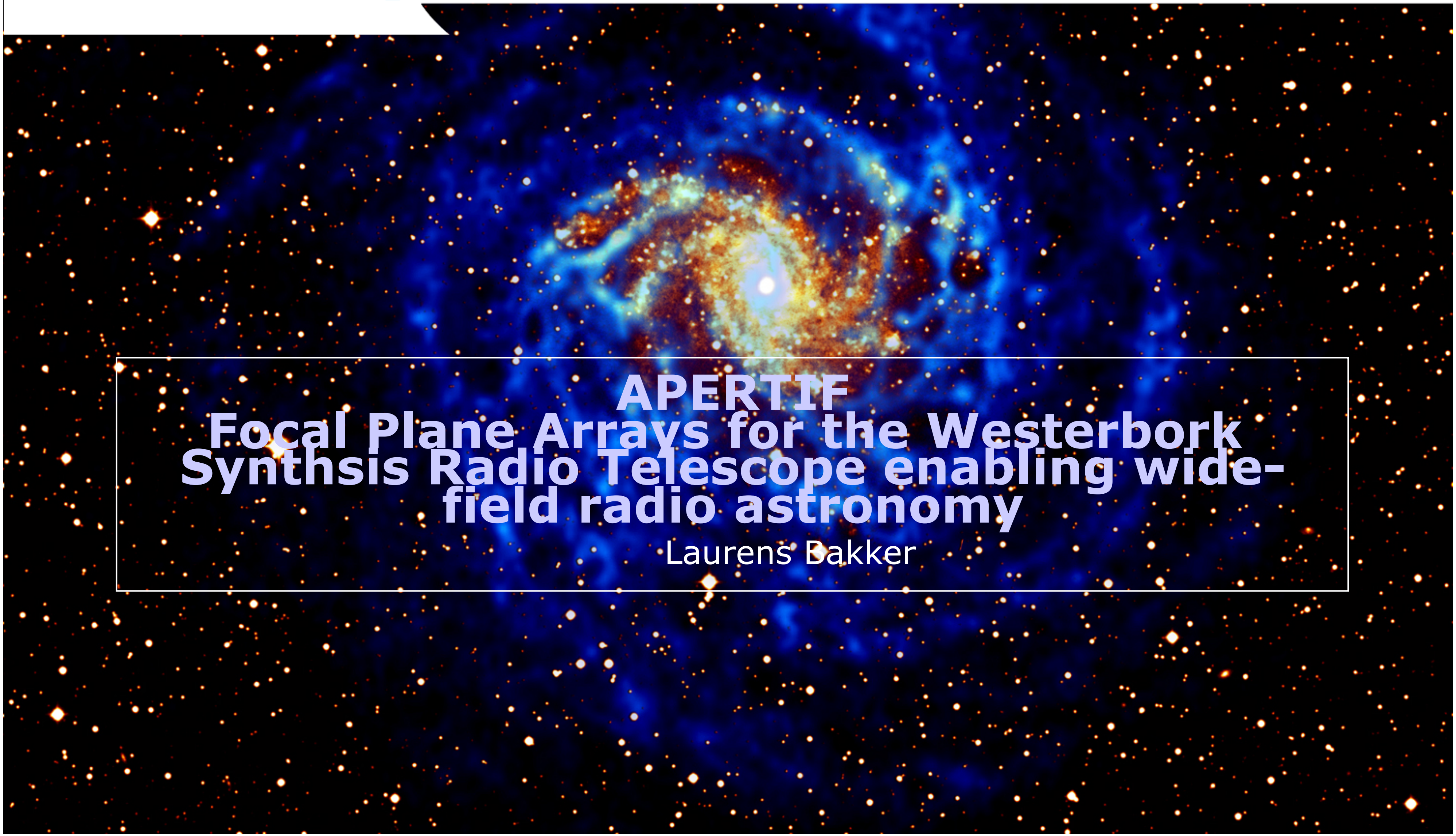
APERTIF
Focal Plane Arrays for the Westerbork Synthsis Radio Telescope enabling wide-field radio astronomy

Laurens Bakker



Outline

- introduction APERTIF
- Description of the first prototype
- Results of the recent second prototype prototype
- Ongoing developments
- Conclusion on future work

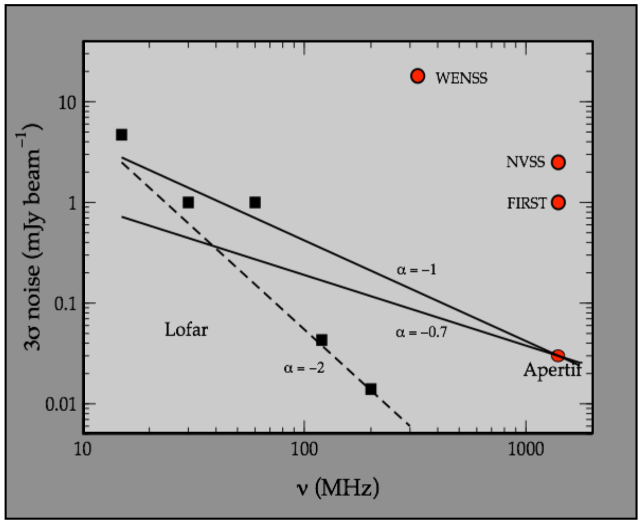
APERTIF (APERture Tile In Focus)

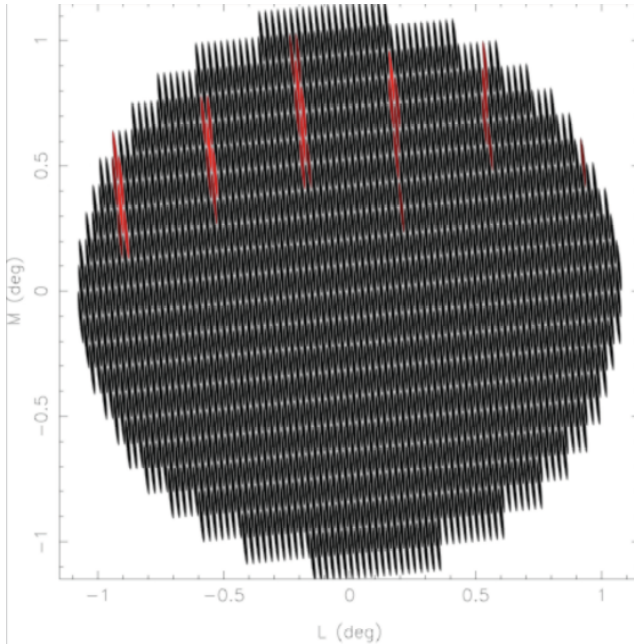
- APERTIF aims to increase the field of view of the WSRT with a factor 25
  - survey speed increase with factor ~20.
- Enables new astronomical science, especially large surveys
- Operational in 2012
- Only feasible with dense Phased Array Feed (PAF) technology for small f/D telescope

• Frequency range	**1000 – 1750**
• Instantaneous bandwidth	300 MHz
• System temperature	**< 55 K**
– Couple of thousand LNAs required (uncooled)	
• Aperture efficiency	75%
• Polarization	Dual linear
• Beamforming	All digital
• Number of simultaneous beams	37 dual pol
• Field of view	8 deg^2
• Dish	
– diameter	25 m
– f/D	0.35
– equatorial mount	

Specific APERTIF surveys

- HI survey of the Sloan Digital Sky Survey (SDSS) area
  - Shallow and deep (relatively large collecting area)
- Overlap with LOFAR surveys
  - All-sky continuum and polarisation survey
- Efficient pulsar survey
  - Regular array → 8-grate mode





Technical challenges

- To achieve the stability of the whole system
- Achieving uncooled Tsys of <55K
- RFI environment at Westerbork
- Realizing all the digital processing required (~100TMAC for all dishes, all beams, including correlator. BF~75%)
- How to put the beams on the sky
  - Achievable FoV with uniform sensitivity (especially for higher frequencies) determined by available processing, not phased array feed
- Large number of receiver channels
  - Cost per channel should be low
  - Manufacturing must be outsourced

Beam stability

- Horn system:
  - Beam pattern is only determined by mechanics.

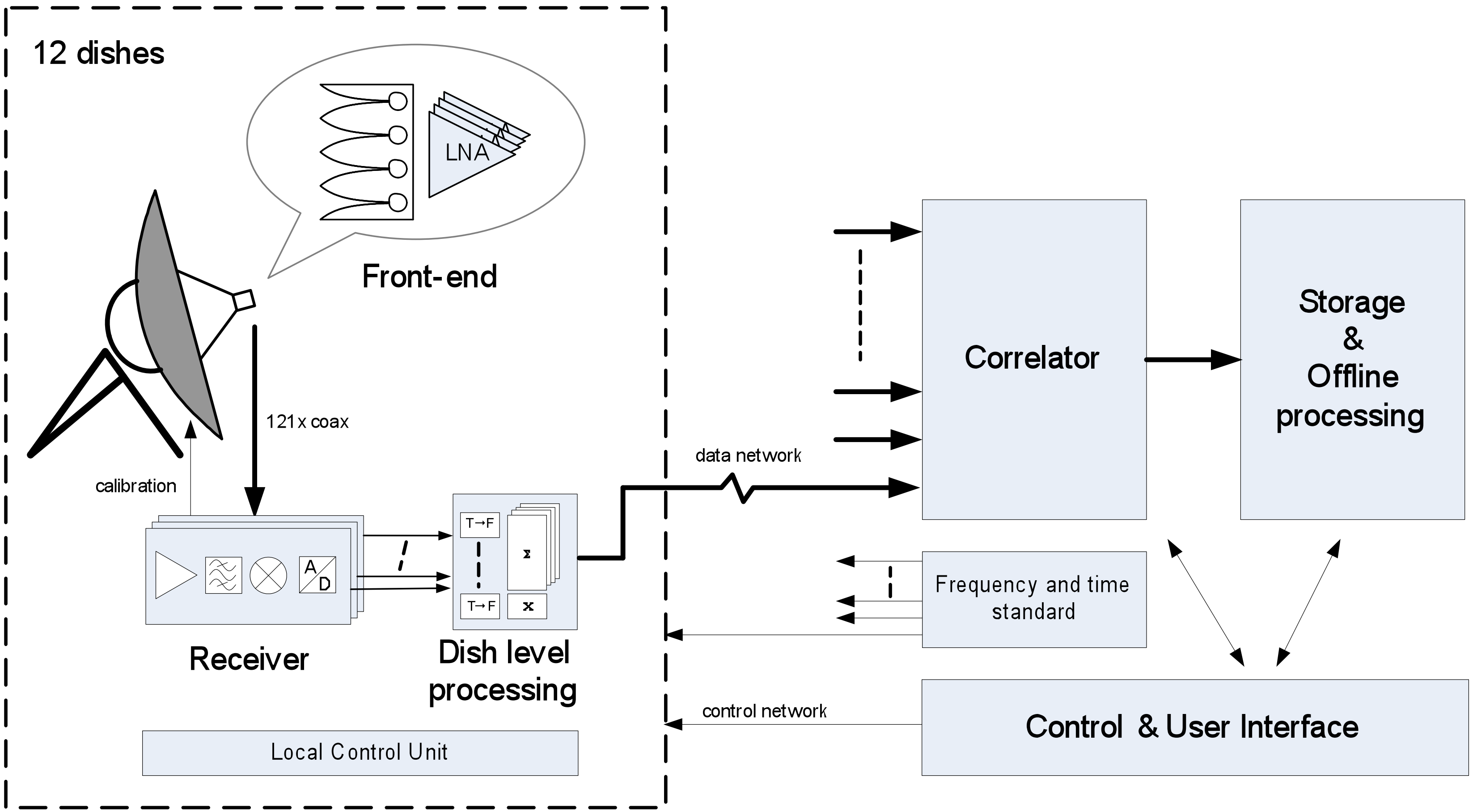
    The stability of the beam pattern is already limiting the dynamic range of some WSRT experiments.
  - Electronic gain variations are only a second order effect and can be corrected relatively easy.

- Focal Plane Array:
  - Multiple elements, with their own receiver channels, are combined to form compound beams
  - The compound beam patterns are depending on electronic gain variations of the receiver channels
  - Beam stability is a serious concern, calibration is critical!

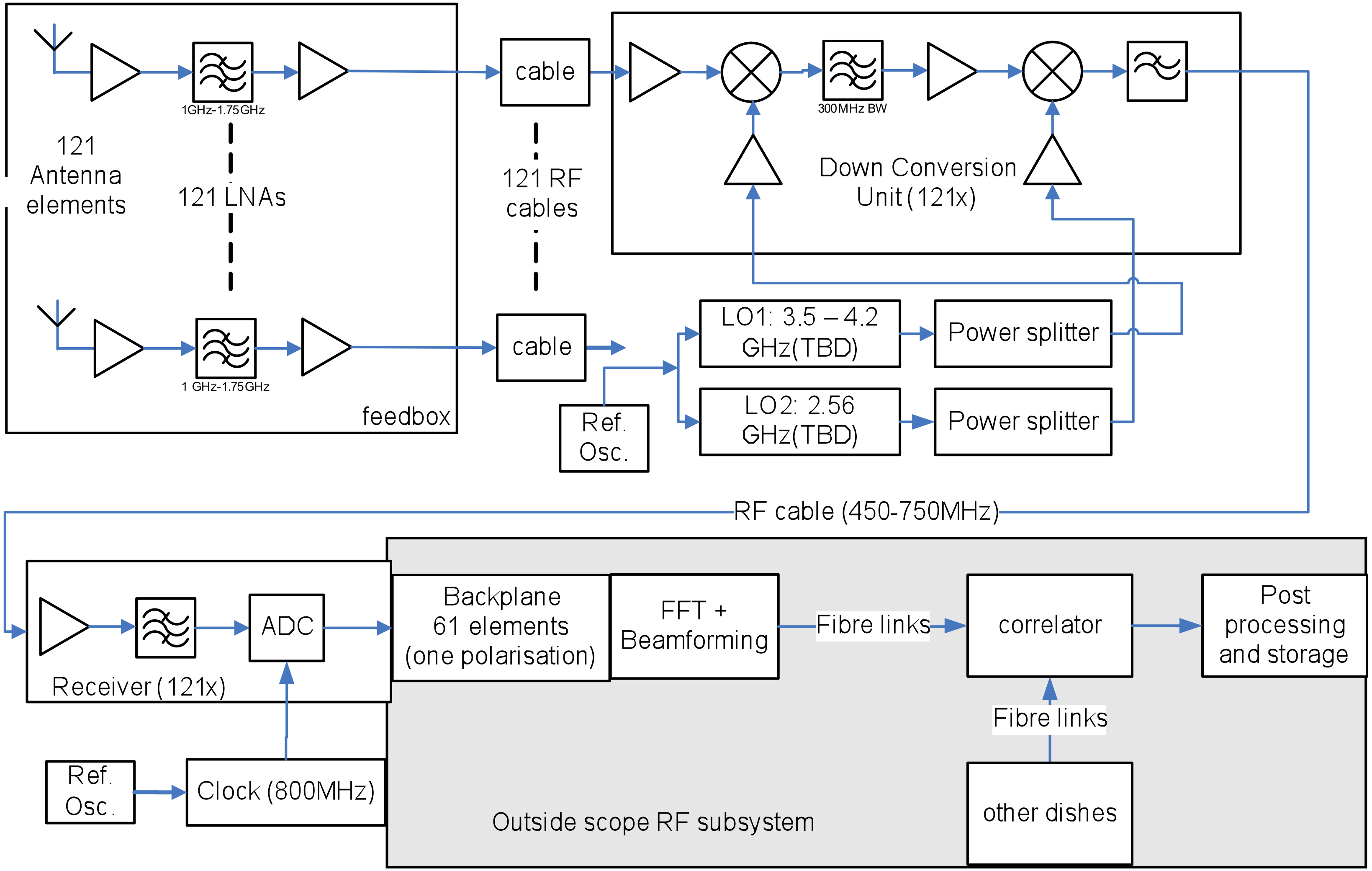
Technical Approach

- First built an End-to-End system to test system level issues
  - Noise performance of secondary importance
  - Bandwidth of secondary importance
- Understand the system
- Upgrade the system stepwise to reach the performance required for APERTIF
- Focus APERTIF is on the analog parts (i.e. up to and including A/D) and system. Processing platform in JIVE led Radionet FP7 project Uniboard

Top level block diagram

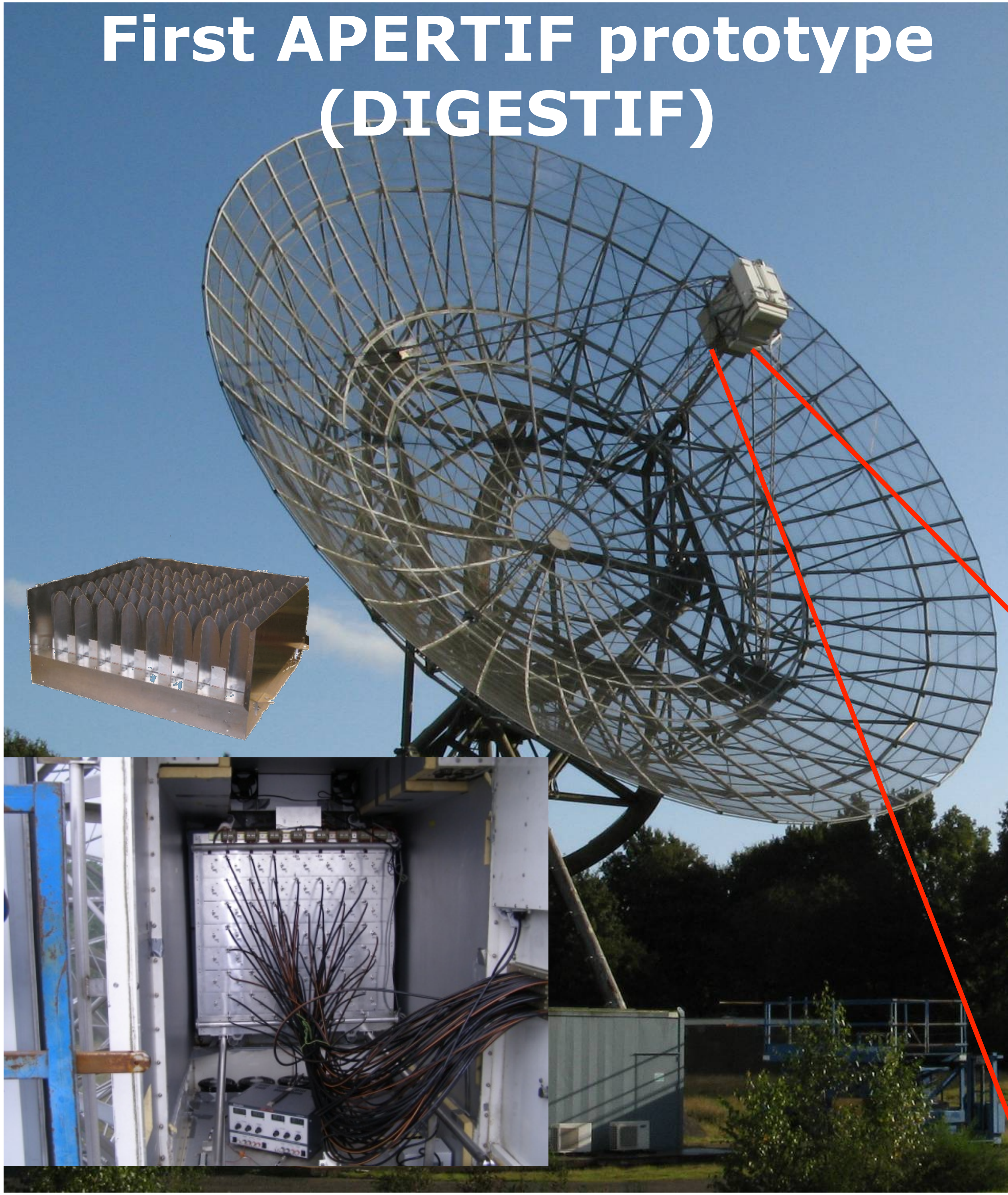


System diagram

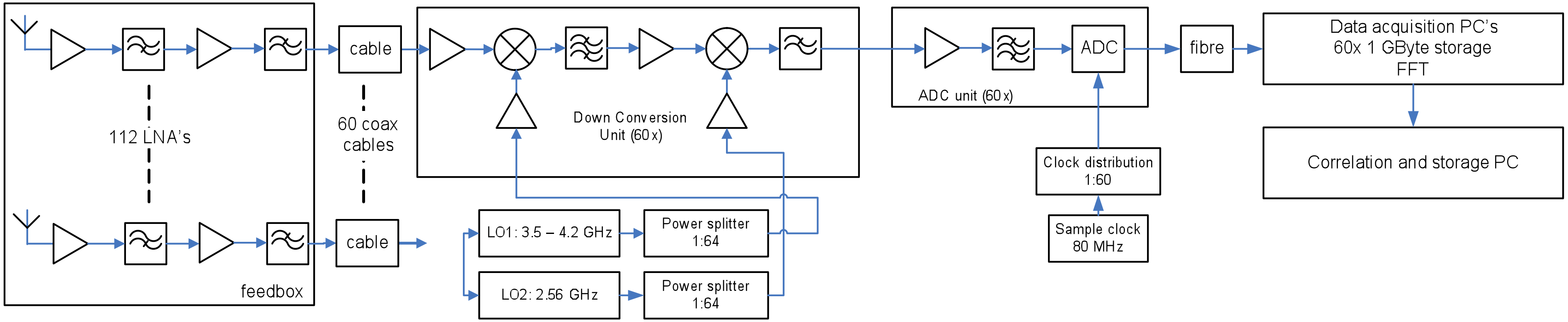


First APERTIF prototype (DIGESTIF)

- FPA for the WSRT
- One dish fully dedicated to FPA
- 8 x 7 x 2 elements Vivaldi array
- Dual polarisation
- Size: 80*80cm
- 60 Receiving chains
- Frequency range 1.0 – 1.7 GHz
- 30 MHz bandwidth
- Element separation: 10 cm
  ($\lambda/2$ @ 1.5 GHz)
- Data recording backend

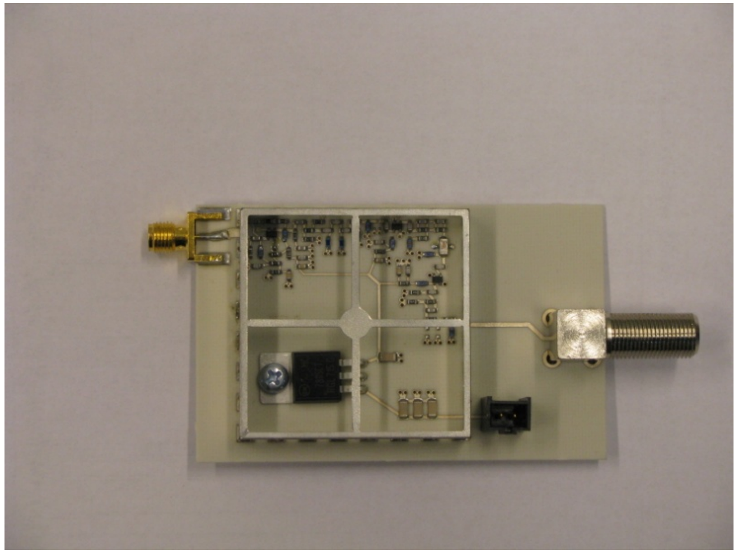


Top level block diagram experimental system

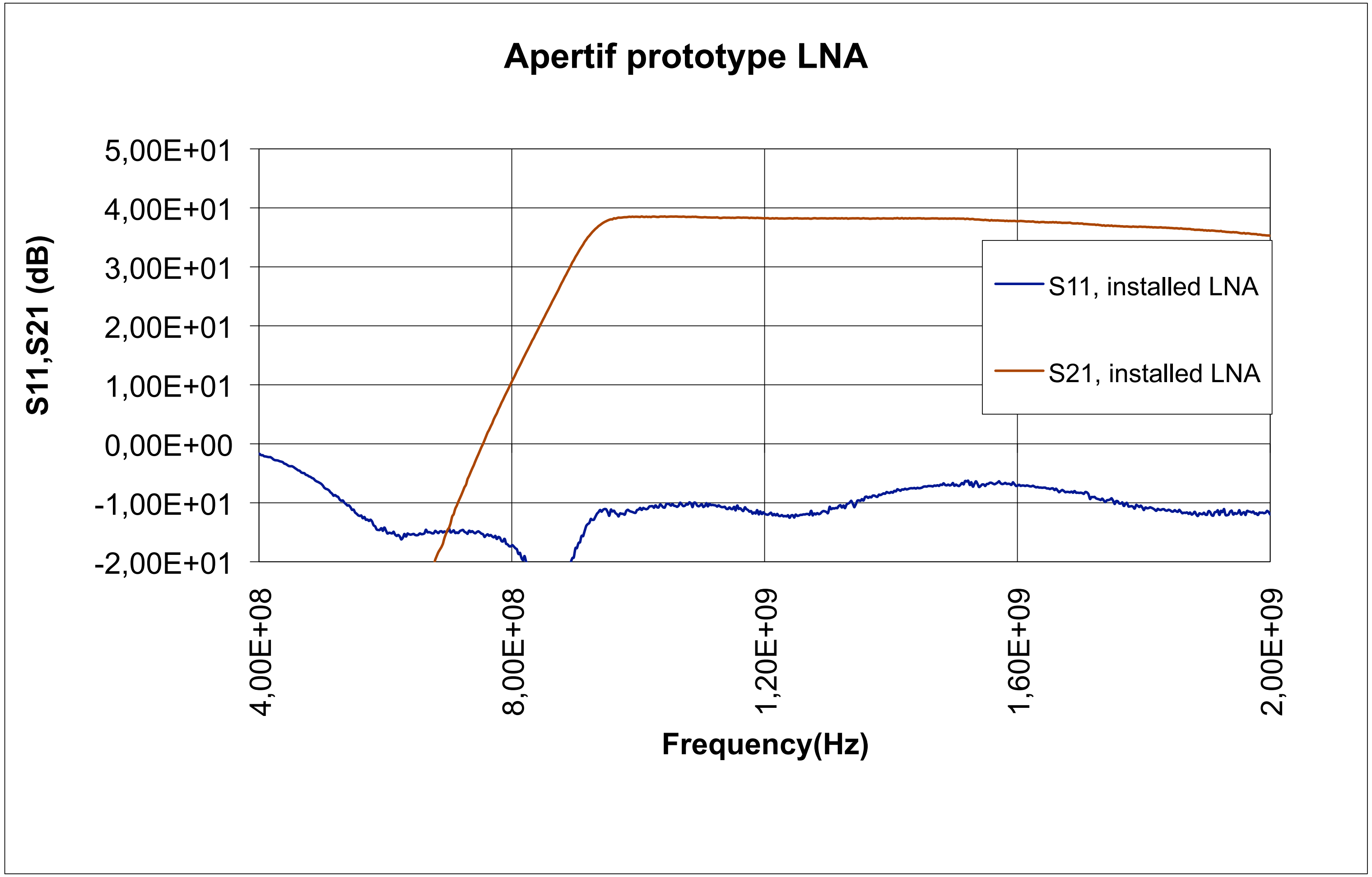


First generation LNA

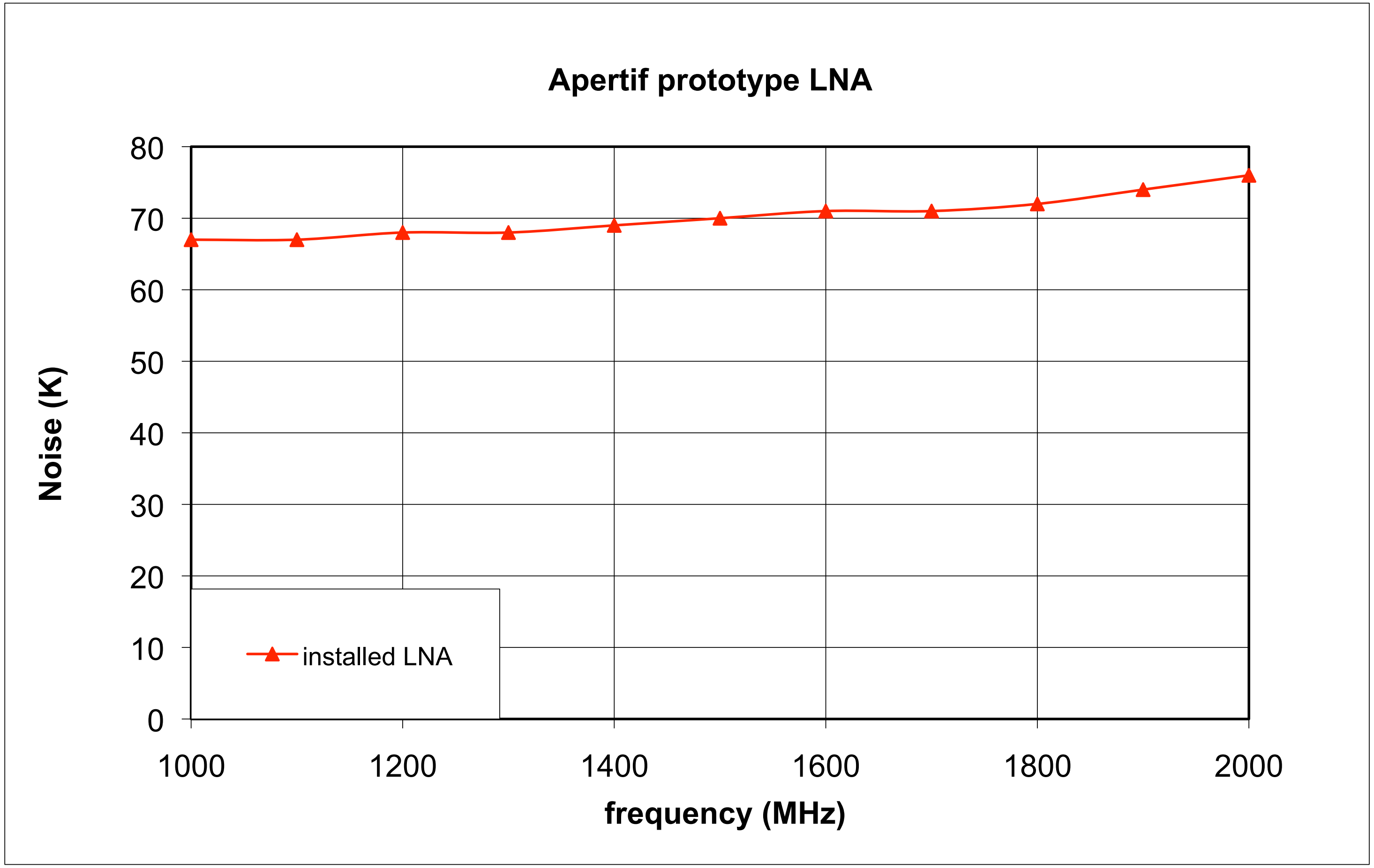
- Design for 50ohm input impedance
- >40 dB gain (flat)
- HPF with 25dB attenuation at 800MHz
- 3 stages, with high pass filtering after first stage and second stage
- Reasonable S11
- OIP2 first stage ~45dBm
- Sma input connector (50ohm)
- F-connector output (75 ohm)
- 120 devices installed in first prototype (externally manufactured)
- LNA based on ATF-54143 ->low Rn



LNA measurement results

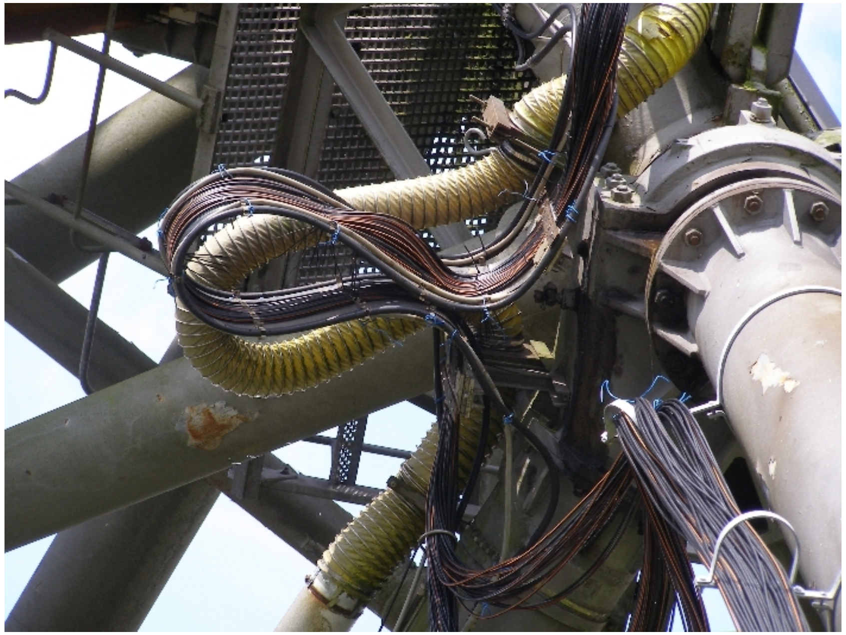
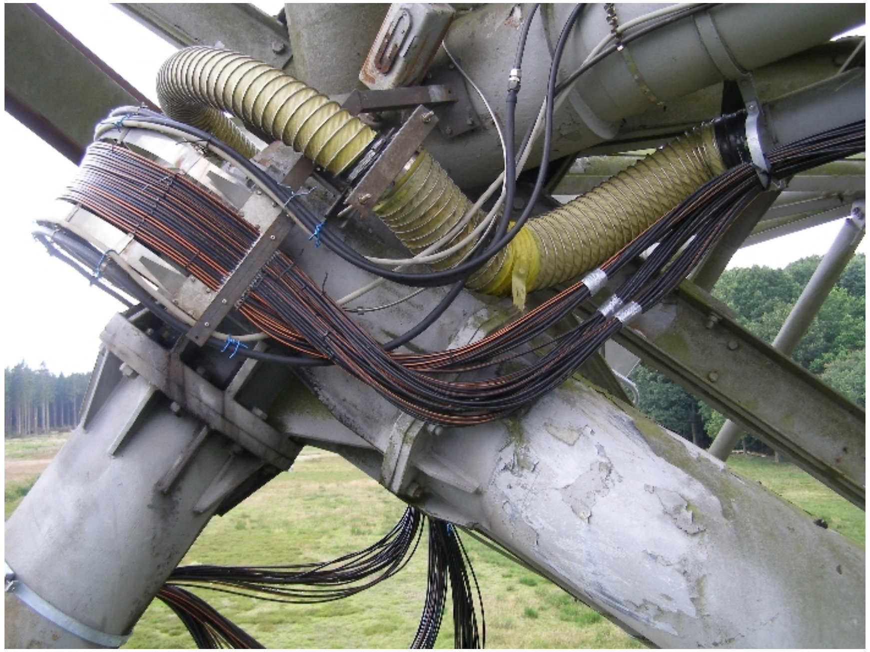
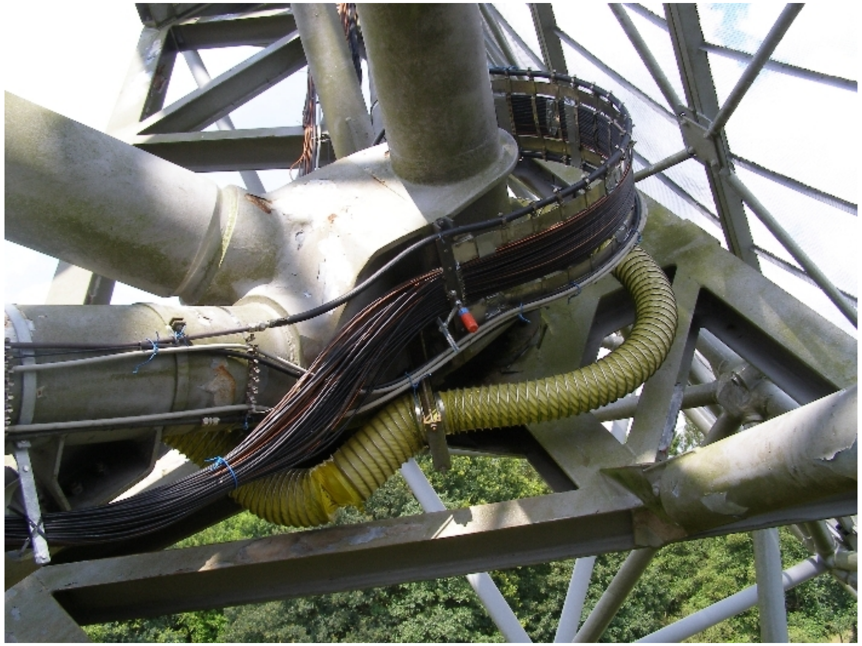


Noise measurements



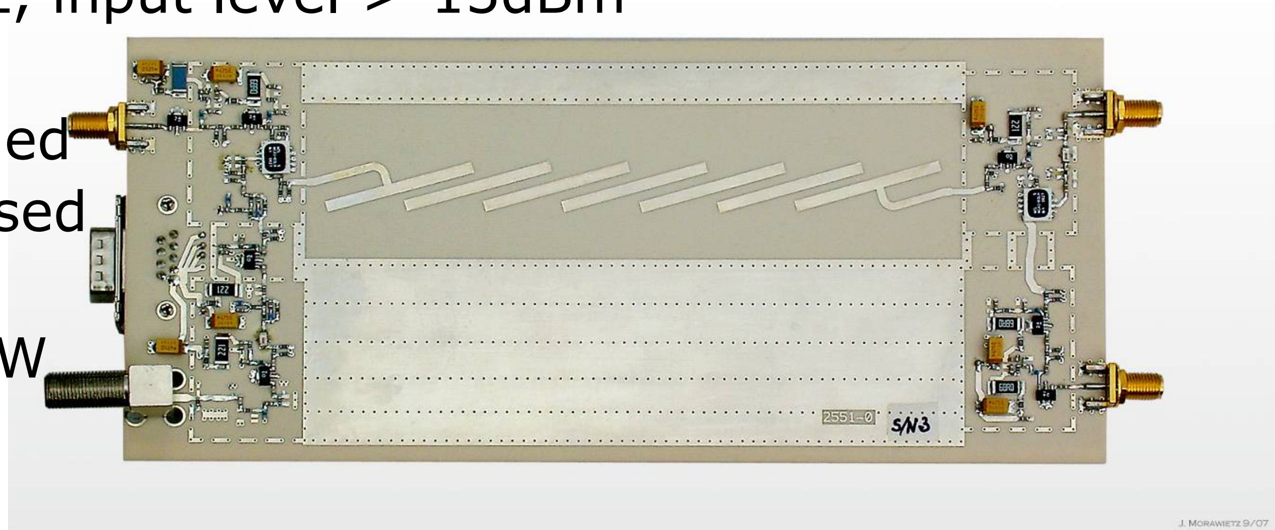
- In 50 ohm using 5.2dB noise source and NFA

Cables going across jumpers

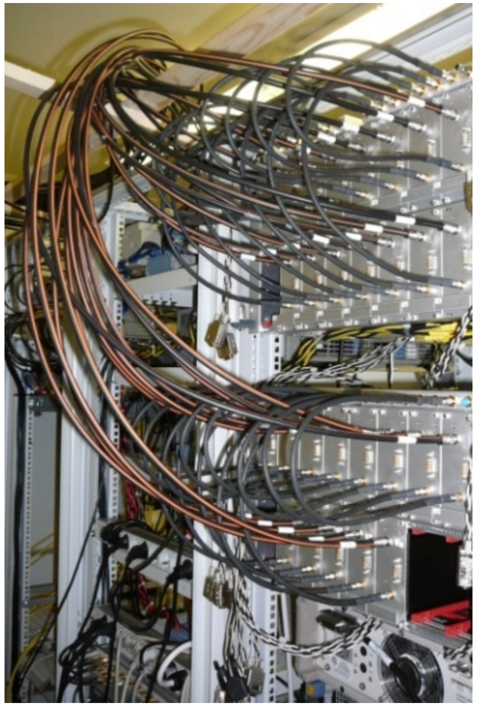

Down Conversion Unit

- Input band 1-1.7GHz
- Bandpass filter 2.5GHz center, 80 MHz BW, 60dB down for $|f_c - f| > 100$MHz, one steep slope required
- Convert to 40-80 MHz band
- 16 dB gain from input to output (1.4GHz input)
- LO1 3.5-4.1 GHz, input level >-13dBm
- LO2 fixed at 2.56 GHz, input level >-13dBm
- 10dBm mixers
- Cable equalizer included
- Additional shielding used
- Single supply voltage
- Power consumption 5W
  - 12V operation

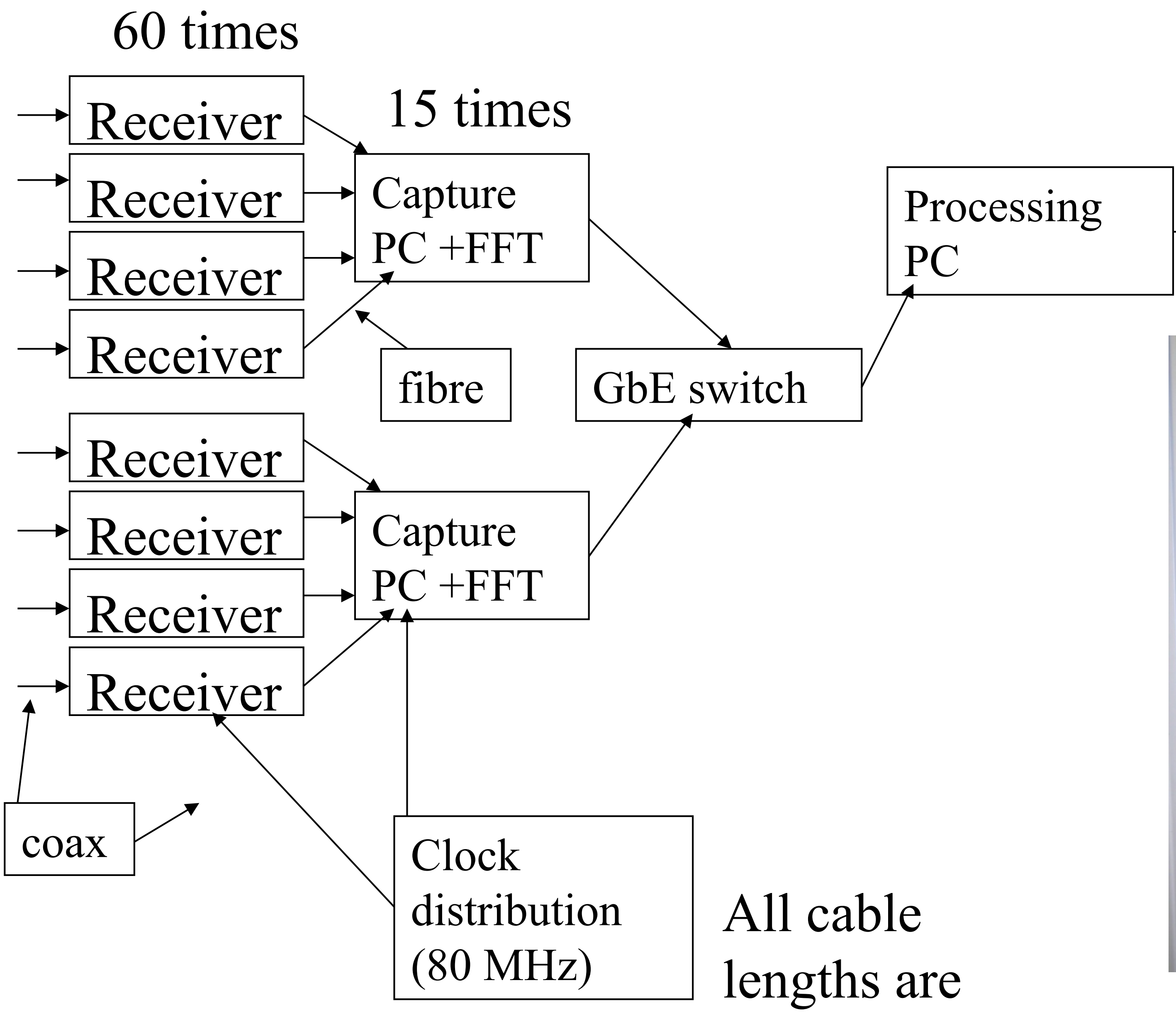


Receiver unit

- LOFAR ITS hardware
- Sampling at 80 MHz
- Sampling in second nyquist zone
- 40-80MHz bandpass filter
  - >60dB down at 38 and 82MHz

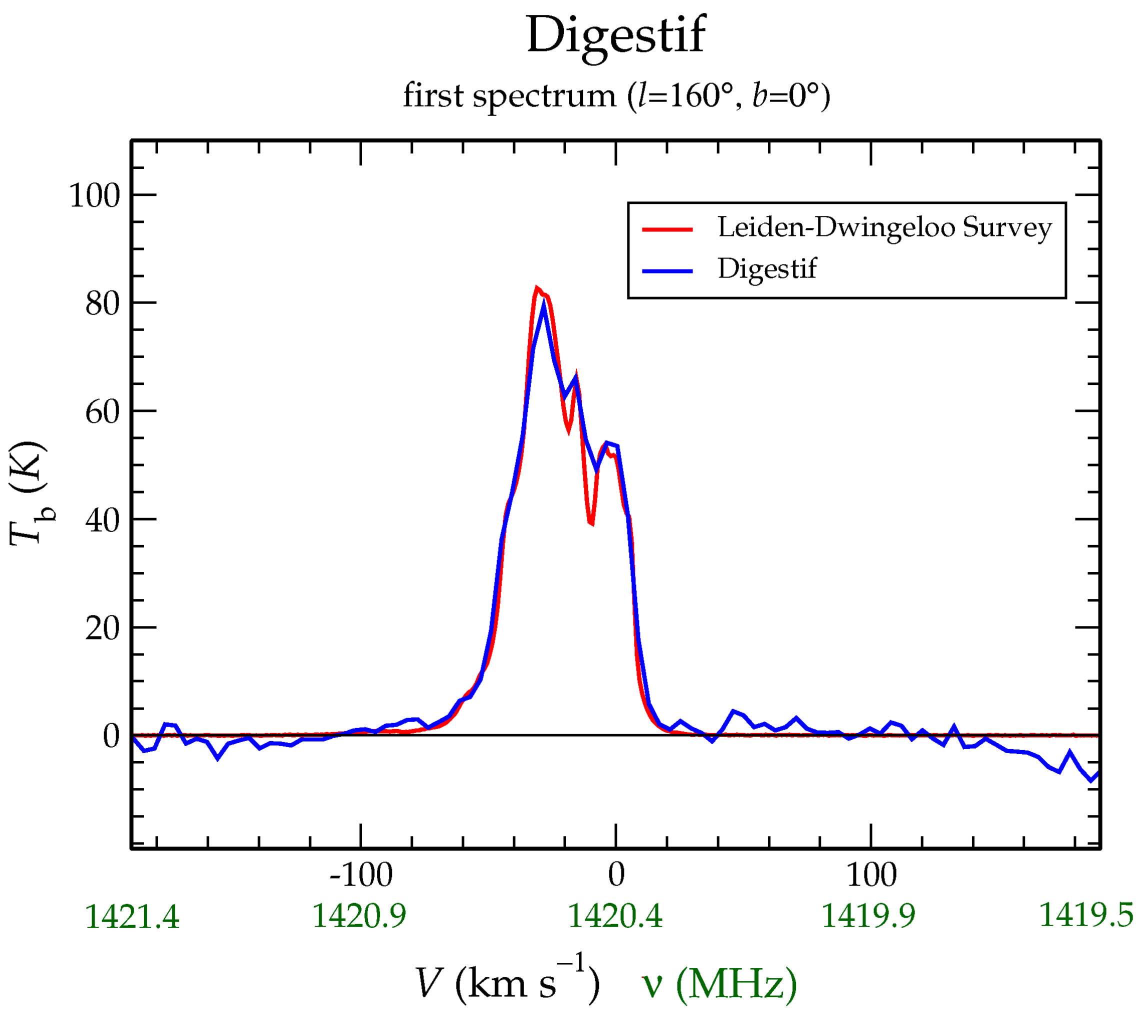


DIGESTIF backend



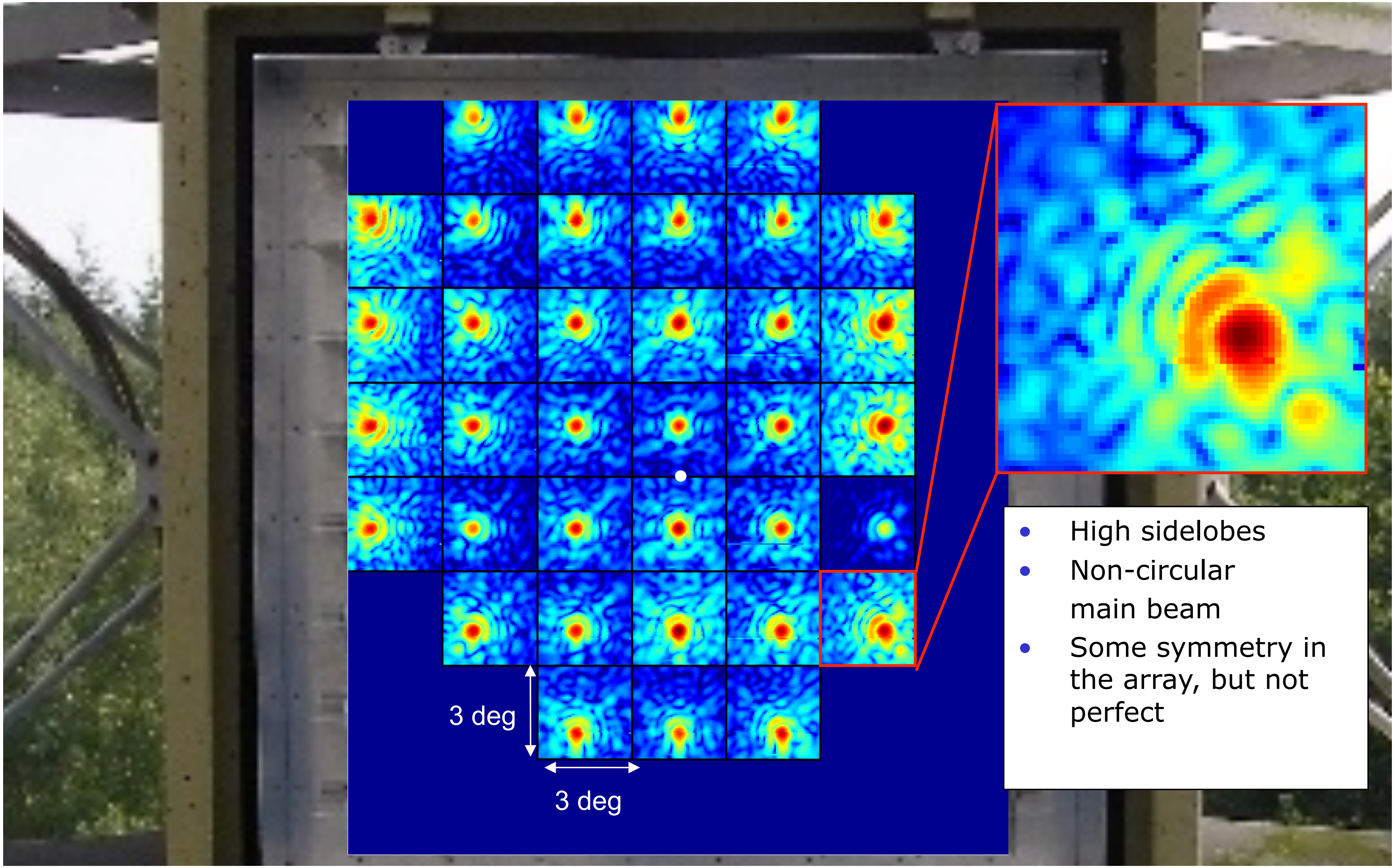
All cable lengths are equal

First Light (September 2007):



Detection of galactic hydrogen

Element patterns on the sky



- High sidelobes
- Non-circular main beam
- Some symmetry in the array, but not perfect

Combining beams

- Weighting coefficients
  - Weighting schemes described by Ivashina, Hay, Warnick
  - Cas A has been used as point source

- Procedure:
  1. Measure ACM on empty spot: $\mathbf{R_n}$
  2. Measure ACM on point source: $\mathbf{R_{ps}}$
  3. Extract dominant eigenvector of $\mathbf{R_{ps}} - \mathbf{R_n}$: $\mathbf{w_{cfm}}$

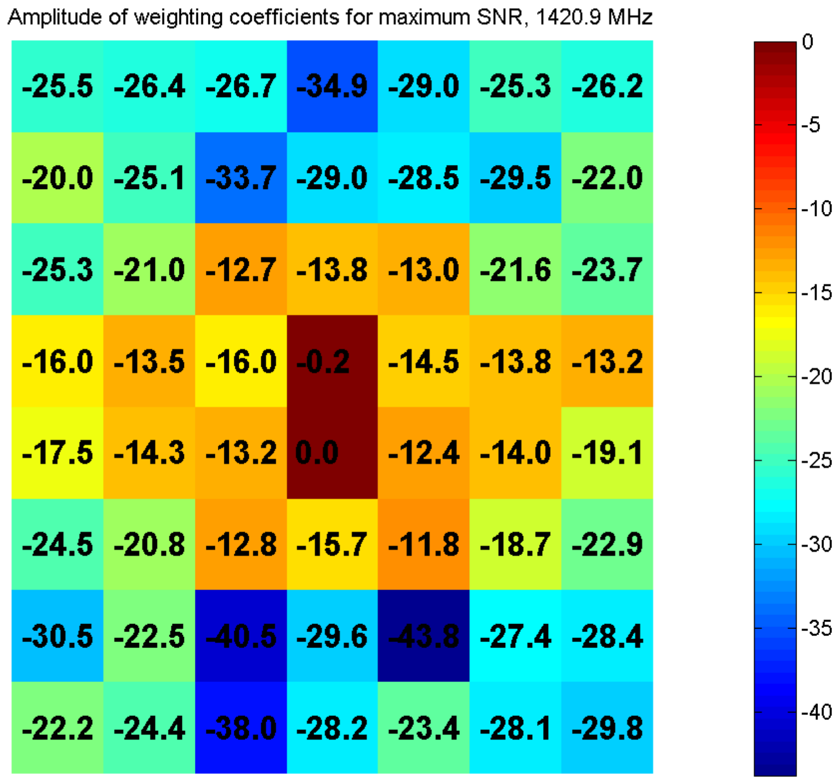
- Conjugate field matching: $\mathbf{w} = \mathbf{w_{cfm}}$

- For maximum SNR: $\mathbf{w} = \mathbf{R_n}^{-1}\mathbf{w_{cfm}}$

Beamformer weights

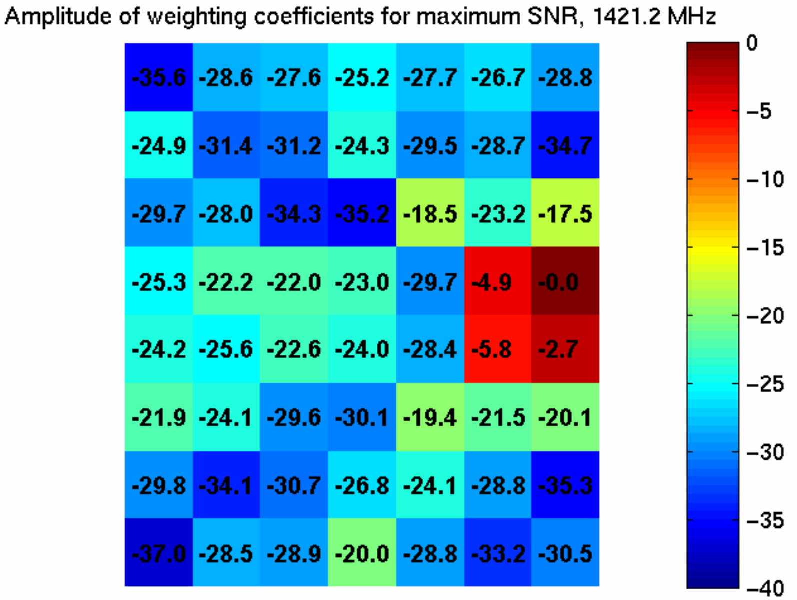
- Beamformer weights are determined on a strong point source (e.g. Cas A)
  - Effects of antenna array and mutual coupling, blockage are included in the weights
- Airy ring structure is recognized in the weighting coefficients

- Amplitude of max SNR weights for on-axis beam @ 1421 MHz

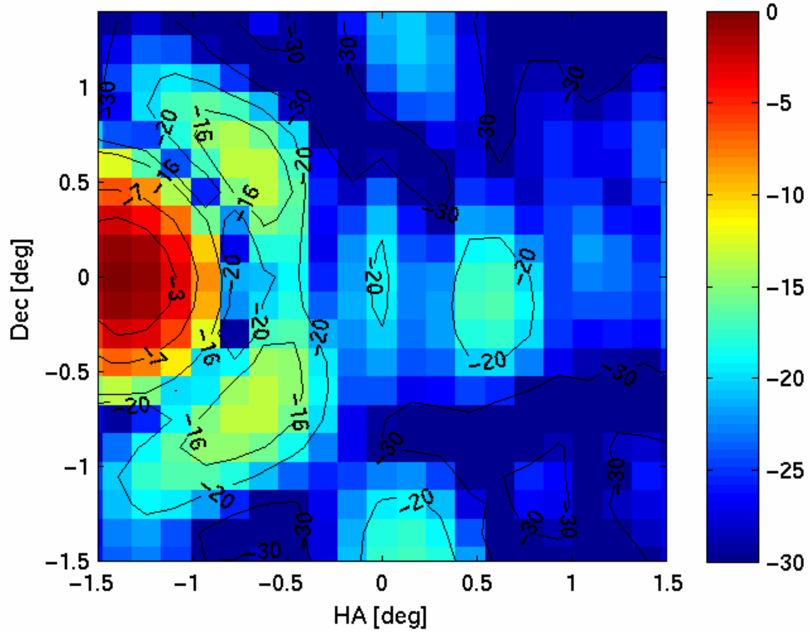


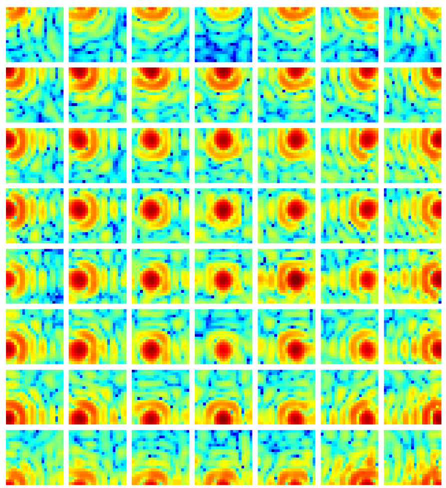
Compound beam patterns

Weights



2D pattern



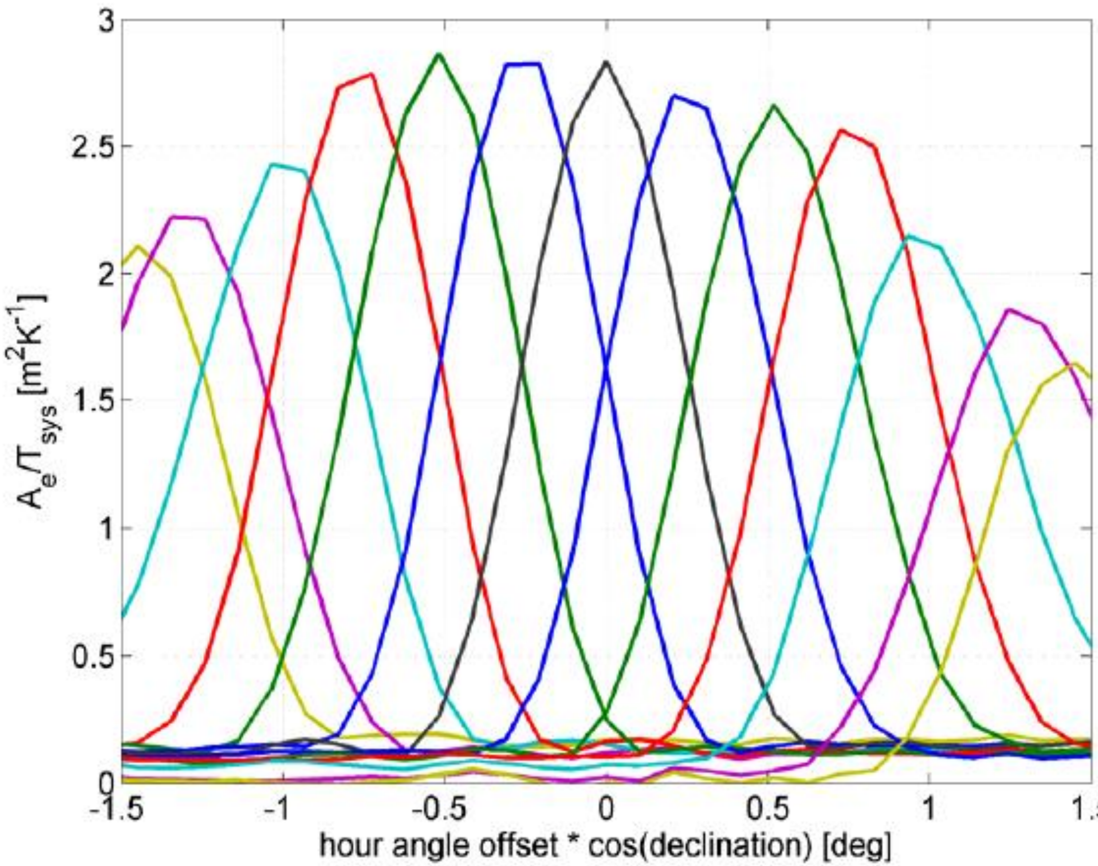


Element Patterns ugly, but compound beams are very well behaved

Measured compound beams

- 56 elements per **beam**
- Single polarisation
- Beams overlap at -0.7 dB points
- Max SNR weights
- Source: Cas A

- Sensitivity almost flat up to ±0.8 deg
- 25-30% sensitivity loss at edge of FoV

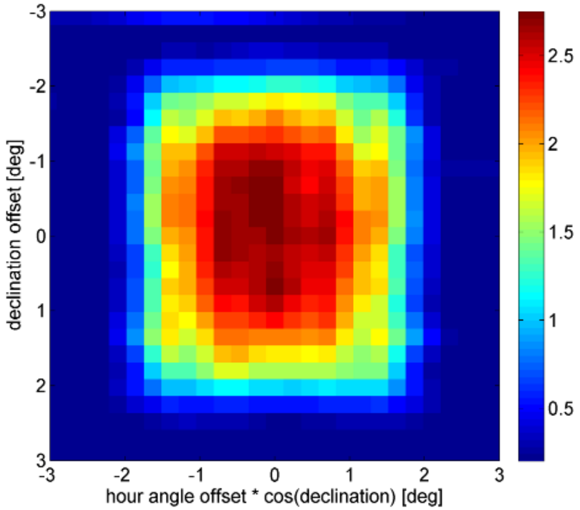


•Measured sensitivity prototype (central beam): A_e/T_{sys} = 2.8
•Corresponding T_{sys}=123 K (with A_e=70%)

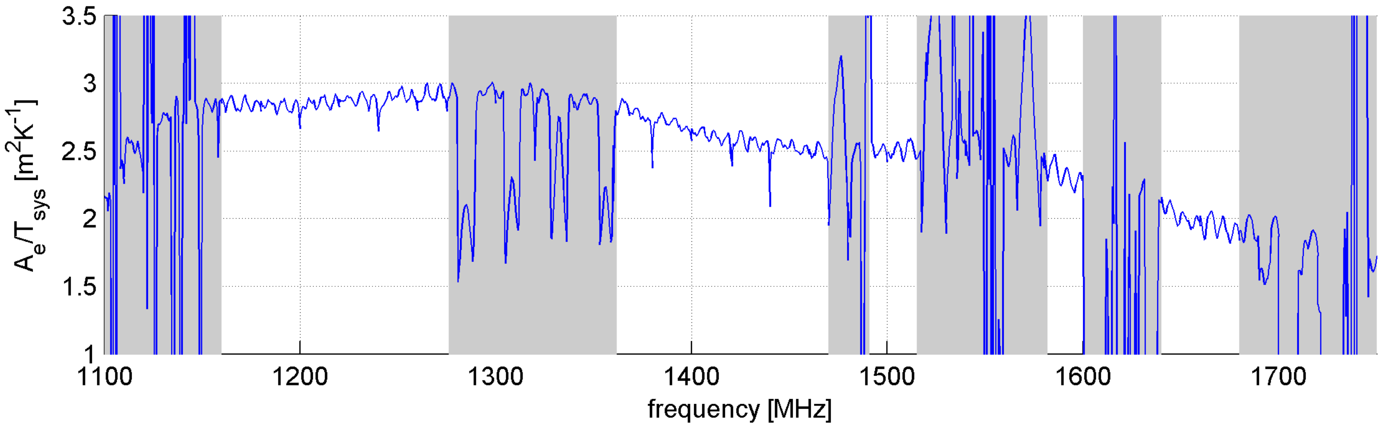
System temperature first prototype

- LNA noise temperature vs. Tsys
- first installed APERTIF LNA(first stage) is ~55K
- First installed APERTIF three stage LNA ~70K
- first measured Tsys ~123K
- So Tsys about 65 K higher than LNA
  - 15K second consecutive stages LNA
  - Feed loss and loss connectors ~15K (‘expensive’ RF material used)
  - Active impedance / Rn effects about 15K
  - Sky noise 3K
  - spillover about 15K

Sensitivity

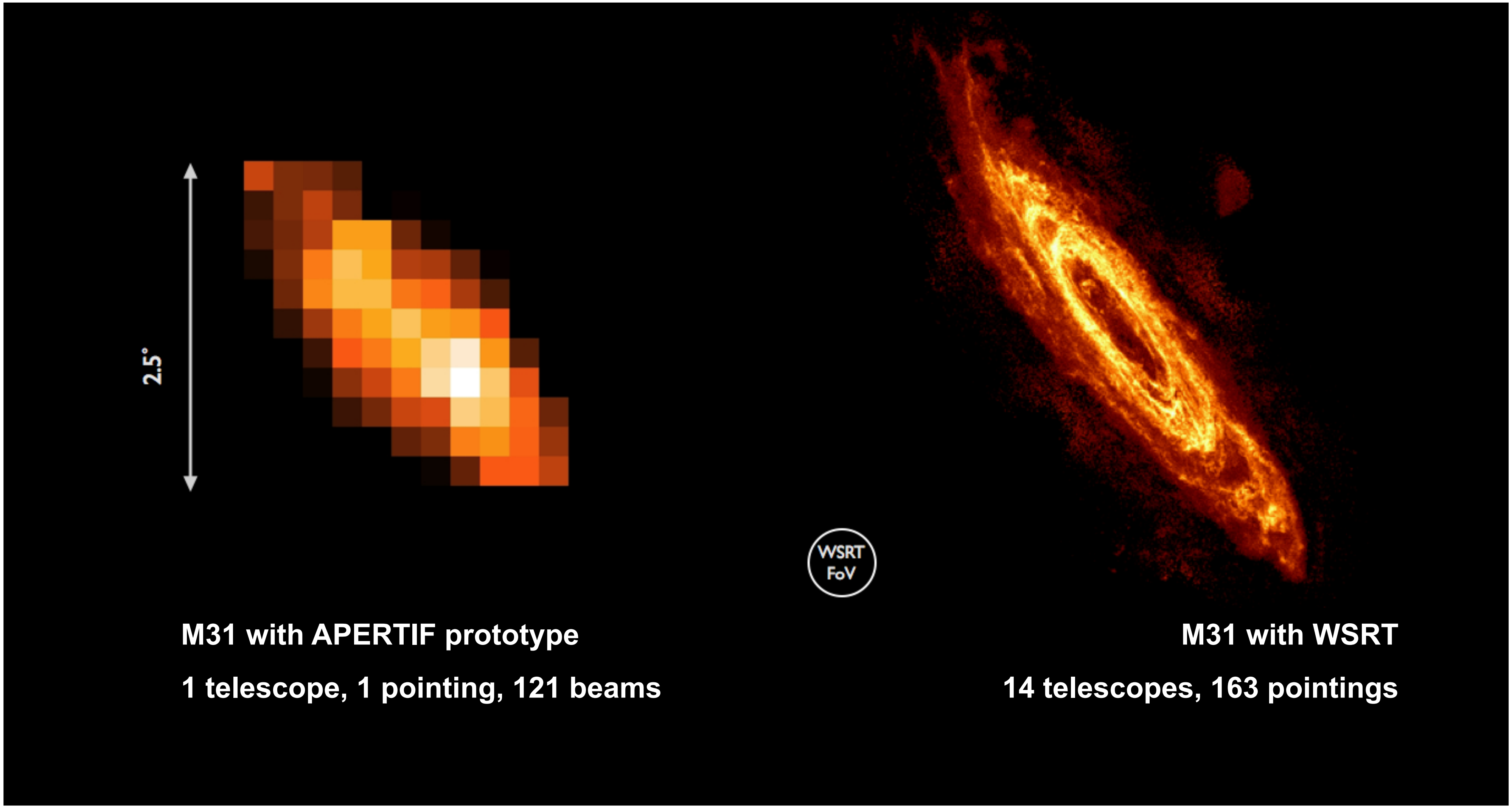


- Source: Cassiopeia A
- 1420 MHz
- Every pixel is from a compound beam in the desired direction



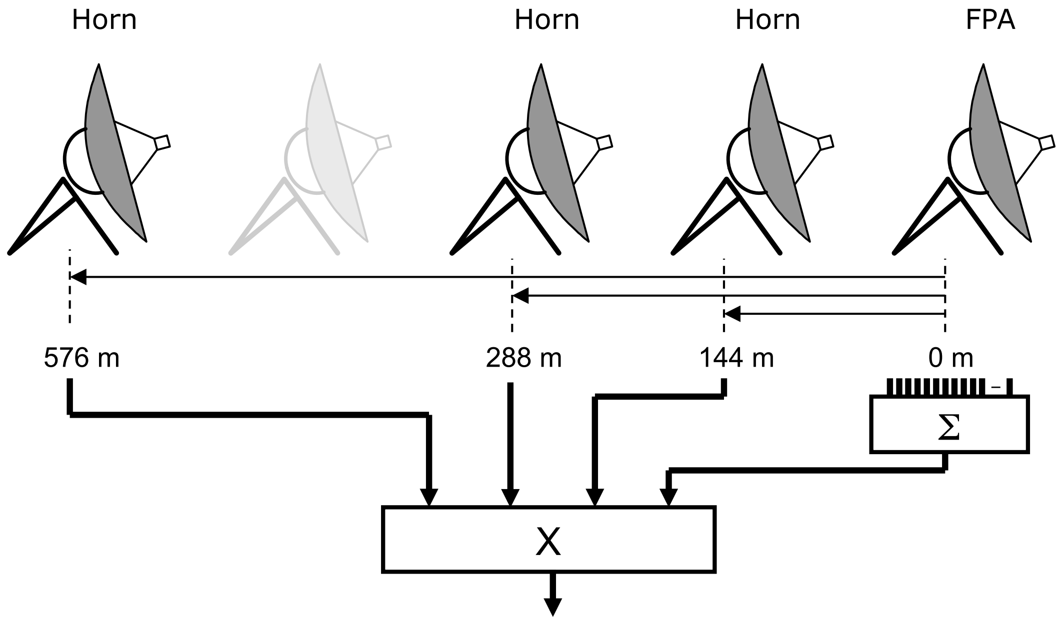
- Sensitivity over frequency on-axis beam
- RFI bands and expected intermods marked grey
- Smooth variations mostly due to LNA T_{min} variation, filters, cable losse

Single dish imaging

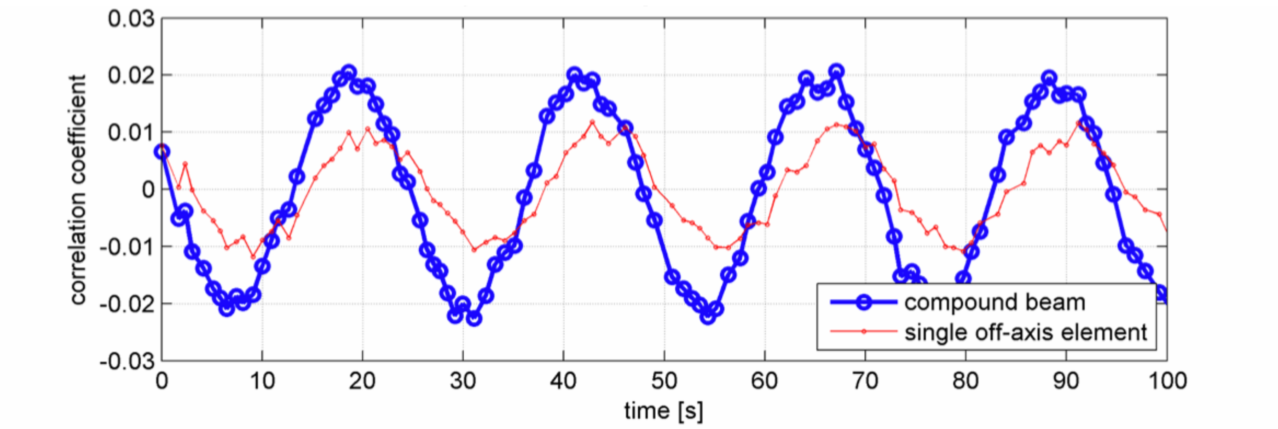


- Single dish, single pointing image!!

PAF in an interferometer

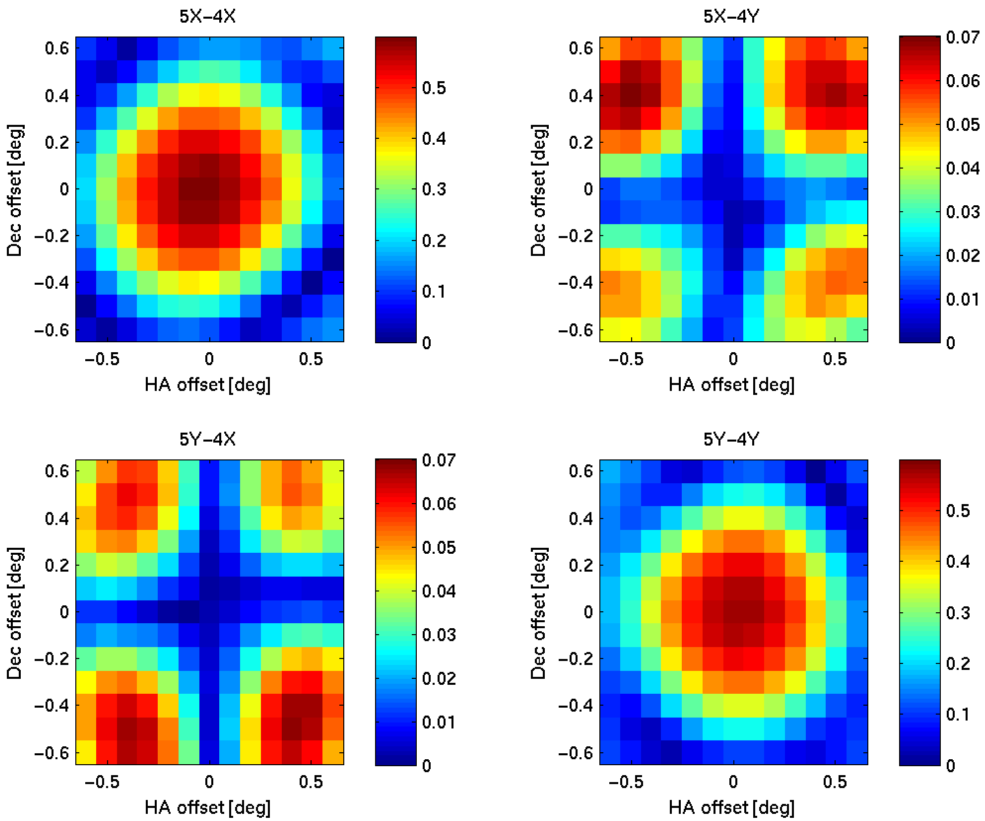


Measured fringes



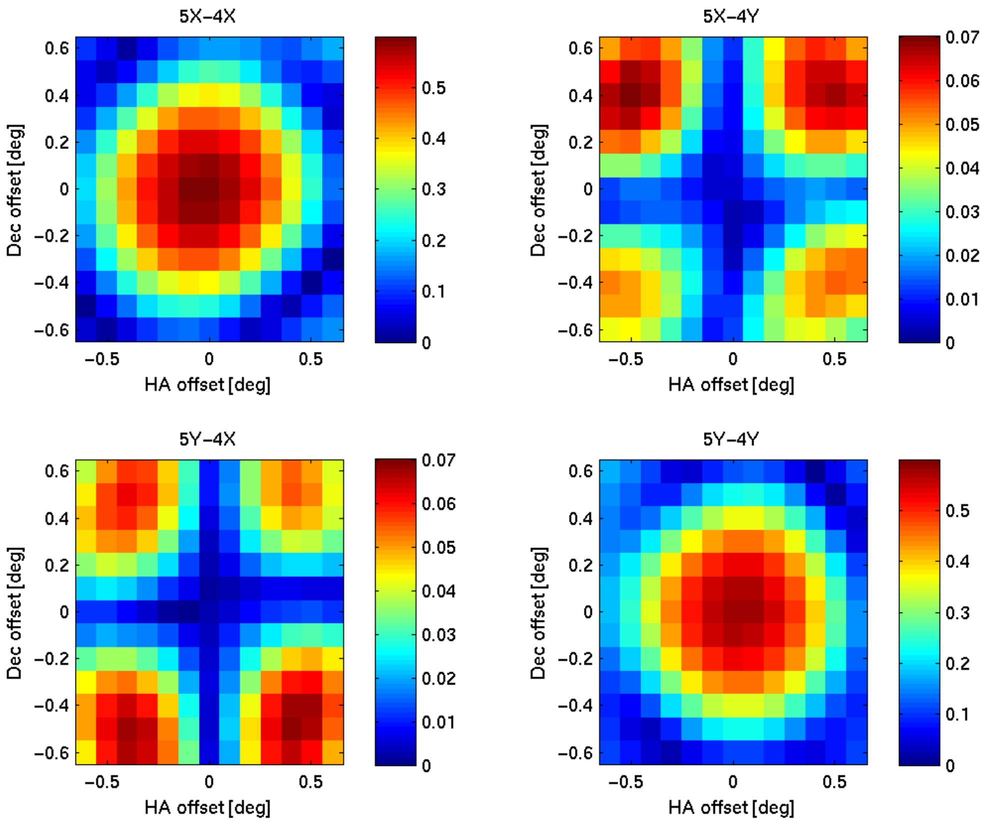
FPA beam – Horn
1420 MHz
144m baseline
Source: 3C286 (14.8 Jy)
Bandwidth: 20 MHz

Measured compound beam



1420 MHz, Source: Cygnus A, on axis cross-pol: 1% (-20 dB)

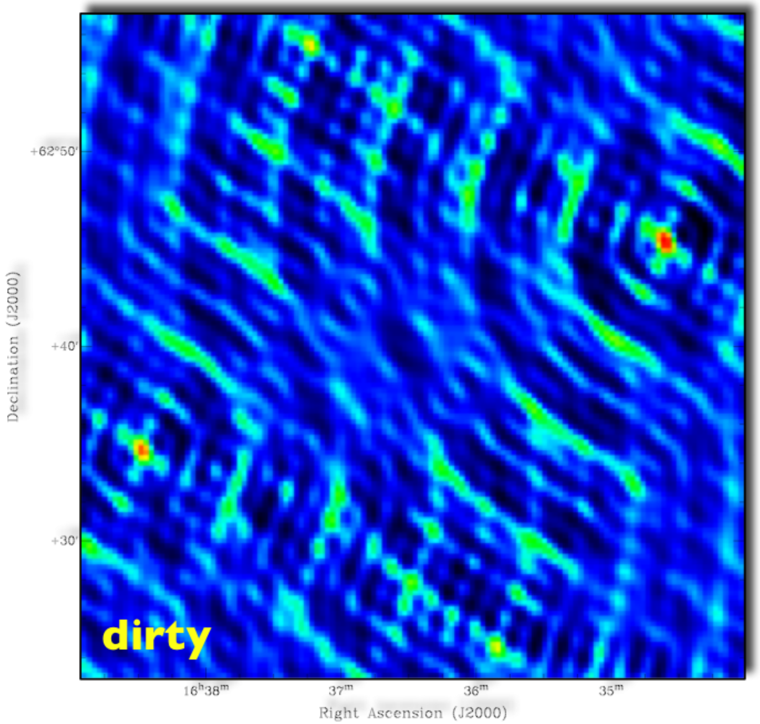
Measured compound beam

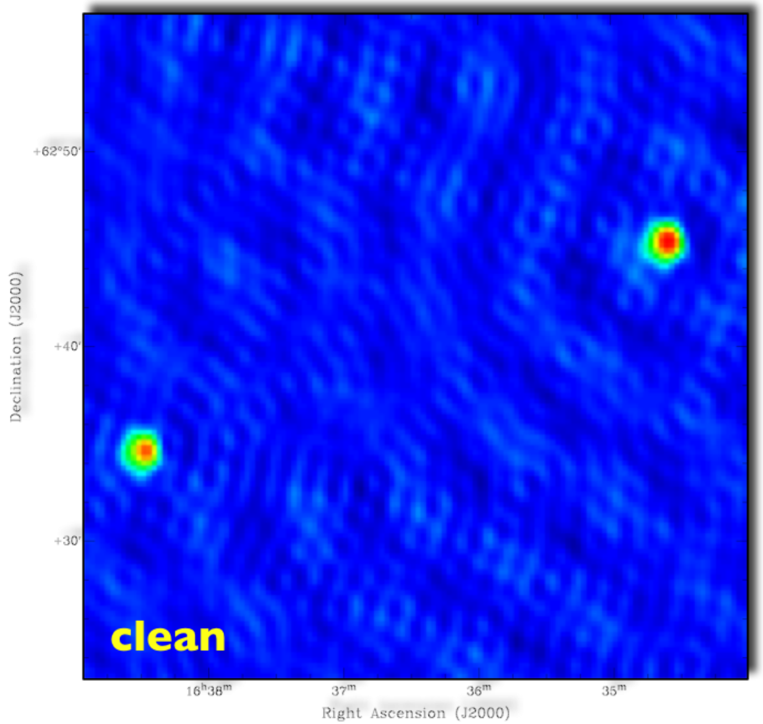


1420 MHz, Source: Cygnus A, on axis cross-pol: 1% (-20 dB)

Synthesis imaging

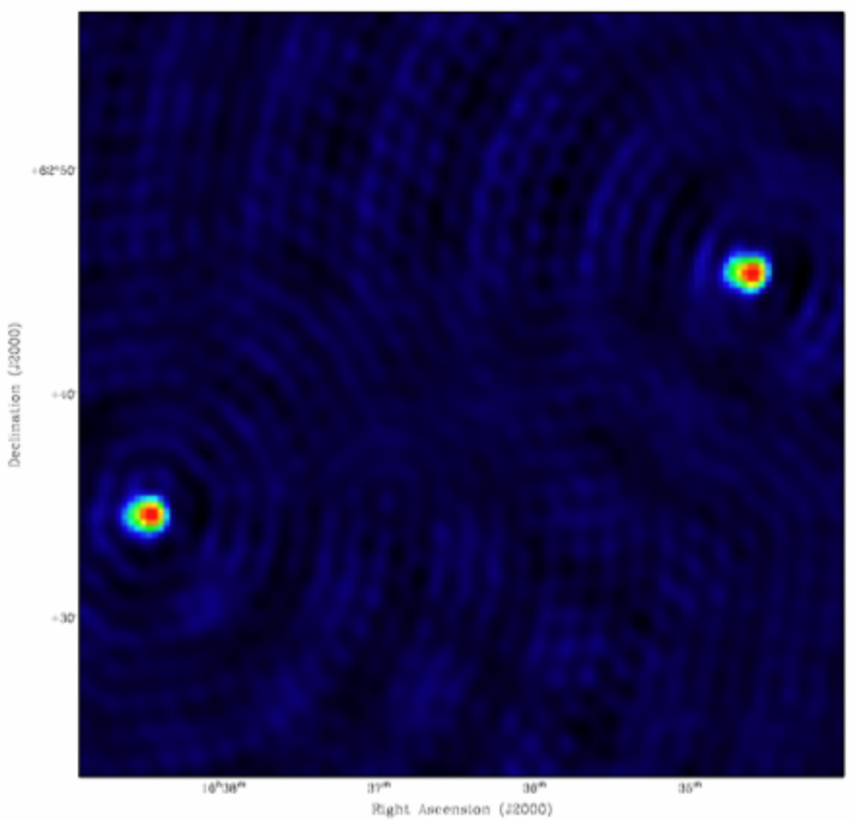
- PAF synthesis image
- Only the PAF – MFFE baselines are used (3)
- 1420 MHz, 20 MHz bandwidth
- Field: 3C343



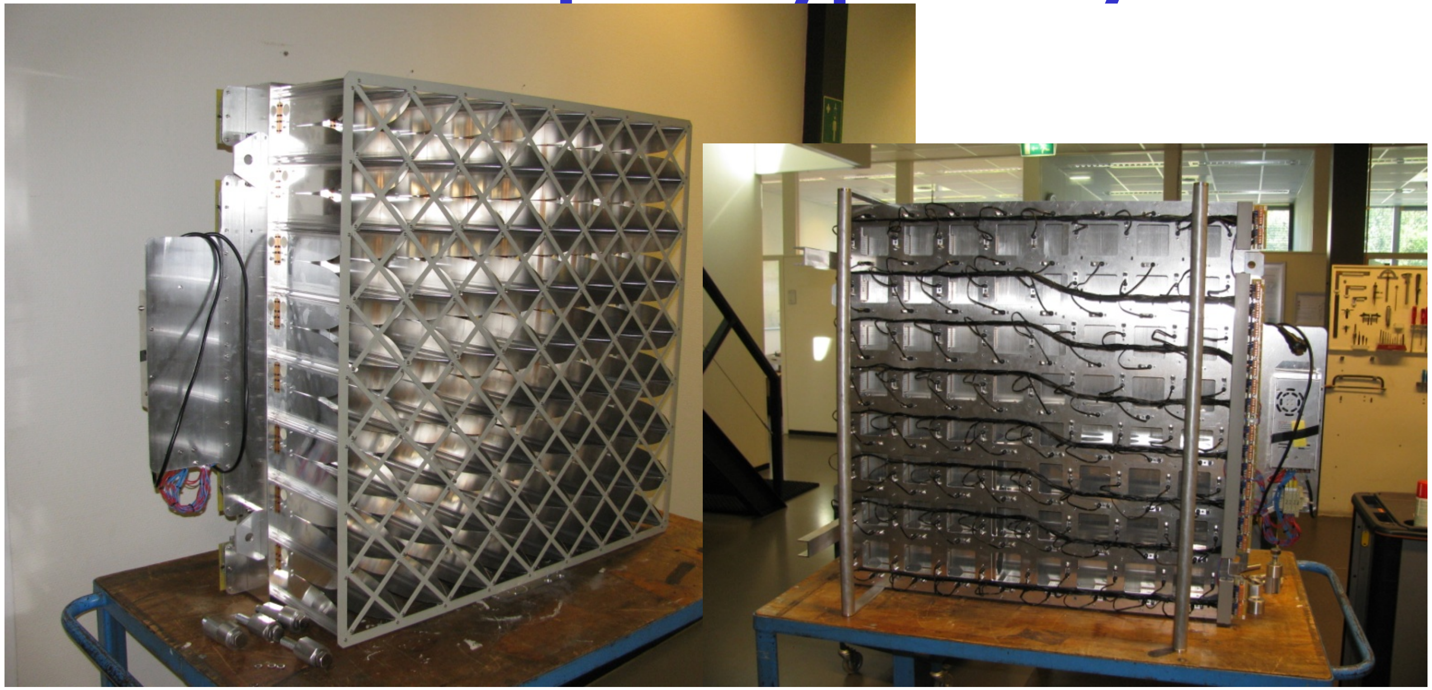


Synthesis imaging

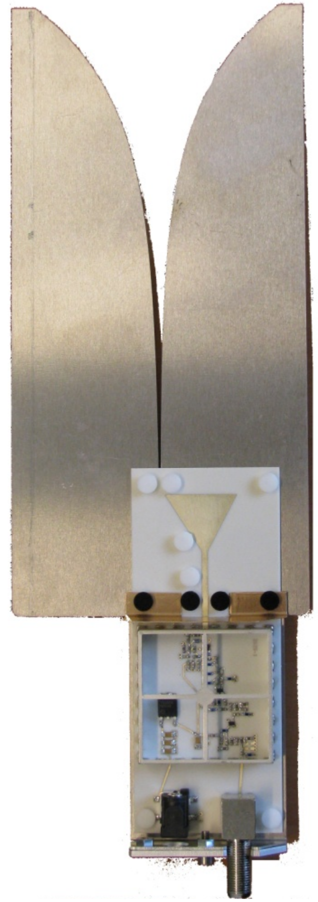
- Compound beam synthesis image
- Only the 3 PAF – MFFE baselines are used
- 1420 MHz, 20 MHz bandwidth
- Field: 3C343



Second prototype array



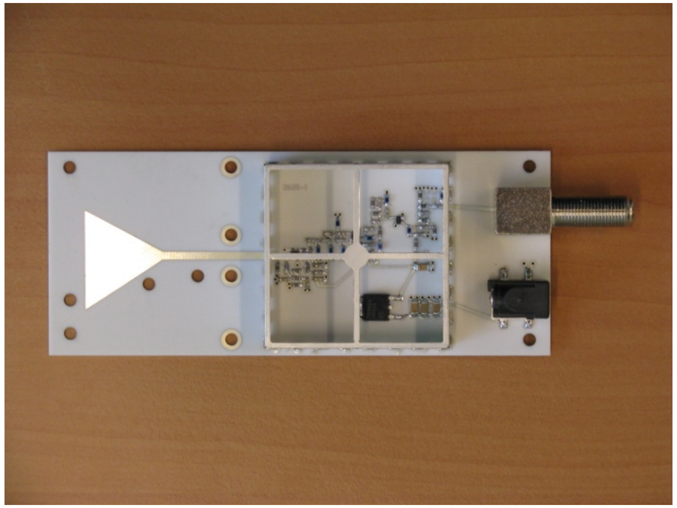
- 144 elements
- Element separation: 11 cm
- Feed integrated with LNA
- Size array 97*97cm



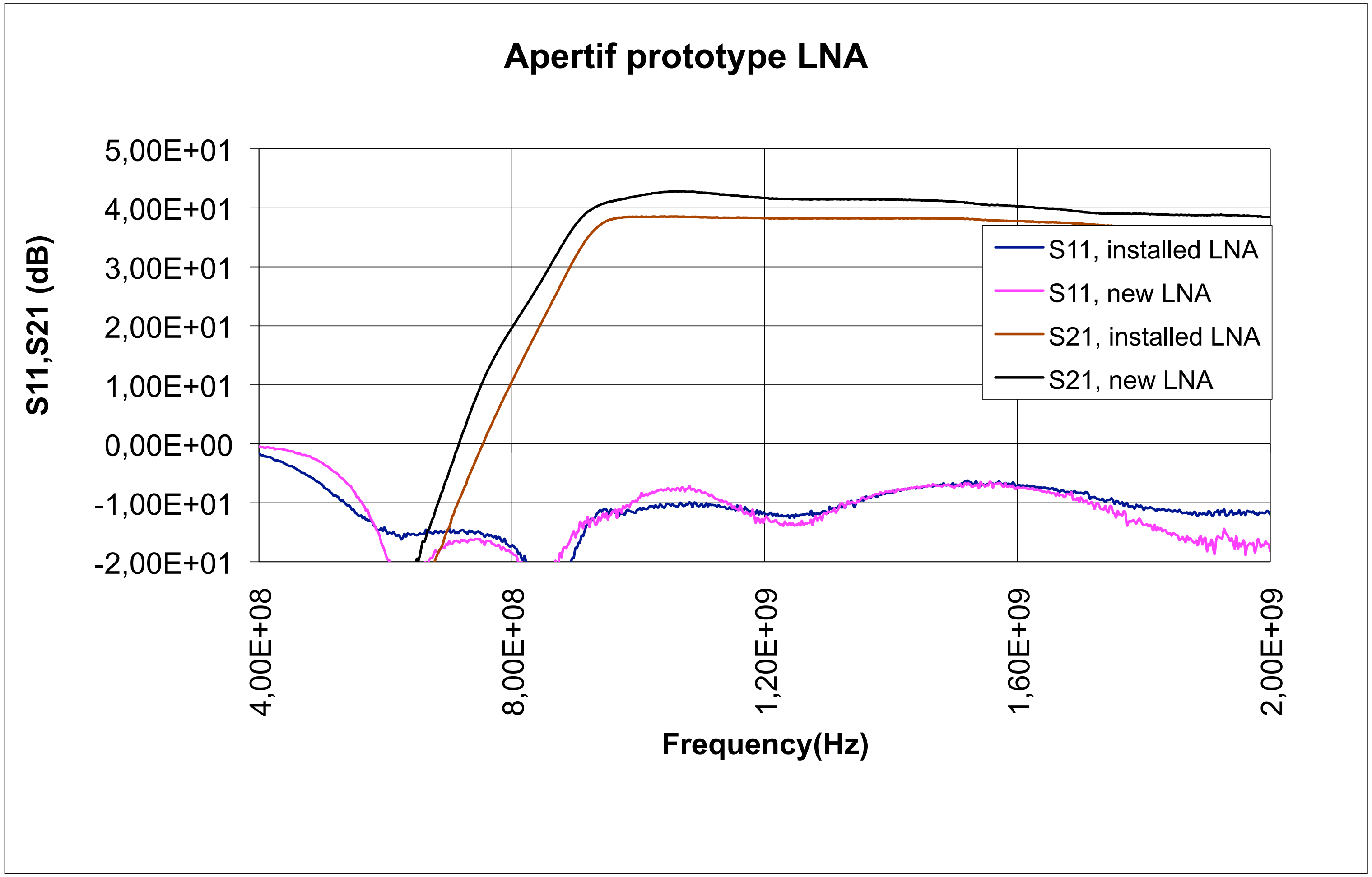
Measured T_{LNA}
< 37 K 1.0 – 1.8 GHz
35 K 1.4 GHz

Second generation LNA

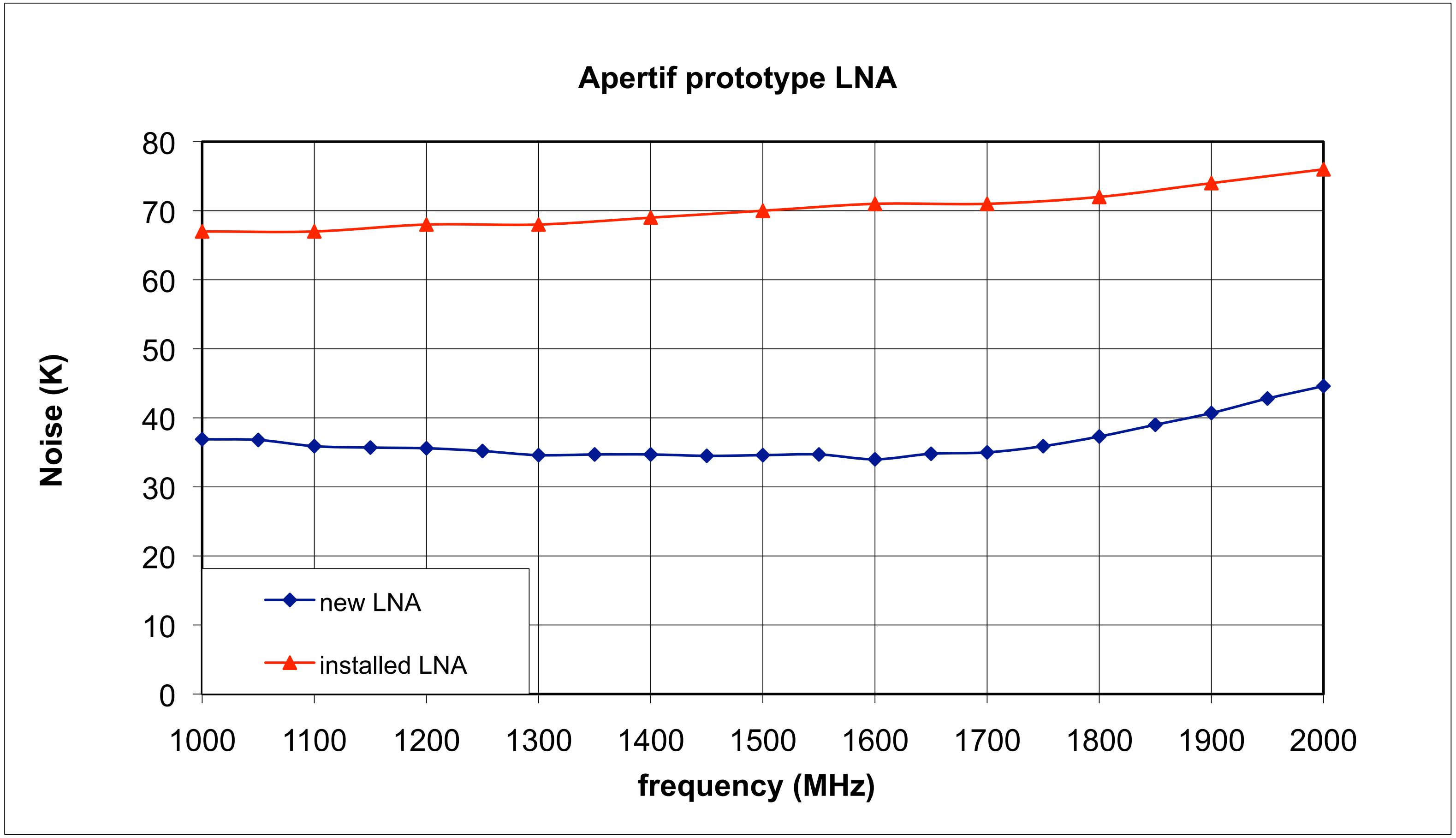
- Feed integrated with LNA
- Design for 50ohm input impedance
- >42 dB gain (flat)
- HPF with 25dB attenuation at 800MHz
- 3 stages, with high pass filtering after first stage
- Reasonable S11
- OIP2 first stage ~45dBm
- F-connector output (75 ohm)
- 160 LNAs were manufactured externally (available Aug. 2009)
- LNA based on ATF-54143



LNA measurement results



Noise measurements



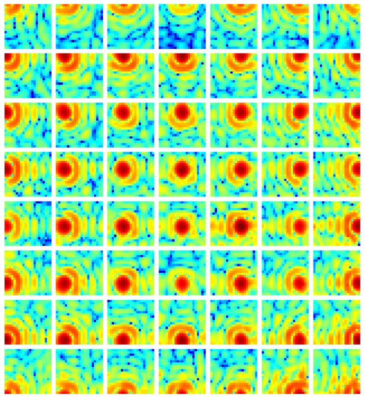
- In 50 ohm using 5.2dB noise source and NFA
  - Liquid nitrogen gives a up to 5K better results
    - But also some points up to 10K worse
- New LNA measured with connector soldered at input

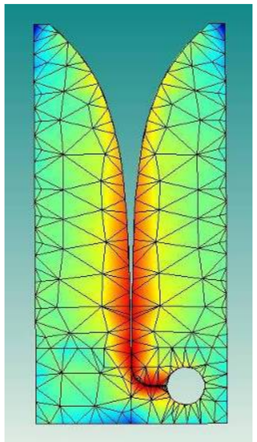
Noise budget (prediction)

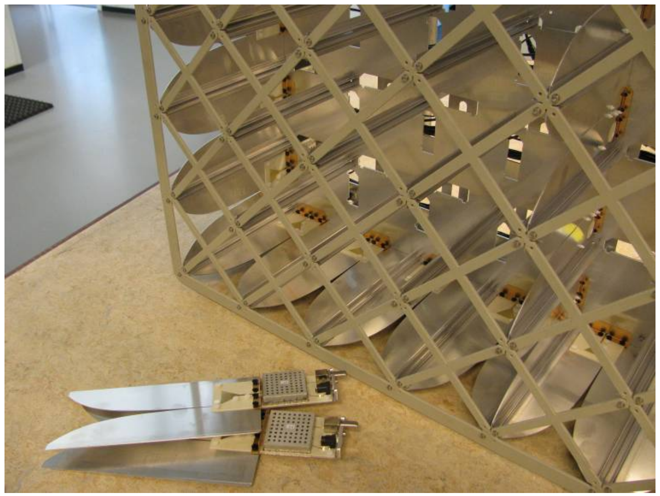
APERTIF prototype		Sept '09	Final APERTIF 2012
Spill-over	15 K	10 K	10 K
Vivaldi feed losses+conn.	15 K	6 K	7 K
Receiver noise (single)	75 K	40 K	28 K
Active Impedance/Rn effects	15 K	9 K	7 K
Sky	3 K	3 K	3 K
Total	123 K	68 K	55 K

Recent Measurement results

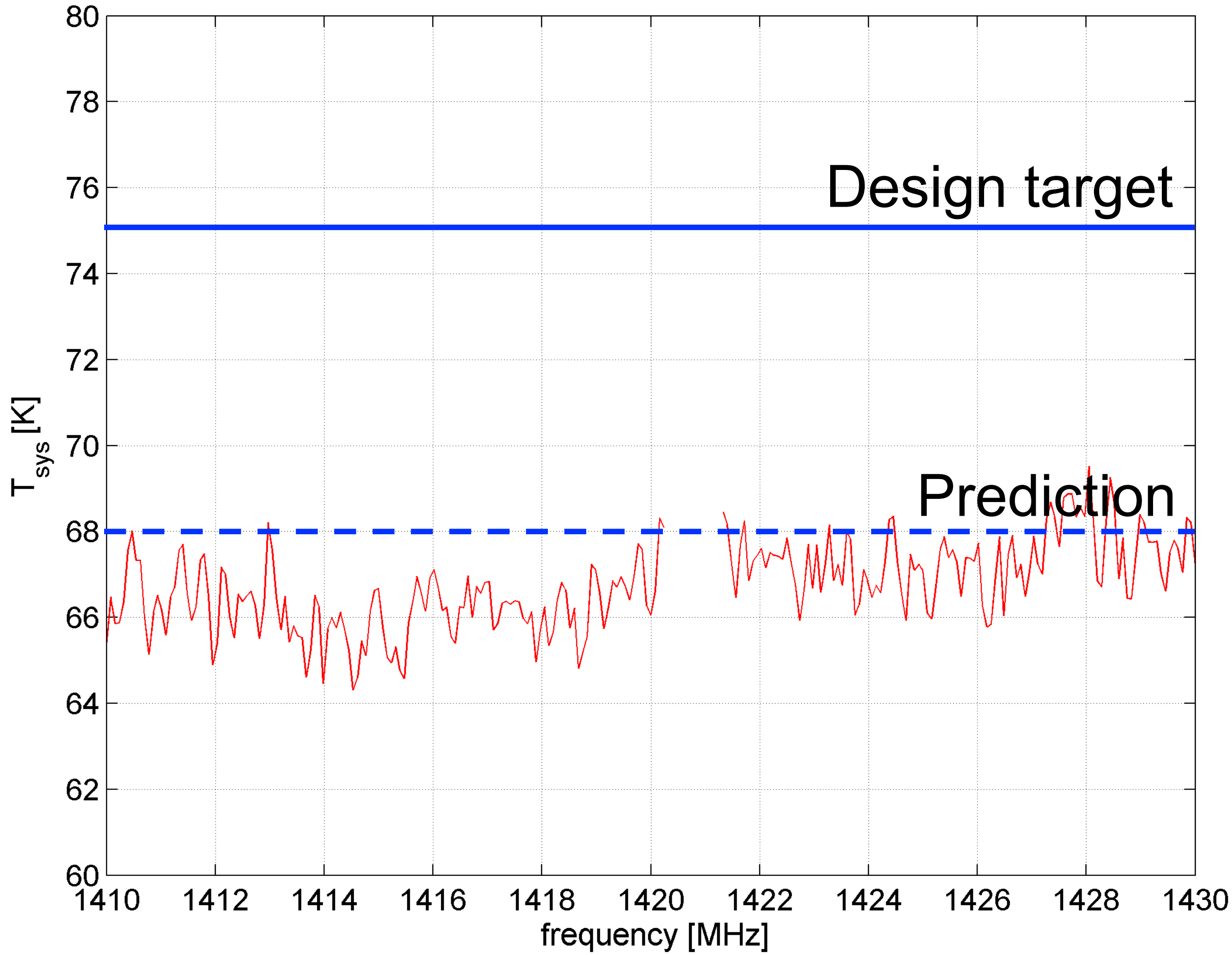
- Upgraded antenna array in WSRT dish (Oktober 2009)
  - Measured T_{sys}/η = 91 K, T_{sys} ~ 68 K
  - Excellent agreement between simulated and measured sensitivity
  - On planned path to T_{sys}=55 K goal
- Front-end redesigned for low noise
  - Noise due to antenna losses: 4 K
  - LNA integrated on antenna
  - Using commercial ATF-54143 transistor





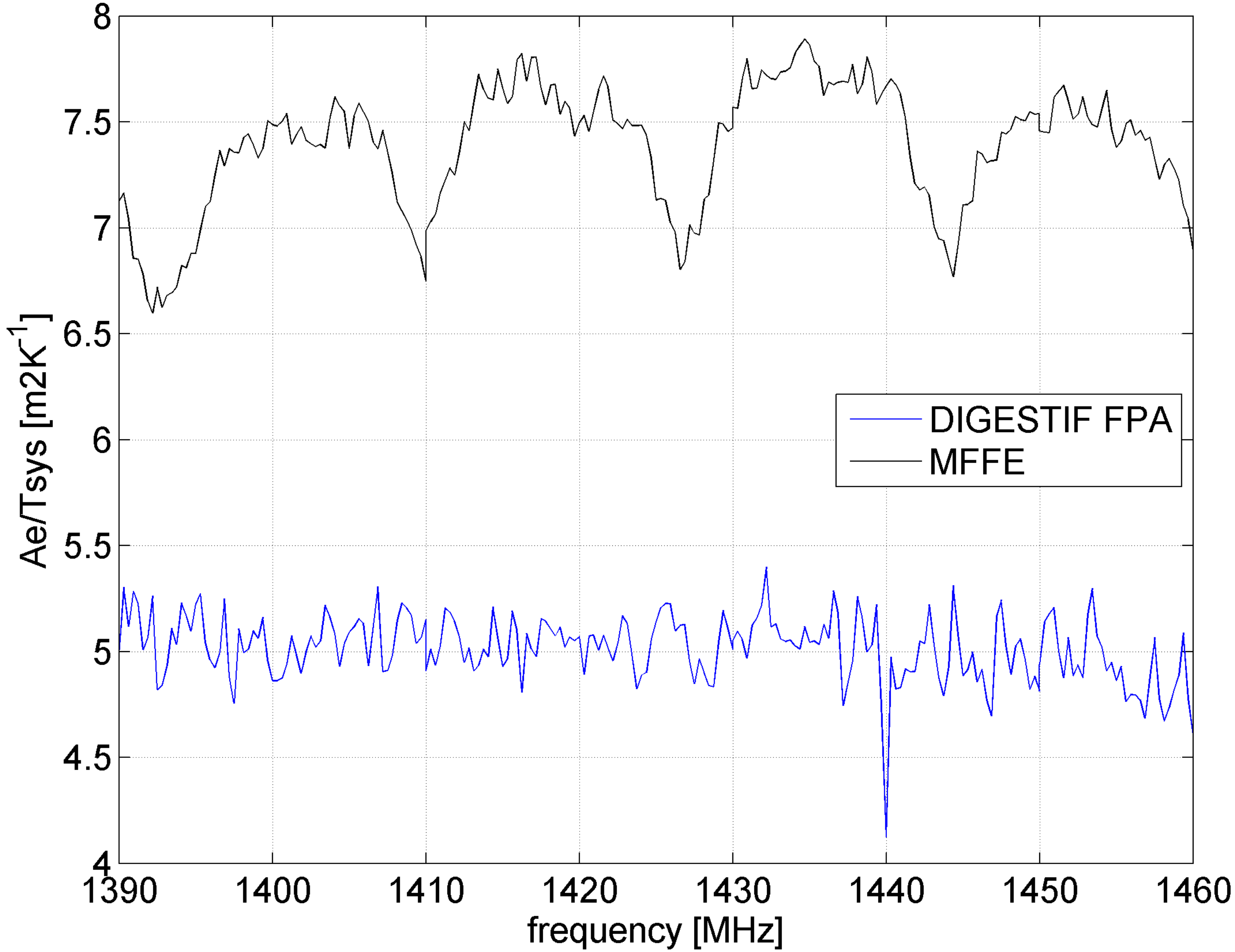


Interferometric measurement on 3C147

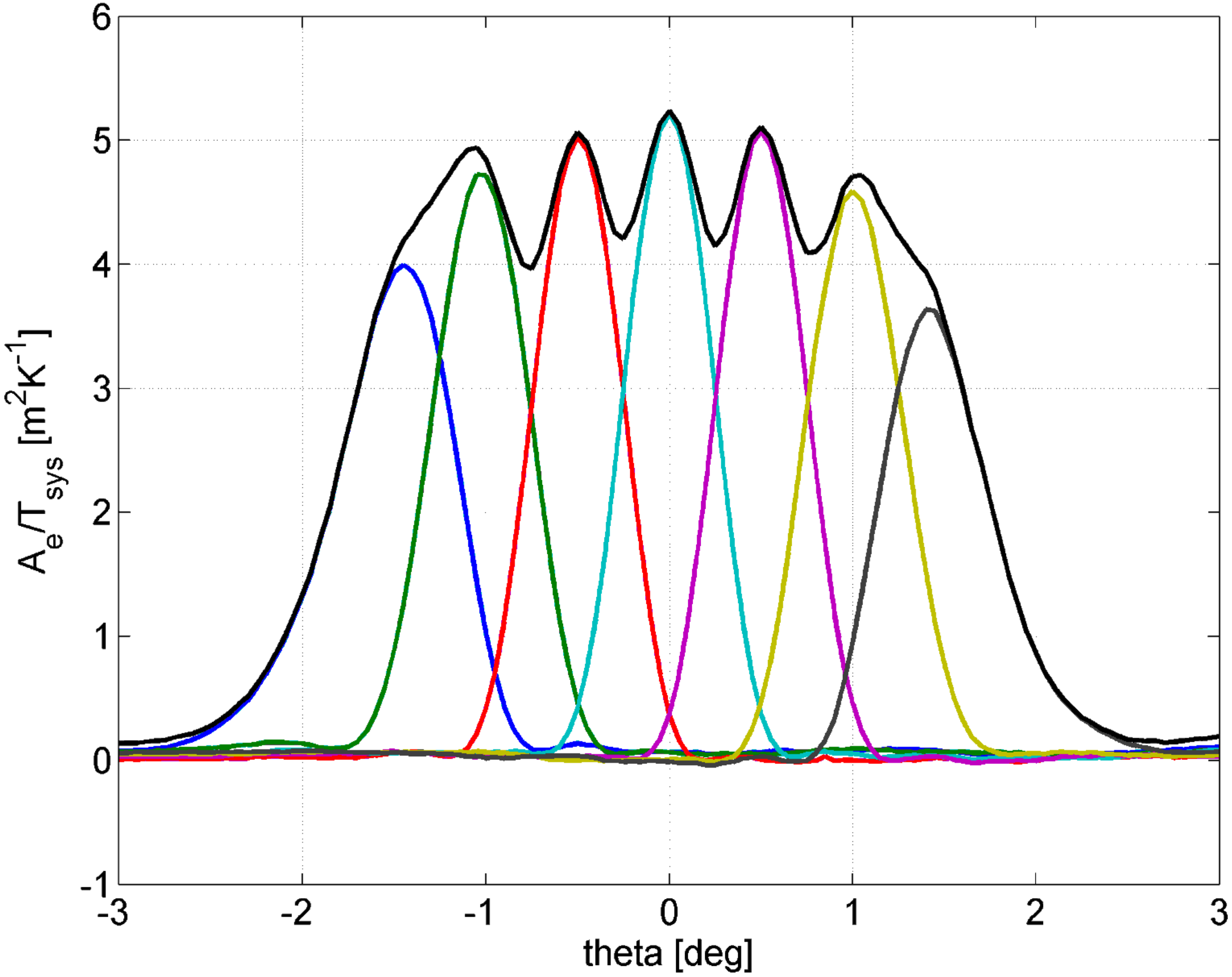


- Assuming antenna efficiency of 75%

No sign of 17 MHz ripple yet…

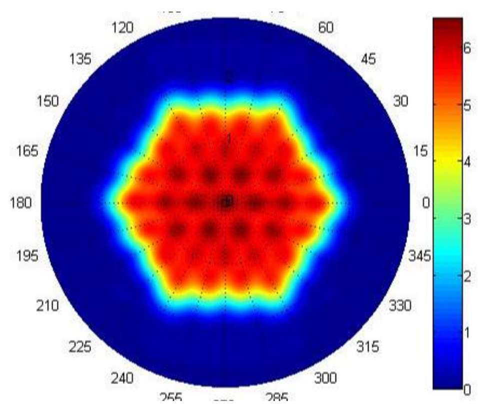


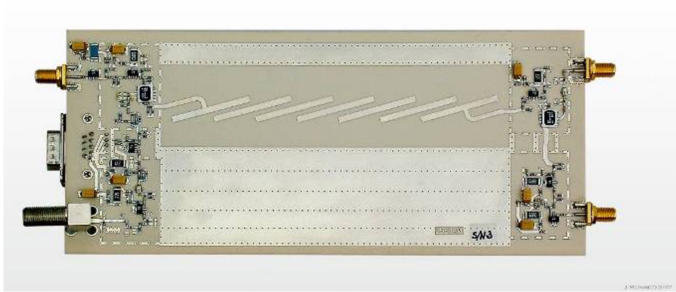
Measured sensitivity over field of view (phi=0)

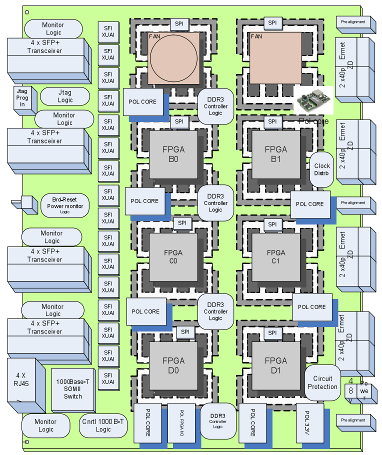


On-going work

- Detailed design of APERTIF hardware
  - Downconverter with 300MHz instantaneous bandwidth
  - Sampling board sampling at 800MHz, 8-bit
  - Digital processing platform development (Uniboard, radionet)
  - Design new PAF prototype
- Continuing experimental verification with DIGESTIF
- System calibration (esp. temporal stability), beamforming algorithms (e.g. minimizing sensitivity ripple over FoV, polarization purity, stability)
- Optimization of front-end (antenna + LNA) for minimum noise.
- Transistor testing with Tuner setup

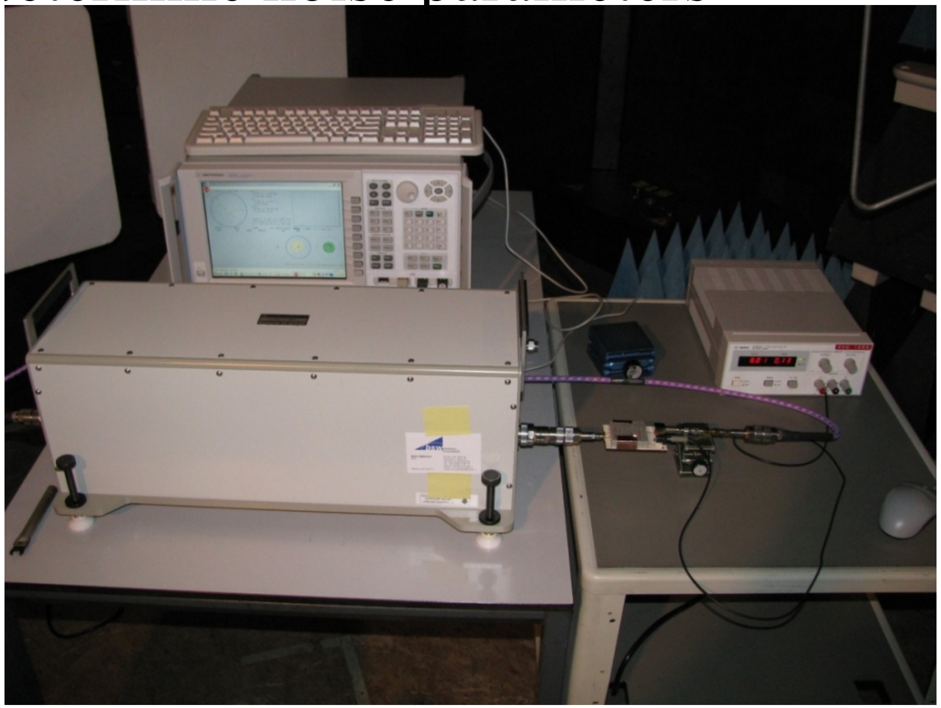






Noise parameter measurements

- Maury tuner
- Measured in shielded (EMC) room
- Agilent 5.2dB noise source
- PNA-X
- Commercial Maury software
  - Both hot/cold and cold method possible
  - Different algorithms to determine noise parameters
- Very repeatable results



Conclusions and future work

- Excellent agreement between modeling and measurement of Tsys
- Tsys ~68K achieved
- APERTIF passed PDR in August 2009
  - System level issues most important, not subsystem (i.e. calibration)
- LOFAR backend will be coming month(s)
  - 32MHz instantaneous bandwidth
  - Real time beamforming (also several beams)
  - Check temporal stability
  - Check calibration algorithms
- Detailed design of hardware