LESSONS FROM EDGES

Ground-based constraints on the global 21 cm signal and implications for lunar observations

Judd D. Bowman (ASU)
Alan E. E. Rogers (MIT/Haystack)

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IN SEARCH OF REIONIZATION

	Location	No. of antennas	Baseline	Completion
Low Frequency Array (LOFAR)	The Netherlands	44,160	1500 km	2010
Murchison Widefield Array (MWA)	Australia	8,192	3 km	2010
21 Centimeter Array (21CMA)	China	10,287	6 km	2006
Long Wavelength Array (LWA)	New Mexico, U.S.A	12,800	400 km	2010
Precision Array to Probe Epoch of Reionization (PAPER)	Australia	32		2009
Experiment to Detect the Global EOR Signature (EDGES)	Australia	1		2009–2012
PROPOSED				
Hydrogen Epoch of Reionization Array (HERA II)	Australia	5,000		2017
Square Kilometer Array (SKA)	Australia or S. Africa	50 million	3000 km	2018–2022
Lunar Radio Array (LRA)	Far side of the moon	~ 100,000	10 km	2020–2030

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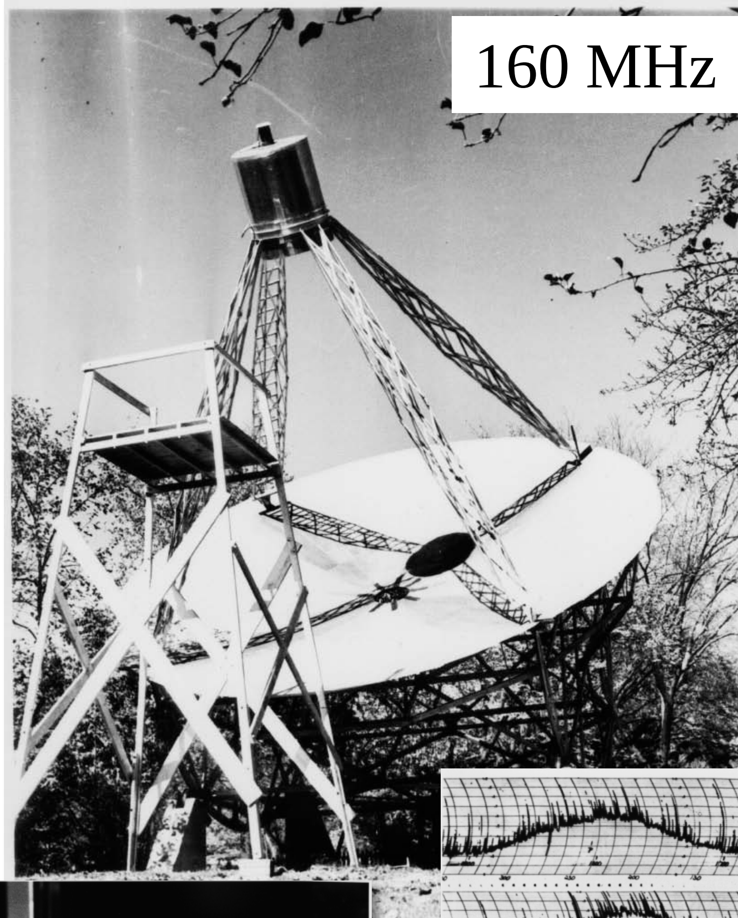
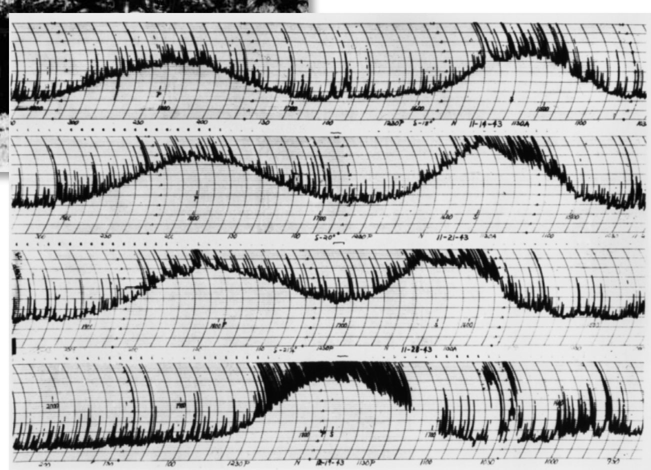
Technical requirements

Spectral coverage:	30 and 200 MHz (50>z>6)
Spectral resolution:	<20 kHz due to RRLs
Sensitivity:	<10 mK sensitivity in 1 MHz channels
Dynamic range:	$>10^4$ to see signal underneath Galaxy $>10^6$ to characterize at 1% level
Field of view:	>100 deg^2 for “global” all-sky spectrum
Abs. calibration:	10% absolute in each spectral channel
Rel. calibration:	3rd-order polynomial fit to calibrated bandpass removes structure to 0.0001%

The dawn of radio astronomy



Grote Reber



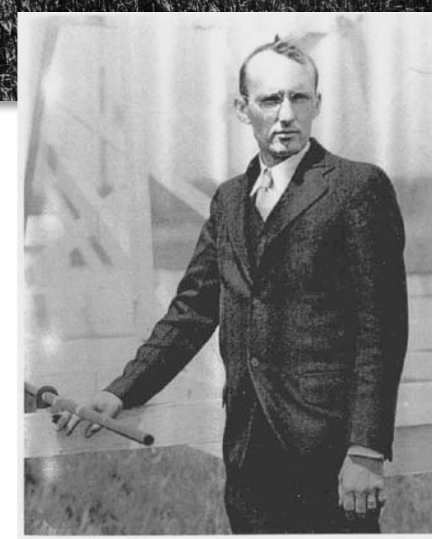
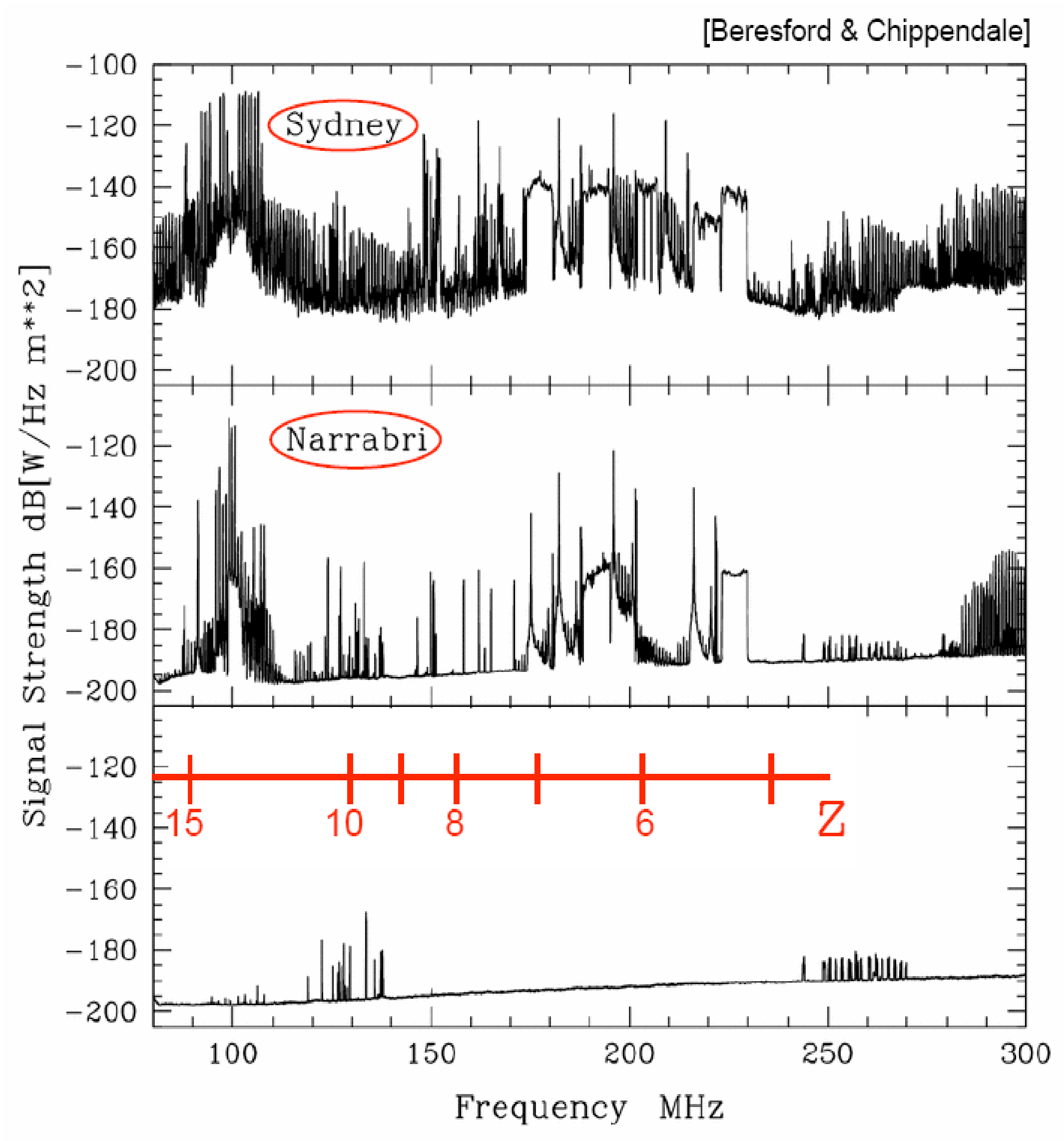


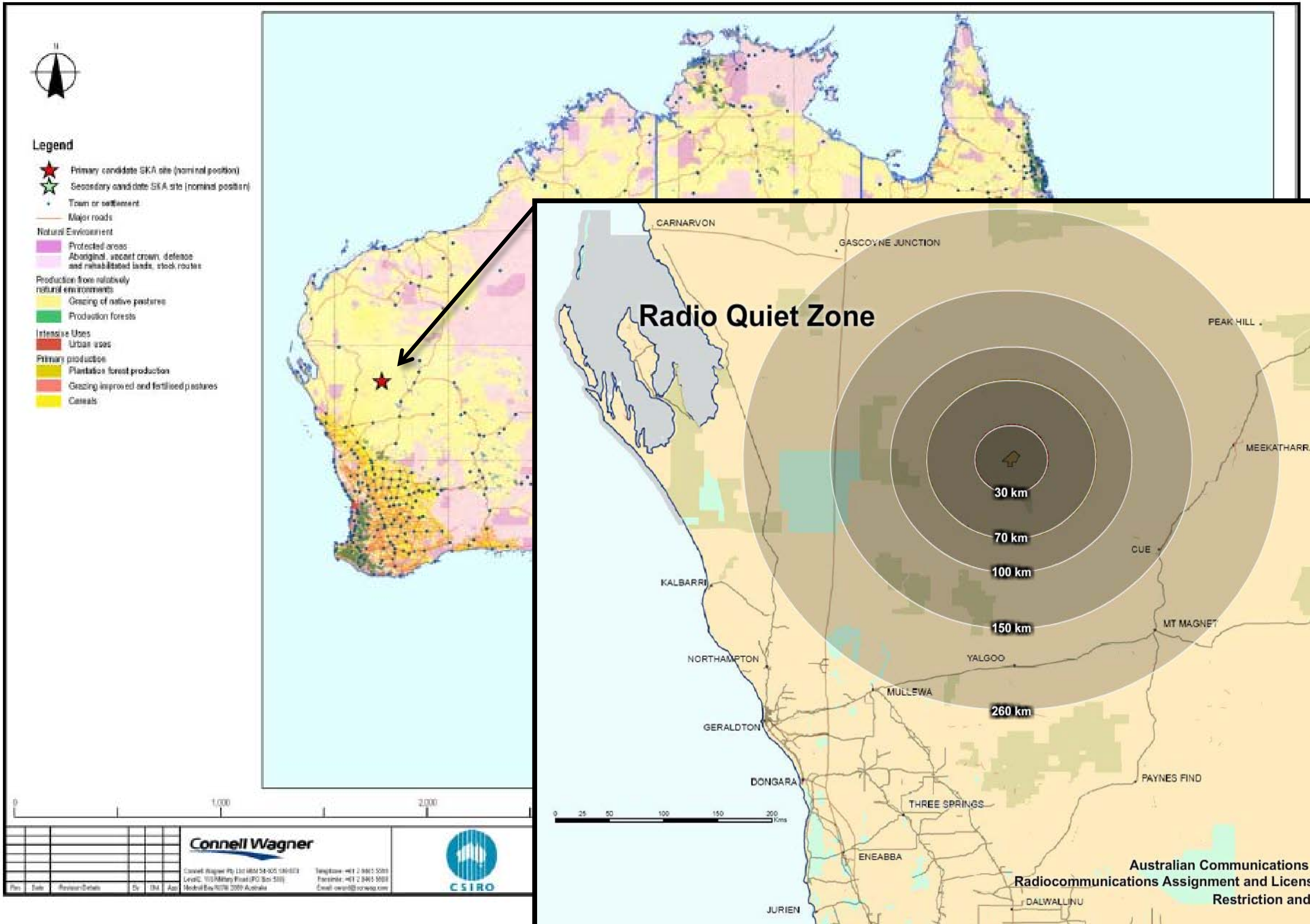
FIG. 1—Karl Guthe Jansky, about 1933.

Karl Jansky

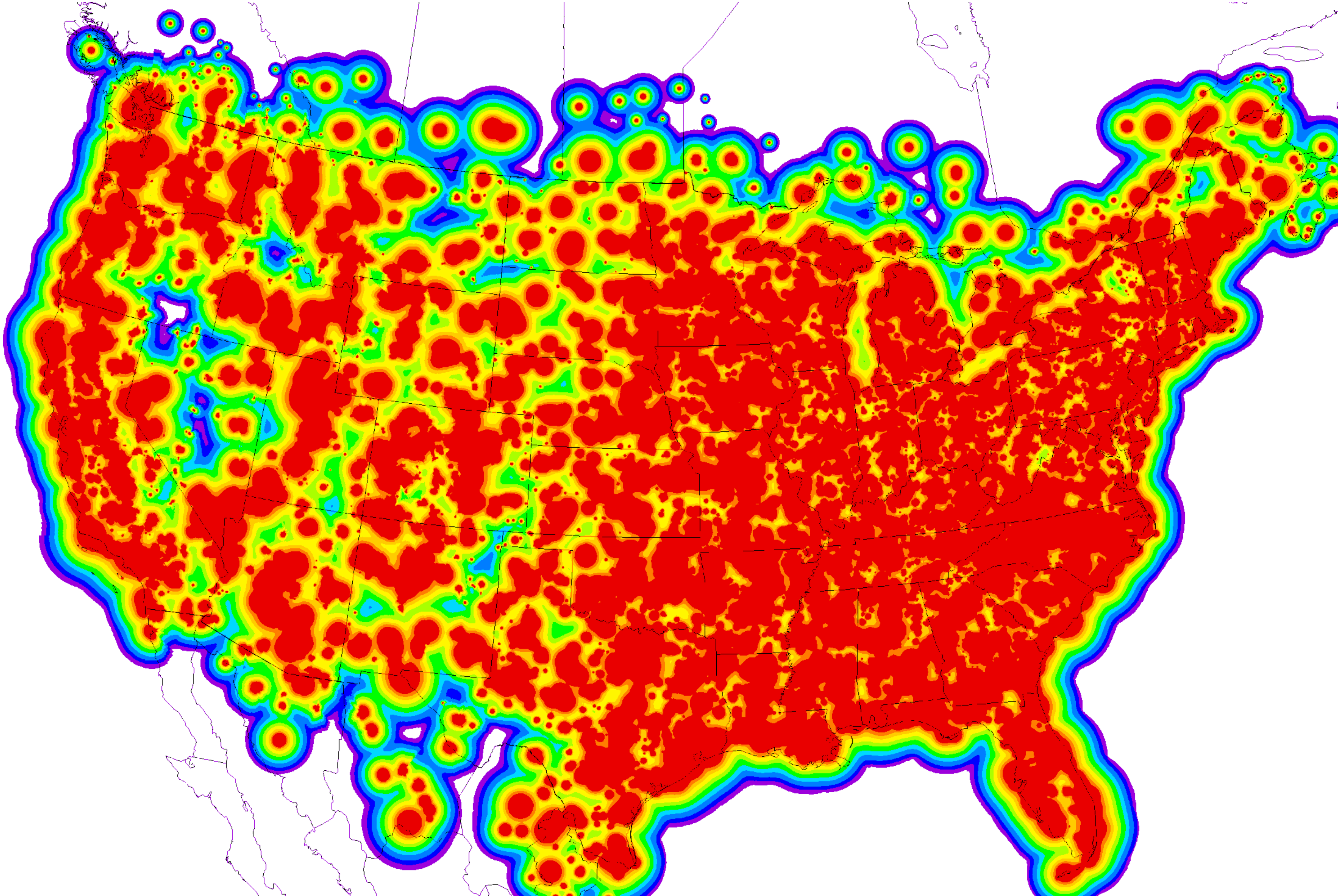
The bigger problem:
Radio Frequency Interference (RFI)



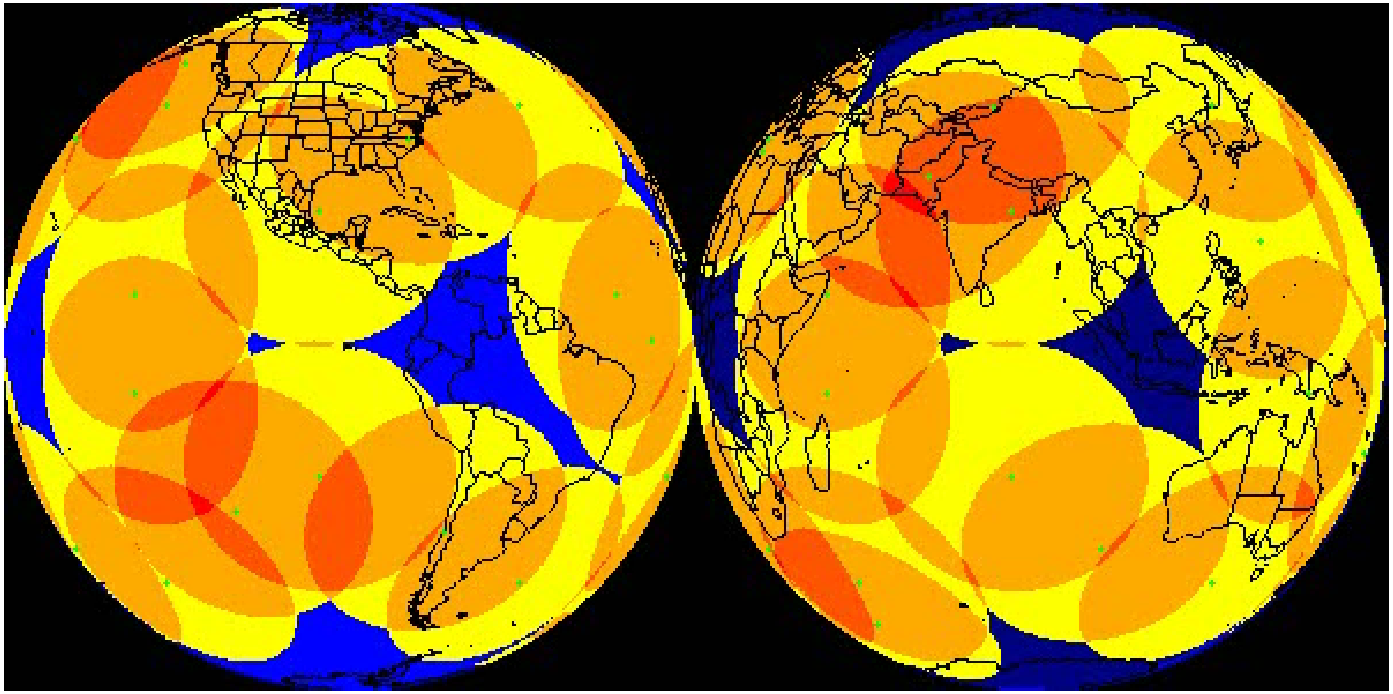
Murchison Radio-astronomy Observatory



US FM and TV radio “pollution”



Orbcomm LEO satellite constellation



Experiment to Detect the Global Epoch of Reionization Signature (EDGES)

2006 - 2010

EDGES

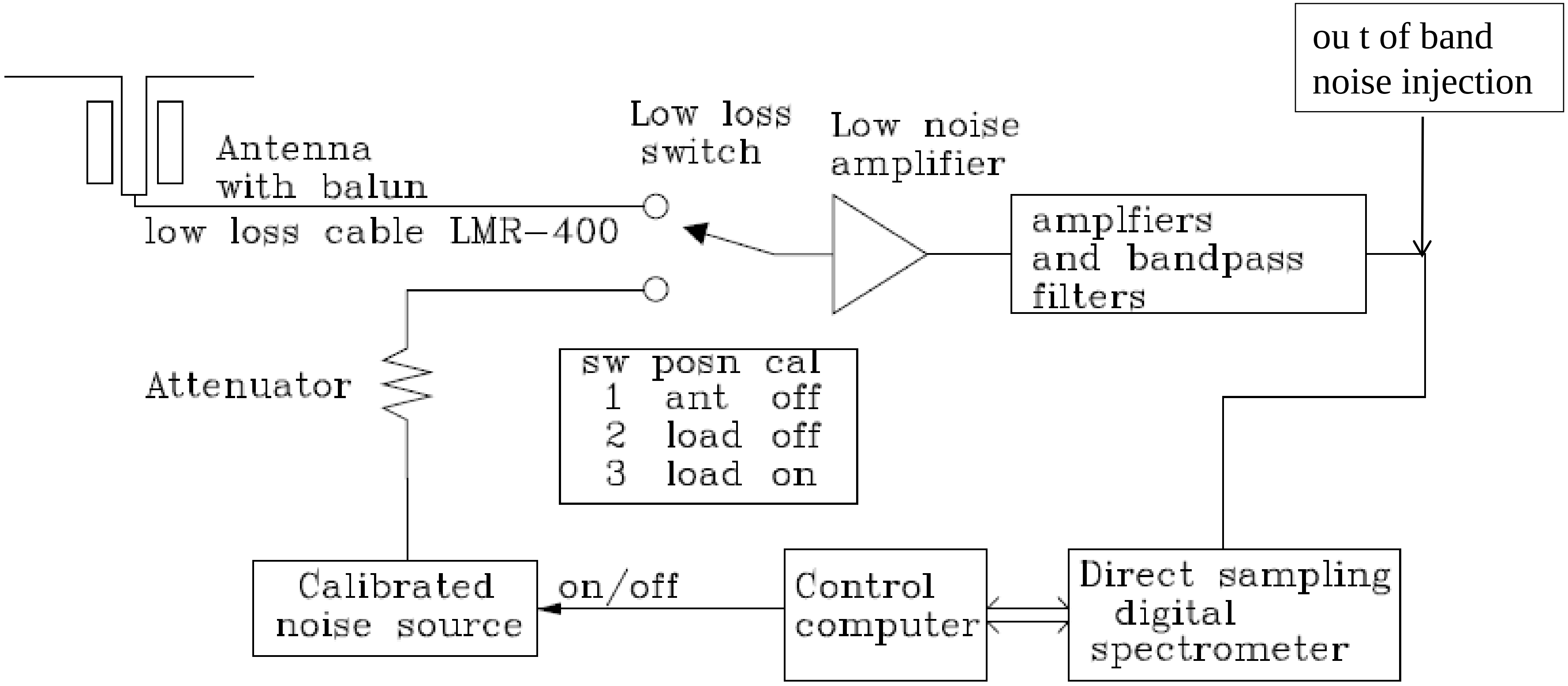
Table 1. EDGES Specifications

Antenna configuration	"Fourpoint" dipole (Suh et al. 2003)
Antenna beam (FWHM)	$\sim 80°$
Instantaneous band	90 to 205 MHz
Polarization	Single
Digitizer sample rate	420 Ms/s
FFT samples	32,768
FFT spectral resolution	12.817 kHz
Window function	Blackman–Harris
Window function efficiency	0.5
Window function resolution	26 kHz
Operational dynamic range	$> 10^6$

EDGES

Bowman & Rogers 2010 (submitted)

EDGES block diagram



AEER

Internally-switched calibration

- 3-position switch to measure (cycle every 10s):

$$\begin{aligned} p_0 &= g\,(T_L + T_R) \\ p_1 &= g\,(T_L + T_R + T_{cal}) \\ p_2 &= g\,(T_A + T_R) \end{aligned}$$

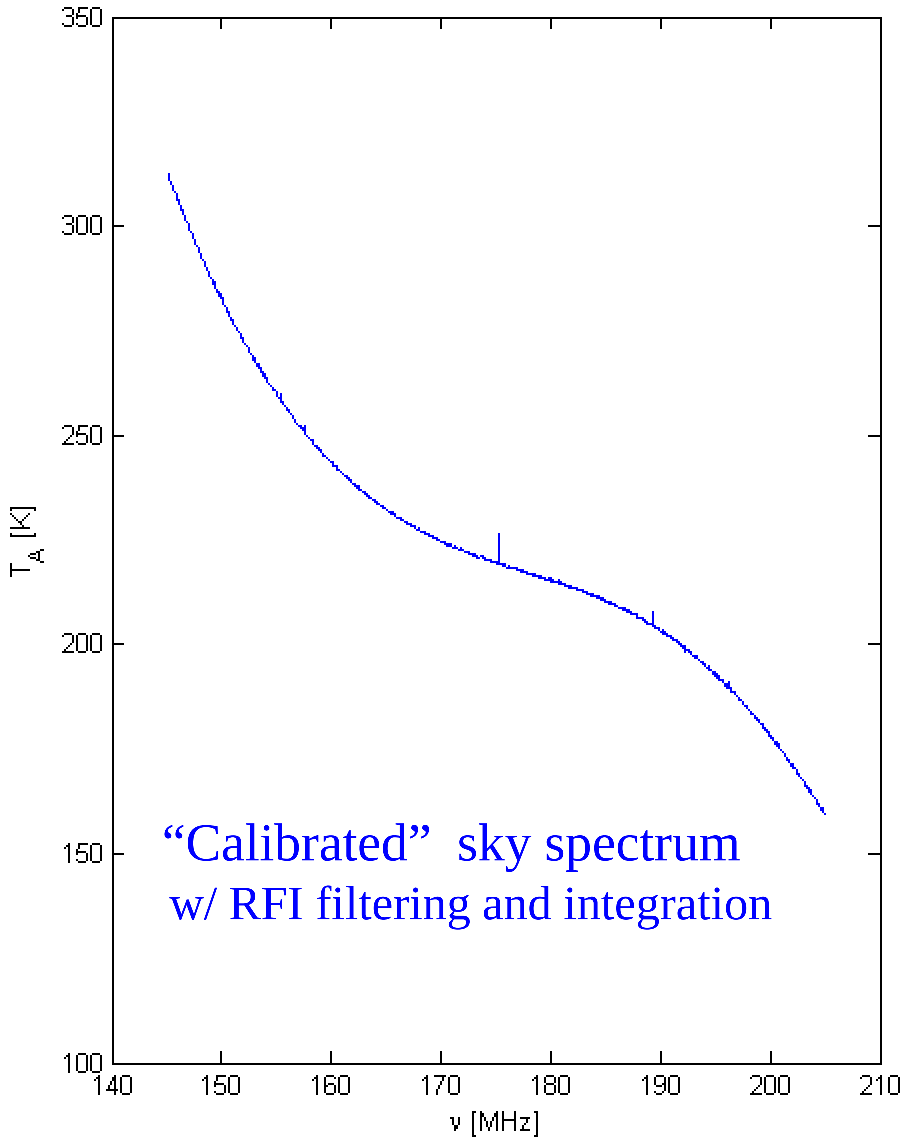
- Solve for antenna temperature:

$$T_A = T_{cal}\frac{p_2 - p_0}{p_1 - p_0} + T_L$$

($T_{cal} > T_L \approx 300$ K, $T_A \approx 250$ K, $T_R \approx 20$ K)

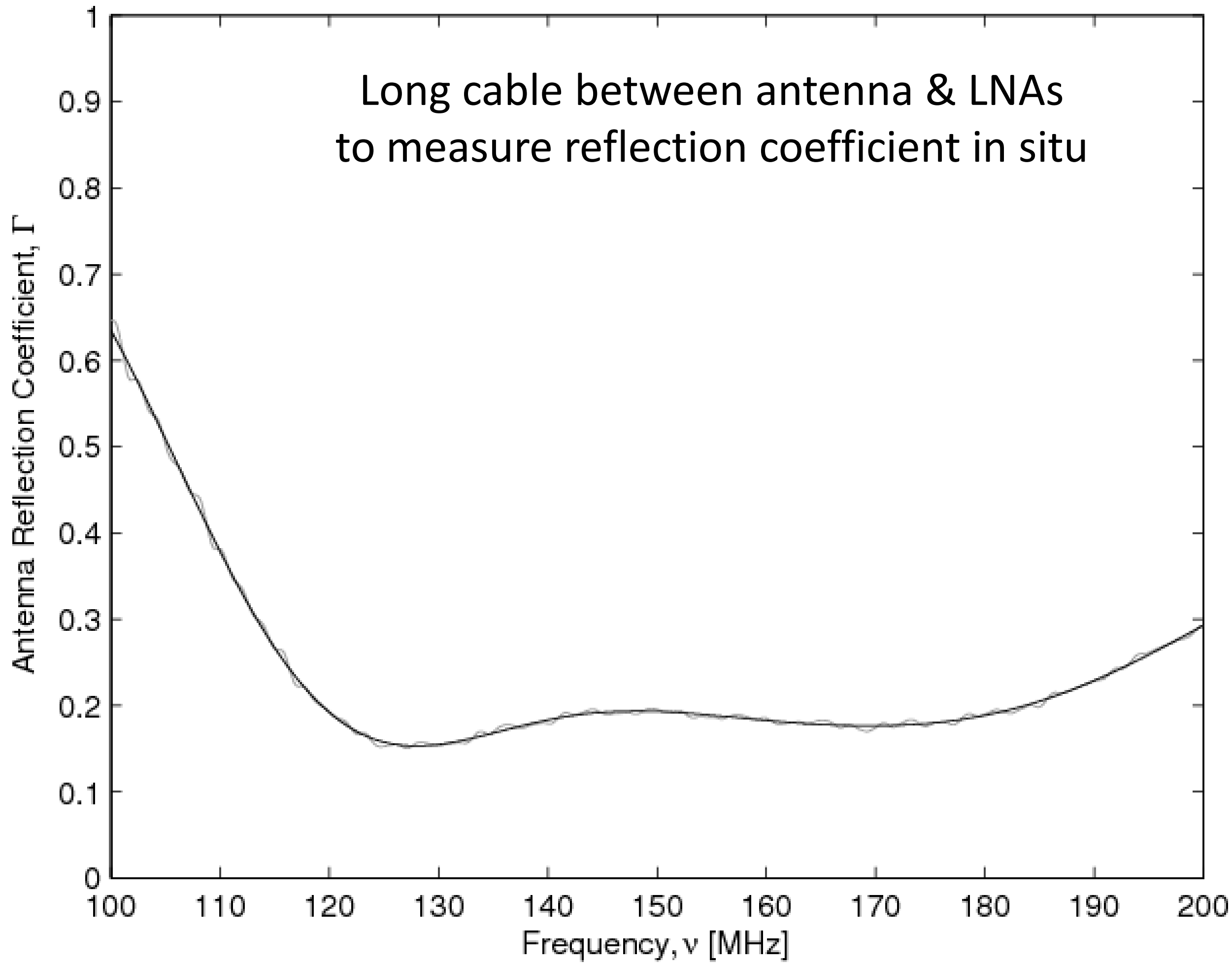
- Results: >10^5 dynamic range achieved with EDGES
- Limitations:
  - Total power differences between T_L and T_A can leave systematic errors
  - Temporal variations: comparing measurements at different times

Internally-switched calibration

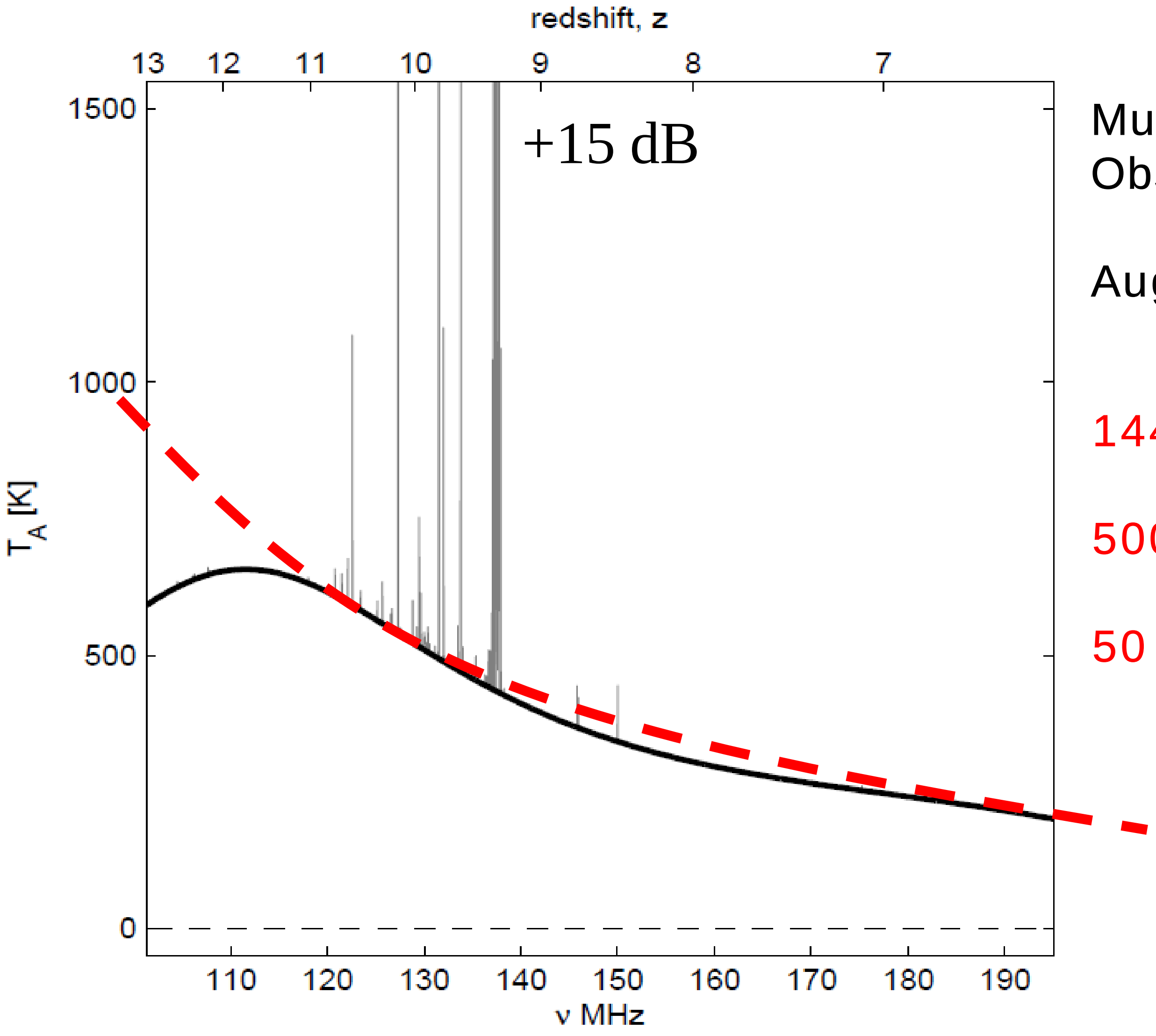


Antenna Impedance Causes Trouble

$$T_{ant}(\nu) = \left[1 - |\Gamma(\nu)|^2\right] T_{sky}(\nu) + \left[2\varepsilon|\Gamma|\cos(\beta) + \varepsilon^2|\Gamma|^2\cos^2(\beta) + (1-\varepsilon)^2|\Gamma|^2\right] T_{rcv}(\nu) \quad + \quad \cdots$$



Measured spectrum



Murchison Radio-astronomy Observatory (MRO)

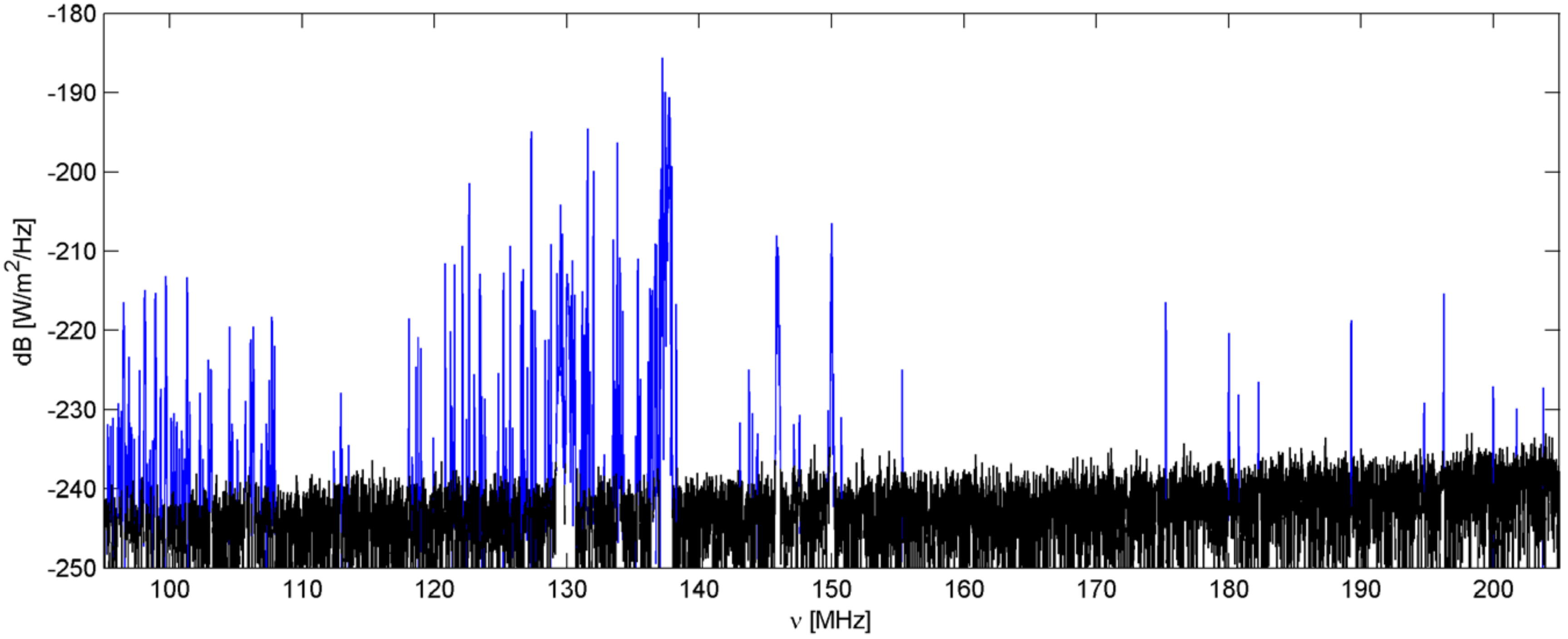
Aug 20 – Oct 20, 2009

1440 wall-clock hours on sky

500 hours after RFI cuts

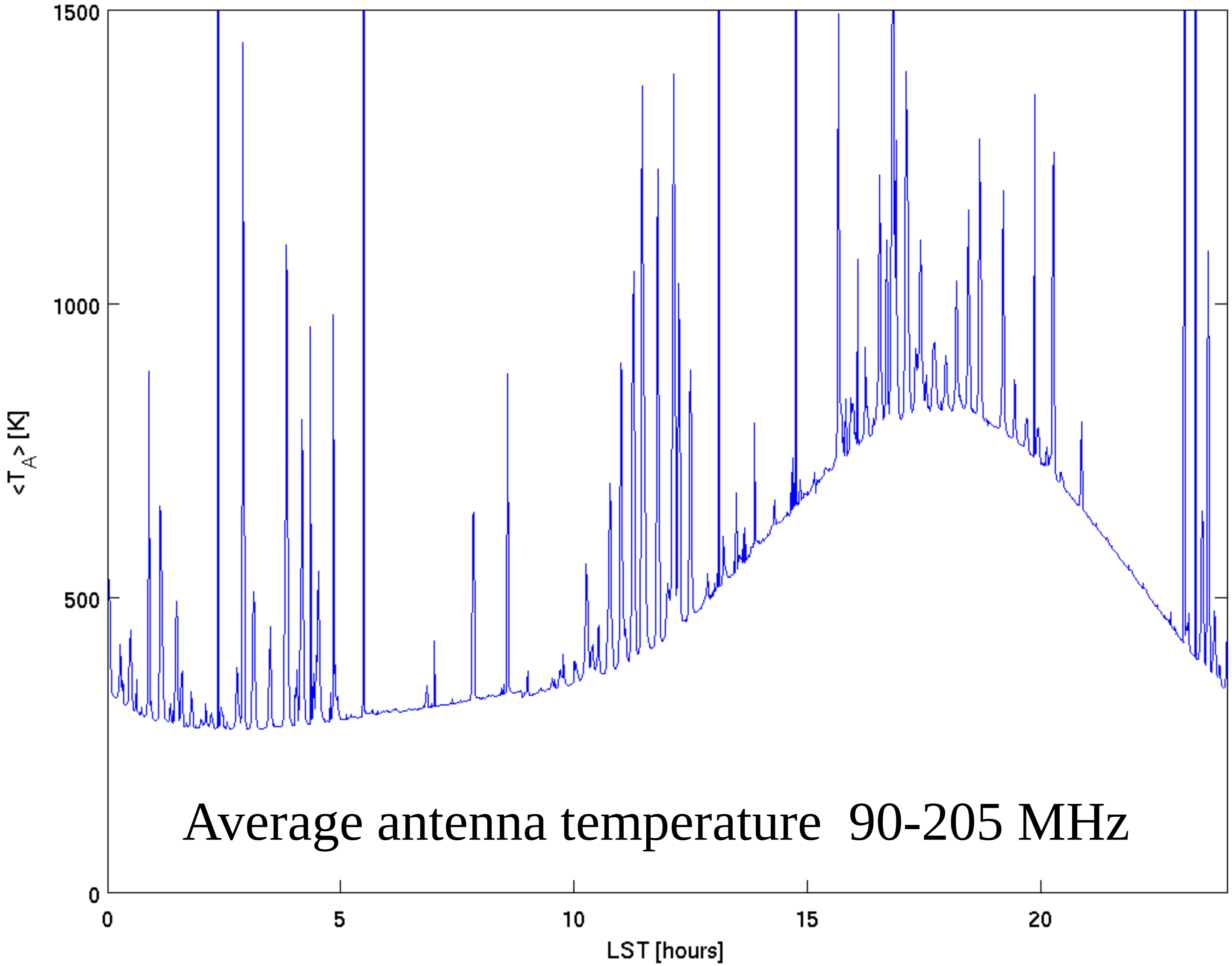
50 hours eff. integration

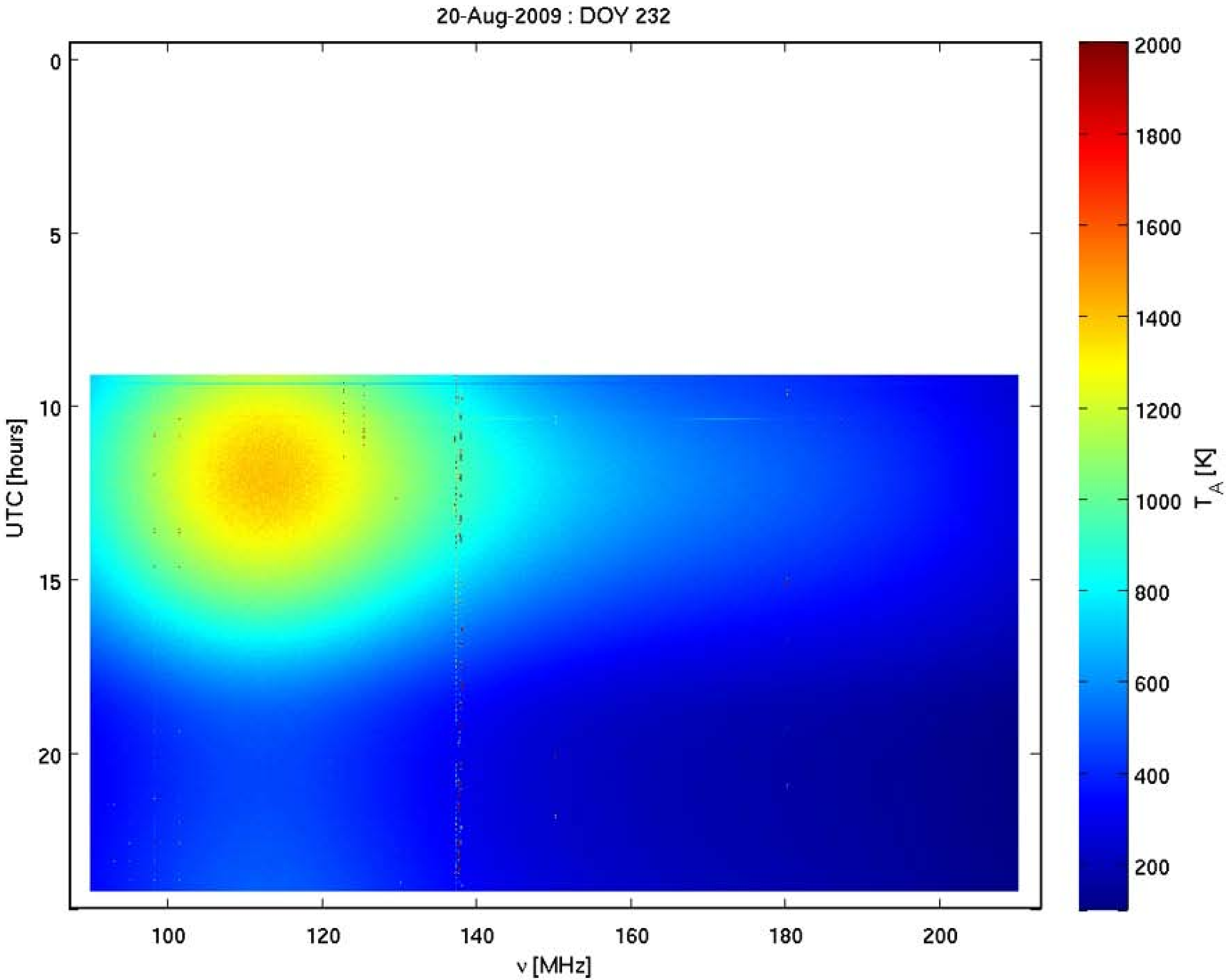
Integrated RFI
(time excision only – by broadband power level in FM, Orbcomm, DTV bands: 30% removal)



Bowman & Rogers 2010

Total power in band vs. time (Aug 23, 2009)

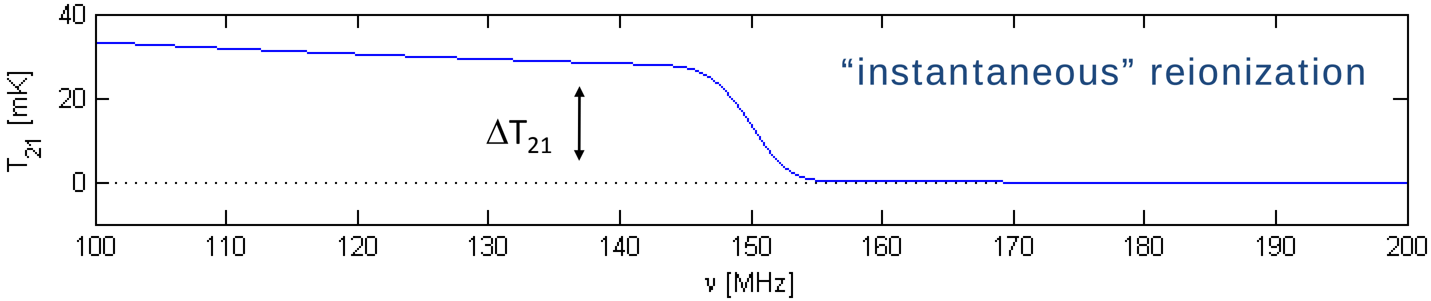



20-Aug-2009 : DOY 232
UTC [hours]
0
5
10
15
20
100
120
140
160
180
200
ν [MHz]
2000
1800
1600
1400
1200
1000
800
600
400
200
T_A [K]

Model fitting

- Polynomial term: $p = \sum_{n=0}^{m} a_n \nu^n$ to account for impedance mismatch + galactic spectrum

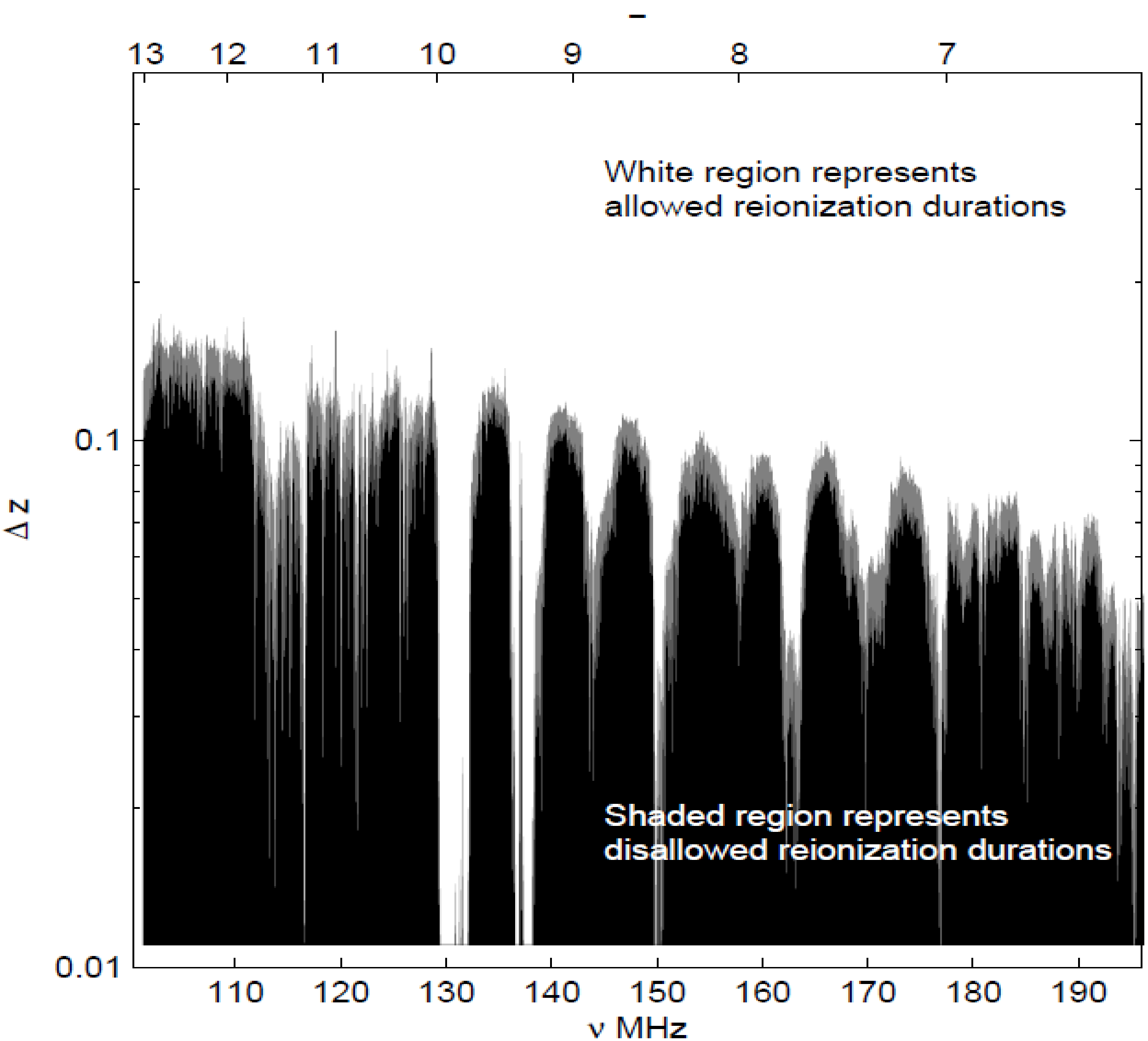
- Simple step model of reionization: $s = \frac{\Delta T_{21}}{2}\left(1 + \tanh\left[\alpha\left(\nu - \nu_0\right)\right]\right)$



3 science parameters: ΔT_{21}, α, and ν_0

5-15 nuisance parameters: a_n

21 cm results



Lessons from EDGES

Technical problems for ground-based experiments	DARE
Complex environment Prevents transferring laboratory calibration of the antenna impedance and beam pattern to the deployed instrument	**Simple environment** Simple, compact, stable geometry of spacecraft enables accurate modeling of the antenna and facilitates *in situ* calibration.
Multipath reflections Trees, mountains, and other structures can reflect sky noise	**No multipath** No external structures are in proximity to the spacecraft.
RFI is always present	**No RFI** Full spectrum is usable for science.
Dynamic range is difficult to achieve A/D converters must use large bit-depths and be highly linear to accommodate RFI. Particularly susceptible to internal clock stability errors and digital noise.	**Easy to achieve needed dynamic range** A/D converter can use low bit-depth, industry standard specifications. Receiver based on 50 years of proven RF flight hardware.
The Earth's ionosphere Refraction of astronomical radio waves leads to frequency-dependent variations in the intensity and position of the radio sky.	**No ionosphere**

* No transmission line cable between antenna and receiver, low duty cycle

The end

This scientific work uses data obtained from the Murchison Radio-astronomy Observatory.
We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site.