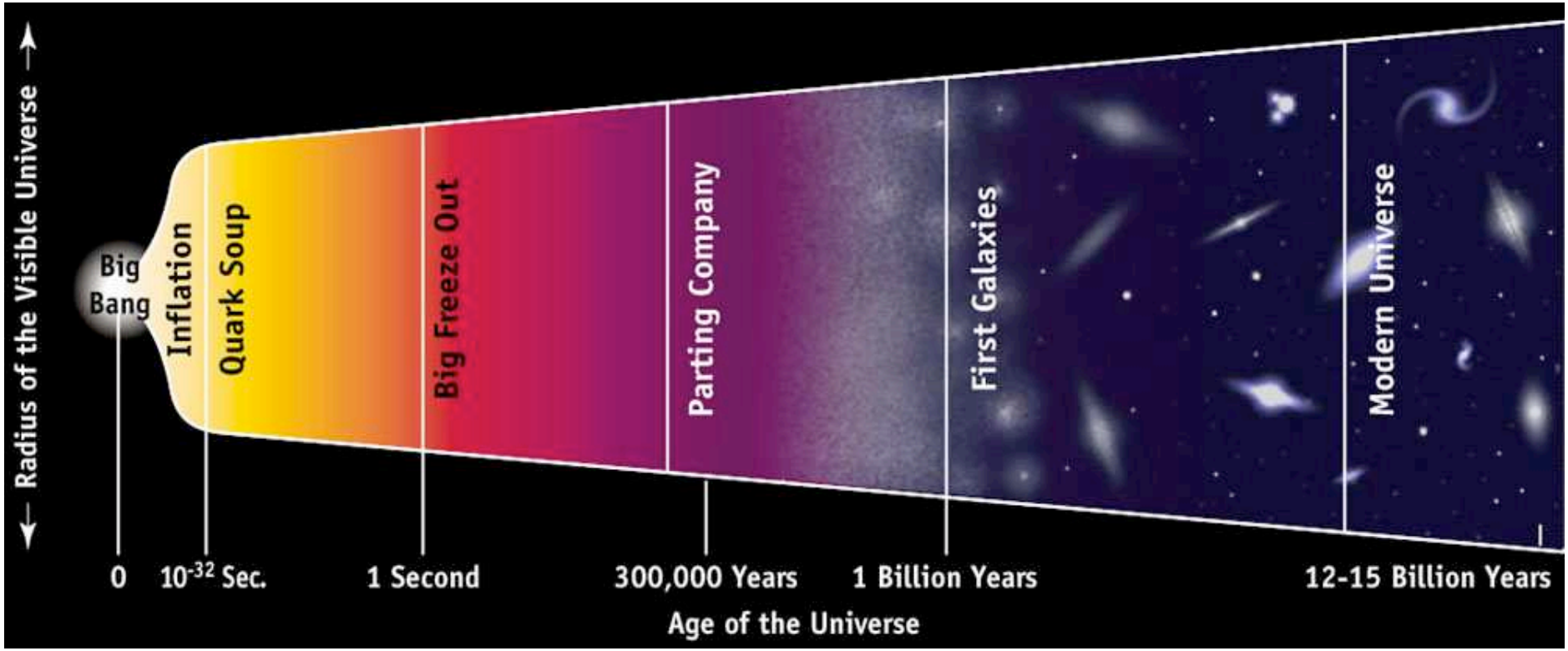
21cm Observations of the Epoch of Reionization

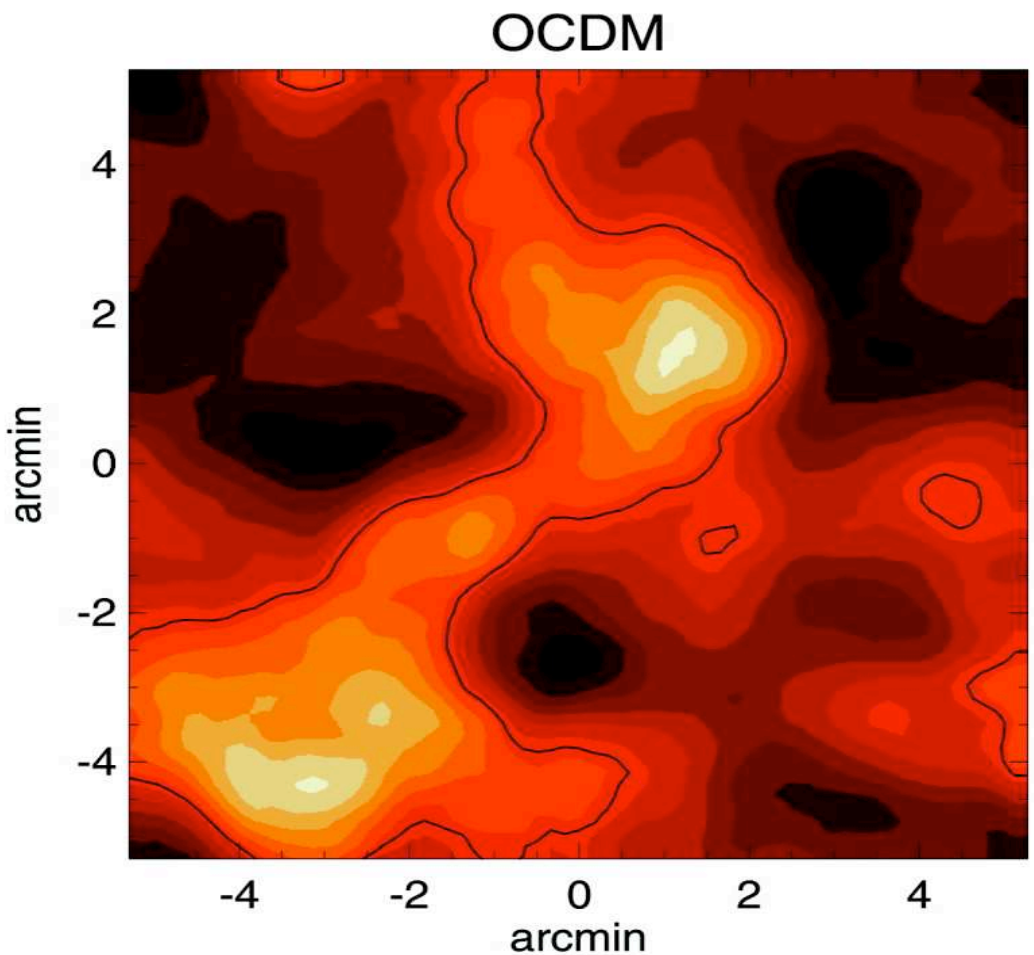
Jacqueline N. Hewitt
for the Mileura Widefield Array collaboration

Epoch of (Reheating and) Reionization



Reheating

HI Fluctuations



z=8.5

Size of box is 20/h comoving Mpc

Resolution = 1'
Bandwidth = 1 MHz
Frequency = 150 MHz

rms is about 10 mK

Tozzi et al. (2000), ApJ, 528, 597

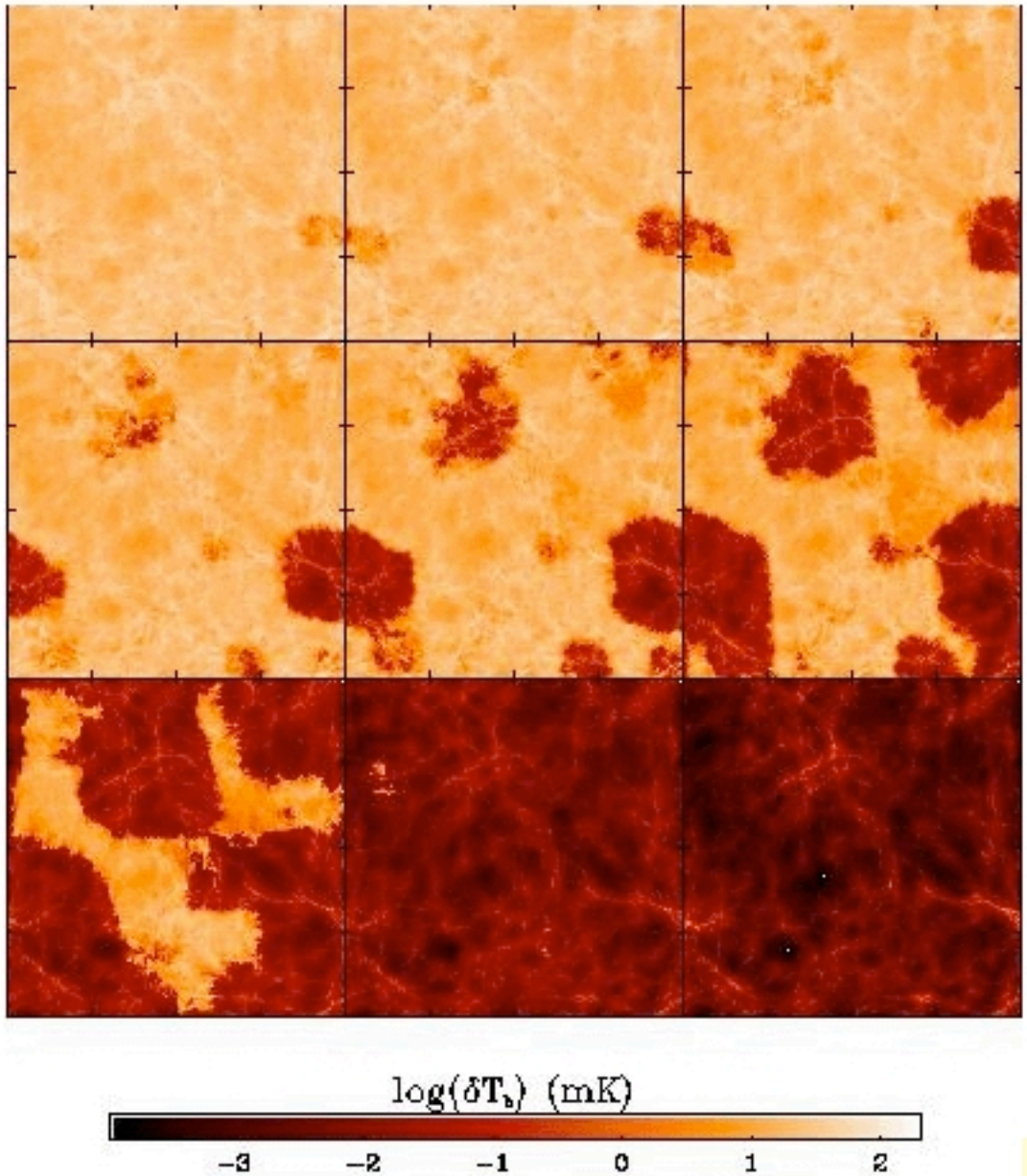
Reionization

z = 12.1, 11.1, 10.4, 9.8, 9.2, 8.7, 8.3, 7.9, 7.6

Bandwidth = 100 kHz
Box size = 10/h comoving Mpc

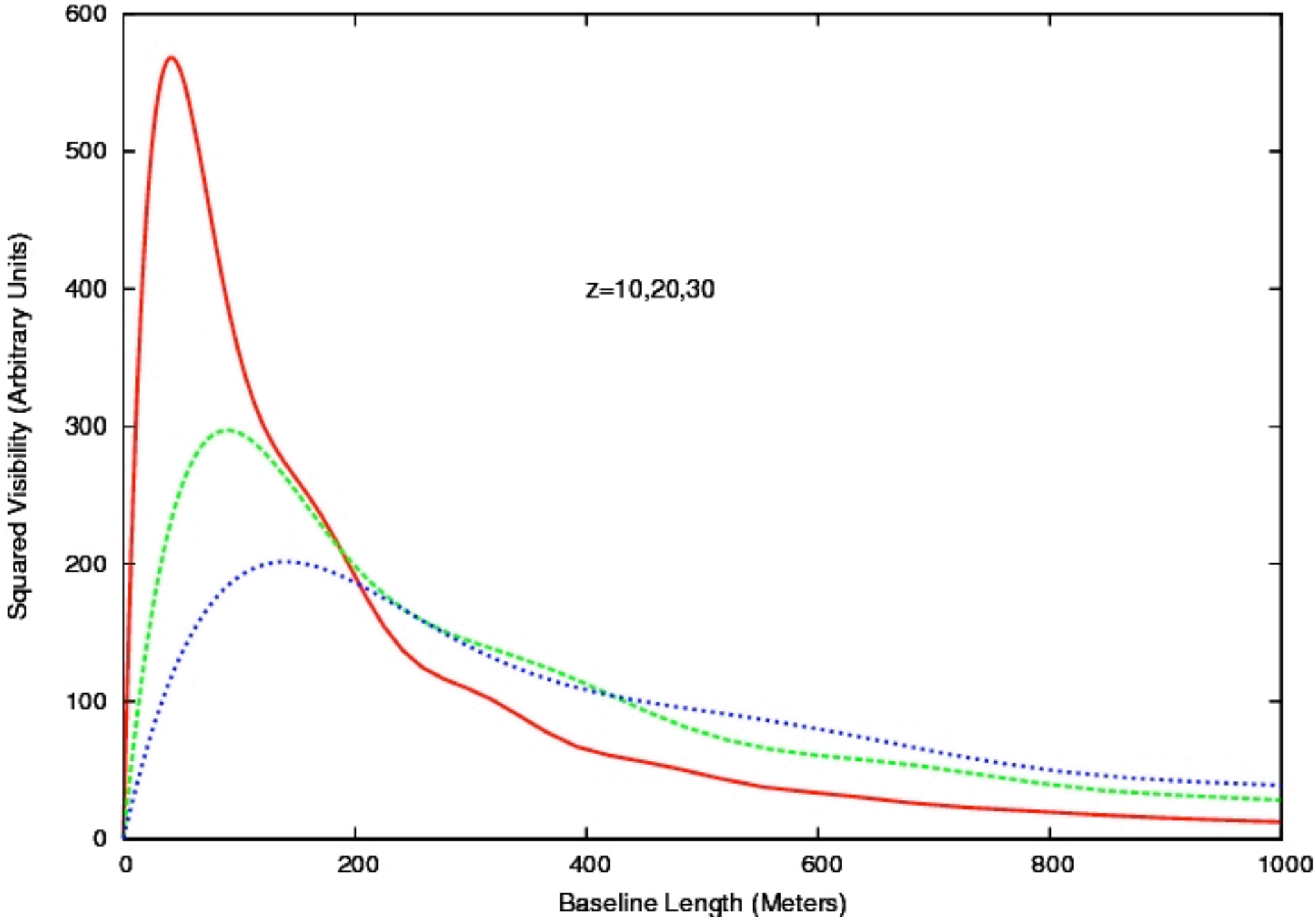
Fluctuations are about 10 mK

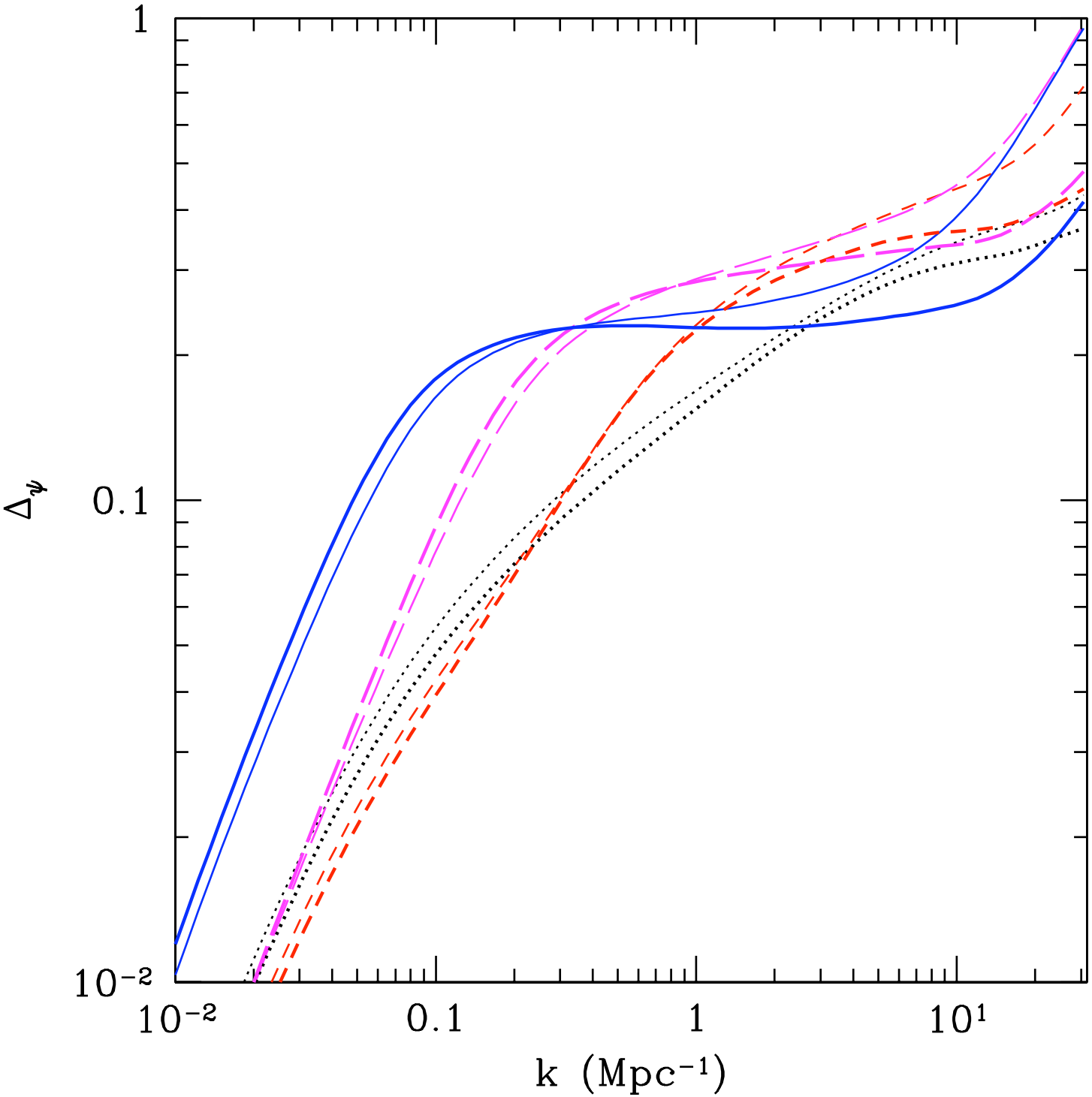
Furlanetto, Sokasian, Hernquist 2004



Power Spectrum

Reheating





Furlanetto, Zaldarriaga & Hernquist 2004
Ionization fraction
x = 0.96, 0.8, 0.5, 0.26

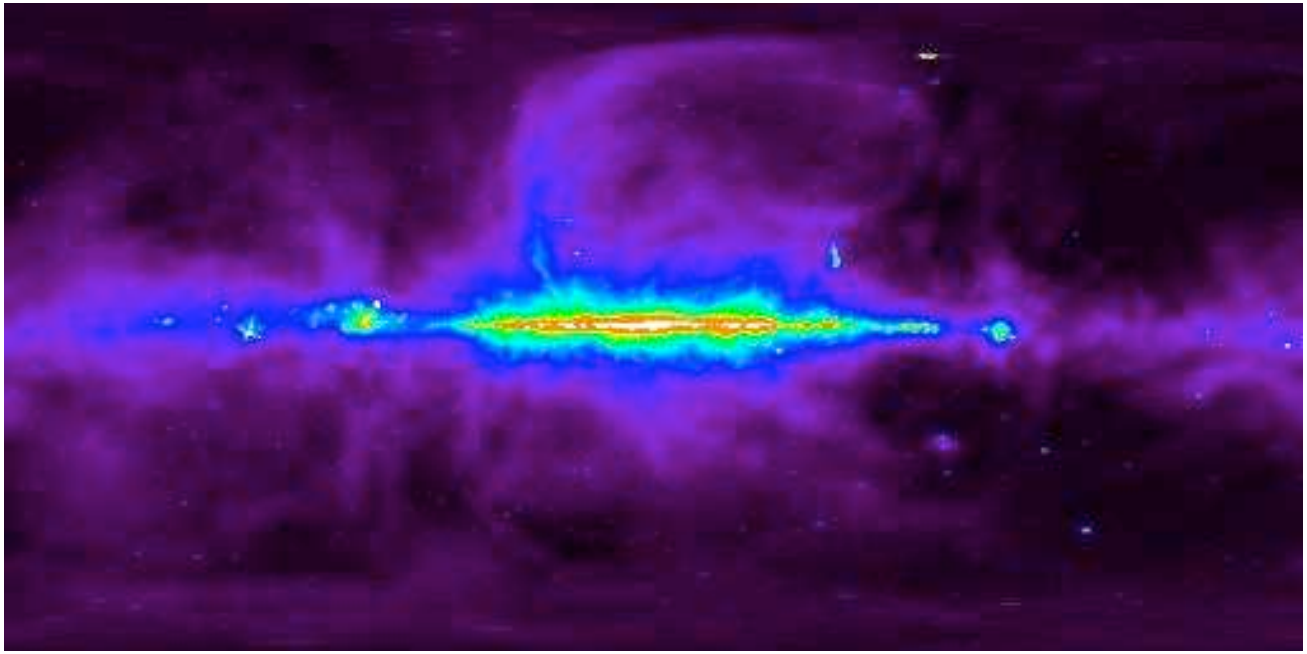
Many bubbles are large because of clustering

Fundamental Problem:
Low frequency radio astronomy is hard

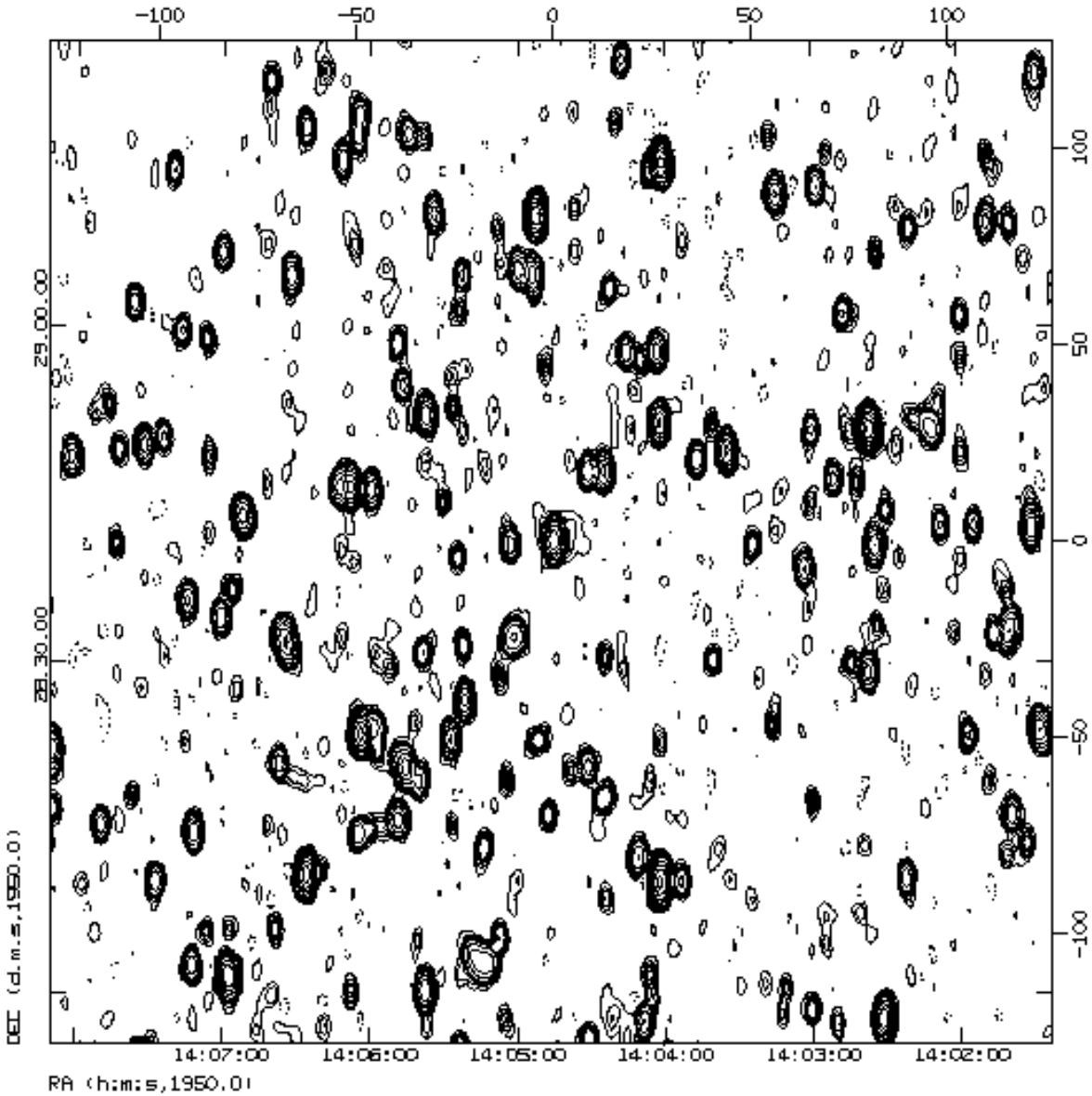
- Sky noise
- Confusion
- RFI
- Aperture synthesis flat sky approximation fails
- Ionospheric fluctuations
- Field of view larger than isoplanatic patch

408 MHz Radio Map of the Sky – 1982

Resolution 0.85 degrees

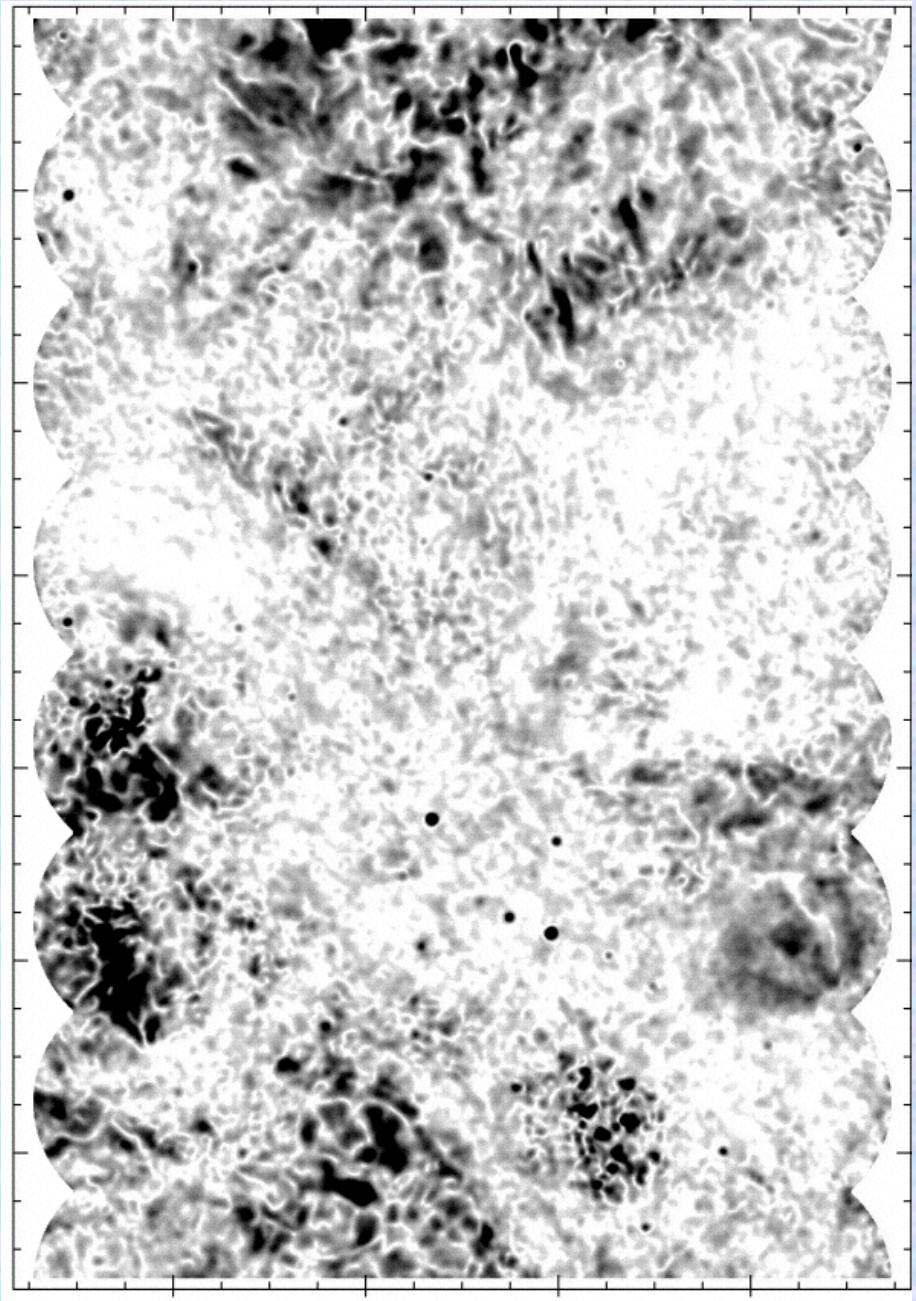


Haslam et al. 1982 A&A Supp 47 1



Westerbork map
325 MHz
1.5 X 1.5 degrees
Lowest contour = 4K

Polarimetry II



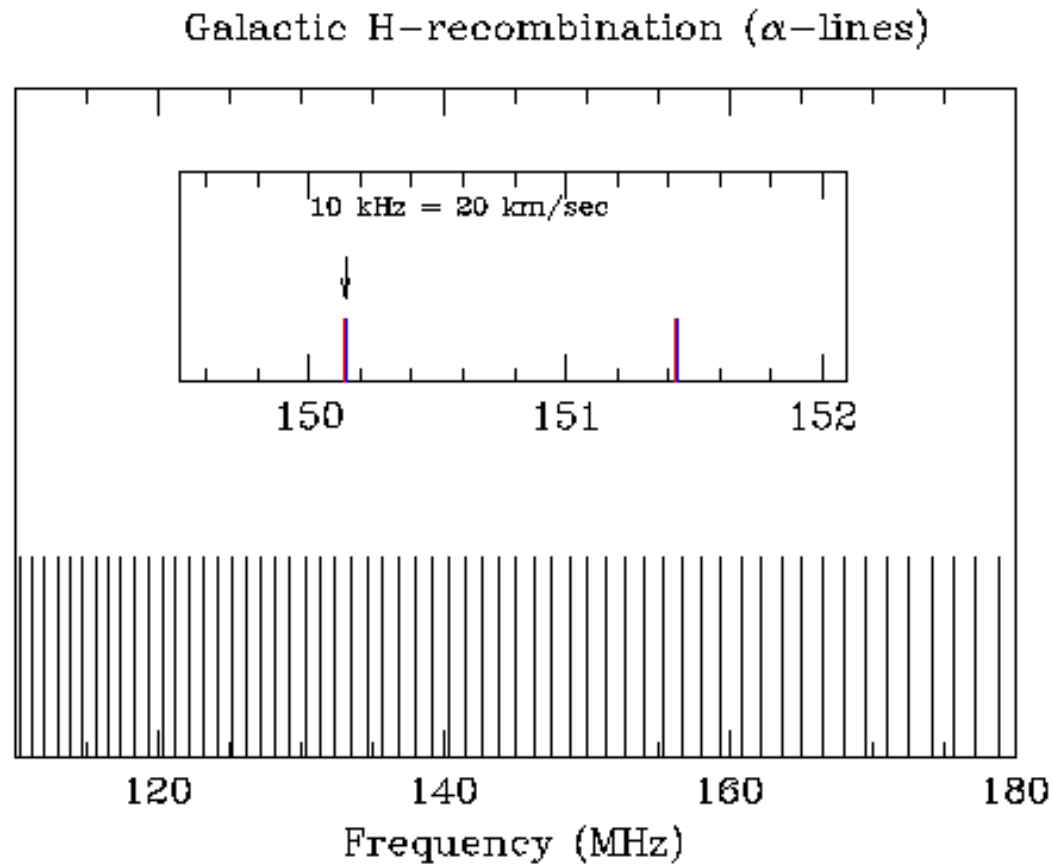
by Bryan Gaensler
Marijke Haverkorn

Polarization from Cygnus (Uyaniker et al 2003)

Galactic hydrogen/carbon recombination lines:

- In Galactic plane: ~100 - 500 mK (at 325 MHz, e.g. Roshi et al, 2001)
- Out of plane: probably less than 50 mK

Fluctuations on 3-10' scale probably an order of magnitude smaller still
Lines around 150 MHz probably weaker



NB: IF recomb lines are detected they will be helpful for fidelity checks.

Lines can easily be excised:

(~20 kHz / ~1 MHz or ~ 2% of spectrum)

de Bruyn 2005

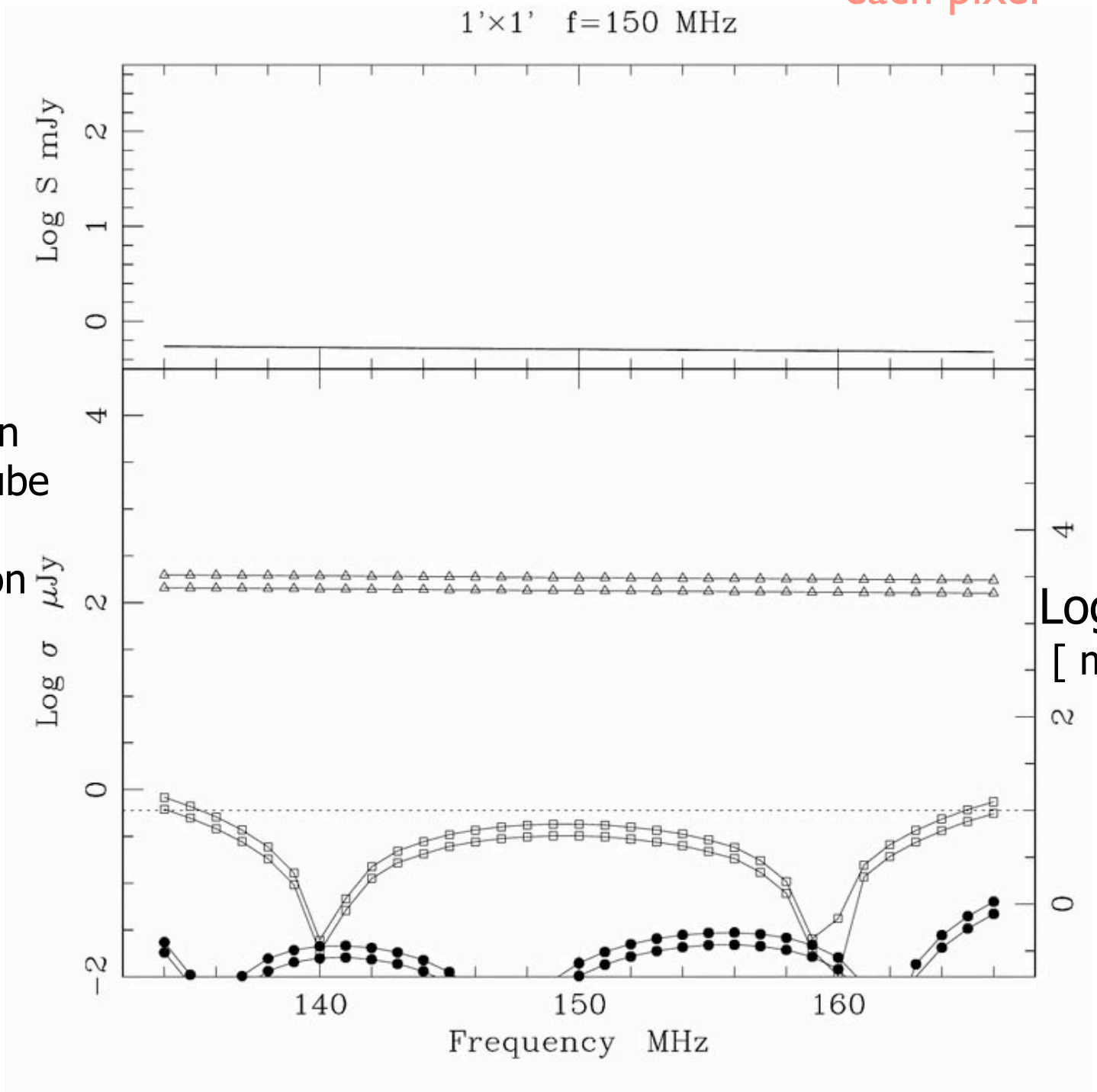
Briggs & de Bruyn, unpublished

After subtraction of continuum in each pixel

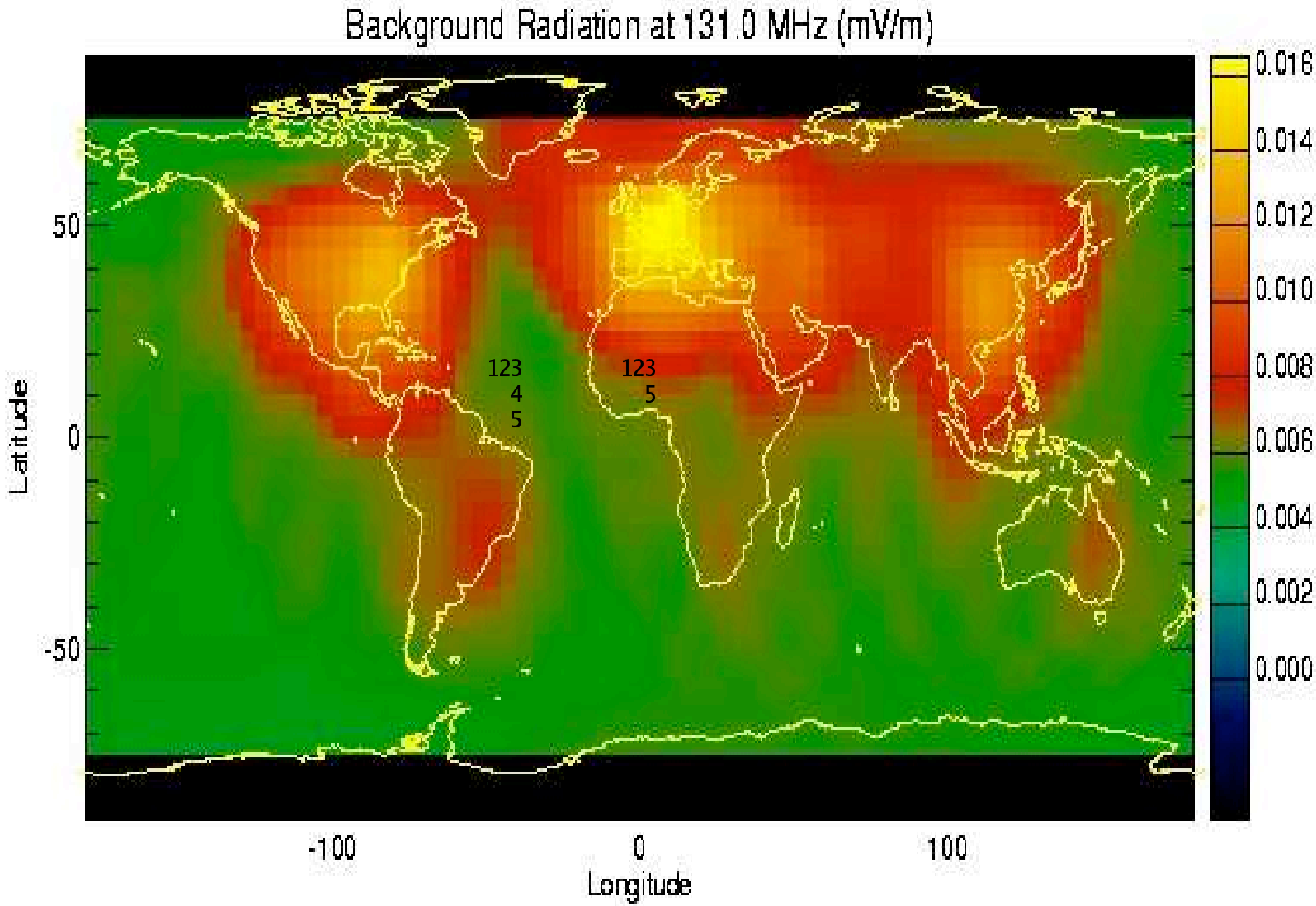
Average Flux Density per pixel

RMS fluctuation per plane in cube

- no subtraction
- linear
- quadratic



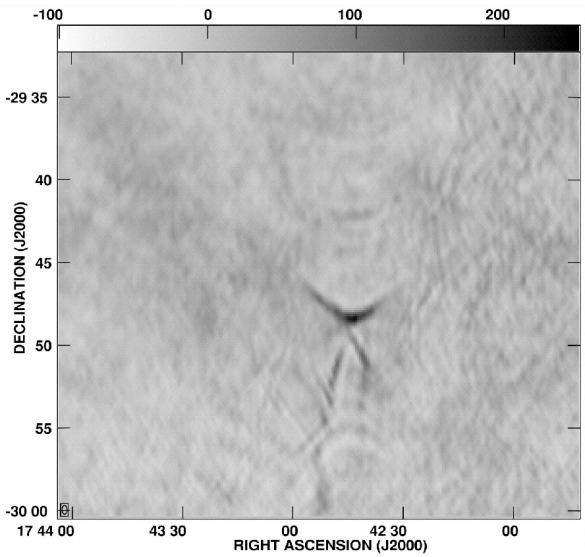
Radio Frequency Interference



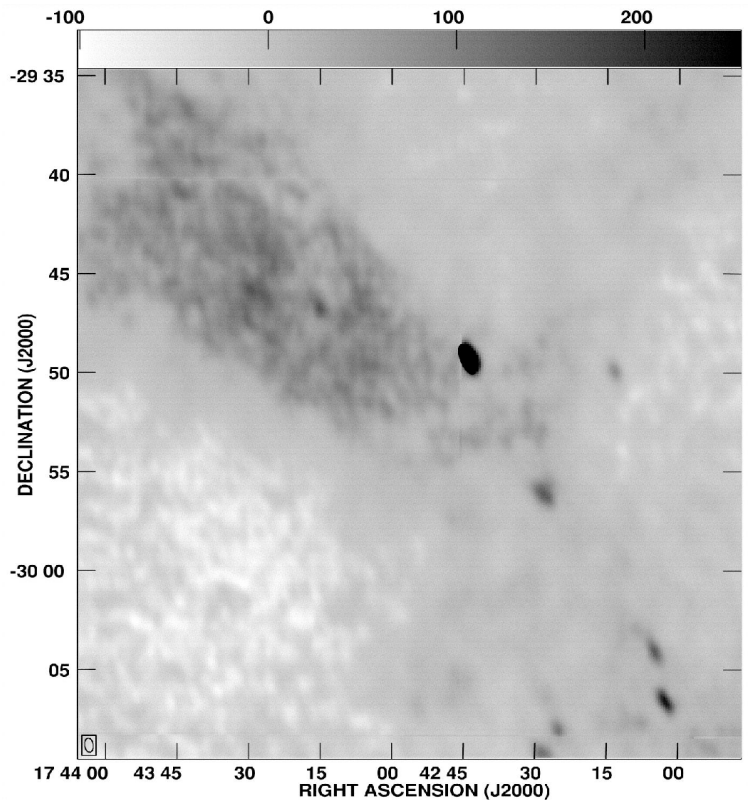
FORTES satellite

Wide-field Imaging

Unfaceted



Faceted



Ionospheric Fluctuations

Another approach: Measure grid of bright sources on short time scales; fit for phase variation across field

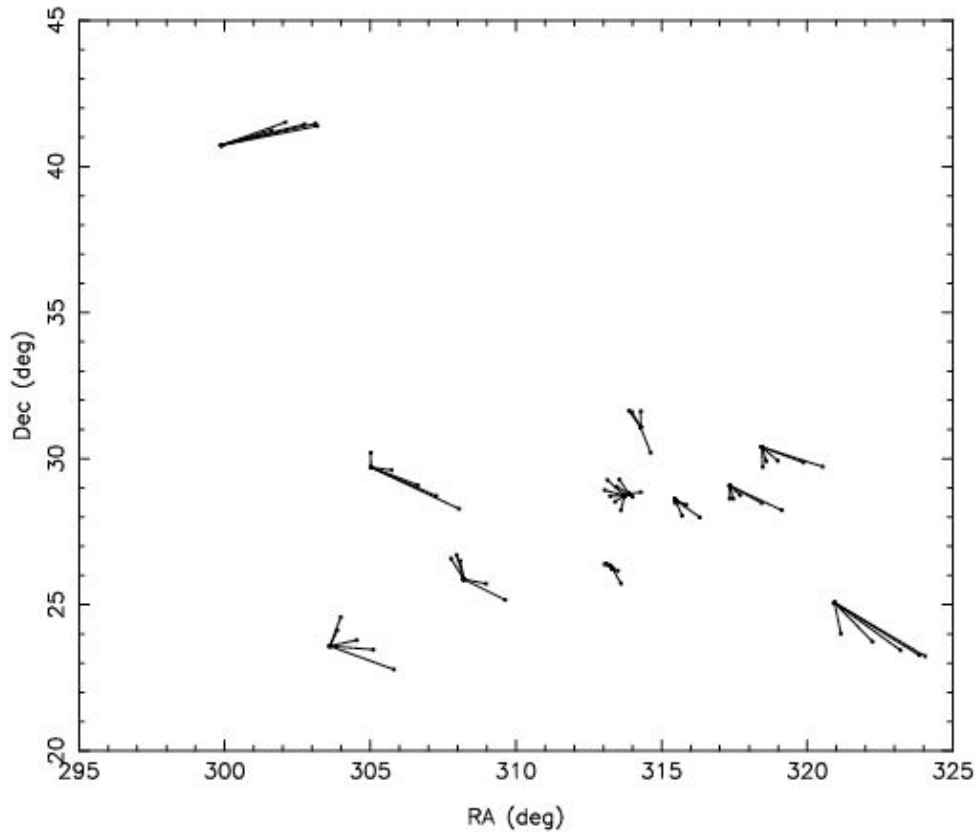


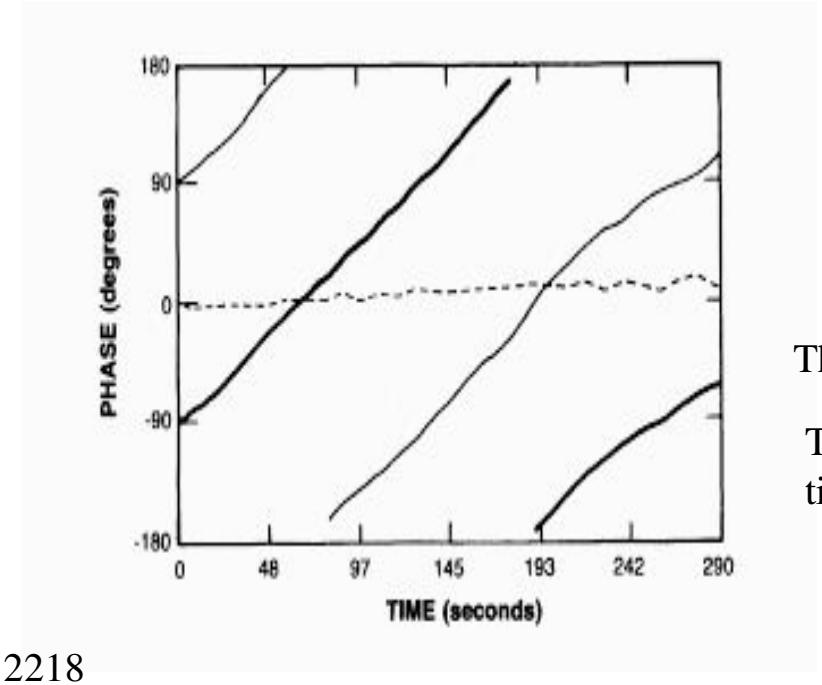
Fig. 11.— Position offsets (magnified ×100) for a variety of bright sources, derived from a series of one-minute snapshot images of a field at 74 MHz. The pointing center was ra = 315°, dec = 29.8°. The outlier source in the upper left corner is Cygnus A, which is bright enough to be easily visible 20° from the pointing center. It is clear that the refractive effects of the ionosphere vary across the field of view.

"Perley et al., "The 4-Meter All-Sky Survey"

Ionospheric Fluctuations

Electrical path length proportional to wavelength squared!

Ionospheric phase fluctuations are usually smooth in frequency and time



15 km VLA baseline

Thick line: 74 MHz phase

Thin line: 330 MHz phase times ratio of frequencies

Kassim et al. 1993 AJ 106 2218

“Field Calibration”

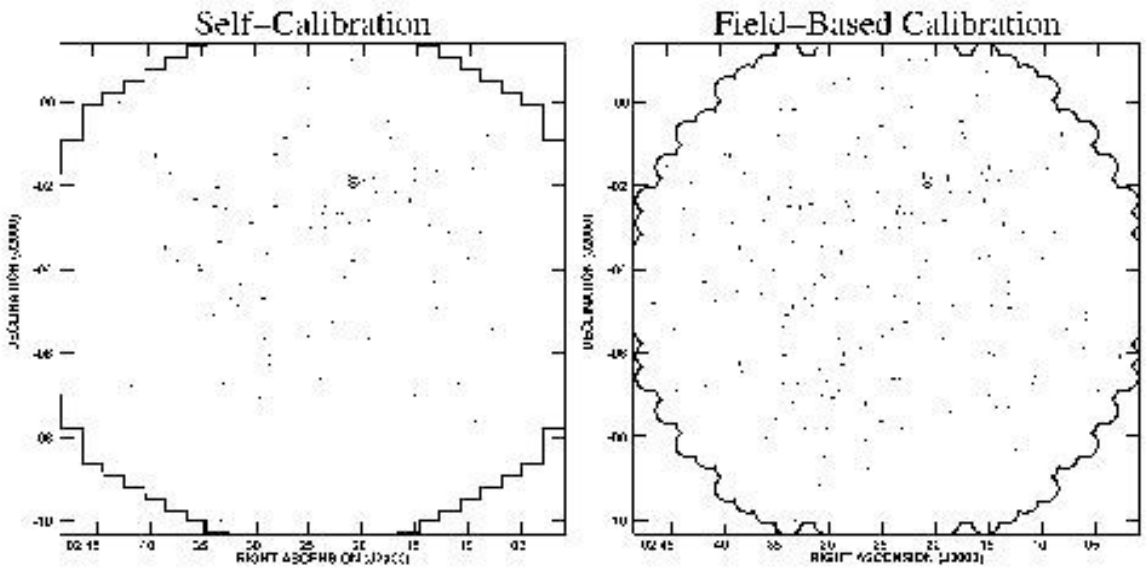


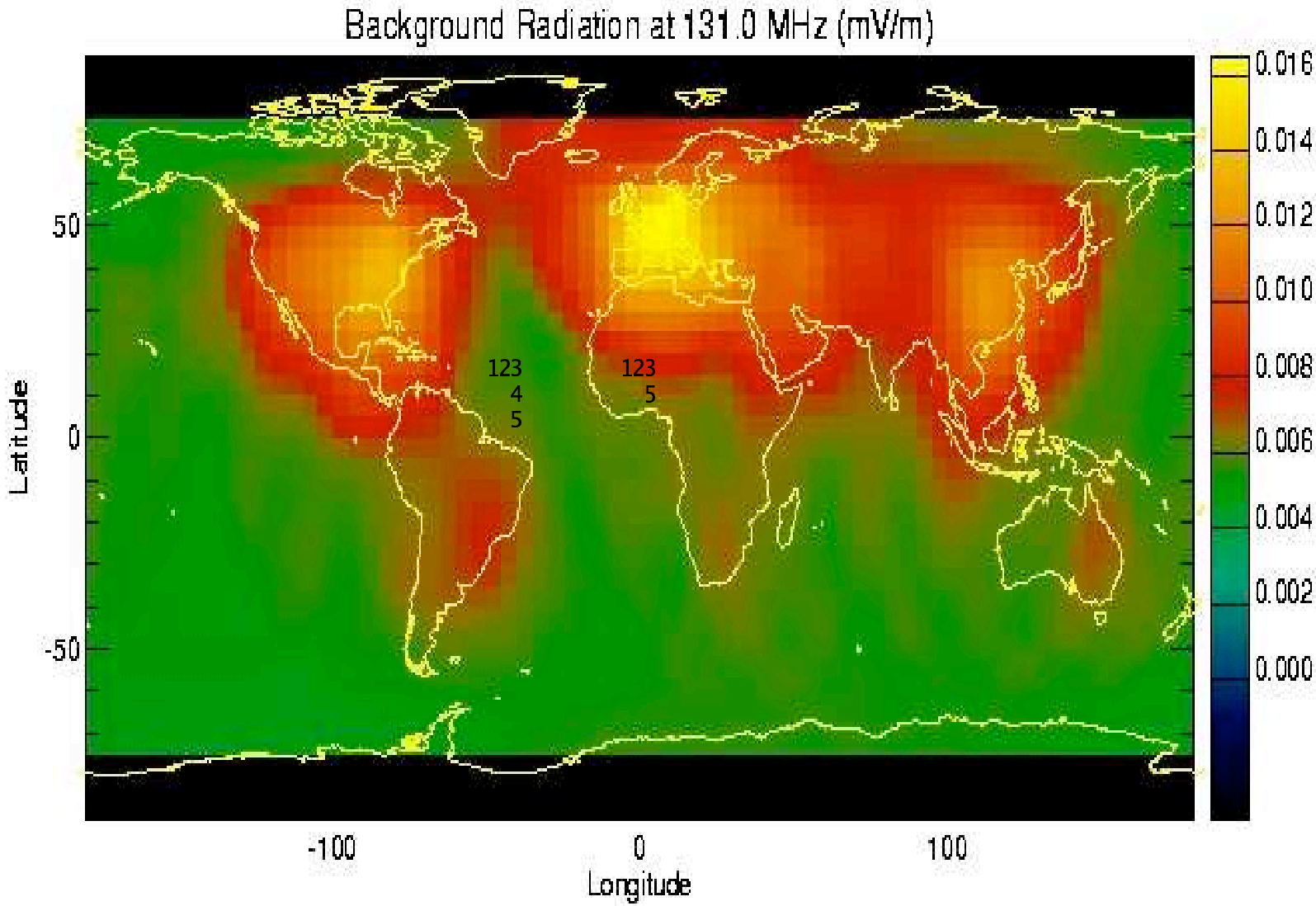
Fig. 1.— A comparison of traditional, angle-invariant self-calibration (left), and Zernike-based, angle-dependent field calibration (right). Both images show the positions of sources stronger than a set peak flux cutoff in maps made from the same dataset. The source circled in the upper right of each panel is a bright 3C source which dominates the field. Traditional self-calibration applies only a single phase correction and cannot correct the ionospheric phase fluctuations far from the 3C source. These uncorrected fluctuations appear as time variable refractive errors in the map which, when averaged, smear out the distant sources, causing them to effectively disappear. By contrast, the position dependent field calibration, as implemented by VLAFM, allows for varying phase corrections across the field of view. With the refractive errors corrected, source brightness is preserved, and the source distribution across the field is more uniform.

Perley et al., “The 4-Meter All-Sky Survey”

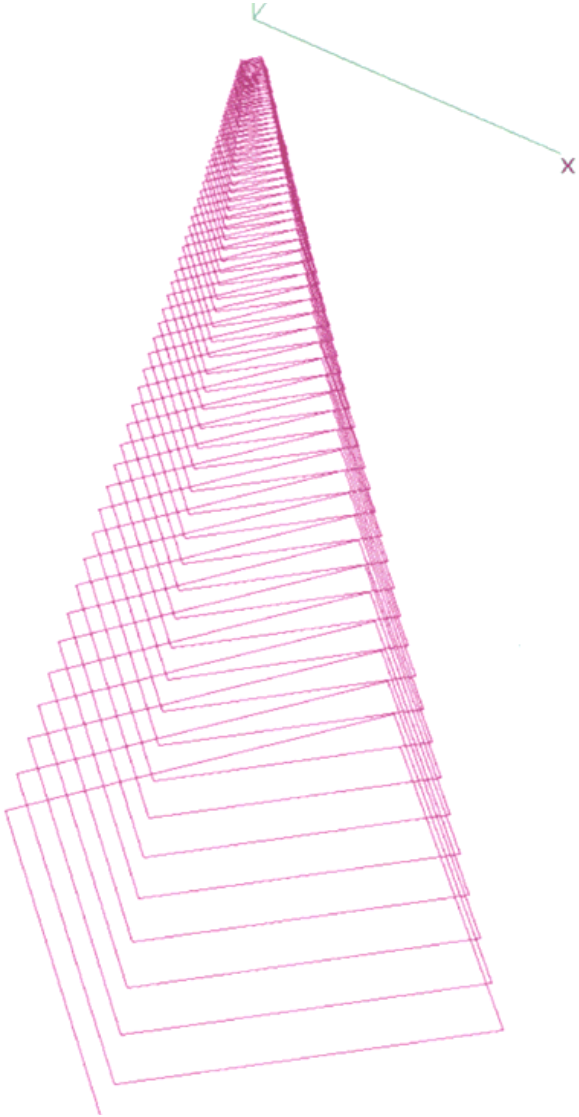
EOR Experiments

Expt	Freq (MHz)	FOV (deg)	N	A (sq m)	B (km)	Cost
Ekers	114-228	60	1		0	small
VLA	190-200	4.3	27	4000	1	small
MWA	80-240	20-25	500	8000	1	$10M
PaST	70-200	2 (one pol)	15	70,000	3?	??
LOFAR	30-80,120-200	2	32 in core	100,000	2-100	$100M?
SKA	100-25,000?	Large?	?	1,000,000	Need core for EOR	$1B

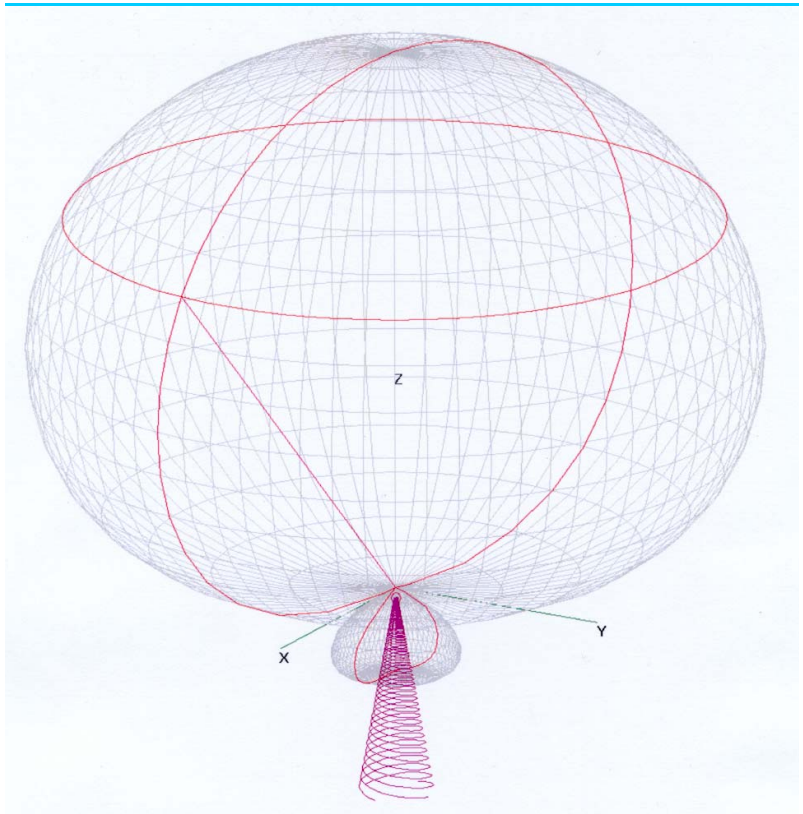
Radio Frequency Interference



FORTES satellite



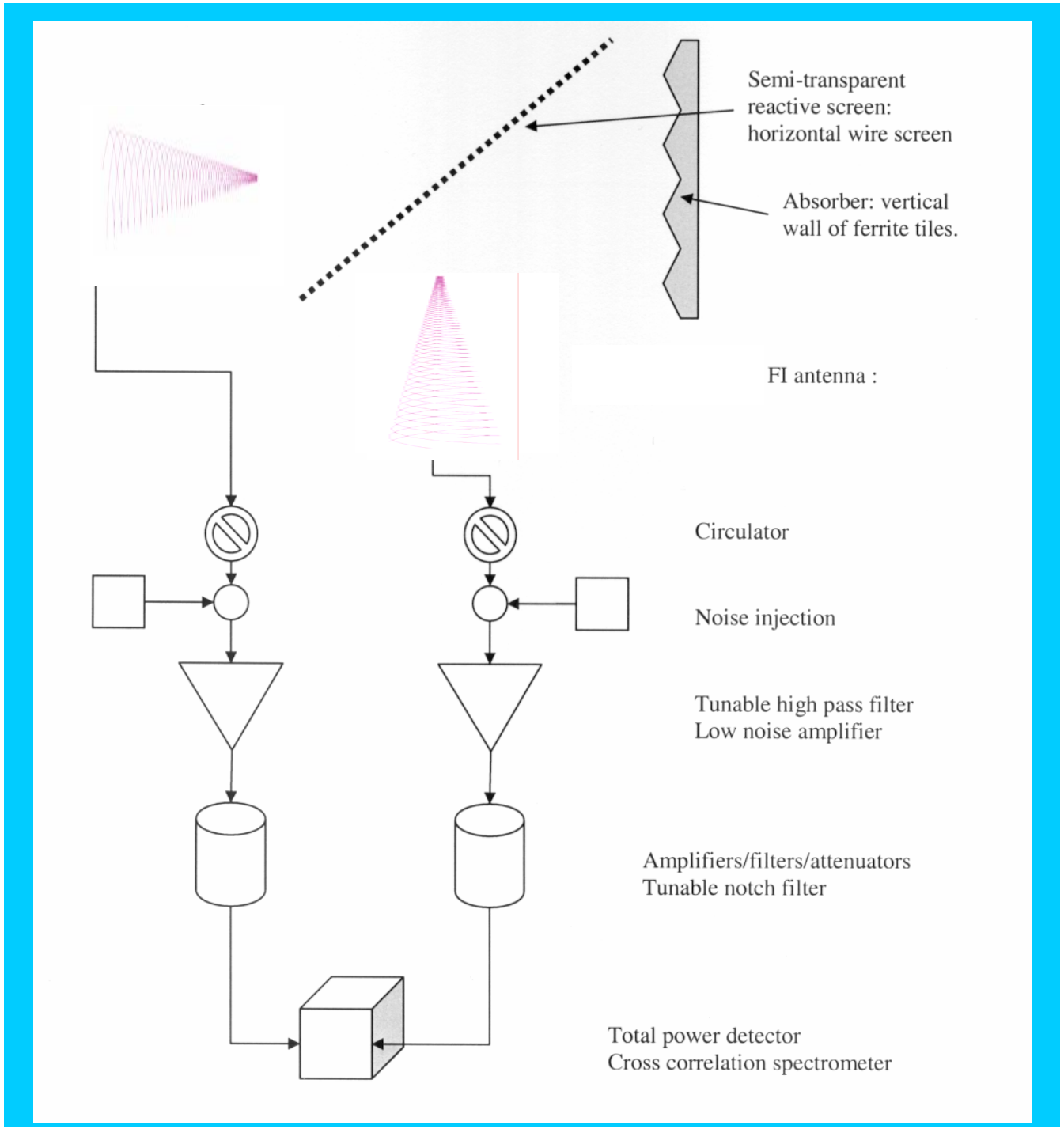
Goal: frequency independent beam over one octave of bandwidth



Subrahmanyan, Ekers, Chippendale 2005

Initial tests at Sydney

Subrahmanyan, Ekers,
Chippendale 2005



Subrahmanyan, Ekers, Chippendale 2005

EOR Experiments

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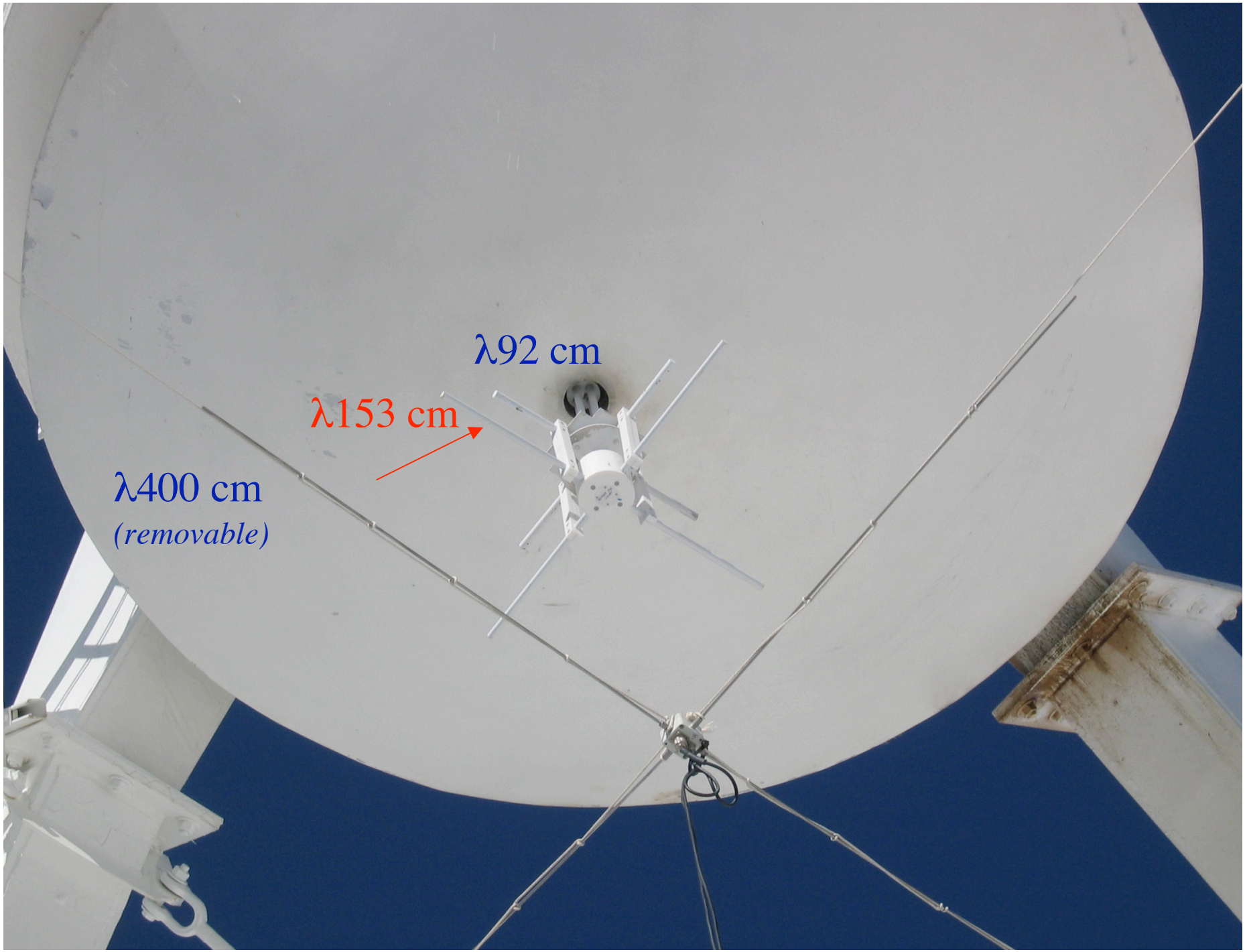
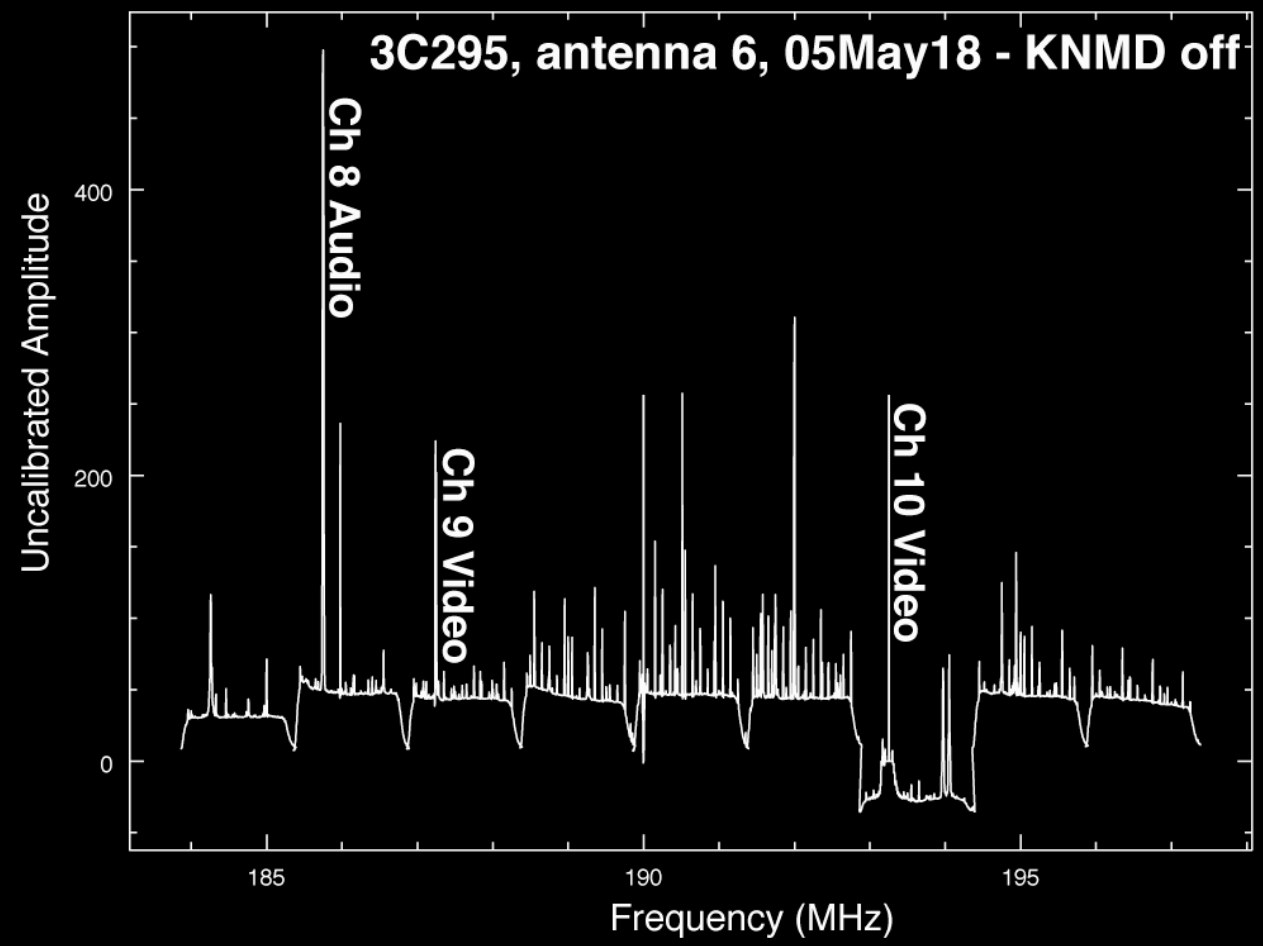
MWA	80-240	20-25	500	8000	1	$10M
PaST	70-200	2 (one pol)	15	70,000	3?	??
LOFAR	30-80,120-200	2	32 in core	100,000	2-100	$100M?
SKA	100-25,000?	Large?	?	1,000,000	Need core for EOR	$1B

Greenhill
Blundell
Carilli
Furlanetto
Loeb
Perley
Zaldarriaga


λ92 cm
λ153 cm
λ400 cm
(removable)

RFI is a major problem

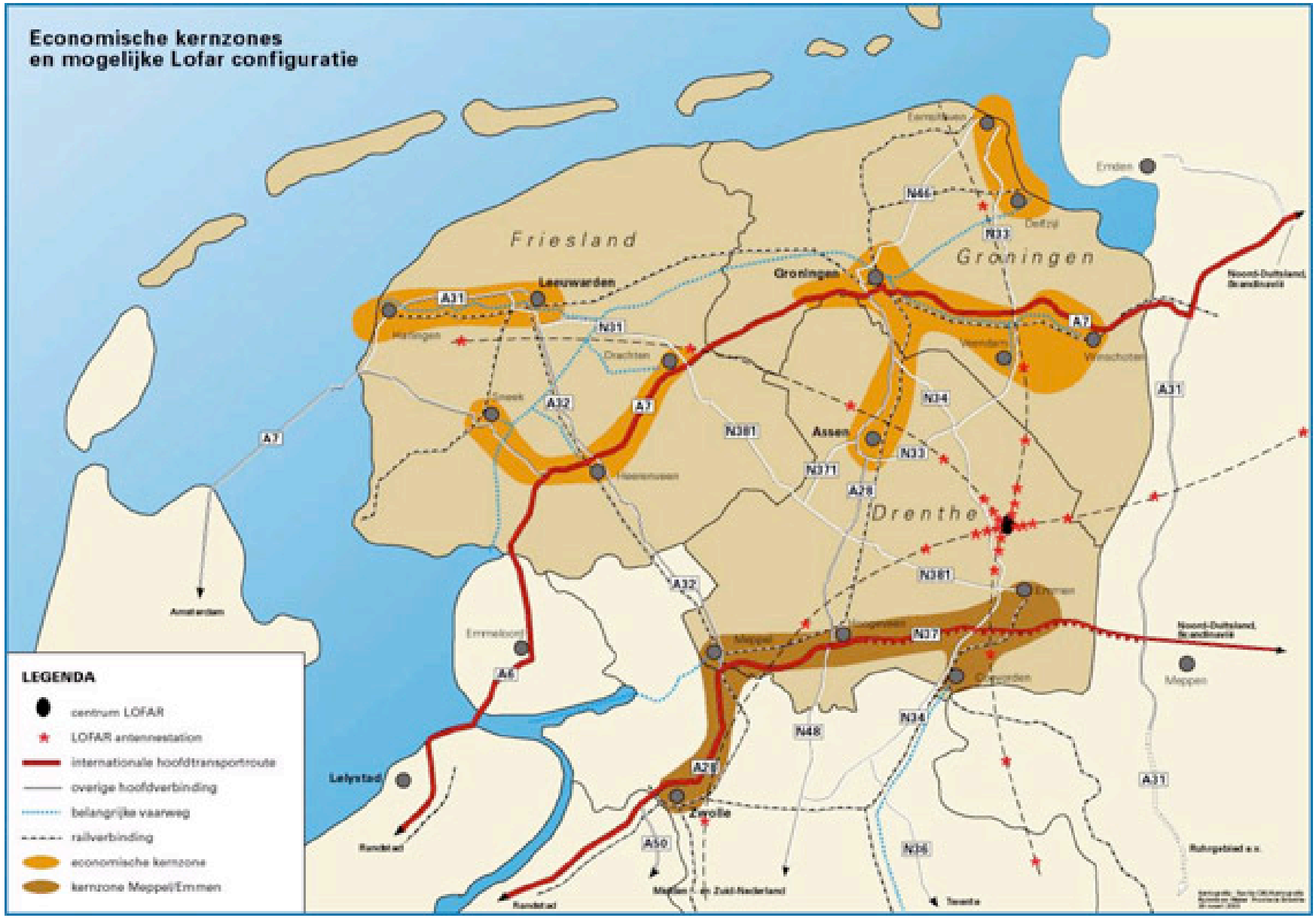
Internal / External RFI



EOR Experiments

Expt	Freq (MHz)	FOV (deg)	N	A (sq m)	B (km)	Cost	Status
Ekers	114-228	60	1		0	small	Prototyping
VLA	190-200	4.3	27	4000	1	small	Construction
MWA	80-240	20-25	500	8000	1	$10M	Prototyping
PaST	70-200	2 (one pol)	15	70,000	3?	??	Construction
LOFAR	30-80,120-200	2	32 in core	100,000	2-100	$100M?	Construction
SKA	100-25,000 ?	Large?	?	1,000,000	Need core for EOR	$1B	Design

LOFAR Site


Economische kernzones
en mogelijke Lofar configuratie
Friesland
Groningen
Drenthe
Leeuwarden
Groningen
Assen
Emmen
Meppel
Zwolle
Lelystad
Amsterdam
Emmeloord
Meppen
Emden
Delfzijl
Drachten
Heerenveen
Hoogeveen
Veenschoten
Hengelo
Twente
Randstad
Rotterdam en Zuid-Nederland
Ruhrgebied e.a.
Noord-Duitsland, Scandinavië
A7
A31
A32
A6
A28
A50
N31
N361
N371
N33
N34
N37
N48
N46
LEGENDA
centrum LOFAR
LOFAR antennestation
internationale hoofdtransportroute
overige hoofdverbinding
belangrijke vaarweg
railverbinding
economische kernzone
kernzone Meppel/Emmen

LOFAR Initial Test Station

A 4-tile test setup being erected near the WSRT (June 2005)

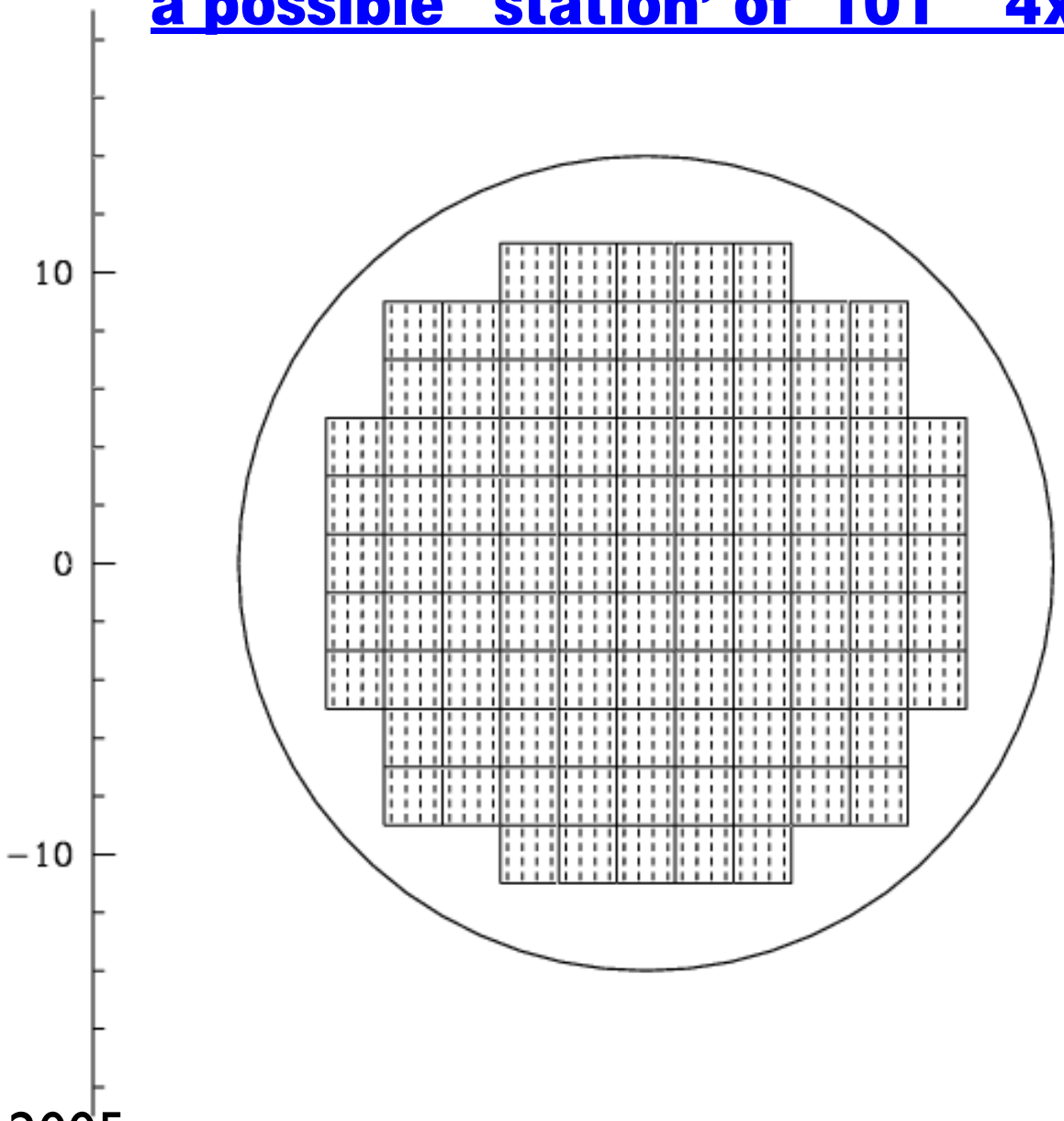
WHAT = Westerbork Highband Antenna Teststation

First results, including cross-correlation with WSRT, expected mid-July

de Bruyn 2005

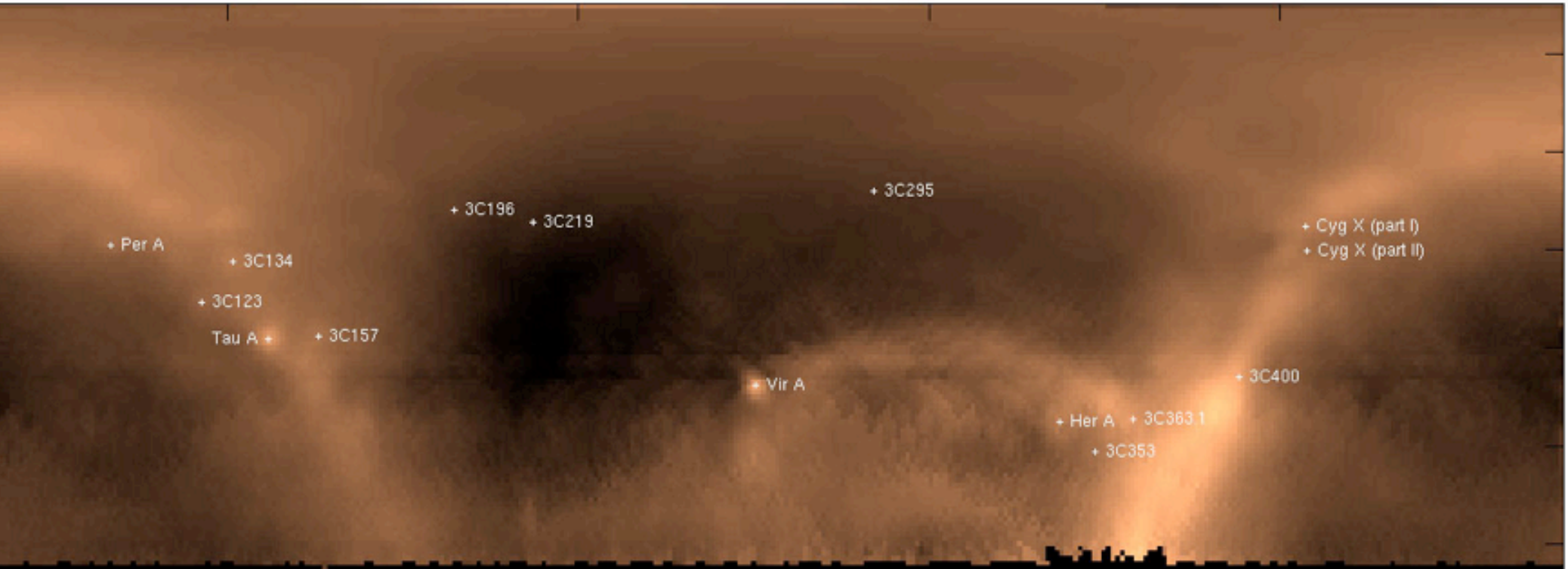
a possible `station' of 101 `4x4 tiles'

Size in λ



de Bruyn 2005

ITS all sky survey map with detected 3C sources



	flux @178MHz (Jy)	source	flux @178MHz (Jy)
s A	58	Hercules A	325
	175	3C363.1	90
	66	Cygnus X (part I)	230
A	1420	Cygnus X (part II)	410
	210	3C353	203
	59	3C295	73
	44	3C400	400
A	970		

This map was produced using 86 snapshots with 6.7s of integration and 9.7kHz channels. First RFI free channels between 29.5 and 30.5 MHz were selected using a median filter. The selected channels were calibrated on the four strongest 3C sources (Cas A, Cyg A, Tau A, Vir A). After the calibration a first map was made by a flux conserving projection from the (l, m) grid of the individual snapshots to the (α, δ) grid of the all sky image. This map was dominated by the averaged out sidelobes of Cas A and Cyg A. Therefore these two sources were cleaned from the image resulting in this map.

5 10 15 20

α (hours)

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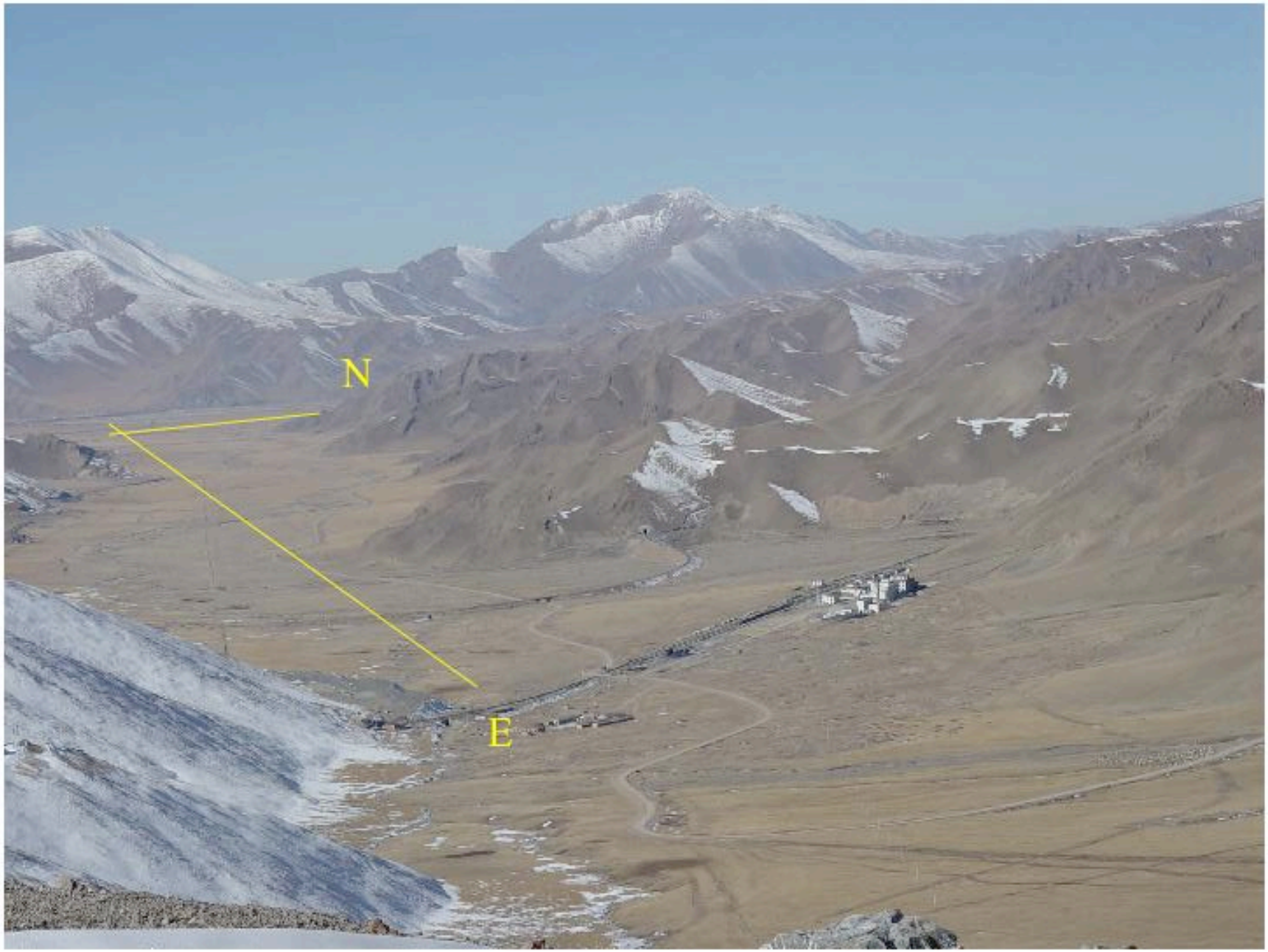
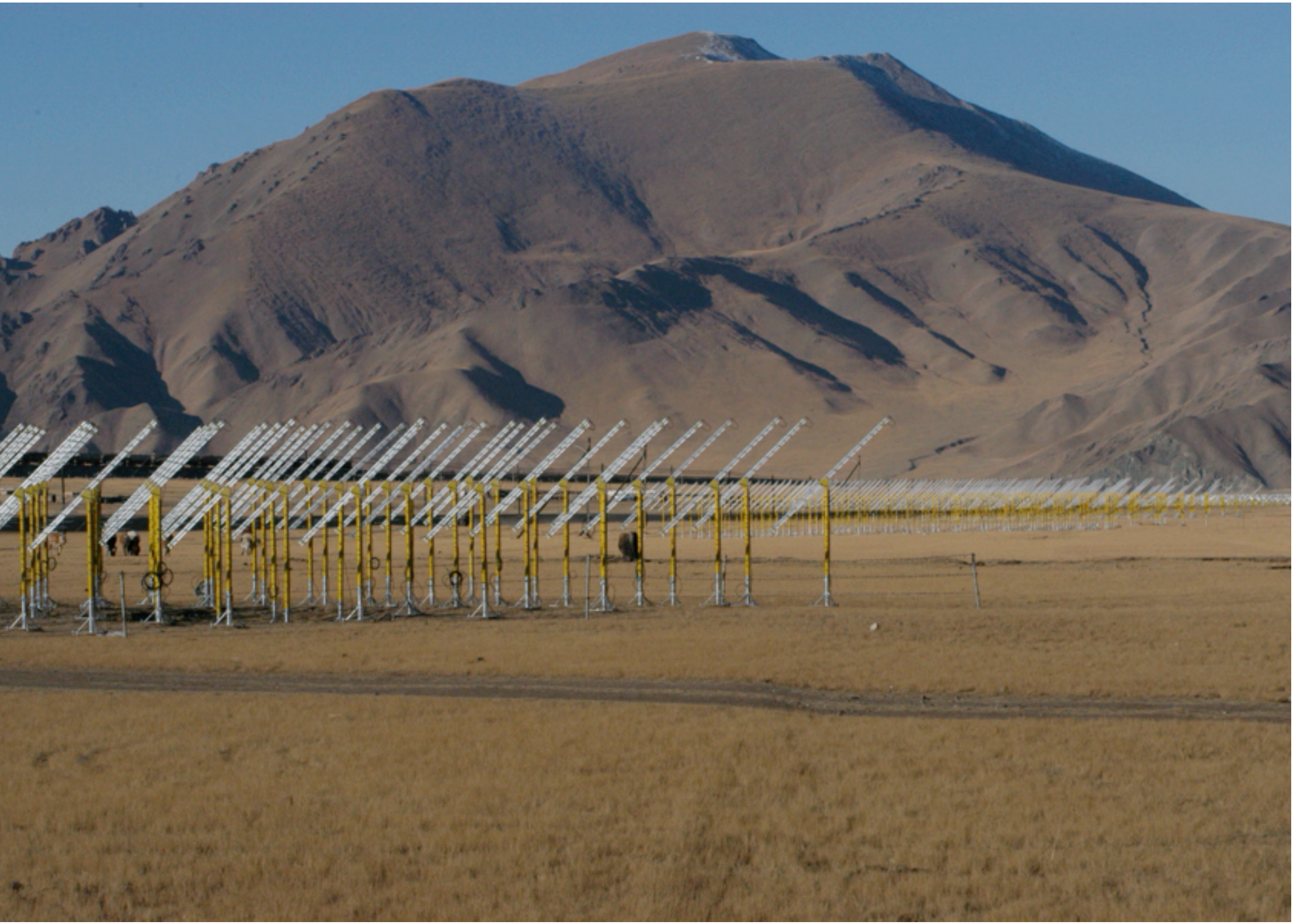
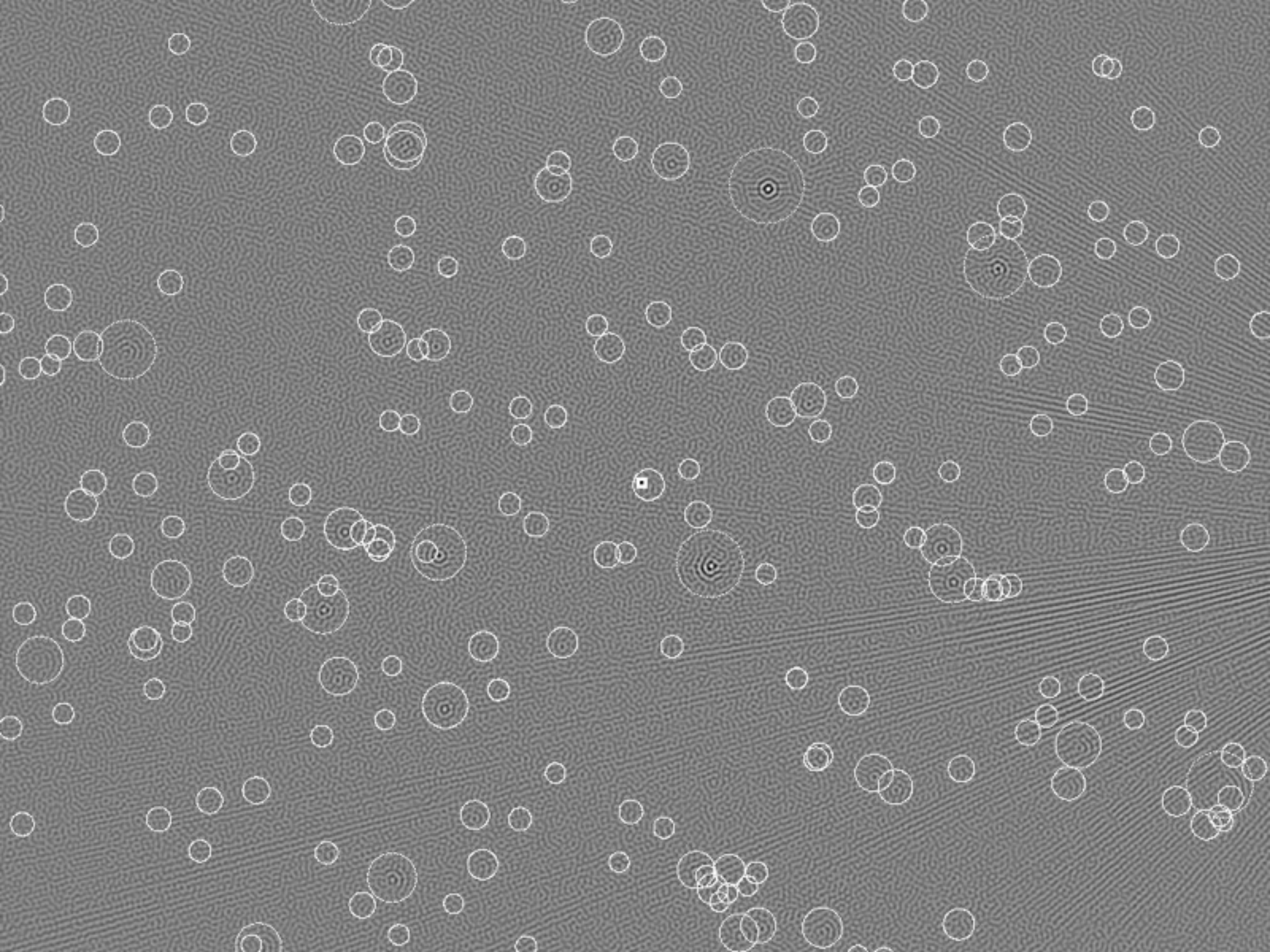
PAST



Peterson,
Pen, Wu



Status as of May 2005: 20 127-antenna pods assembled; 12 collecting data
New: two correlators on site



EOR Experiments

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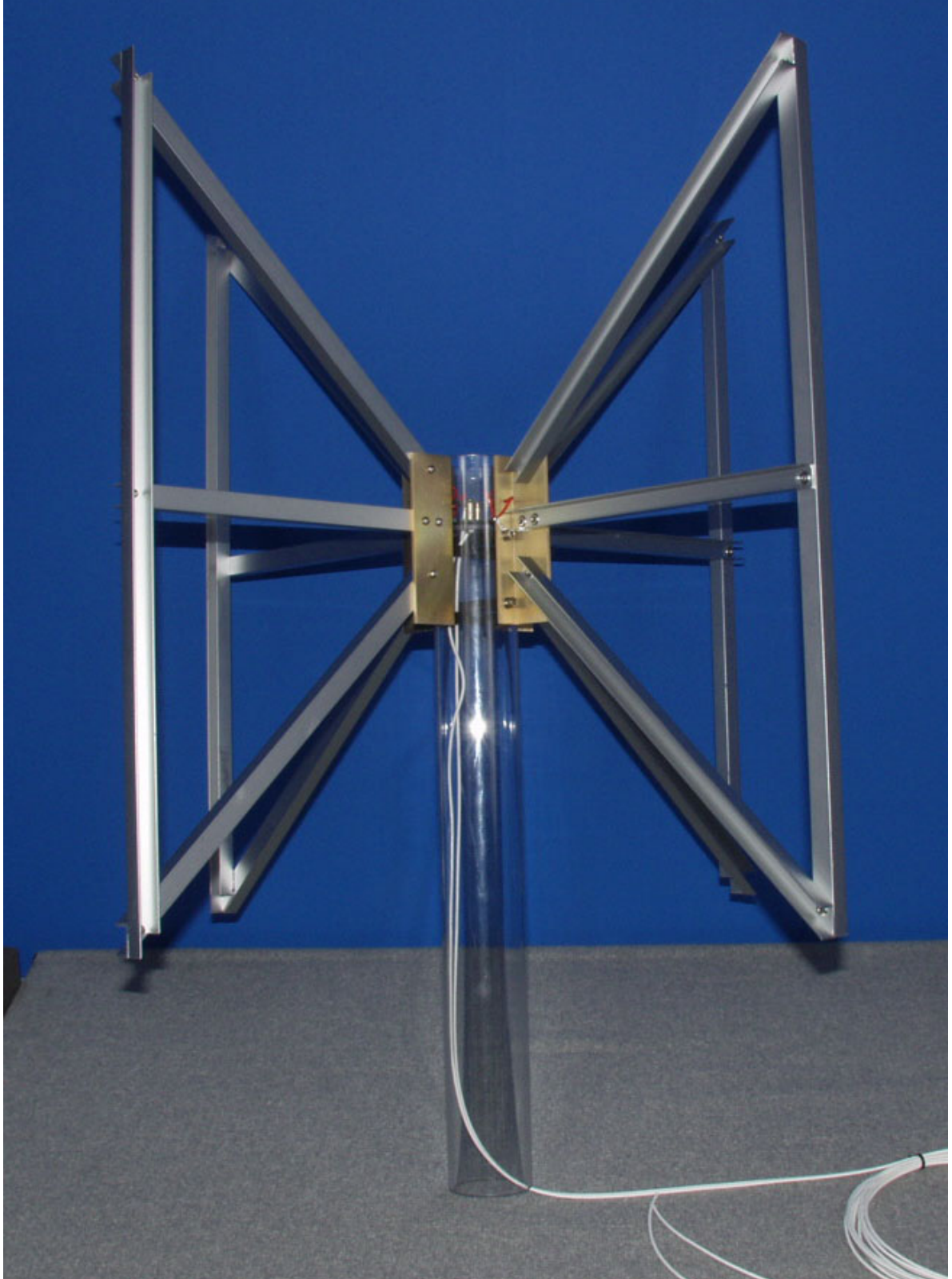
LOFAR	30-80,120-200	2	32 in core	100,000	2-100	$100M?
SKA	100-25,000?	Large?	?	1,000,000	Need core for EOR	$1B

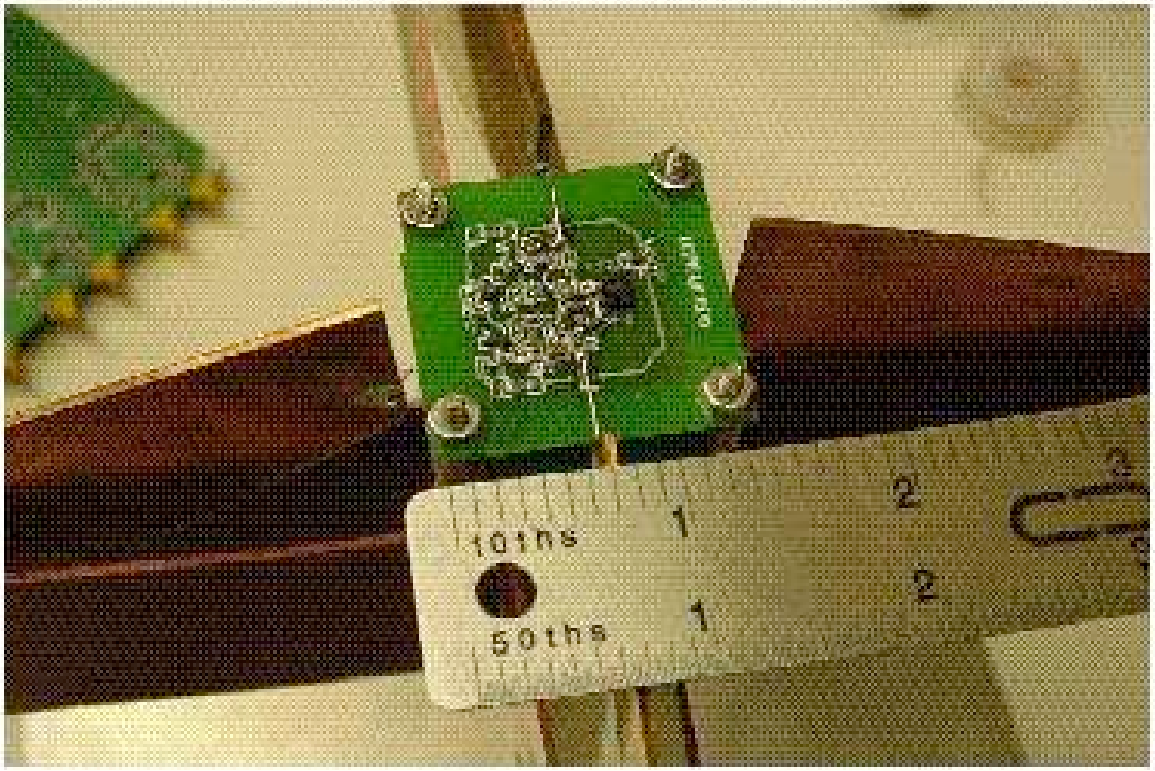
Mileura Widefield Array


MILEURA STN
MILEURA

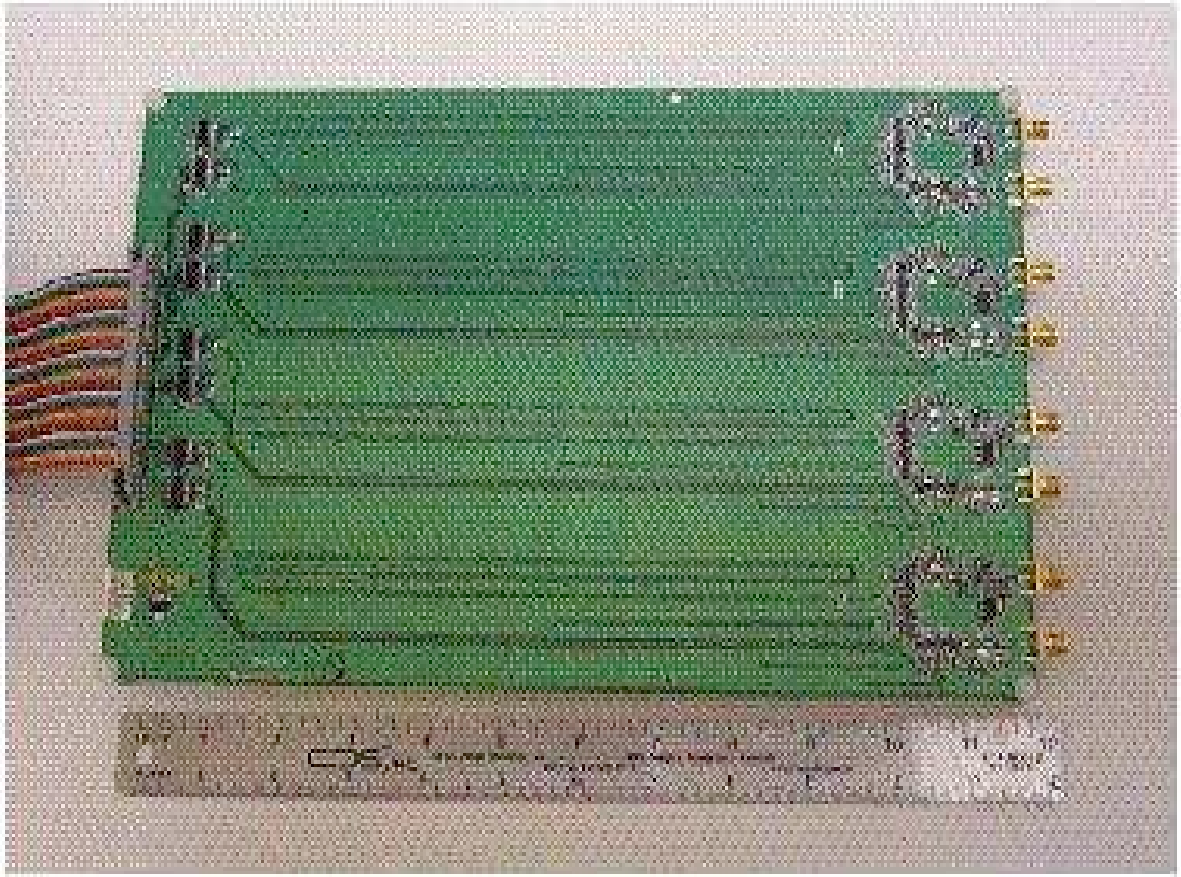


MWA
Antenna
Element

HBA LNA (single polarization channel)



Prototype HBA 4-channel beamformer

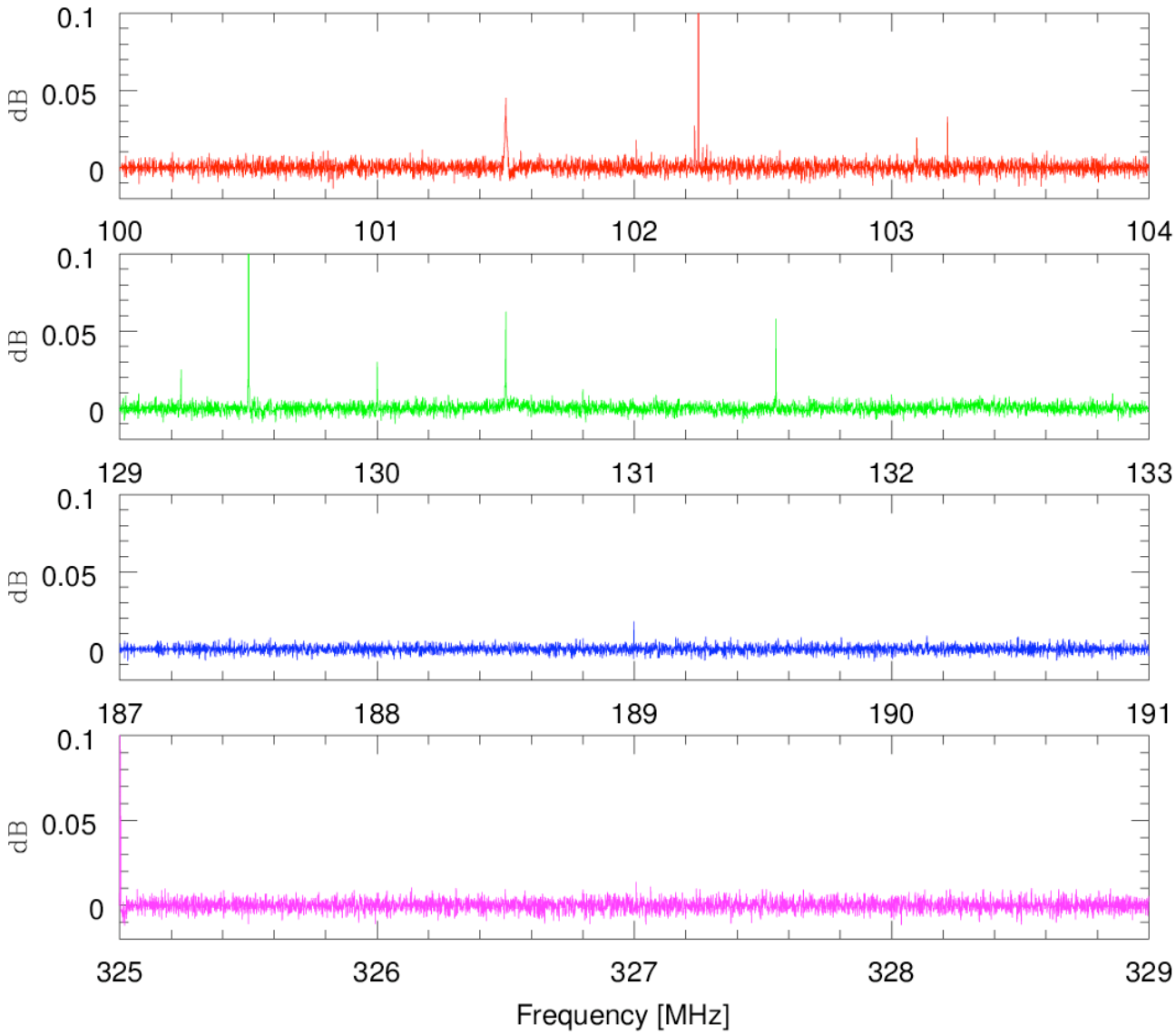


April 2005

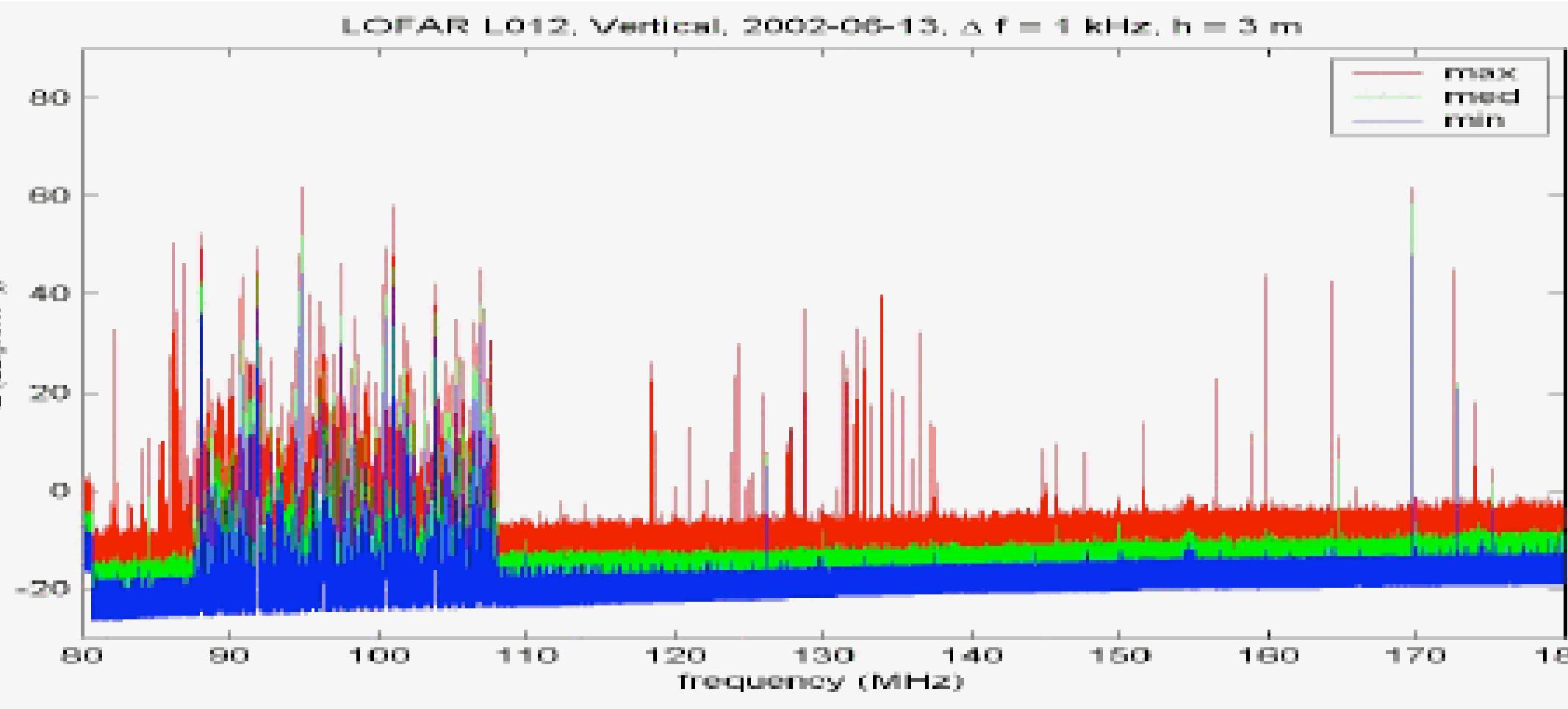
April 2005

April 2005

Figure 5. The full ED2 setup. The two tiles, 145 meters apart, are just visible at the edge of the bushes, with the equipment caravan and vehicles in the middle.



Sky spectrum at Mileura Station



Sky spectrum at LOFAR site

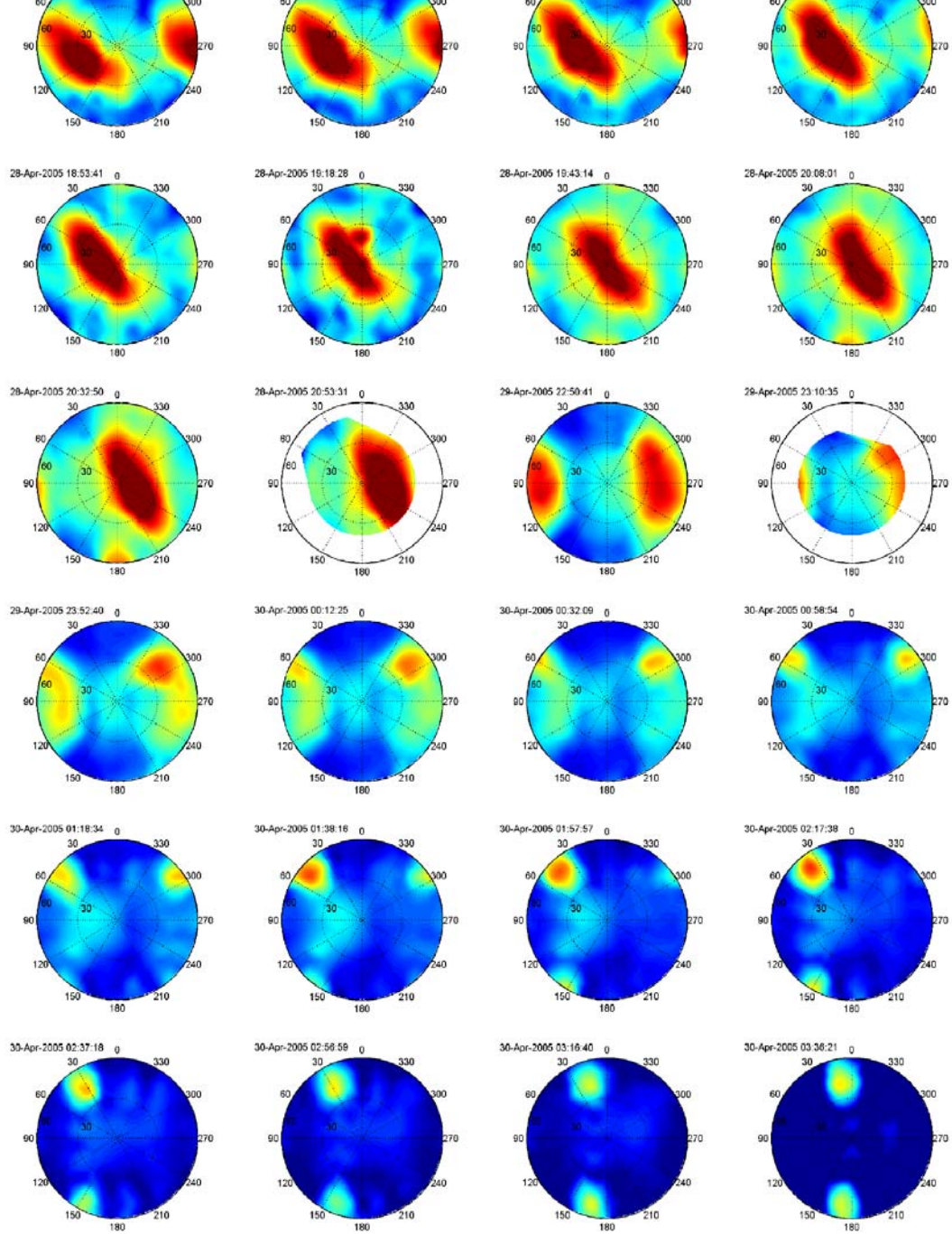


Figure 7. Sky image sequence at 200 MHz. These plots show the Mileura sky in the same way as figure 6, but in this case 110 pointings per image were used. The images cover a LST range of about 10 hours, sampled over 2 days, and the spacing between frames is not uniform. Also, frames 10 and 12 have some missing data. At 200 MHz, the tile has a beamwidth of ~18 degrees, and the expected grating lobes ~100 degrees apart are clearly apparent in the "doubling" of features at high zenith angles. The color range, as in figure 6,

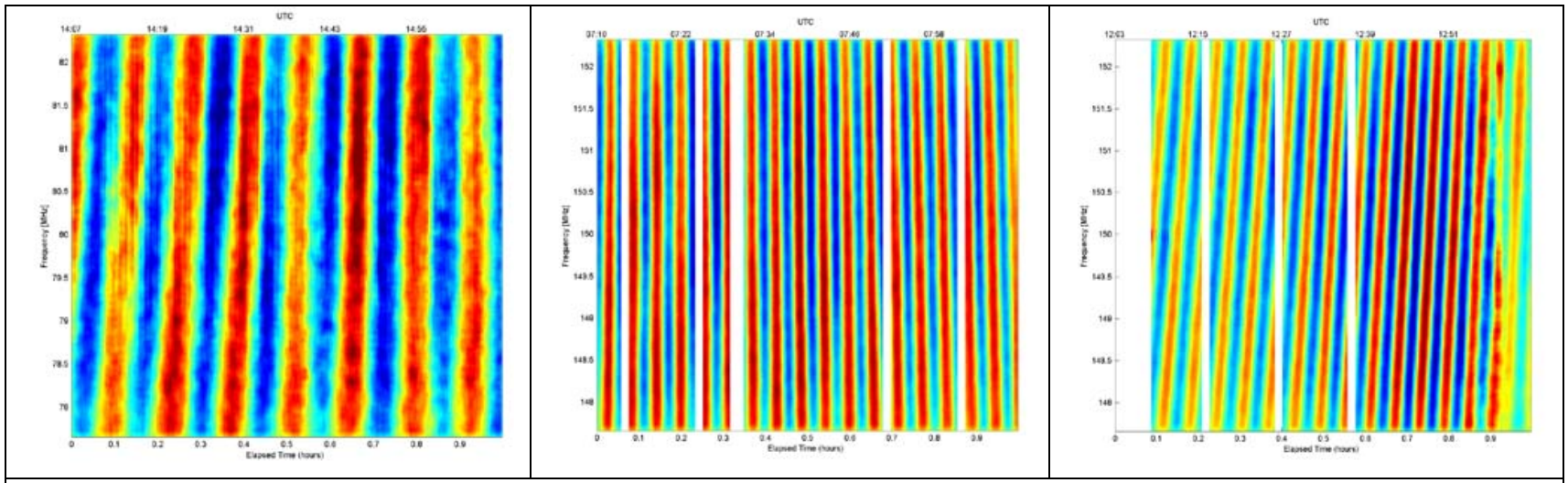
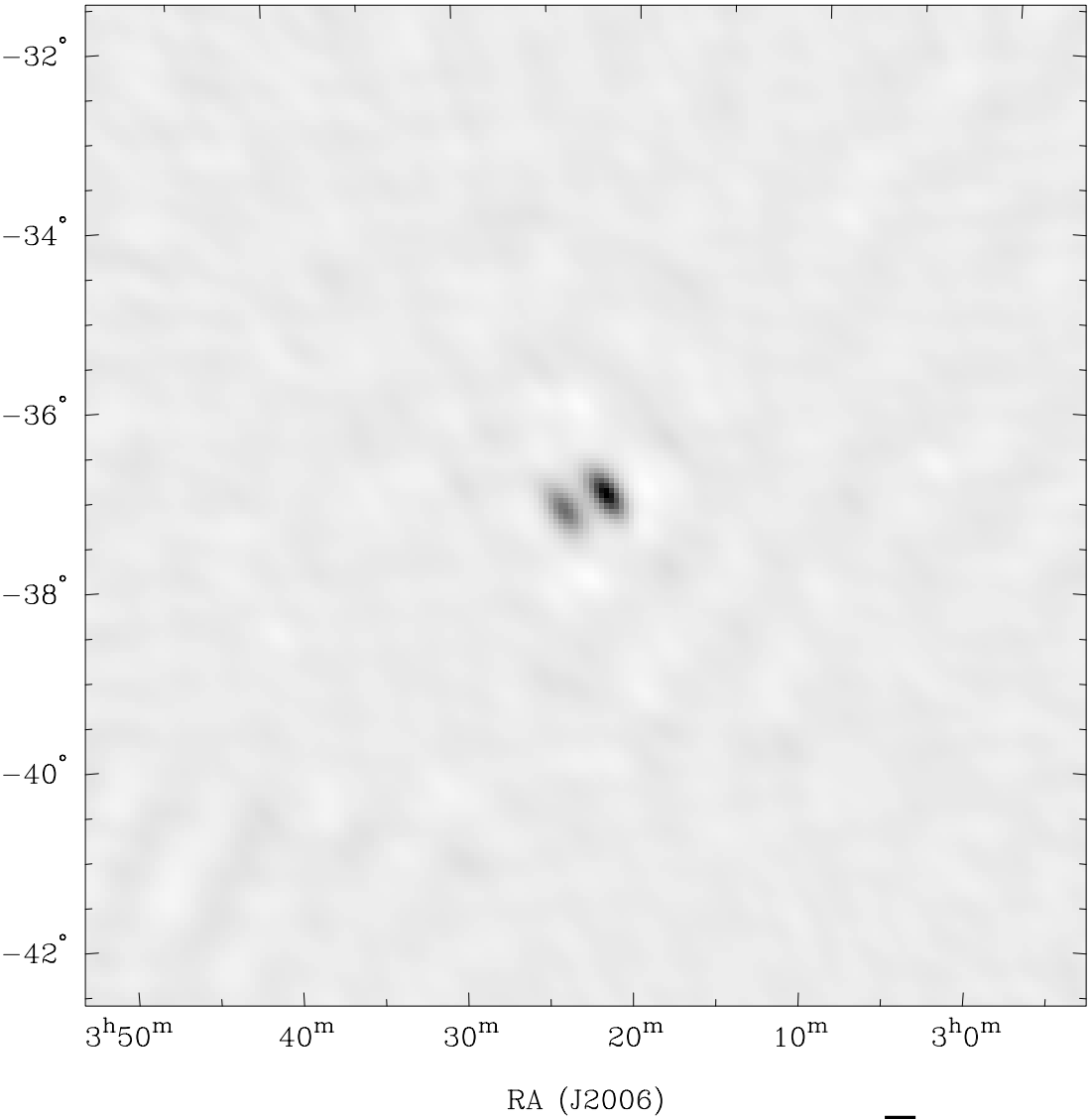
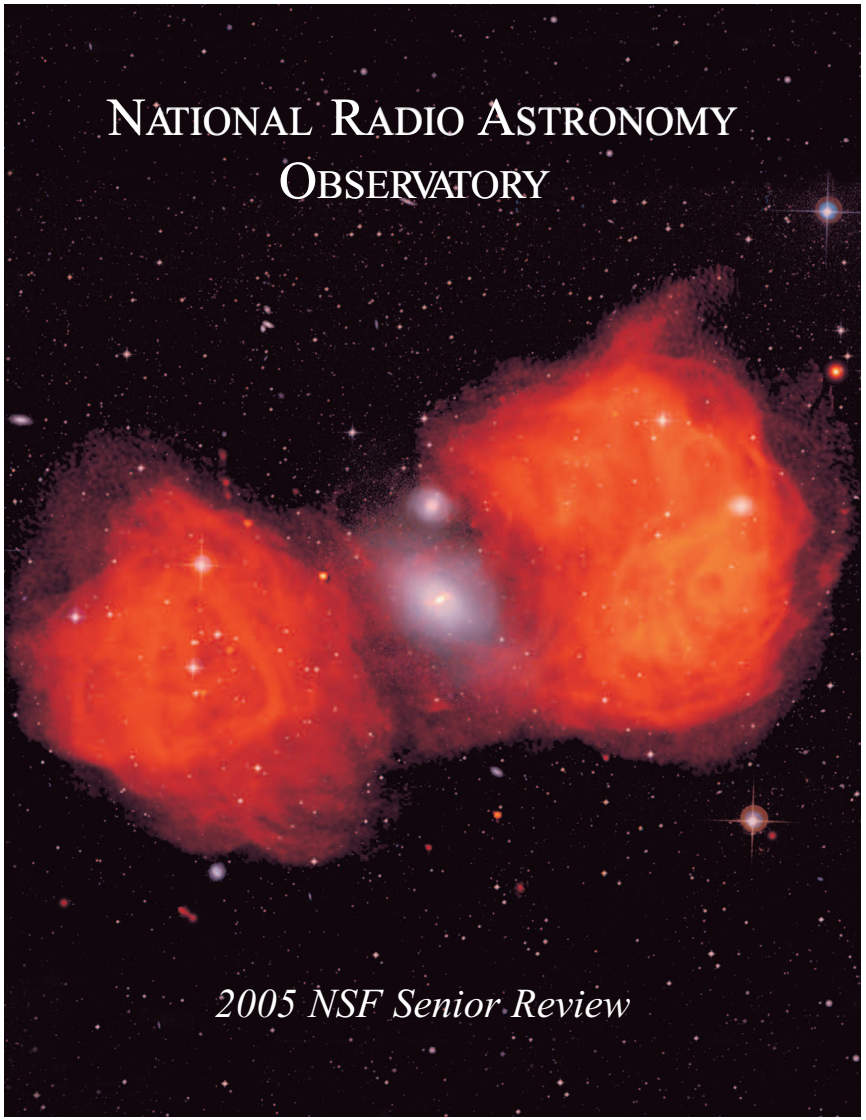


Figure 9. Interferometry data for three discrete sources. The axes are frequency (vertical) covering ~4.5 MHz, and time (horizontal) covering 1 hour. The colors represent the value of the real part of the interferometric complex visibility, and the stripes are a manifestation of phase ramps in time and frequency due to delay and fringe rate in the interferometer. Slanting lines (phase changes with frequency) indicate a delay between the antennas on the baseline, while the horizontal spacing of the stripes measures the phase rate from the changing baseline geometry due to earth rotation. The three sources from left to right are Centaurus A at 80 MHz, Taurus A (the Crab) at 150 MHz, and Virgo A at 150 MHz. There is an intermittent narrowband interferer at just above 150 MHz which has been edited out of the Taurus and Virgo data (white vertical lines). The frequency and time resolutions are 144 kHz and 70 seconds respectively, and the observing duty cycle within each time cell is 30%. The data indicate nominal performance of the equipment. The tile 1 to tile 2 baseline (145 meters) is too short to show pronounced ionospheric effects.





Fornax A

N=3

N=many

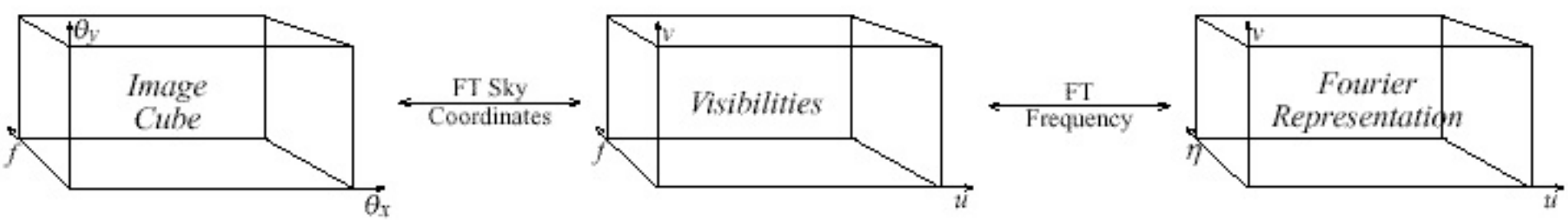
Measuring the power spectrum:

We measure the visibility in many frequency channels:

$$V(u, v, \Delta f)$$

A Fourier transform along the frequency axis gives us $\Delta\tilde{I}(u, v, \eta)$:

$$\Delta\tilde{I}(u, v, \eta) = \int V(u, v, \eta) e^{-2\pi i \Delta f \eta} d(\Delta f)$$



Measuring the power spectrum (con.):

The specific intensity relative to the cosmic radio background is due to fluctuations in the neutral hydrogen density:

$$\Delta I(\vec{r}) = (2.9\ mK)h^{-1}\frac{(1+z)^2}{E(z)}\left(\frac{T_s - T_{\rm CMB}}{T_s}\right)\frac{\rho_{\rm HI} - < \rho_{rmHI} >}{< \rho_{\rm HI} >}$$

Therefore, by measuring the expectation value of the square of the visibilities we measure the neutral hydrogen power spectrum:

$$< |\Delta\tilde{I}(u_1, v_1, \eta_1)|^2 >= \int P_{\rm HI}(u, v, \eta)|W(u_1 - u, v_1 - v, \eta_1 - \eta)|^2 dudv$$

where $W(\theta_x, \theta_y, \eta)$ is the weighting function of the observations (field of view and bandwidth), and $W(u, v, \eta)$ is its Fourier transform.

Morales & Hewitt 2004

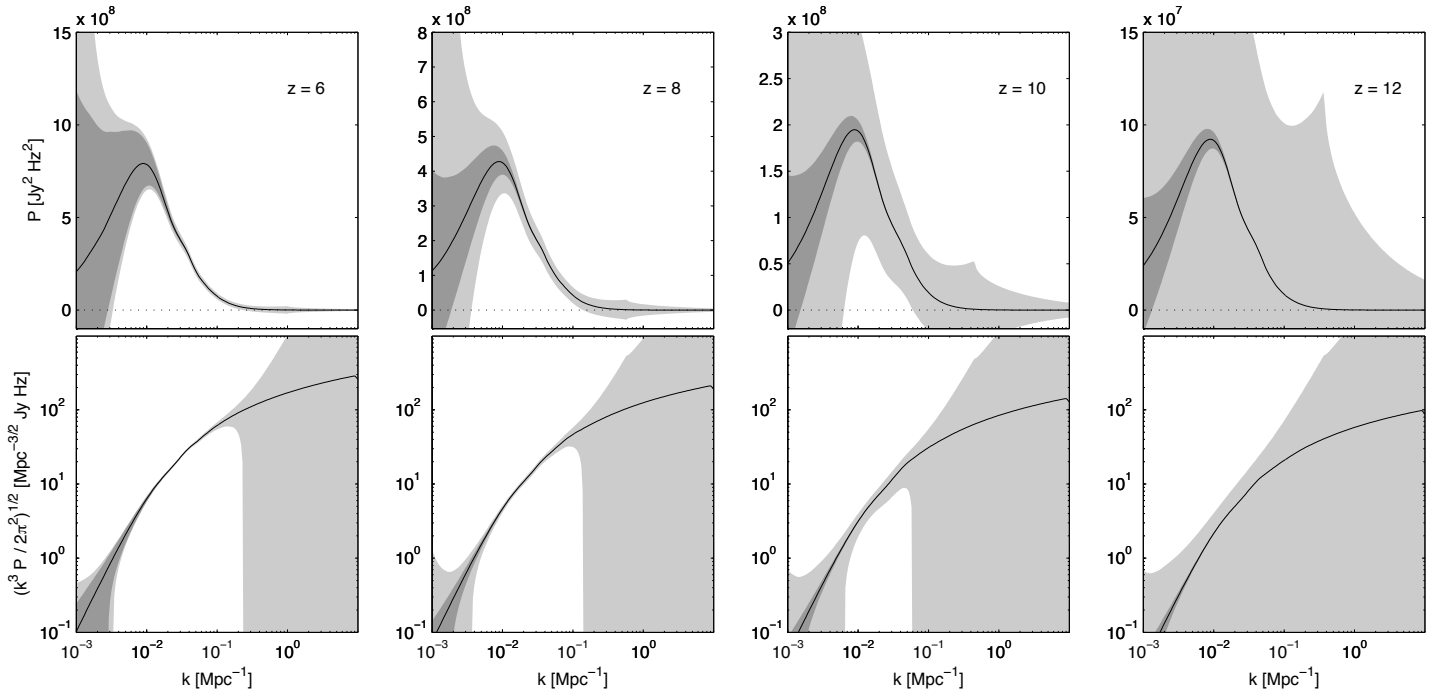
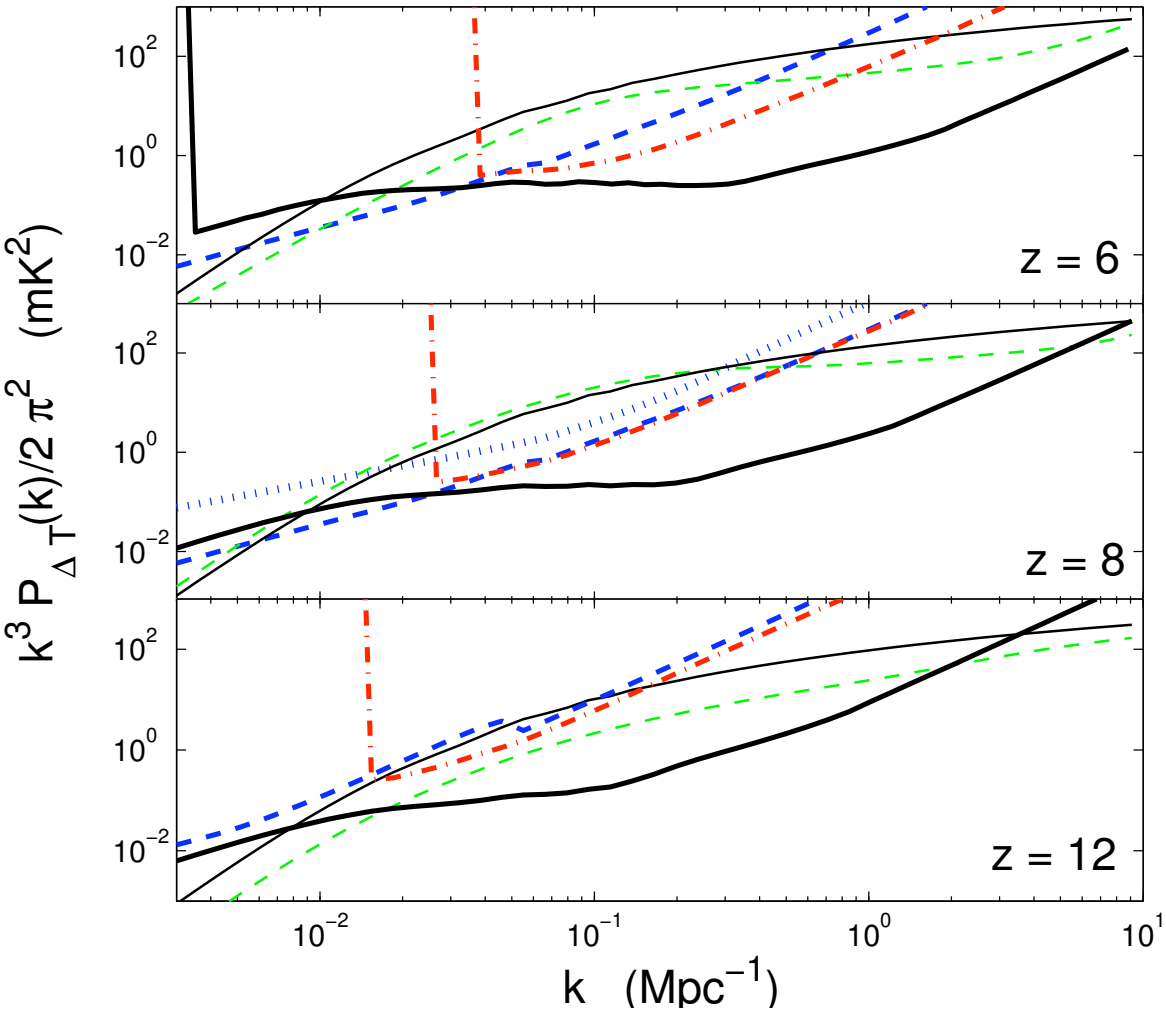


FIG. 4.— Same as Figure 3, but computed for observations at four redshifts. From left to right, the redshifts are $z = 6$, 8, 10, and 12. Note that the vertical scales are different for each of the upper plots. The small peaks in uncertainty at $k \approx 0.5$ for $z = 10$ and 12 correspond to the increase in uncertainty due to thermal noise at length scales sampled by the largest baselines (see Figure 2).

500 tiles; 8 MHz bandwidth; 360 hours integration; no foregrounds

Bowman, Morales & Hewitt 2005

Comparison of arrays for power spectrum measurement



Thermal noise plus sample variance

MWA 500 is blue
LOFAR is red
SKA is black
Signal is green

McQuinn et all 2005

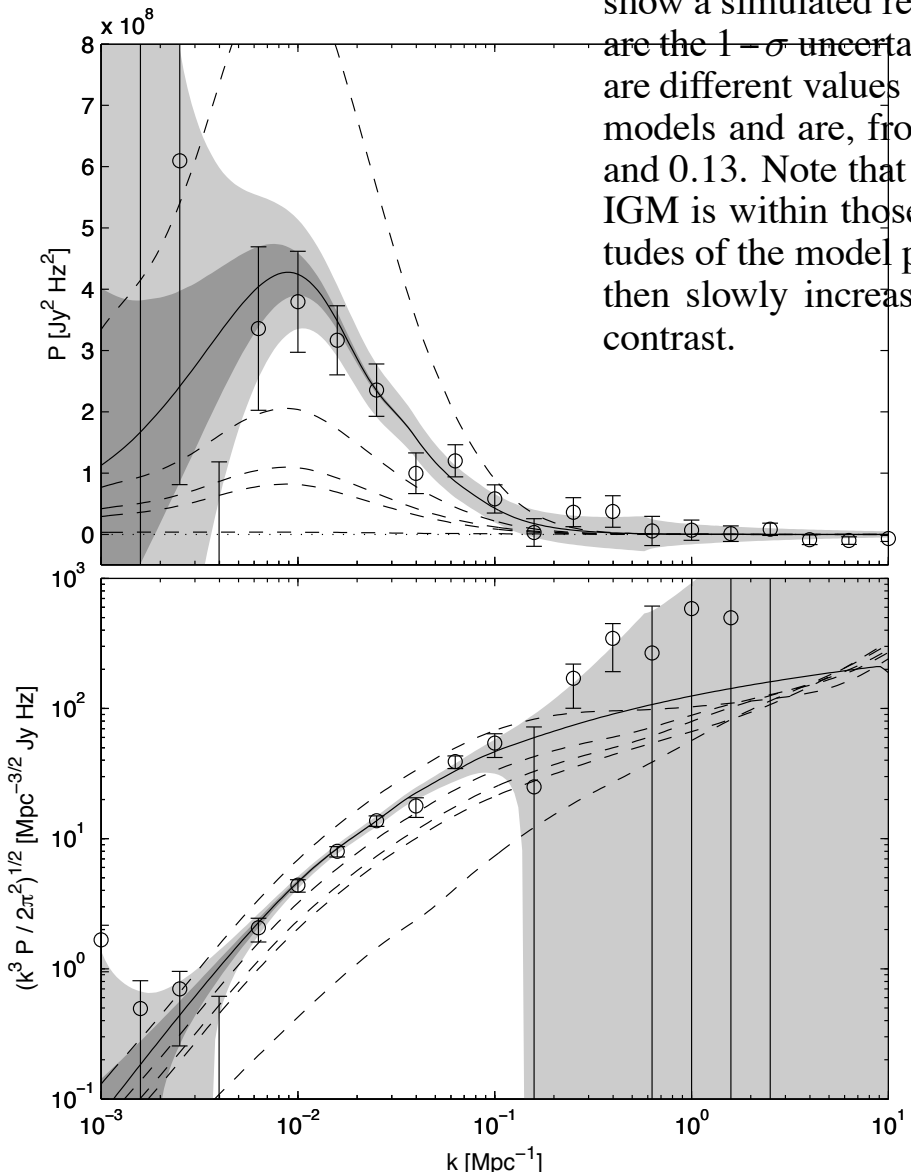
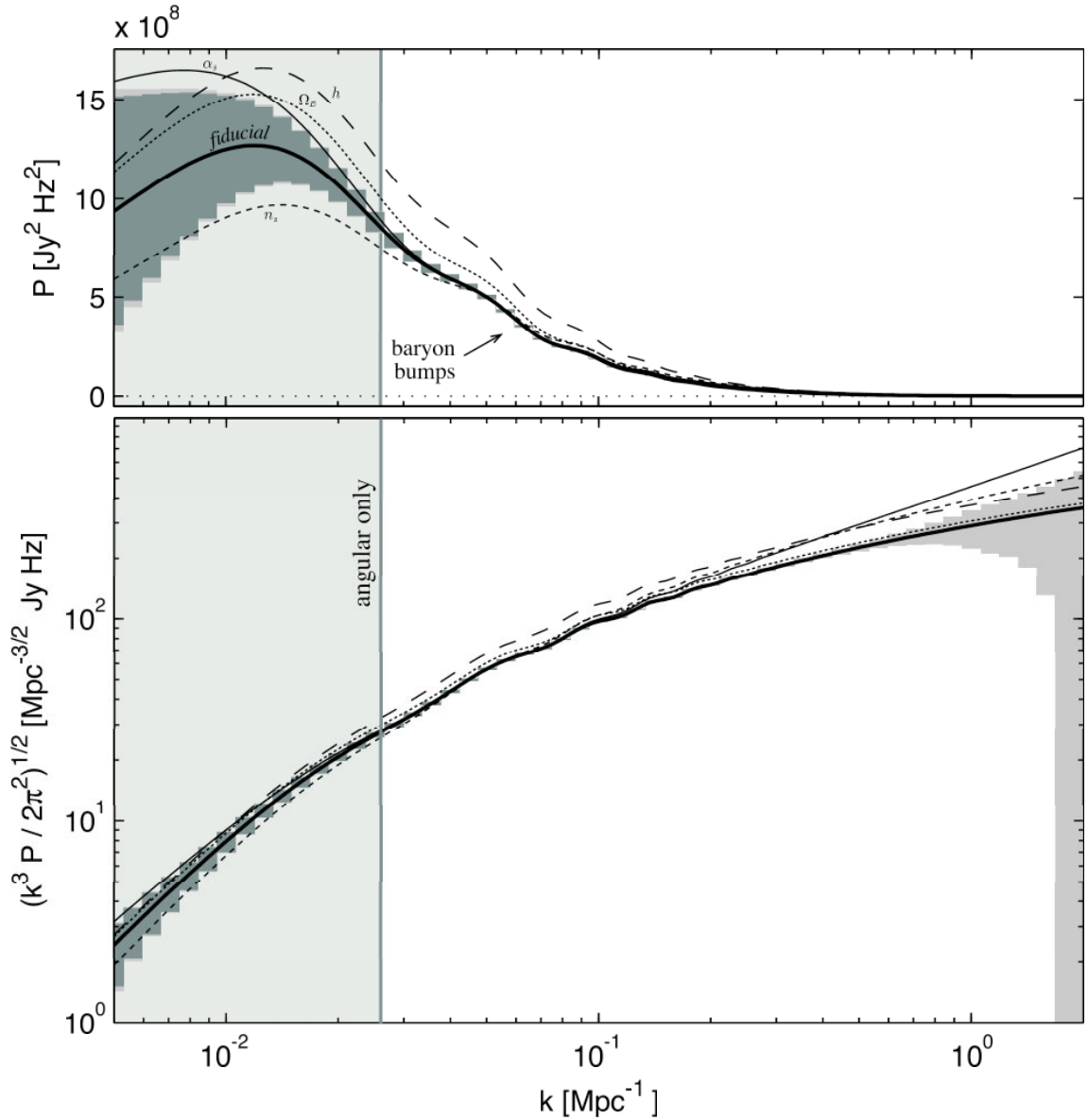


FIG. 5.— Same as Figure 4, Column 2 for redshift $z = 8$, but the data points show a simulated realization of the measured power spectrum. The error bars are the $1-\sigma$ uncertainties calculated from the thermal noise. The dashed lines are different values of the ionization fraction in the Furlanetto et al. (2004a,b) models and are, from top to bottom, $x_i = 0.51$, 0.0 (solid), 0.43, 0.38, 0.25, and 0.13. Note that the amplitude of the power spectrum for the fully neutral IGM is within those of the other ionization fractions. In general, the amplitudes of the model power spectra drop rapidly between $x_i = 0.0$ and 0.13, and then slowly increase with ionization fraction as large bubbles increase the contrast.

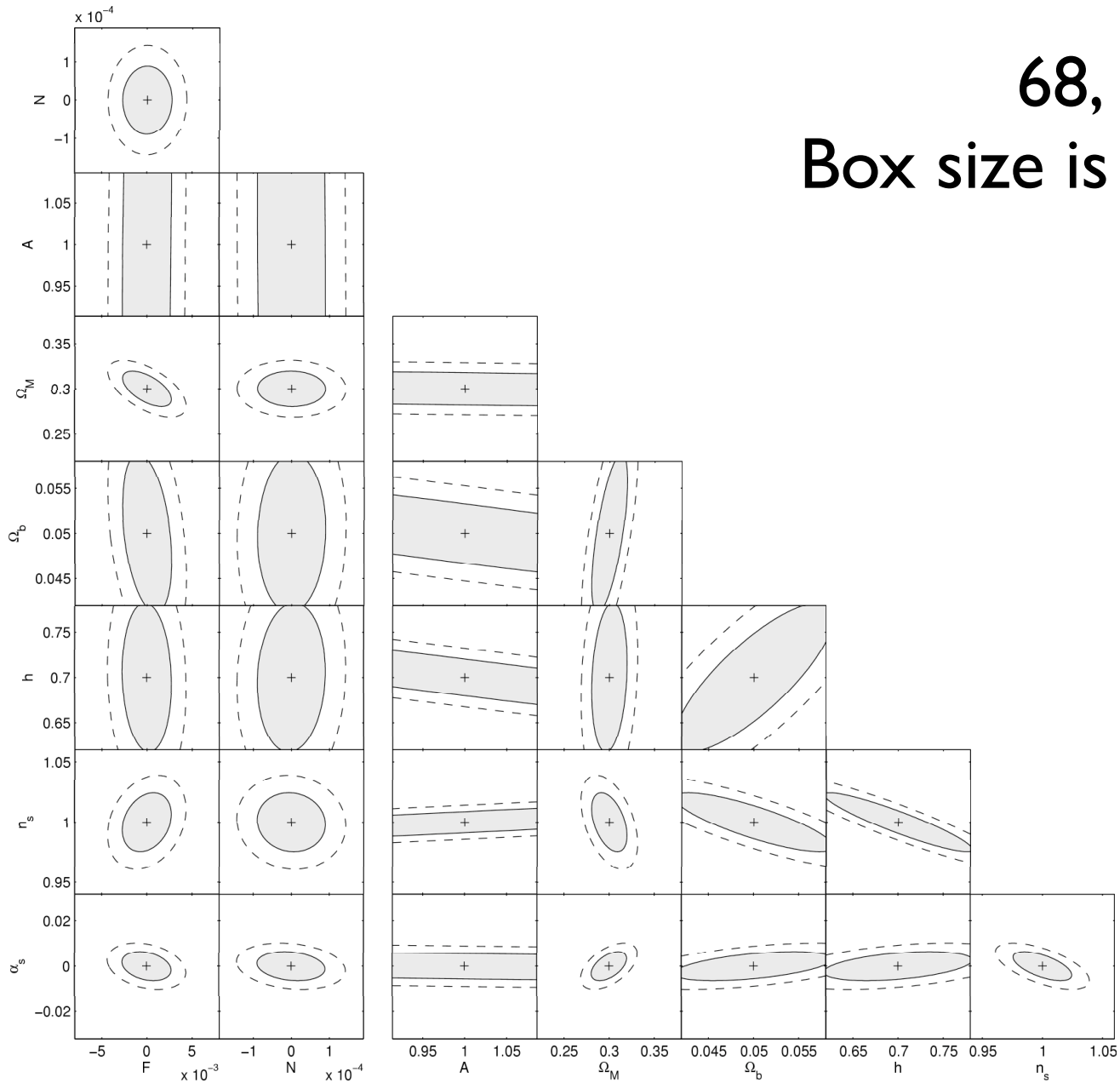
In your dreams: power spectrum without gastrophysics

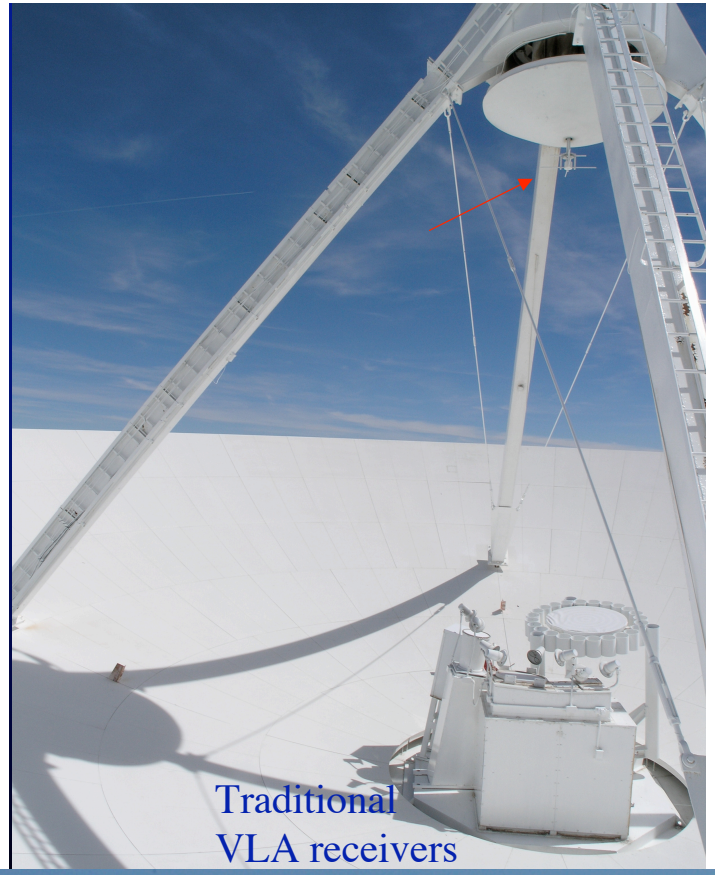


MWA 5000
z=8 to10
No
reionization

Bowman,
Morales,
Hewitt 2005

68, 95% C.I.
Box size is WMAP 2-sigma




Traditional
VLA receivers