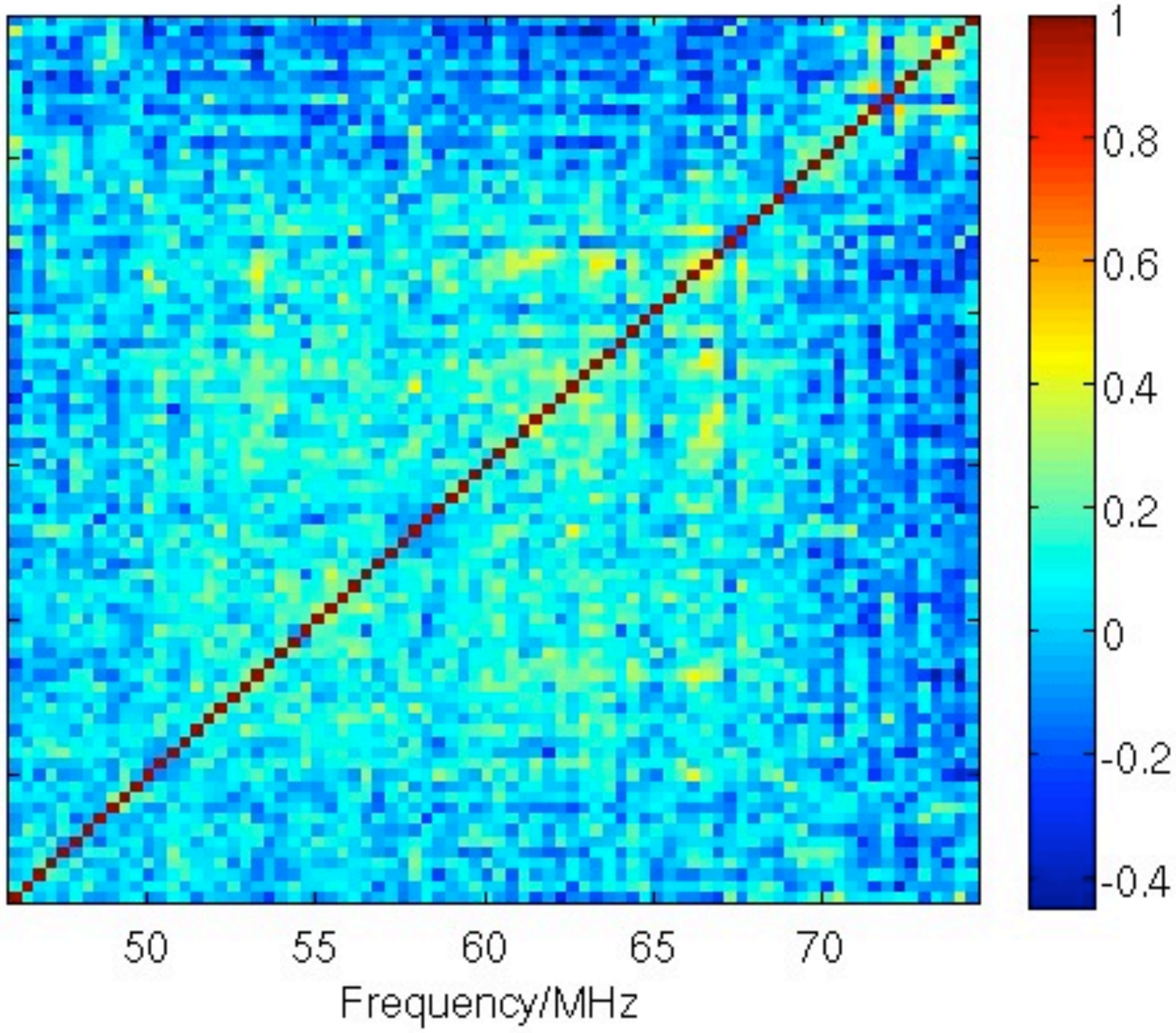
These effect can also be directionally dependent.

Ionospheric Effects

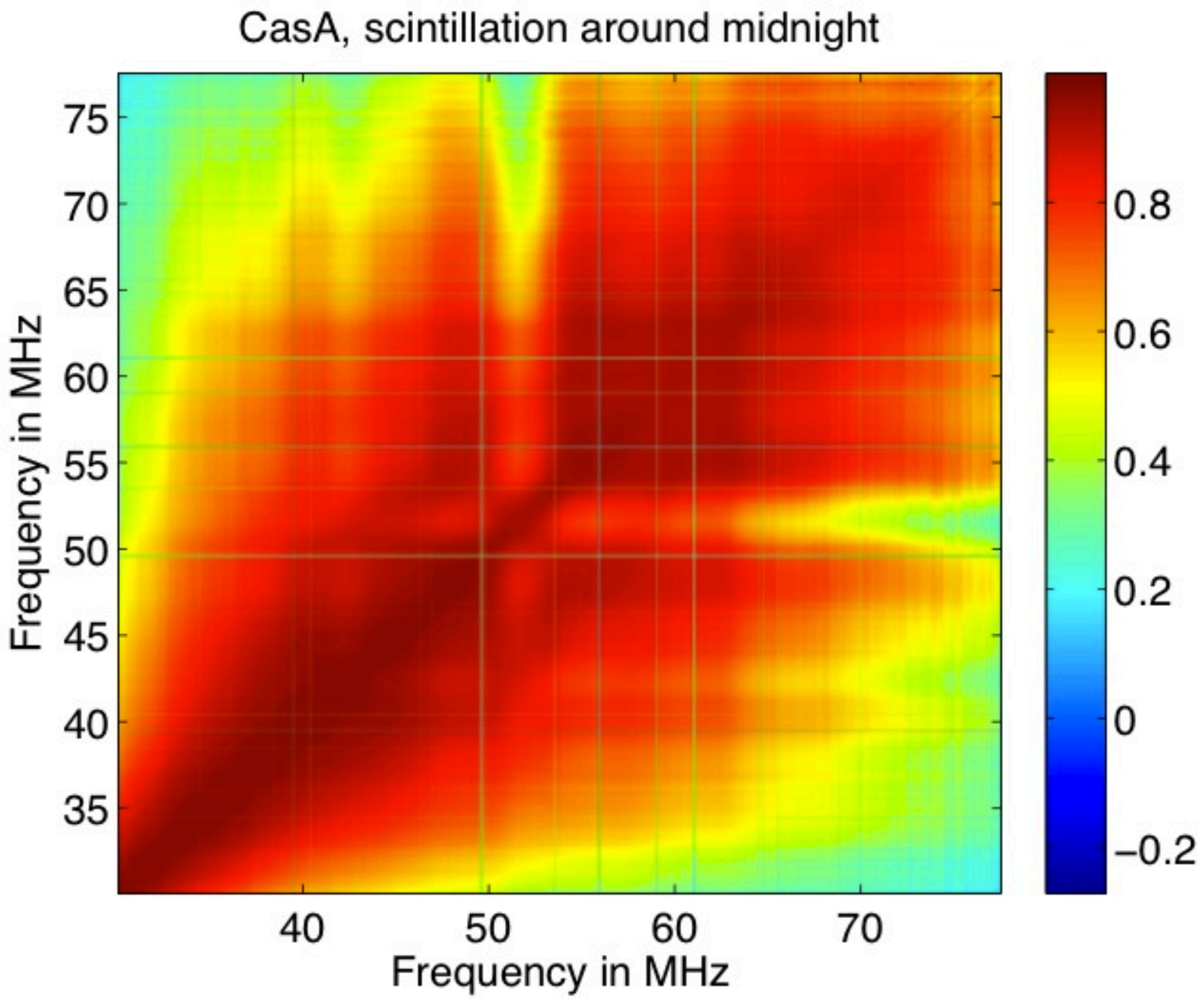
Plot showing the correlation between scintillation (power vs time) on different frequencies. Each freq here is a sub-band. The channel showing low correlation has RFI in it. The square features are not well understood at the moment.

Same plot as above but in the absence of scintillation showing the uncorrelated nature of thermal noise.





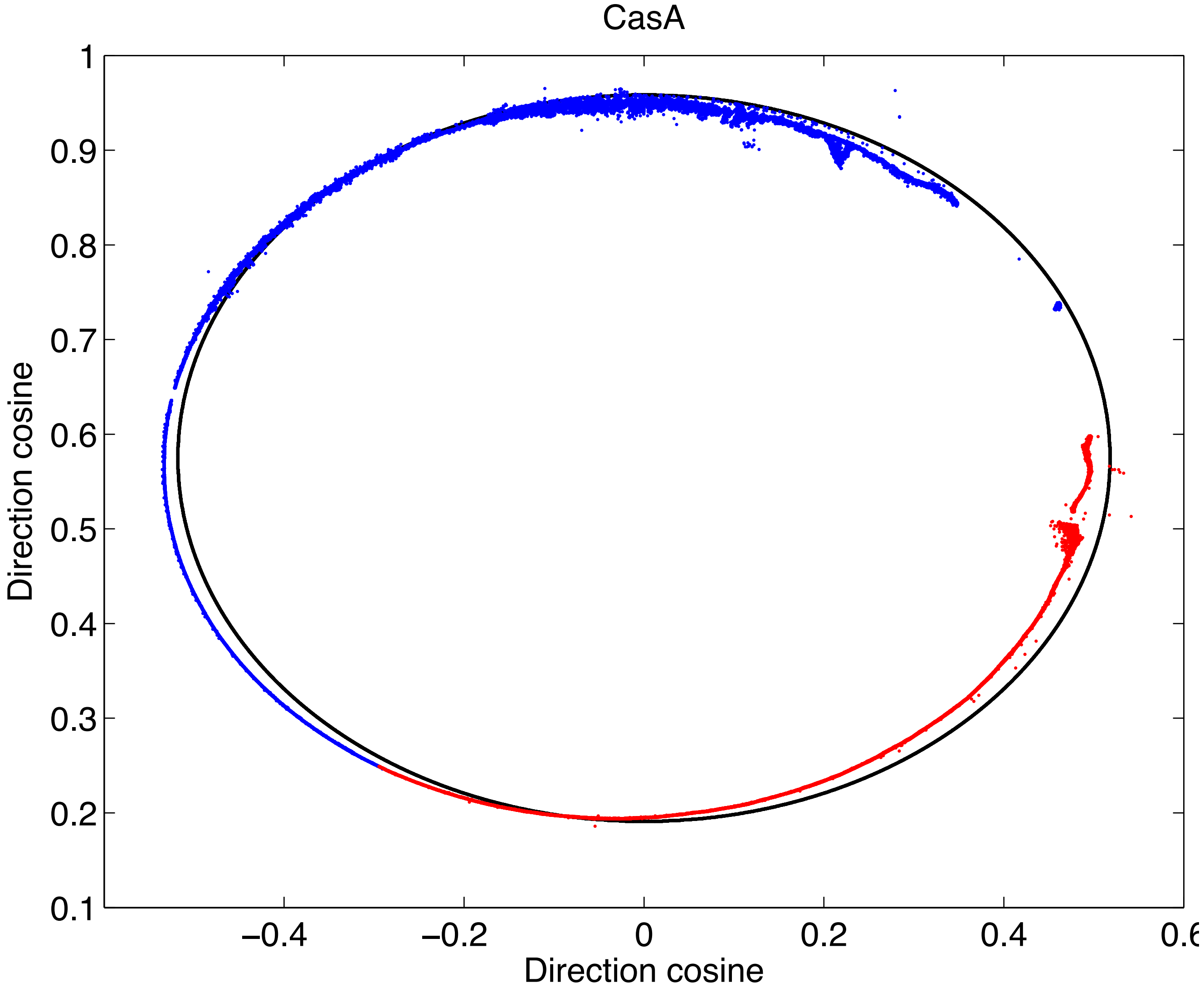
Ionospheric Effects

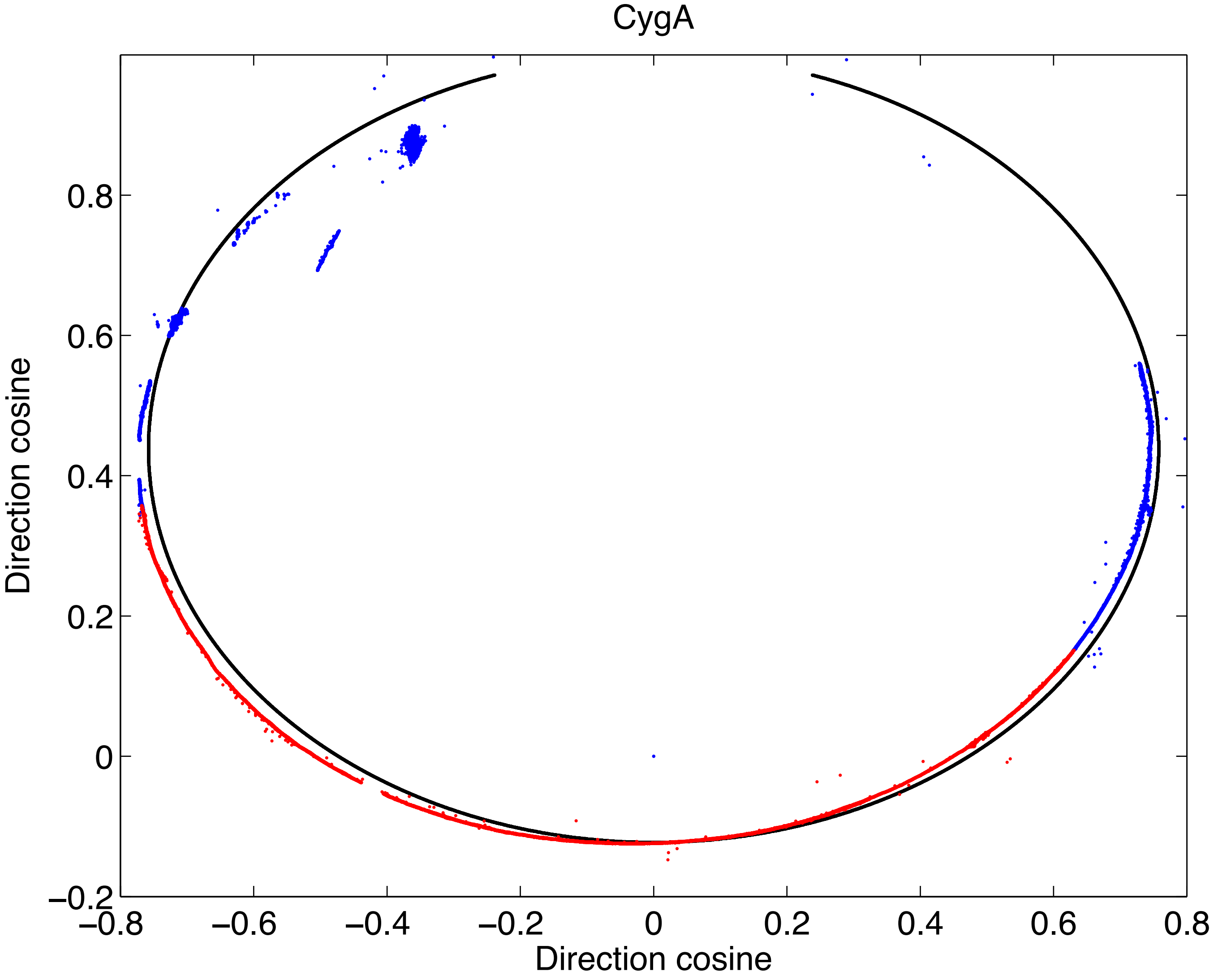


Same but for LOFAR array data with much better time/freq. resolution.

Ionospheric Effects

Refractive effects near the horizon causes sources to “dance around”. Tests on CasA/CygA show this very clearly. This could lead to (de)magnification of these source, hence total power fluctuations.

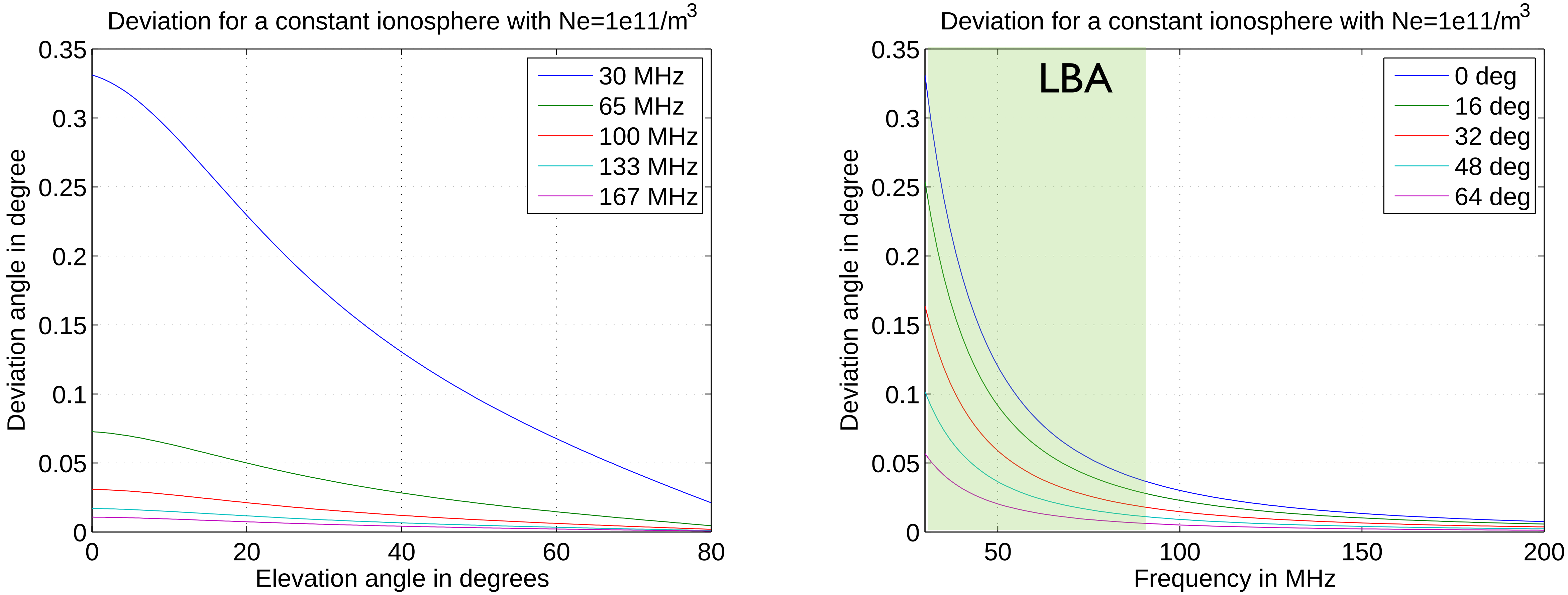




Ionospheric Effects

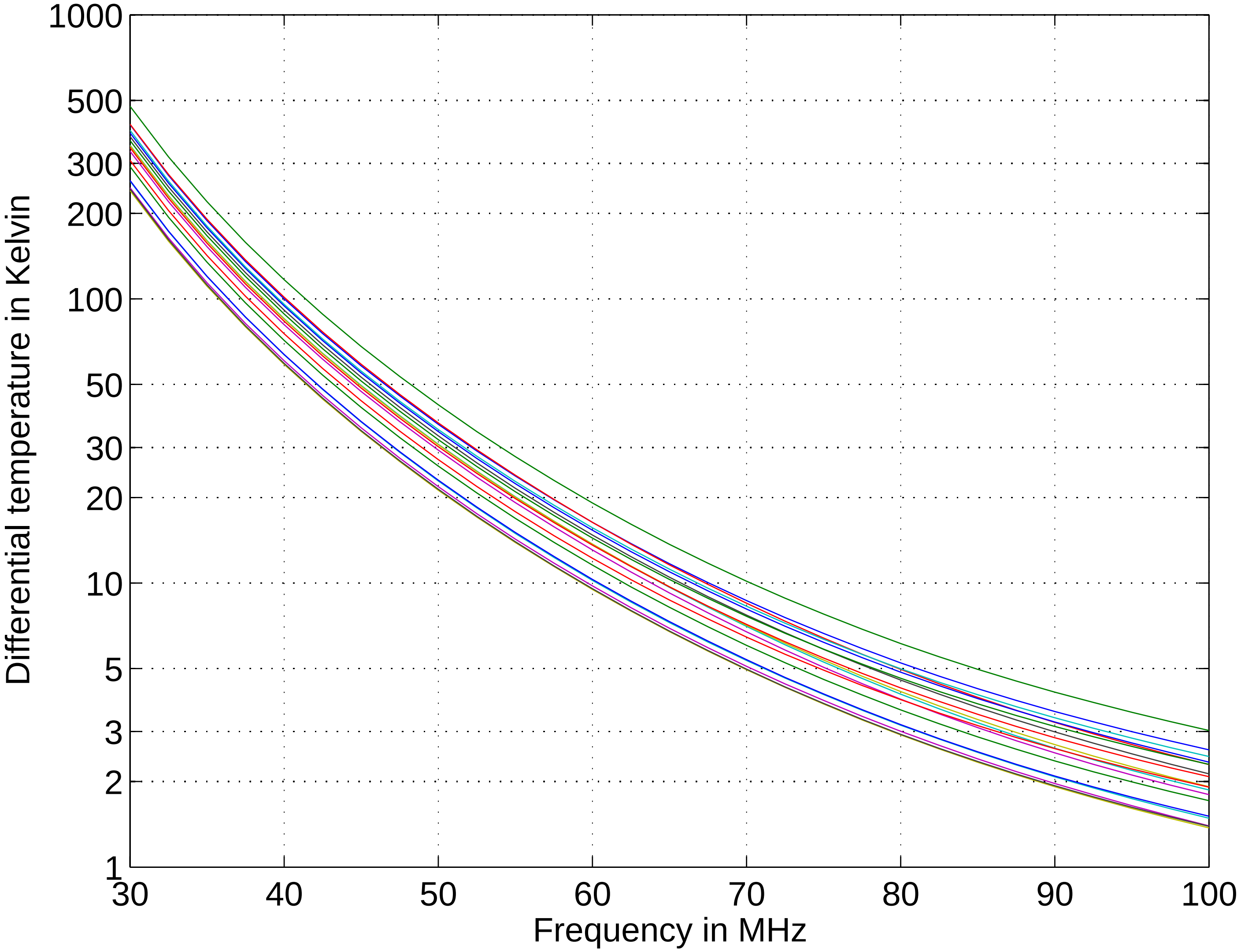
The ionosphere for a 2π FoV acts as a converging refractive lens that is frequency dependent. Hence power from the sky is enhanced and the effect is strong toward the horizon and at longer wavelengths.

(talk: Vedantham)

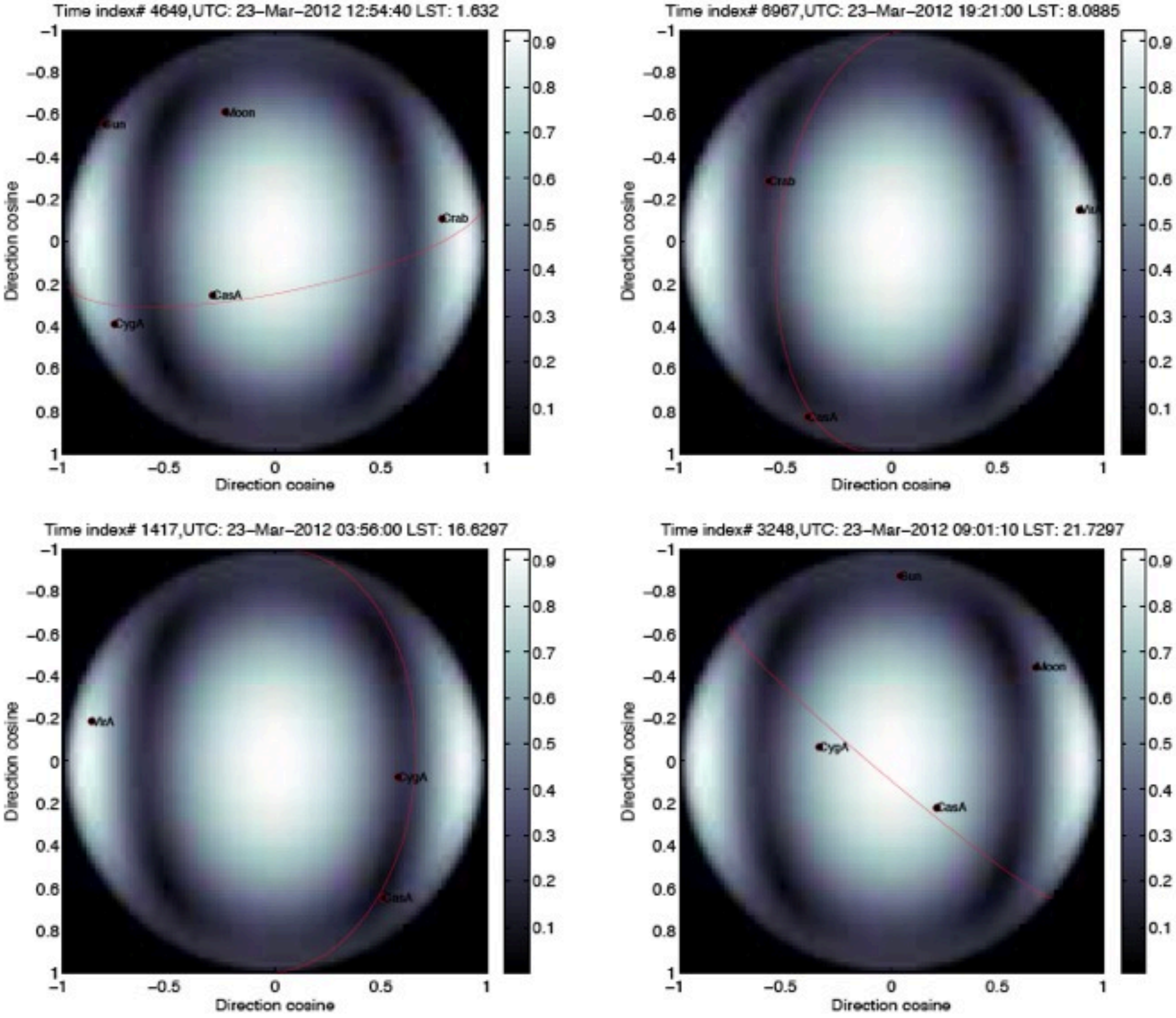


Ionospheric Effects

Refraction leads to a change in T_b of the sky as function of frequency



Beam Effects

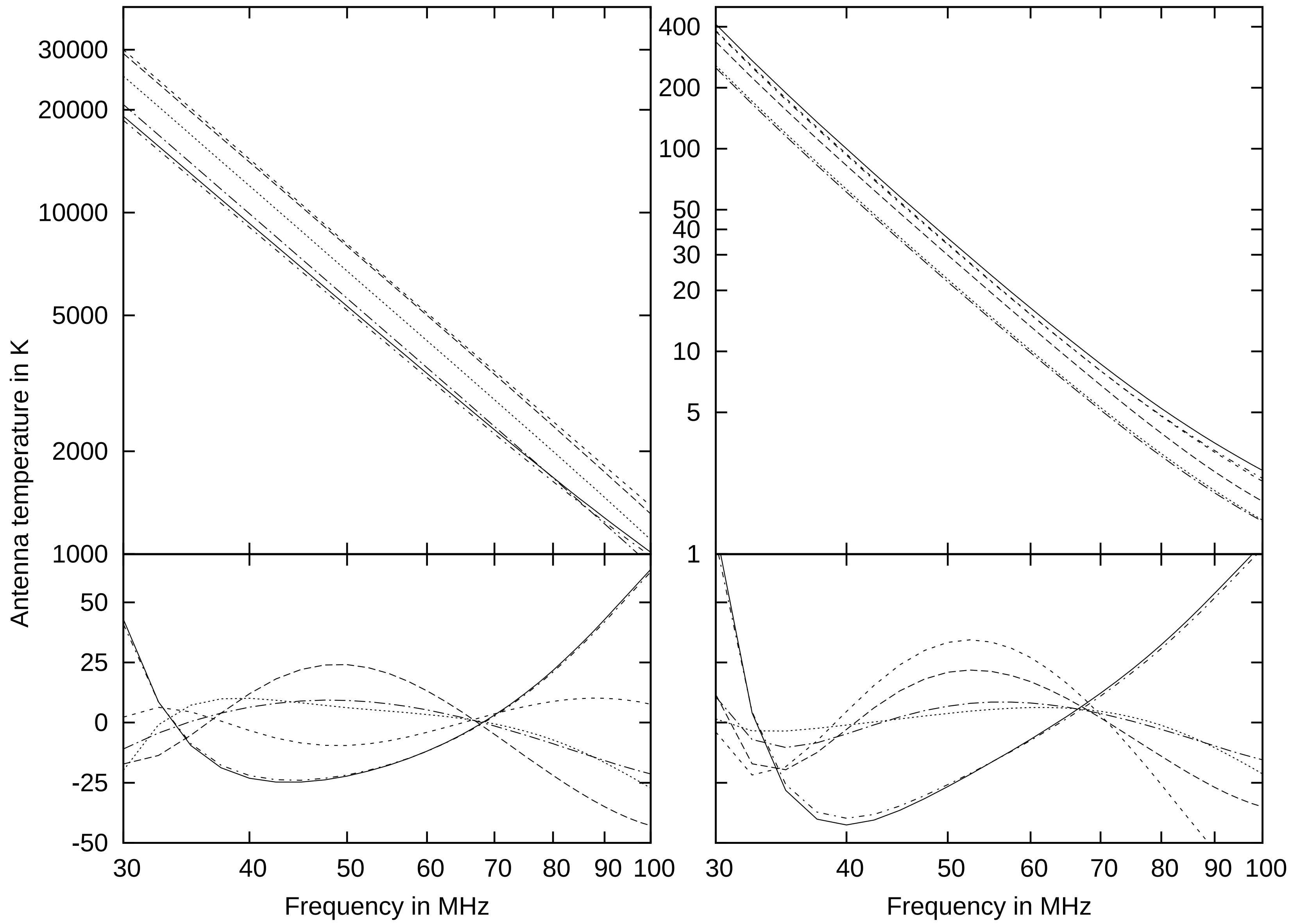


Beam shapes vary with frequency and have a hard cutoff at the horizon (although the ionosphere makes them effectively larger).

Structure/Sources moving through the side-lobes or nulls cause variations with frequency and time

Ionospheric Effects

Combining sky, beam and ionosphere.

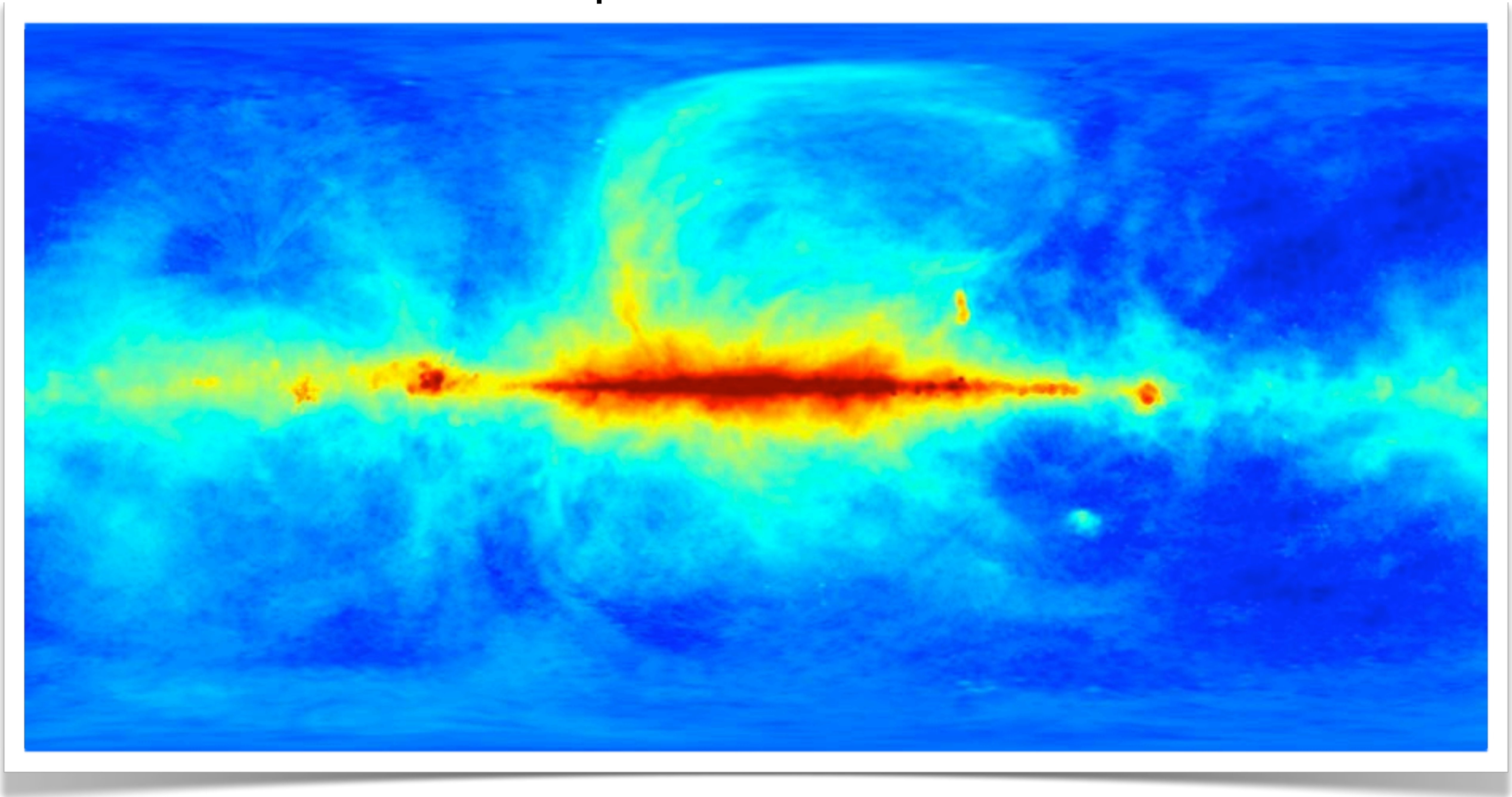


Folding ionospheric and beam effects into the model leads to a deviation from a simple power-law model in the dynamic spectra.

Hence even in a stationary case with only a revolving sky, do we find effects that alter the dynamic spectrum due to the ionosphere and beam.

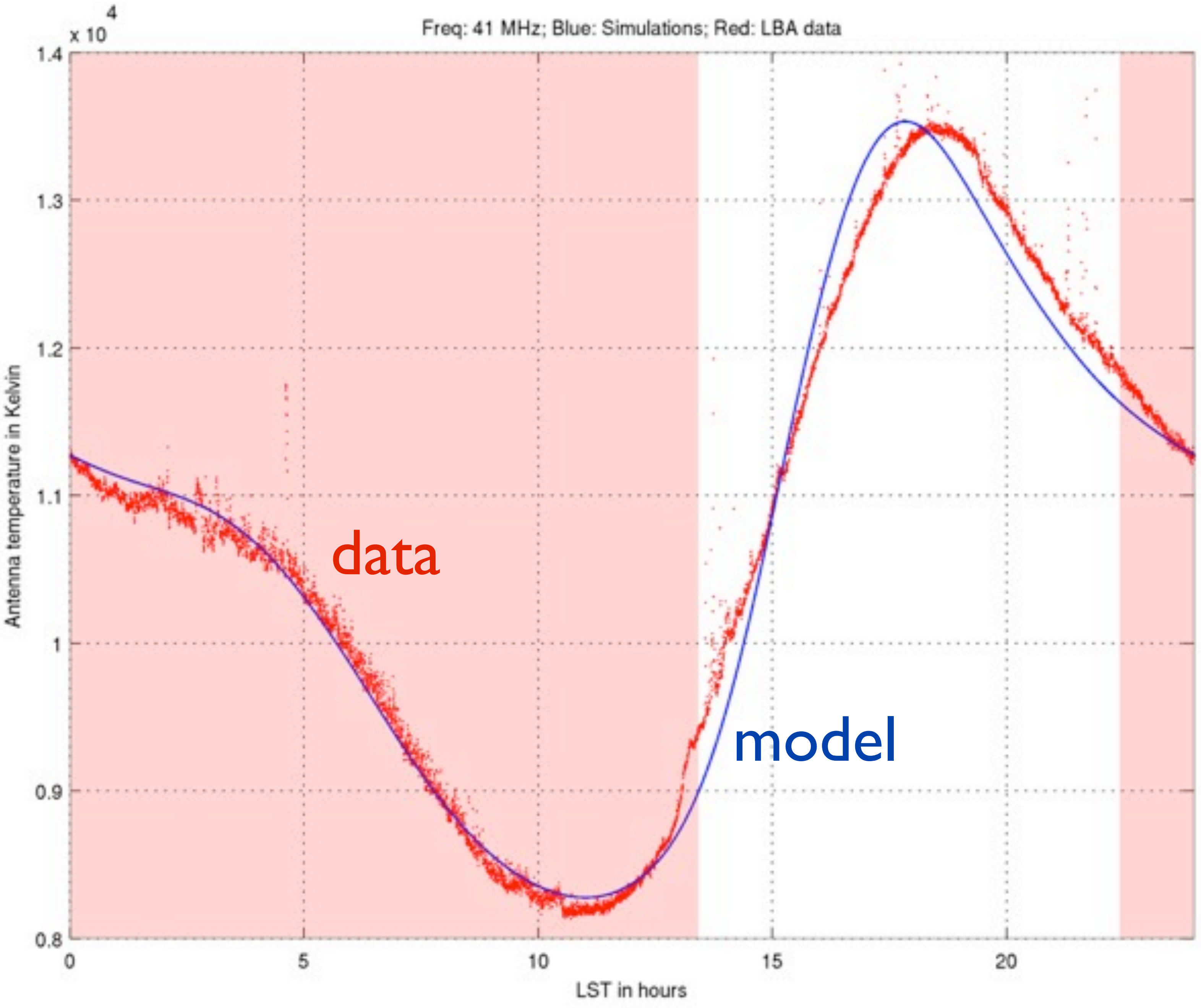
Raw Data Versus the Haslam Model

To assess the effects of FGs on the total intensity, we use the Haslam 408MHz all sky map, scaled as $T \sim \nu^{-2.55}$ to LBA frequencies, being one of the best and lowest-frequency maps available to date.



Raw Data Versus the Haslam Model

Remarkably good agreement between a simple sky+beam model and the data is achieved, suggesting that (data-model) could be analyzed (non-)parametrically using BSS methods rather than the data itself.



The Haslam model is used with -0.7 s.i. down to 41 MHz.

The model is multiplied with a the LBA-dipole beam model. [Stationary ionospheric refraction can be included.]

The model is then integrated over the visible sky and the power is determined per time slice.

The agreement is already good!

A Very Steep Learning Curve

(1) RFI is an issue and originates partly locally (cabinet). It does not seem to be a showstopper yet and is less of an issue at the LOFAR-array level (with smaller BW and time slices and beam-forming/correlations reduce RFI)

(2) Station gain calibration is hard because a very precise time and freq. varying sky-model needs to be build. But redundancy might help here.

(3) Band-pass calibration is very hard at the station level, because non-zero baselines have lower SNR than the zero-baselines, show mutual coupling on very short baselines. The addition of a noise-load on some dipoles might be a cheap solution.

(4) Frequency-dependent beams cause more spectral variations because the sky is differentially weighted. Differences between dipoles might also cause problems with building a sky-model (DD-Calibration?)

(5) Ionosphere caused refractive and diffractive effects that are directionally dependent and cause effects on all baselines.

(6) Reasonable models can be build but most likely BSS techniques are needed as well to separate the signal from the FGs.

Future Requirements and Steps

(1) Addition (if possible) of noise-loads to some dipoles.
In preparation

(2) Improvements of the station-based correlator.
Being developed in Oxford for many purposes (Uniboard)

(3) Use multiple beam-formed data to improve band-pass calibration (i.e. multiple beams on CasA/CygA) and one on a cold-spot. *Ongoing*

(4) Use the super-terp (w/AARTFAAC) rather than a remote station at full time/freq. resolution (1s/1Khz).
Pilot in 2013

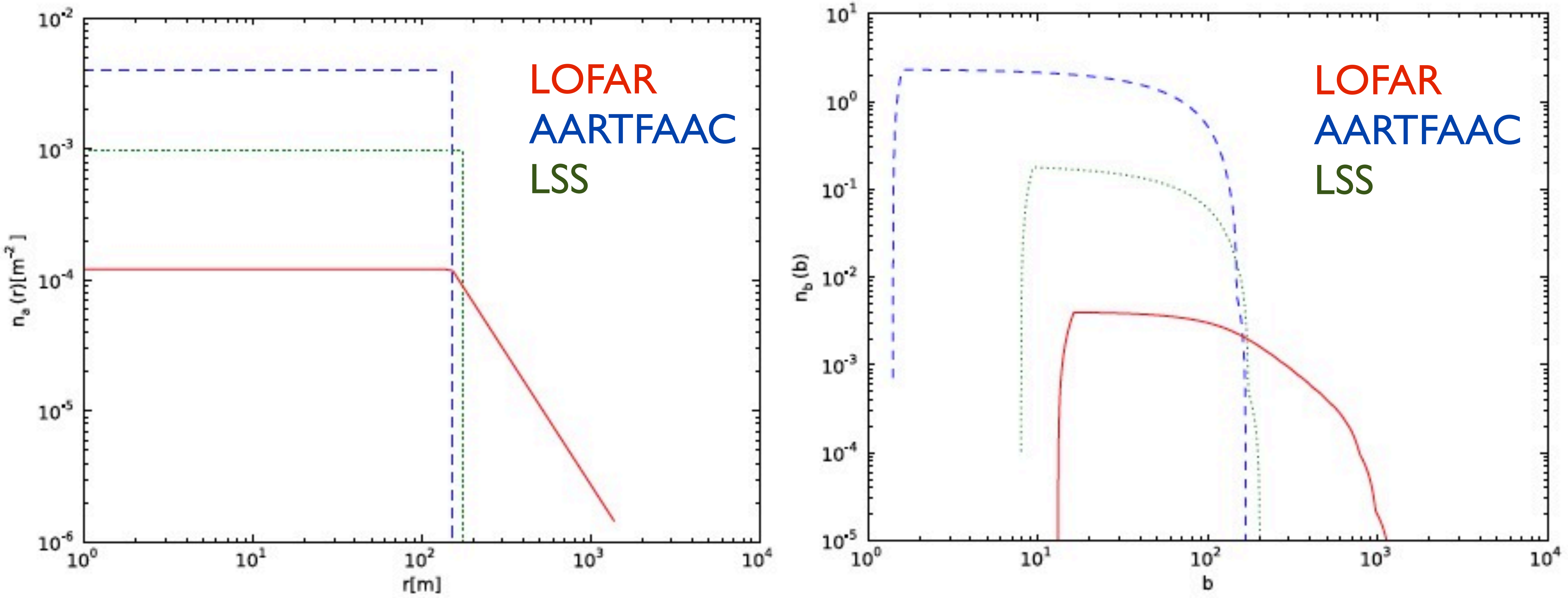
(5) Use full LOFAR array to maximize internal redundancy, checks and SNR *Nov/Dec. 2012*

(6) Development of a full end-to-end simulation and inversion algorithms: Data (sky+ionosp+instr.) model plus non-param. BBS methods (e.g. PCA, ICA, etc) to separate signals. *Ongoing*

LOFAR-Superterp: AARTFAAC
and the
LOFAR Super Station

LOFAR Extensions - AARTFAAC & LSS

Why interesting?
Very good UV coverage and wide FoV



Joseph (2012; BSc thesis)

LOFAR-AARTFAAC

- AARTFAAC: Amsterdam – ASTRON Radio Transients Facility and Analysis Center

- Goal: 24/7 all-sky radio monitor
  - Correlate 288 LBA dipoles against each other
  - Produce real-time trigger for transient phenomena

- 6 super-terp stations (on a single clock)

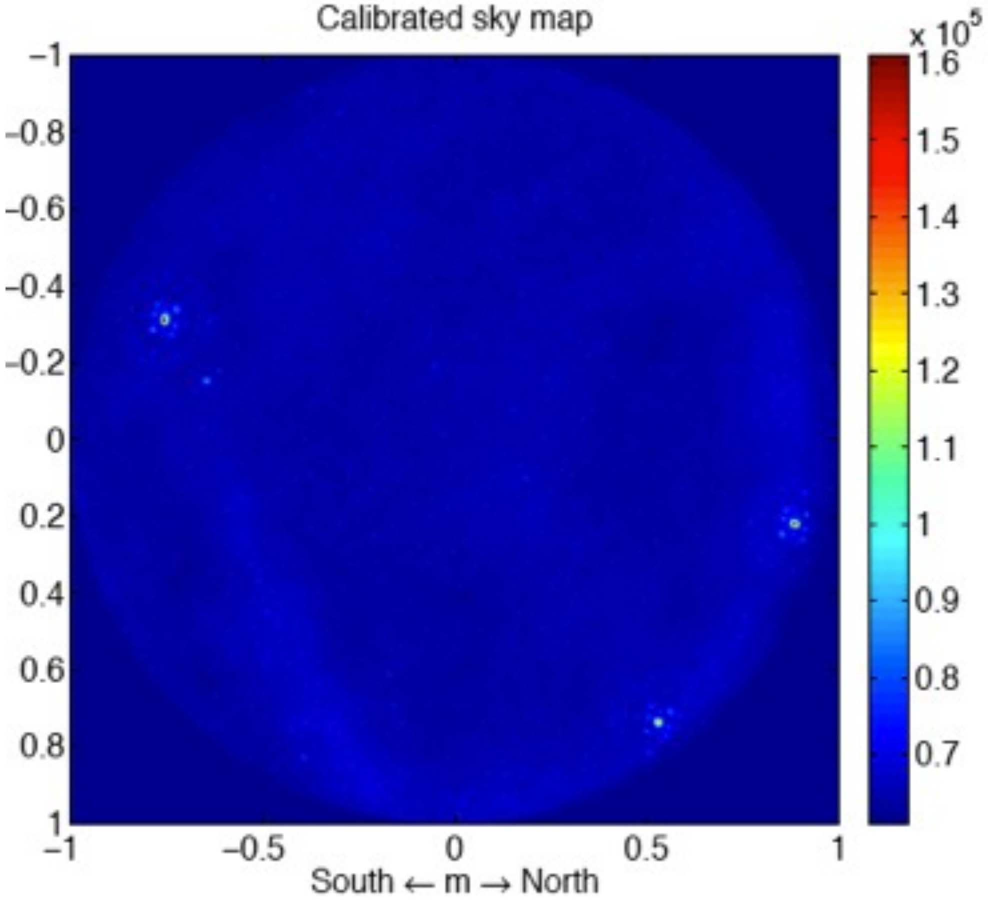
- Distributed correlator based on uniboards. At each station 1/6th of the bandwidth is correlated (~14 MHz)
  - 288 LBA/HBA dual dipole antennas (576 signal paths)
  - Baselines up to 350 meter
  - All sky field-of-view (single dipole)
  - 14 MHz instantaneous total bandwidth
  - 24 kHz resolution after correlation; 1 channel / subband
  - Integration time: 1 sec – 10 sec

- Post-processing (flagging, calibration, imaging) to be done in the Concentrator node or in Groningen

- Transients detection: produce trigger to follow up with full array
  - Real time, low-latency performance

LOFAR-AARTFAAC

Also a “perfect” HI-signal detection machine!



(Auto-)Correlate all 288 LBA or HBA elements, 14 MHz band (8-bits), 1sec-24 KHz spectral resolution. Zenith pointing, snapshot observation mode. Dedicated hardware correlator and imaging pipeline.

[Pilot project: connect to the EoR Processing cluster in 2013. 4FTE funded.]

LOFAR-AARTFAAC

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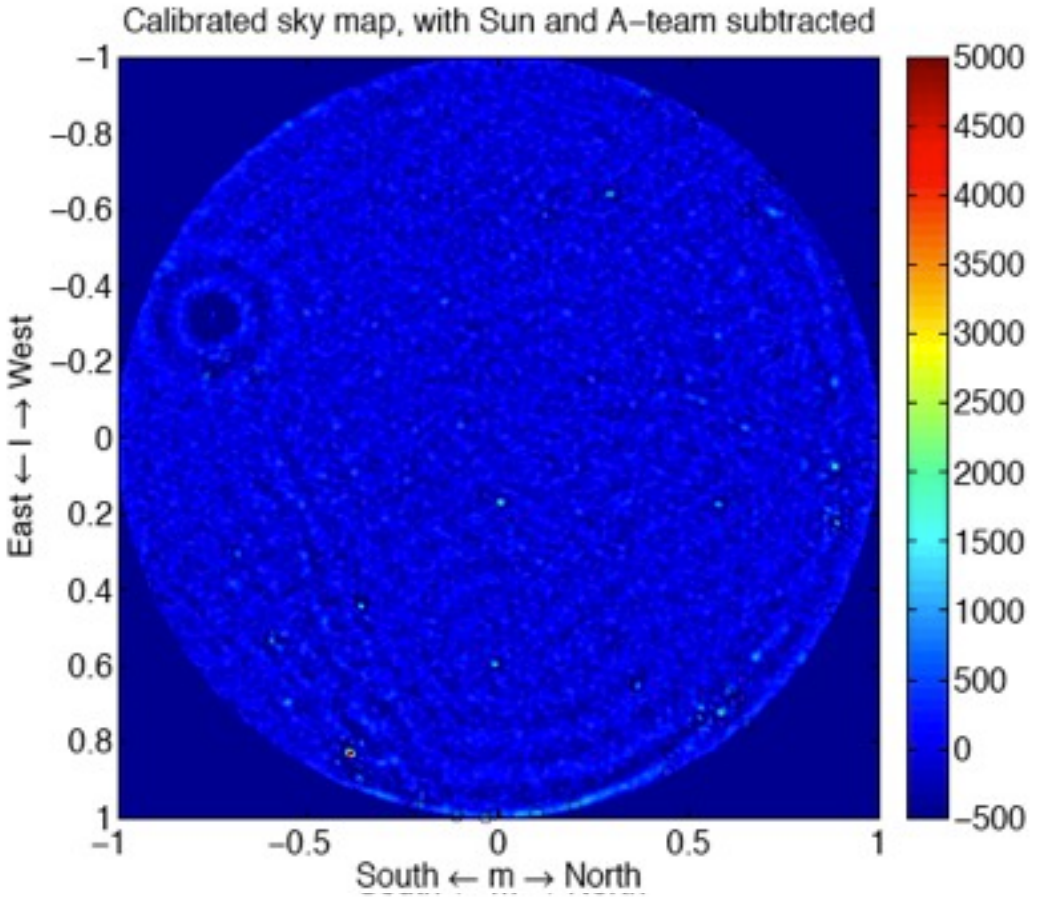

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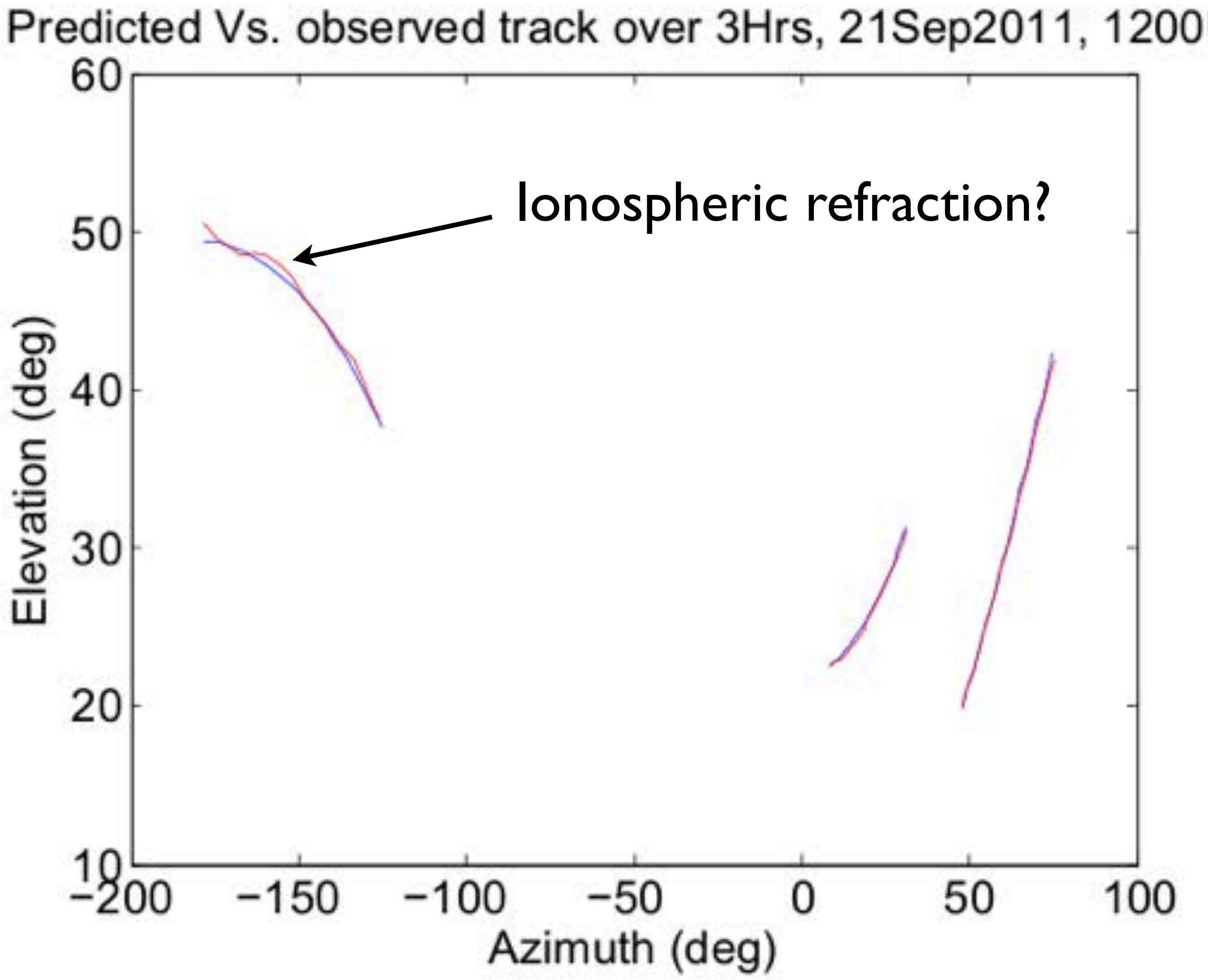
[Pilot project: connect to the EoR Processing cluster in 2013. 4FTE funded.]

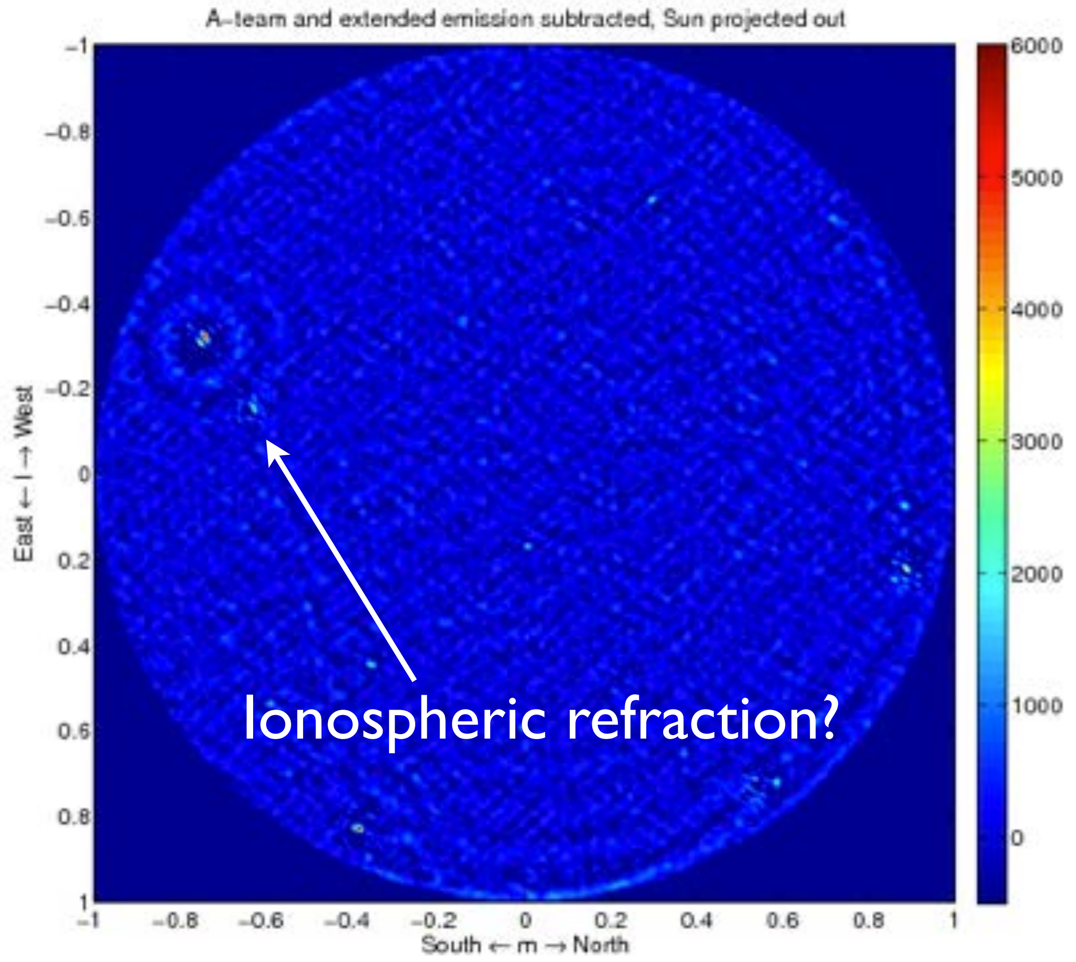
LOFAR-AARTFAAC

As with DE601 the time-varying refraction of the ionosphere will cause lensing of the ionosphere. They become more apparent for longer (superterp) baselines.

(see also Vedantham et al. 2012, in prep)



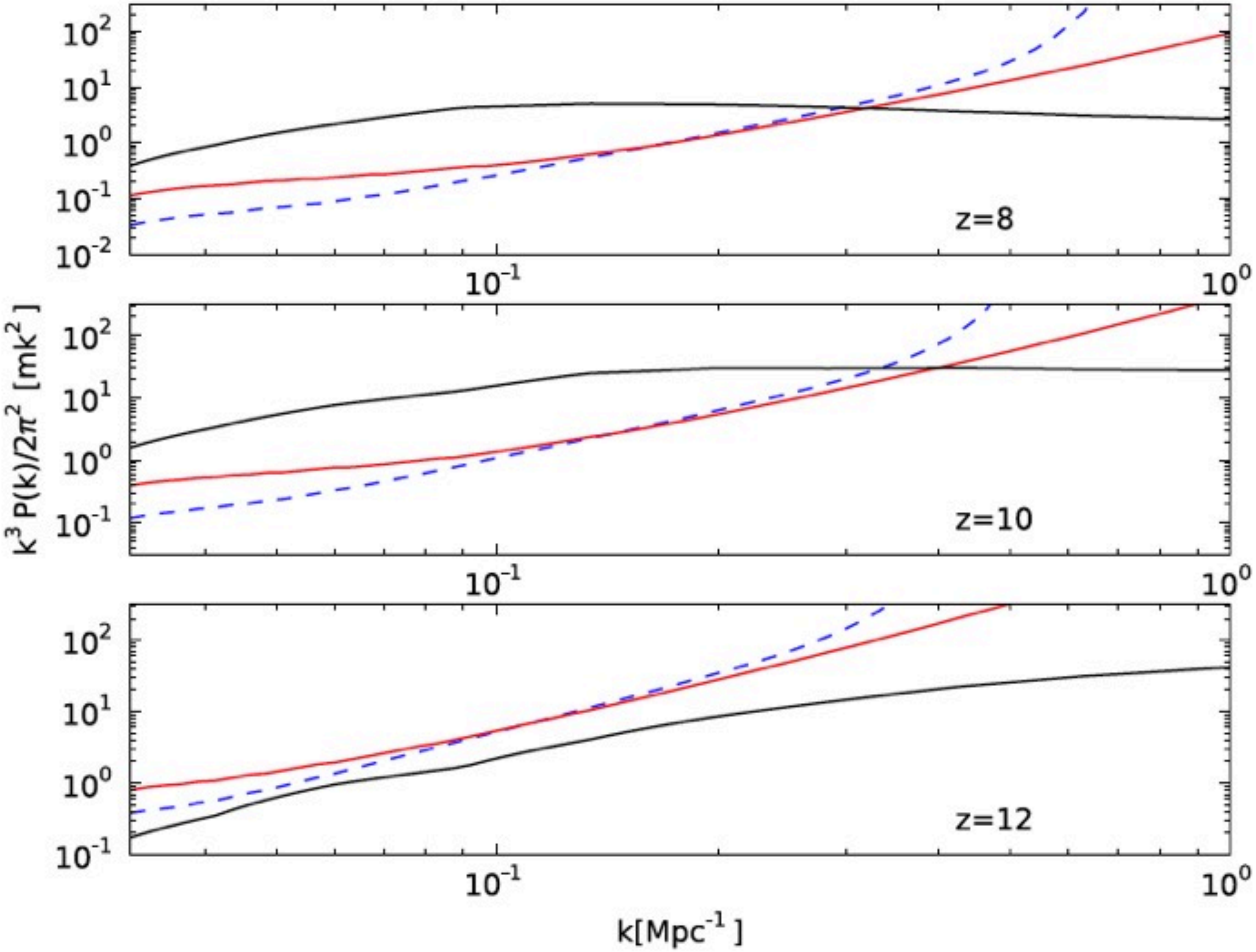
Ionospheric refraction?



Ionospheric refraction?

LOFAR-AARTFAAC

Besides being an excellent global EoR machine (288 dipoles/tiles with 12 outrigger LBA-dipoles that could connect to noise-loads, AARTFAAC can also improve the detection of fluctations on k=0.01-0.1 scales by a factor of 5x



LOFAR Super Station

Low-frequency Arrays - comparison

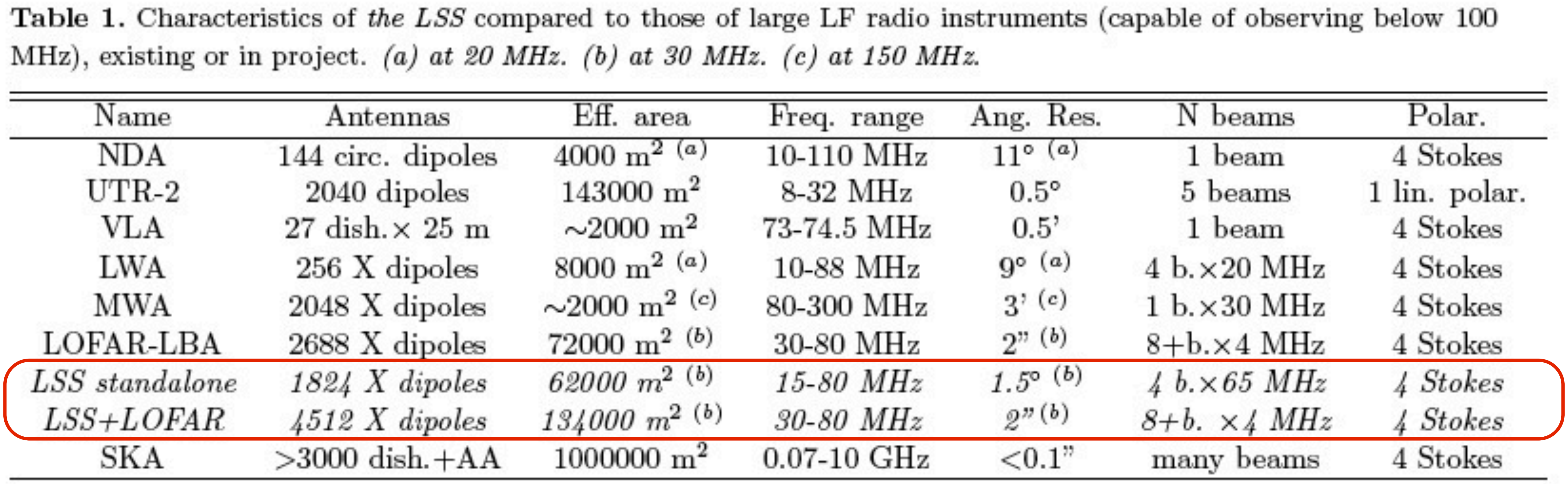
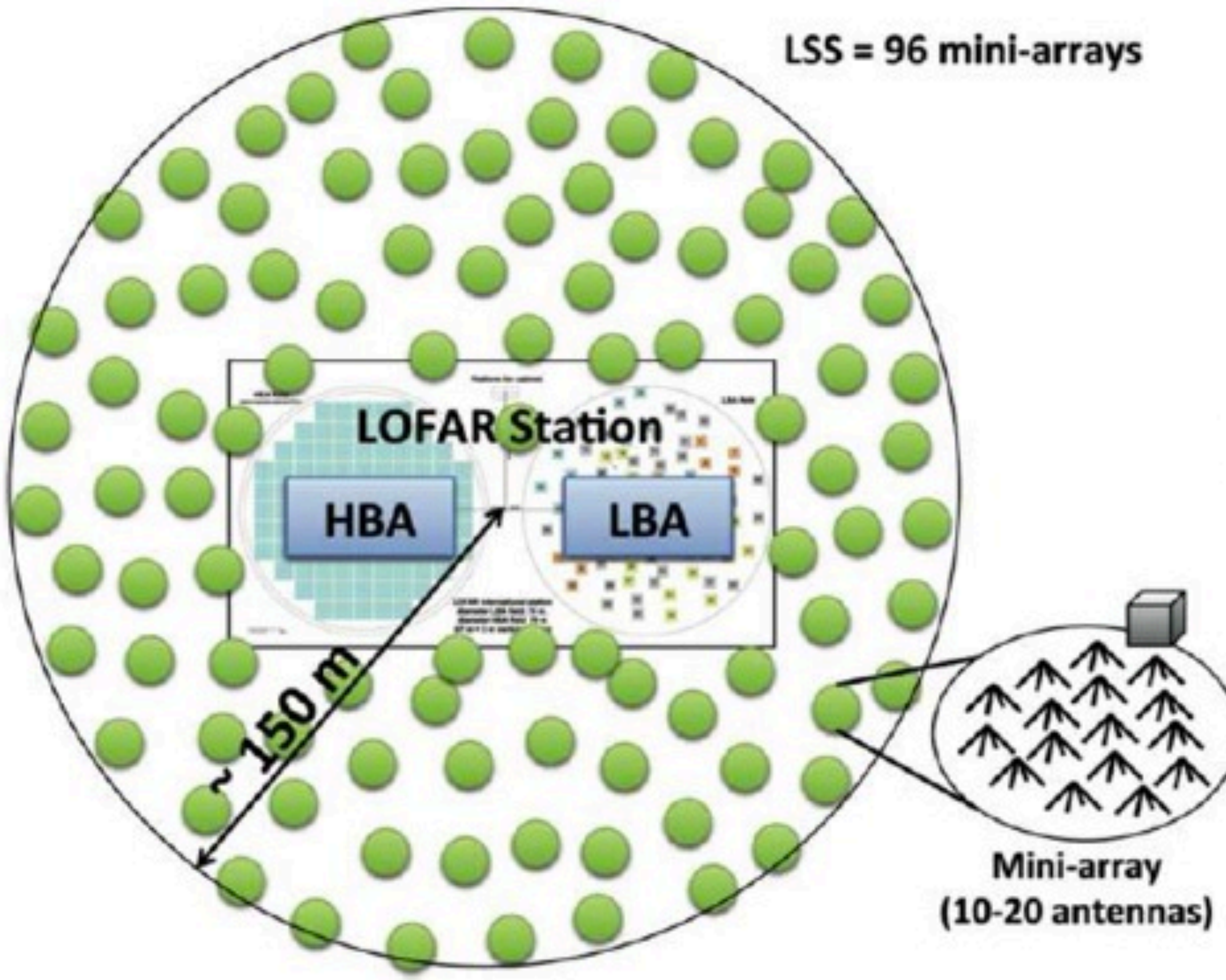


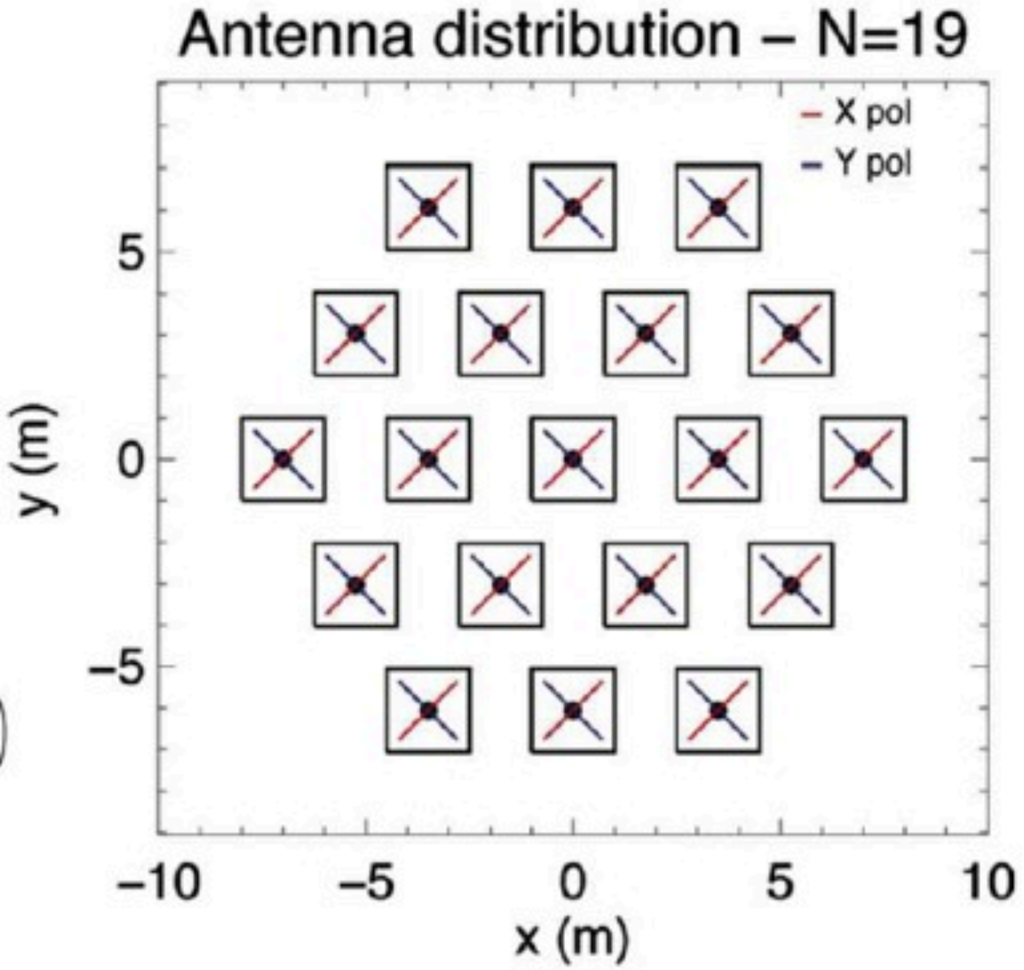
Table 1. Characteristics of *the LSS* compared to those of large LF radio instruments (capable of observing below 100 MHz), existing or in project. *(a) at 20 MHz. (b) at 30 MHz. (c) at 150 MHz.*

Name	Antennas	Eff. area	Freq. range	Ang. Res.	N beams	Polar.
NDA	144 circ. dipoles	4000 m^2 (a)	10-110 MHz	11° (a)	1 beam	4 Stokes
UTR-2	2040 dipoles	143000 m^2	8-32 MHz	0.5°	5 beams	1 lin. polar.
VLA	27 dish.× 25 m	∼2000 m^2	73-74.5 MHz	0.5'	1 beam	4 Stokes
LWA	256 X dipoles	8000 m^2 (a)	10-88 MHz	9° (a)	4 b.×20 MHz	4 Stokes
MWA	2048 X dipoles	∼2000 m^2 (c)	80-300 MHz	3' (c)	1 b.×30 MHz	4 Stokes
LOFAR-LBA	2688 X dipoles	72000 m^2 (b)	30-80 MHz	2" (b)	8+b.×4 MHz	4 Stokes
LSS standalone	*1824 X dipoles*	*62000 m^2 (b)*	*15-80 MHz*	*1.5° (b)*	*4 b.×65 MHz*	*4 Stokes*
LSS+LOFAR	*4512 X dipoles*	*134000 m^2 (b)*	*30-80 MHz*	*2" (b)*	*8+b. ×4 MHz*	*4 Stokes*
SKA	>3000 dish.+AA	1000000 m^2	0.07-10 GHz	<0.1"	many beams	4 Stokes

LOFAR Super Station

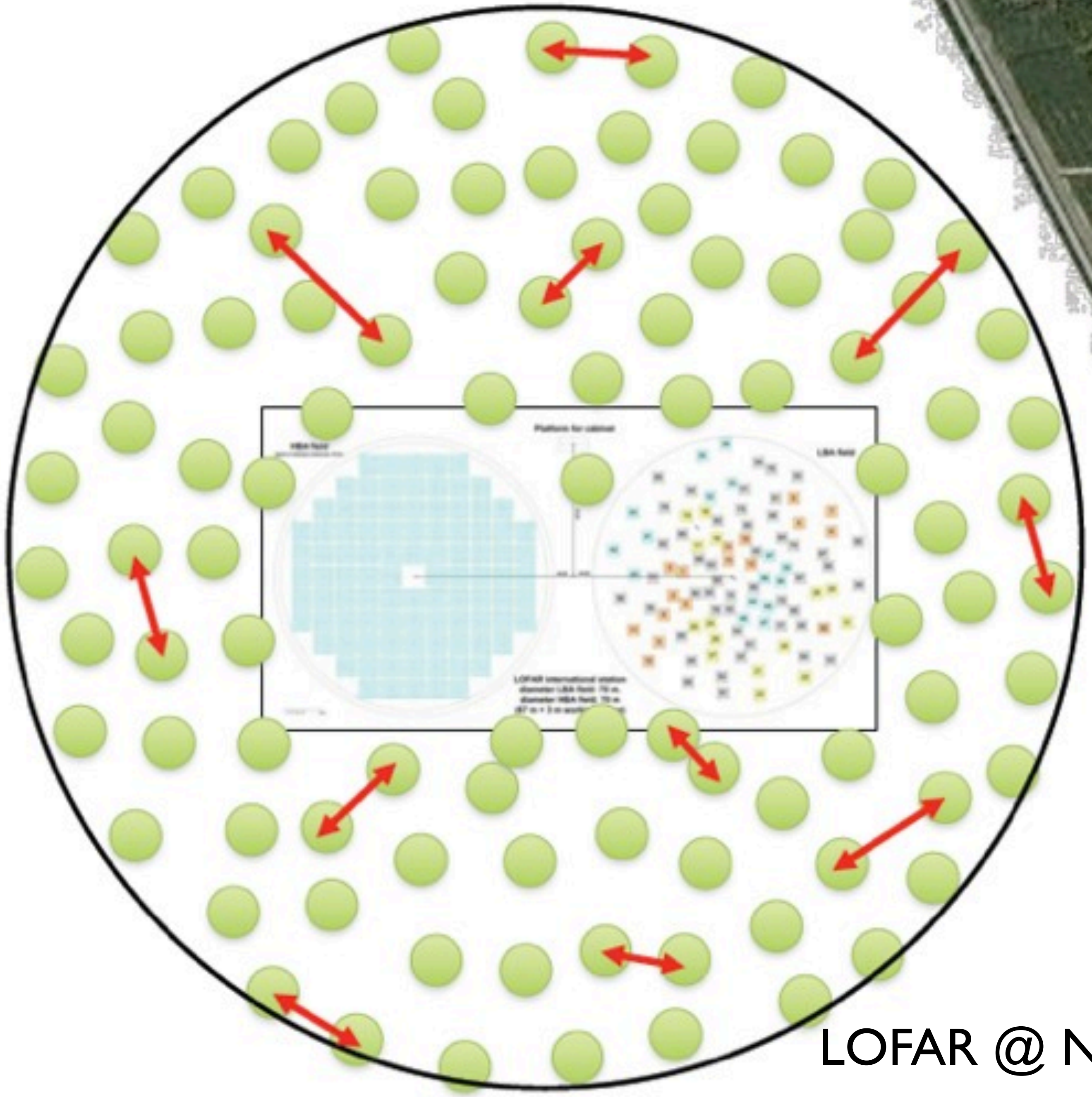
LSS has ~19x the collecting area of one LOFAR LBA station, the size of the LOFAR Superterp, and the FoV 19x smaller than an LBA dipole.





1sec-24KHz, 30-80MHz

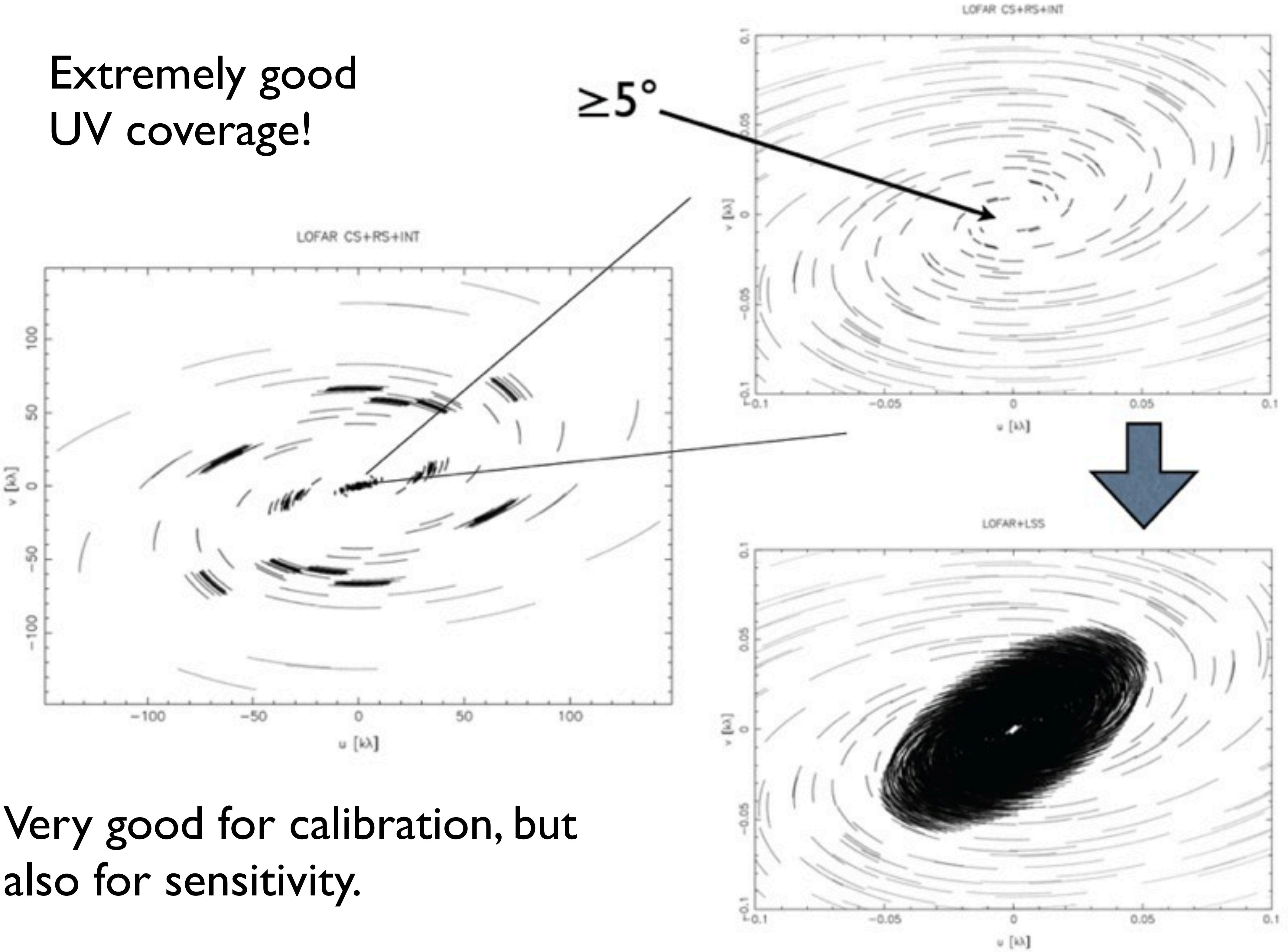
LOFAR Super Station



LOFAR @ Nançay-OP : FR606

LOFAR Super Station

Extremely good
UV coverage!

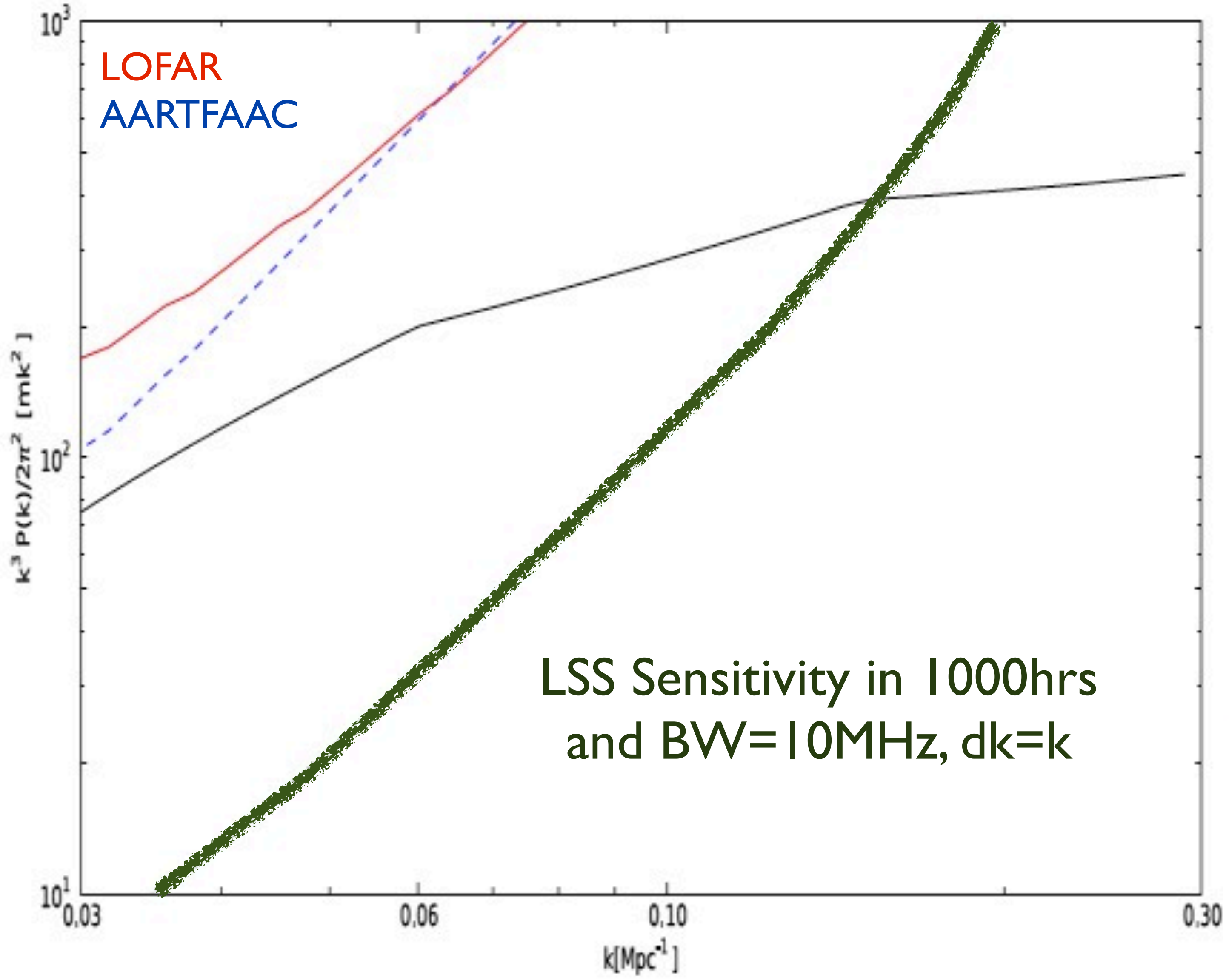


≥5°

Very good for calibration, but
also for sensitivity.

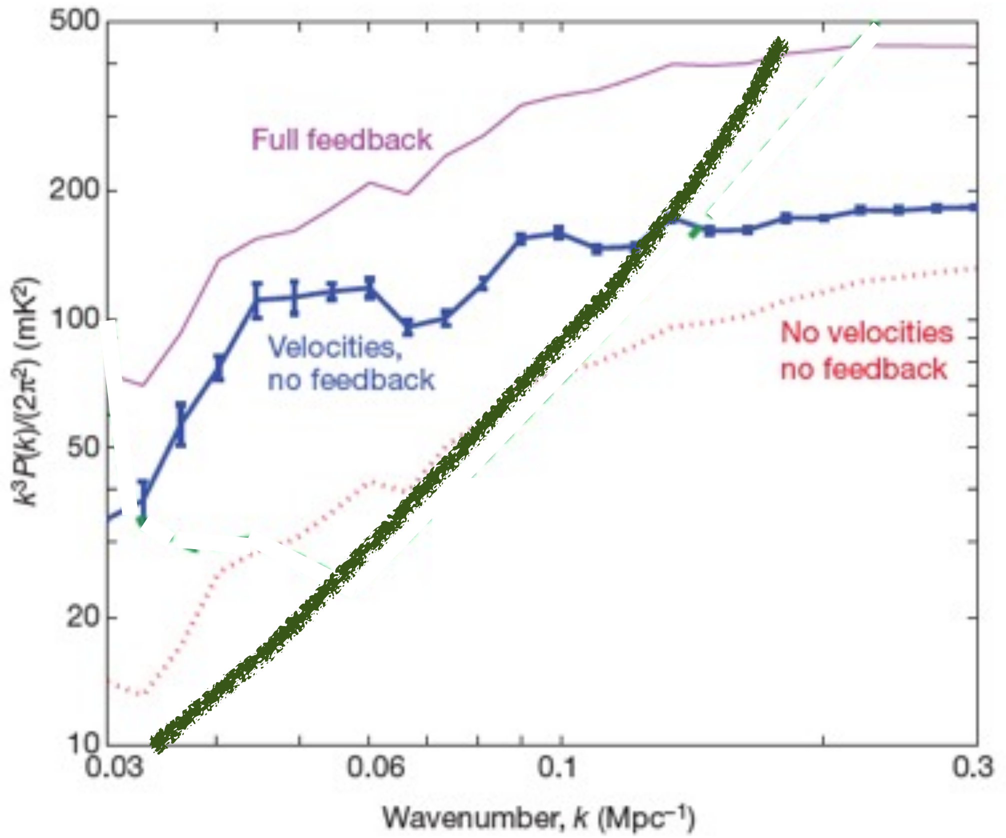
LOFAR Super Station

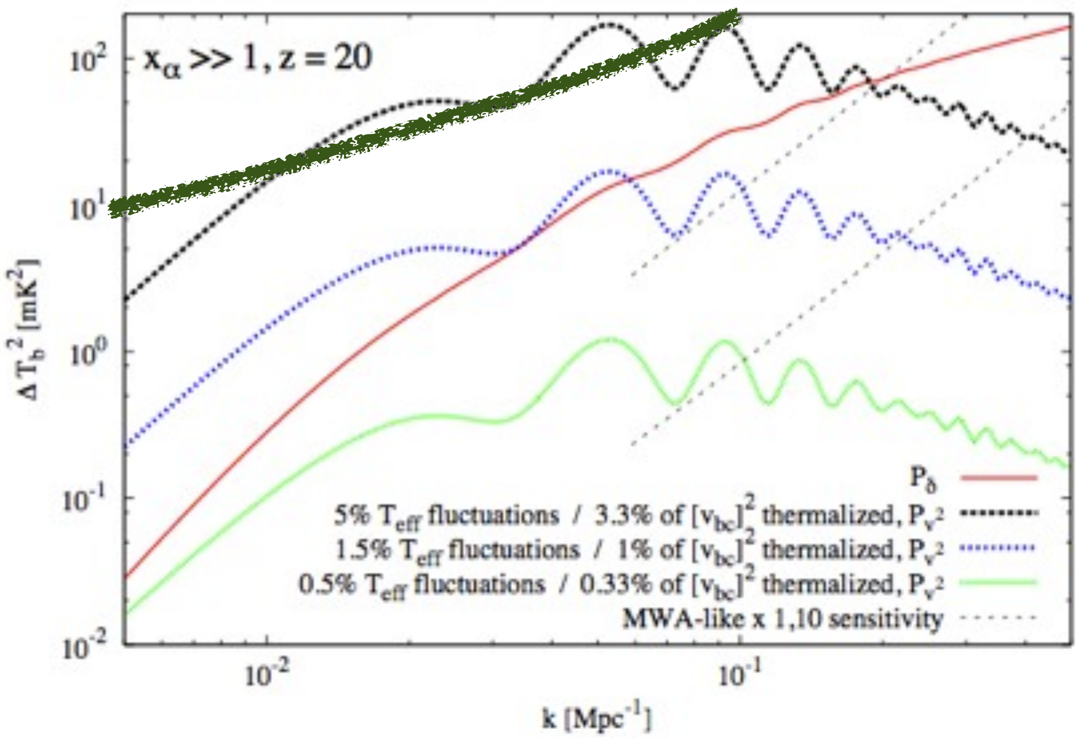
Possibly Power-Spectra @ z=20,
not just the global signal!



LSS Sensitivity in 1000hrs
and BW=10MHz, dk=k

Visbal et al (2012) & McQuinn et al. (2012)





FUTURE

LOCOS -

2012-13 Obtain station-based correlator data for all stations while piggy-backing on LOFAR-EoR observations.

AARTFAAC

2013- Use LOFAR-AARTFAAC to obtain LBA/HBA Superterp data, while piggy-backing on all HBA/LBA observations and select/combine the best data sets.

LSS

201? - Funding/role-out of full LSS (current 3 test stations). Use in LBA mode for high-z global-signal measurements and power-spectra around z~20.

Observations vs Hardware

2012-13 Development of noise-loads for the 12 outrigger LBA dipoles

General Conclusions

- Doing total power experiments with (arrays of) dipoles is very difficult!
- Bandpass calibration is the most difficult aspect of the problem, further exacerbated by RFI, beam variations, receiver noise and the ionosphere.
- However, using an array with huge redundancy (e.g. LOFAR) seems one way forward, possible with some improvements (noise loads and better station correlation).
- Similar experiments are planned with (part of) the full LOFAR array: Advantages: better time/freq. resolution, smaller better controlled beams, multi-beaming on bright calibrators (CasA/CygA). AARTFAAC/LSS might be the way forward, with noise-loads added to some (or all) dipoles/tiles.
- Novel algorithms for signal extraction will be needed.