EMBRACE

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Nançay, Observatoire de Paris

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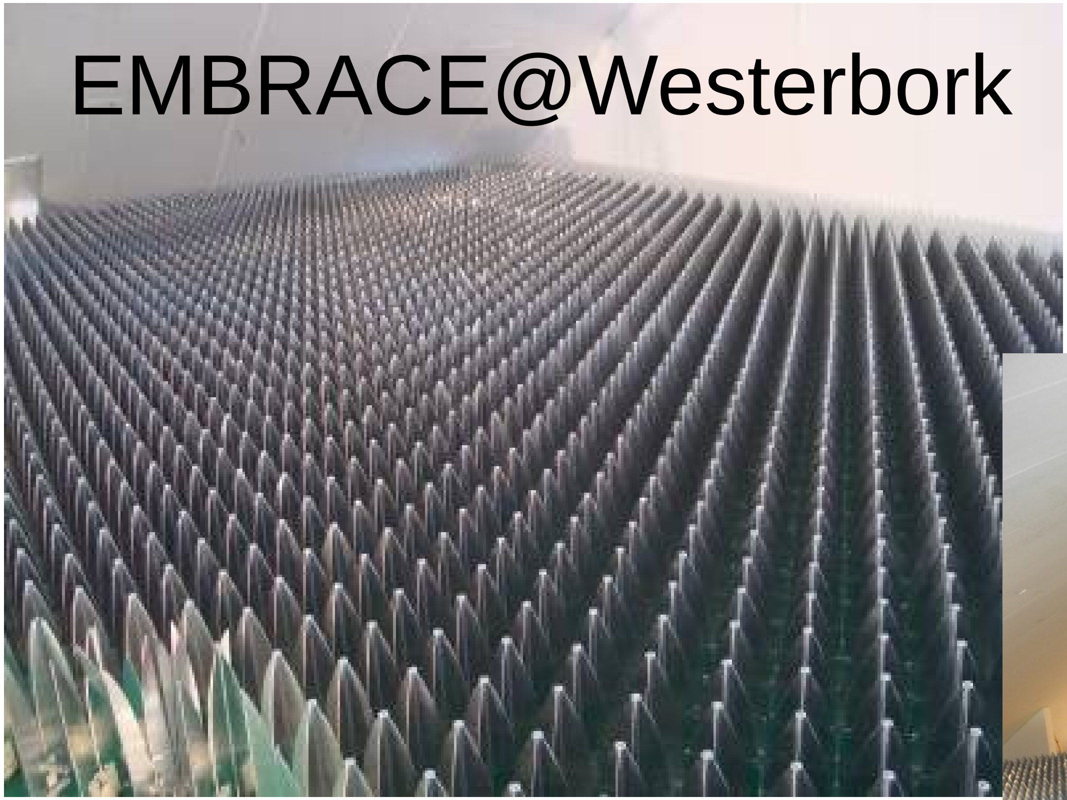
ASTRON

On behalf of the EMBRACE team

Two EMBRACE sites



Electronic MultBeam Radio Astronomy ConcEpt (EMBRACE)

- EMBRACE is an AAmid Pathfinder for SKA
- Largely funded within EC FP6 Project SKADS (2005-09)
- For EMBRACE:
  - ASTRON: Project Leader, overall architecture, antennas, industrialization,...
  - Nançay: Beamformer Chip, Monitoring and Control Software
  - MPI Bonn and INAF Medicina: design of multiplexing circuits for RF reception, down conversion, command/control, power supply
- Two demonstrators built. One at Westerbork (144 tiles) and one at Nançay (64 tiles currently)

EMBRACE@Nançay

- 4608 Vivaldi antenna elements
- Single polarization (second polarization antennas are there for a total of 9216 elements, but only one polarization has a complete signal chain)
- 4 level hierarchical analog beamforming/signal summing
  - Beamformer chip:
    - 4 inputs, 2 outputs (2 independent beams)
    - 45º phase steps
  - Analog summing output from 3 beamformer chips
  - Analog summing of 6 inputs = 1 tile (72 elements)
  - 15m cable → Analog summing of 4 inputs = 1 tileset
  - Down conversion → 32 inputs to LOFAR backend (16 A-beam, and 16 B-beam)

EMBRACE@Westerbork

- 10368 Vivaldi antenna elements
  (4032 currently connected end-to-end)
- Single polarization (second polarization antennas are there for a total of 20736 elements, but only one polarization has a complete signal chain)
- 3 & 4 level hierarchical analog beamforming/signal summing
  - Beamformer chip:
    - 4 inputs, 2 outputs (2 independent beams)
    - 45º phase steps
  - Analog summing output from 3 beamformer chips
  - Analog summing of 6 inputs = 1 tile (72 elements)
  - For 2nd RF beam: analog summing of 4 tiles
  - Down conversion → 180 inputs to LOFAR backend
    (70 currently connected: 56 A-beam and 14 B-beam)

EMBRACE@Nançay

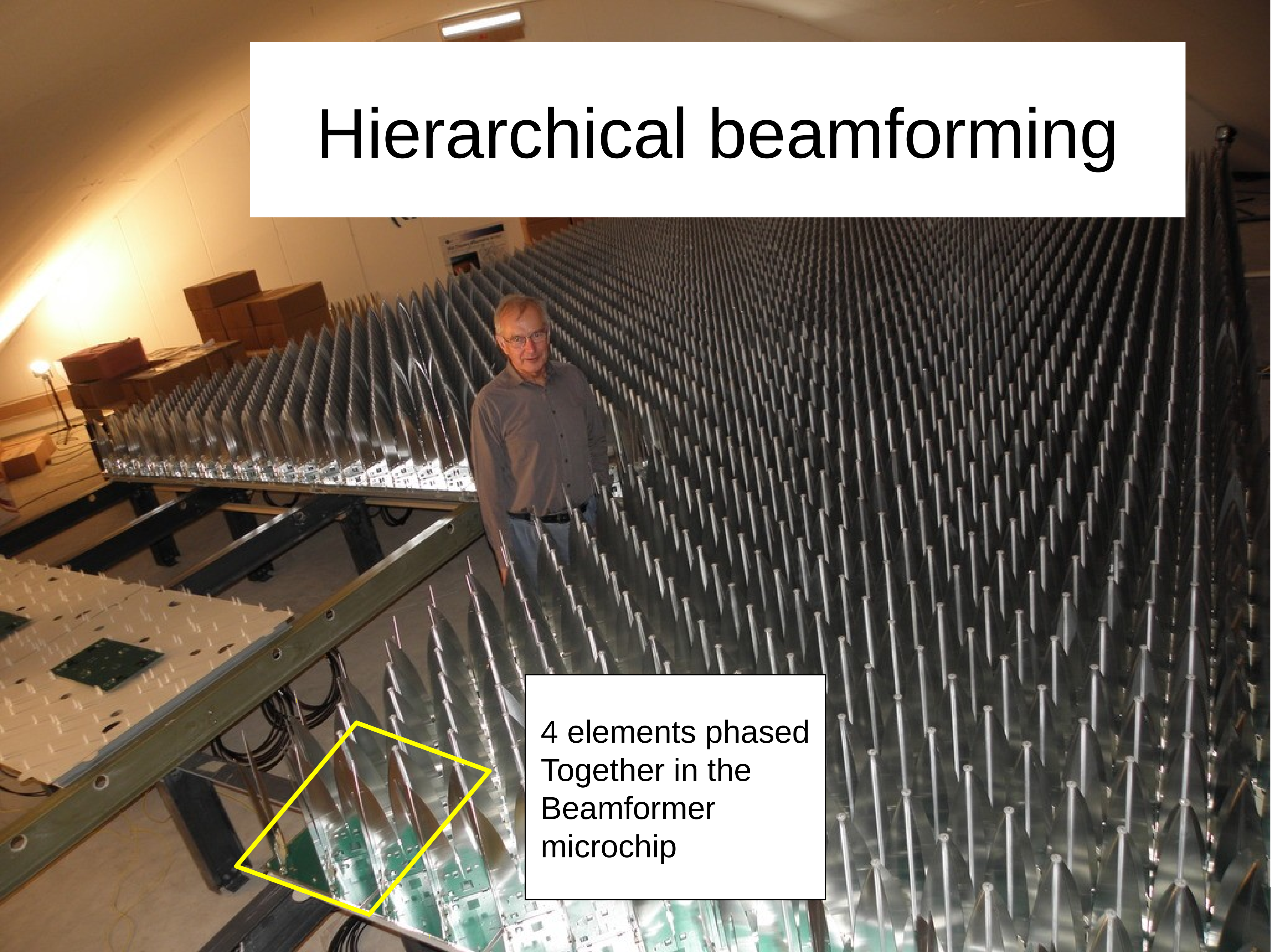
- 500 – 1500 MHz
  - But high pass filter at 900 MHz to avoid digital television
- 70 m^2 (10.5m X 10.5m)
- Instantaneous RF band: 100 MHz
- Maximum instantaneous beam formed:
  - 36 MHz x 2 directions (single polarization)
  - 186 “beamlets” each of 195.3 kHz bandwidth
  - ie. 3 “lanes” for high speed data from RSP
  - Can trade off beam width vs. number of beams

EMBRACE@Westerbork

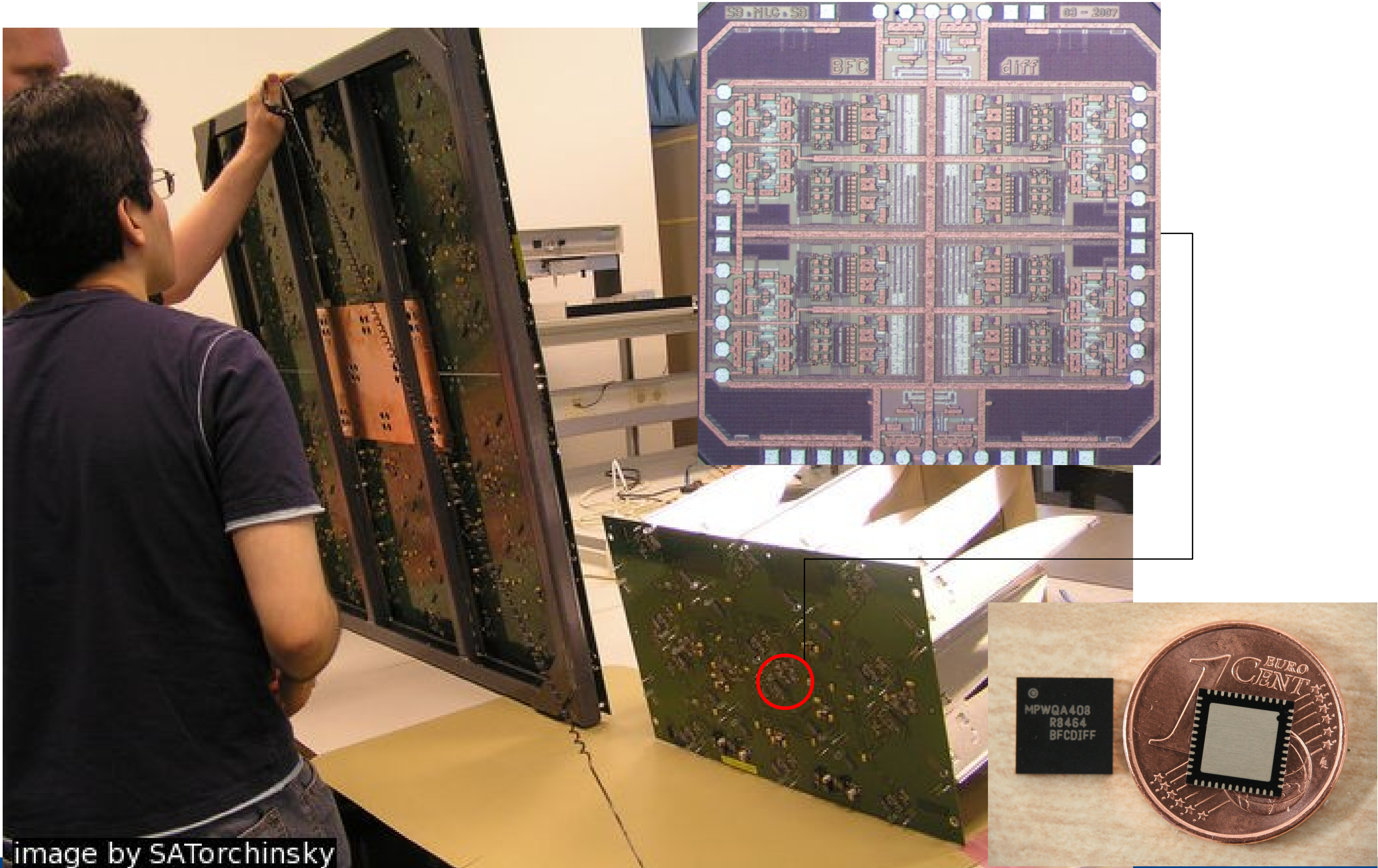
- 500 – 1500 MHz
  - But high pass filter at 900 MHz to avoid digital television
- 161 m^2 (12.7m X 12.7m)
  - Currently 63m^2
- Instantaneous RF band: 100 MHz
- Maximum instantaneous beam formed:
  - 48.4 MHz x 2 directions (single polarization)
  - 248 “beamlets” each of 195.3 kHz bandwidth
  - ie. 4 “lanes” for high speed data from RSP
  - Can trade off beam width vs. number of beams

Hierarchical beamforming

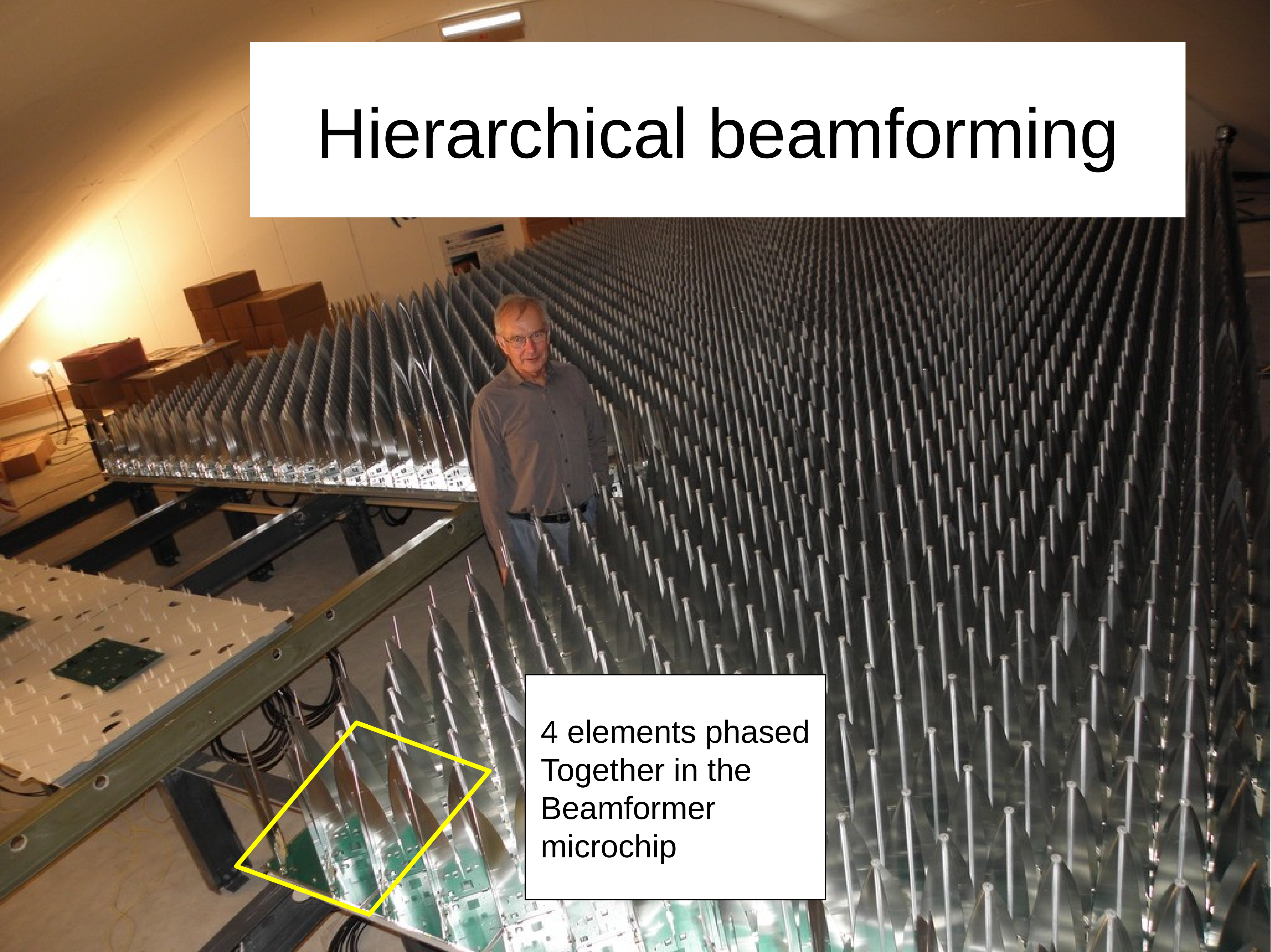
Hierarchical beamforming



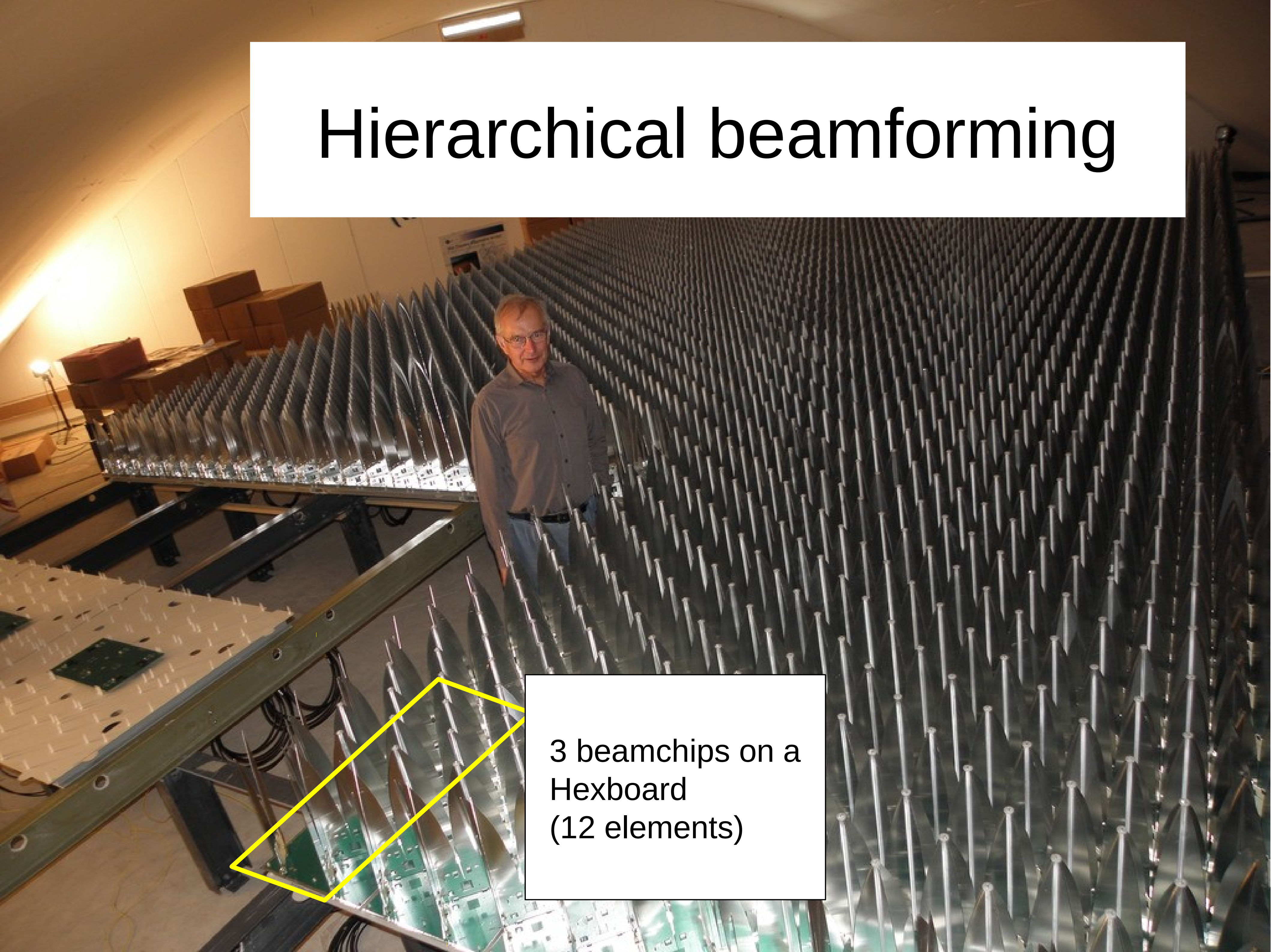
Nançay Beamformer Chip



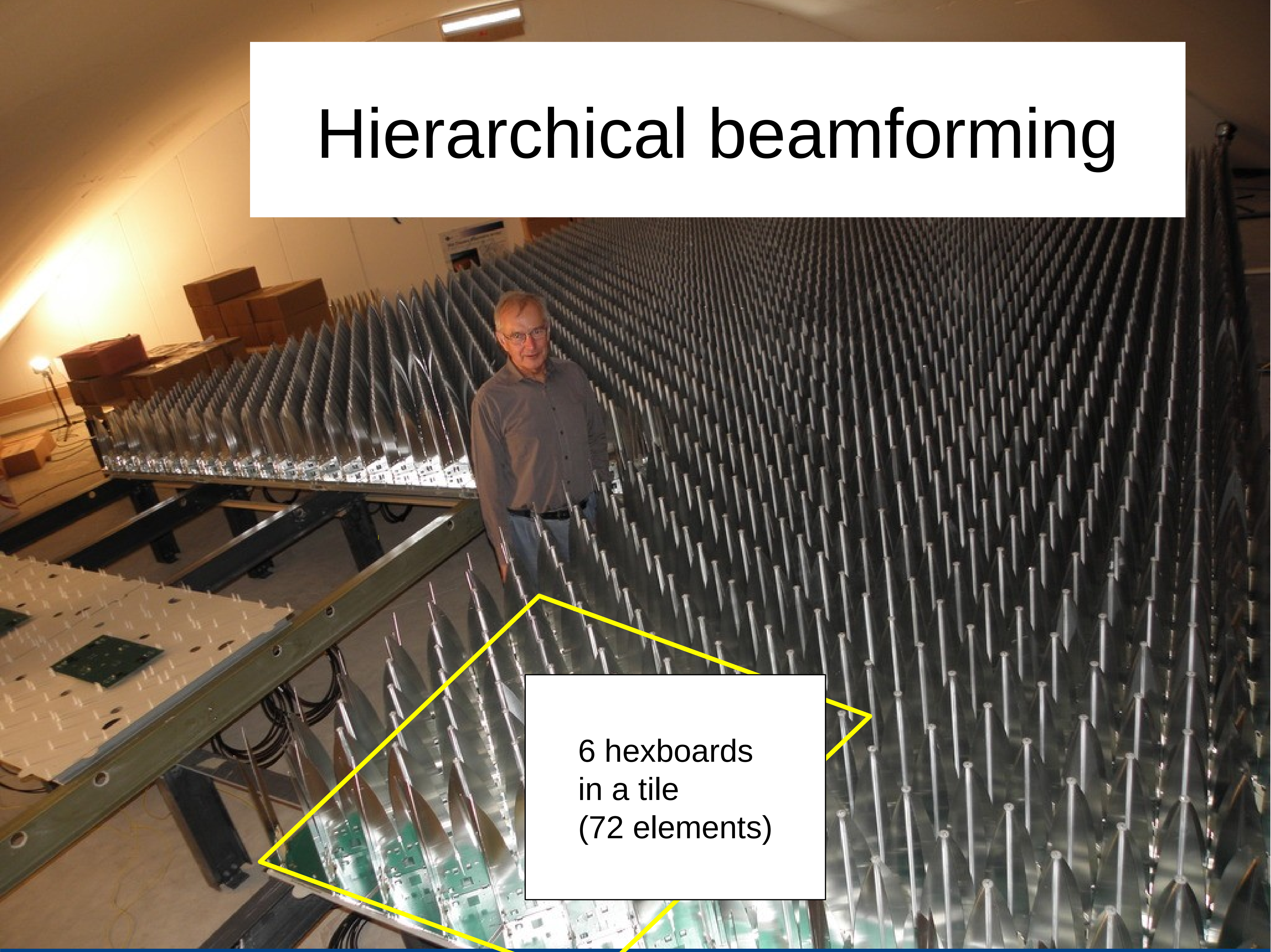
Hierarchical beamforming



Hierarchical beamforming

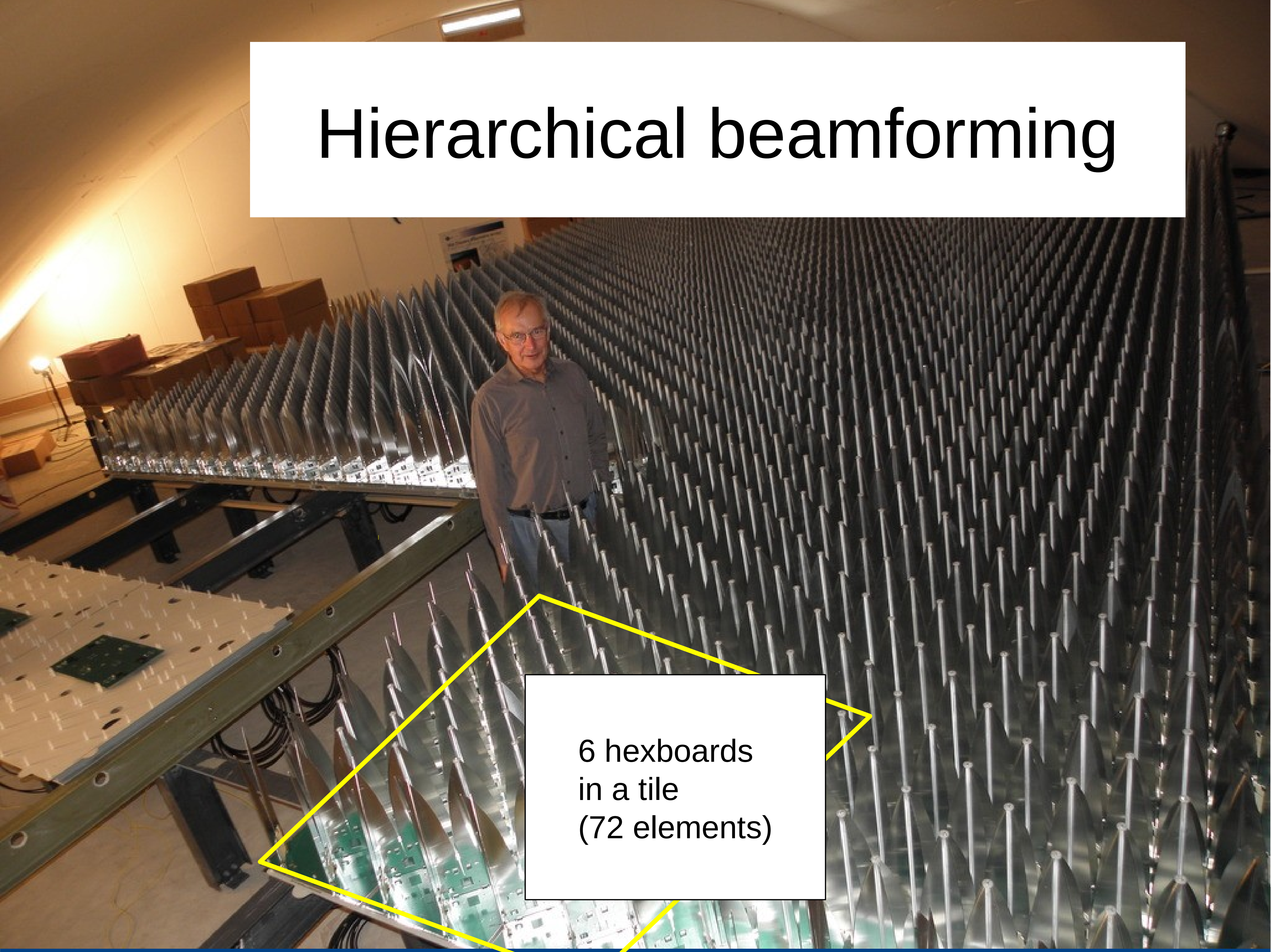


Hierarchical beamforming

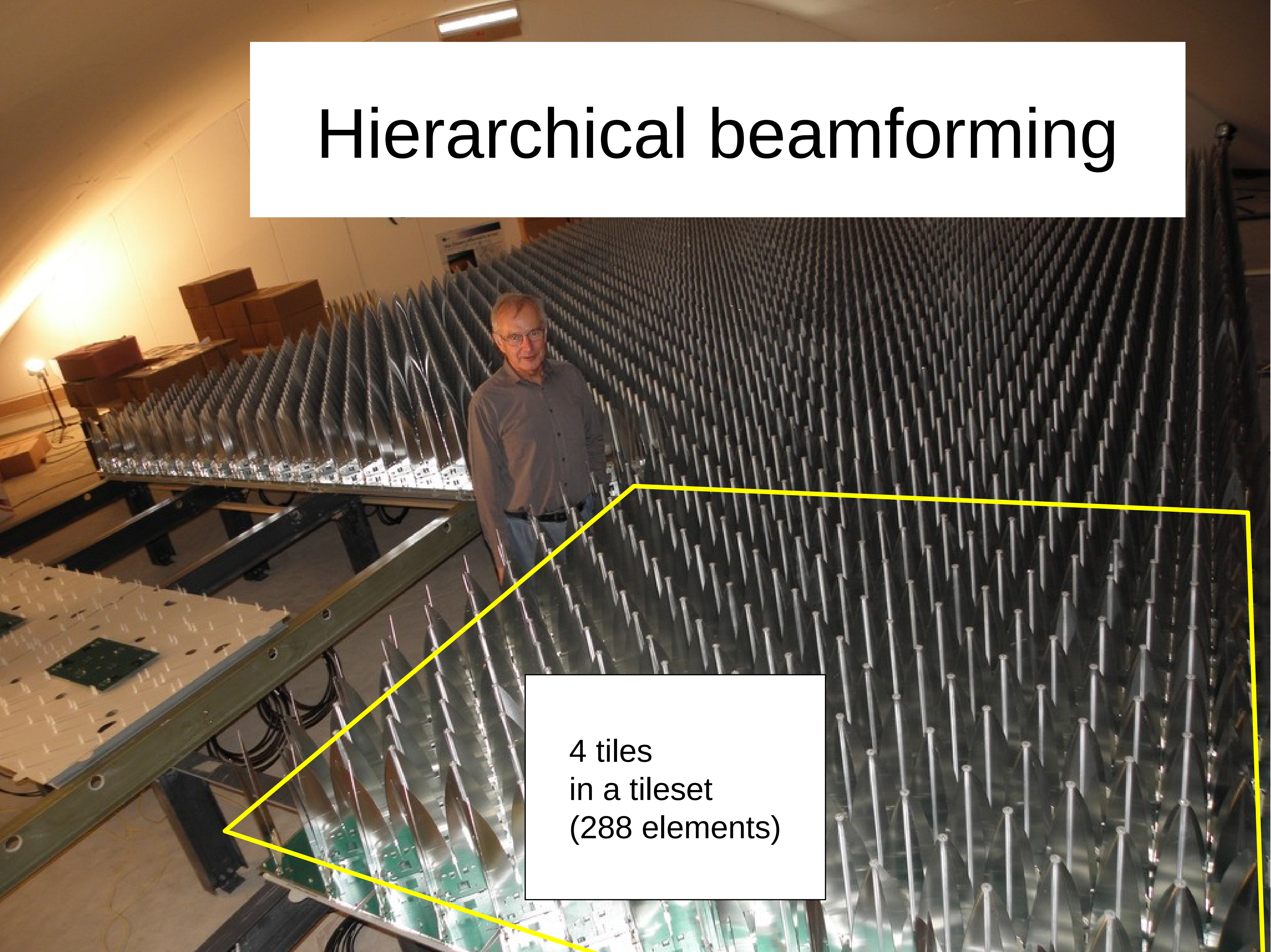


Two coaxial outputs per tile

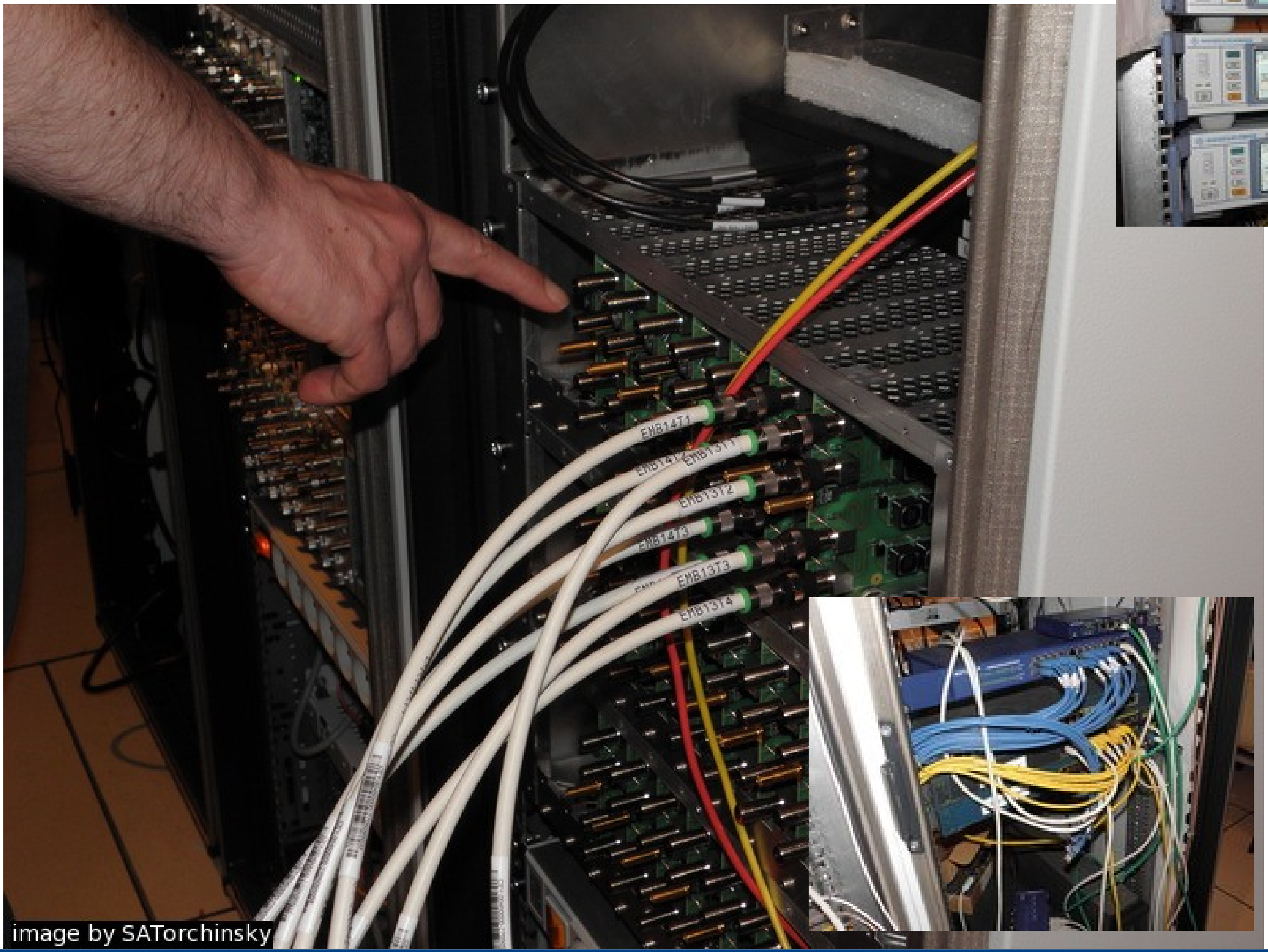
Hierarchical beamforming



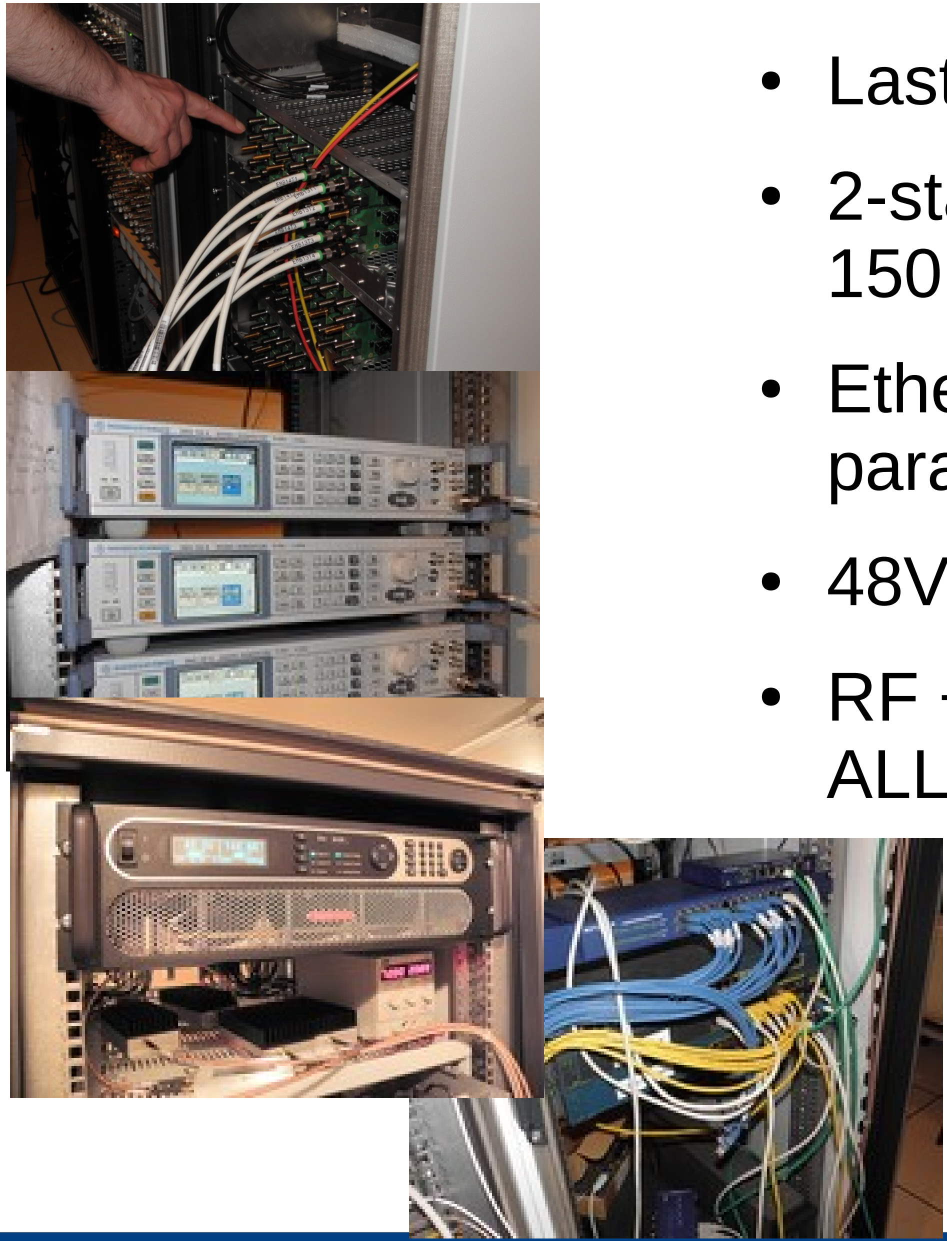
Hierarchical beamforming



4th stage analog beam forming @Nançay



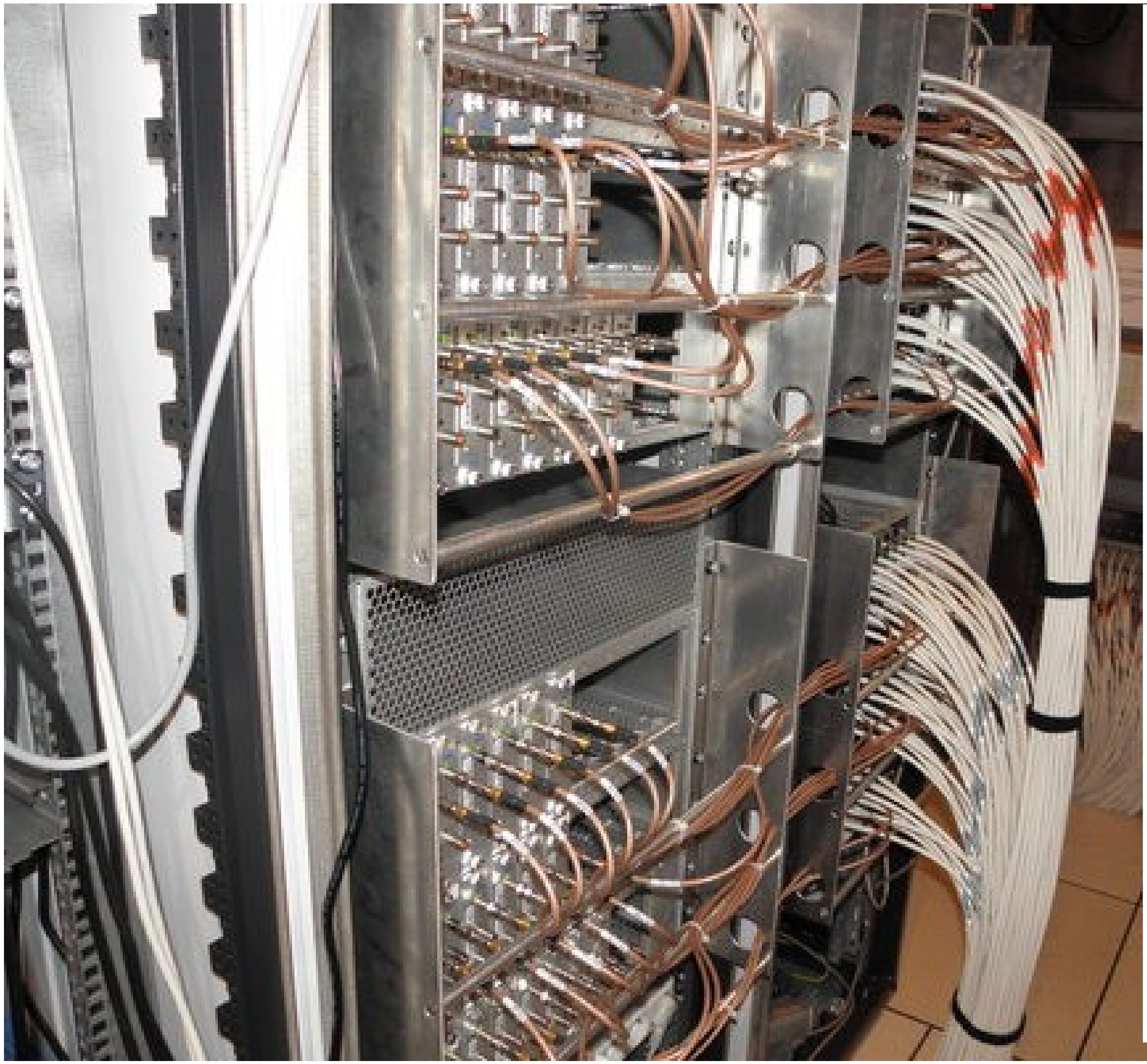
Control and Down Conversion



- Last stage analog summing of four tiles
- 2-stage mixing to convert RF down to 150 MHz +/- 50MHz
- Ethernet protocol for beamformer chip parameters and housekeeping
- 48V DC
- RF + Digital Commands + Power
  ALL ON THE SAME COAX!

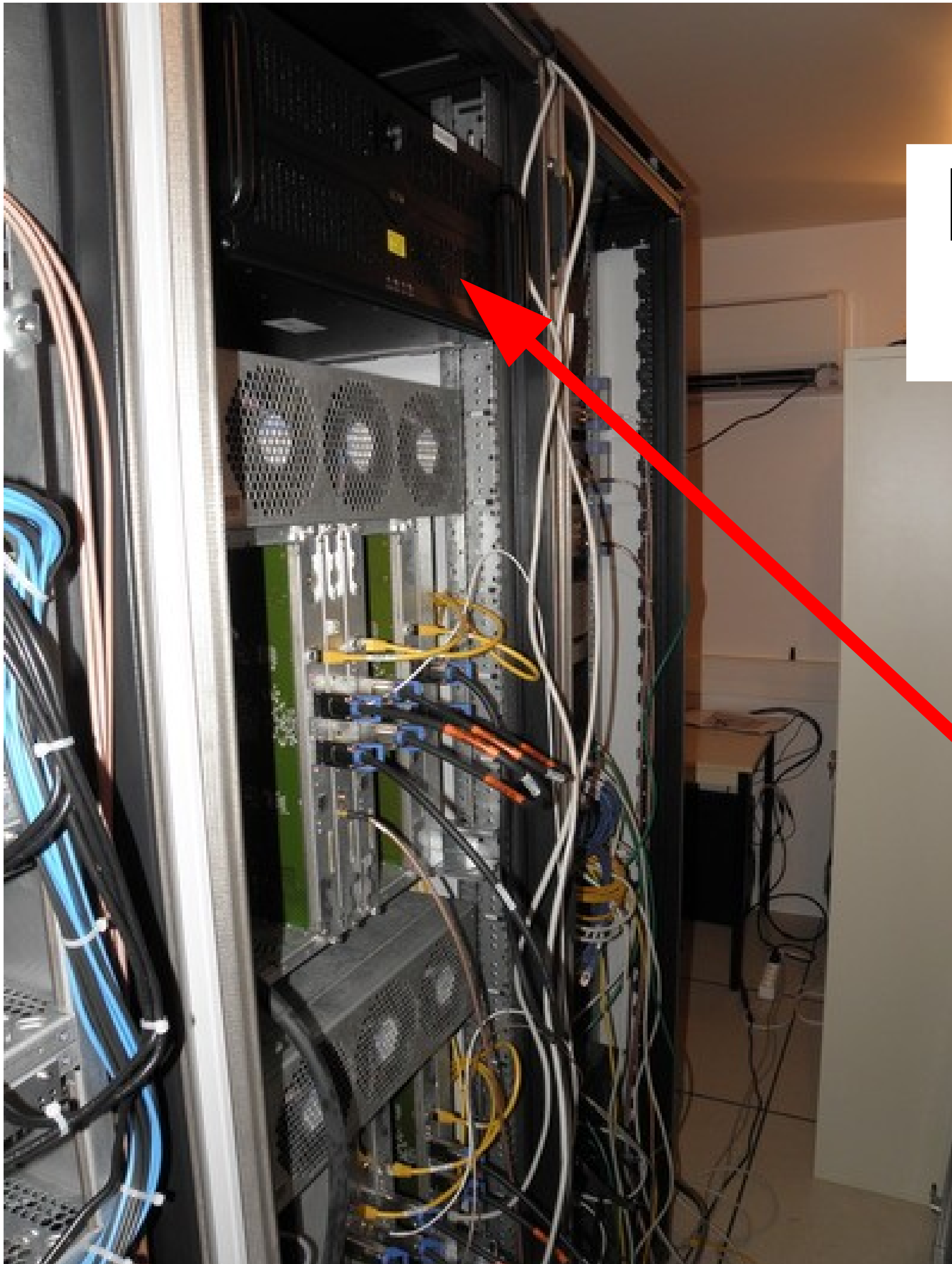
CDC cards designed by
MPIfR/INAF-IRA/ASTRON

LOFAR Backend



- Output from CDC goes to LOFAR Receiver Unit (RCU) boards for digitization
- And then to LOFAR Remote Station Processing (RSP) boards for digital beamforming

High Speed Data Acquisition



ARTEMIS

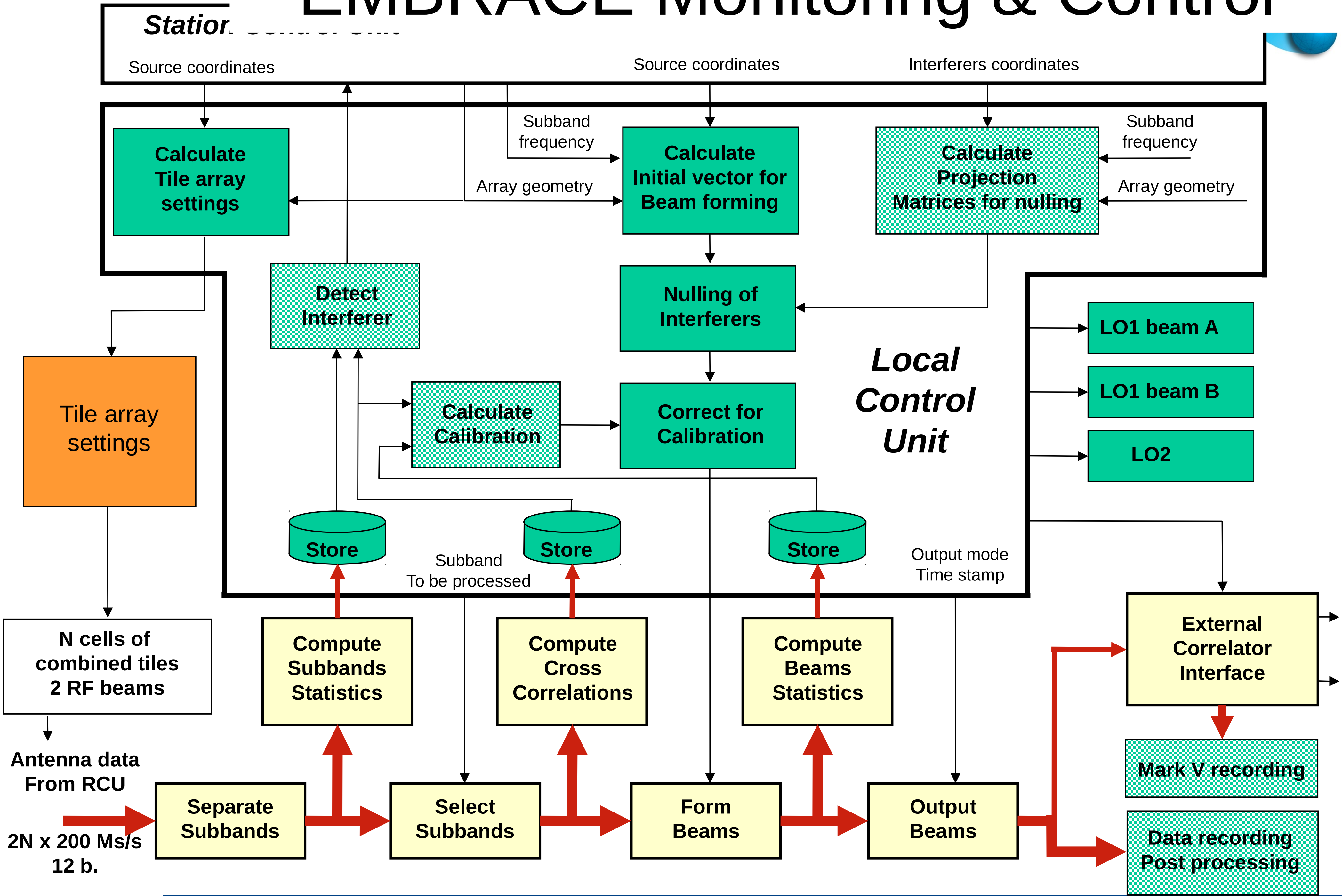
System Control and Data

- Enormous flexibility with the dense array
  - Multi-beam
  - Instantaneous reconfiguration
  - Real time calibration
  - Multiple observing mode possibilities with tradeoff between bandwidth, number of beams, field of view

System Control and Data

- Extension of LOFAR Local Control Unit Software
  - More complex task with EMBRACE especially regarding beamformer chip control
- Station Control Unit software
  - Python modules
  - User interface simple, but highly adaptive using python scripts
  - Statistics saved in FITS files

EMBRACE Monitoring & Control



Ease of Use

```
torchinsky@scu-desktop: ~/scripts
torchinsky@scu-desktop:~/scripts$ ll -t|head -20
total 5852
drwxr-xr-x  5 torchinsky torchinsky  204800 2011-12-10 22:21 ./
-rw-r--r--  1 torchinsky torchinsky      55 2011-12-10 22:21 BeamPointings10-12-11_22:21:22.log
-rw-r--r--  1 torchinsky torchinsky     357 2011-12-10 22:21 SCUlog-20111210-2221.txt
drwxr-xr-x 15 torchinsky torchinsky    4096 2011-12-10 22:20 ../
-rw-r--r--  1 torchinsky torchinsky  267249 2011-12-09 22:41 SCUlog-20111209-1721.txt
-rw-r--r--  1 torchinsky torchinsky     545 2011-12-09 18:24 BeamPointings09-12-11_17:22:00.log
-rw-r--r--  1 torchinsky torchinsky   81840 2011-12-09 18:24 RFcalibrationParameters.txt
-rw-r--r--  1 torchinsky torchinsky    3034 2011-12-09 17:28 SourceTrack_J2000_20111209-1727.submitlog
-rw-r--r--  1 torchinsky torchinsky    2087 2011-12-09 17:28 observation.cfg
-rw-r--r--  1 torchinsky torchinsky    5472 2011-12-09 17:28 SCUlog-20111209-1727.txt
-rw-r--r--  1 torchinsky torchinsky     483 2011-12-09 17:27 GPSBIIR-2_digital_20111209-1824.txt
-rw-r--r--  1 torchinsky torchinsky    1452 2011-12-09 17:27 GPSBIIR-2_RF_20111209-1824.txt
-rw-r--r--  1 torchinsky torchinsky   32728 2011-12-09 17:27 ObsFunctions.pyc
-rw-r--r--  1 torchinsky torchinsky    7474 2011-12-09 17:24 SourceTrack_J2000.py
-rw-r--r--  1 torchinsky torchinsky  272467 2011-12-09 16:06 SCUlog-20111209-1450.txt
-rw-r--r--  1 torchinsky torchinsky     544 2011-12-09 14:54 BeamPointings09-12-11_14:50:15.log
-rw-r--r--  1 torchinsky torchinsky    2772 2011-12-09 14:51 SourceTrack_J2000_20111209-1451.submitlog
-rw-r--r--  1 torchinsky torchinsky     500 2011-12-09 14:51 GPSBIIF-2_digital_20111209-1454.txt
-rw-r--r--  1 torchinsky torchinsky    1477 2011-12-09 14:51 GPSBIIF-2_RF_20111209-1454.txt
torchinsky@scu-desktop:~/scripts$ python SourceTrack_J2000.py --sat="GPS BIIF-2" --source="PSR B0329+54" --dat
e="2011-12-11 21:34" --caldate="2011-12-11 14:06"
```

Track a source with a python script and a few, optional, command line arguments

Ease of Use

artemis@andante: ~/EMBRACE

```
artemis@andante:~/EMBRACE$ ll -tlhead
total 65G
drwxr-xr-x  2 artemis artemis  12K 2011-12-10 23:31 ./
-rw-r--r--  1 artemis artemis 2.6K 2011-12-10 23:31 lane1_1-B0329.xml
-rw-r--r--  1 artemis artemis 2.6K 2011-12-10 23:31 lane1_2-B0329.xml
drwxr-xr-x 17 artemis artemis 4.0K 2011-12-10 23:29 ../
-rw-r--r--  1 artemis artemis 576K 2011-12-10 18:03 B0329+54_x_20111209_PSR_0329+54.pfd.ps
-rw-r--r--  1 artemis artemis 2.3K 2011-12-10 18:03 B0329+54_x_20111209_PSR_0329+54.pfd.bestprof
-rw-r--r--  1 artemis artemis 1.2M 2011-12-10 18:03 B0329+54_x_20111209_PSR_0329+54.pfd
-rw-r--r--  1 artemis artemis 2.6G 2011-12-09 23:42 B0329+54_x_20111209.dat
-rw-r--r--  1 artemis artemis 2.6G 2011-12-09 23:42 B0329+54_y_20111209.dat
artemis@andante:~/EMBRACE$ TZ=UT at -f startEMBRACEobsB0329 21:35 tomorrow
```

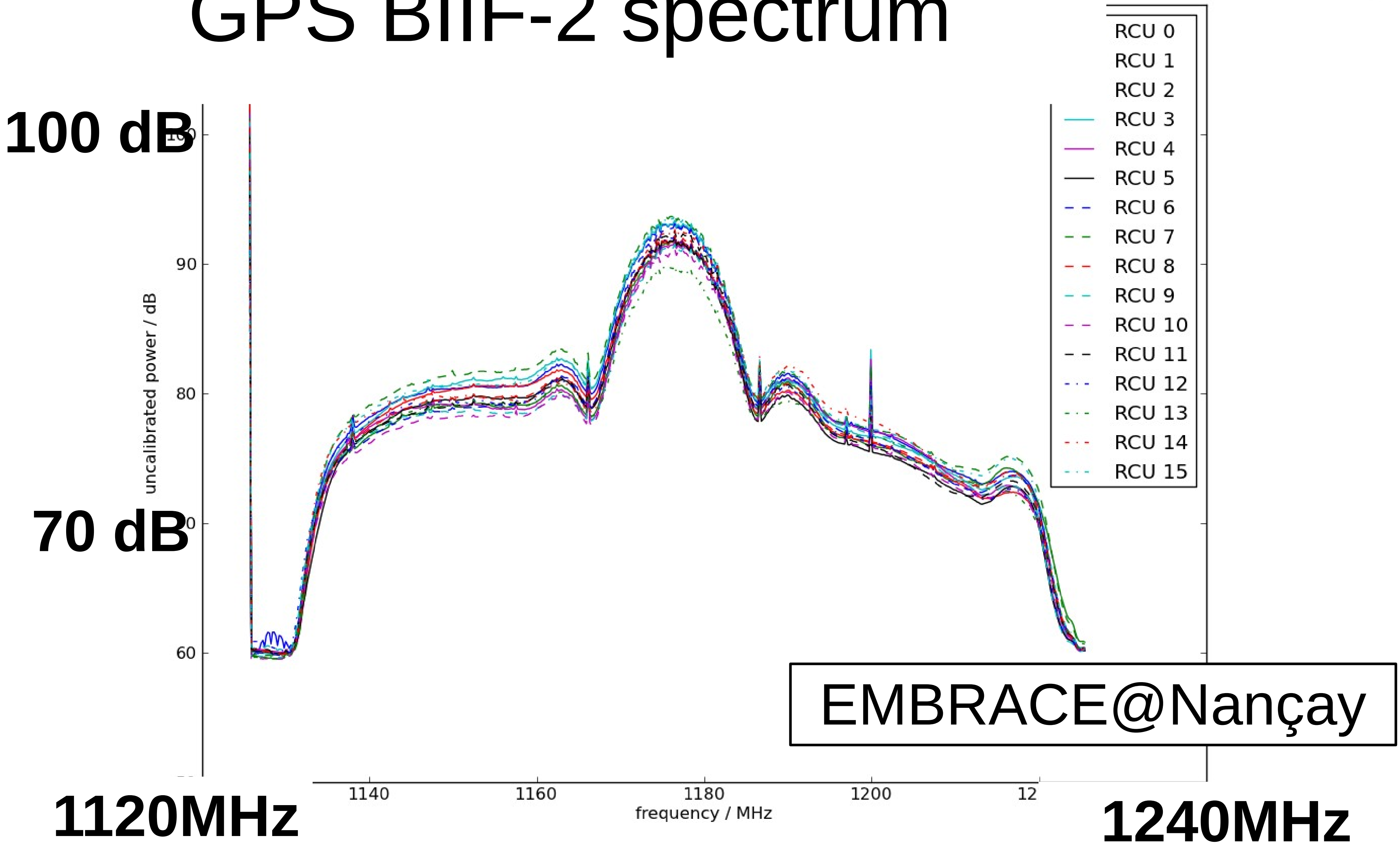
ARTEMIS is also easy to use!

Some results

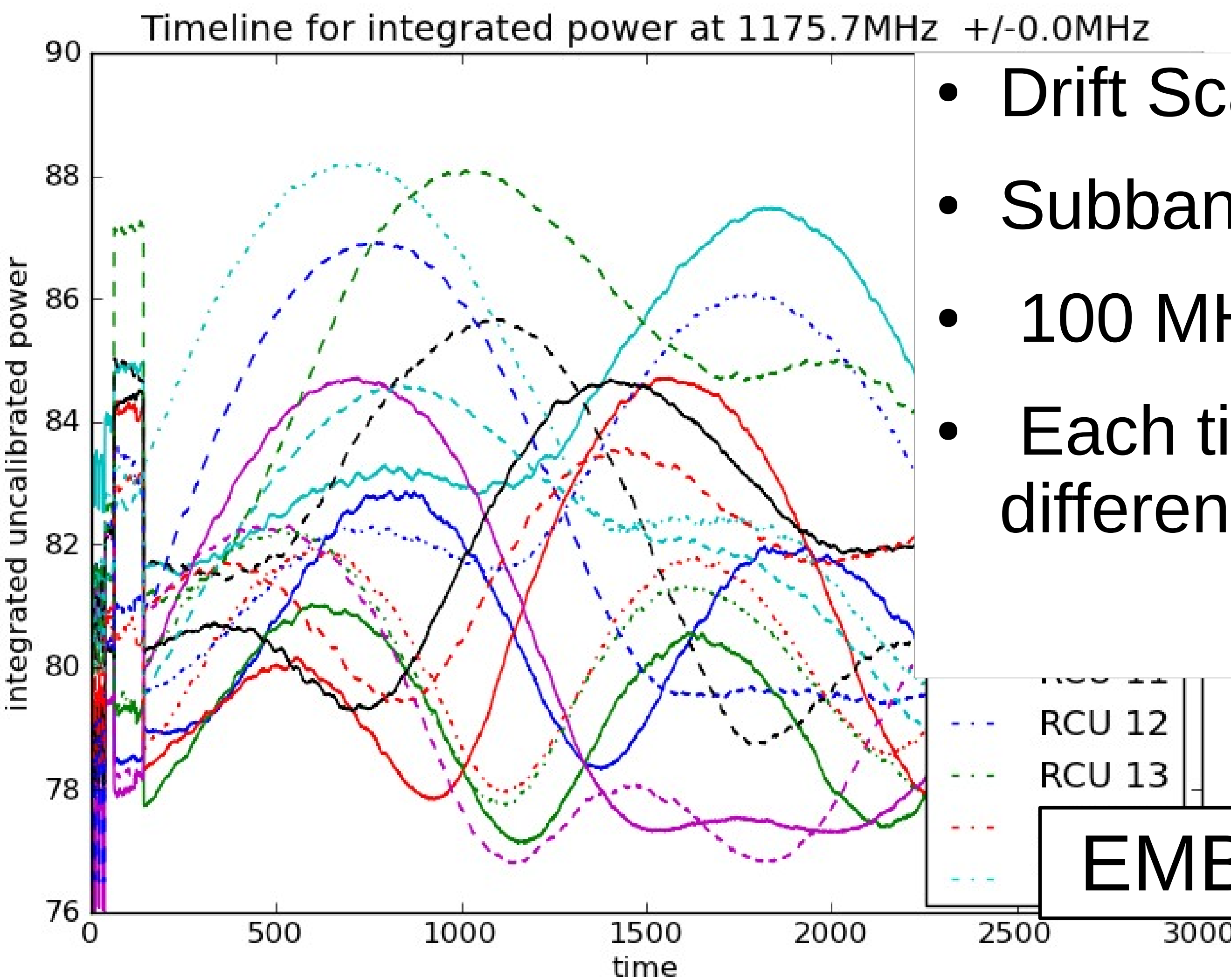
Phase Calibration using GPS

- GPS BIIA-nn:
  - Strong carrier at 1227.6MHz
  - Narrow band
- GPS BIIF-1:
  - Strong carrier at 1175.6 MHz
  - Wider band (~7 MHz)

GPS BIIF-2 spectrum



Without Phase Calibration



- Drift Scan
- Subband statistics
- 100 MHz band per tileset
- Each tileset pointing differently (or not properly)

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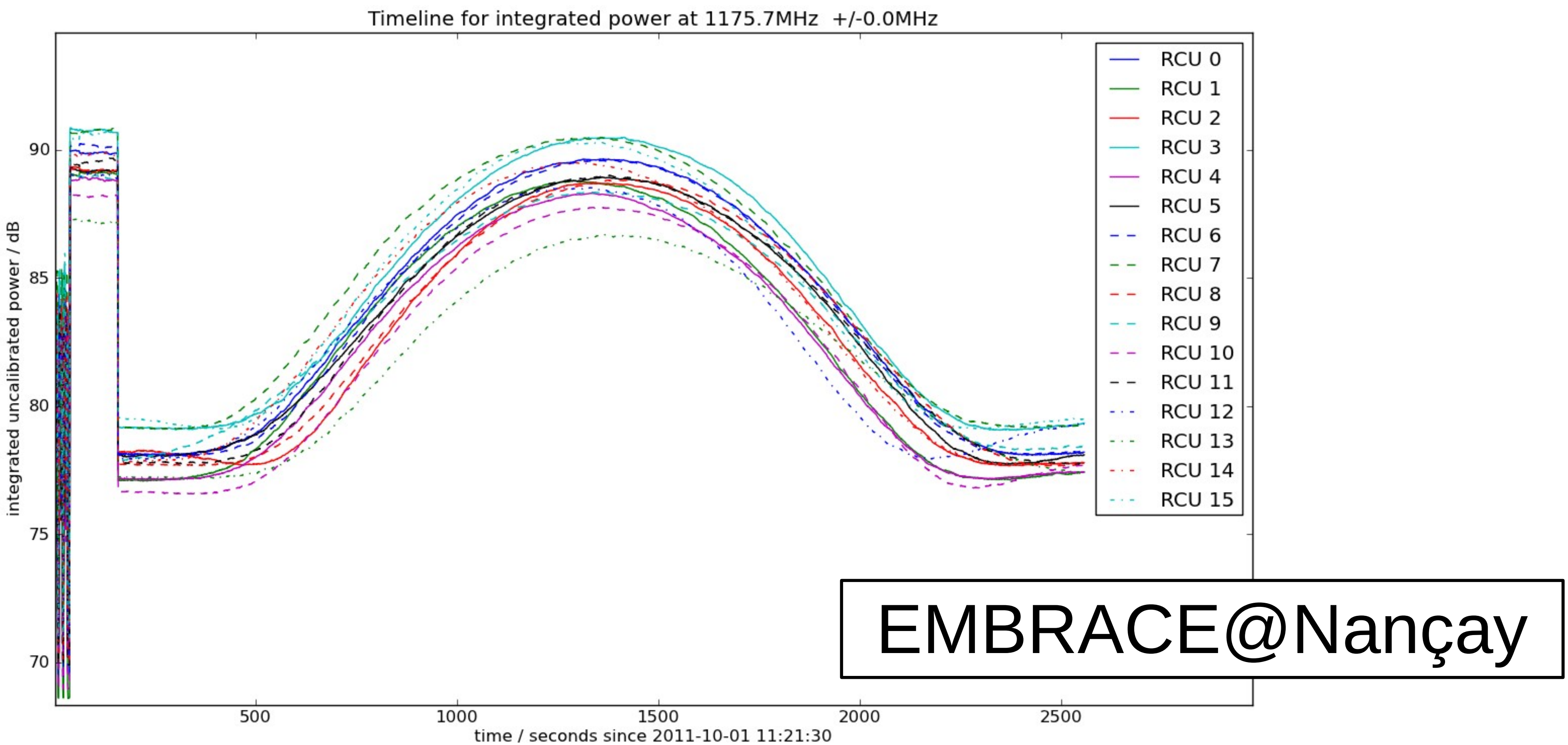
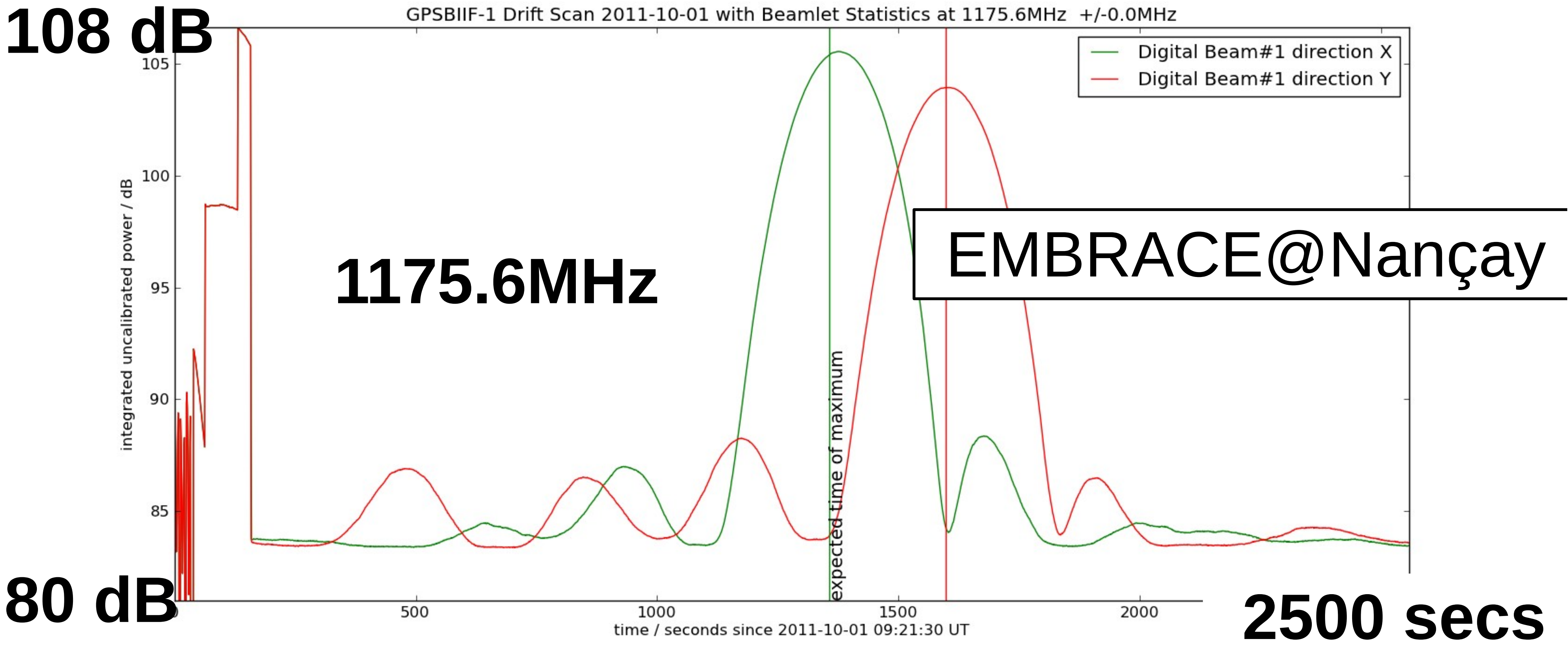
With Phase Calibration



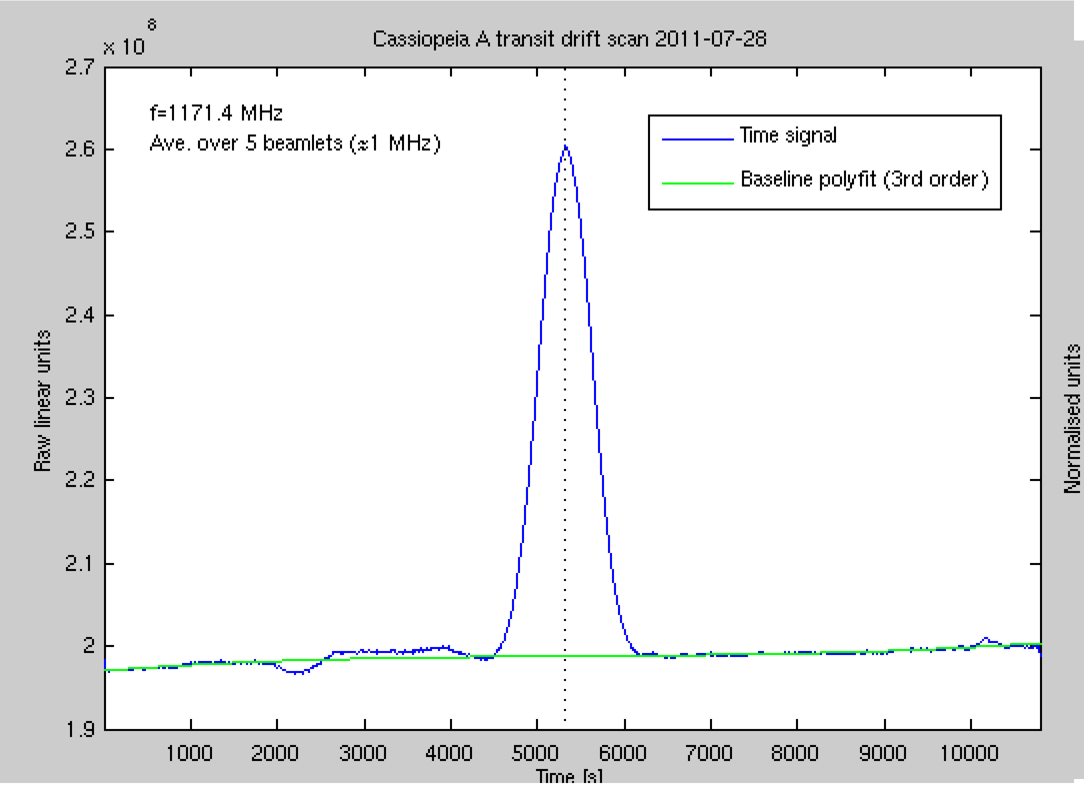
- Tilesets are together

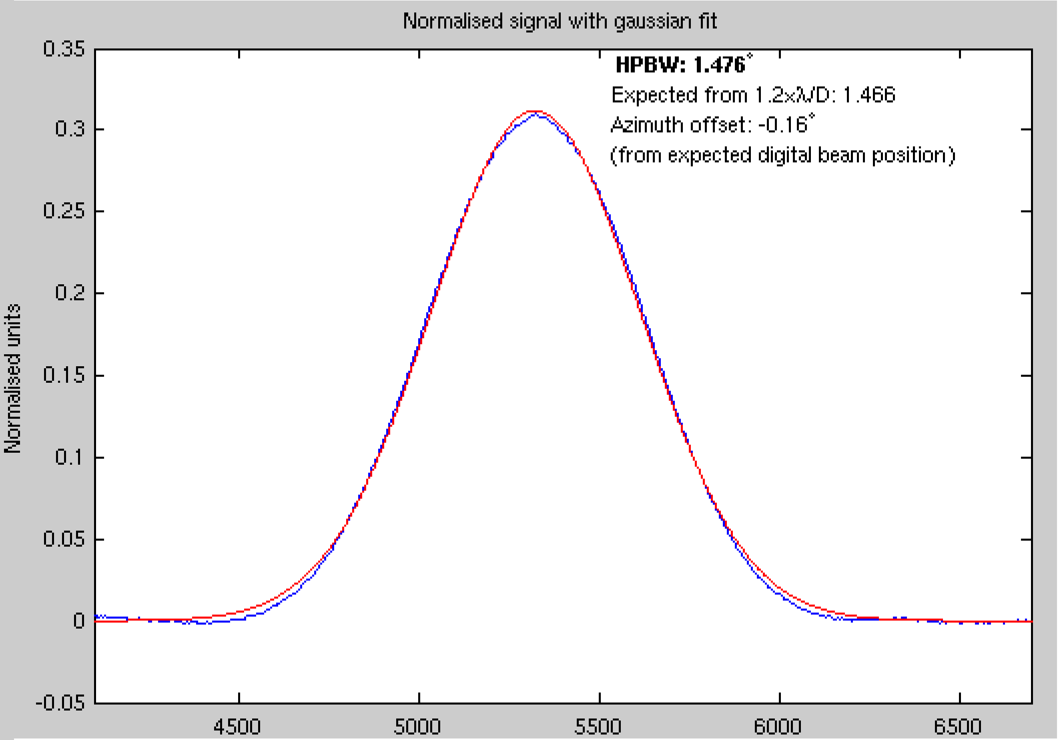
Drift Scan of GPS BIIF-1



- digital beam formed with 2 directions (EMBRACE beamlets)
- Second direction is 4 time minutes ahead in the path of the satellite

Drift Scan of Cas-A





- Gaussian main lobe
- FWHM 1.476º
  - 1.2λ/D = 1.486º

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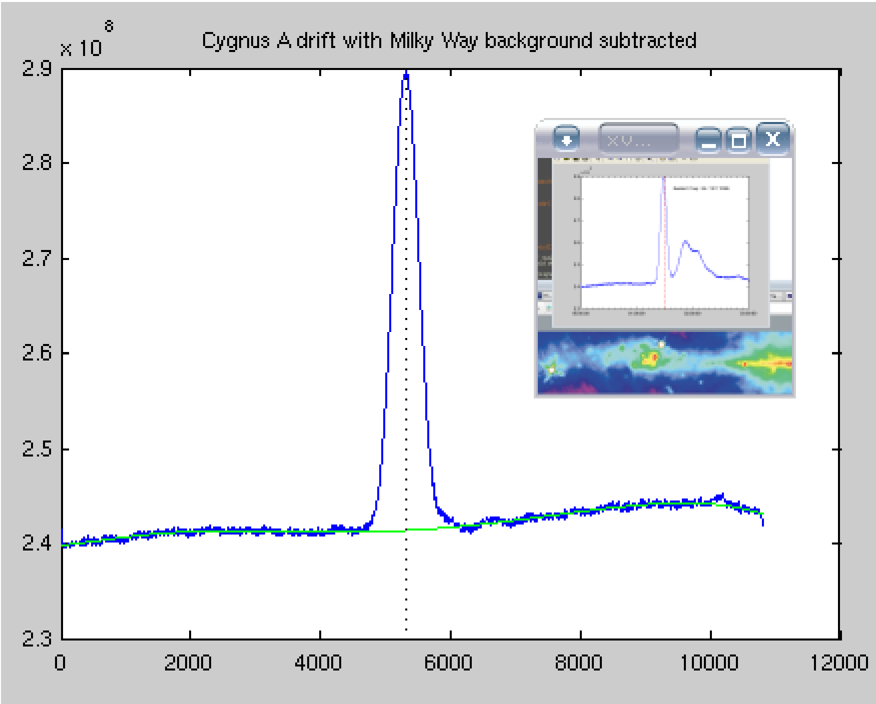
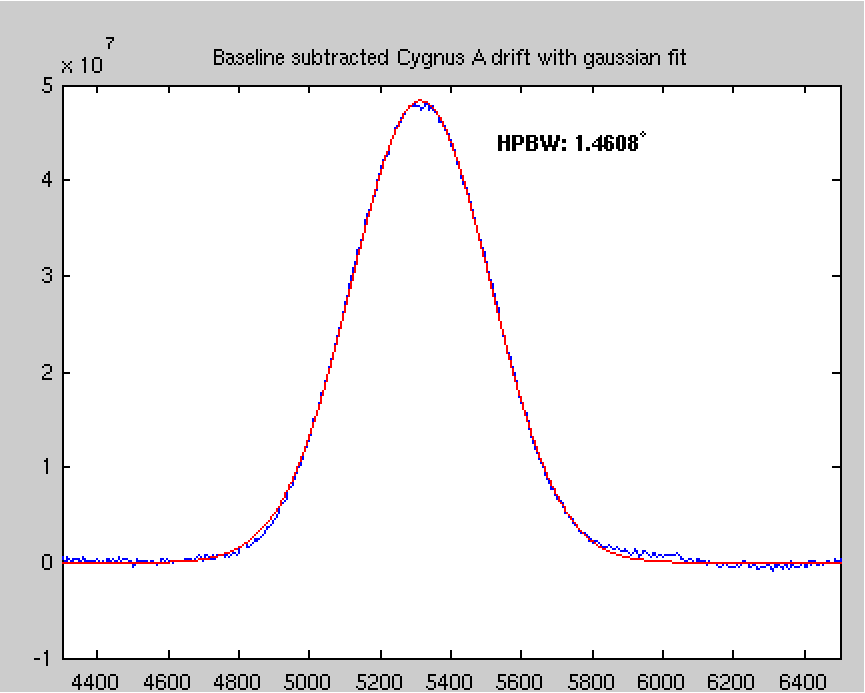
Drift Scan of Cyg-A





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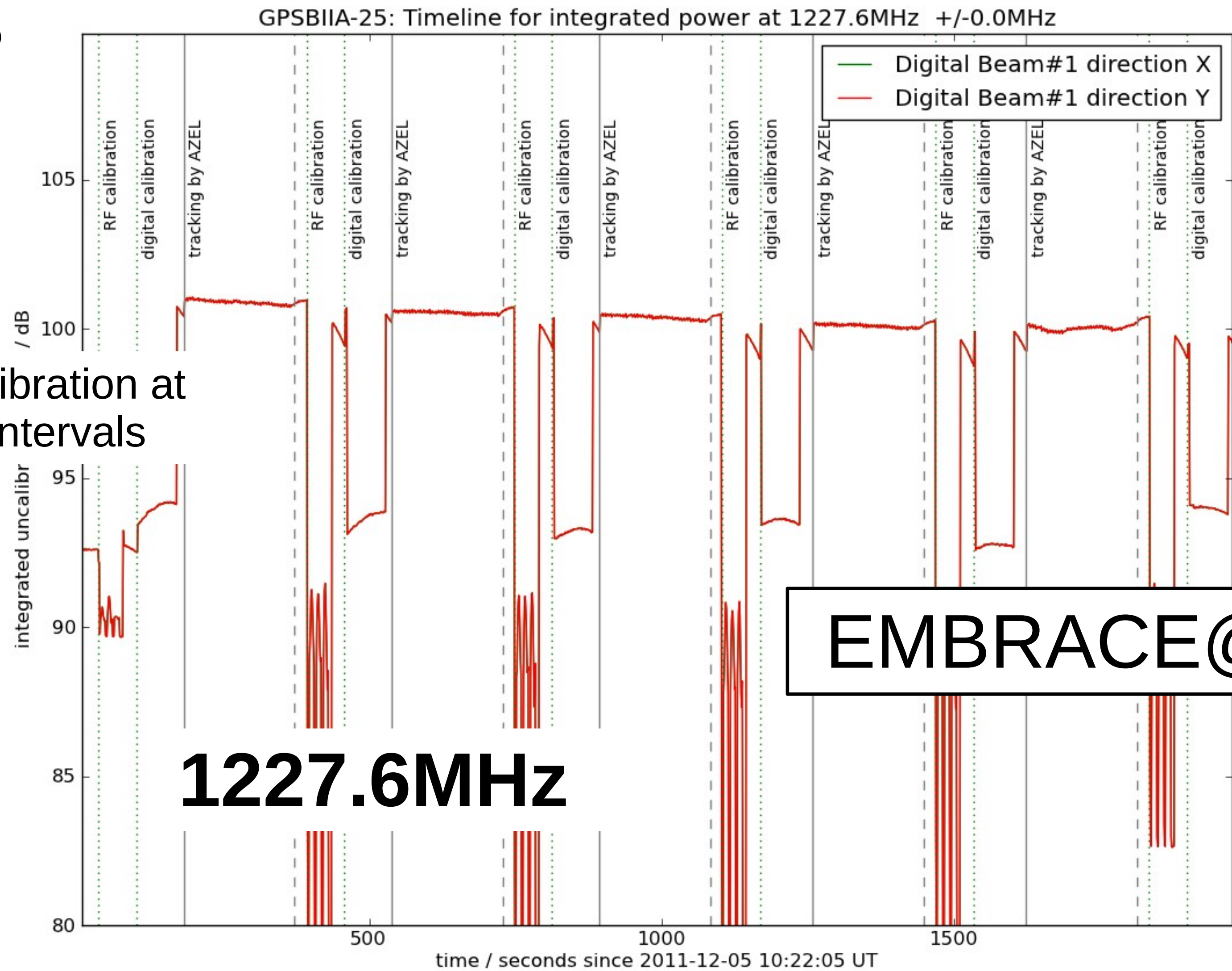
Satellite Tracking with digital beams

110 dB



Phase calibration at
3 minute intervals

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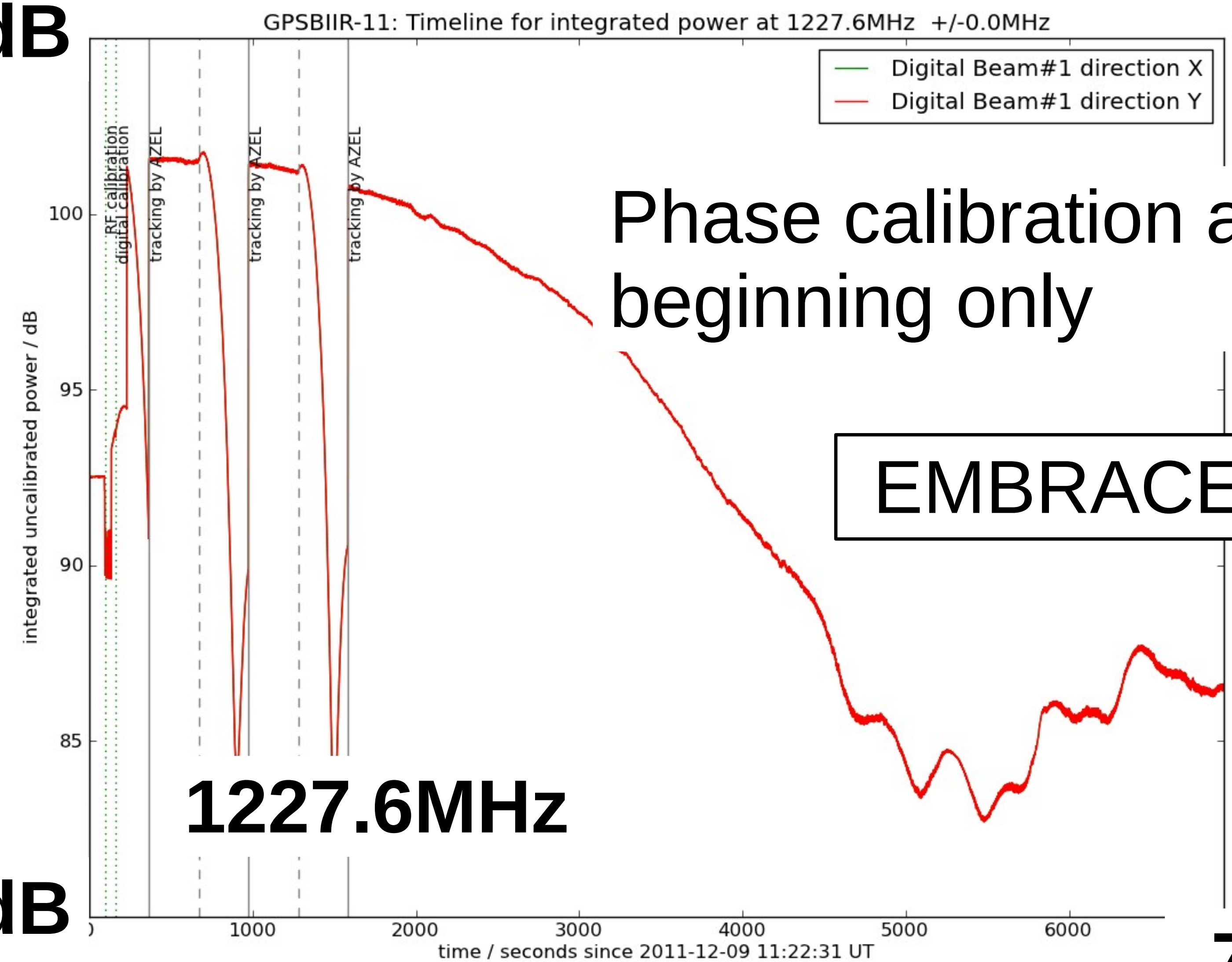
1227.6MHz

80 dB

2000 secs

Satellite Tracking with digital beams

105 dB



Phase calibration at beginning only

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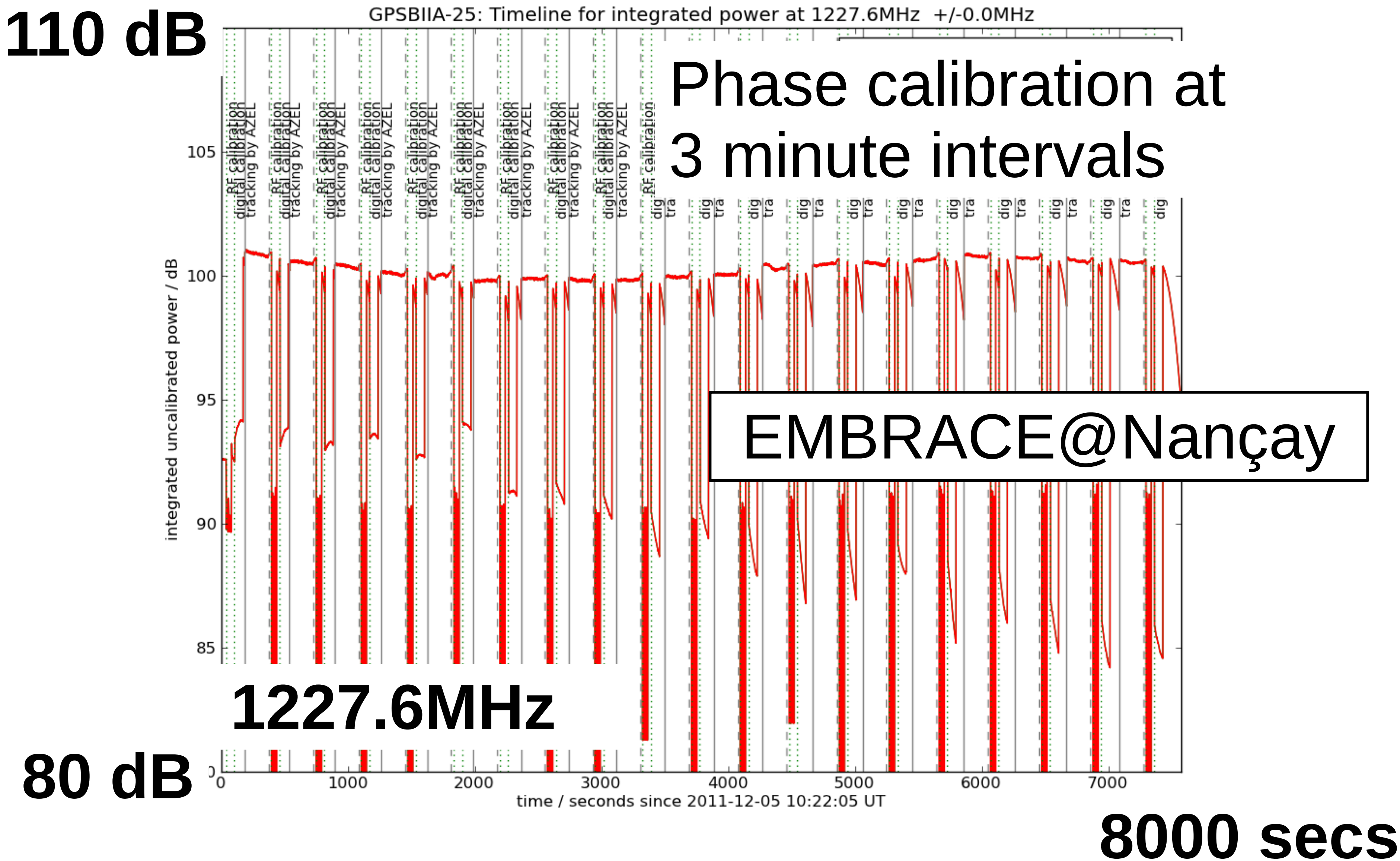
1227.6MHz

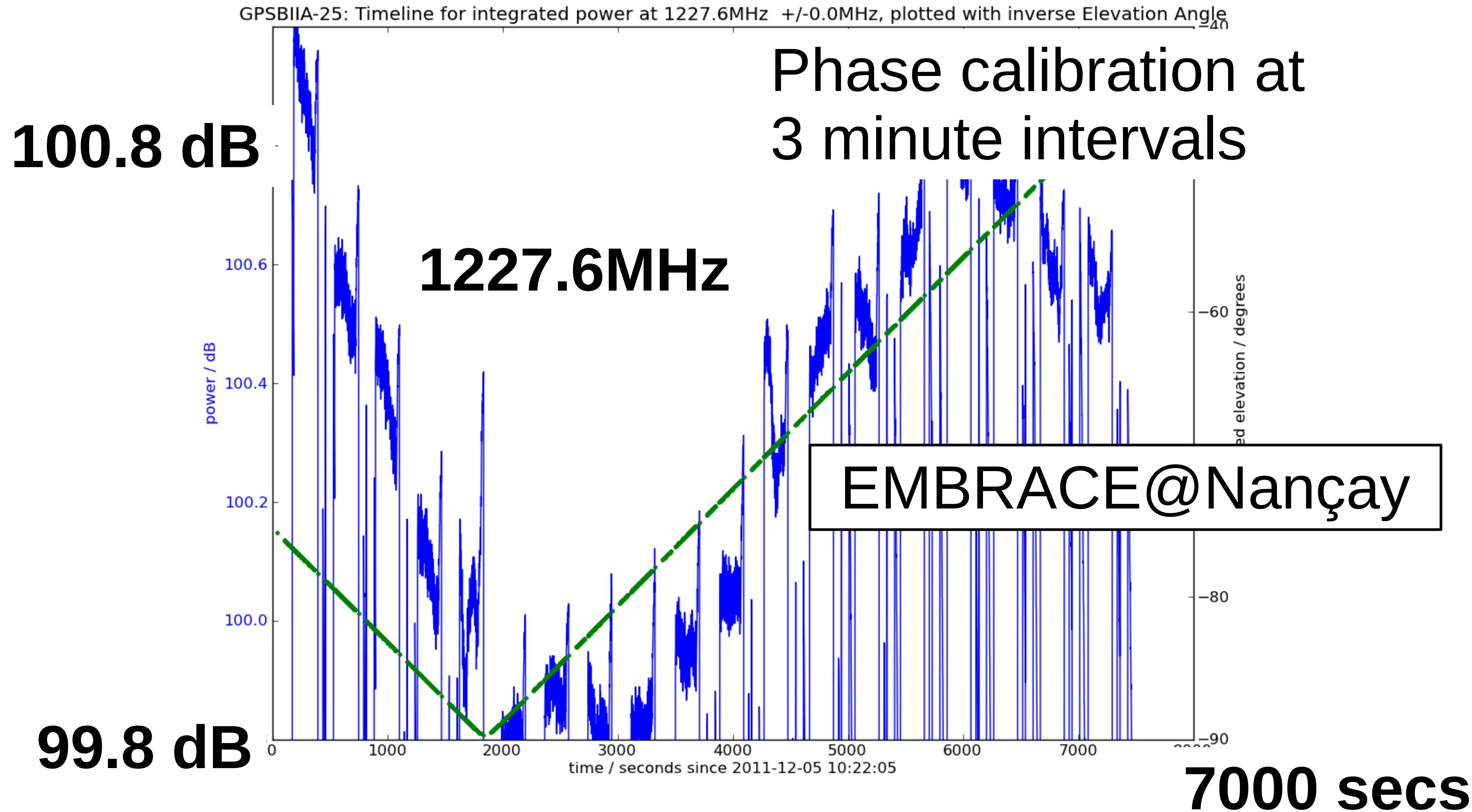
80 dB

7000 secs

Satellite Tracking with digital beams

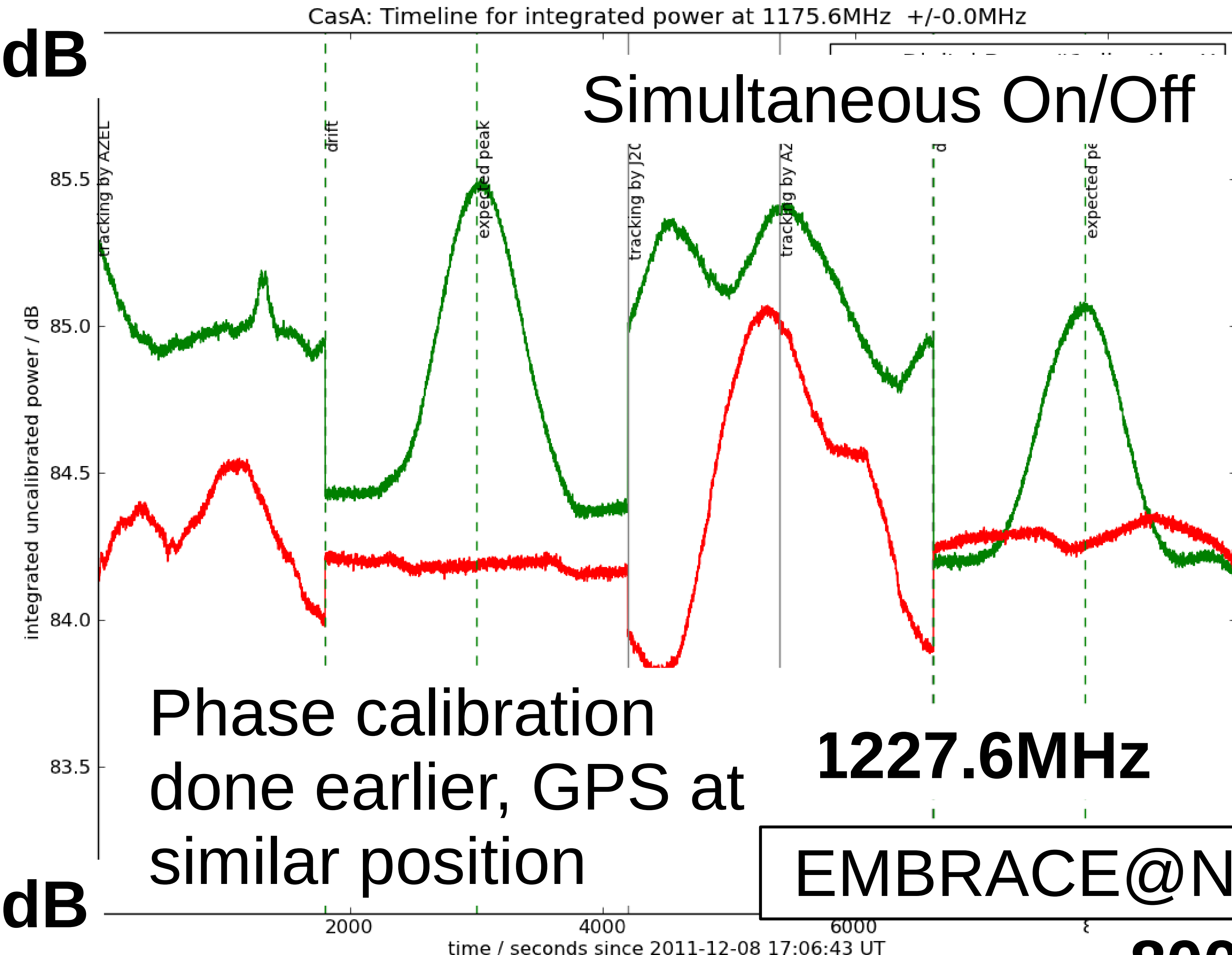


Variation with elevation angle



Cas-A drift and Track

86 dB



Simultaneous On/Off

Phase calibration done earlier, GPS at similar position

1227.6MHz

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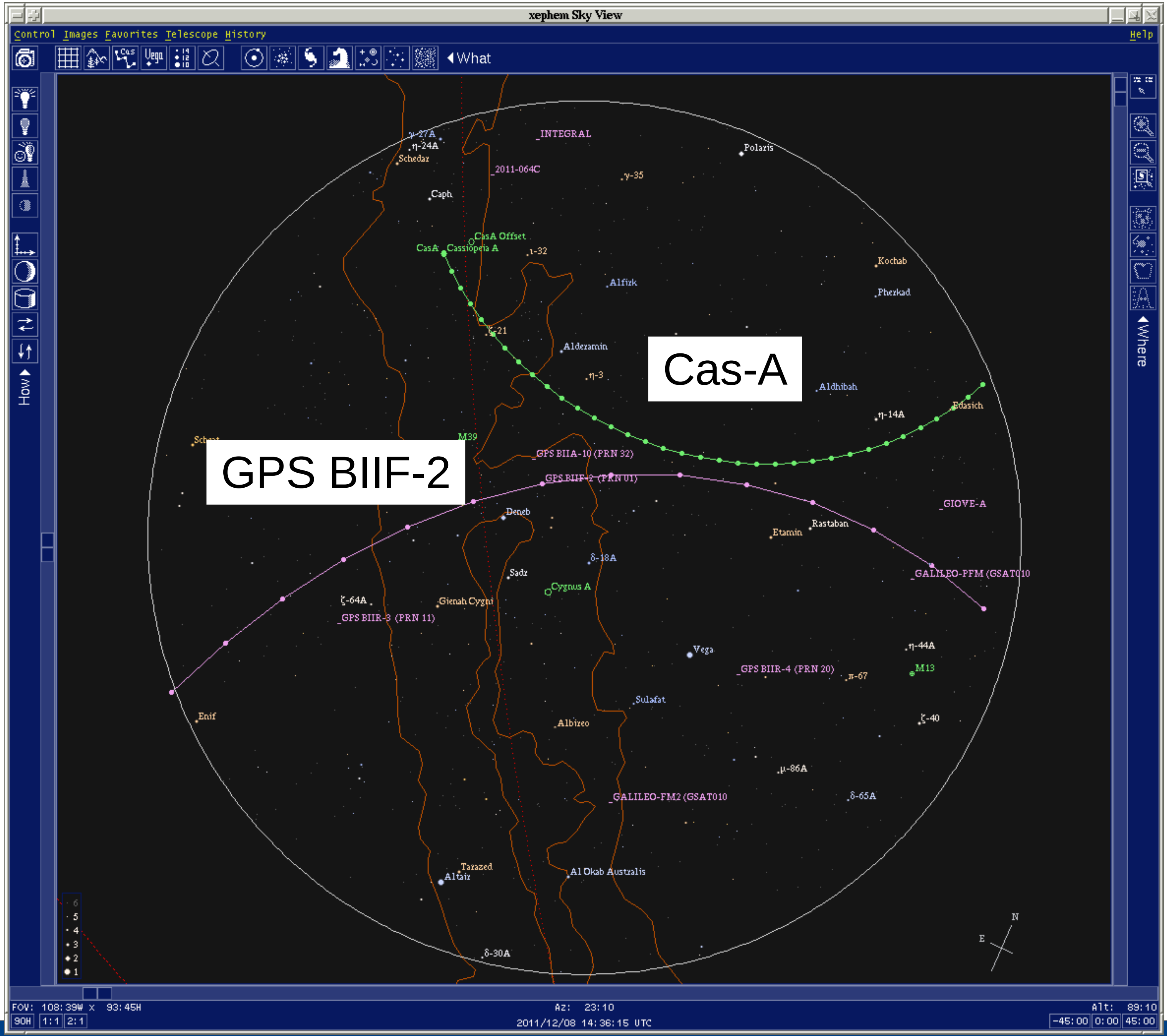
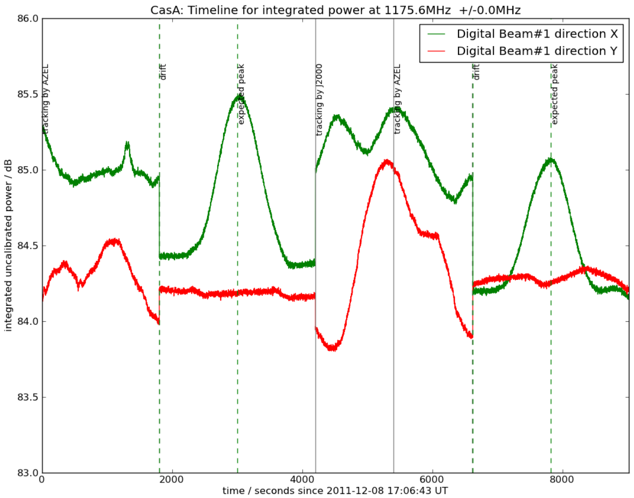
83 dB

8000 secs

Calibration for CasA done earlier



Cas-A drift and Track



- Variation while tracking ~1dB
- Repeatable
- Gain variation? Pointing?
- Can make a pointing model

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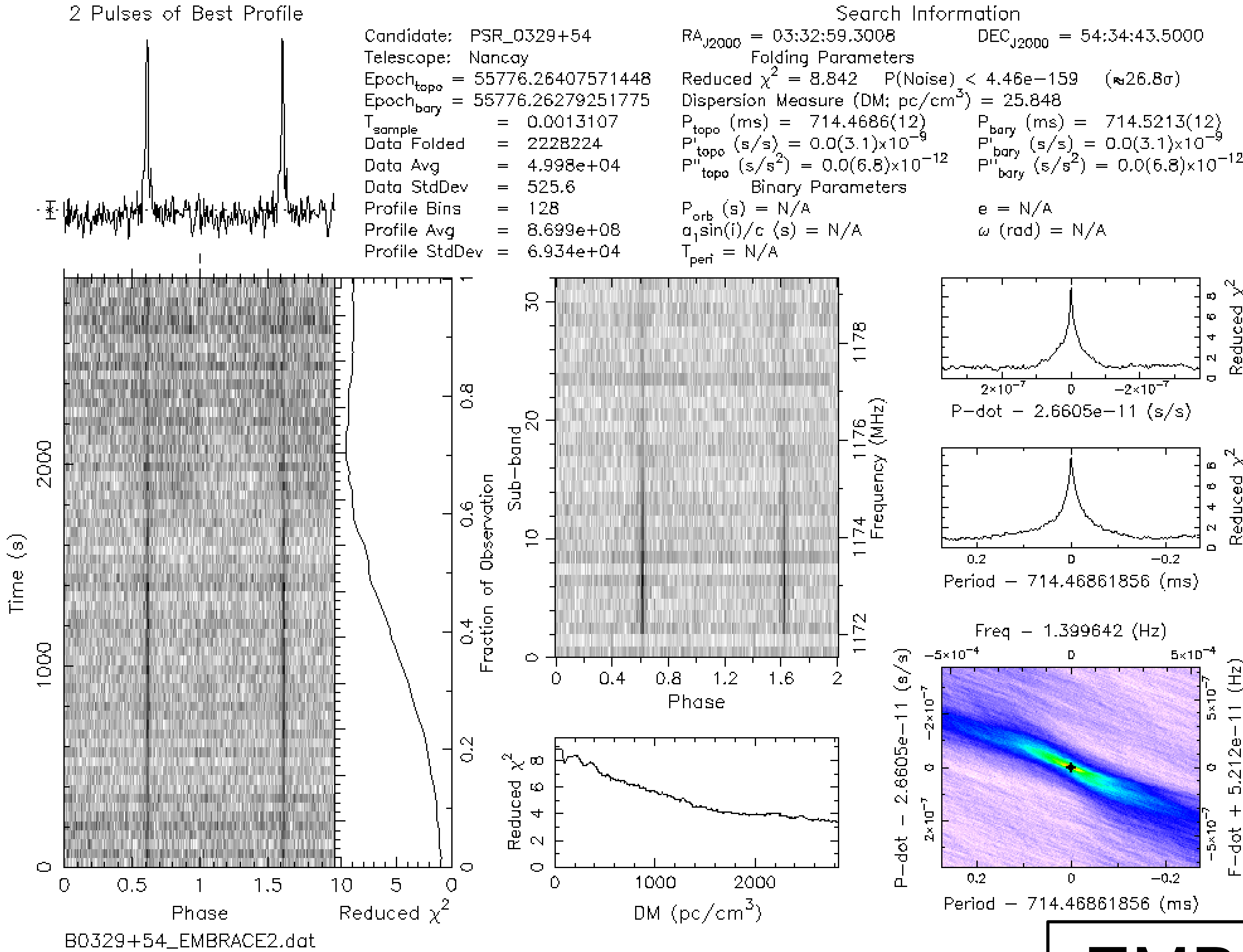
But pointing is sufficiently good for ...

Pulsar B0329+54



Pulsar B0329+54
1175.6MHz
3 August 2011

EMBRACE@Nançay
connected to
ARTEMIS backend
(courtesy U. Oxford)

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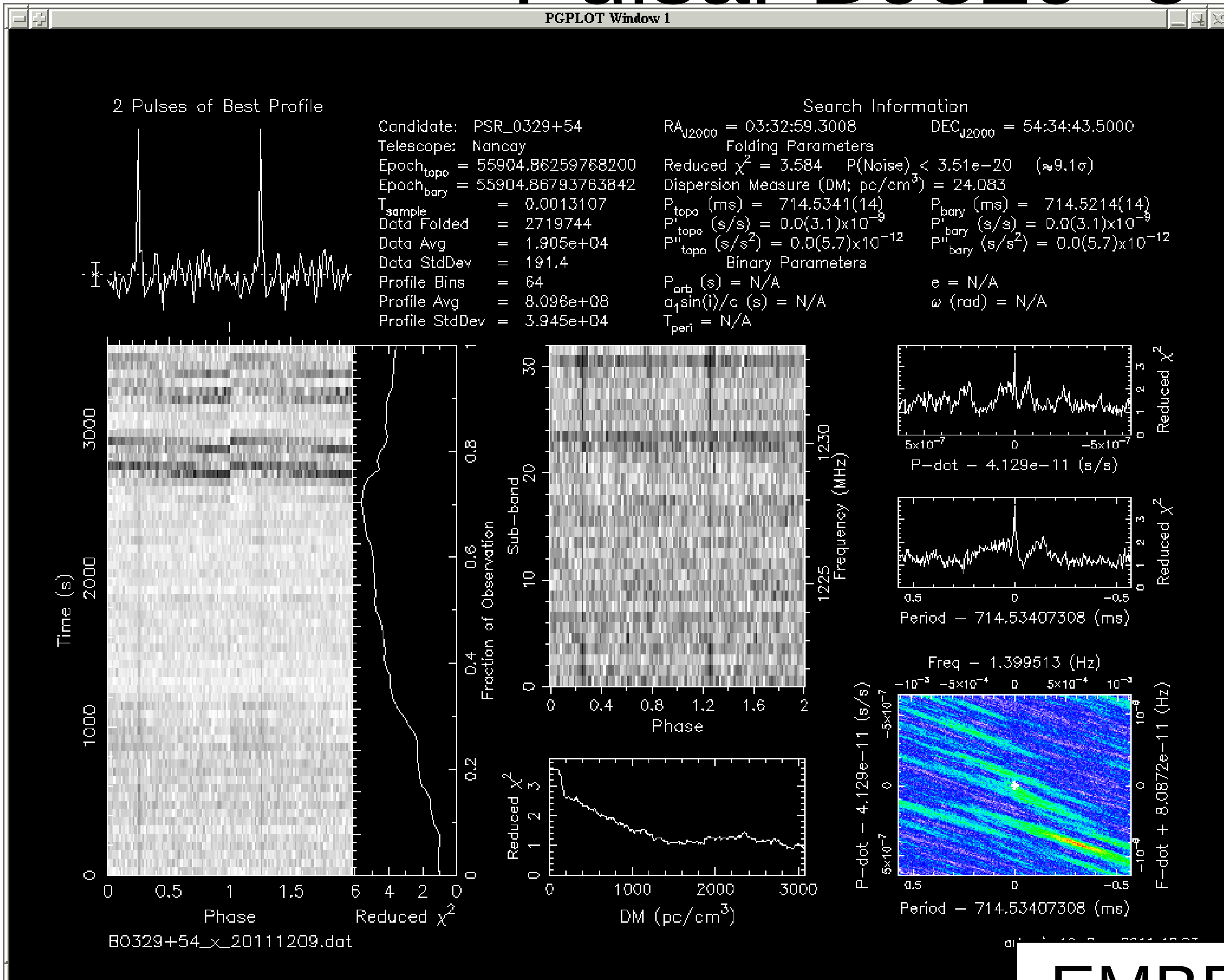
Pulsar B0329+54



Pulsar B0329+54
1227.6MHz
9 December 2011

EMBRACE@Nançay connected to ARTEMIS backend (courtesy U. Oxford)

EMBRACE@Nançay

Scanned Tile Beam pattern measured on Afristar satellite

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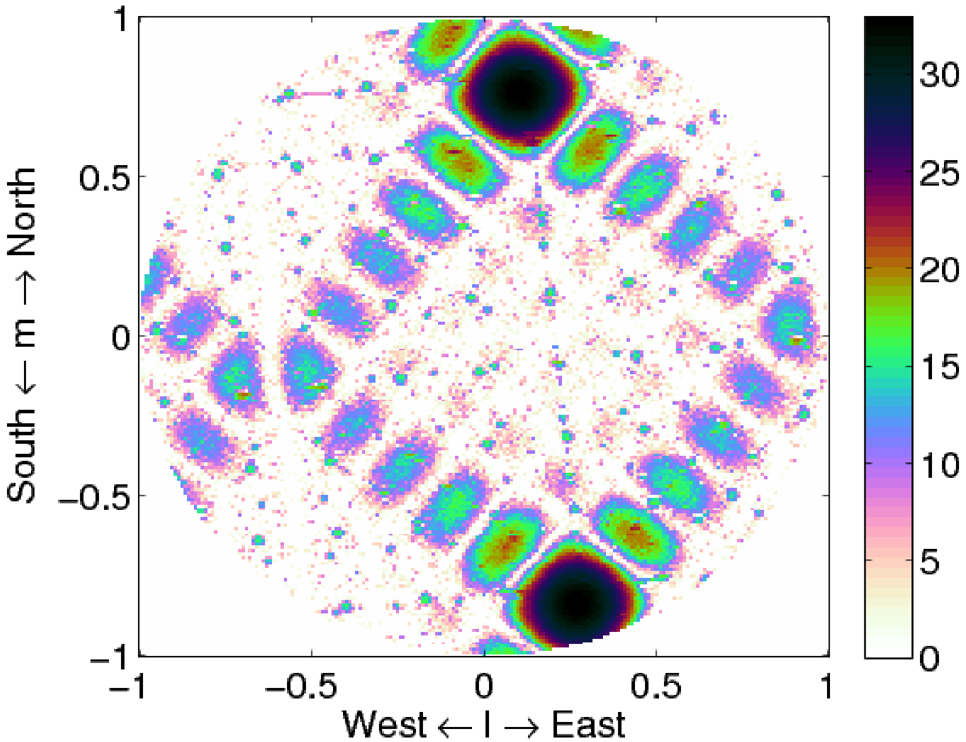
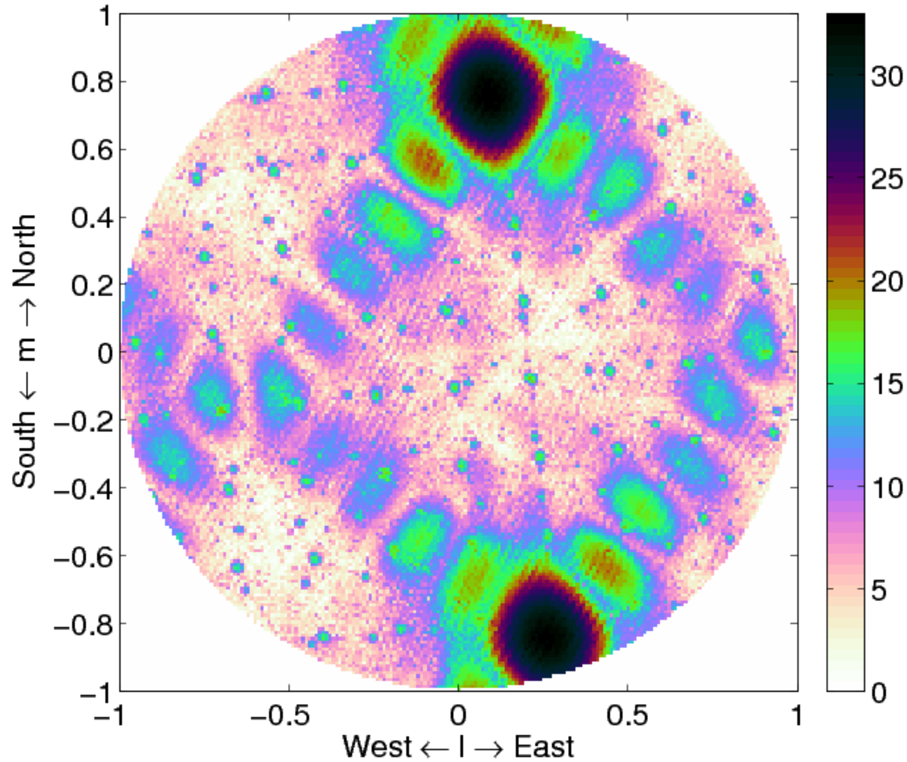


Model



Measurement

Fringes of Cas A

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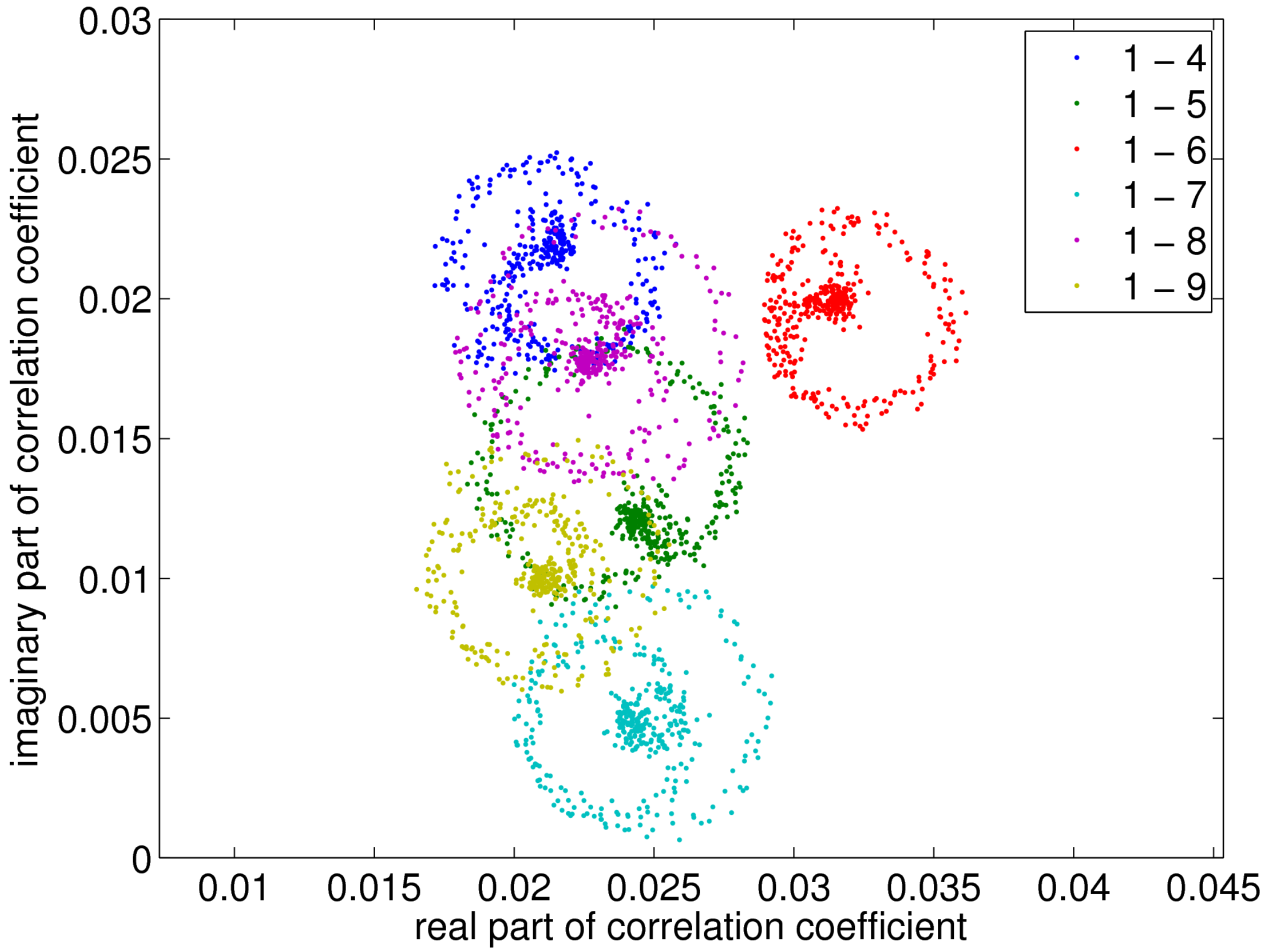
- **Experimental settings**
- 3x3 array
- 1254 MHz
- 30 s integration
- 195 kHz bandwidth

- **Initial conclusions**
- Confirms A/T
- Correlation offsets



Measuring Pulsars (1)

The Challenge:

Current nr. of tiles is insufficient to detect mJy pulsars on the fly. They are hidden in the system noise. Therefore we have to increase sensitivity by increasing the BT product.

- And some requirements:
  - Stable phase coherent system
  - Tracking software for analog and digital beam
  - Calibration of analog and digital beam
  - Real-time correlation of large bandwidths
  - Real-time Storage of processed data
  - Real-time alignment of output data (slip detection)
  - Post processing software

Conclusion:
Every part of the system must function to detect pulsars!

Measuring Pulsars (2)

Some figures:

- Measuring mode: Real-time dump to file
- Correlation mode: Auto correlation of all tiles
- Station Output Bandwidth: 12 MHz (62 sub bands)
- Output data rate: 776 Mb/s
- Measurement Time: 13 hours
- Integration time: 0.3 ms
- Number of tiles: 25 (4x4 and 3x3)

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Measuring Pulsars (2)

Some figures:

• Measuring mode:	Real-time dump to file
• Correlation mode:	Auto correlation of all tiles
• Station Output Bandwidth:	12 MHz (62 sub bands)
• Output data rate:	776 Mb/s
• Measurement Time:	13 hours
• Integration time:	0.3 ms
• Number of tiles:	25 (4x4 and 3x3)

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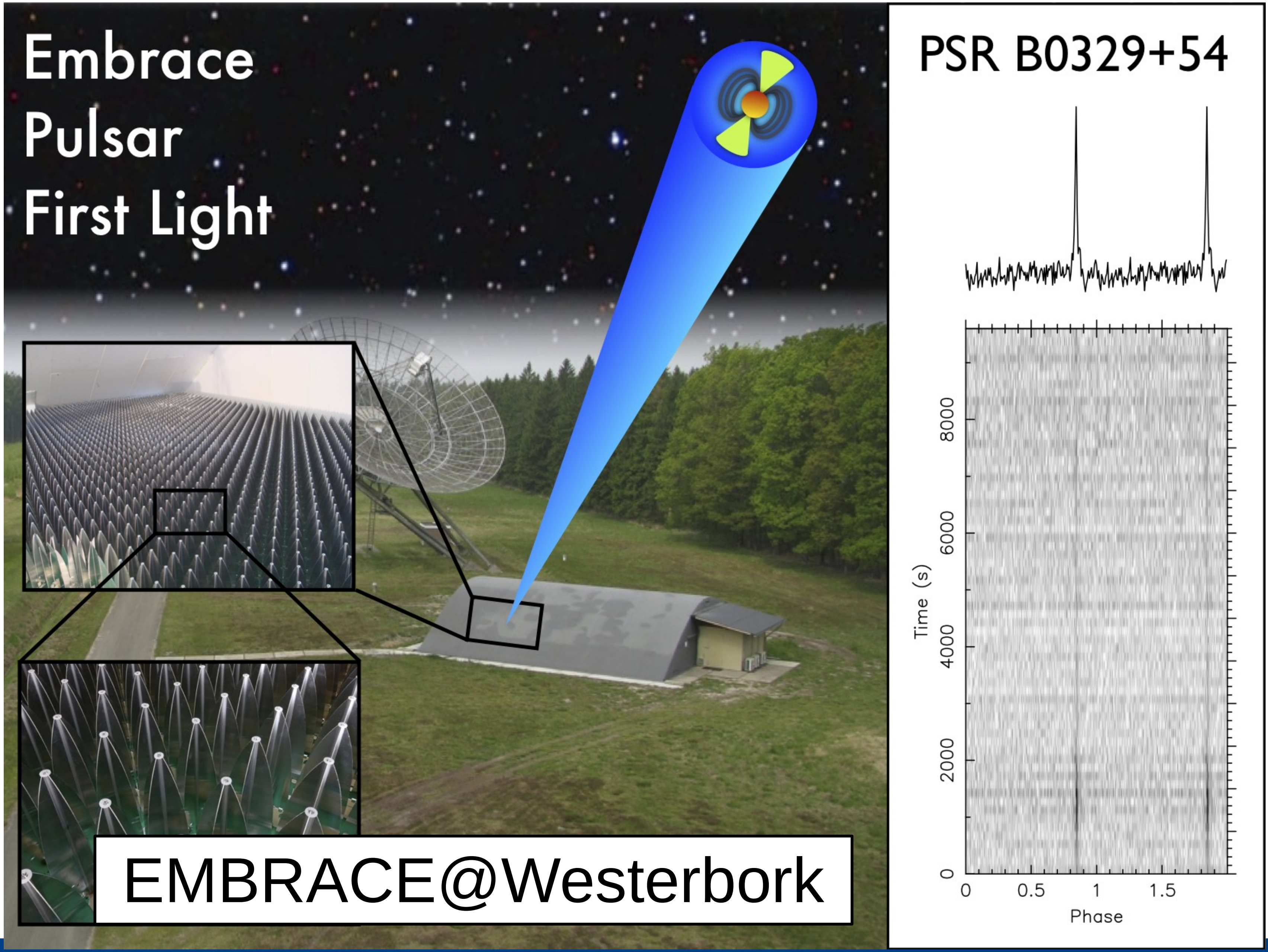
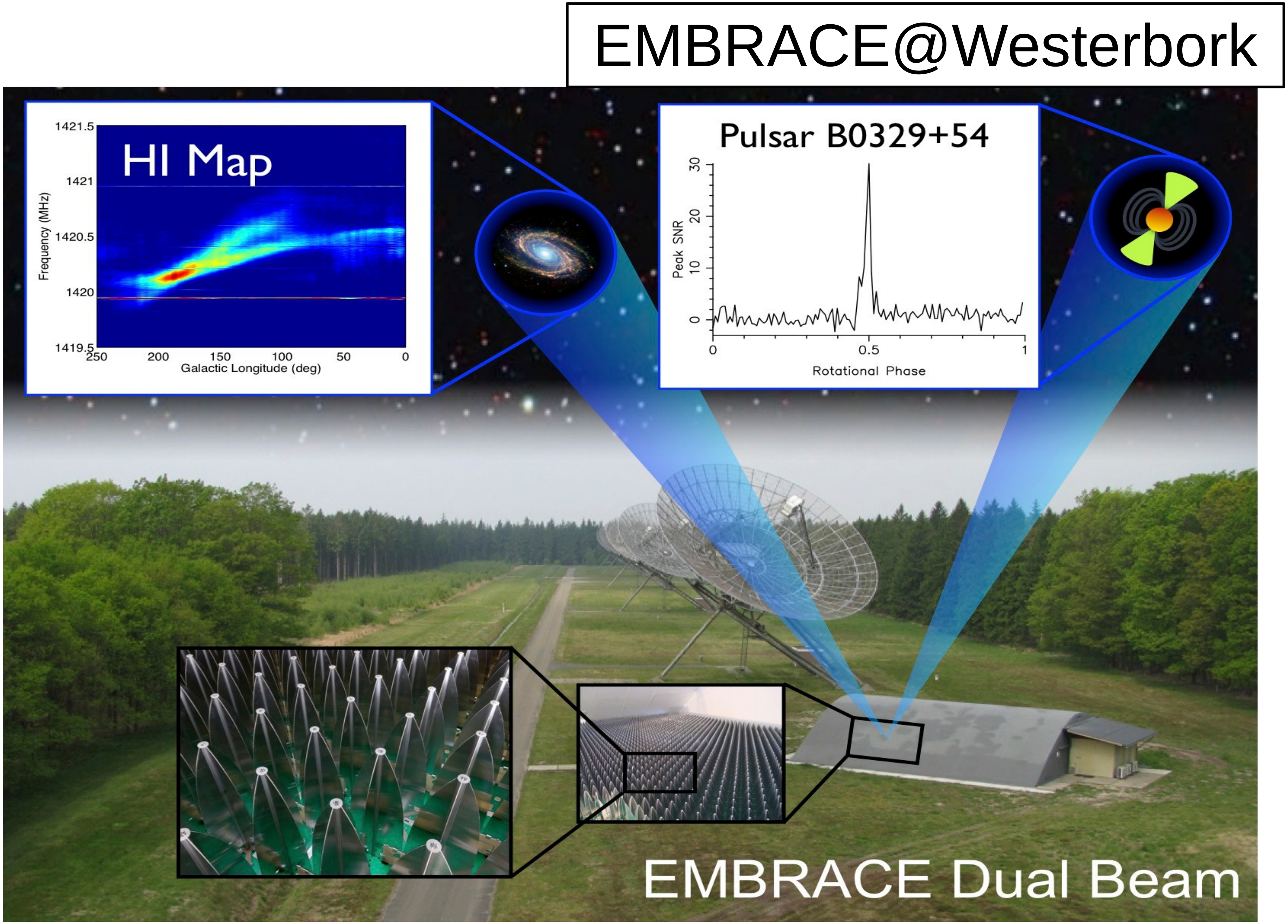
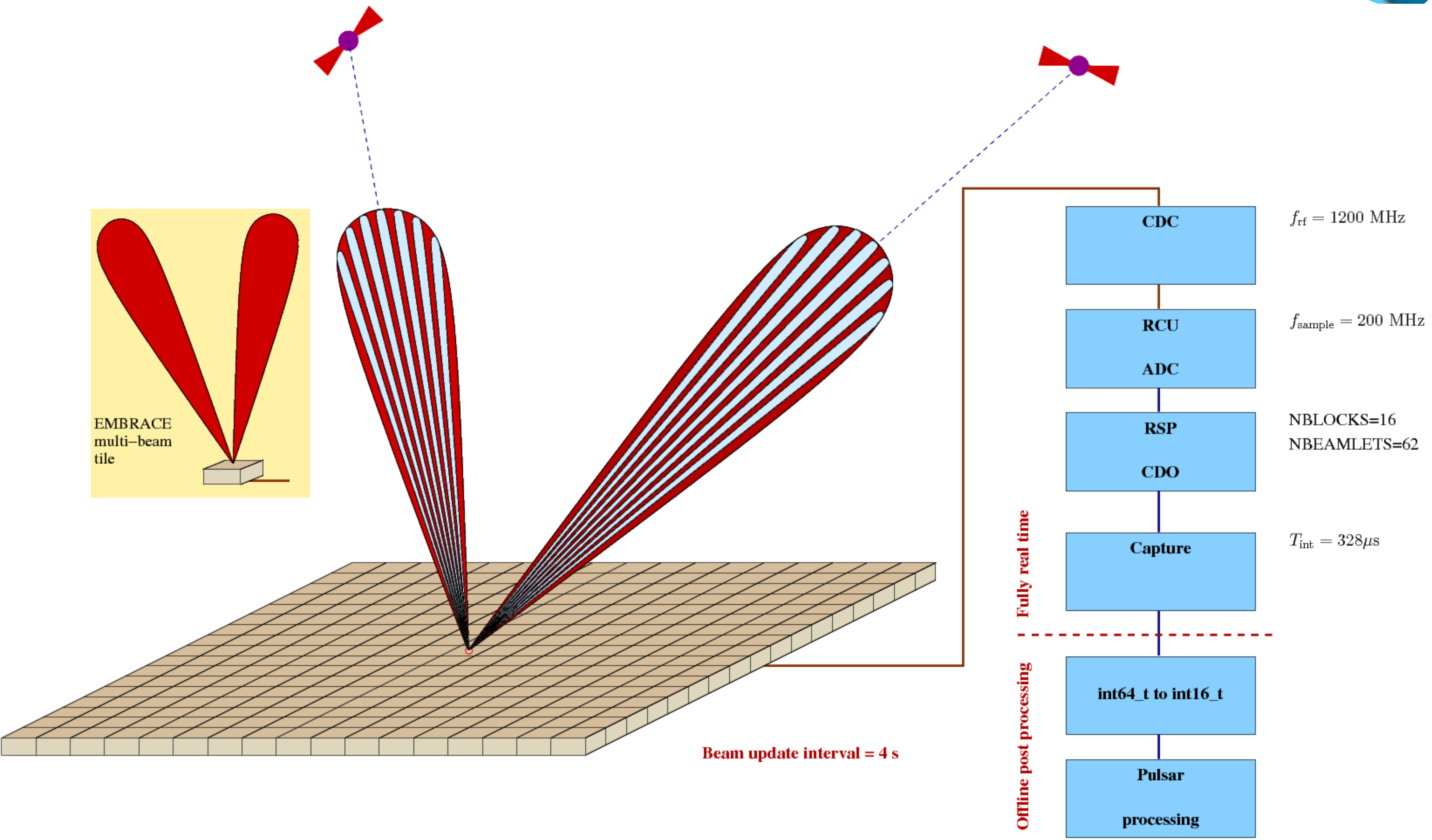
EMBRACE first pulsar result



EMBRACE dual beam result



Pulsar detection Setup details



Measuring HI with EMBRACE (1)

Some Issues:

The subbands of the LOFAR back end are too large to do H1.

- Make smaller sub bands by implementing real-time FFT in CAPTURE®

Output data rate of 62 subbands make huge data files.

- Correlate and Integrate real time all 124 E-beam lets in CAPTURE®
- Return results to the measurement CAPTURE® class in MATLAB/OCTAVE

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Measuring HI

Some figures:

• Measuring mode:	FFT network mode
• Correlation mode:	Autocorrelation of 4x4 tiles
• Station Output Bandwidth:	12 MHz (62 subbands)
• Output data rate:	776 Mb/s
• Resolution bandwidth:	4 kHz
• Integration time:	14 s
• Postprocessing:	gain compensation, removal of polyphase filter

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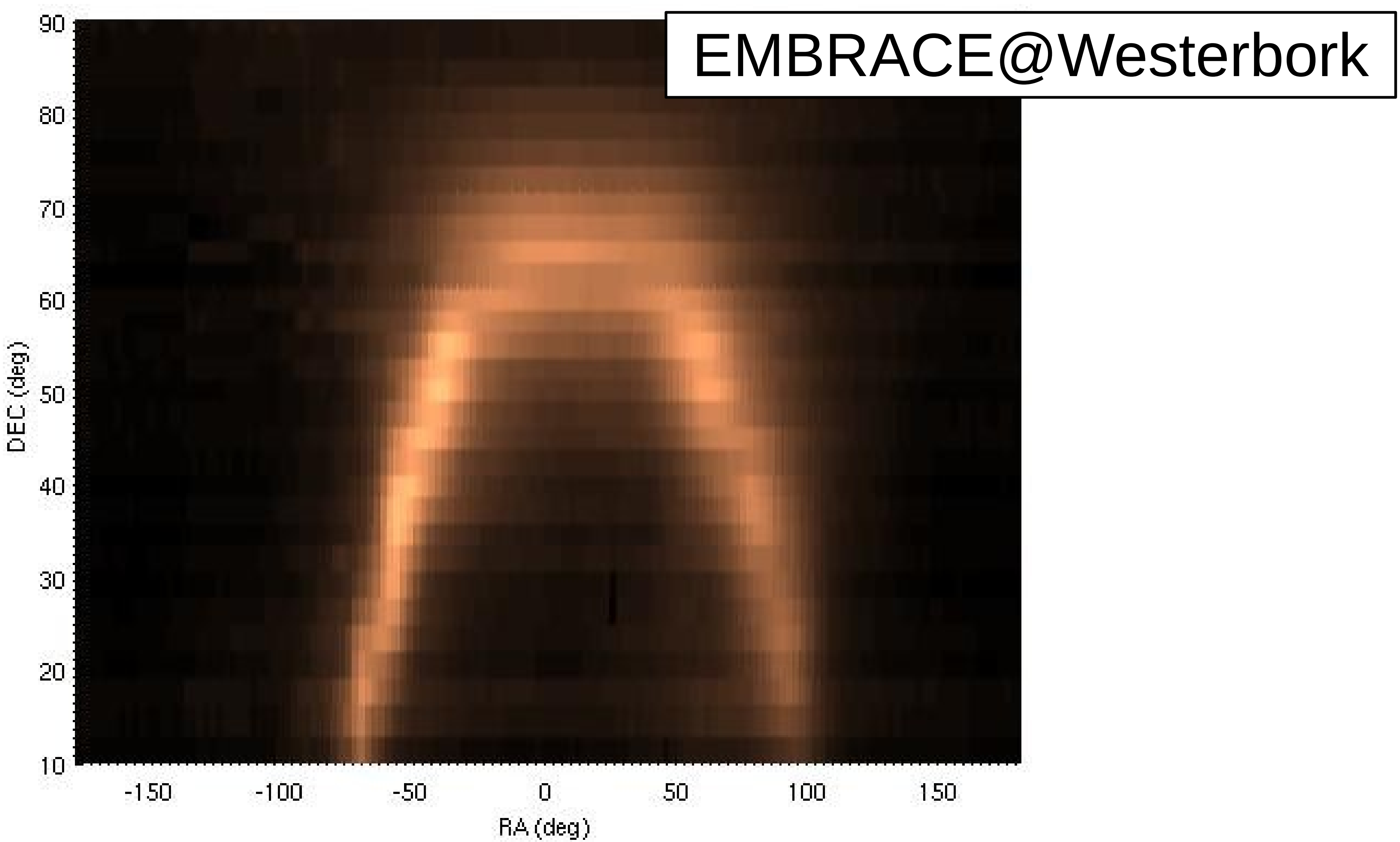
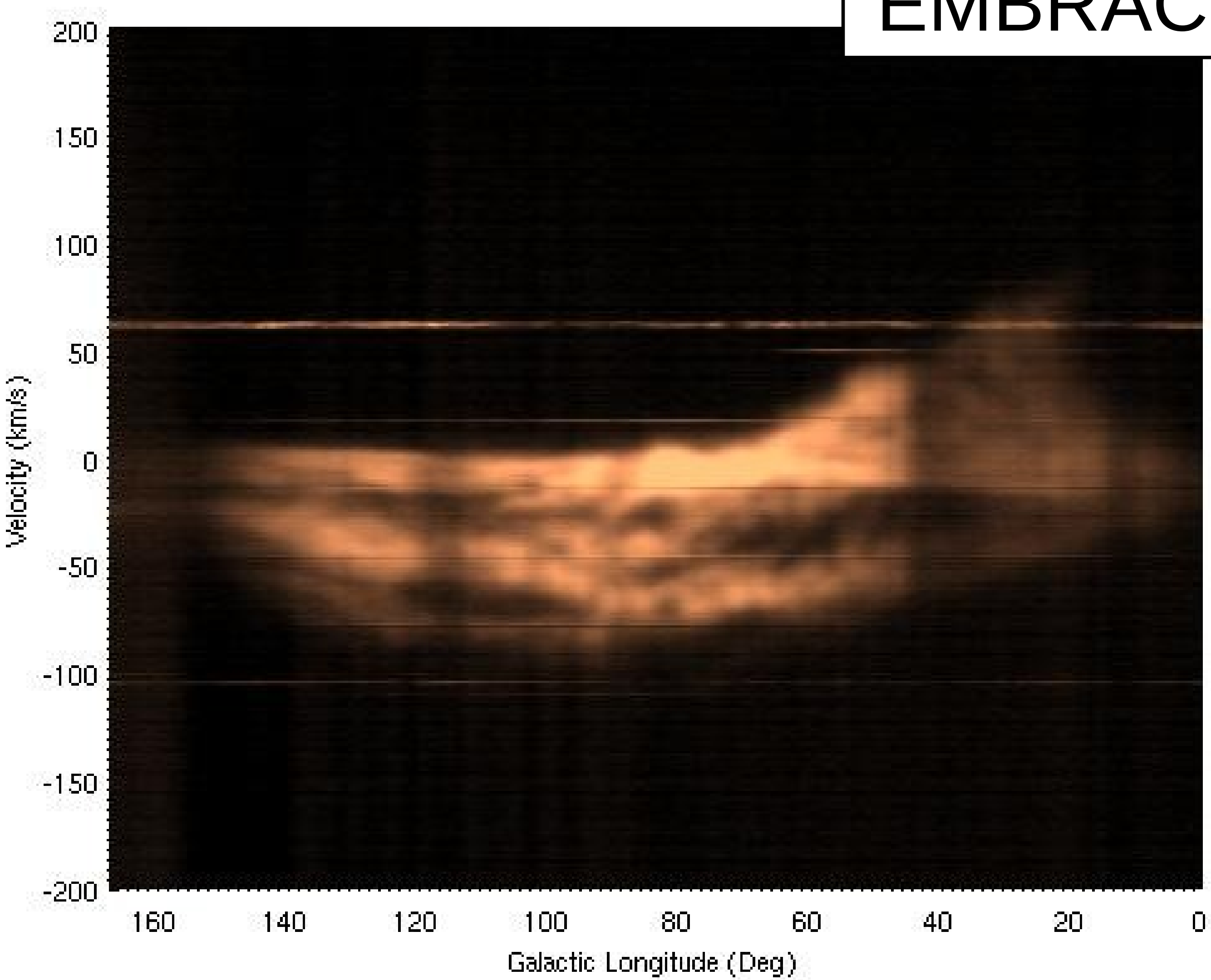
HI MAP



14 sec integration time, 1 day

HI LINE

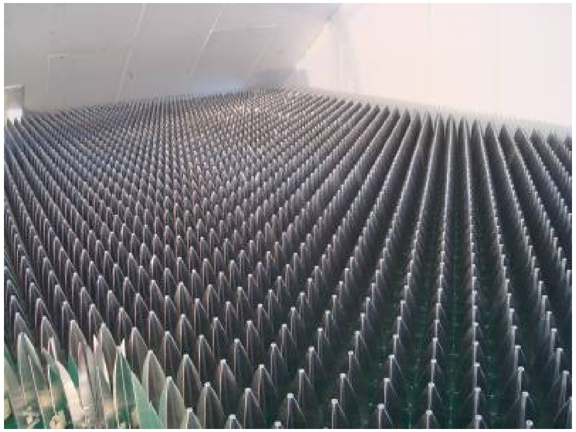
EMBRACE@Westerbork



10 sec integration time, 30 minutes total

Future plans (partial list)

- Phase calibration database
- Pointing model
- Characterize system
  - understand the tracking wobble
  - Tsys, effective area, etc
- Multiple digital beams in multiple RF beams
- M42 – high spectral resolution HI observation
- M33 – mapping extragalactic HI
- Regular observations (semi weekly): pulsars, CasA, CygA, TauA
  - demonstrate EMBRACE as a facility instrument (reliability)
- Long term observations of Cas-A
  - Measure 1% / year flux change
  - Demonstrate long term stability of EMBRACE and flux calibration
- Science Data Model – EMBRACE as a testbed
  - Use MeqTree for EMBRACE calibration
- Fringes between EMBRACE@Nançay and EMBRACE@Westerbork
- Validate dense aperture array for radio astronomy



EMBRACE

Science Data Model v2

- Collaboration with Obs Paris - LERMA (F. Viallefond)
  - Evolution of the ALMA SDM
  - SDMv1 currently used on ALMA and EVLA
  - Mathematics of “categories”
  - Naturally object oriented
  - XML and Schema
  - See CALIM2011 and ADASS2011 for more details:

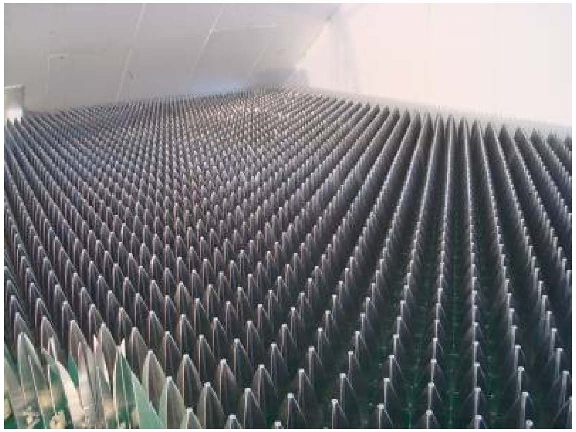
http://www2.skatelescope.org/indico/conferenceOtherViews.py?view=standard&confId=171

Science Data Model v2 - Goals

- Generalised model for any radio telescope
  - Single dish
  - Aperture synthesis
    - (eg. ALMA, EVLA, PdB, ...)
  - VLBI
  - Aperture plane phased arrays (eg. EMBRACE)
  - Focal Plane Arrays
    - Feed clusters (eg. Parkes, Arecibo, Effelsberg, ...)
    - Phased array feeds (eg. ASKAP, APERTIF)

SDMv2 Main Features

- Can be easily pruned for a specific instrument
- Can be applied to any instrument of any complexity or simplicity
  - eg. future radio telescopes: ASKAP, APERTIF, EMBRACE, ALMA, EVLA, VLBI, etc
- eg. for SKA: It will be composed of multiple technologies, but all can produce data in SDMv2



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