LOFAR: the LOw Frequency ARray

Radio Observatory
ASTRON, Dwingeloo, The Netherlands

LOFAR data school 2016

LOFAR: Lots Of Flimsy Antenna Rigs

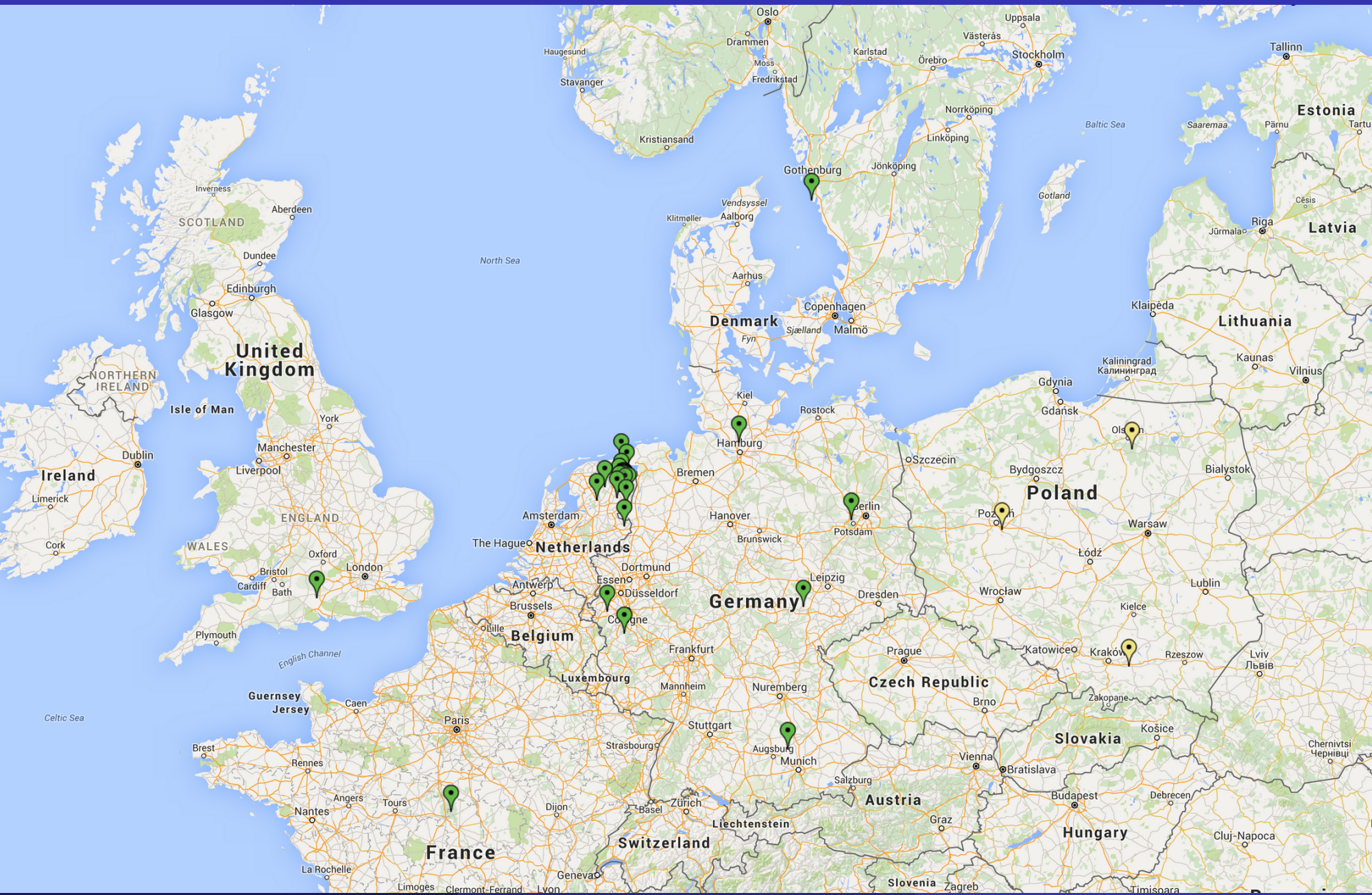
Radio Observatory
ASTRON, Dwingeloo, The Netherlands

LOFAR data school 2016

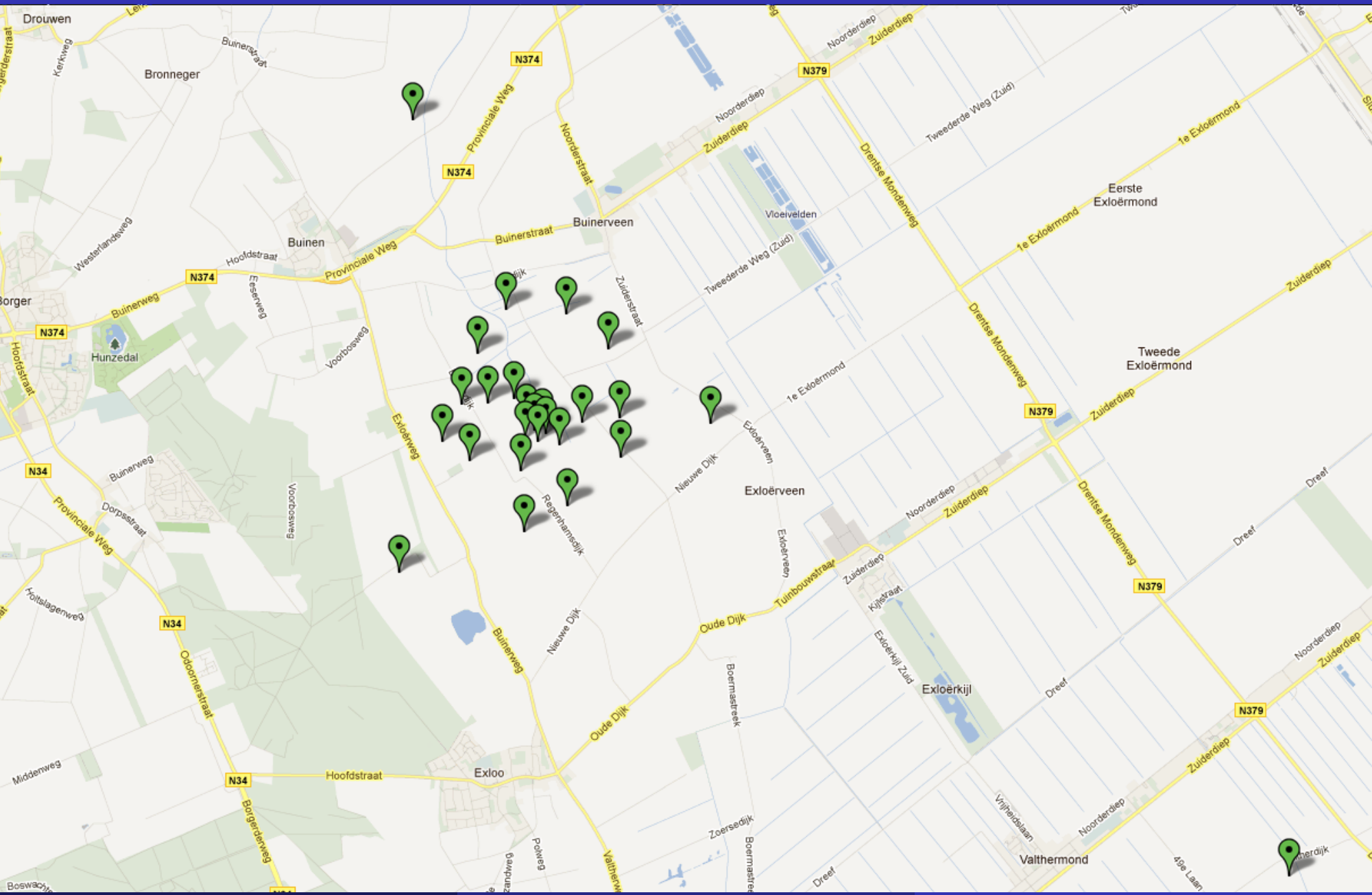
Outline

1. Architecture
2. Stations
3. C O F F E E
4. Central processing
5. Beams, beams, beams. . .
6. More beams. . .
7. If all goes well

A BIG radio telescope

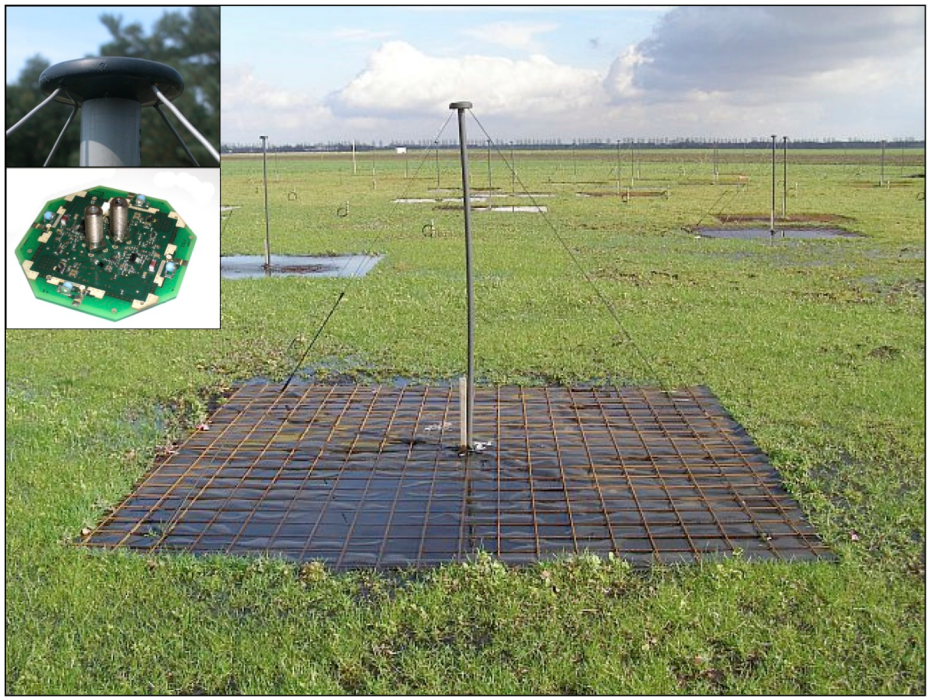


With a dense core



Antenna types

Low Band Antenna (LBA)

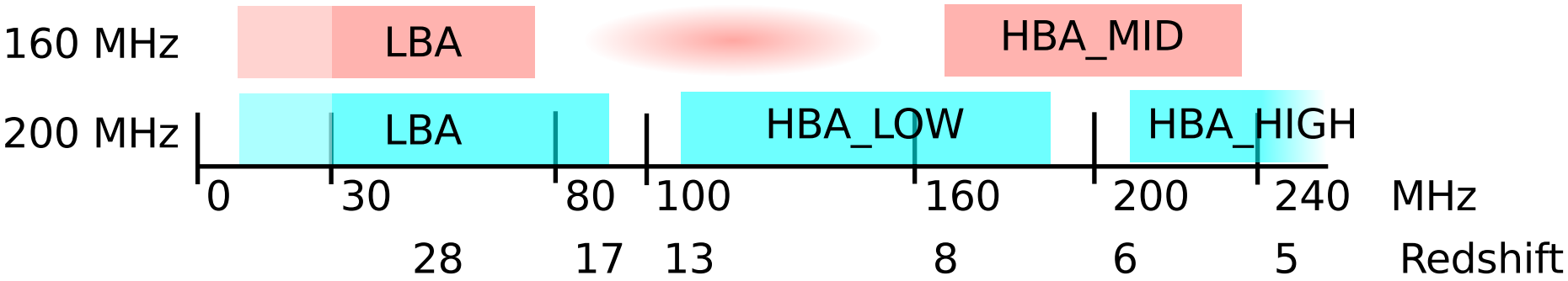


- 10–90 MHz
- All digital beam forming

High Band Antenna (HBA)

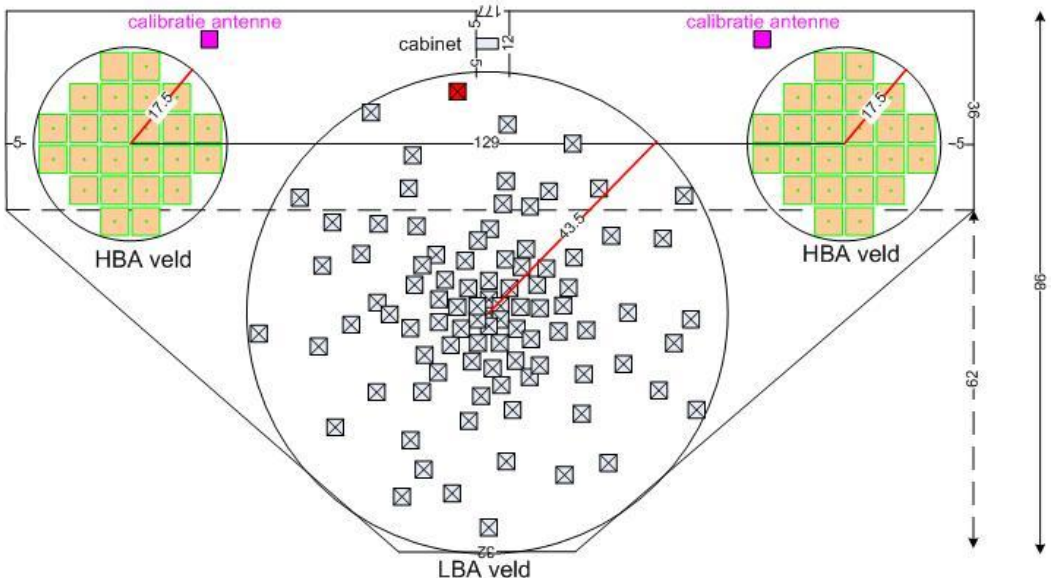
- 110–240 MHz
- 4*x*4 antennas per analoguely beam formed tile
- Tiles beam formed digitally

LOFAR observing bands

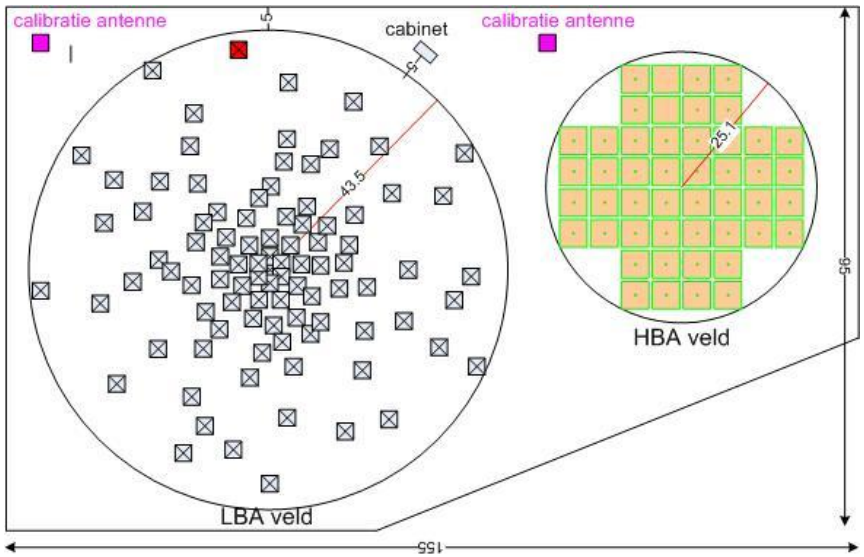


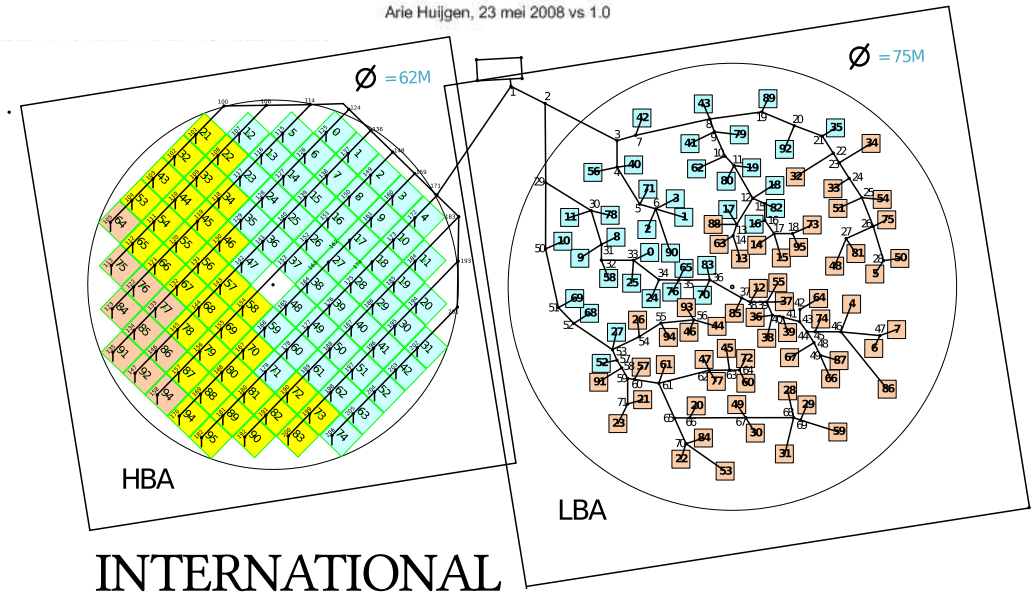
Station types

CORE



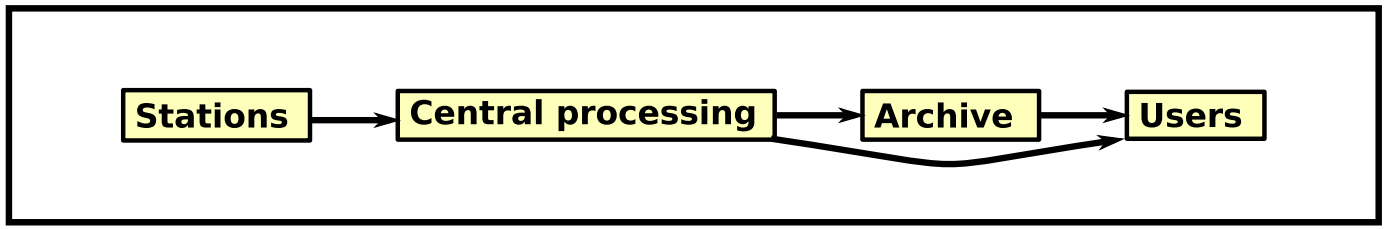
REMOTE

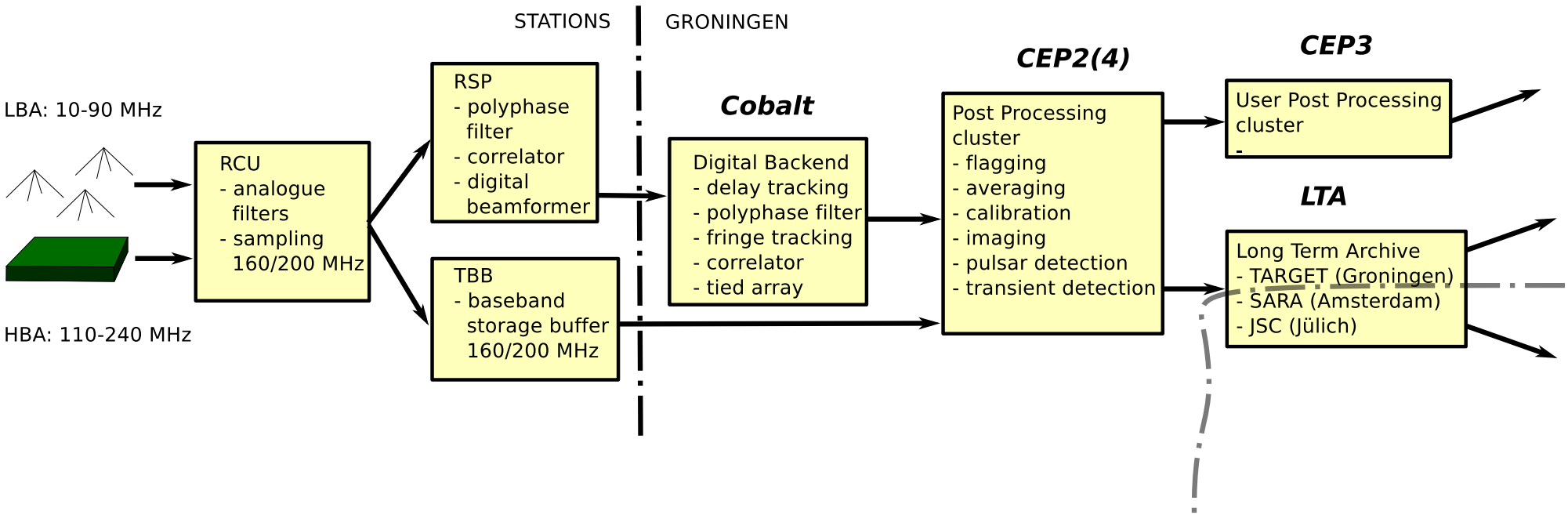




INTERNATIONAL

Signal/data path





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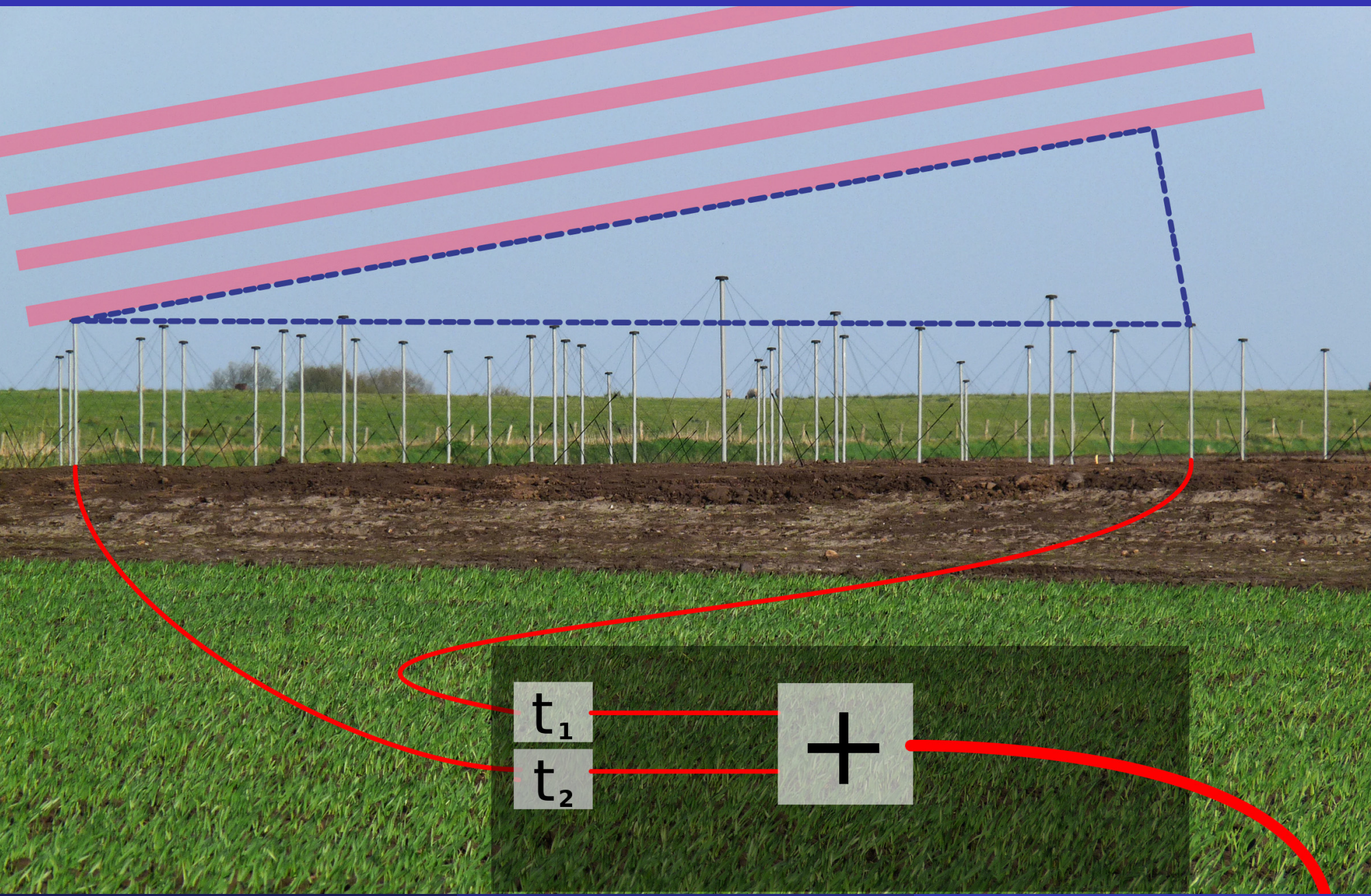
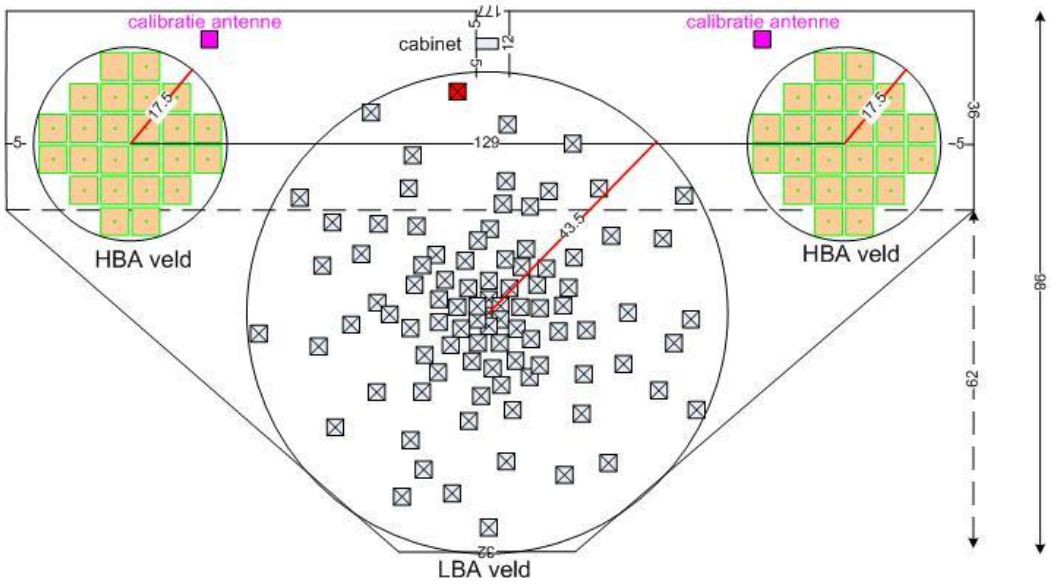
Beam forming



Cables

CORE



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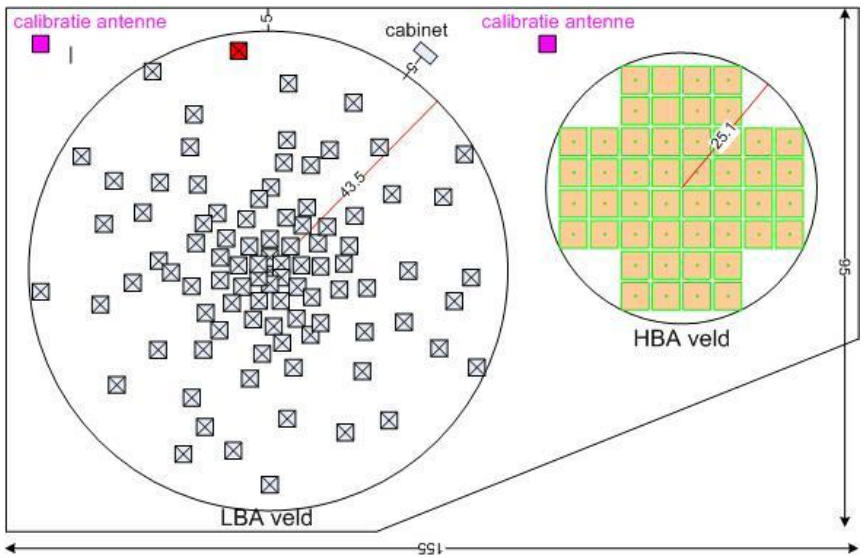

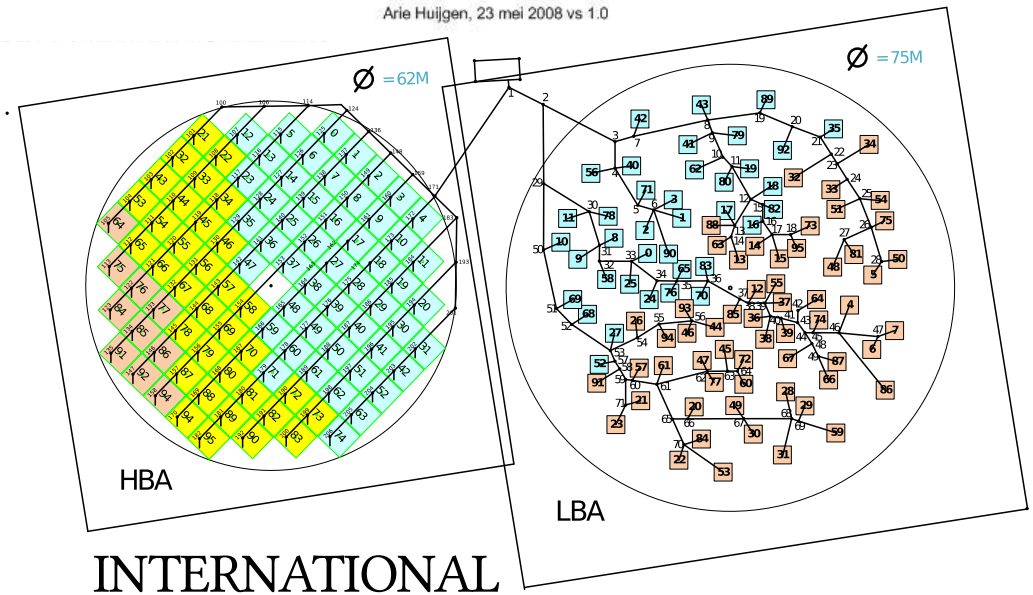

INTERNATIONAL

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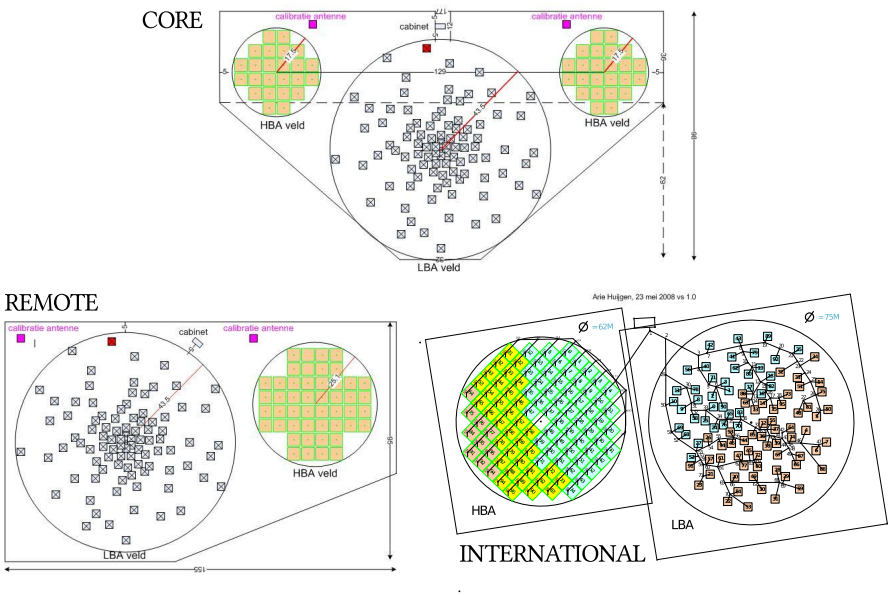


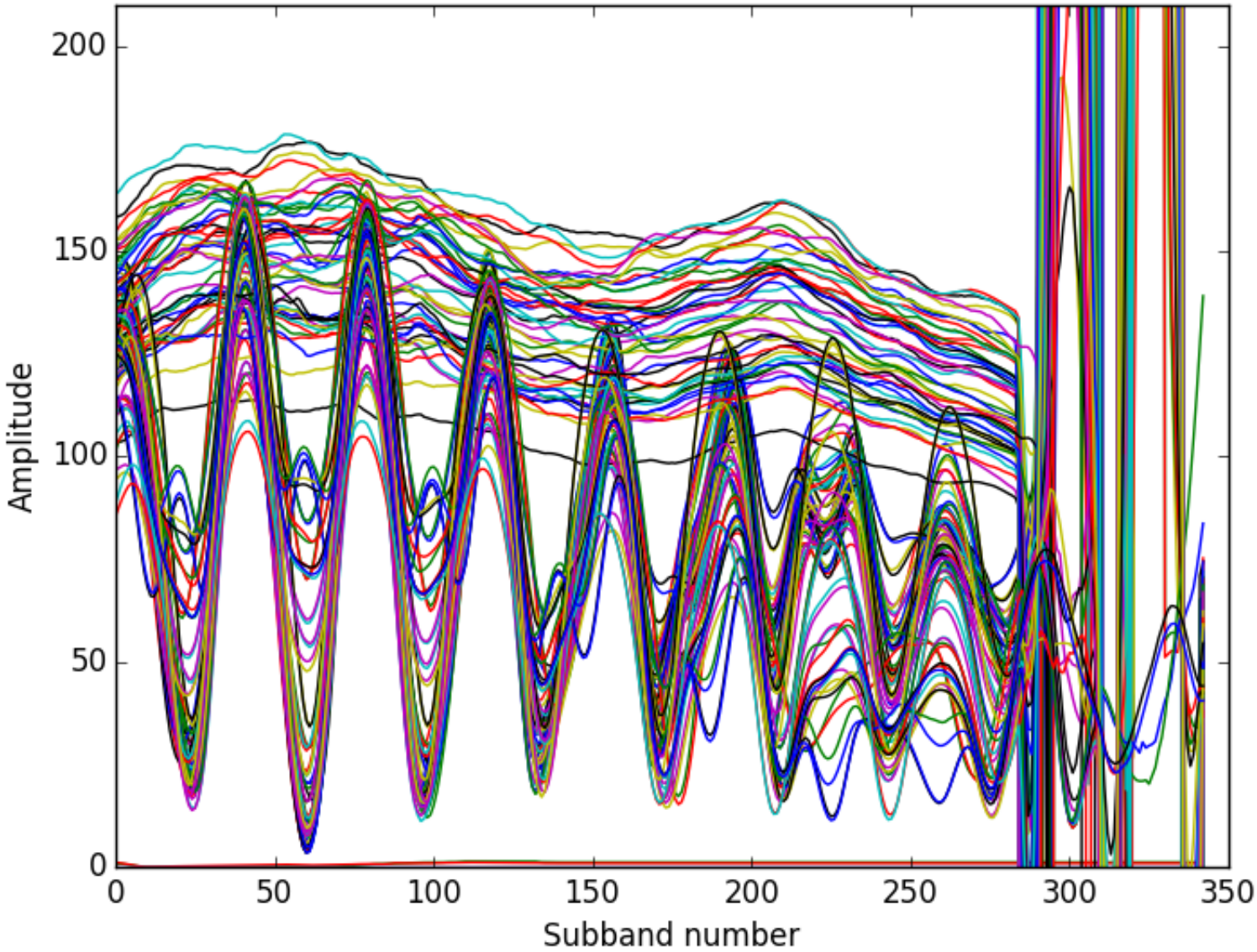
Possible cable lengths

Velocity factor ~ 0.82

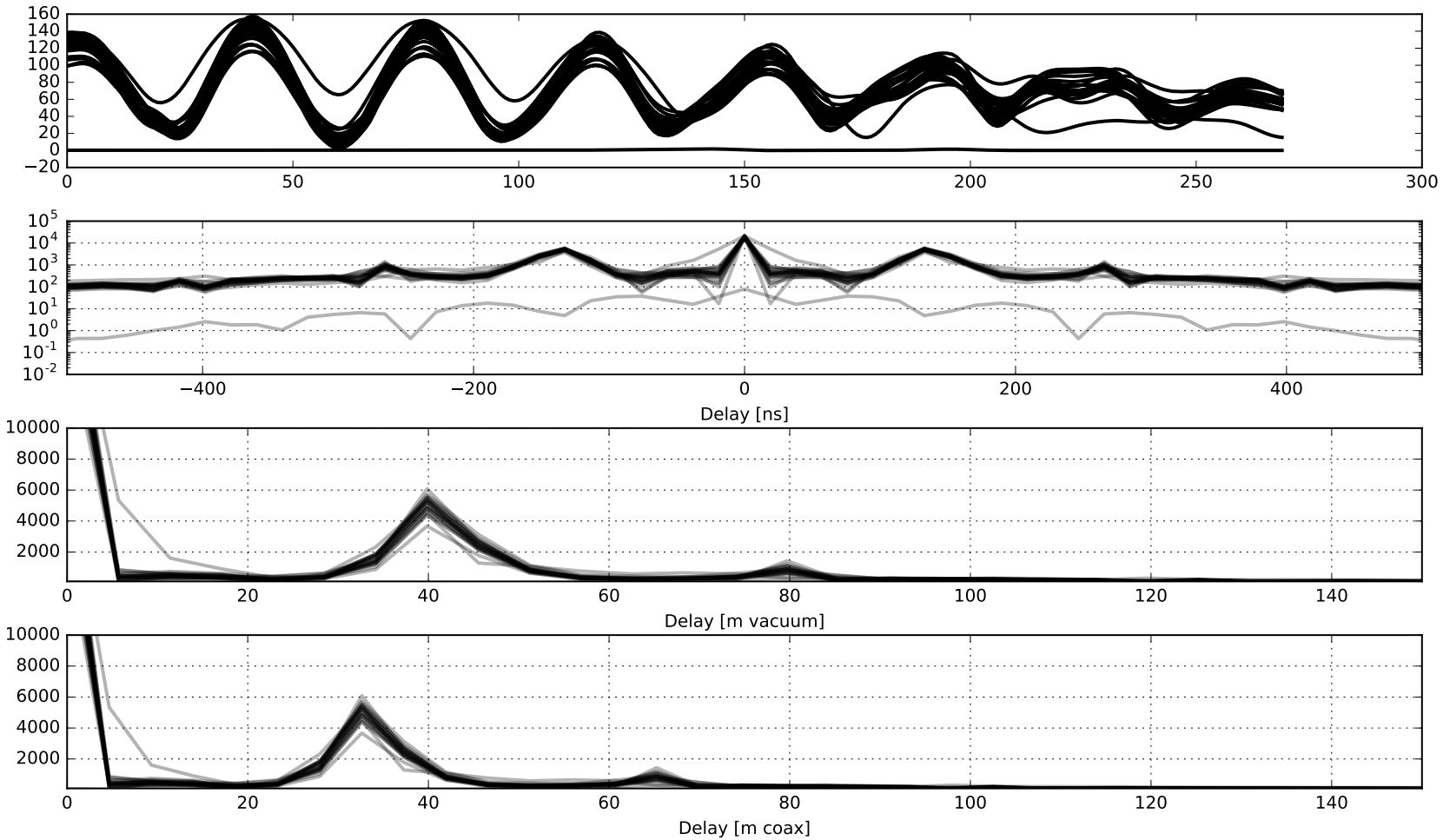
Length (m)	Appr. delay (ns)
50	199
80	327
85	343
115	466
130	531

Compensated in Receiver Units after digitization.

So...what's wrong here? *D. Hoang*



Fourier transforms to the rescue!



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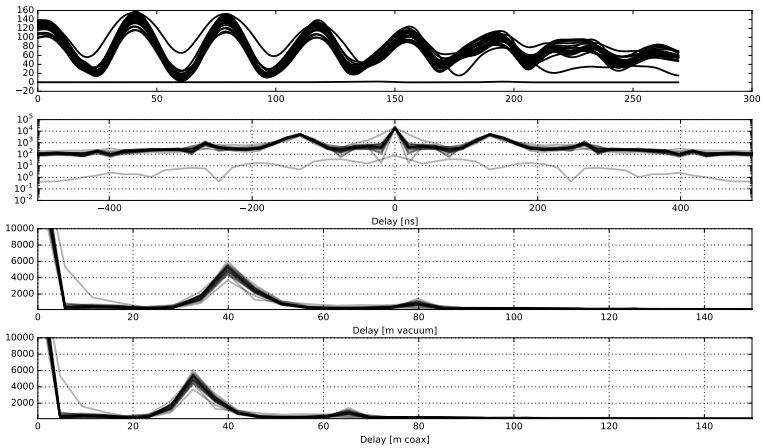

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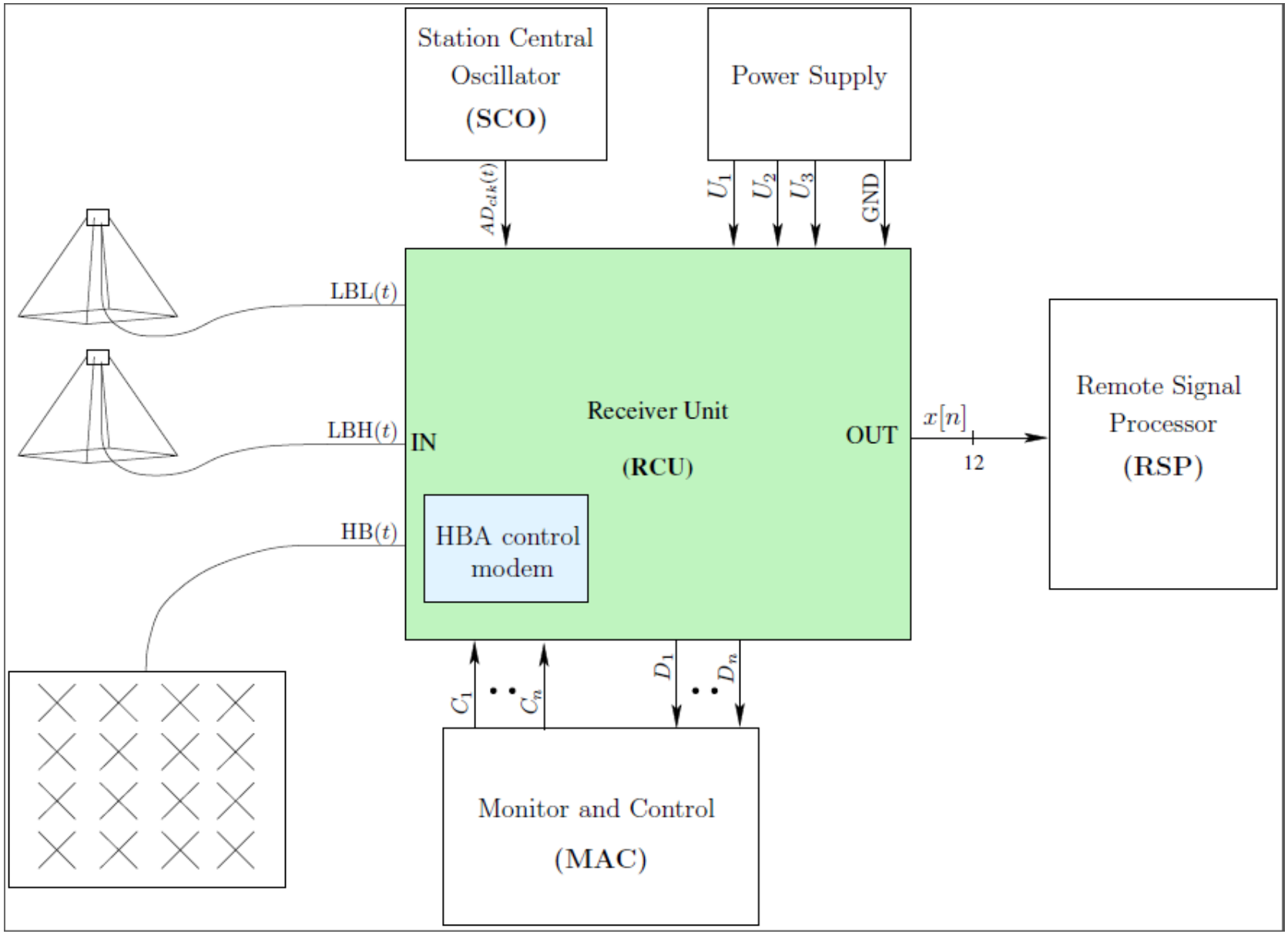
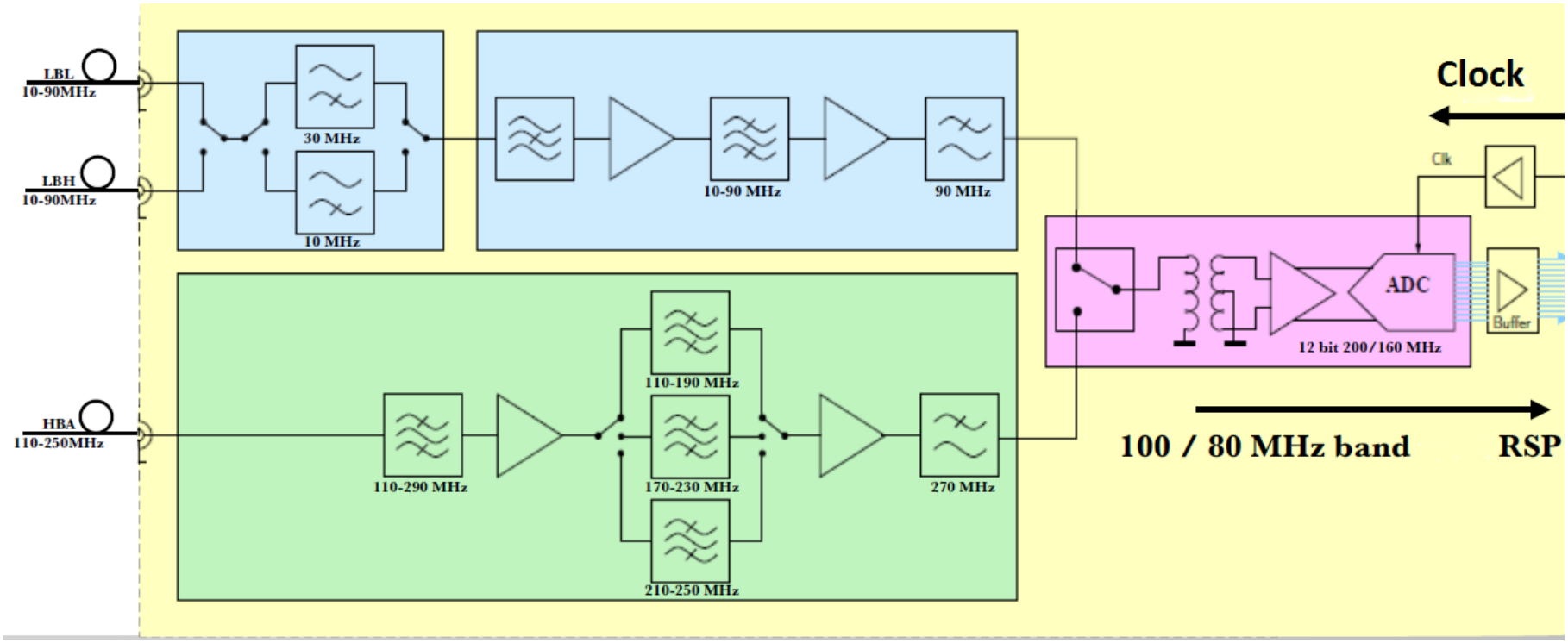
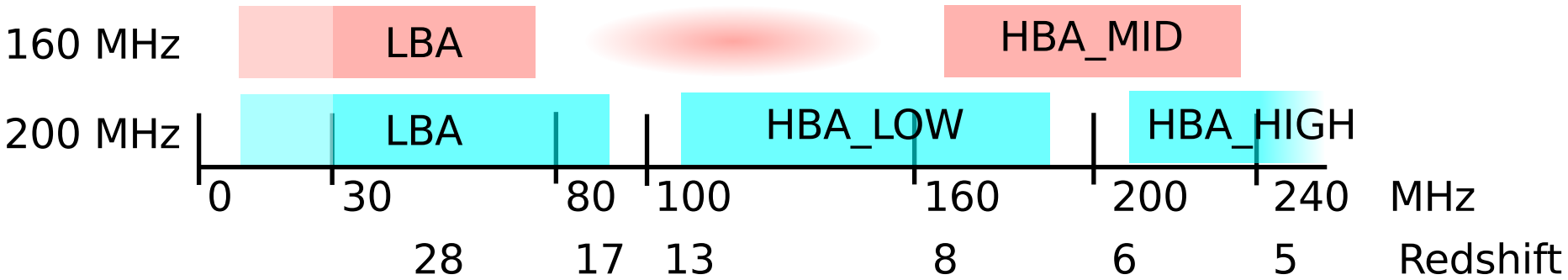
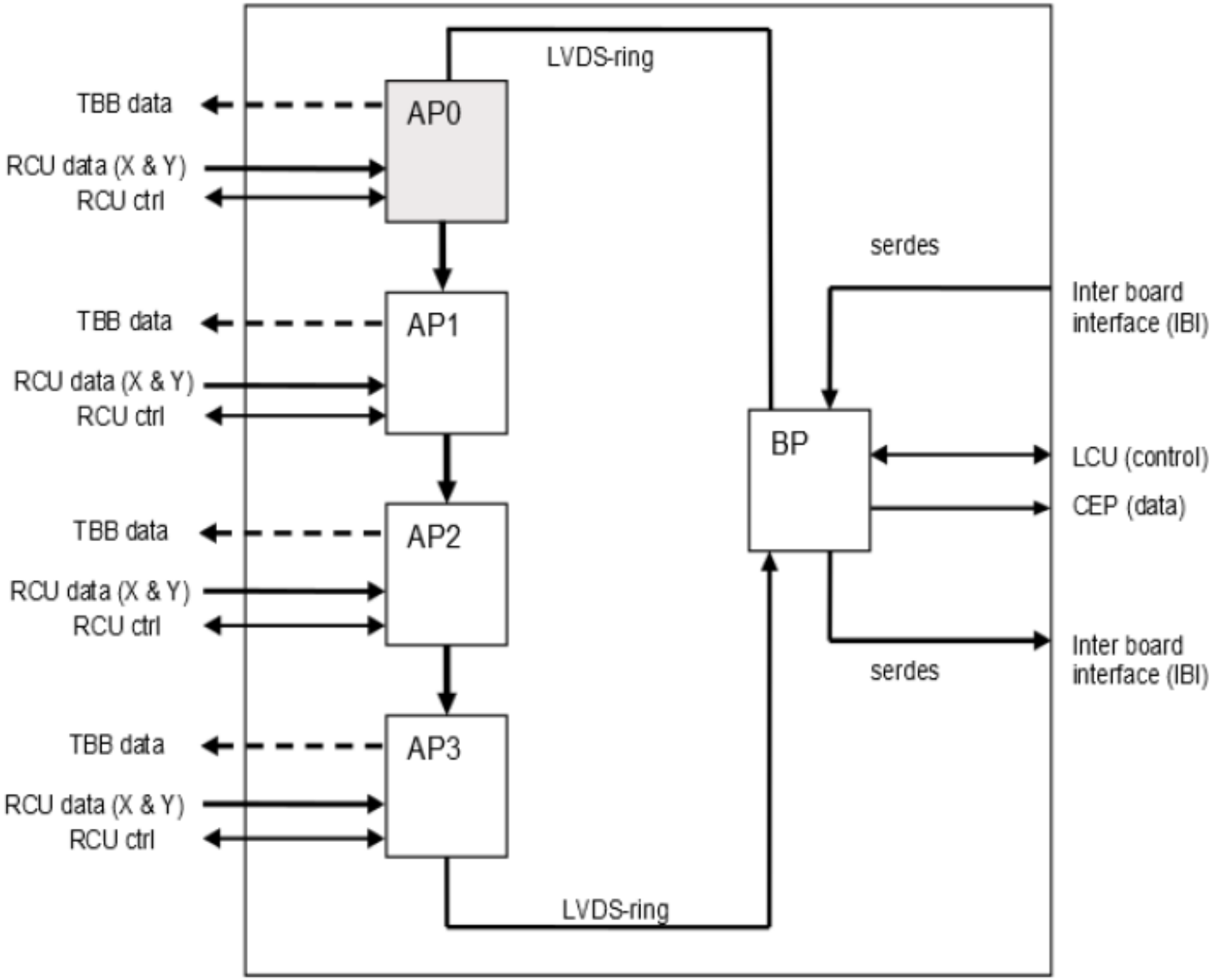

Station Central Oscillator (SCO)
Power Supply
$AD_{clk}(t)$
U_1
U_2
U_3
GND
LBL(t)
LBH(t)
HB(t)
IN
Receiver Unit (RCU)
HBA control modem
OUT
$x[n]$
12
Remote Signal Processor (RSP)
C_1
C_n
D_1
D_n
Monitor and Control (MAC)

The Receiver Unit (RCU) *M. Norden*





Remote Station Processing (RSP) *M. Norden*



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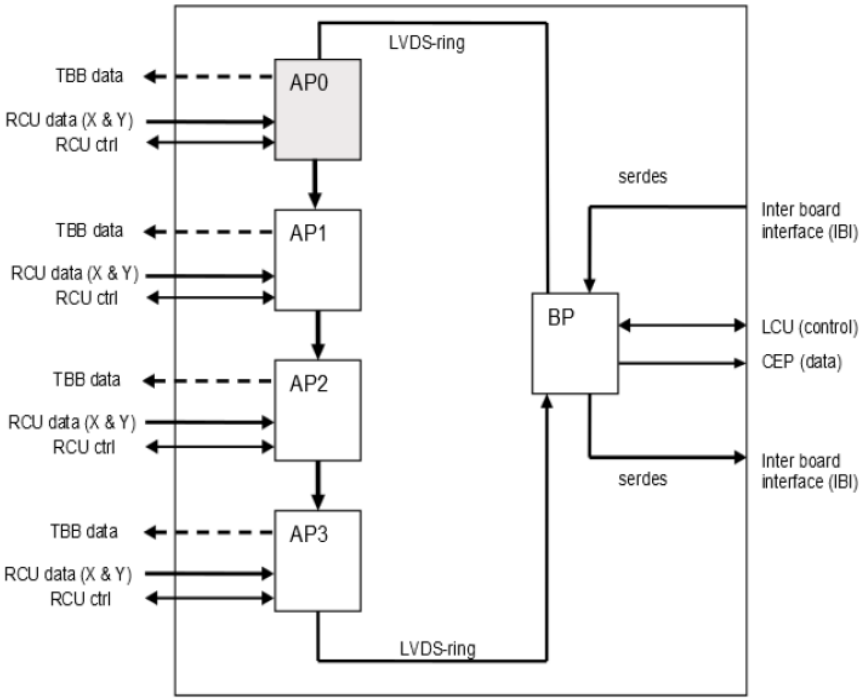
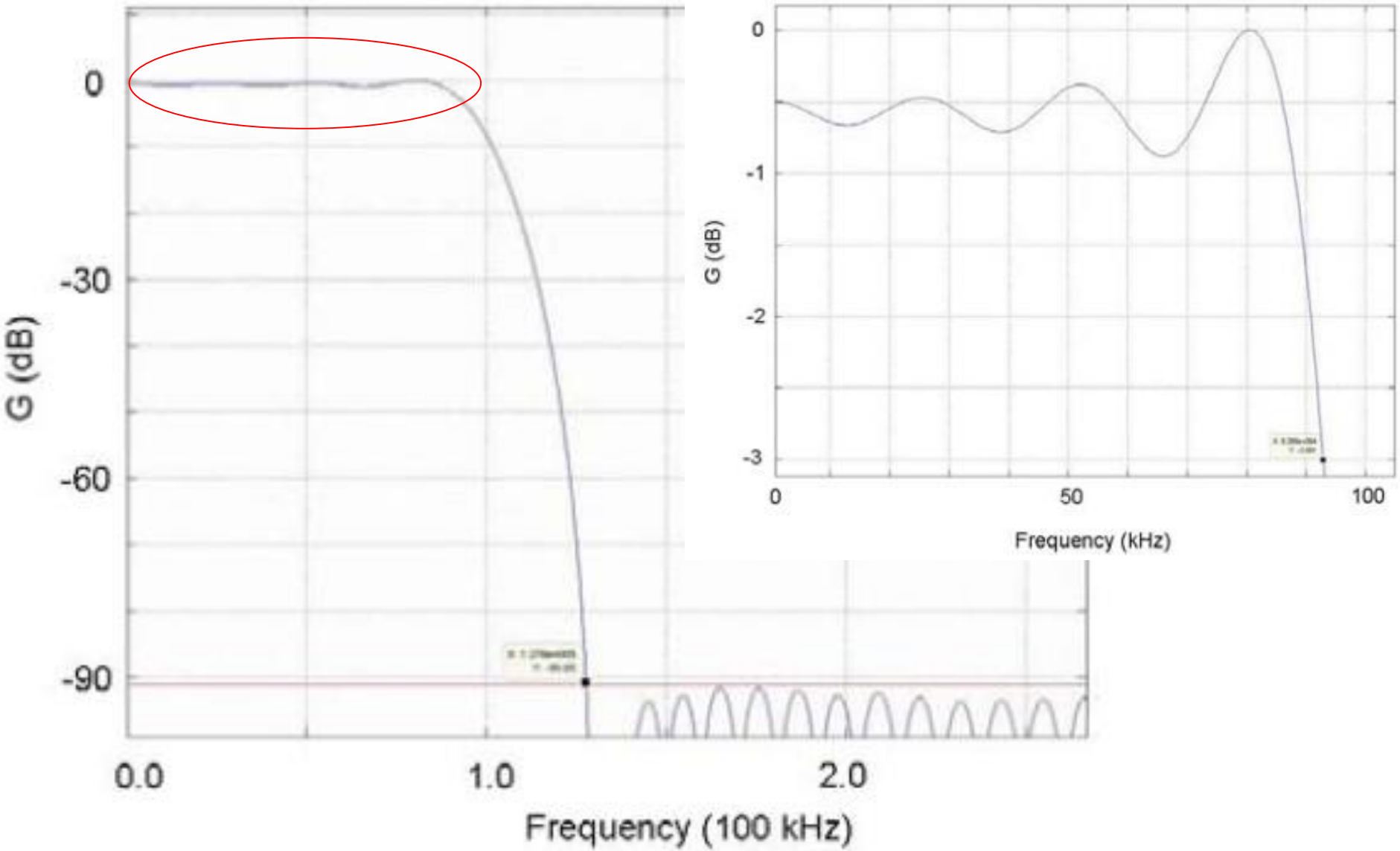
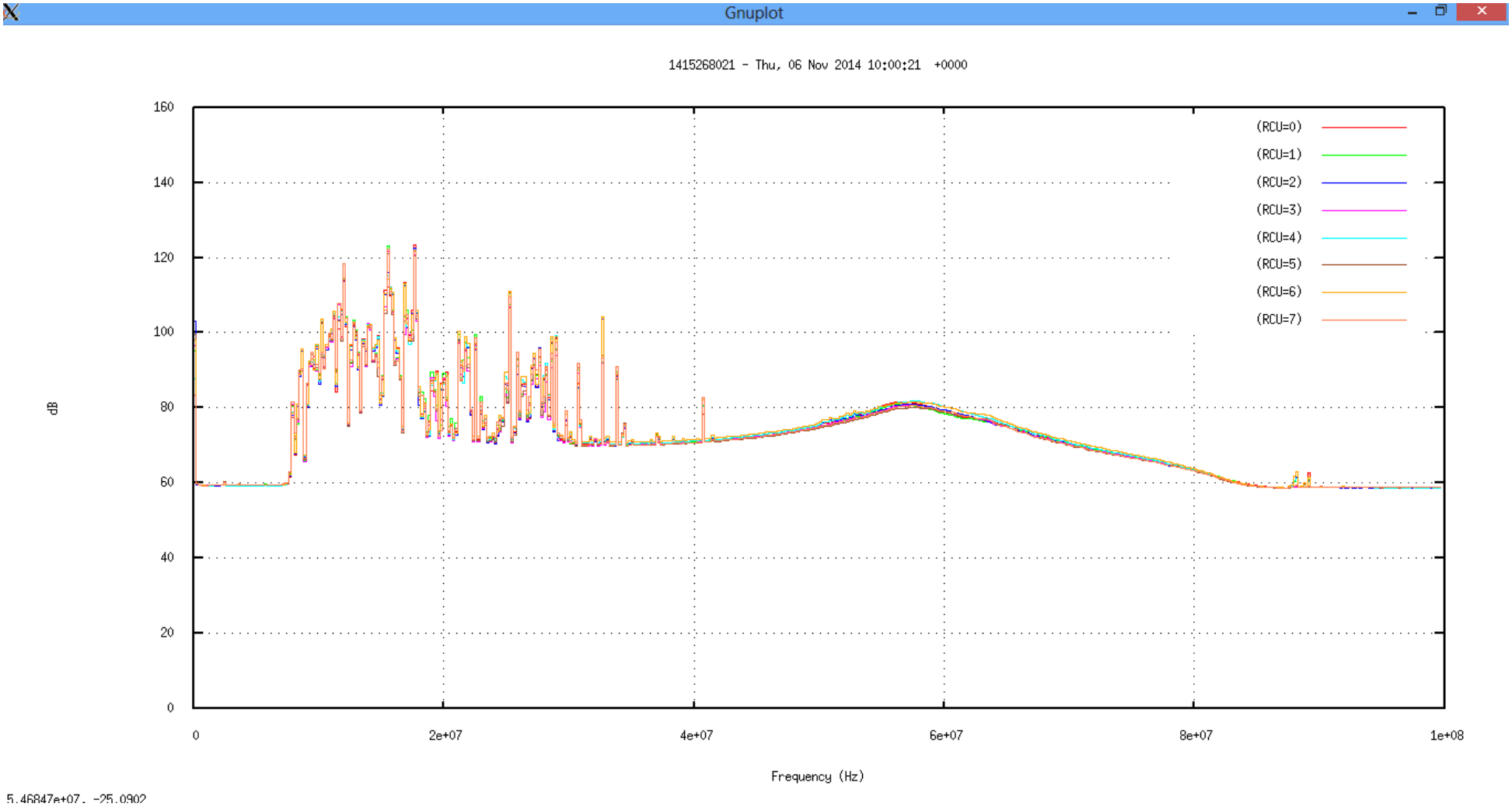


- Make 512 sub bands (polyphase filter)
- Beam forming
- Cross correlation
- Data transport to Central Processing

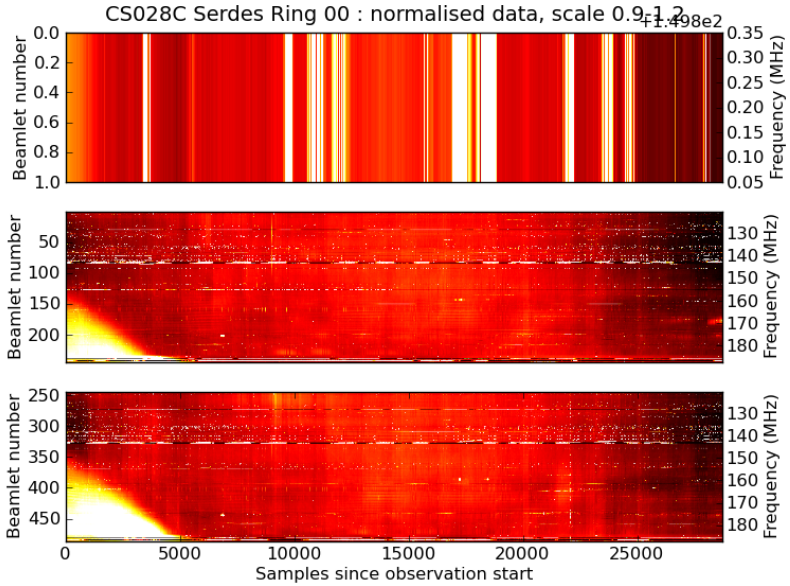
Station subband band pass *M.Norden*

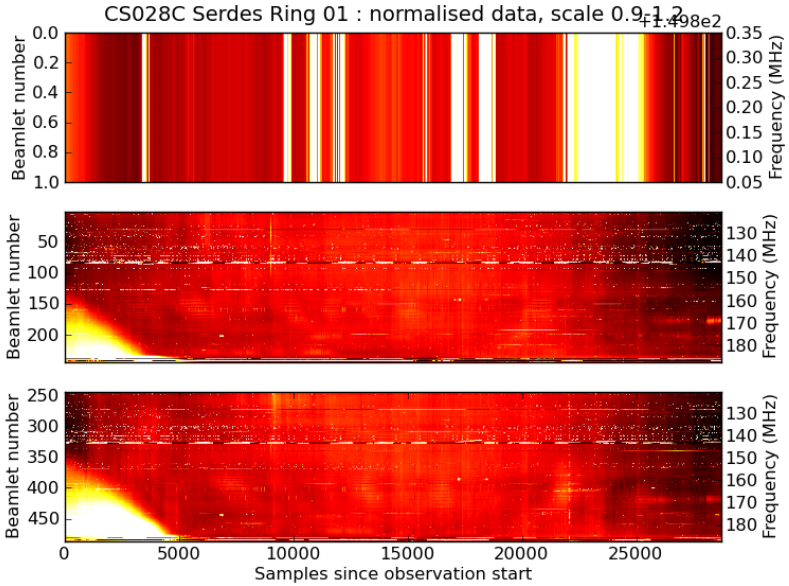


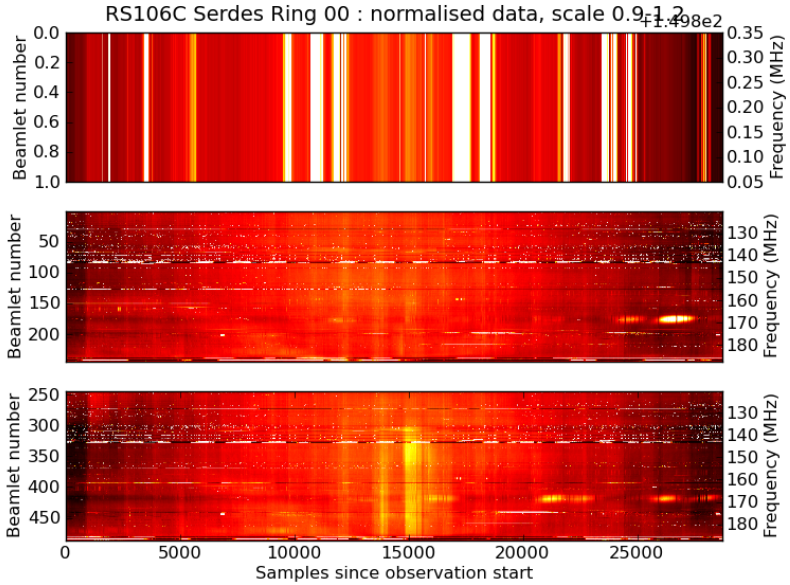
LBA dipole spectra

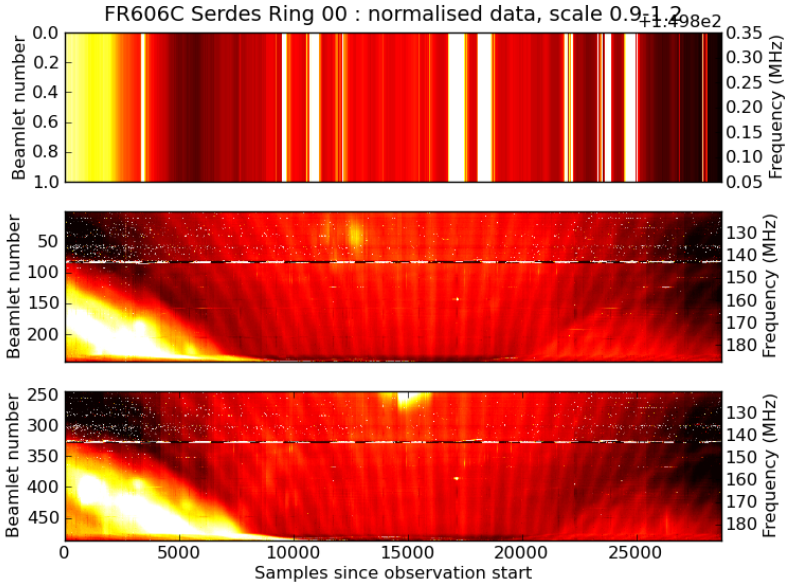


Dynamic spectra

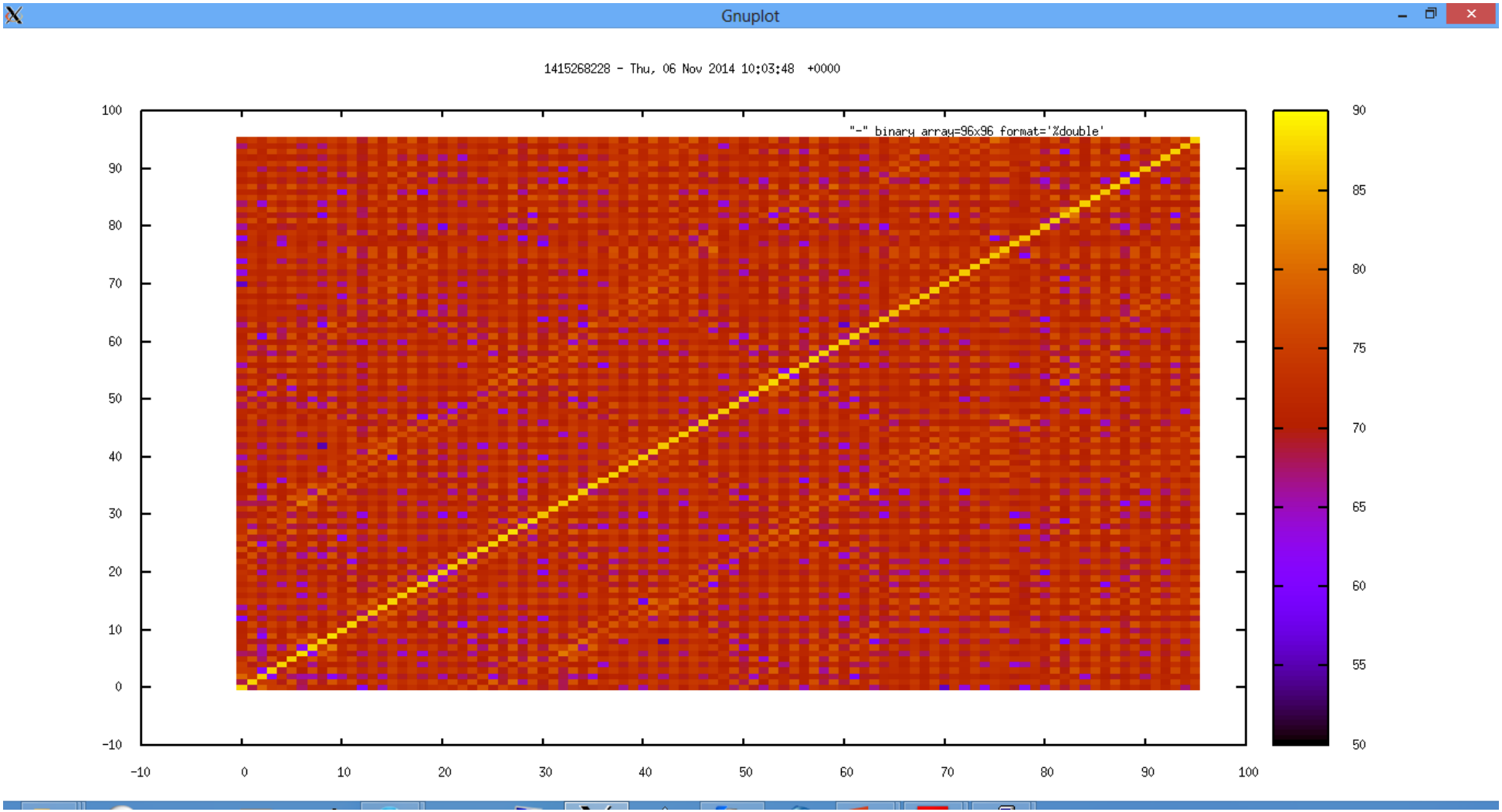




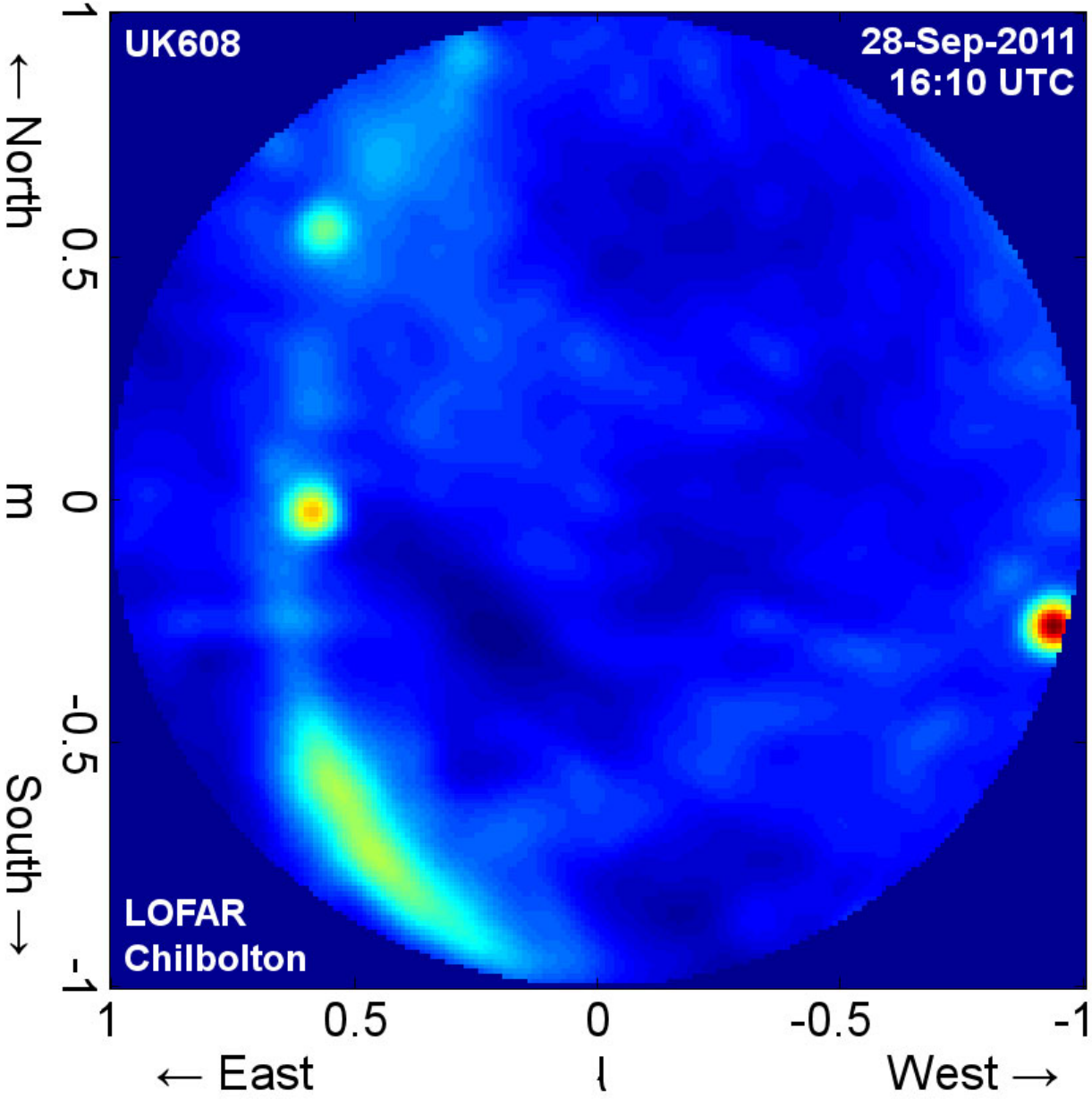




Station cross correlation



Station cross correlation



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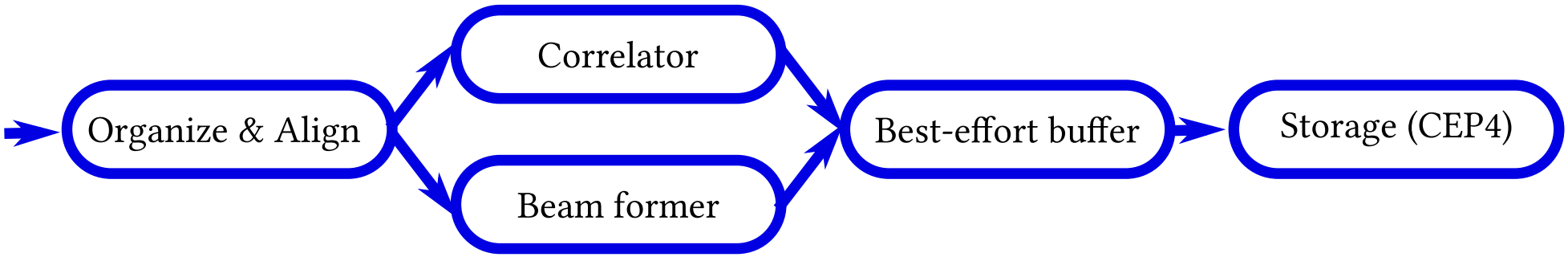
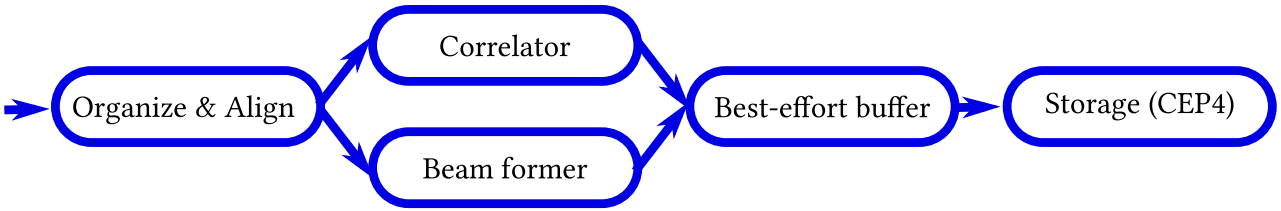
Digital backend: COBALT

Data flow

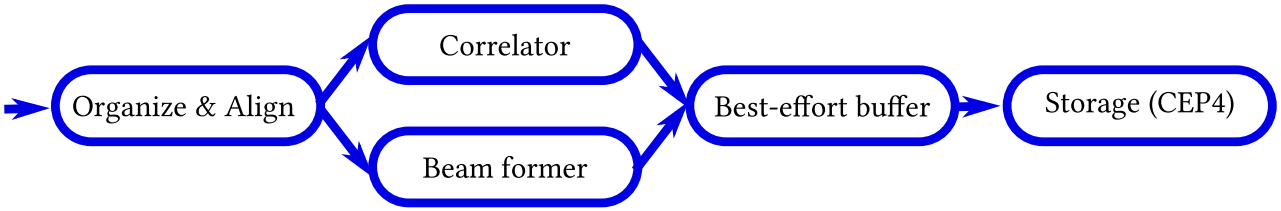

Organize & Align
Correlator
Beam former
Best-effort buffer
Storage (CEP4)

(Re)organize and coarse alignment (CPUs)



- Sort incoming data by sample time
- Flag missing data
- Transpose data from “per station: all sub bands” to “per sub band: all stations”
- Coarse delay compensation: error 2.56 μs
- Ship data to GPUs

Correlator (GPUs)



Per station

- Polyphase filter
- Compensate remaining phase slope due to coarse delay step
- station sub band bandpass correction

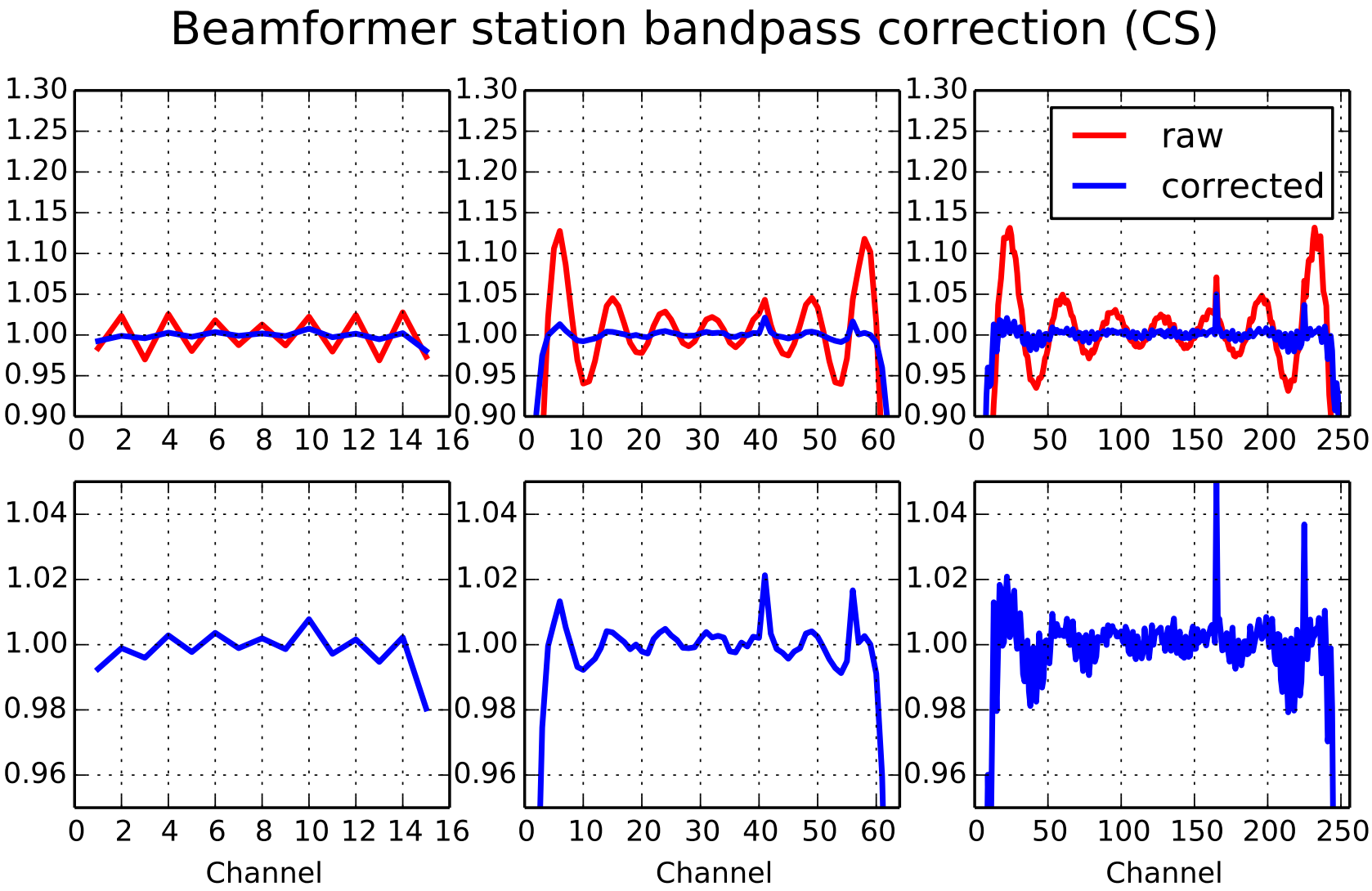
Per baseline per channel

- Compute

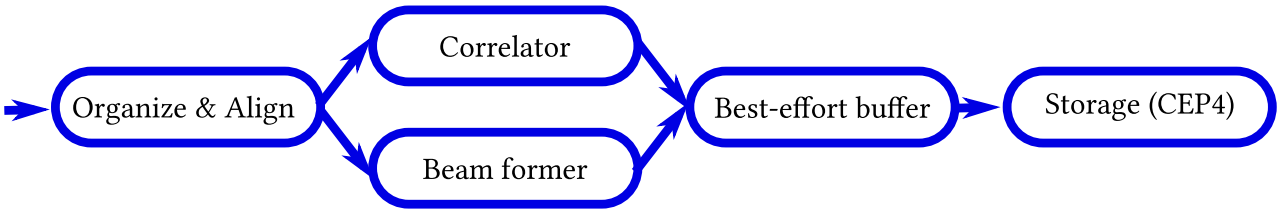
$$\begin{pmatrix} x_i x_j^* & x_i y_j^* \\ y_i x_j^* & y_i y_j^* \end{pmatrix} \quad (1)$$

- Average to 0.25 – a few s

Sub band bandpass correction



Beam former (GPUs)



Per station

- 256pt FFT
- phase slope correction
- sub band bandpass correction
- 256pt inverse FFT

Combine all fields

- Complex Voltage: $\sum_i \mathbf{e}_i$ OR
- Coherent Stokes: $\mathrm{Stokes}(\sum_i \mathbf{e}_i)$ OR
- Incoherent Stokes: $\sum_i \mathrm{Stokes}(\mathbf{e}_i)$
- Average to 5.12 μs – $\sim$0.01 s (Stokes modes)
- Can be done on dozens of “tied array” beams simultaneously
- Output data rates up to 100 Gbit/s!

Further processing

CEP4

- Data *REDUCTION* (tens of TB to a few TB)
- Batch processing only (Slurm)
- No user access
- Almost^{TM} ready for production
- Send data off to Long Term Archive (LTA)

CEP3

- user processing for limited time ($\sim$ 4 weeks)
- all LOFAR software pre-installed
- 24 Dell PowerEdge R720 servers
- 128GB memory
- 20 Cores (2 ten-core Intel Xeon e5 2660v2 processors)
- Dell PERC H710P RAID controller 8 x 4TB disks in RAID6 setup, 22TB net diskspace, XFS filesystem

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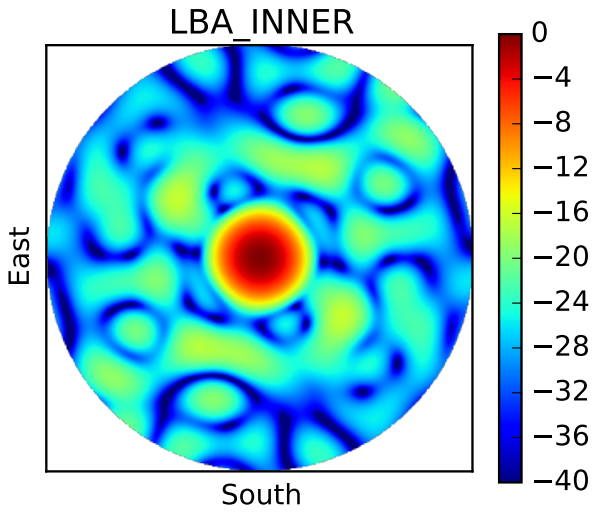
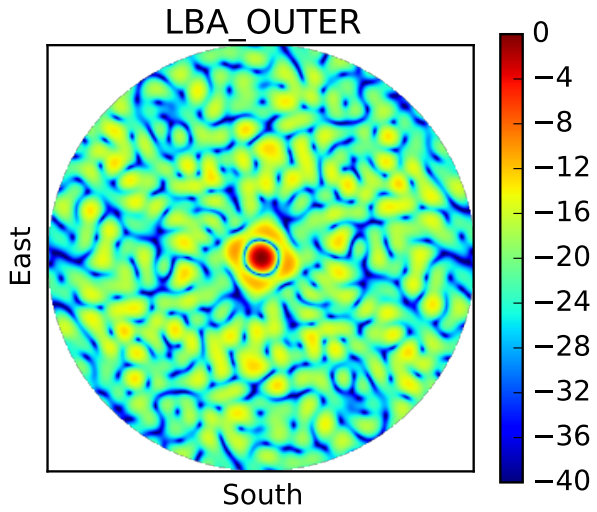
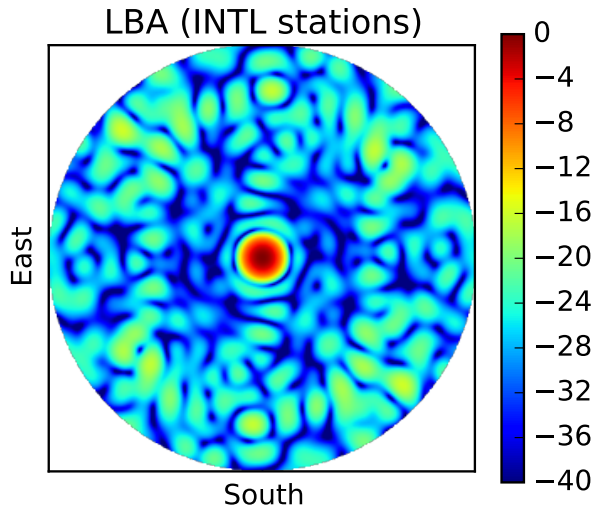
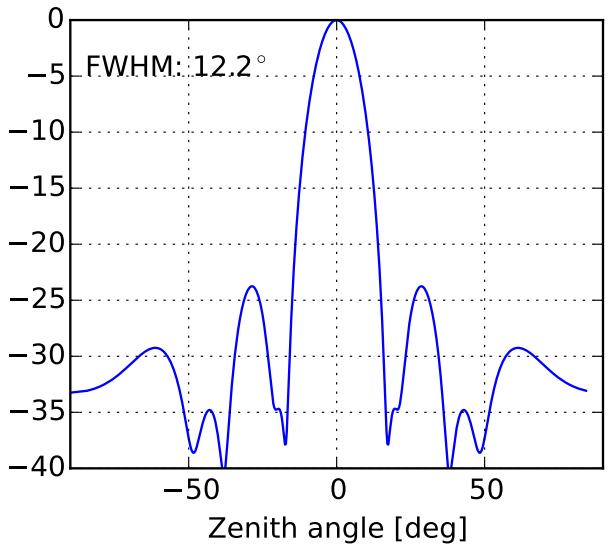
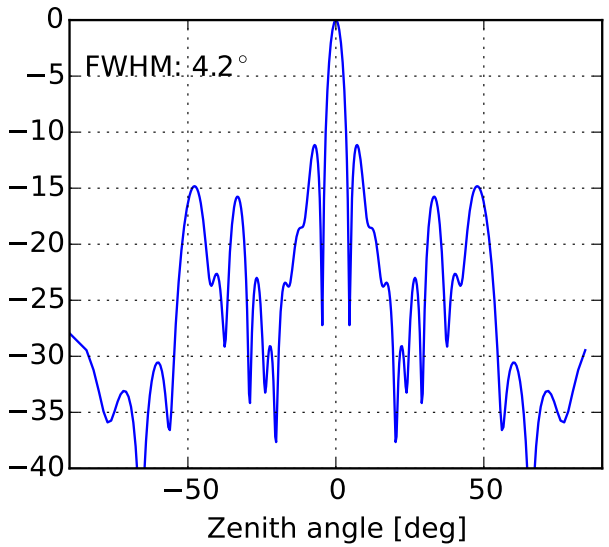
LBA beams at 50 MHz

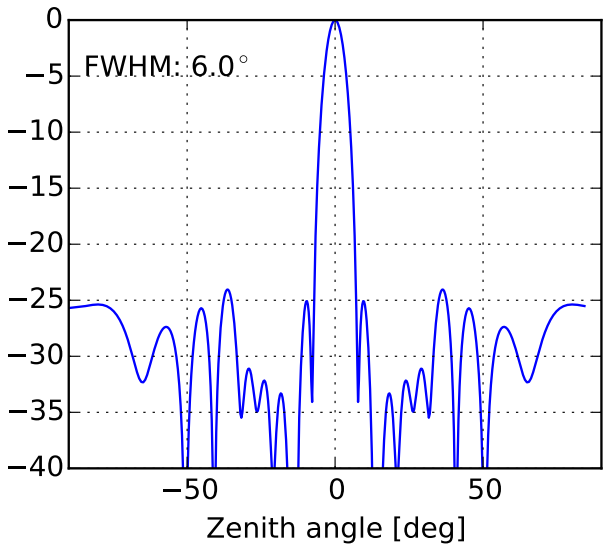






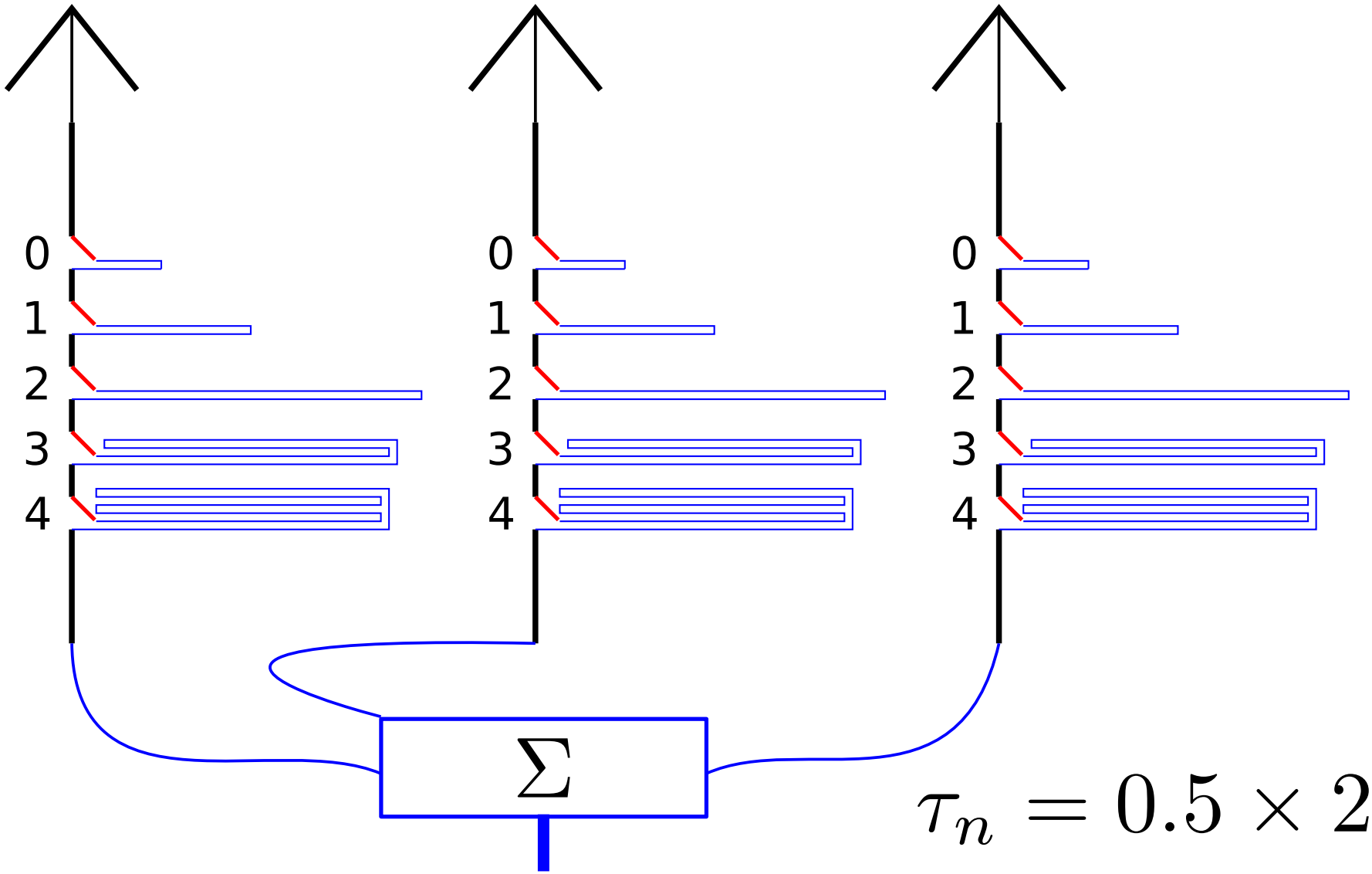






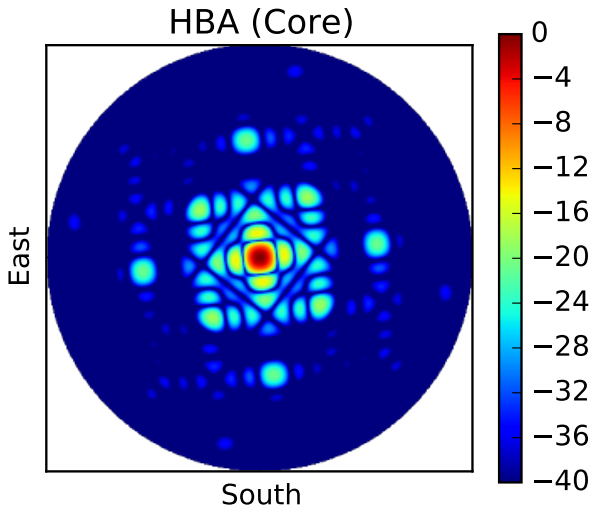
HBA tile

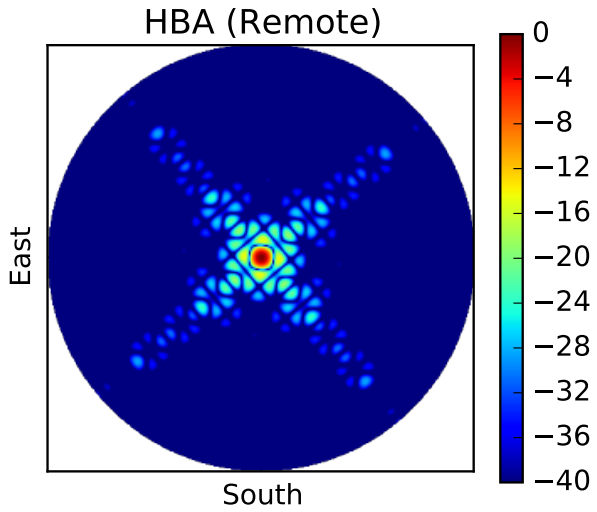
Analogue beam forming

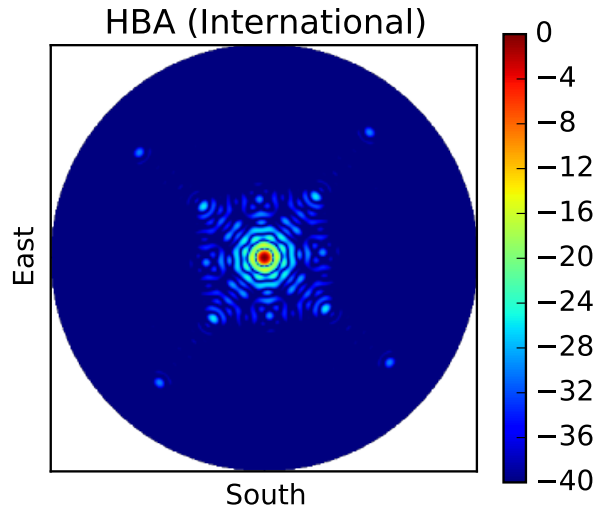


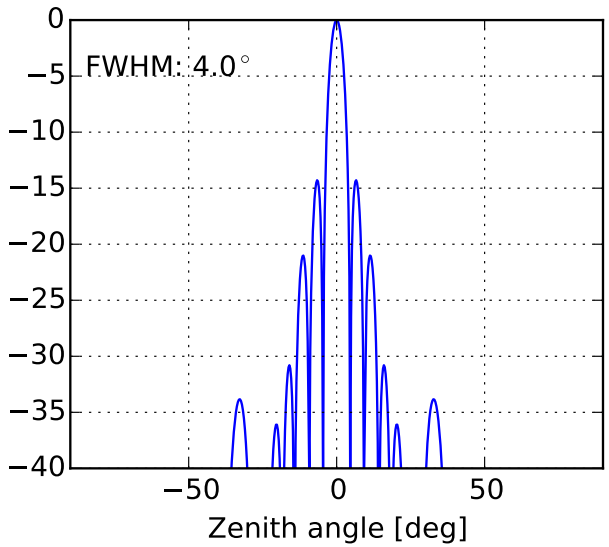
$$\tau_n = 0.5 \times 2^n \text{ns}$$

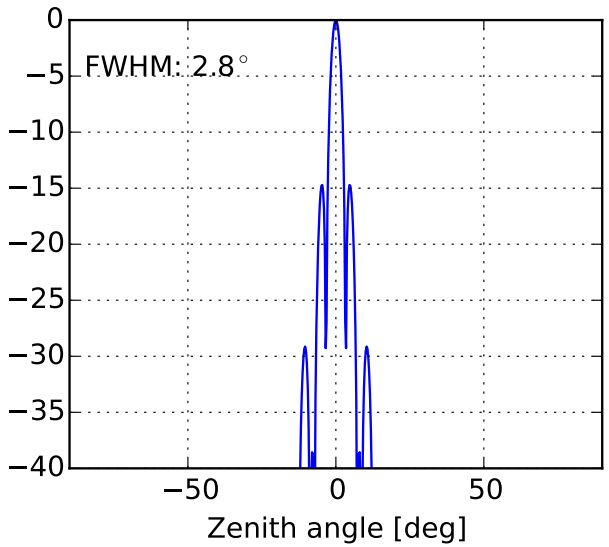
HBA beams at 150 MHz

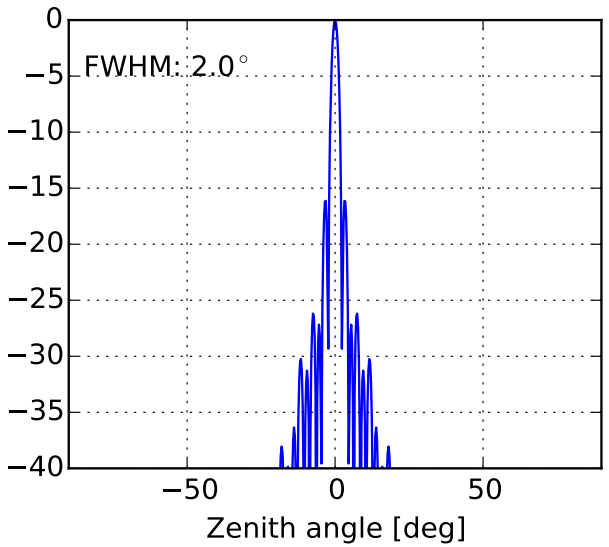




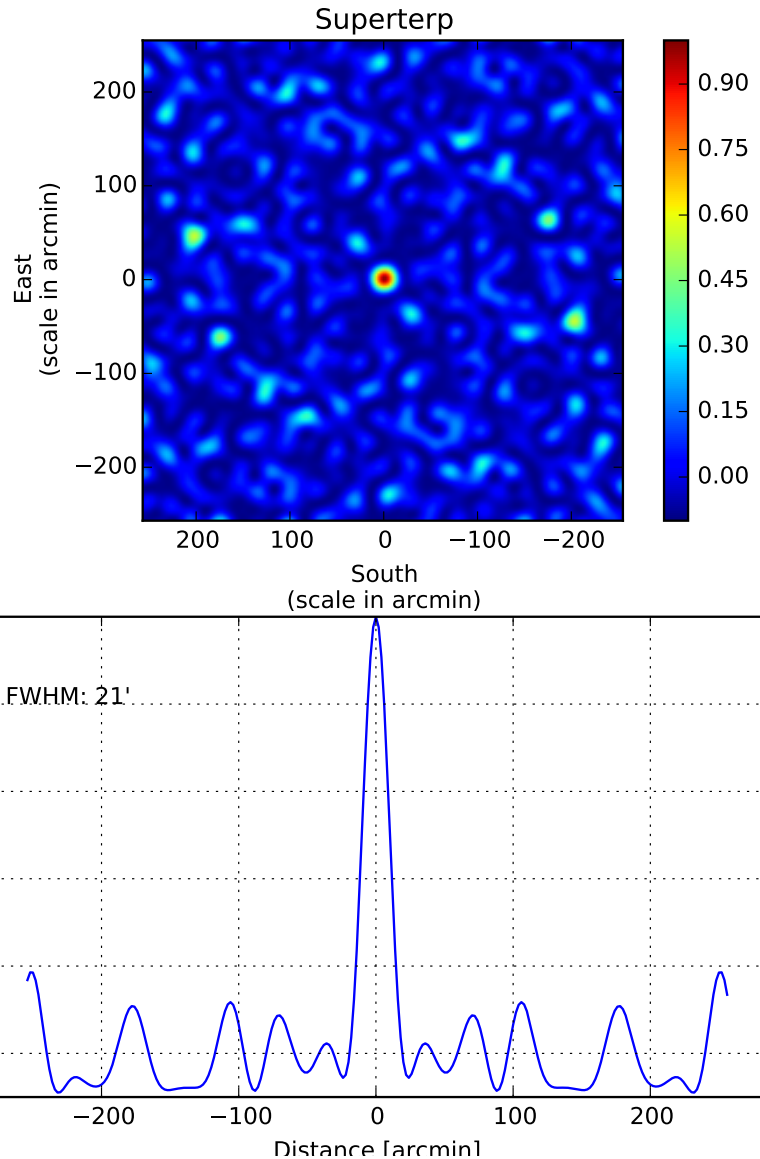


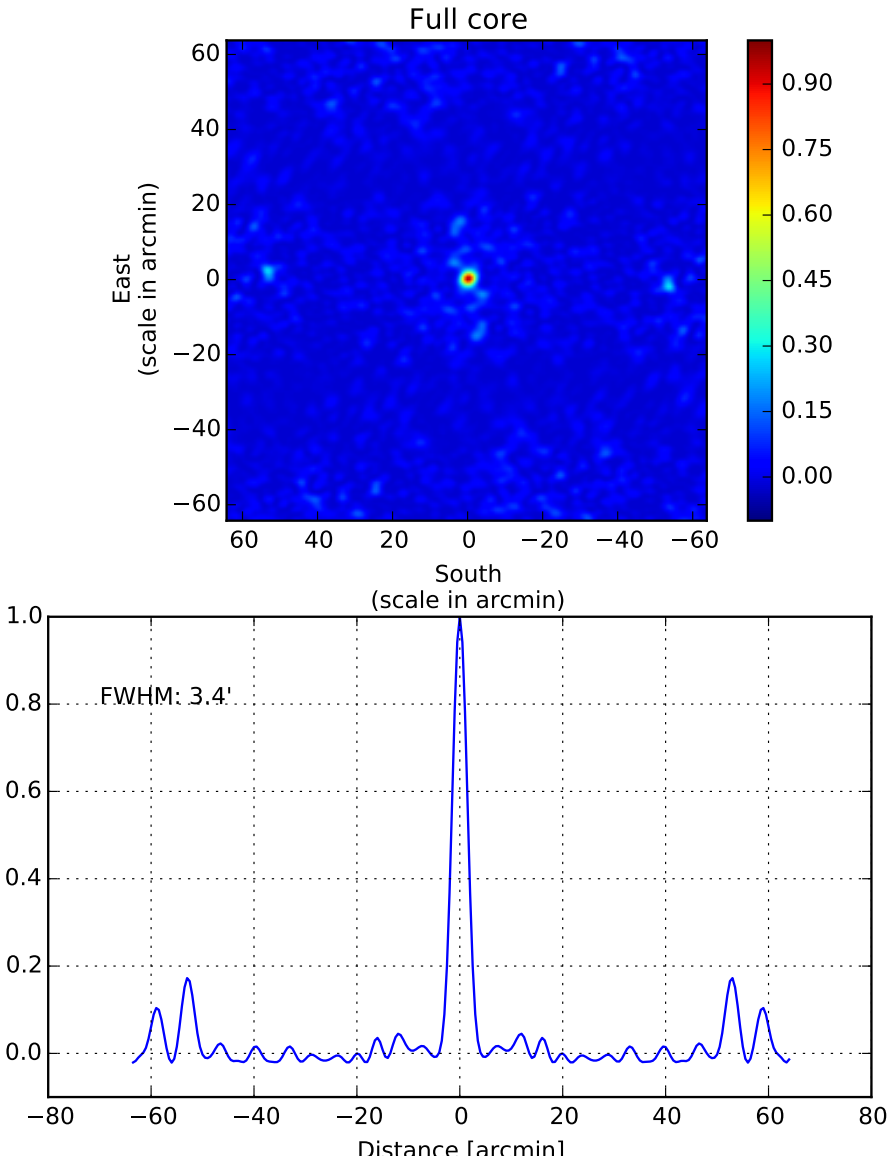






Coherent sum of stations at 150 MHz

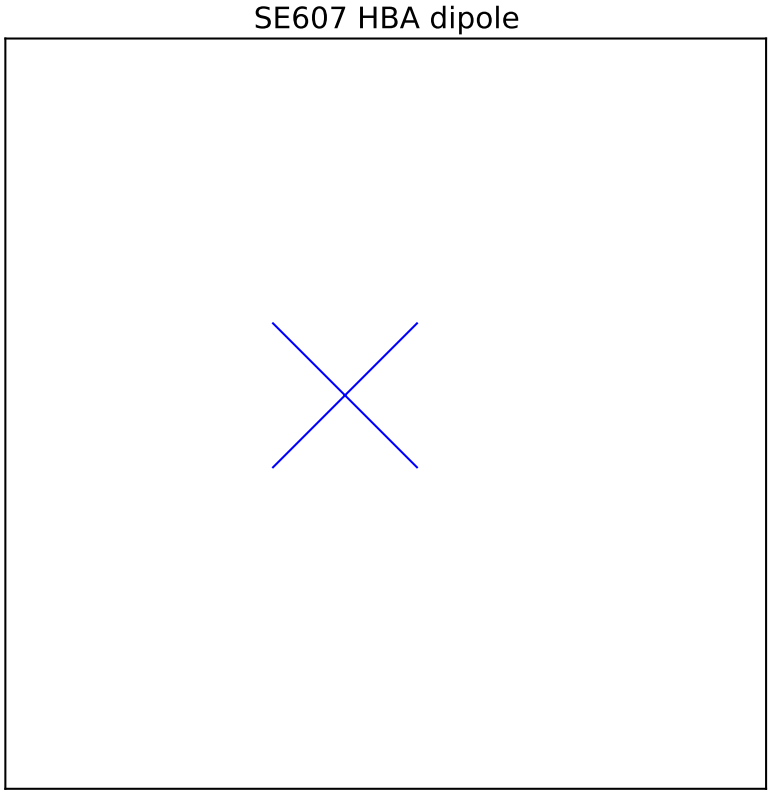


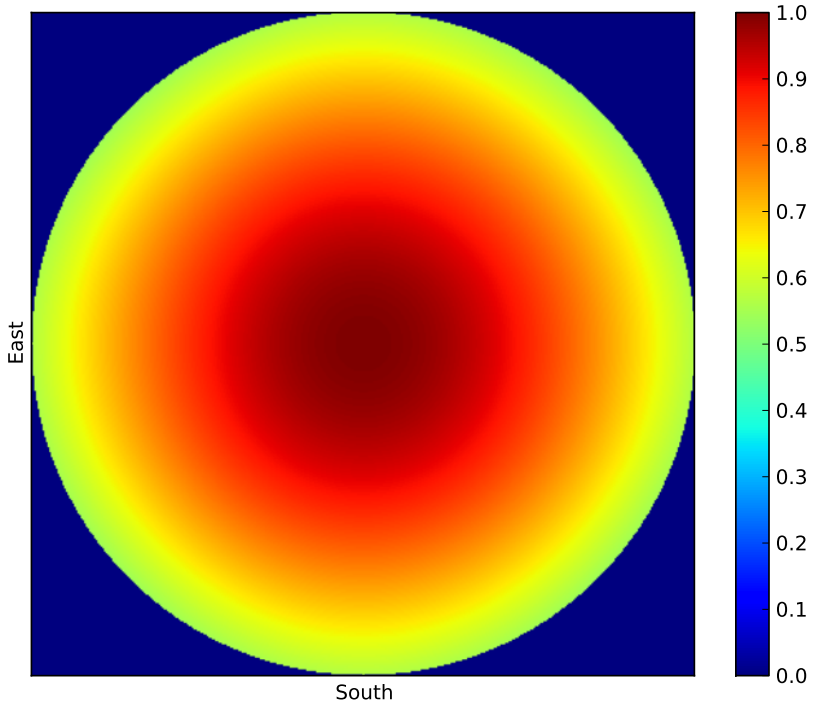


Outline

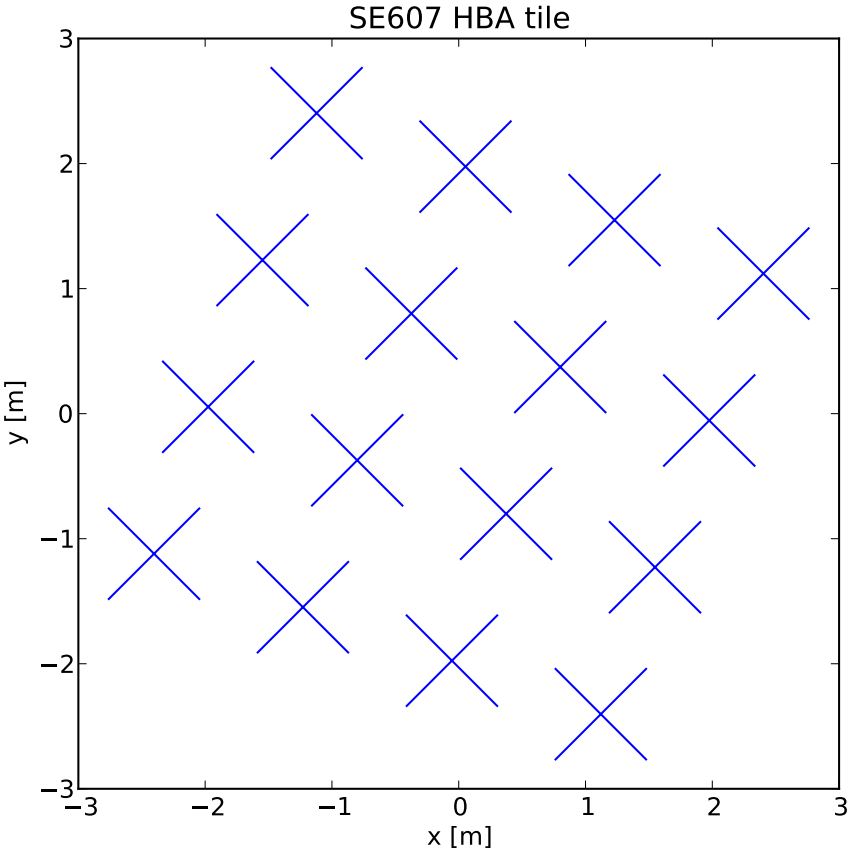
1. Architecture
2. Stations
3. C O F F E E
4. Central processing
5. Beams, beams, beams. . .
6. More beams. . .
7. If all goes well

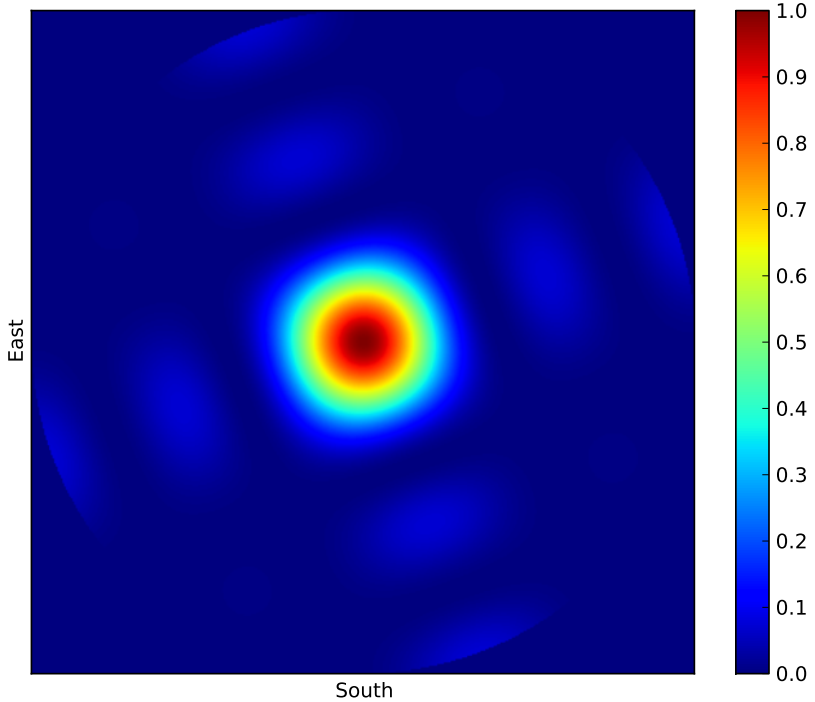
HBA element beam 150 MHz



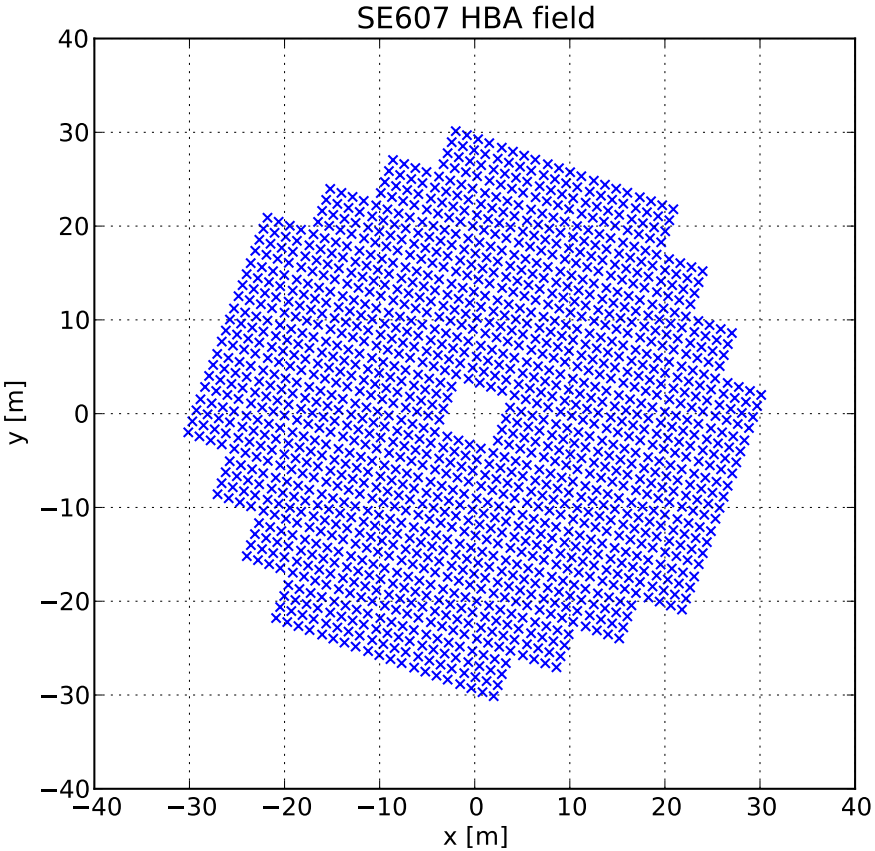


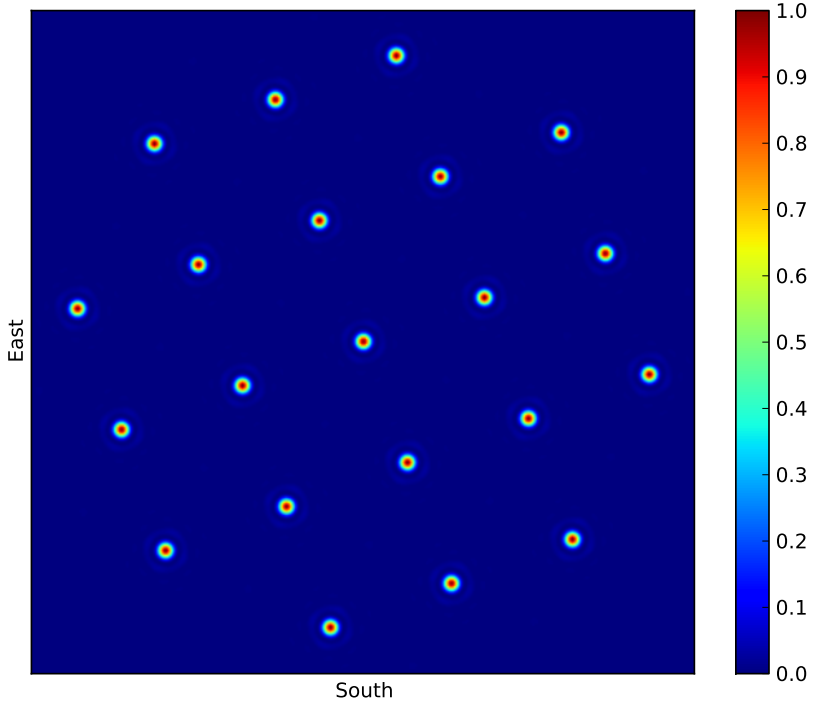
HBA analogue tile beam 150 MHz



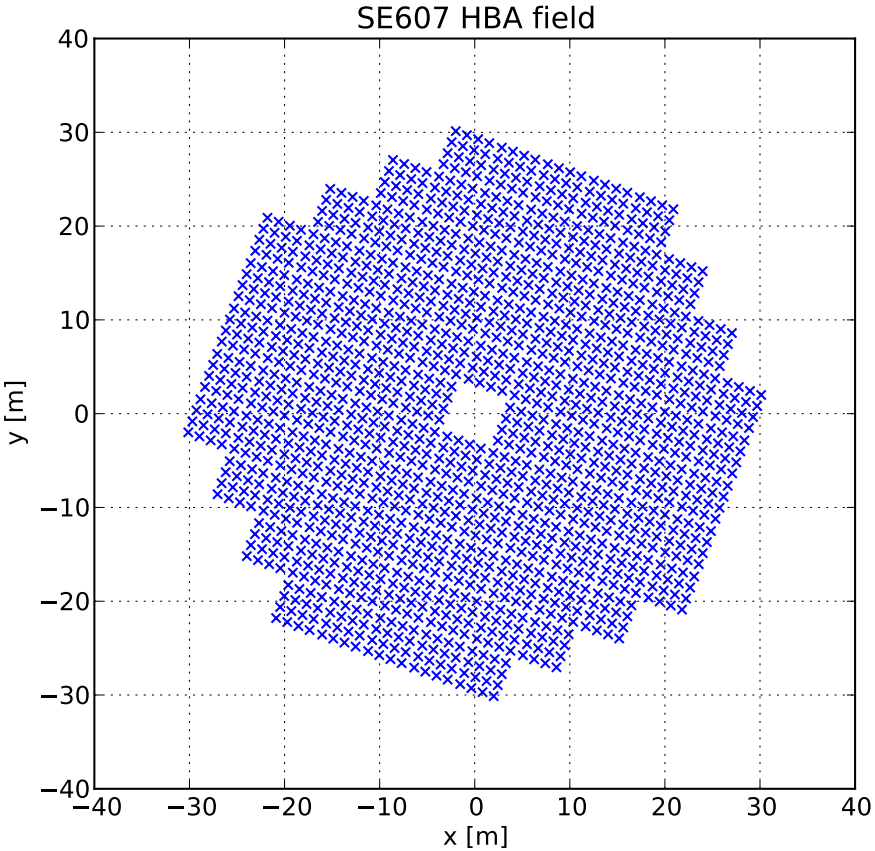


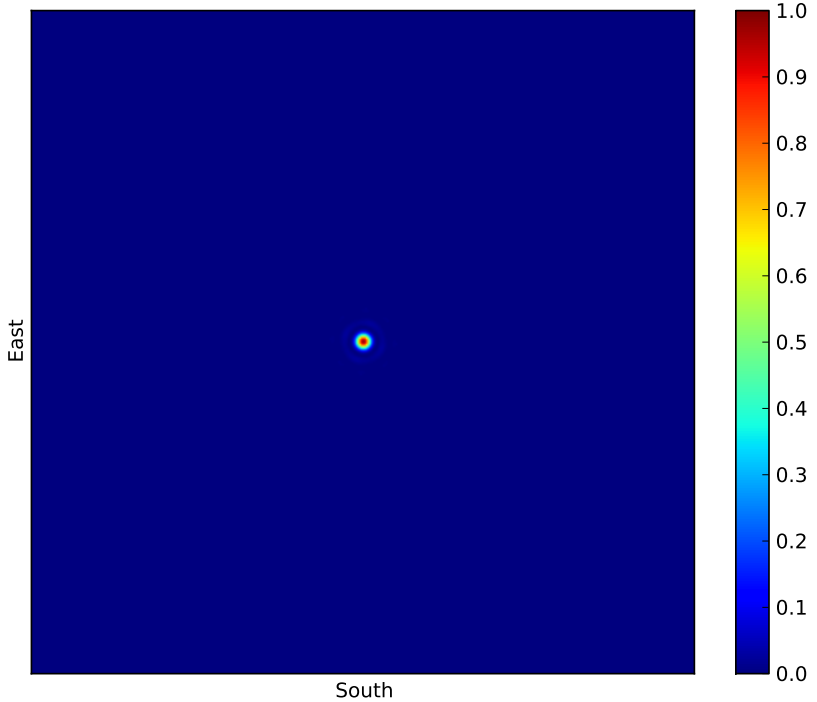
HBA digital beam 150 MHz



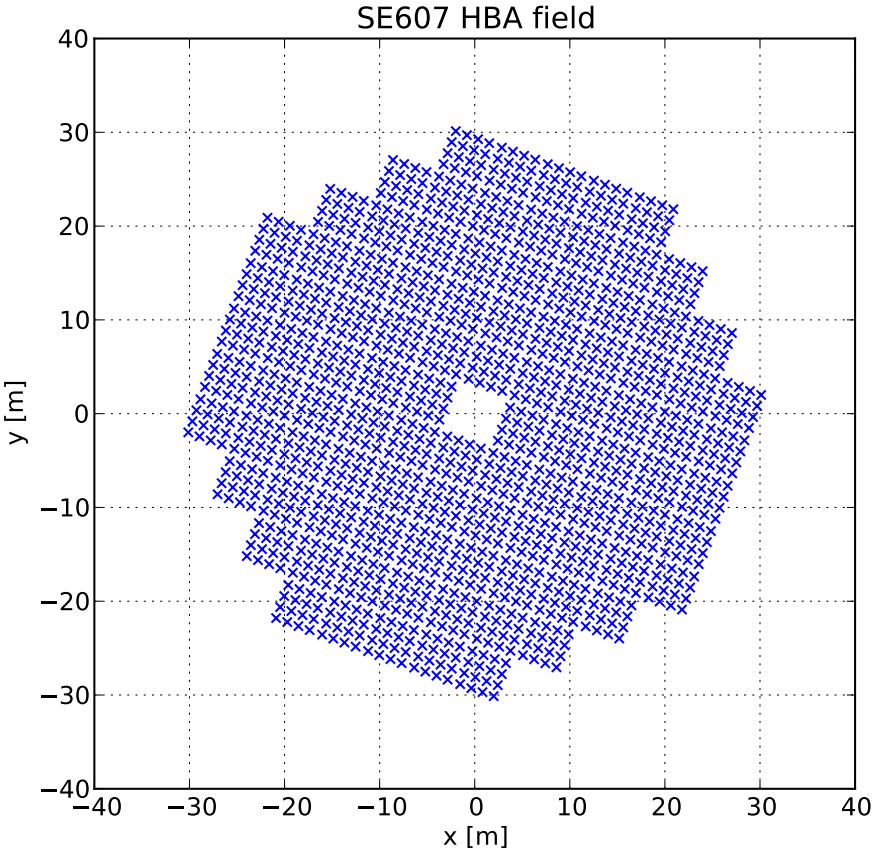


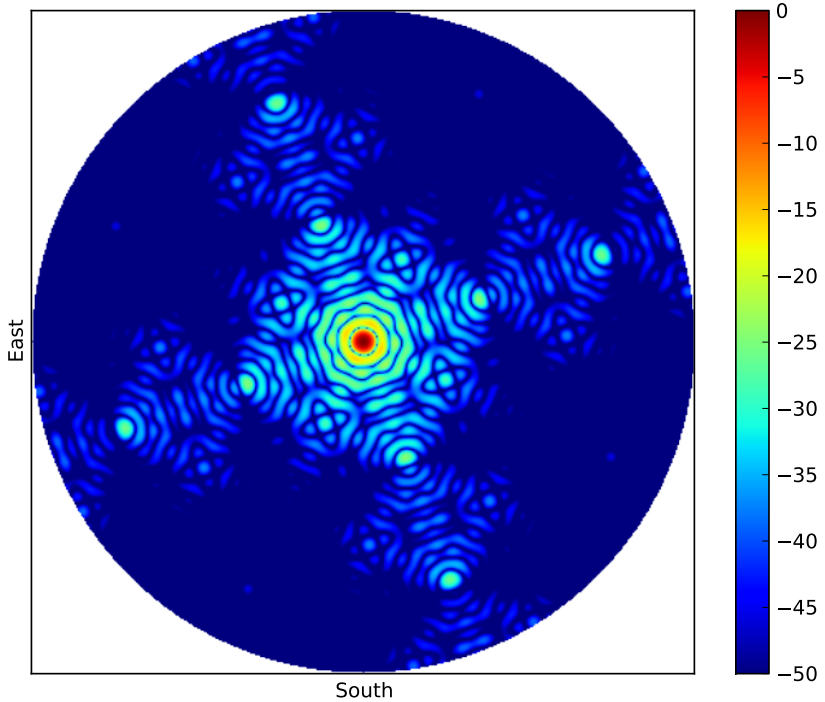
HBA station beam 150 MHz



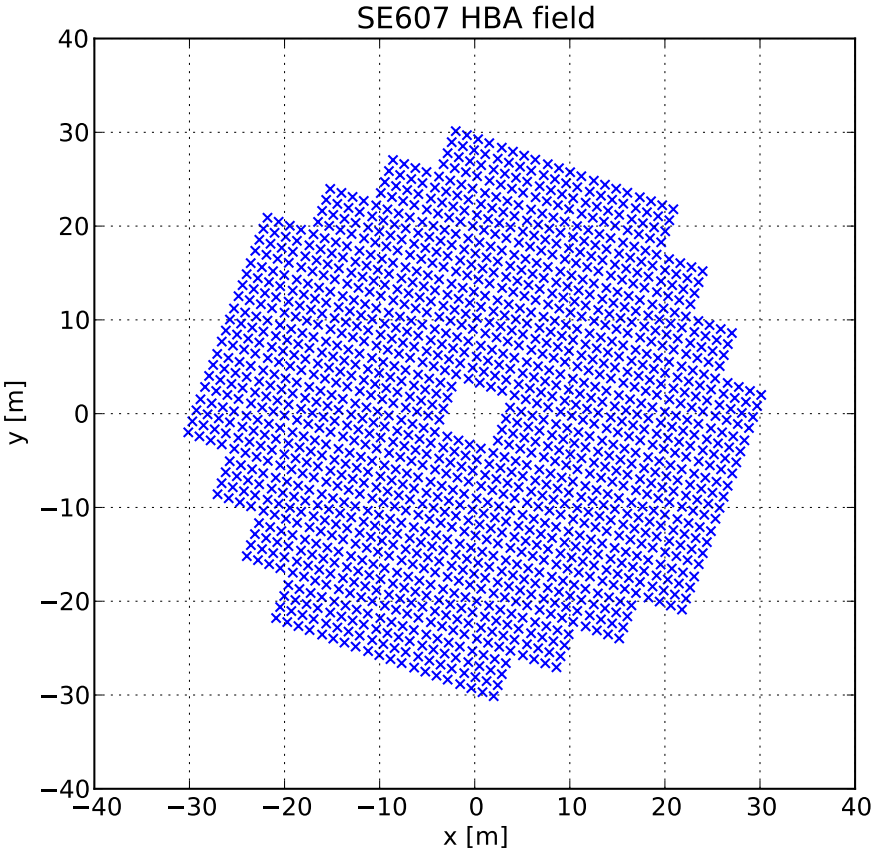


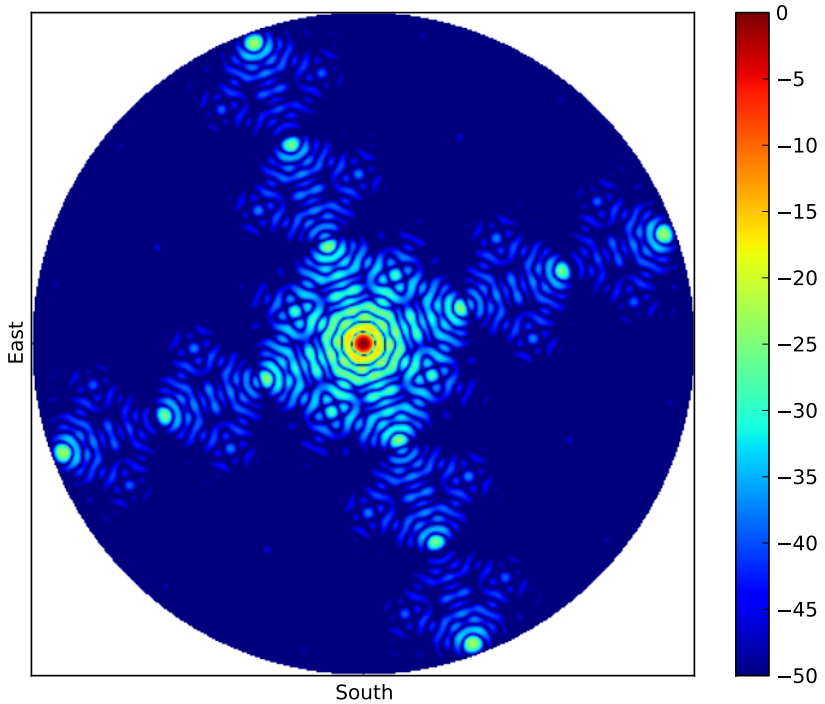
HBA station beam 150 MHz (dB)



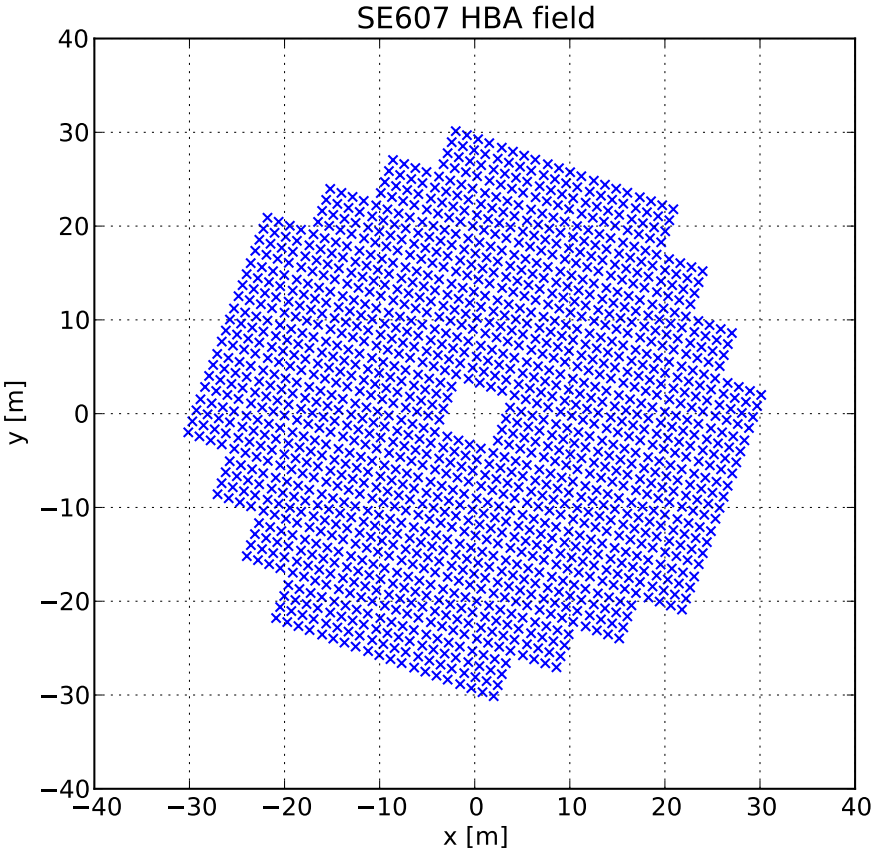


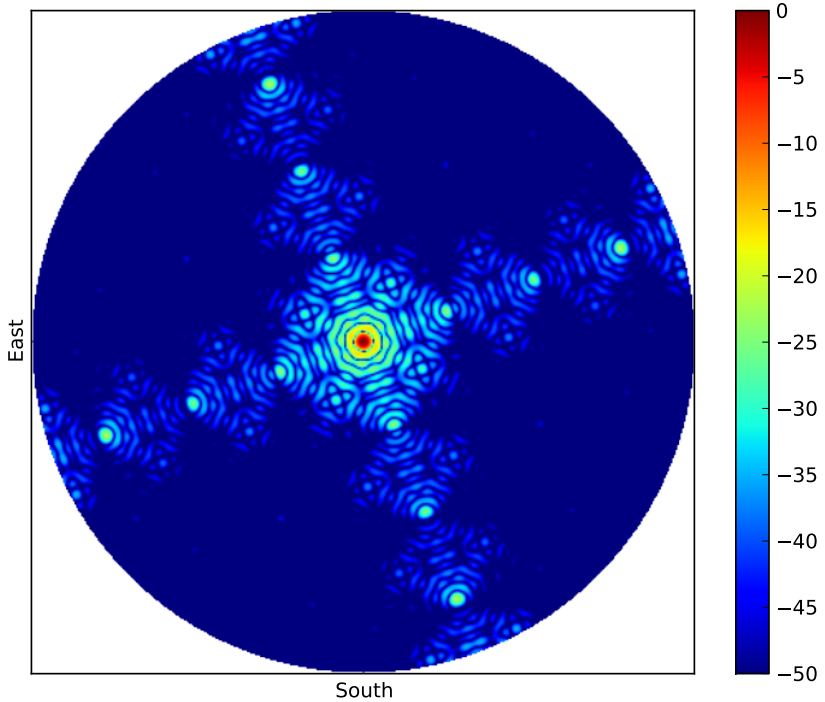
HBA station beam 180 MHz (dB)



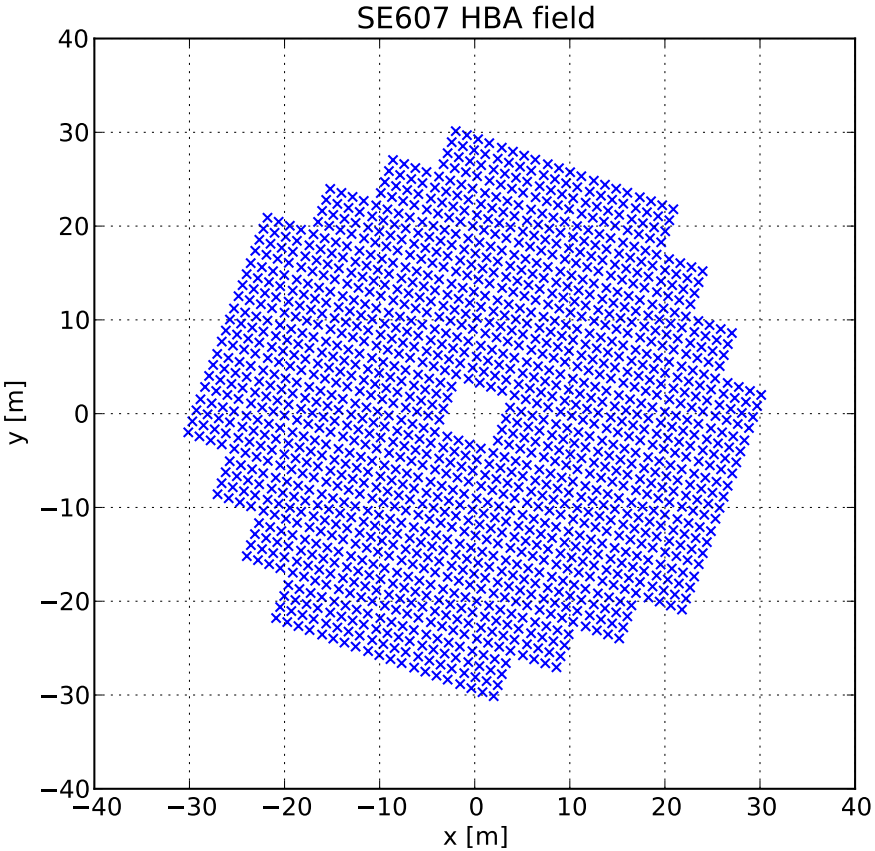


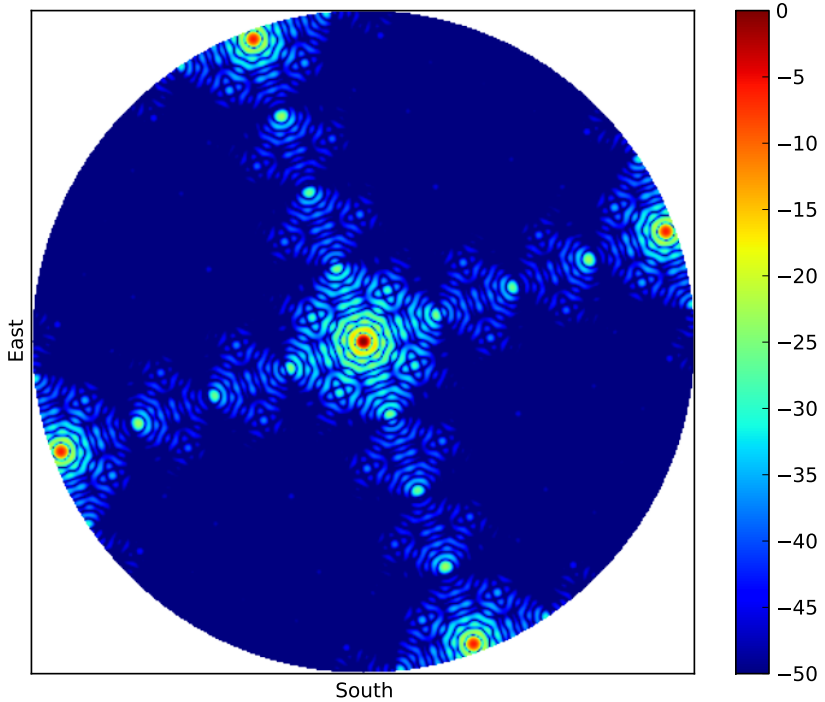
HBA station beam 210 MHz (dB)



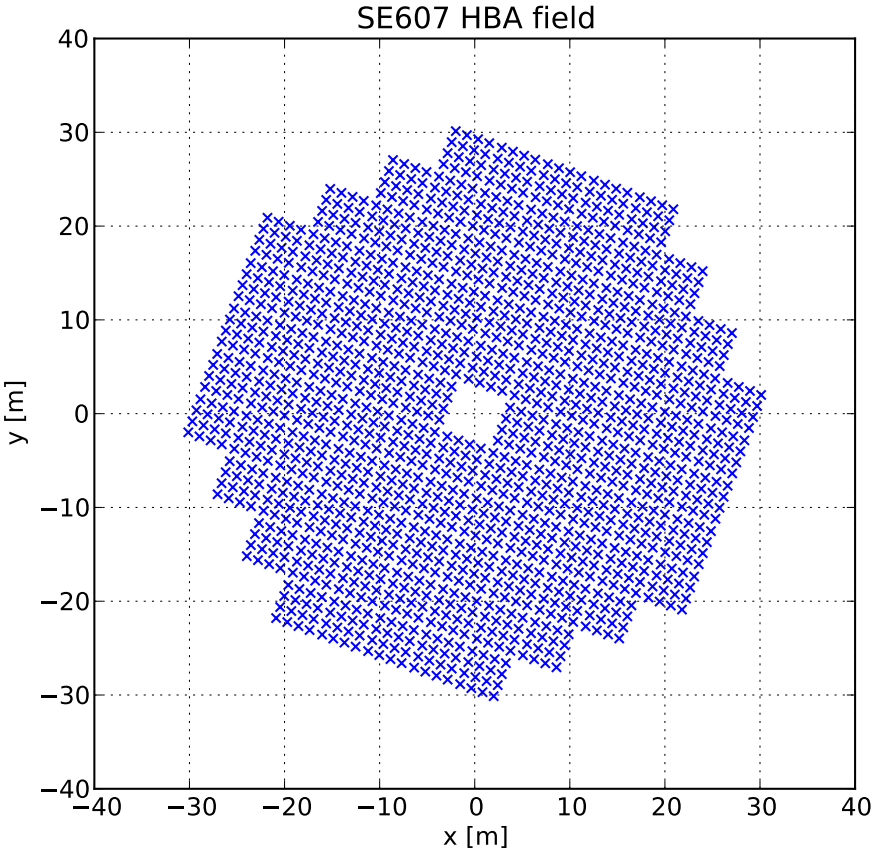


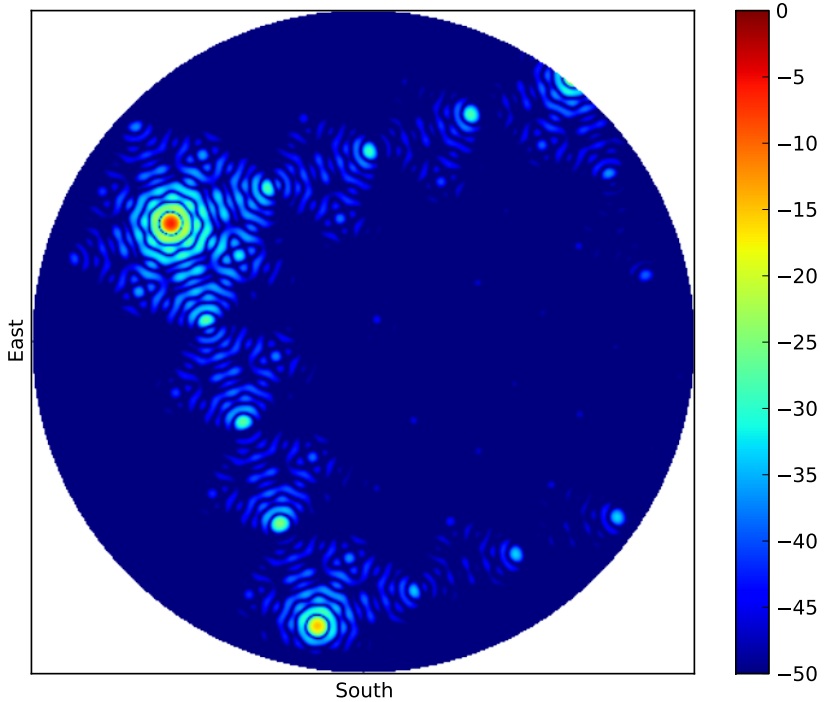
HBA station beam 240 MHz (dB)



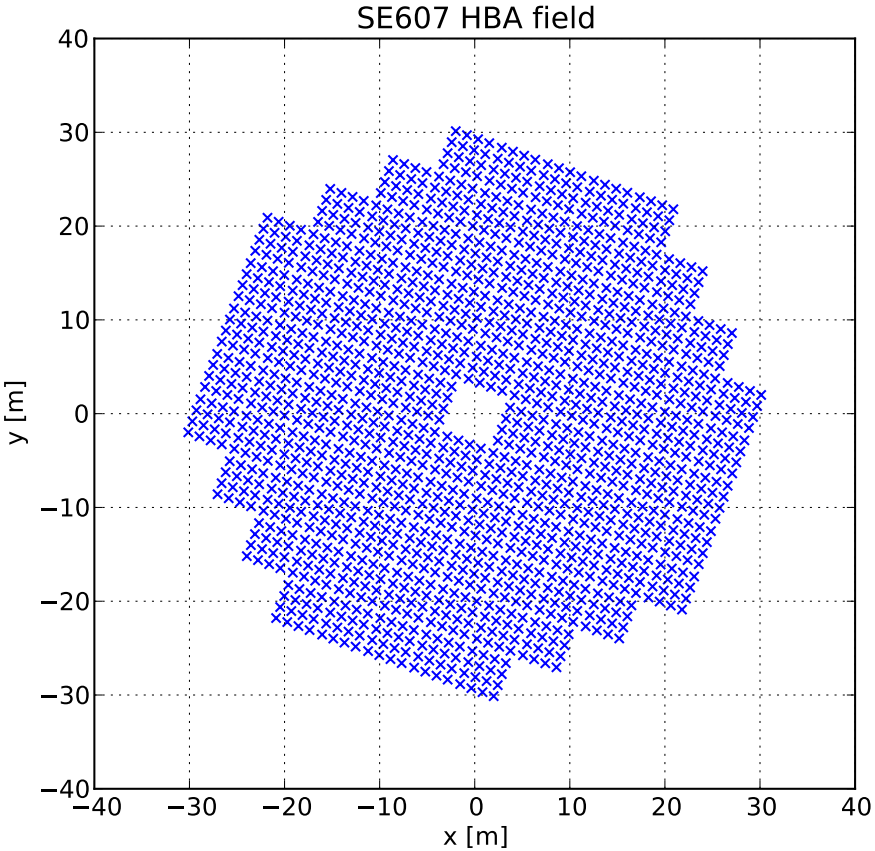


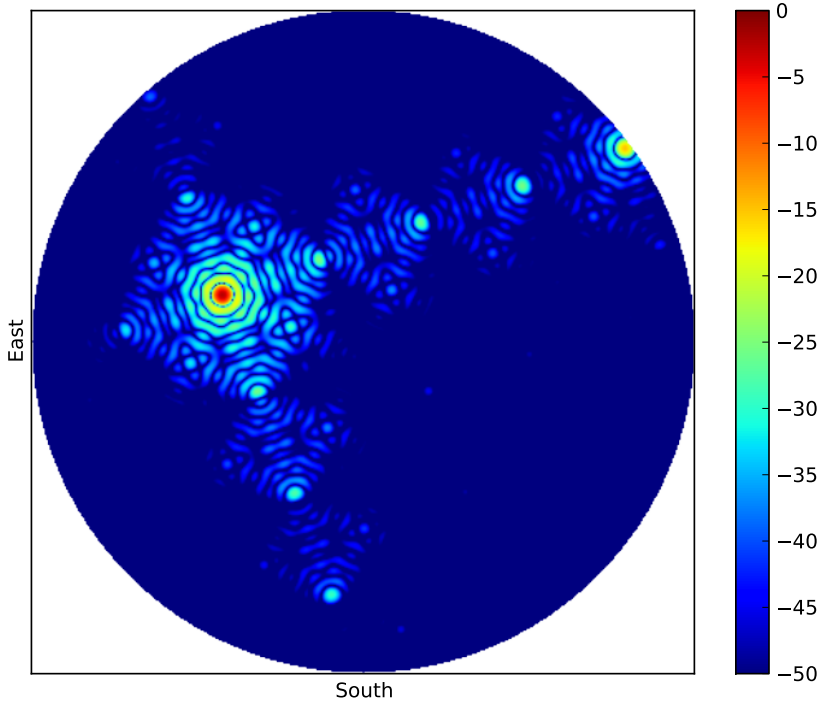
HBA station beam tracking 180 MHz (dB)



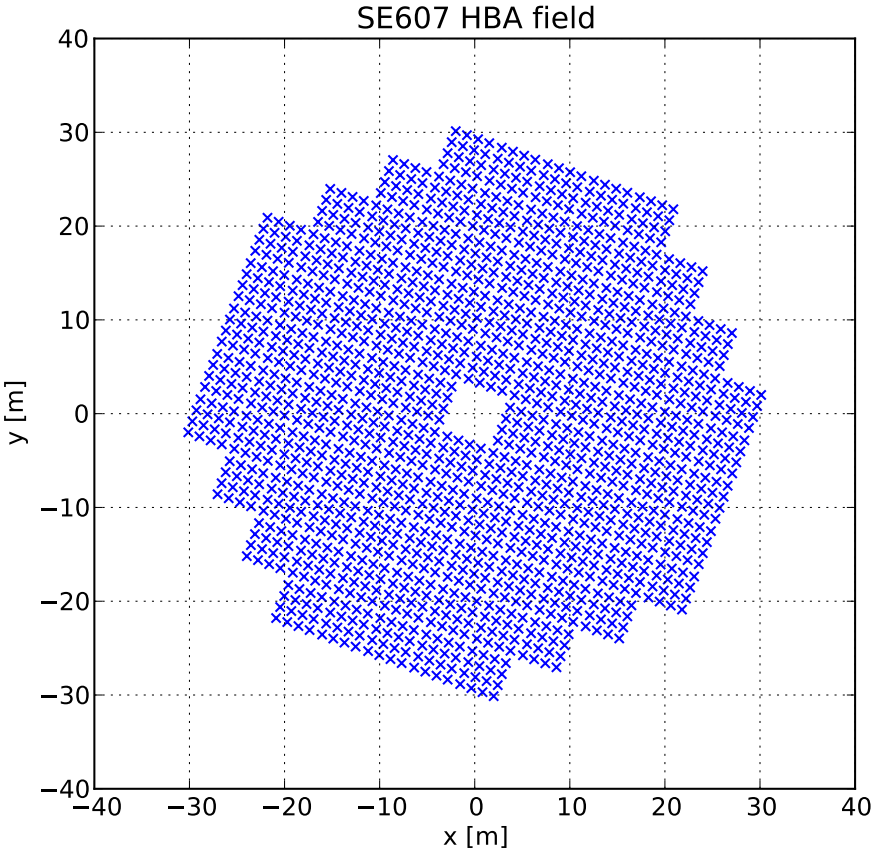


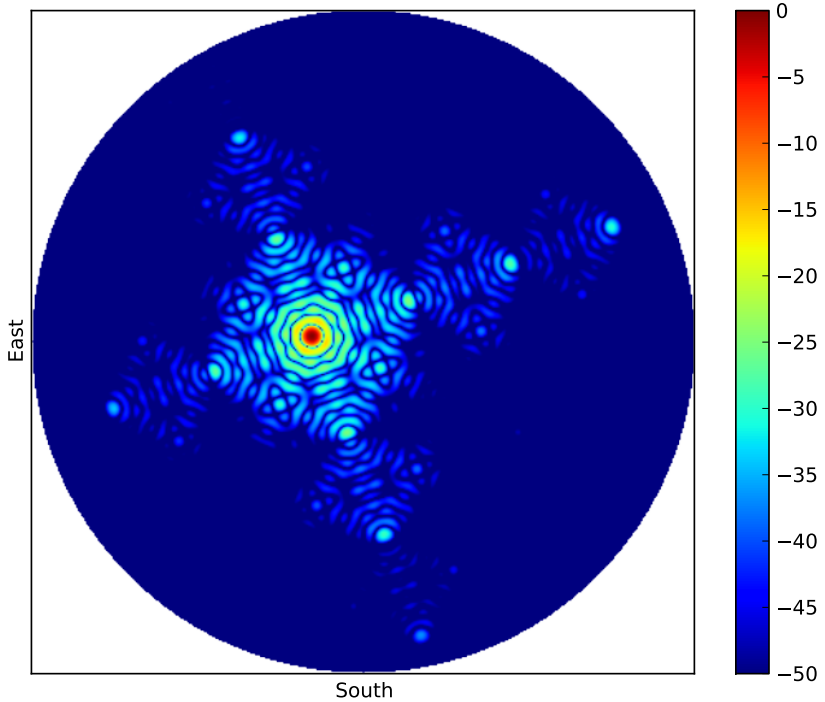
HBA station beam tracking 180 MHz (dB)



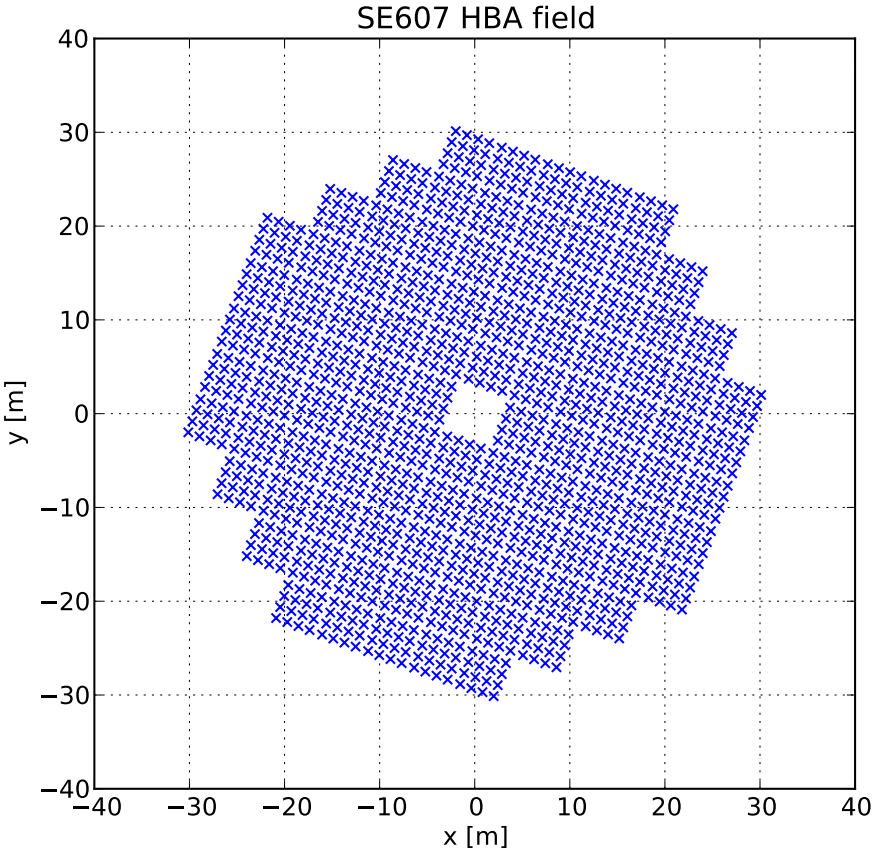


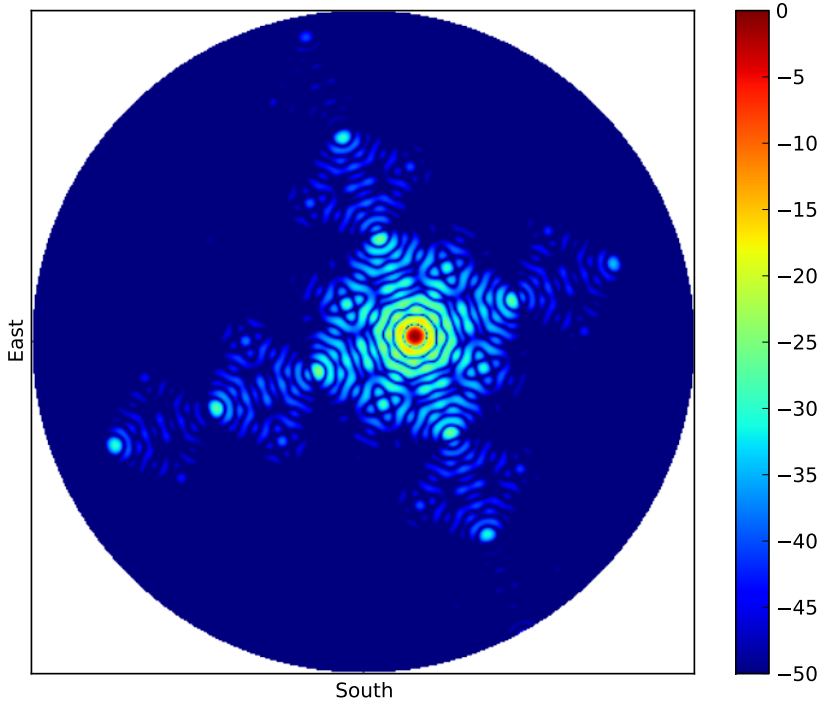
HBA station beam tracking 180 MHz (dB)



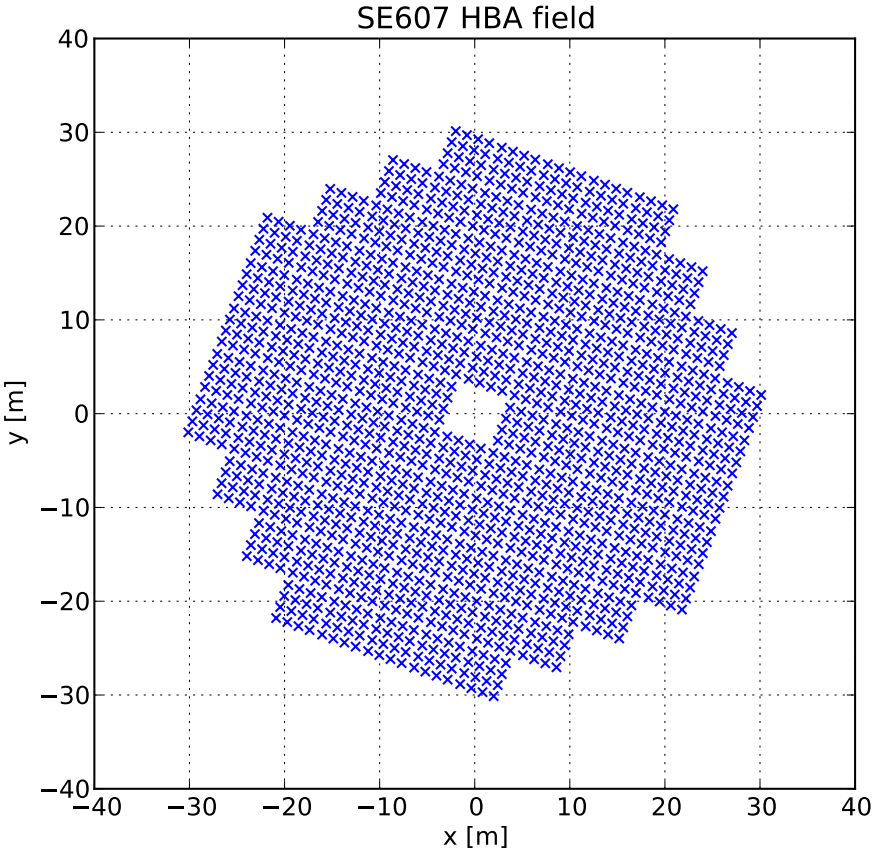


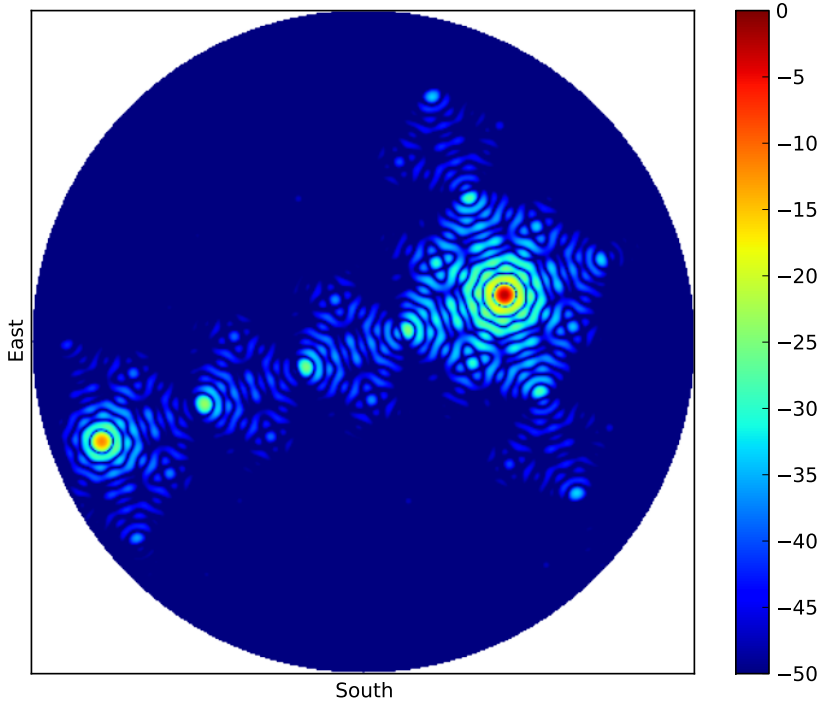
HBA station beam tracking 180 MHz (dB)



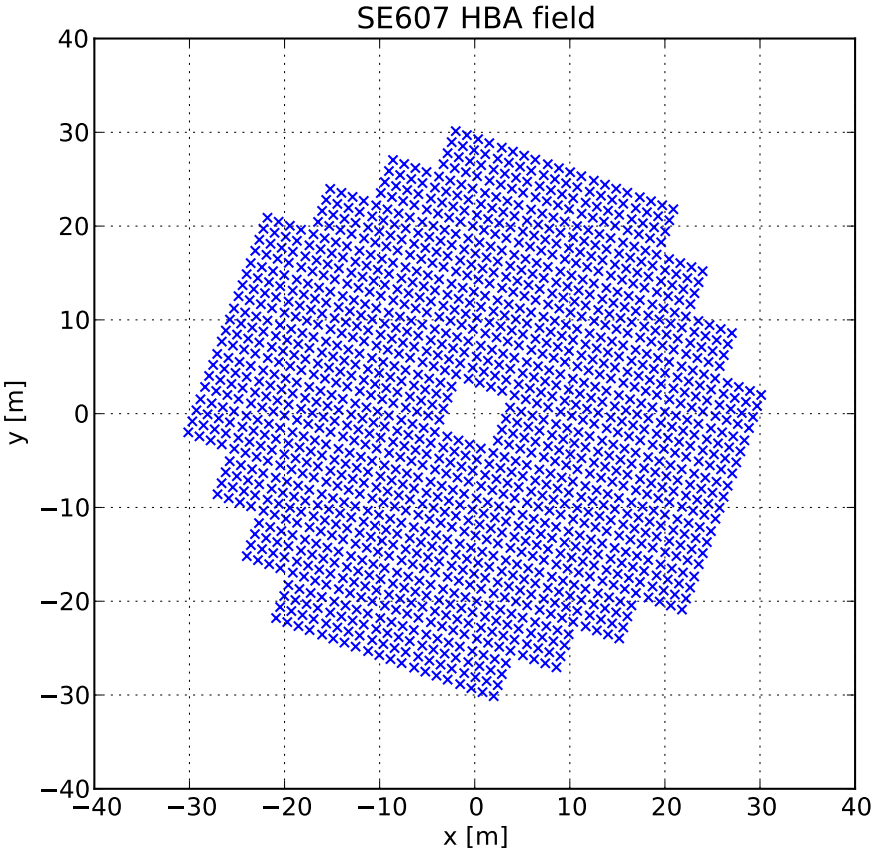


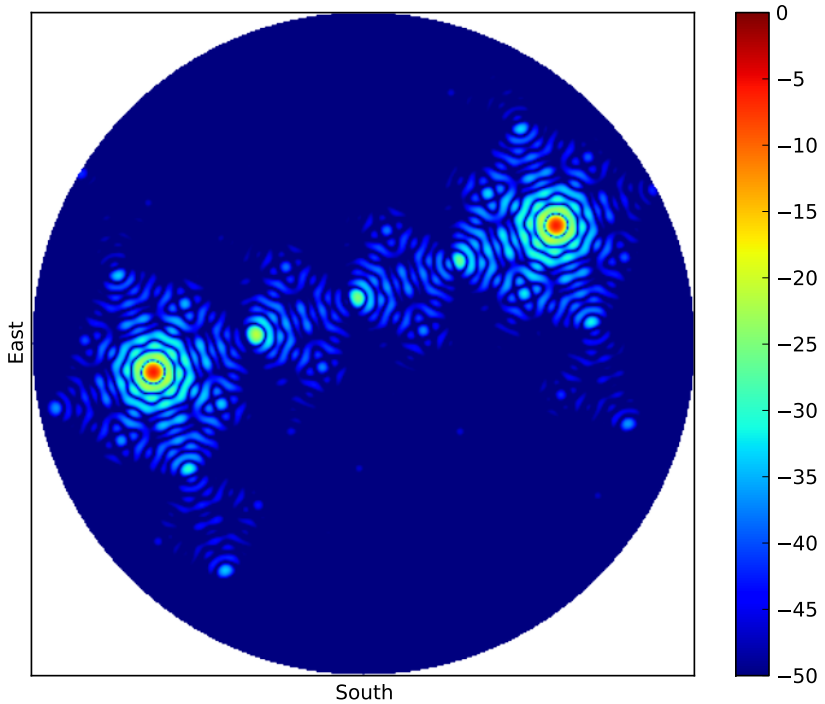
HBA station beam tracking 180 MHz (dB)



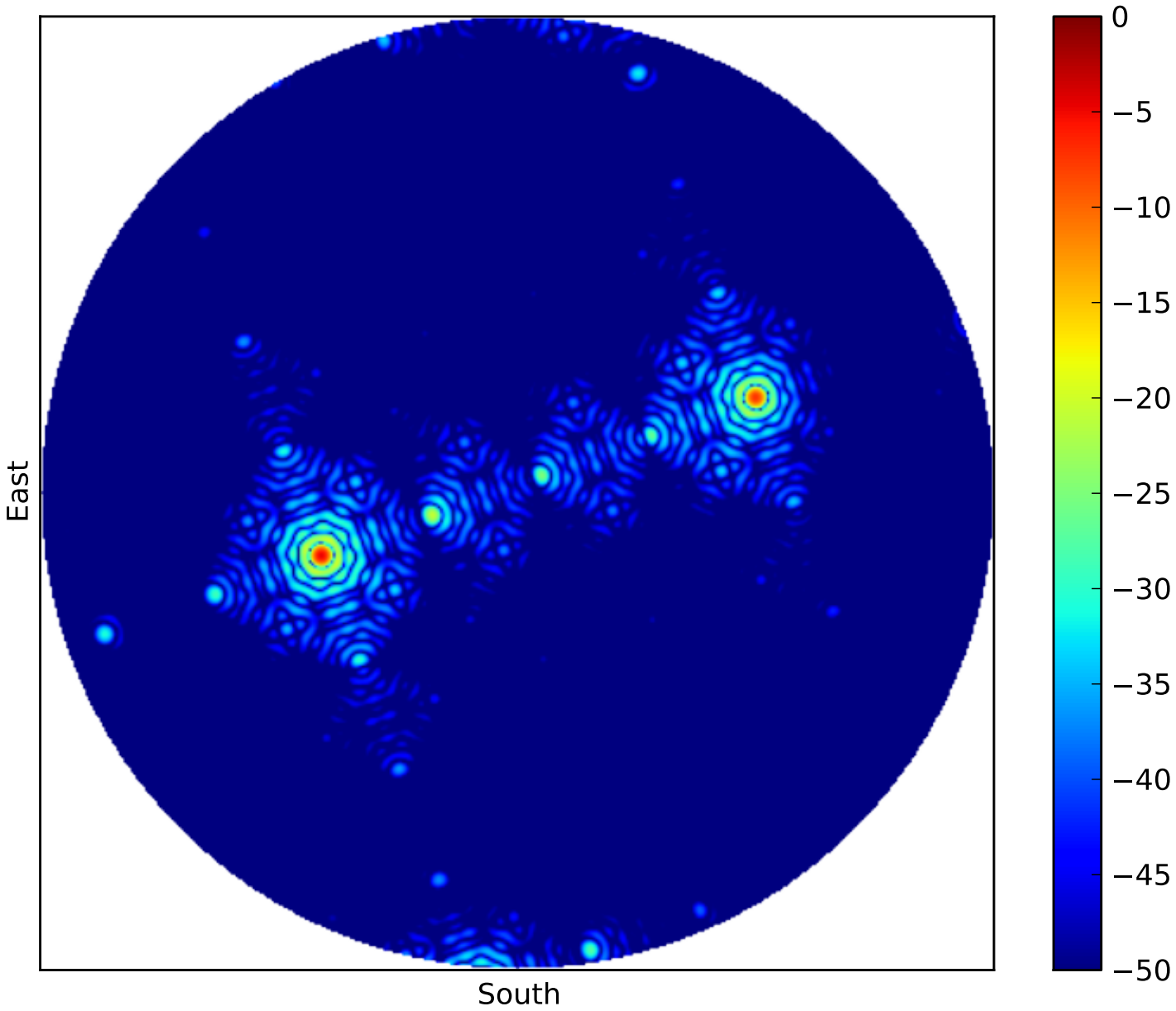


HBA station beam tracking 180 MHz (dB)

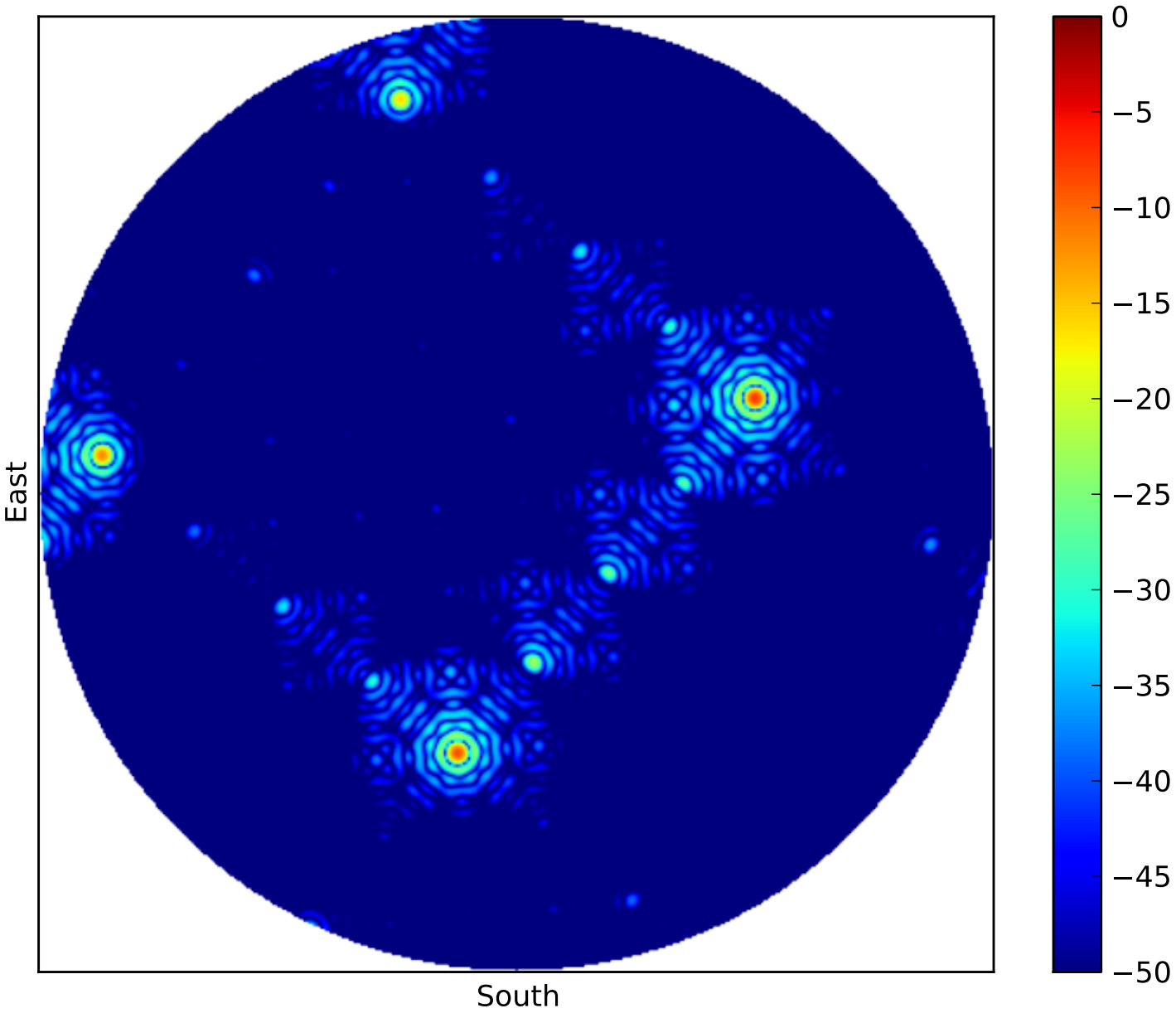




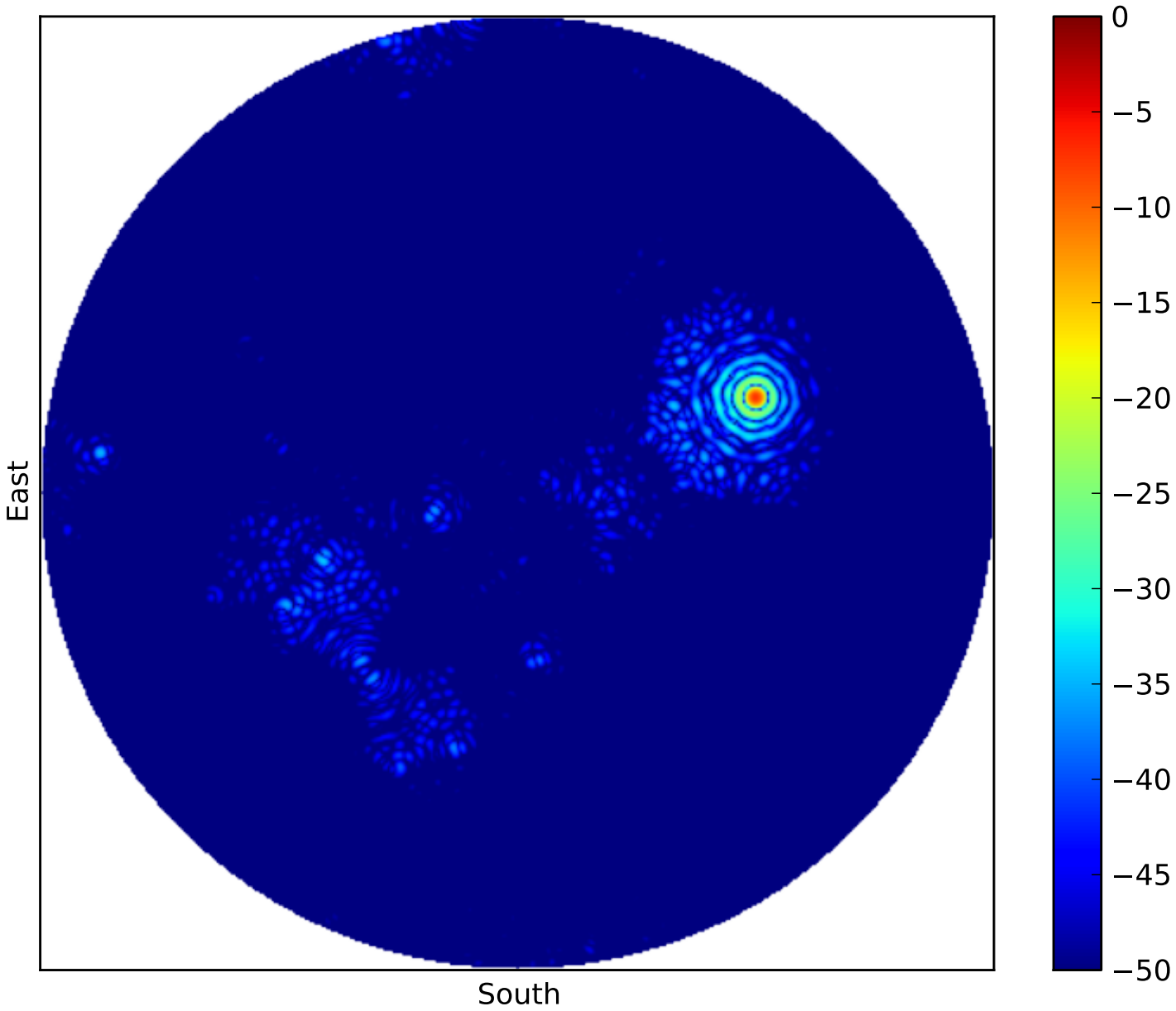
SE607 beam 240 MHz (dB)



UK608 beam 240 MHz (dB)



SE607-UK608 beam 240 MHz (dB)



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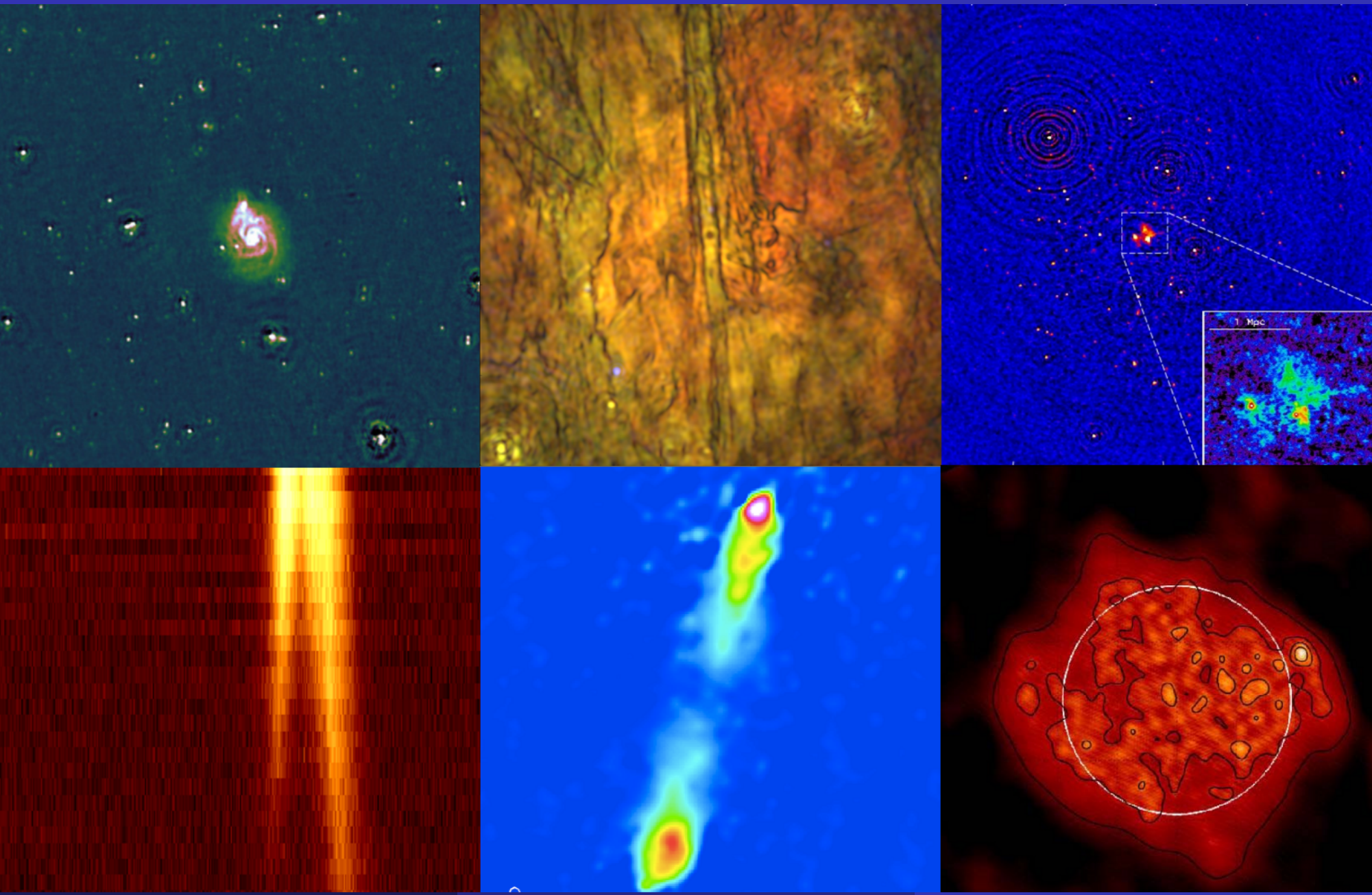
4. Central processing
5. Beams, beams, beams. . .
6. More beams. . .
7. If all goes well

End of this week?