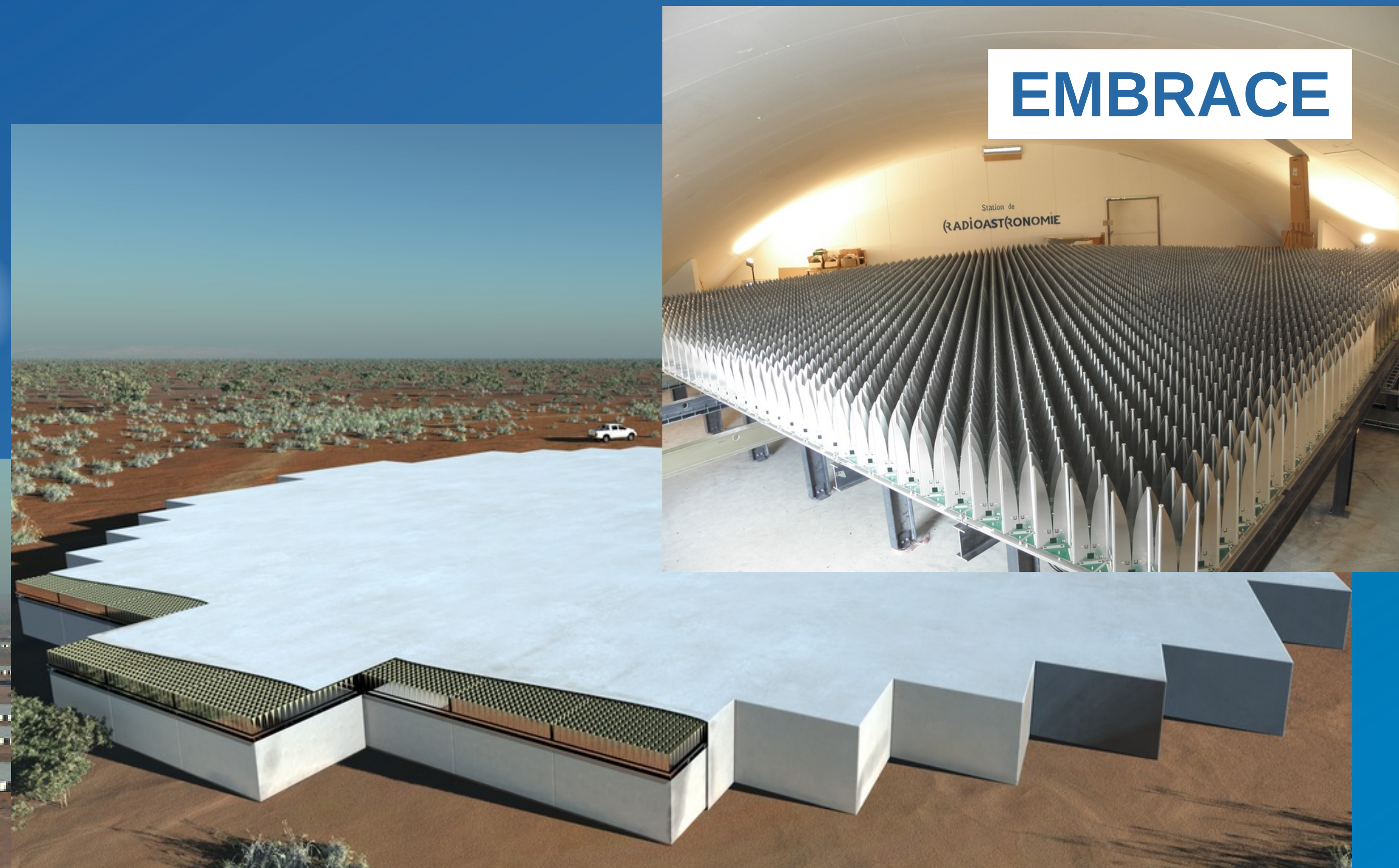
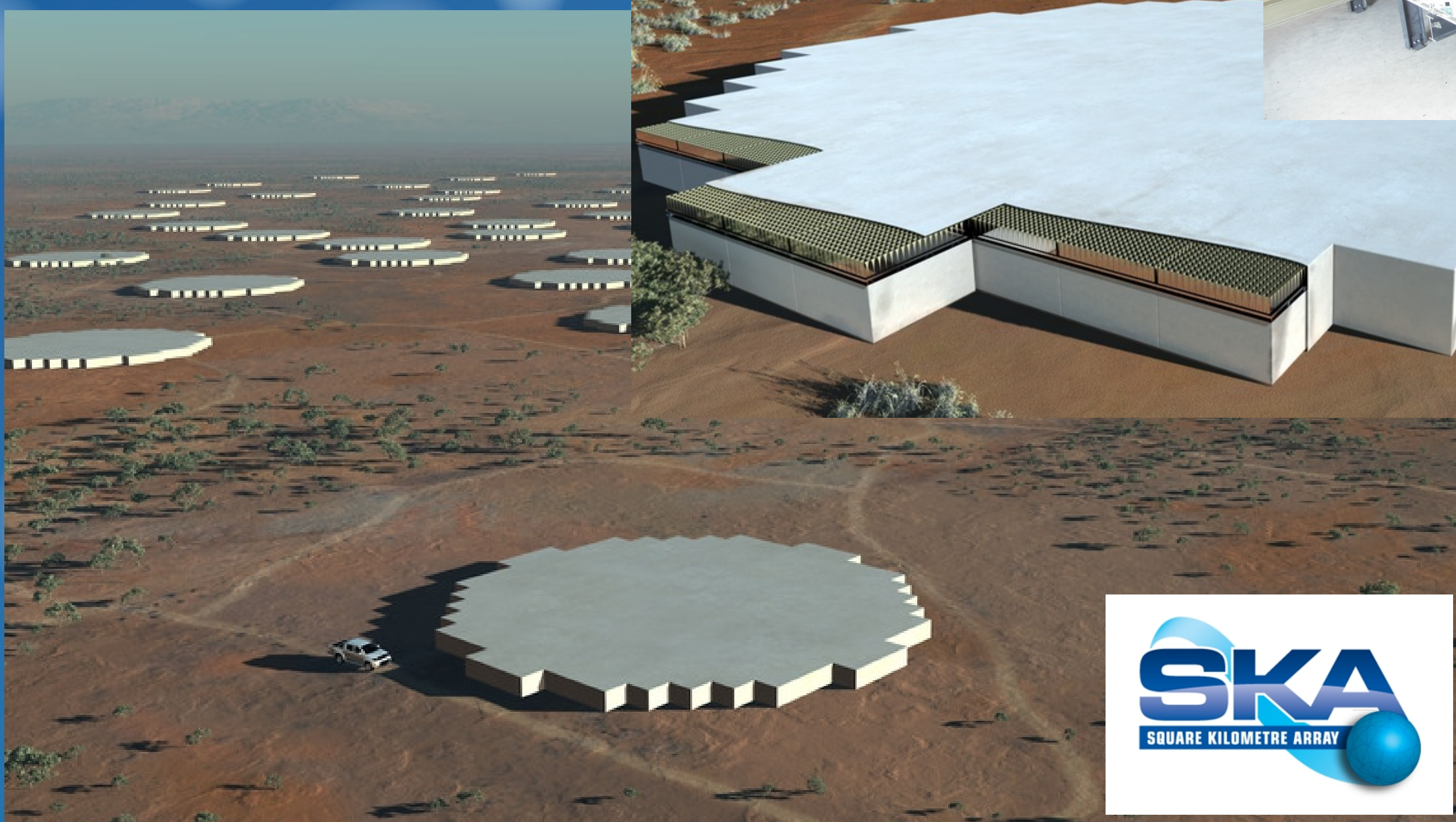
Dense Aperture Array for SKA

Steve Torchinsky

Station de Radioastronomie de Nançay





SKA
SQUARE KILOMETRE ARRAY

Overview

- Historical motivation for dense aperture array
- A comment on SKA Phase 1 and SKA
- EMBRACE
  - Brief system overview
  - Results
  - Future work

Why a Square Kilometre?

- Detection of HI in emission at cosmological distances
  - R. Ekers, SKA Memo #4, 2001
  - P. Wilkinson, 1991
  - J. Heidmann, 1966 !

SKA Memo #4: 2001

SKA Memorandum #4

SKA Technical Specifications

Ron Ekers

December 2001

The SKA specs have been evolved in a series of workshops over many years and in some cases the origin of the various specifics has been lost. In order to provide input to the science and engineering groups now looking at the scientific drivers and the specification trade-offs, I have provided this somewhat personal review of how we got to the present set of specifications. The specifications I have used and their definitions, which are repeated here, are from the 'SKA Science Case', p17.

A_{eff}/T_{sys} (2×10^4 m^2/K)
The effective collecting area divided by the system temperature. This may be a function of frequency.

- Sets the point source sensitivity and corresponds to 1 square kilometre collecting area, eg A_{eff} = 50% total aperture with T_{sys} = 25K. It is formulated this way to include the differences in aperture efficiency, and to allow different technologies to trade effective area for T_{sys} .
- The spec is set by the HI brightness sensitivity at a moderate spectral resolution ($\nu/d\nu = 10^4$ corresponding to 30 km/sec). This enables detection of a normal galaxy like M101 at any z by using HI up to z = 4 and CO at any z > 4.

The Hydrogen Array

428

Radio Interferometry: Theory, Techniques and Applications, IAU Coll. 131, ASP Conference Series, Vol. 19, 1991, T.J. Cornwell and R.A. Perley (eds.)

THE HYDROGEN ARRAY

P.N. WILKINSON
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK11 9DL, United Kingdom

ABSTRACT The time is ripe for planning an array with a collecting area of 1 km^2 (14 times larger than Arecibo and 75 times larger than the VLA). In view of its major astronomical target I have dubbed this concept 'The Hydrogen Array', although 1μJy continuum sources will also be reliably detected. I present some initial thoughts about the issues involved.

1966: 100x Nançay

Station de Radioastronomie de Nançay

CENT FOIS NANÇAY ?

100x Nancay ≈ 700 000m^2

par J. HEIDMANN

(Observatoire de Meudon)

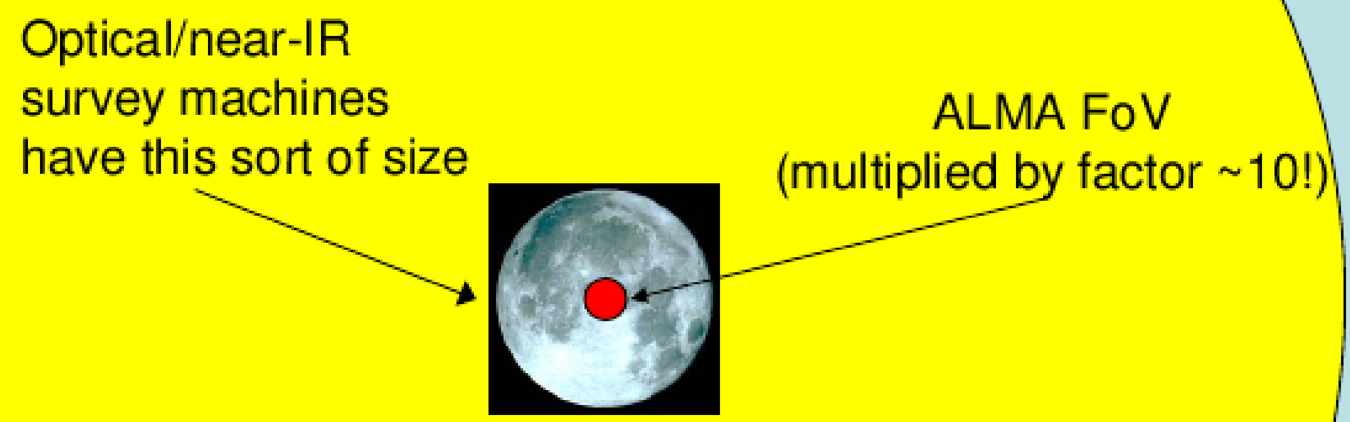
Le film qui vient d'être projeté a été terminé l'été dernier ([1]). Depuis, le grand radiotélescope de Nançay s'anime peu à peu. En 1966 il prendra progressivement sa pleine puissance. Sa portée sera énorme et le classera deuxième au monde, après l'interféromètre à synthèse d'ouverture de Cambridge, instrument très spécialisé mais rapidement construit ; le télescope de Nançay pourra observer des *quasars* paraissant s'éloigner de nous à dix fois la vitesse de la lumière. Selon le modèle d'univers d'Einstein-de Sitter, ces astres seront vus dans l'état où ils étaient 200 millions d'années seulement après le « gros boum » marquant le début de l'expansion ([2]).

Cet appareil étant près d'entrer en exploitation, on doit déjà envisager l'avenir. A ce propos, posons nous une question bien simple et essayons d'y répondre objectivement : quelle serait la situation si nous disposions d'un réflecteur de même qualité que celui de Nançay, mais ayant cent fois sa surface ?

Son pouvoir séparateur serait tellement fin, et sa puissance de captation serait si grande, qu'il pourrait observer effectivement, parmi la multitude d'astres parsemant la voûte céleste, 10 000 000 d'entre eux.

extragalactic survey: 10^7 sources

SKA will give both huge FoV and exquisite resolution

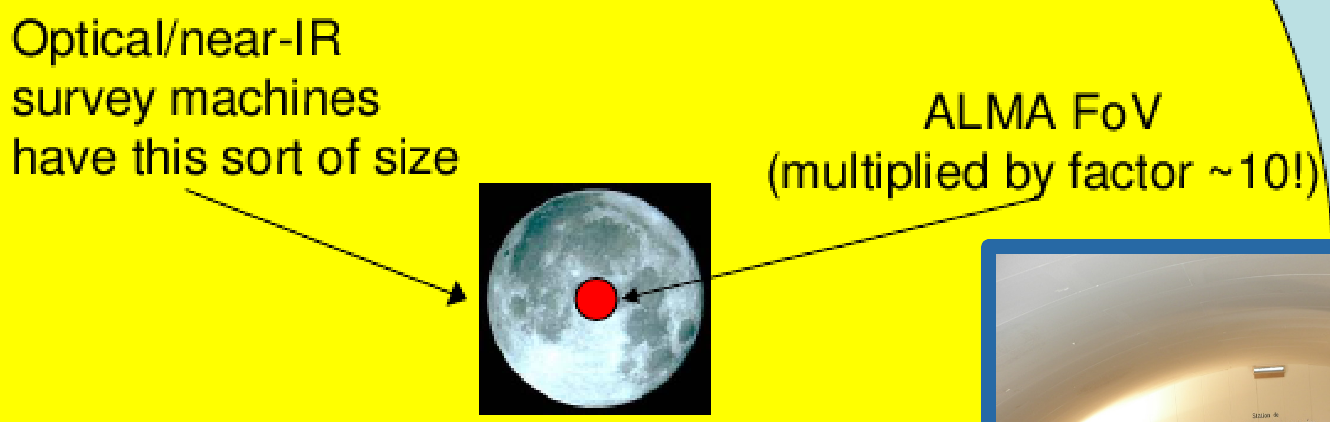


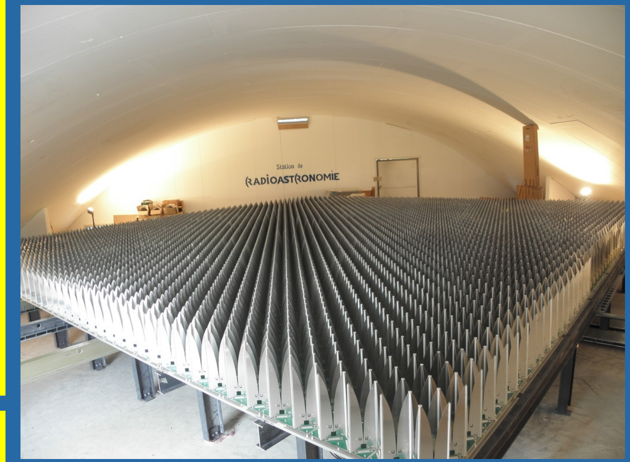
- <1 GHz SKA realizations will give at least 10 deg^2 FOV
- ~100 deg^2 may be achievable!
- With this wide FOV the SKA will be a remarkable SURVEY MACHINE.
- ~3000km baselines gives <milli-arcsec resolution at ~30 GHz

See Rawlings et al. 2004, in “Science with the SKA,” Carilli & Rawlings, eds.

Steve Rawlings, 2005

SKA will give both huge FoV and exquisite resolution





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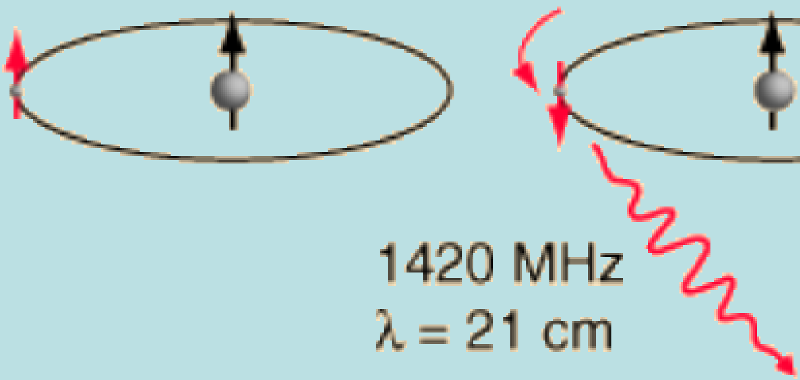
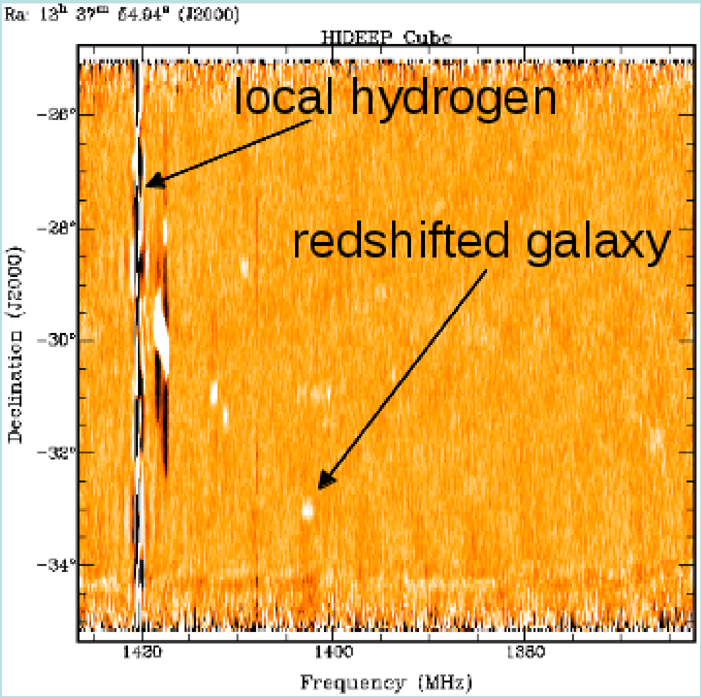
Steve Rawlings, 2005

KSPIV – Galaxies and Cosmology





SPECTRAL domain 0.5 to 1.4 GHz

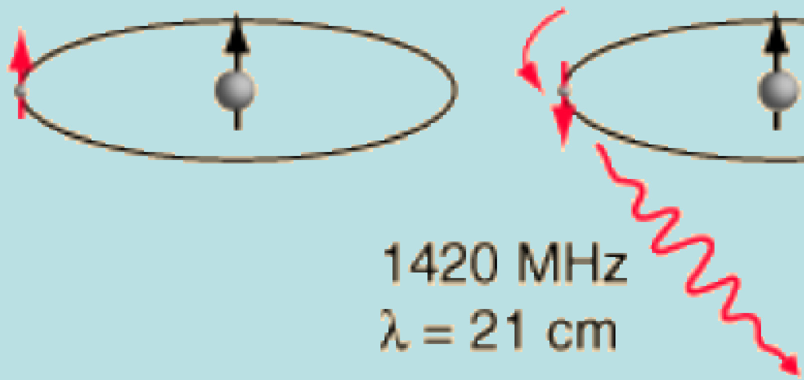
An SKA sensitivity (100x current) needed to get from z=0.2 galaxies to z ~ 2

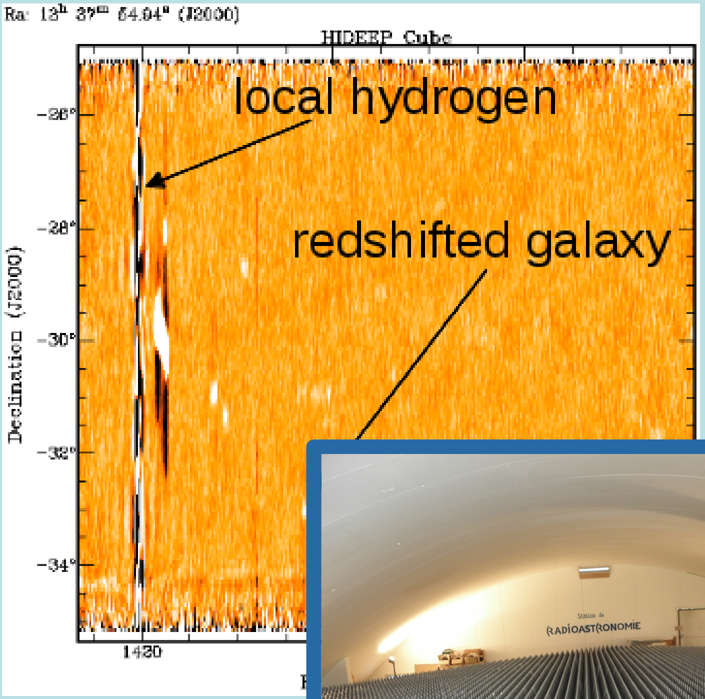
- Radio telescopes can have enormous fields of view (cf optical etc)
- Radio telescopes gain sensitivity on galaxies linearly with A (cf $\sqrt{A}$ optically)
- SKA will quickly pinpoint ~10^9 galaxies in 3D (cf ~10^6 galaxies in Sloan)

Steve Rawlings, 2005

See Rawlings et al. 2004, in "Science with the SKA," Carilli & Rawlings, eds.

KSPIV – Galaxies and Cosmology





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Steve Rawlings, 2005

See Rawlings et al. 2004, in "Science with the SKA," Carilli & Rawlings, eds.

Square Kilometre

"SKA"
Phase 1
100 000 m^2

≠

Detection of HI at cosmological distance

The Original SKA Memo 125

SKA
SQUARE KILOMETRE ARRAY
www.skatelescope.org

Concept Design for SKA Phase 1 (SKA_1)

M.A. Garrett, J.M. Cordes, D. de Boer,
J.L. Jonas, S. Rawlings & R.T. Schilizzi

(SSEC SKA Phase 1 Sub-committee).

1 June 2010

Advanced Instrumentation Programme (AIP) for the full SKA

The SKA_1 baseline concept design presented here represents the first concrete step towards the realisation of the much larger and more ambitious SKA_2. The Advanced Instrumentation Programme (AIP) will seek to capitalise on investments made by the SKA Organisation and others parties in innovative technology development over the pre-construction period 2011-2015. In 2011-2015, advanced instrumentation systems under development for the SKA are expected to include: Phased Array Feeds (PAFs), Dense Aperture Arrays (DAAs), high frequency feeds etc.

Given the progress expected in all of these areas of instrumentation over the next 5 years, a decision identifying the most promising system for SKA_2 can be made in 2016, at the start of the initial SKA_1 construction phase. Advanced instrumentation such as PAFs or high frequency feeds can be deployed as modular sub-systems on the SKA_1 dishes. DAAs will require the construction of a substantial standalone demonstrator. The AIP will realise an advanced system that will either greatly enhance the baseline SKA_1 telescope and/or will demonstrate an important technology prototype of direct relevance to SKA_2.

An amount of 15 M€ is allocated to the AIP as part of the overall SKA_1 budget (see Table 2). In addition, the opportunity for individual research groups to fund new instrumentation relevant to the SKA should not be excluded.

5% budget allocated to AIP

The Neutered SKA Memo 125

Memo 125

A Concept Design for SKA Phase 1 (SKA_1)

SSEC SKA Phase 1 Sub-committee:

M.A. Garrett
J.M. Cordes
D. de Boer
J.L. Jonas
S. Rawlings
R.T. Schilizzi

August 2010

Advanced Instrumentation Programme (AIP) for the full SKA

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Given the progress expected in all of these areas of instrumentation over the next 5 years, a decision identifying the most promising system for SKA_2 can be made in 2016, at the start of the initial SKA_1 construction phase. Advanced instrumentation such as PAFs or high frequency feeds may also be deployed as modular sub-systems on the SKA_1 dishes. DAAs will require the construction of a substantial standalone demonstrator. The AIP will realise an advanced system that will either greatly enhance the baseline SKA_1 telescope and/or will demonstrate an important technology prototype of direct relevance to SKA_2. The opportunity for individual research groups to fund new instrumentation relevant to the SKA should not be excluded.

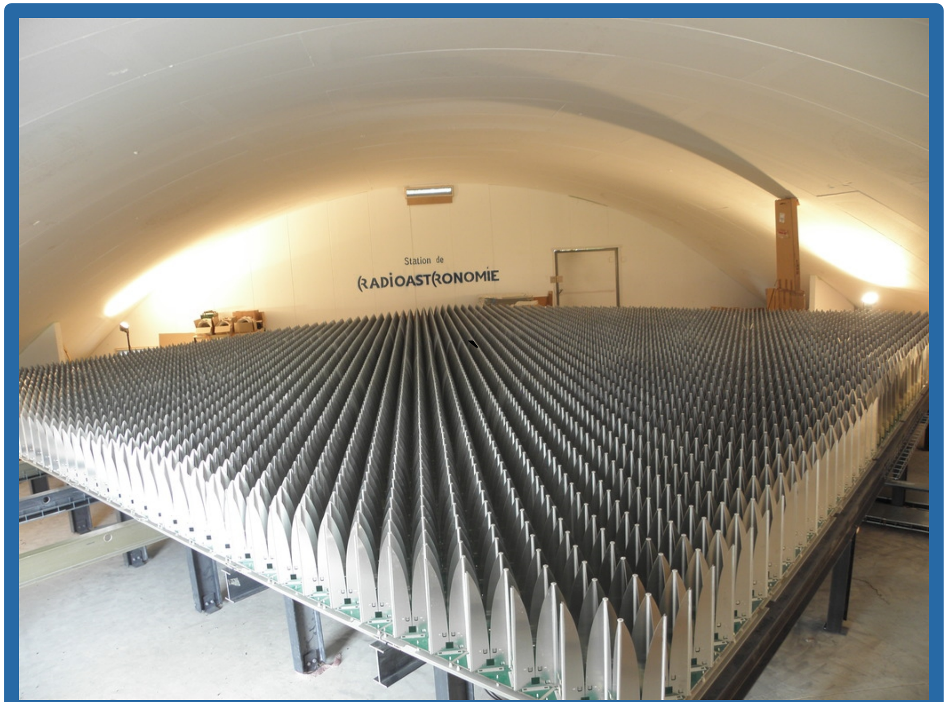
No budget allocated to AIP → **<SNIP>**

Square Kilometre Array

OSKAO should make a concrete commitment to building SKA2 by allocating a portion of the SKA1 construction budget to AIP, as was proposed in the original Memo 125.*

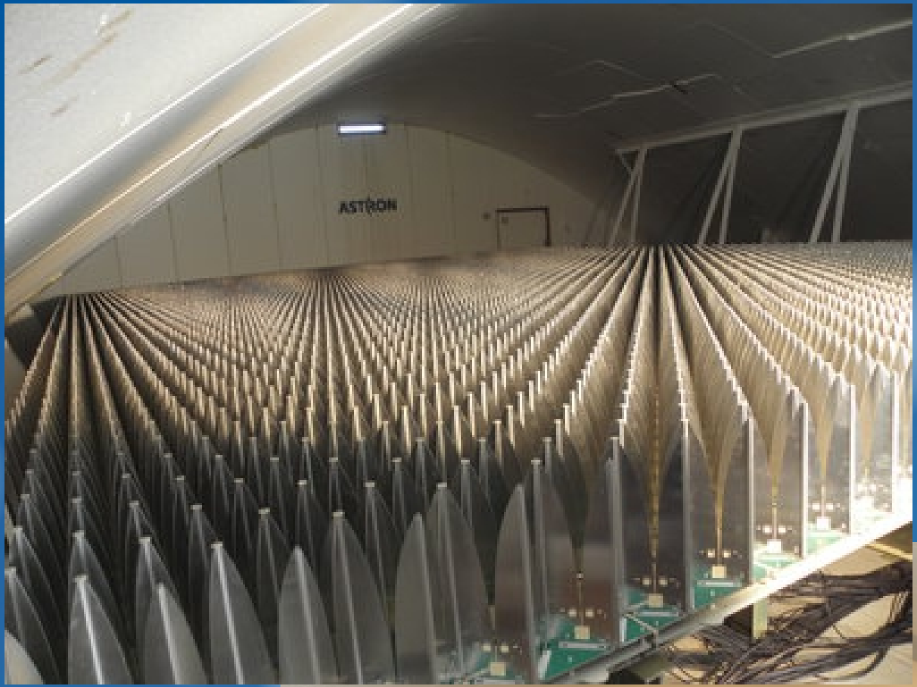
*The views expressed in this presentation are my own, and don't necessarily represent those of...

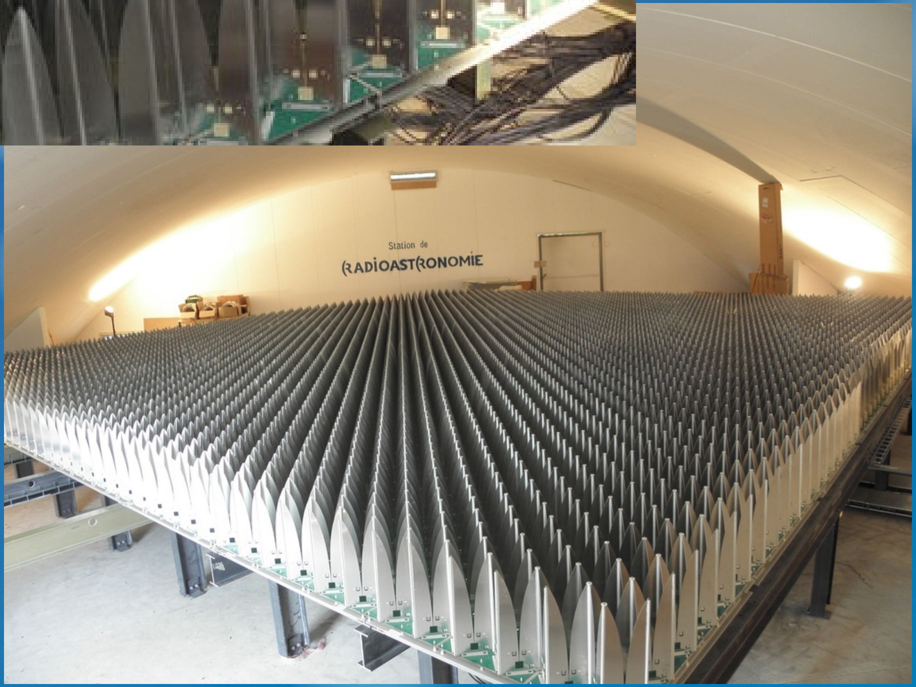
Dense Aperture Plane Array



- Fully sampled, unblocked aperture
- Large field of view (~100 sq. deg)
- Extremely fast survey machine for HI at cosmological redshifts
- **Ideal for BAO survey**

Electronic MultiBeam Radio Astronomy ConcEpt





SKADS

ASTRON

l'Observatoire de Paris

Station de Radioastronomie de Nançay

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

MAX-PLANCK-GESELLSCHAFT

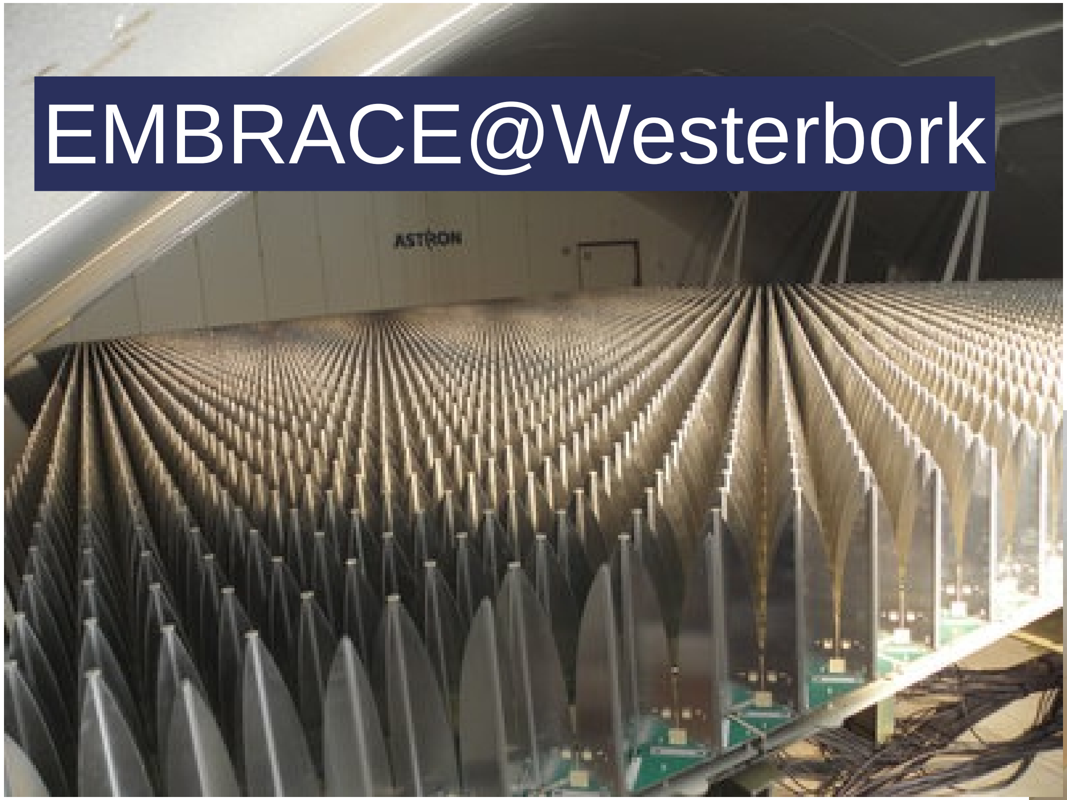
CHALMERS

UNIVERSITY OF OXFORD

Electronic MultBeam Radio Astronomy ConcEpt

- **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 (132 tiles) and one at Nançay (64 tiles)

Two EMBRACE sites



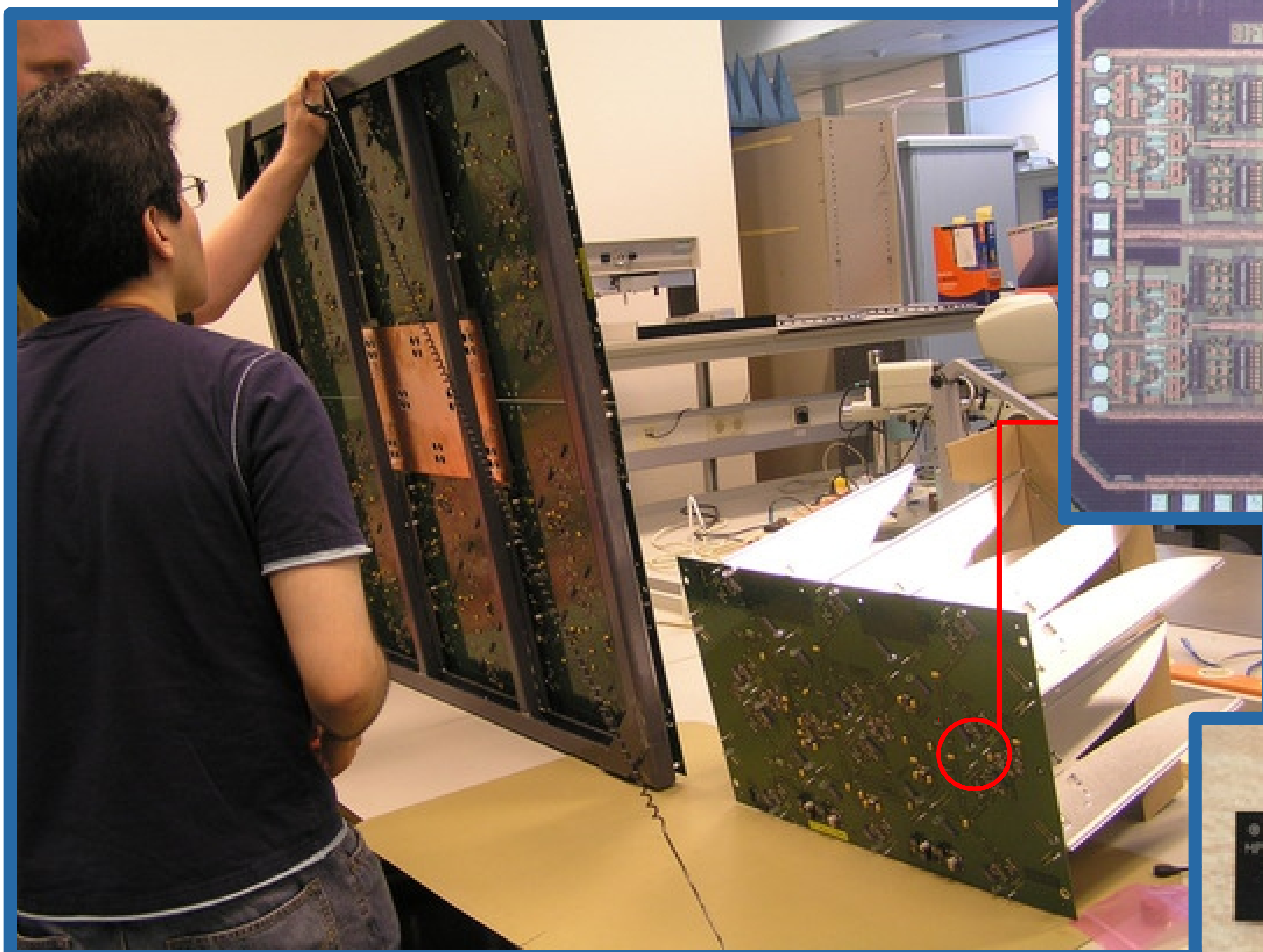
EMBRACE signal chain

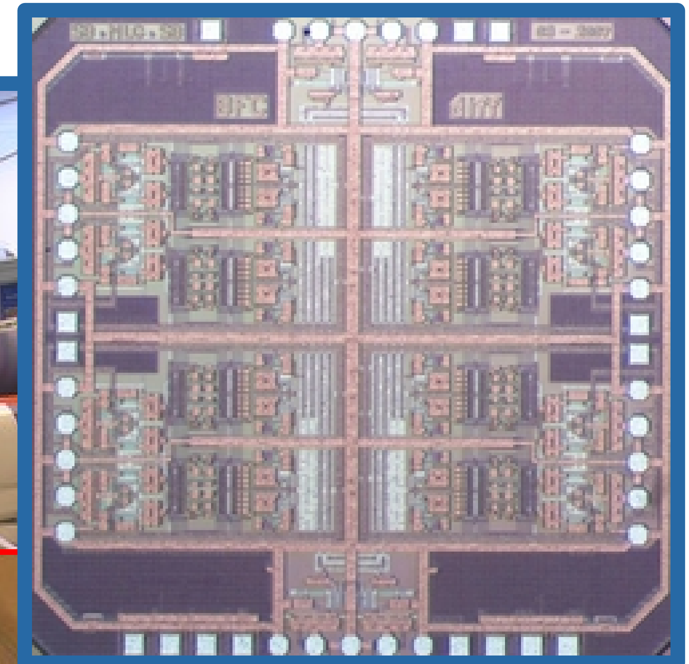
- Nançay: 4608 Vivaldi antenna elements
- Westerbork: 9504 Vivaldi antenna elements
- Single polarization (second polarization antennas are in place, but only one polarization has a complete signal chain)
- 4 level hierarchical analog beamforming/signal summing
  - Beamformer chip:
    - 4 inputs, 2 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
    - Nançay: 32 inputs to LOFAR backend (16 A-beam, and 16 B-beam)
    - Westerbork: 165 inputs to LOFAR backend (132 A-beam, and 33 B-beam)

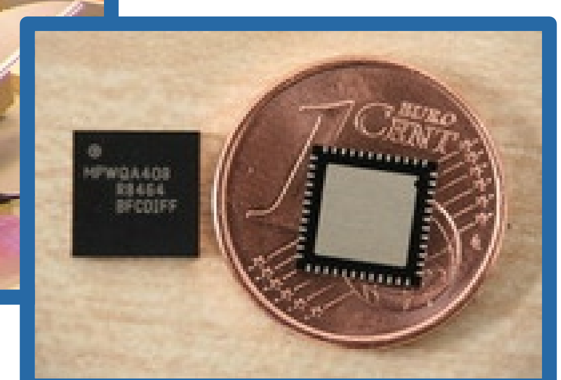
EMBRACE characteristics

- 500 – 1500 MHz
  - But high pass filter at 900 MHz to avoid digital television
- Nançay: 70 m^2 (8.5m X 8.5m)
- Westerbork: 148 m^2 (12.7m X 11.6m)
- Instantaneous RF band: 100 MHz
- Maximum instantaneous beam formed:
  - Nançay
    - 36 MHz x 2 directions (single polarization)
    - 186 “beamlets” each of 195.3 kHz bandwidth
    - i.e. 3 “lanes” for high speed data from RSP
  - Westerbork
    - 48 MHz x 2 directions (single polarization)
    - 248 “beamlets” each of 195.3 kHz bandwidth
    - i.e. 4 “lanes” for high speed data from RSP
  - Can trade off beam width vs. number of beams

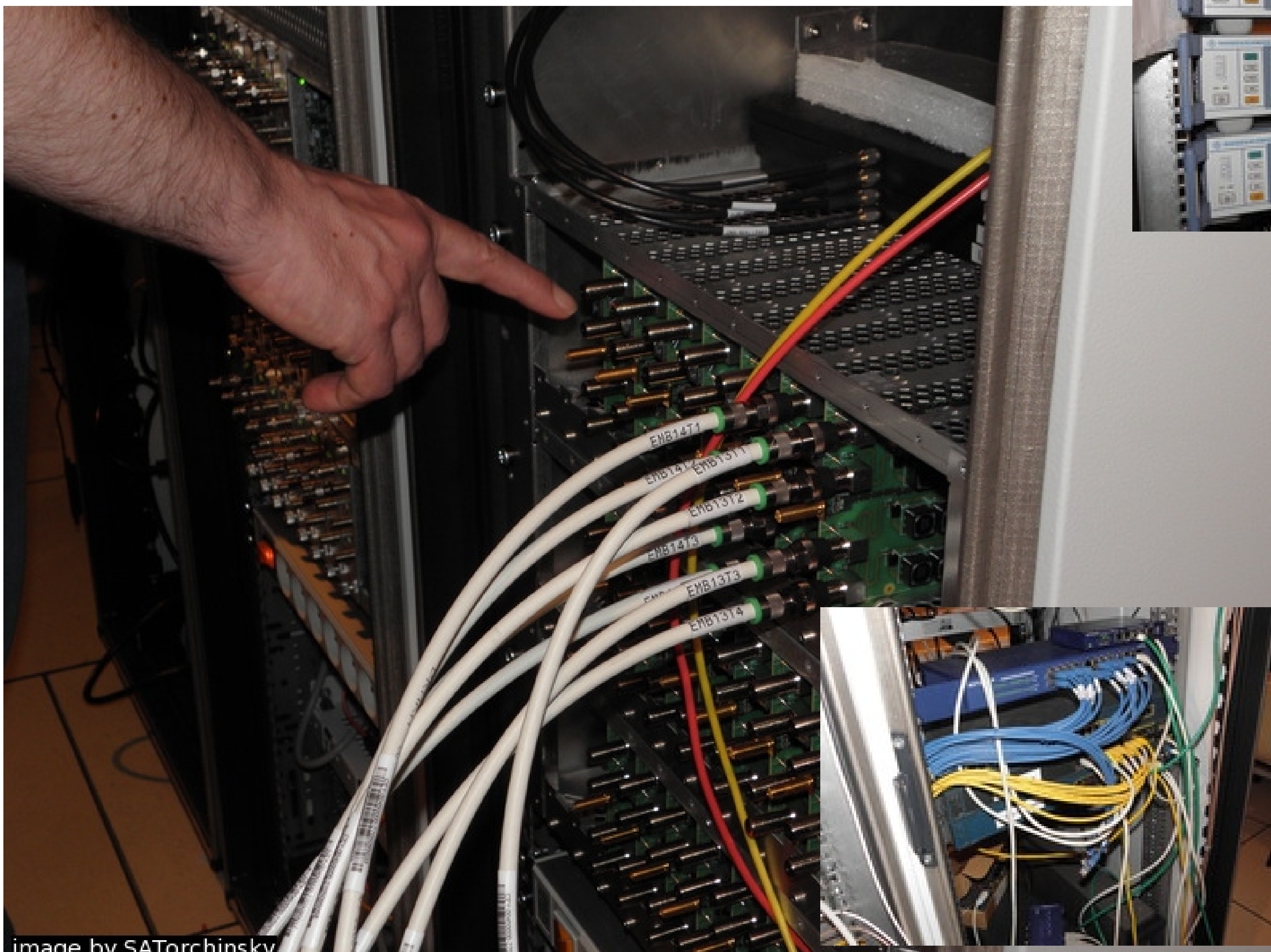
Analog Beamformer Chip

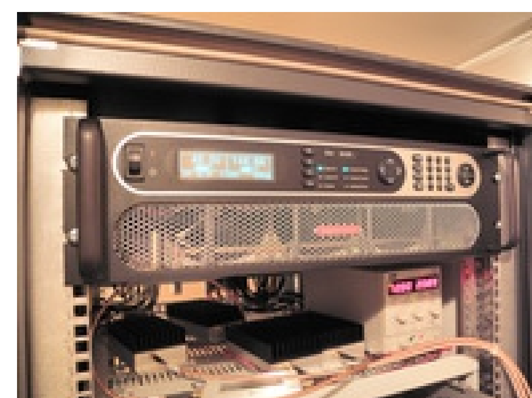




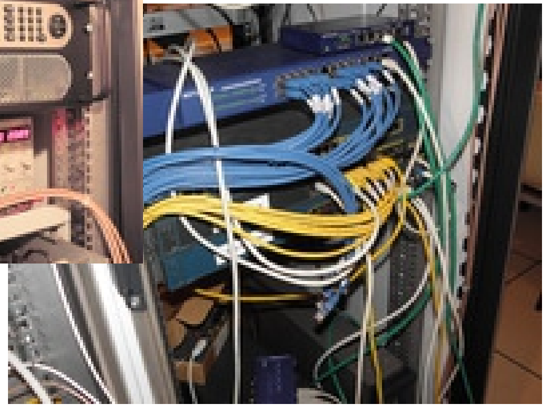


4th stage analog beam forming @Nançay





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!

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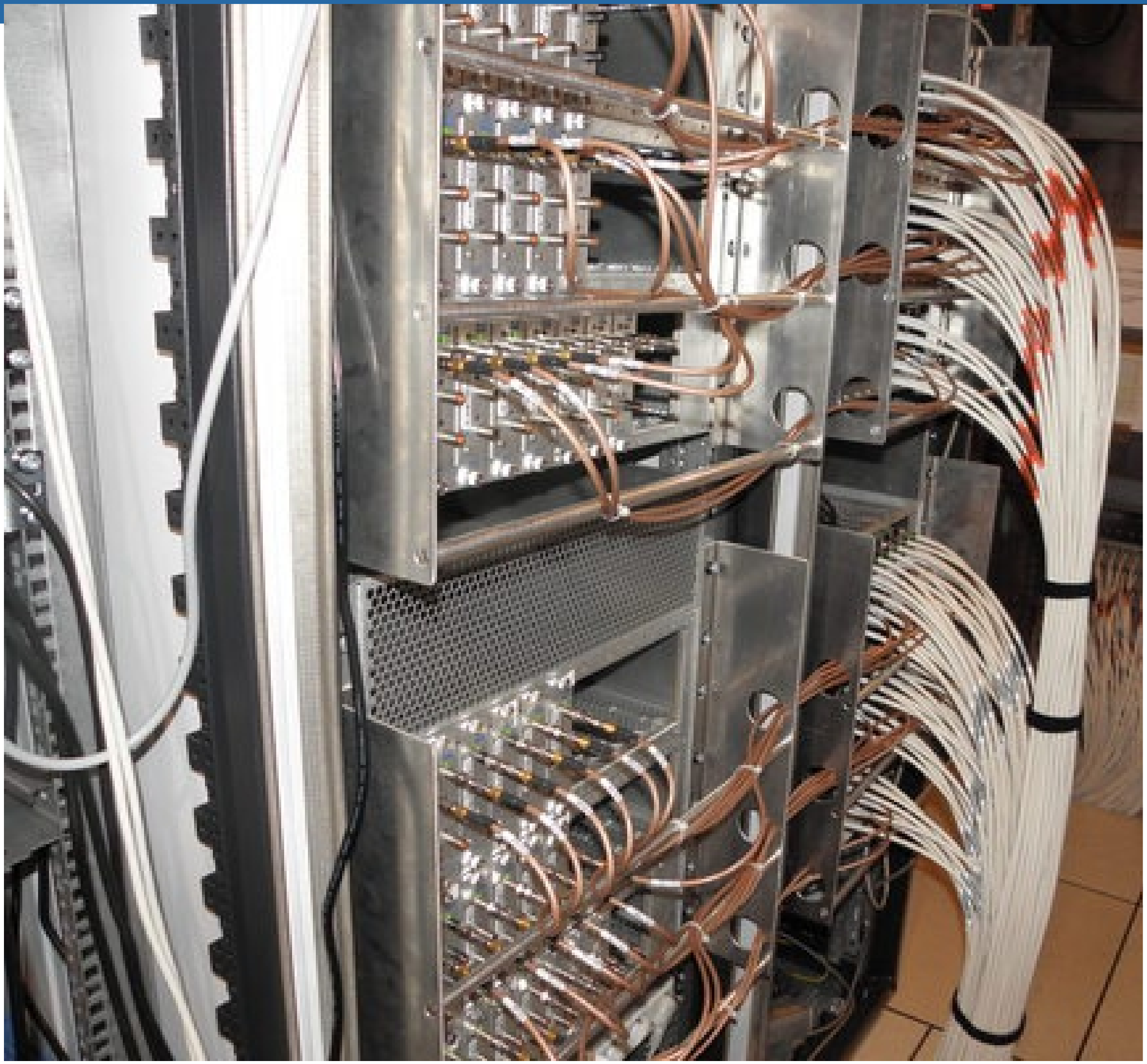
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

ASTRON

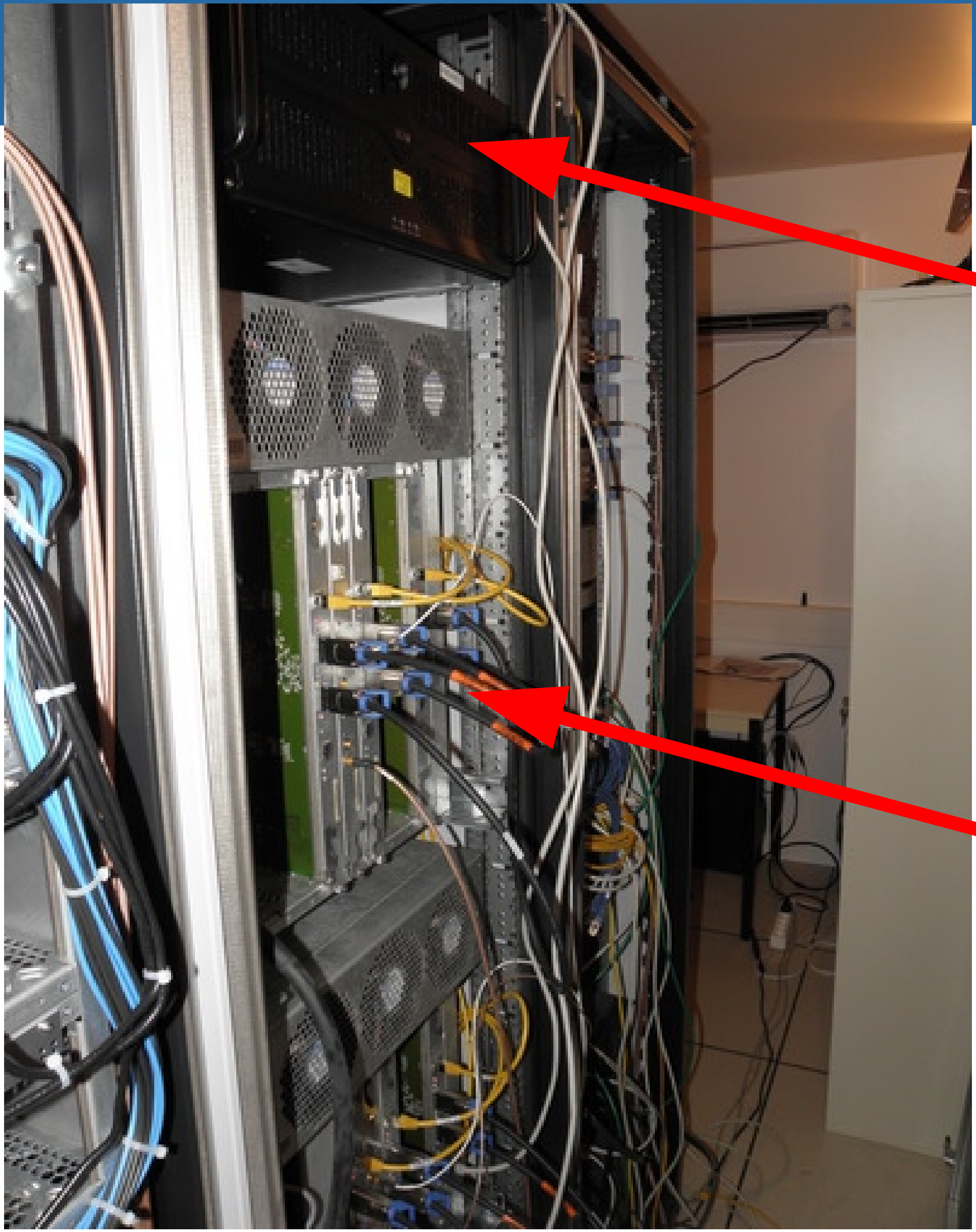
CDC cards designed by MPIfR/INAF-IRA/ASTRON

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

Pulsar acquisition system provided by U. Oxford.
Aris Karastergiou

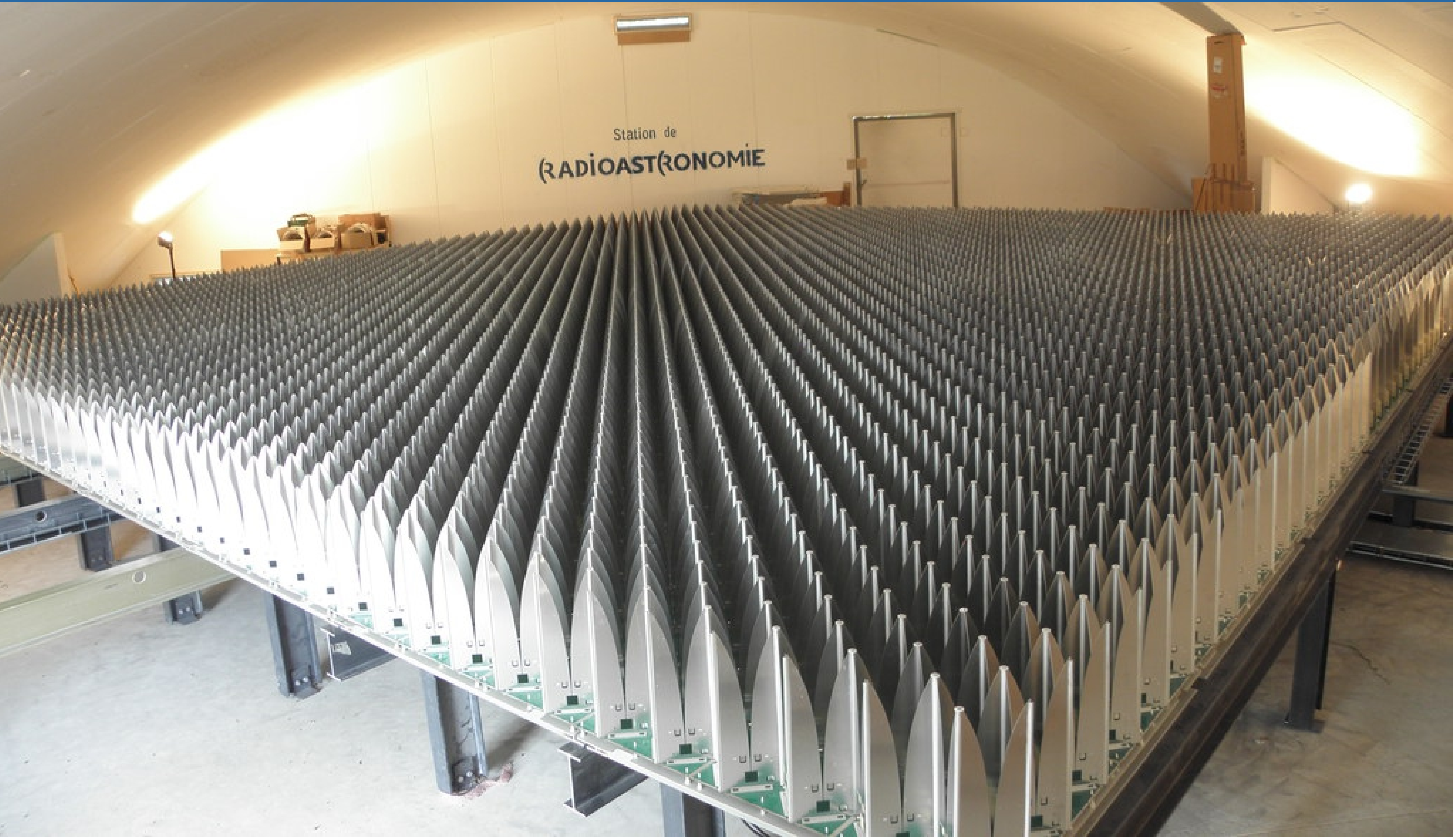
LOFAR Remote Station Processing Boards for digital beamforming

System Control and Data

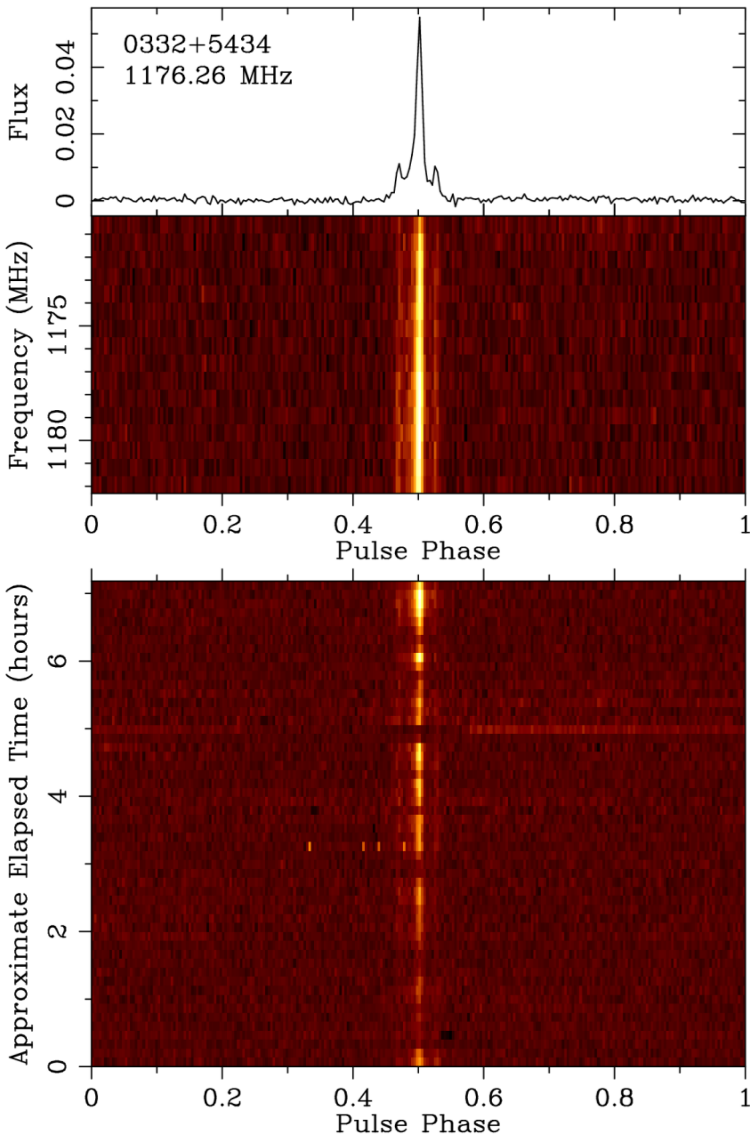
- Enormous flexibility with the dense array
  - Multi-beam
  - Instantaneous reconfiguration
  - Real time calibration
  - Multiple observing mode possibilities with tradeoff between bandwidth, number of beams, field of view

MAC developed at Nançay provides a friendly Python interface for the user to setup complicated observing runs

Some results



Pulsar B0329+54

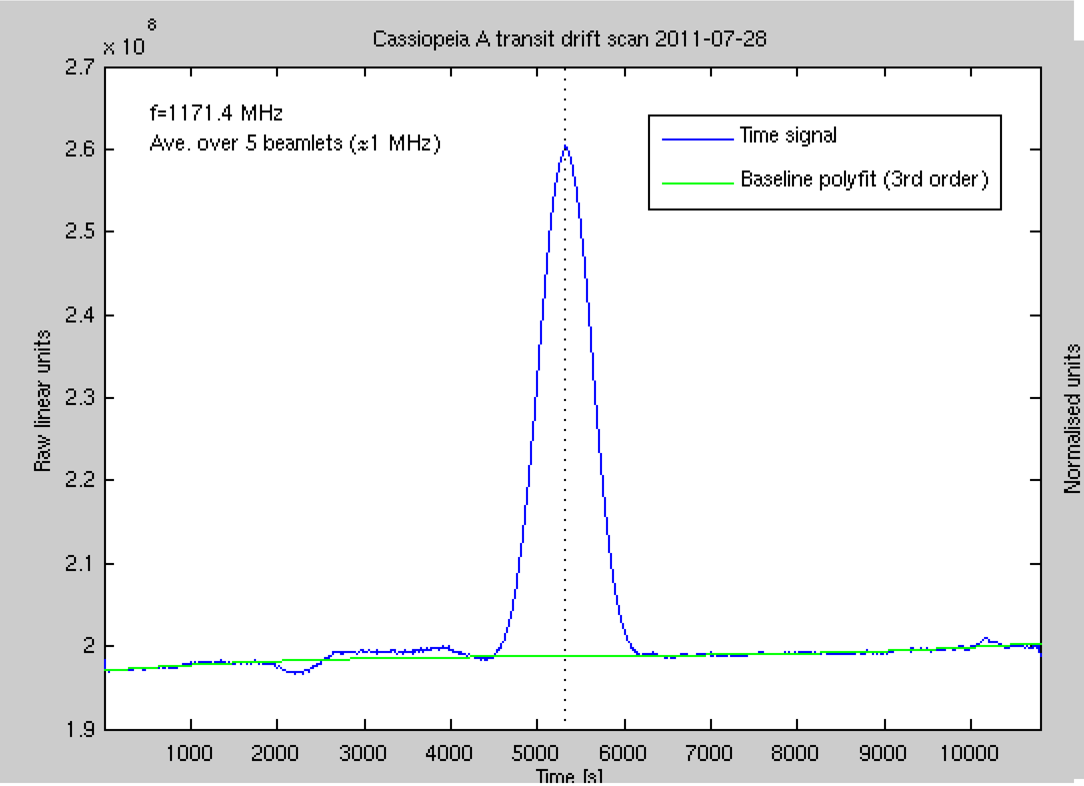


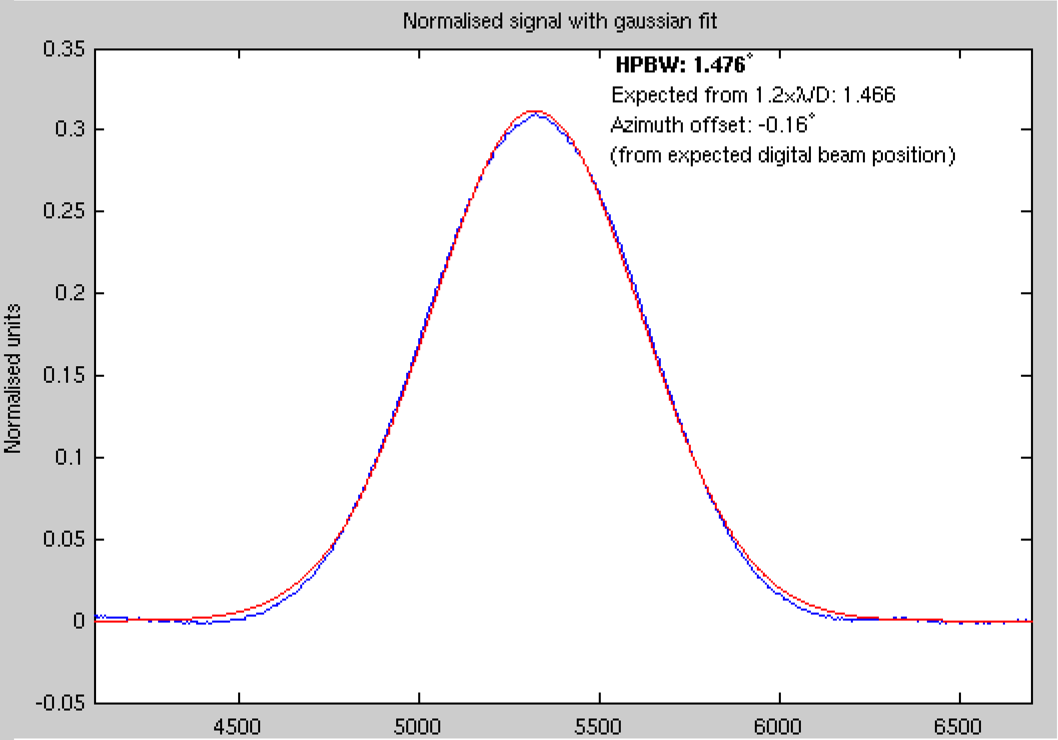
Pulsar B0329+54
1175.6MHz
6 November 2012
>9 hours tracking

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

EMBRACE@Nançay

Drift Scan of Cas-A

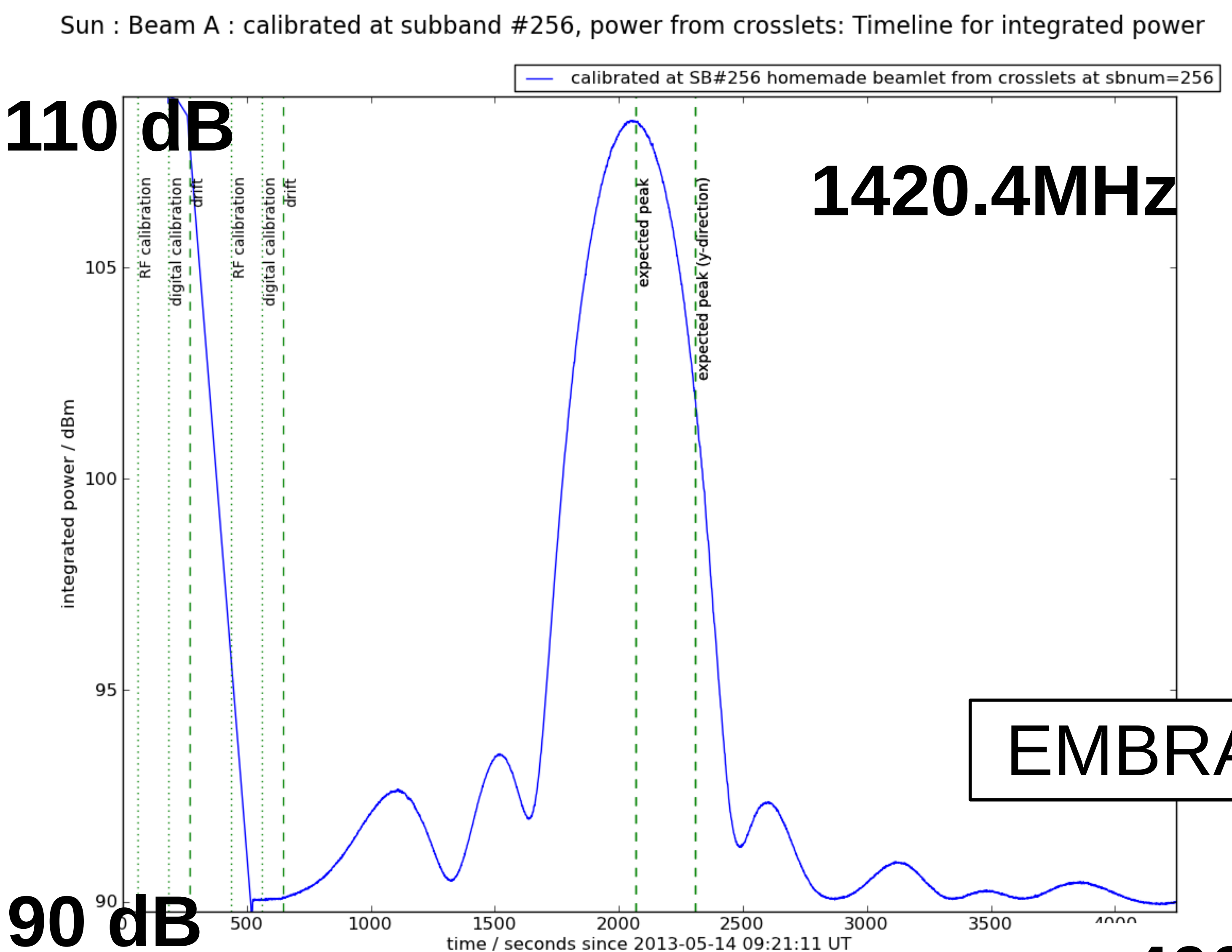




EMBRACE@Nançay

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

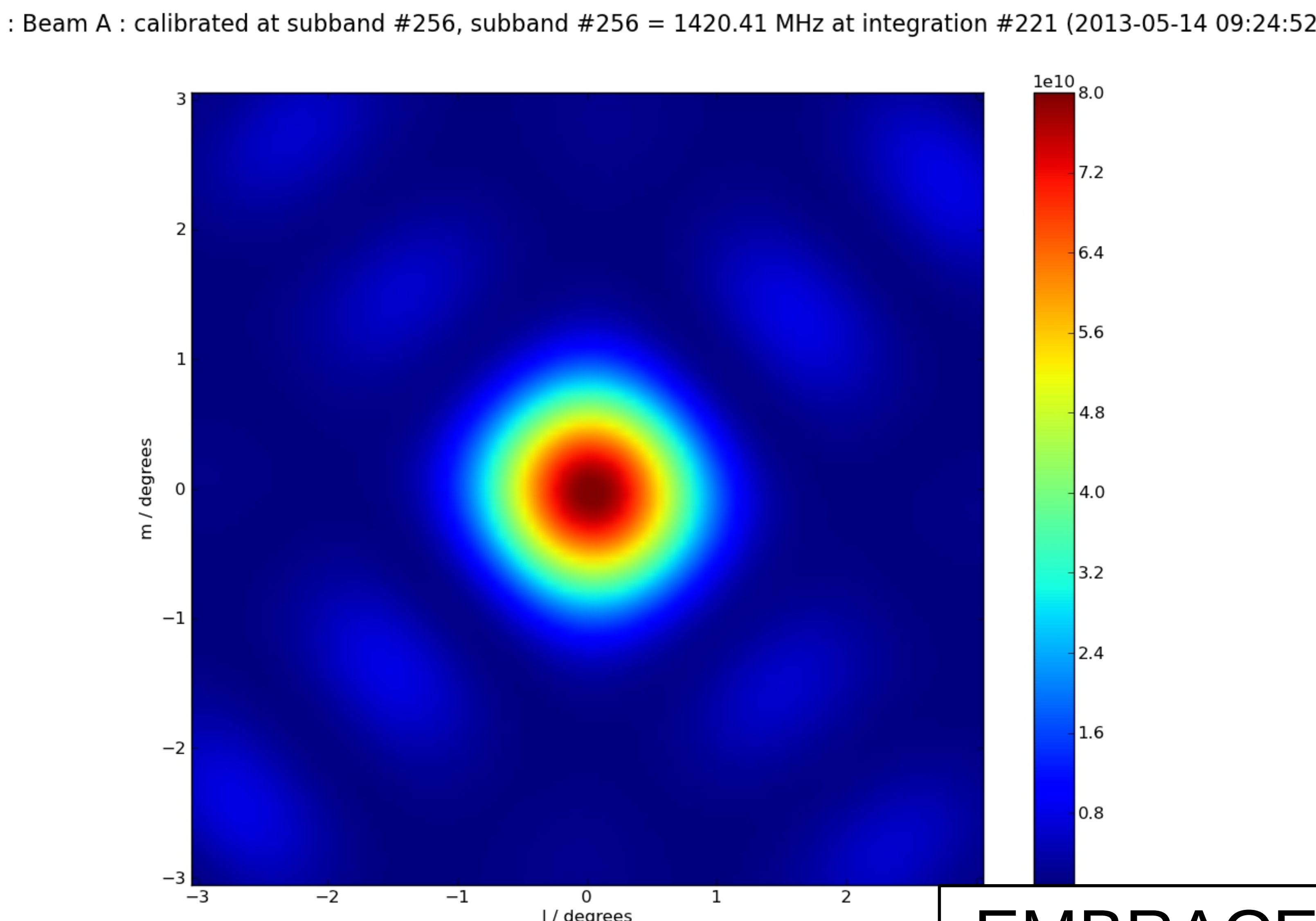
Drift scan of the Sun



EMBRACE@Nançay

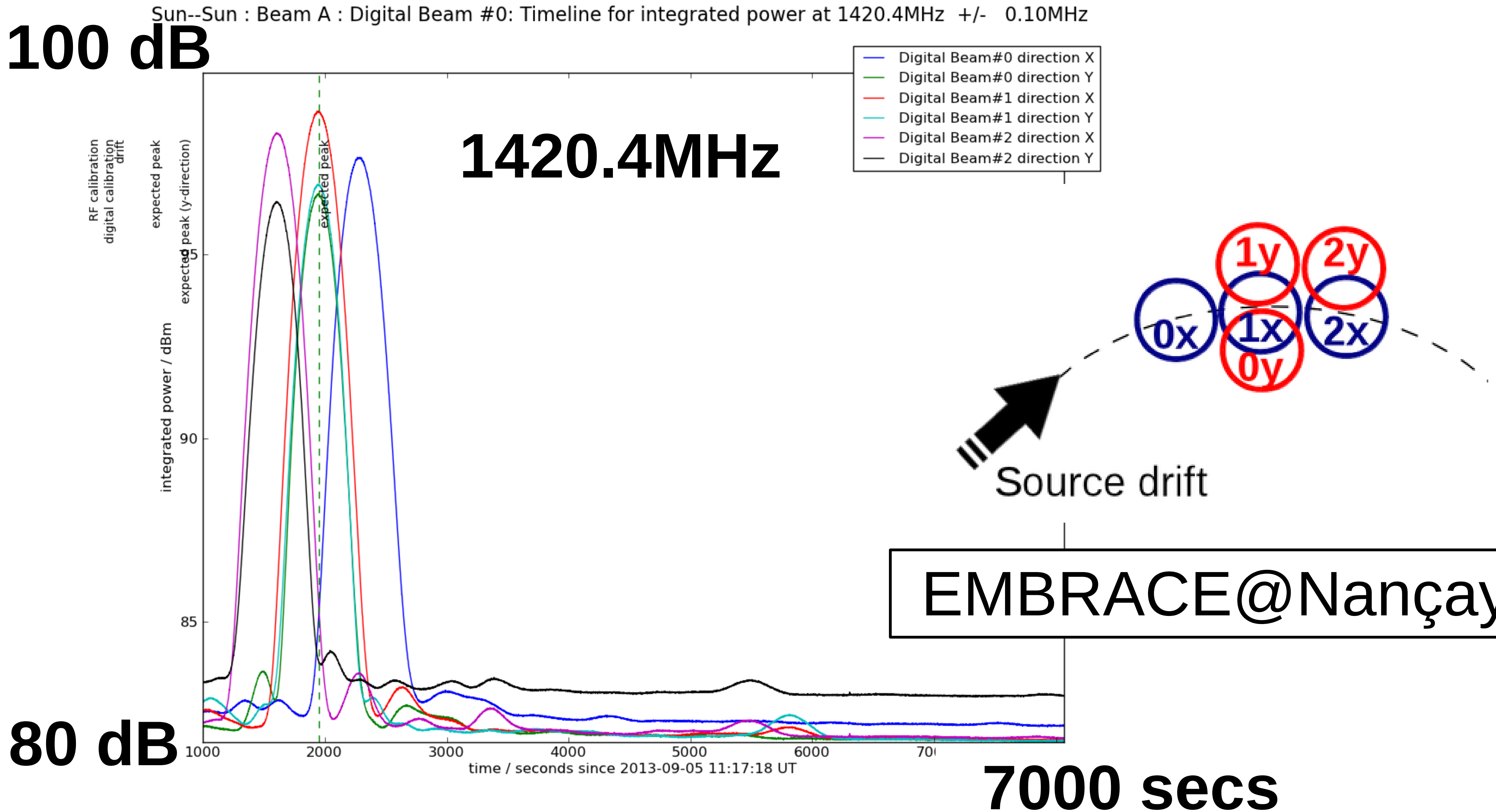
4000 secs

Imaging using X-let statistics



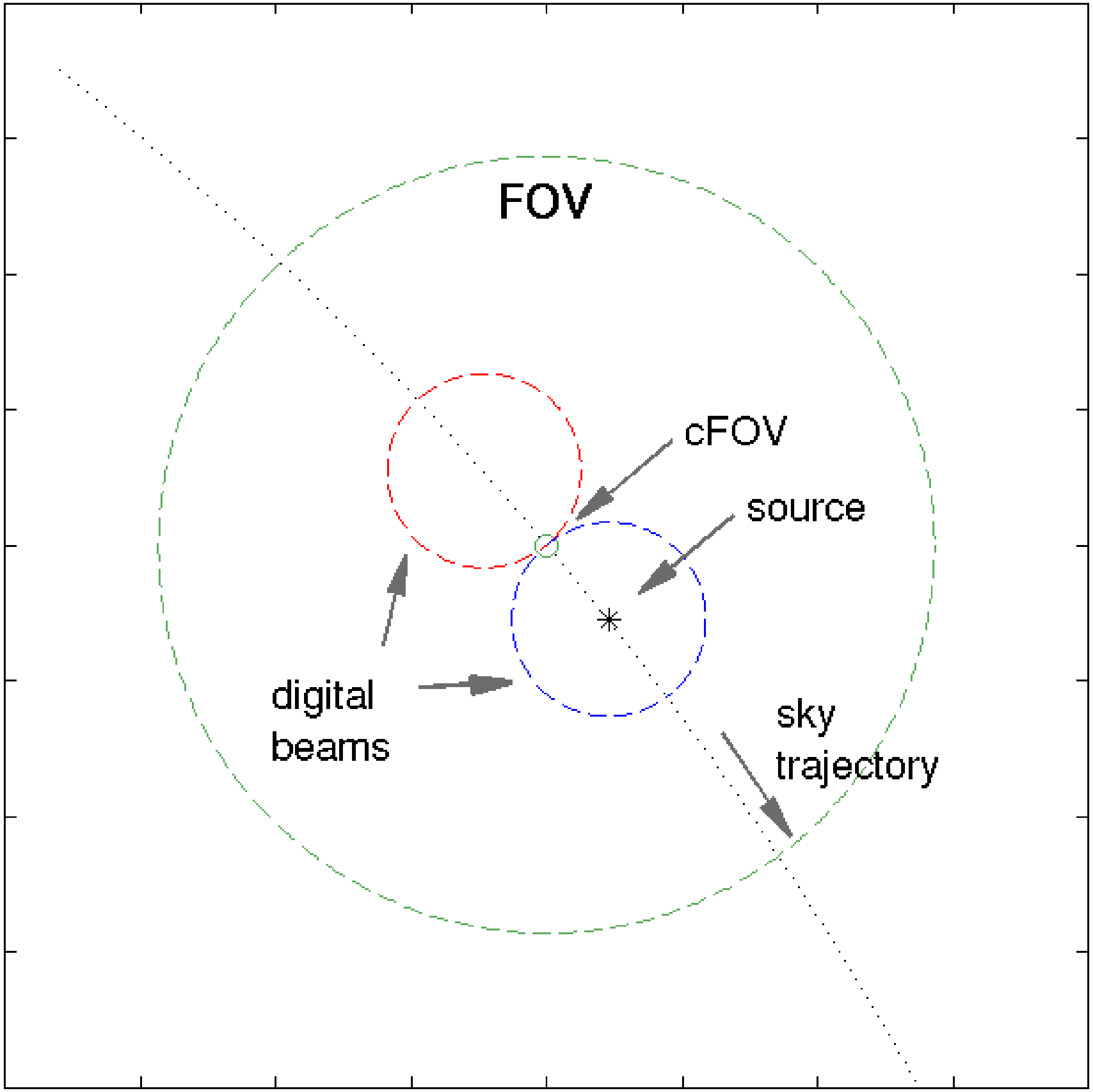
EMBRACE@Nançay

Multibeaming



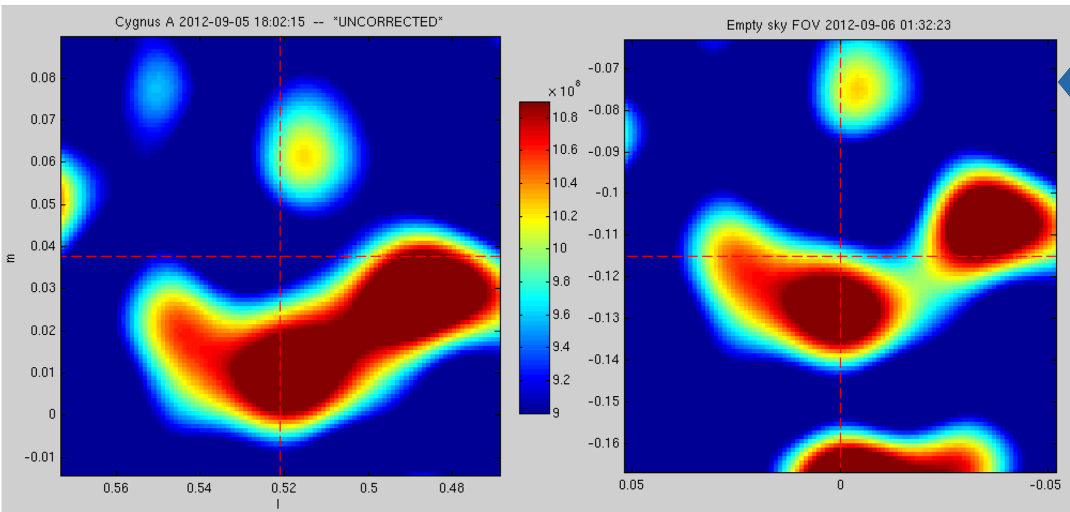
EMBRACE@Nançay

ON-OFF pointing strategy



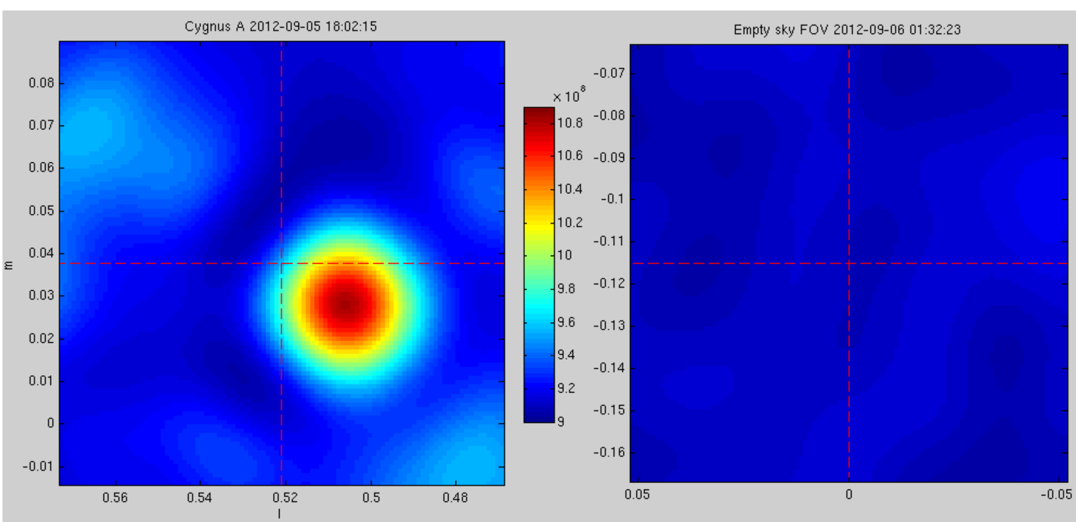
- On and Off observations can be done **simultaneously** with EMBRACE (multibeams)

Another fix: Flat Fielding



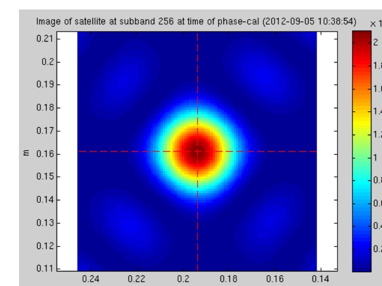
Stable background "image" due to correlator offset

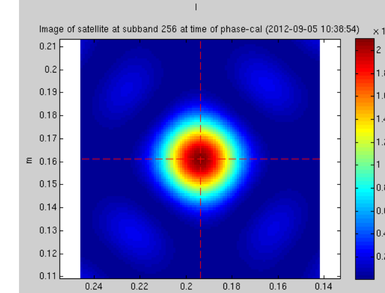
Cygnus A
Same data!
(before/after fix)



GPS satellite
(strong source)

No change





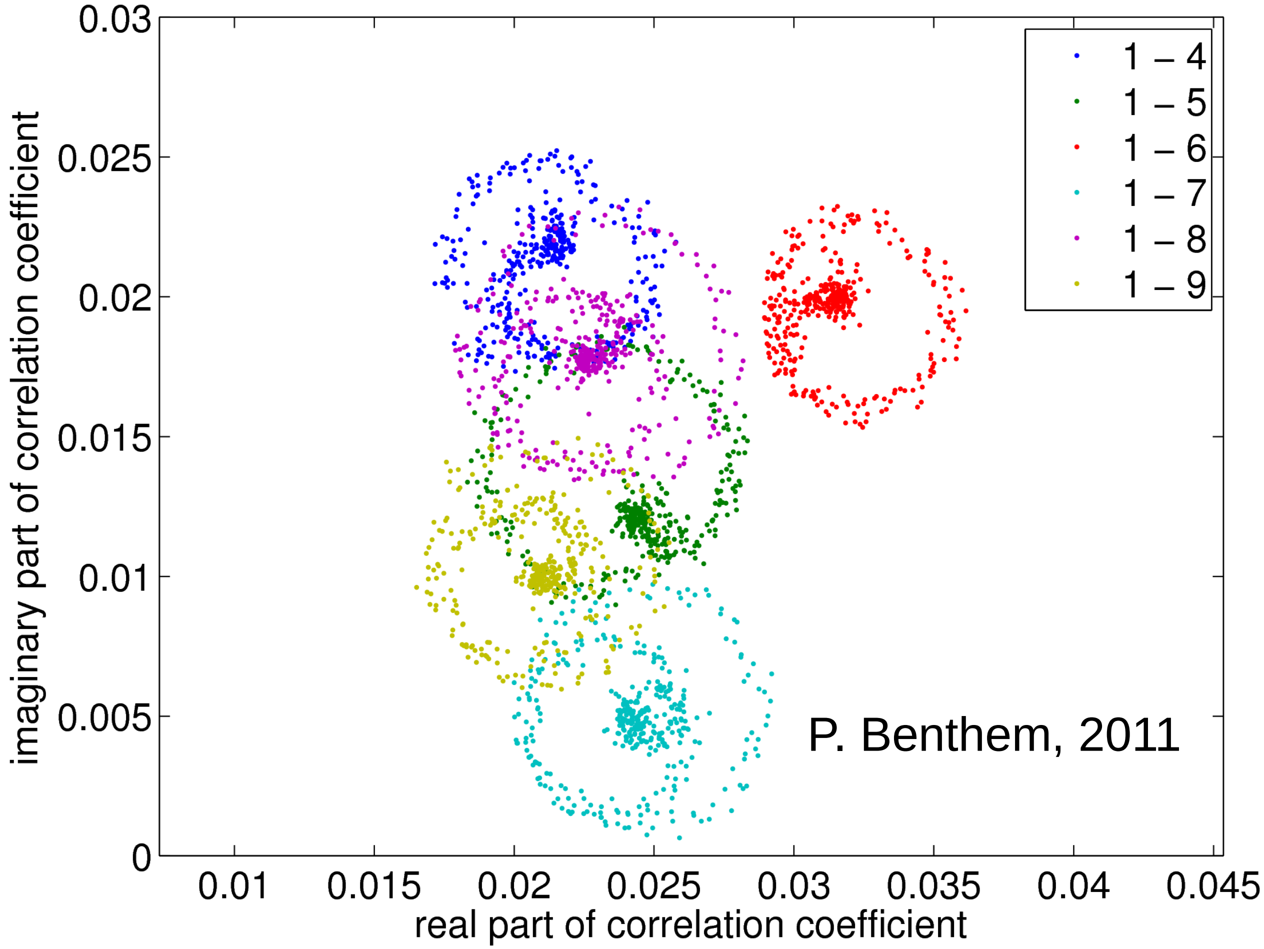
EMBRACE@Nançay

Correlator Offset

EMBRACE@Westerbork

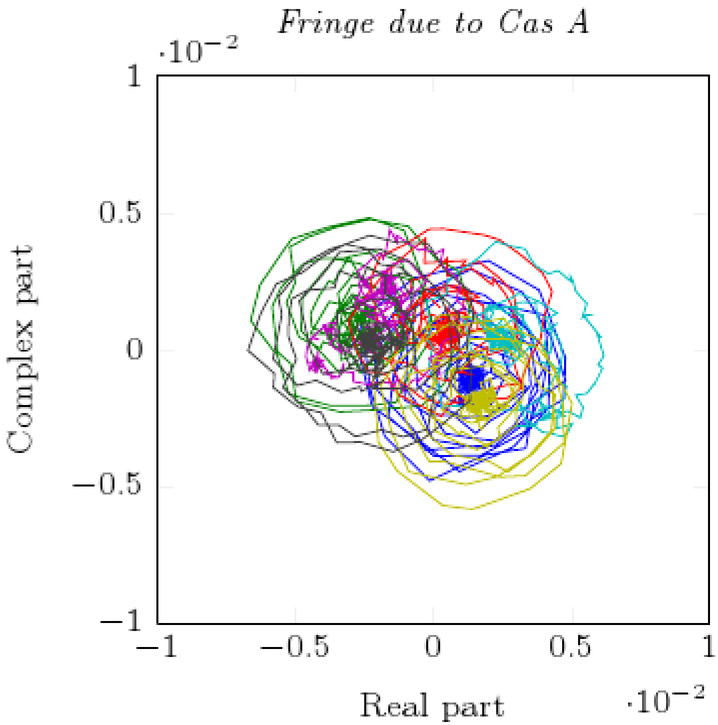
- **Experimental settings**
- 3x3 array
- 1254 MHz
- 30 s integration
- 195 kHz bandwidth

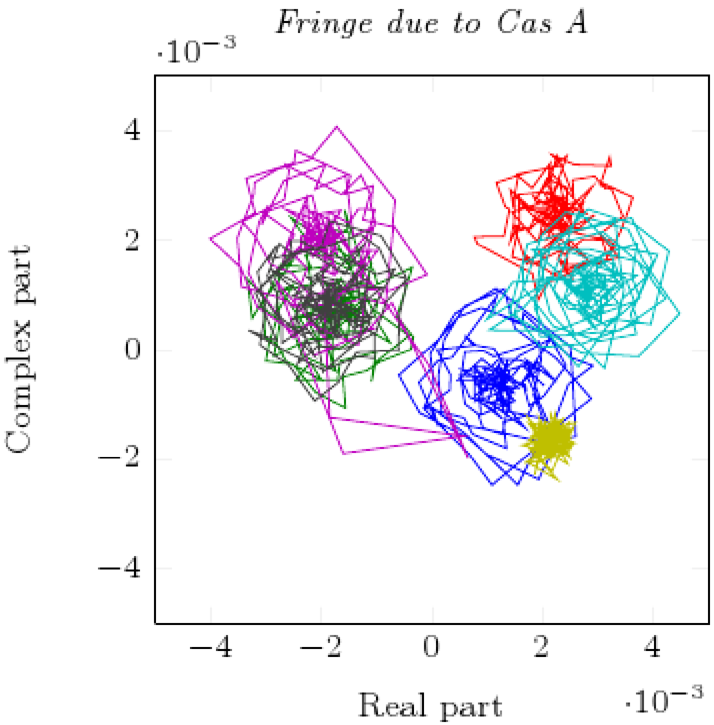
- **Initial conclusions**
- Confirms A/T
- Correlation offsets



Correlator Offset

EMBRACE@Westerbork





B. Hut, Masters Thesis, 2013

Correlator Offset

SKA SQUARE KILOMETRE ARRAY
MID-FREQUENCY APERTURE ARRAY

A. R. Thompson, J. M. Moran, G. W. Swenson Jr.

WILEY-VCH

Interferometry and Synthesis in Radio Astronomy

Second Edition

Other types of additive errors result from interference, cross-coupling of system noise between antennas, and correlator offset errors. The sun is many orders of

noise.

Errors of an additive nature combine by addition with the true visibility values. In the map the Fourier transform of the error distribution $\varepsilon_{add}(u, v)$ is added to the intensity distribution, and we have

$$\mathcal{V}(u, v) + \varepsilon_{add}(u, v) \rightleftharpoons I(l, m) + \overline{\varepsilon}_{add}(l, m). \qquad (10.44)$$

intens... which...

The response to an extended source is the convolution of the sky intensity $I(l, m)$ with the synthesized beam $b_0(l, m)$. Note that since there is often no measured visibility value at the (u, v) origin, the integral of $b_0(l, m)$ over all angles is zero; that is to say, there is no response to a uniform level of intensity. At any point on the extended source where the intensity varies slowly compared with the width of the synthesized beam, the convolution with $b_0(l, m)$ results in a flux density that is approximately $I\Omega_0$. Thus the scale of the map can also be interpreted as intensity measured in units of flux density per beam area Ω_0. For a discussion of mapping wide sources and measuring the intensity of extended components of low spatial frequency, see Section 11.6.

Errors in Maps

A very useful technique for investigating suspicious or unusual features in any synthesis image, continuum or spectral line, is to compute an inverse Fourier transform (i.e., from intensity to visibility) including only the feature in question. A distribution in the (u, v) plane concentrated in a single baseline, or in a series of baselines with a common antenna, could indicate an instrumental problem. A distribution corresponding to a particular range of hour angle of the source could indicate the occurrence of sporadic interference.

An aid in identifying erroneous features is a familiarity with the behavior of functions under Fourier transformation; see, for example, Bracewell (2000) and the discussion by Ekers (1999). A persistent error in one antenna pair will, for an east–west spacing, be distributed along an elliptical ring centered on the (u, v) origin, and in the (l, m) plane will give rise to an elliptical feature with a radial profile in the form of the zero-order Bessel function. An error of short duration

resolution arrays with narrow bandwidths. Cross-coupling of noise (crosstalk) occurs only between closely spaced antennas and is most severe for low elevation angles when shadowing of antennas may occur.

A second class of errors comprises those that combine with the visibility in a multiplicative manner, and for these we can write

$$\mathcal{V}(u, v)\varepsilon_{mul}(u, v) \rightleftharpoons I(l, m) ** \overline{\varepsilon}_{mul}(l, m). \qquad (10.45)$$

The Fourier transform of the error distribution is convolved with the intensity distribution, and the resulting distortion produces erroneous structure connected with the main features in the map. In contrast, the distribution of errors of the additive type is unrelated to the true intensity pattern. Multiplicative errors mainly involve the gain constants of the antennas, and result from calibration errors including antenna pointing and, in the case of VLBI systems, radio interference (see Section 15.3).

Distortions that increase with distance from the center of the map constitute a third category of errors. These include the effects of non-coplanar baselines (see Sections 3.1 and 11.8), bandwidth (see Section 6.3), and visibility averaging (see Section 6.4), which are predictable and therefore somewhat different in nature from the other distortions mentioned above.

Hints on Planning and Reduction of Observations

Making the best use of synthesis arrays and similar instruments requires an empirical approach in some areas, and the best procedures for analyzing data are ...ained by experience. Much helpful information exists in the handbooks on ... instruments, symposium proceedings, and so on; see, for example, Bridle ... A few examples are discussed below.

...hoosing the observing bandwidth for continuum observations, the radial ...ng effect should be considered, since the signal-to-noise ratio for a point ...near the edge of the field is not necessarily maximized by maximizing the ...idth. Then in choosing the data-averaging time the resulting circumferen... ...earing can be about equal to the radial effect. The required condition is ...d from Eqs. (6.75) and (6.80) and for high declinations is

$$\frac{\Delta\nu}{\nu_0} \simeq \omega_e \tau_a. \qquad (10.46)$$

Dual Beam/Dual Mode

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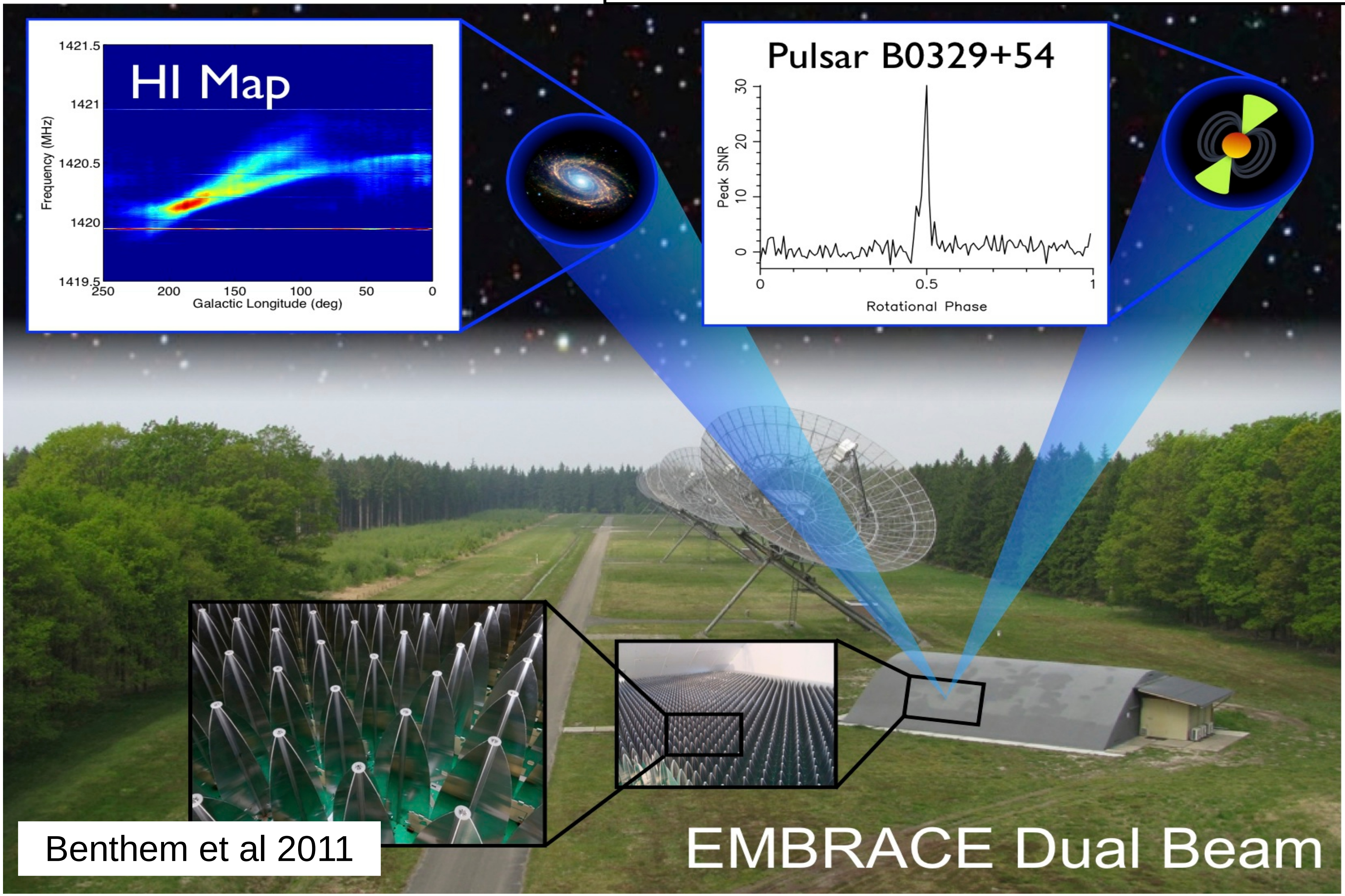


Galaxy Detection: M33

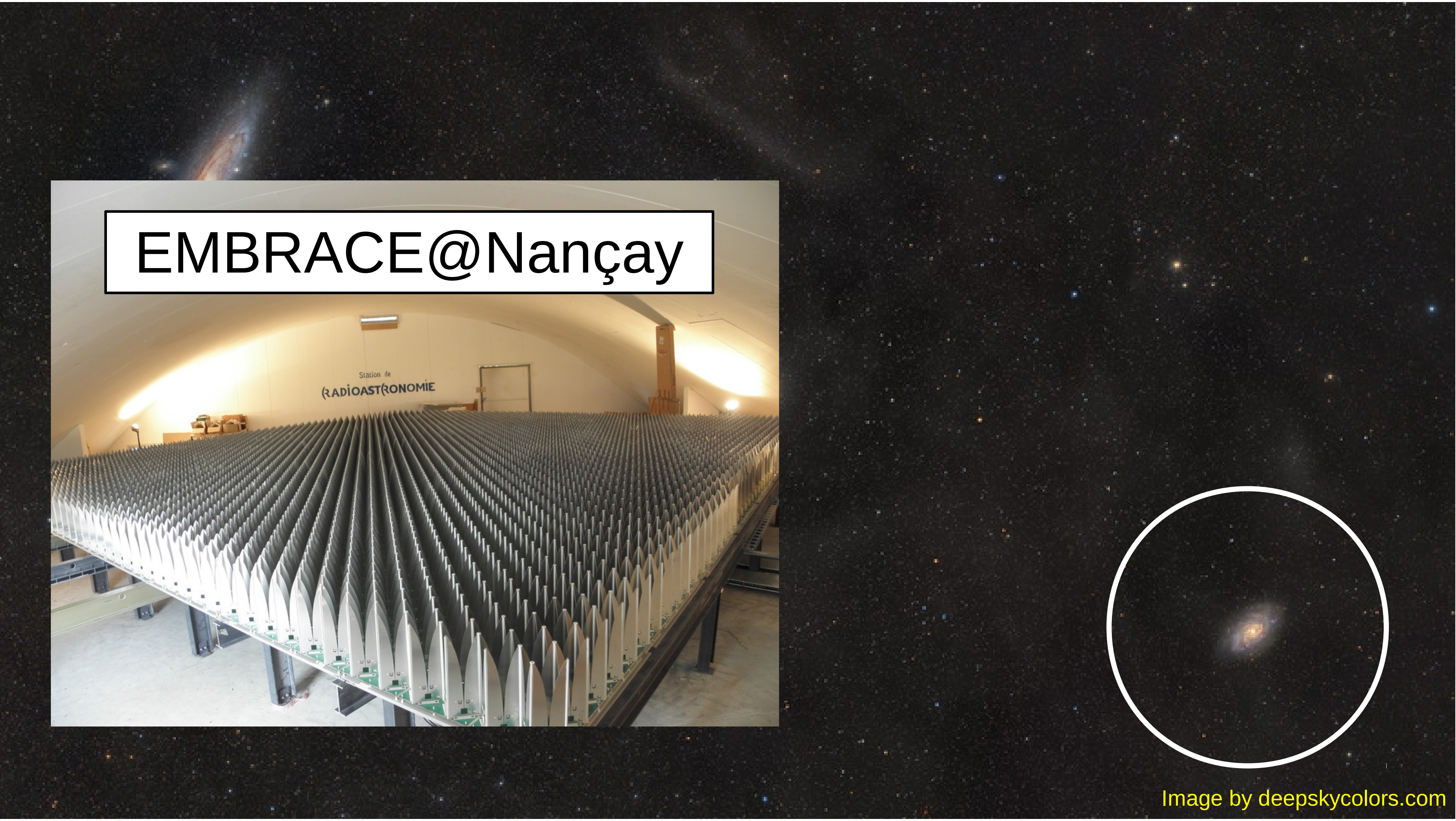
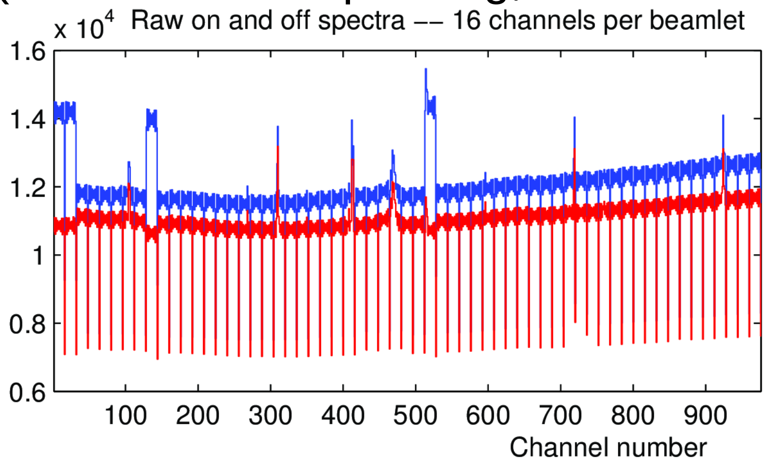
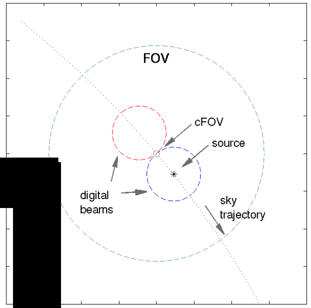


Image by deepskycolors.com

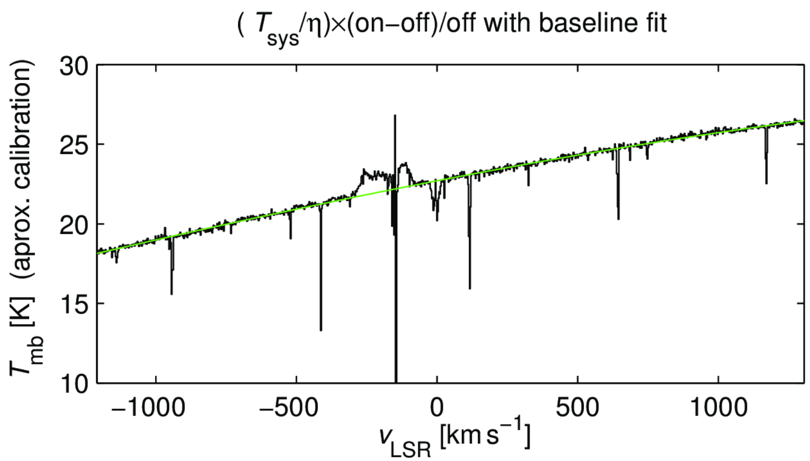
Galaxy Detection: M33

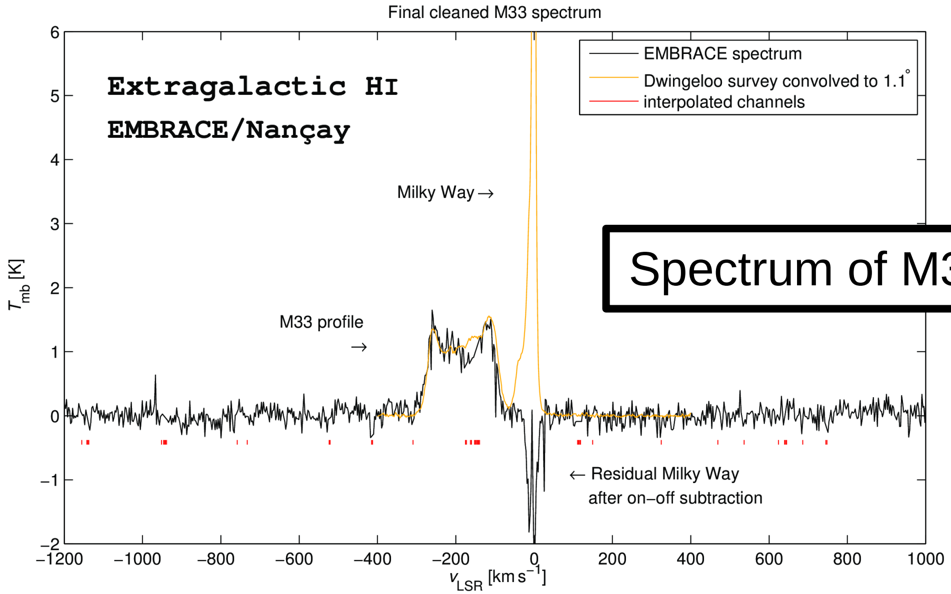
OFF timeline shifted to align with ON
(i.e. same Az-El pointing, earlier time)





(ON – OFF)/OFF





Spectrum of M33

Baseline fit and interpolate past RFI channels

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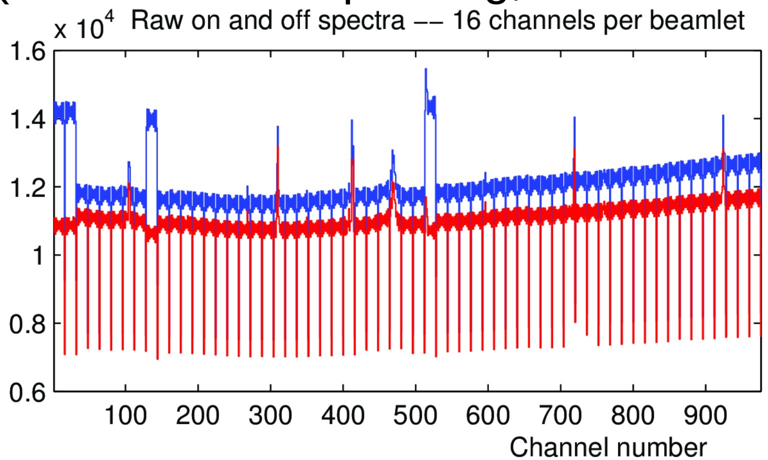
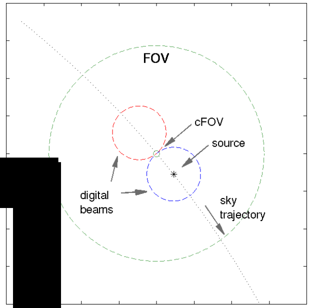
Galaxy Detection: M33

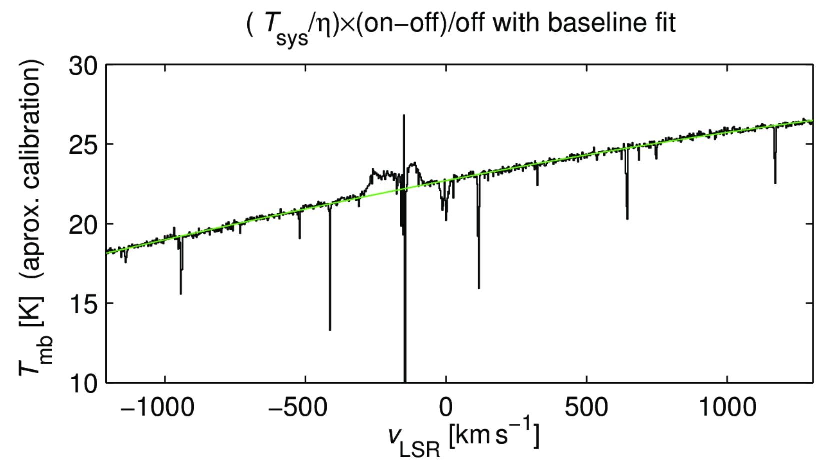
SKA SQUARE KILOMETRE ARRAY
MID-FREQUENCY APERTURE ARRAY

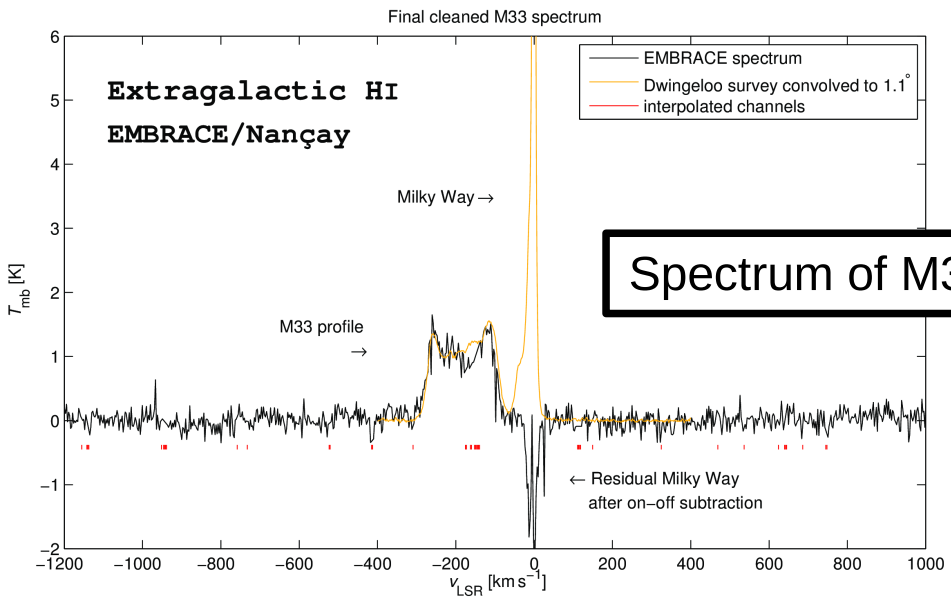
OFF timeline shifted to align with ON
(i.e. same Az-El pointing, earlier time)





(ON – OFF)/OFF





Spectrum of M33

Baseline fit and interpolate past RFI channels

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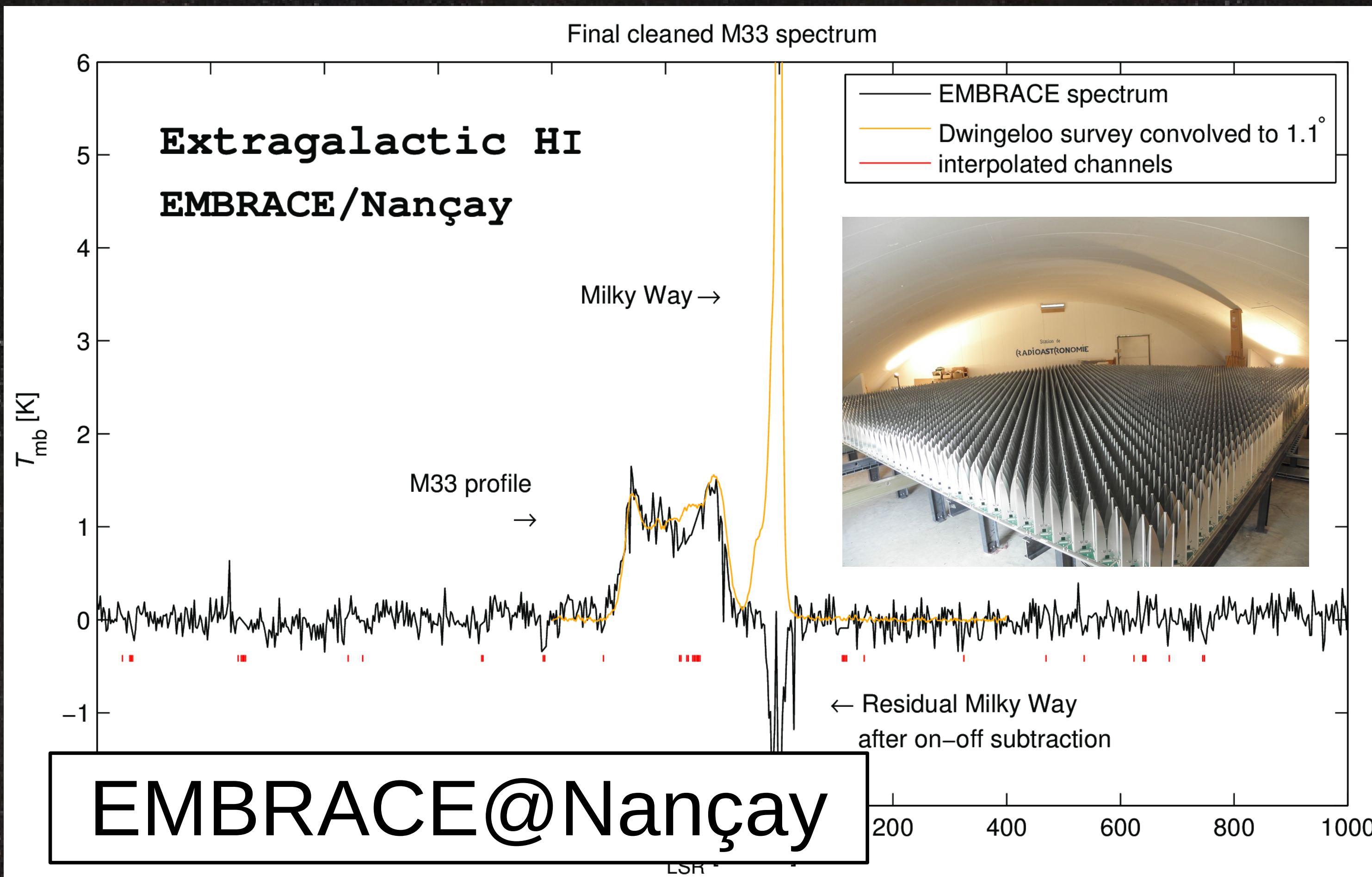
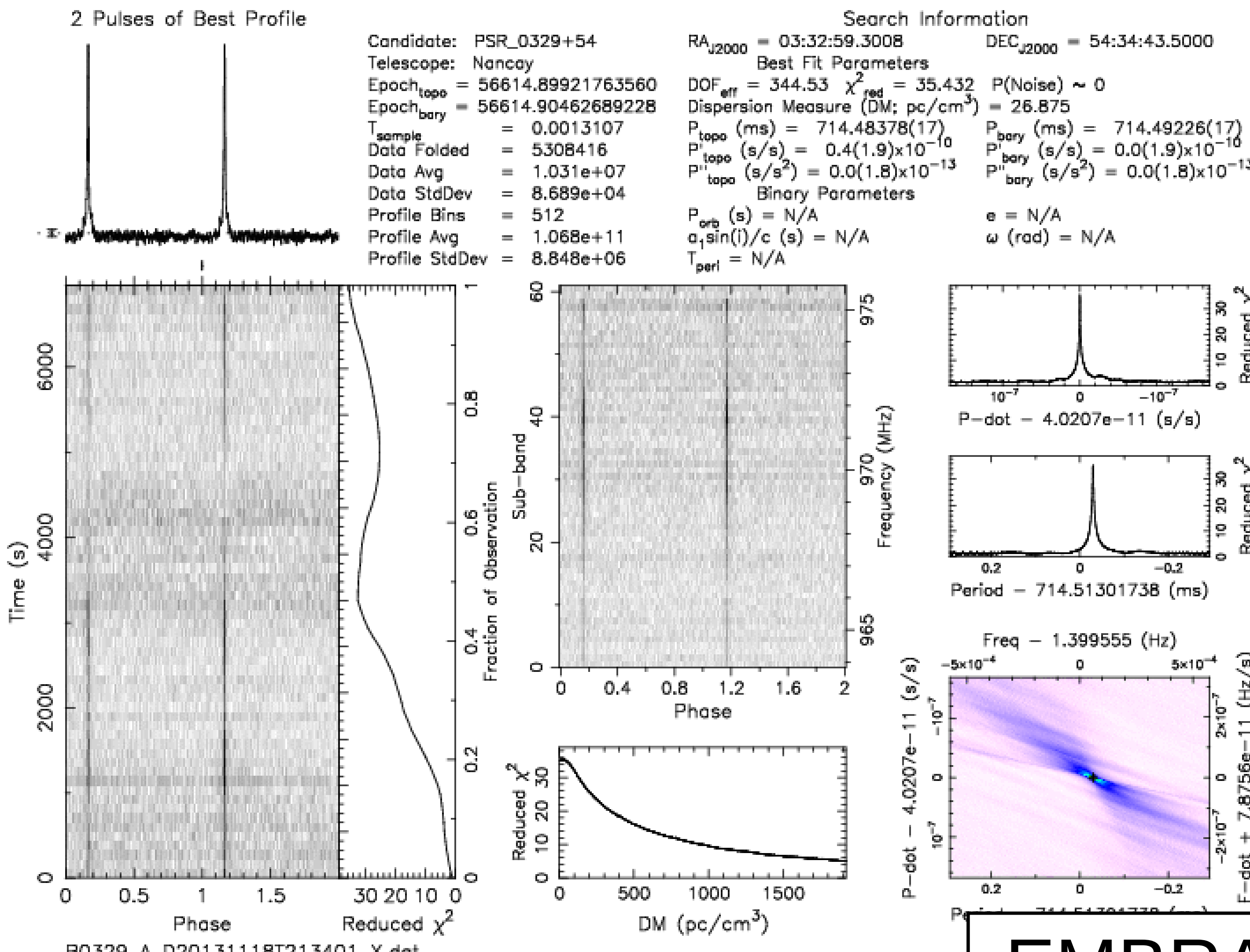
Galaxy Detection



Only 999 999 999 to go ...

Pulsar monitoring



53 observations at 970MHz to date

- Programme of (nearly) daily monitoring of pulsar B0329+54 at 970MHz and 1176MHz simultaneously
- Possibility to detect accretion events in the long term (see e.g. Brook et al. ArXiv:1311.3541v1)

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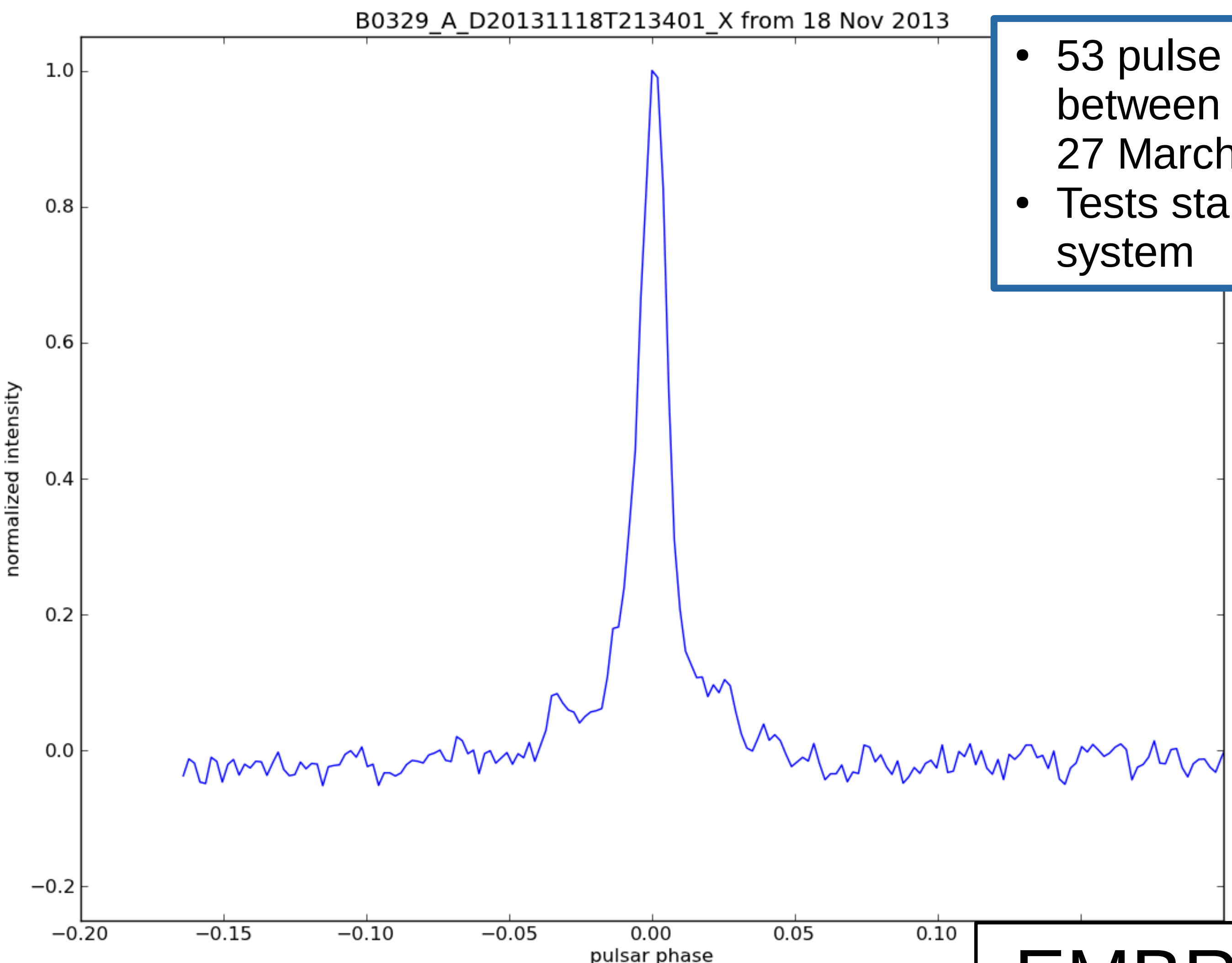
B0329+54 at 970MHz



- 53 pulse profile measurements between 18 Nov 2013 and 27 March 2014
- Tests stability and reliability of the system

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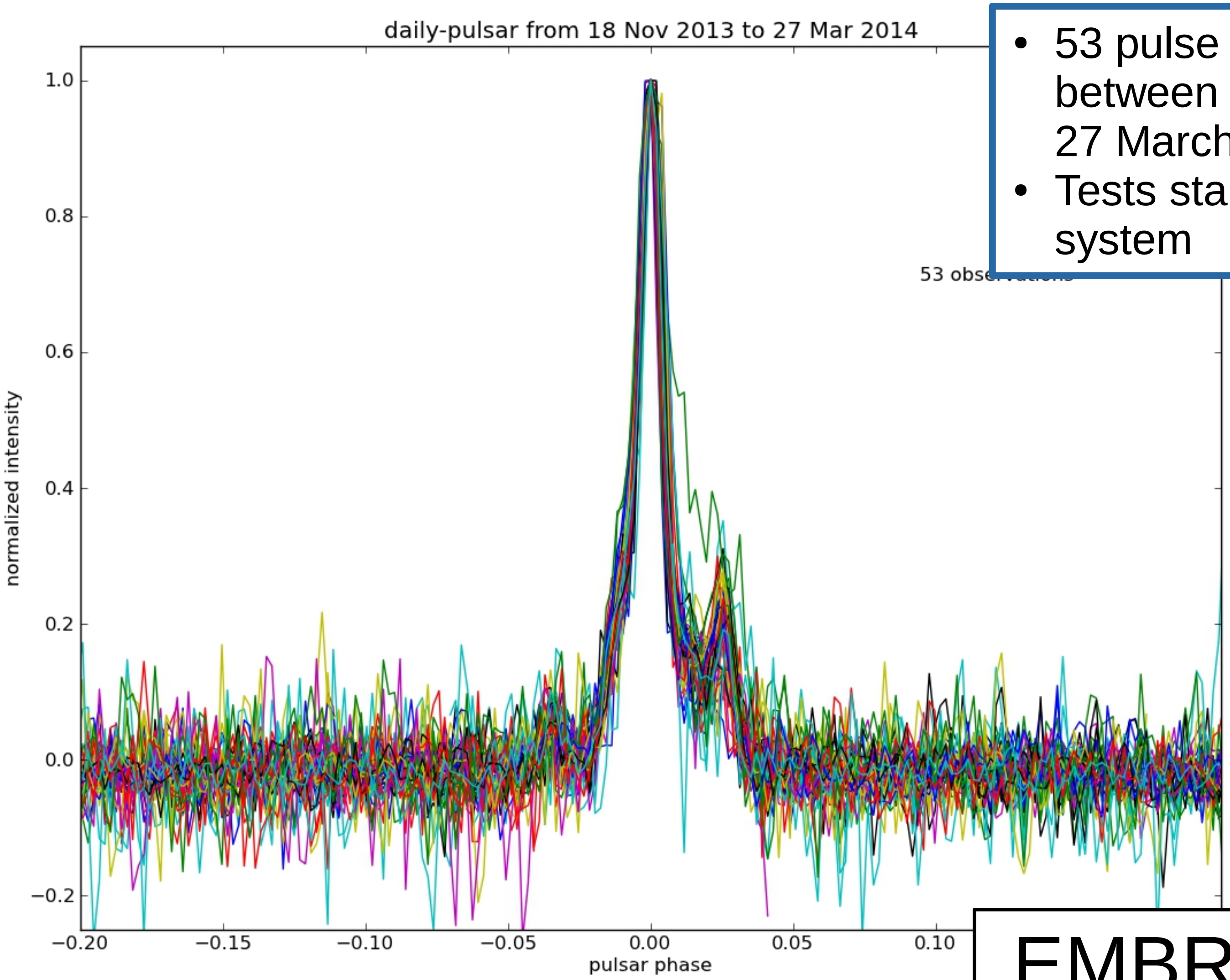
B0329+54 at 970MHz



- 53 pulse profile measurements between 18 Nov 2013 and 27 March 2014
- Tests stability and reliability of the system

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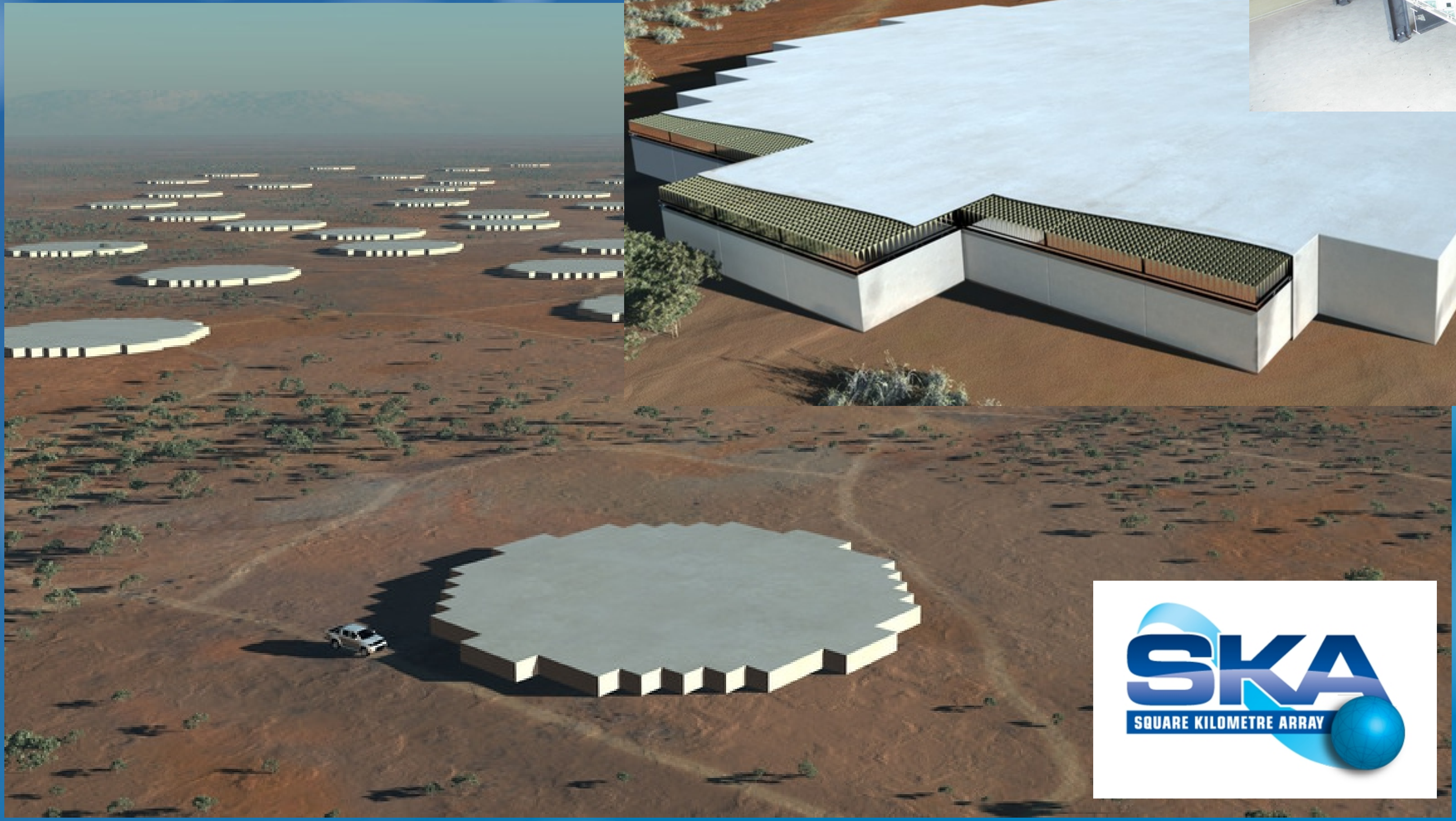
EMBRACE Future Work

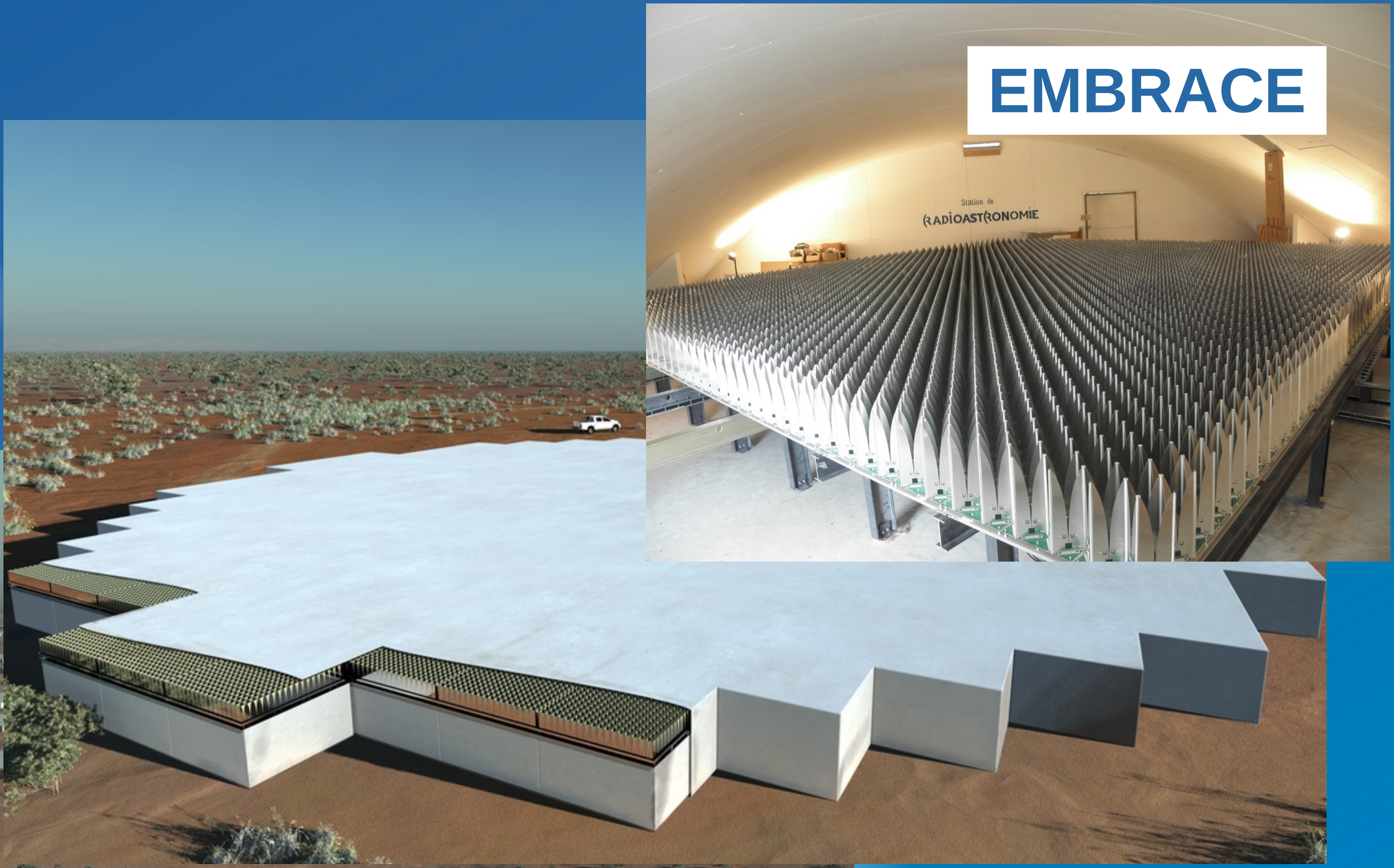
- astro observations
  - daily pulsar B0329+54 at two frequencies: 970MHz 1176MHz
    - possible detection of an accretion event on B0329
    - a good demonstration of long term stability and reliability
  - repeat M33: spectroscopic detection of a galaxy
  - mapping M31 with multibeams (M31 is the Andromeda Galaxy)
  - M42 Radio Recombination Lines (M42 is the Orion Nebula)
    - High spectroscopic resolution observation
- technical tests/improvements
  - implement improved calibration for tilesets
    - i.e. better similarity of pointing and main lobe profile between tilesets
  - use full bandwidth: i.e. 186 beamlets
    - up to now, almost all our tests are with only 61 beamlets
  - 3-lane data acquisition from the RSPs
  - acquisition on UNIBOARD with integrated real-time RFI flagging
  - simultaneous data acquisition of the same beam on different acquisition systems (ARTEMIS and UNIBOARD)

Dense Aperture Array for SKA

Steve Torchinsky

Station de Radioastronomie de Nançay





SKA
SQUARE KILOMETRE ARRAY