The EDGES result: Absorption of the CMB by the 21-cm hydrogen line at redshift 17 – an update and future plans

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aeer NCRA-TIFR 20 March 2019

What I plan to cover

- Introduction
- Brief Science overview

    The Experiment to Detect the Global EoR Signature (EDGES) result
- Instrument description

    Antenna beam – frequency dependence

    receiver and digitizer – use of out of band noise to improve linearity
- Calibration

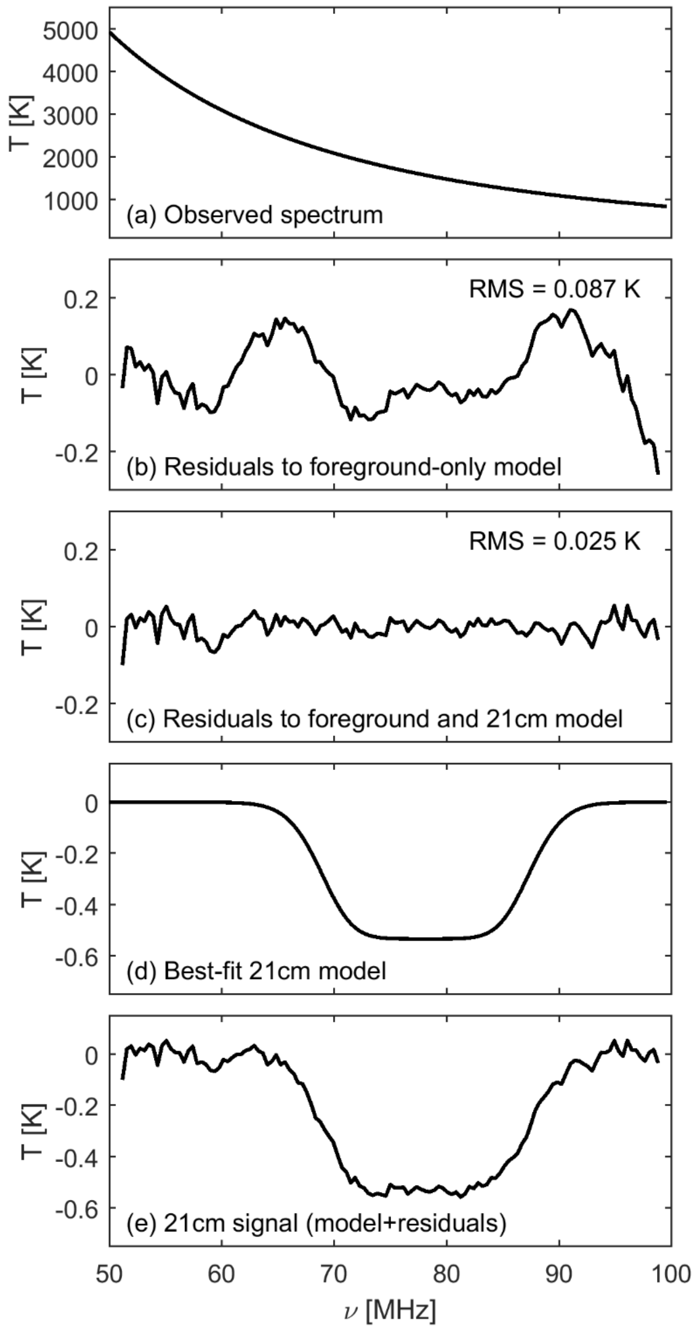
    Method of obtaining higher accuracy VNA measurements

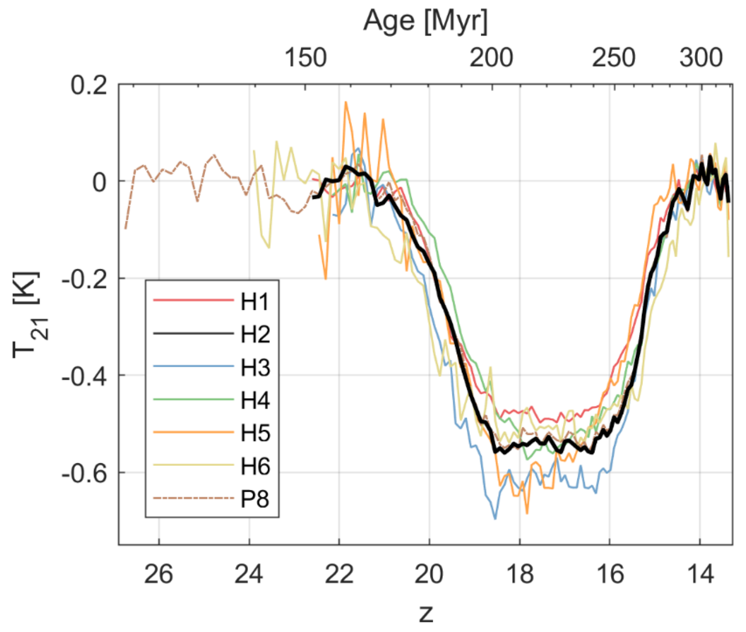
    3-postion switching to obtain gain and offset and remove receiver bandpass

    Measurement of LNA “noise waves”
- Data processing

    Data averaging and removal of RFI

    Removing the foreground and effects of ionospheric absorption and emission
- EDGES-3 and plans to deploy in Oregon in June





H1 – low-1 10x10 ground plane
H2 – low-1 30x30 ground plane
H3 – low-1 30x30 ground plane and recalibrated receiver
H4 – low-2 NS
H5 - low-2 EW
H6 – low-2 EW no balun shield
P8 - physical foreground (51 – 99 MHz) – others 5T poly (60-99) MHz

from: “An absorption profile centered at 78 megahertz in the sky-averaged spectrum” Nature 555, 67-70 (01 March 2018).

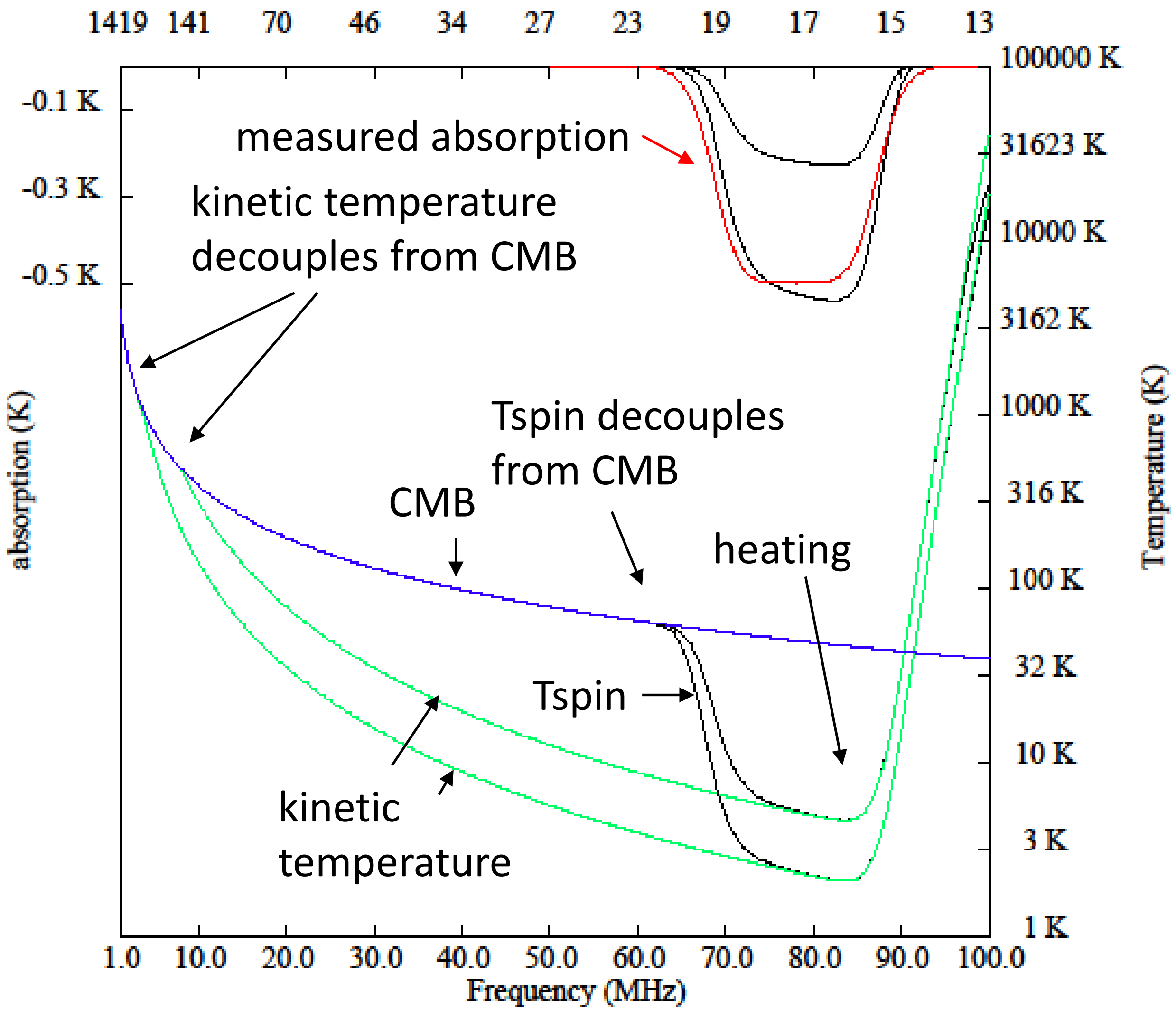
EDGES result: Global absorption in sky-averaged spectrum at

Center Frequency 78+/- 1 MHz red-shift Z = 17
Width 19+/- 3 MHz
Consistent with standard models but with Unexpected
Amplitude 0.5-0.2+0.5 MHz
which is a factor of 2 larger than largest predictions

Possible explanations:

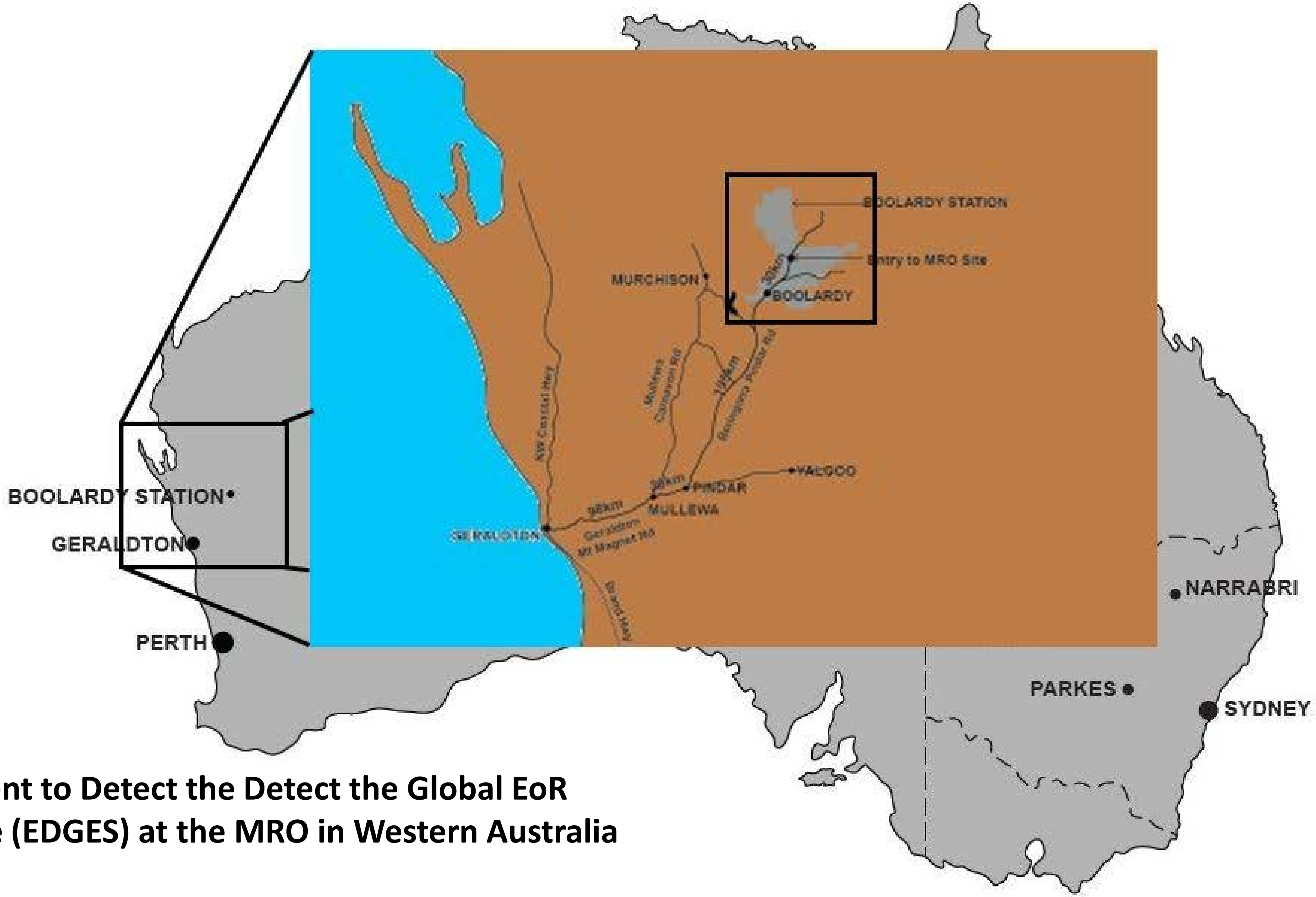
1] Hydrogen gas is much colder than expected – due to effects of Dark matter
or
2] CMB at redshift 17 has added radio background

Illustration of the increased depth of absorption with earlier decoupling of kinetic temperature from CMB and flattening if Tspin "bottoms out" on the kinetic temperature



This is only an illustration as I have "tweaked" the times of decoupling and the coupling strength as well as the time of the start of heating i.e. it is not based on specific Lyman Alpha and collision rates etc.

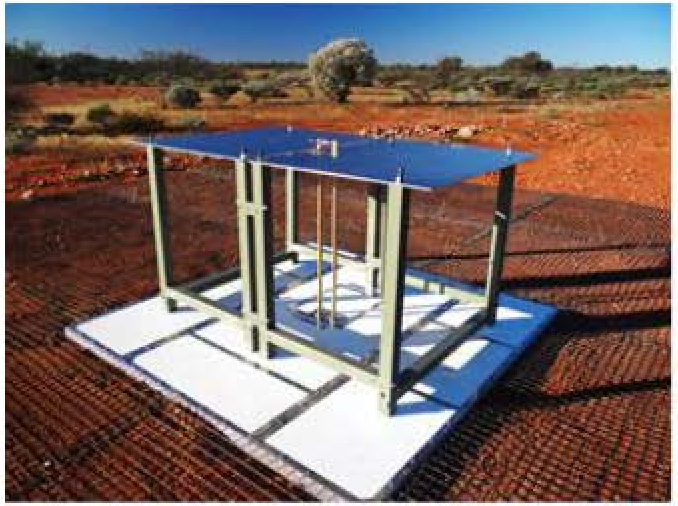
Murchison Radio Observatory

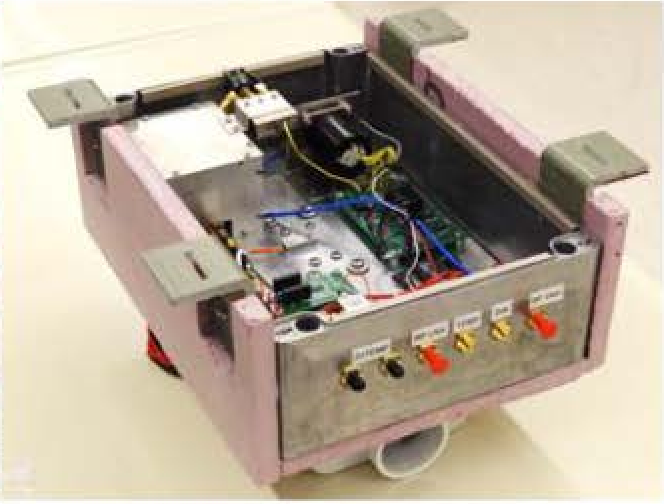


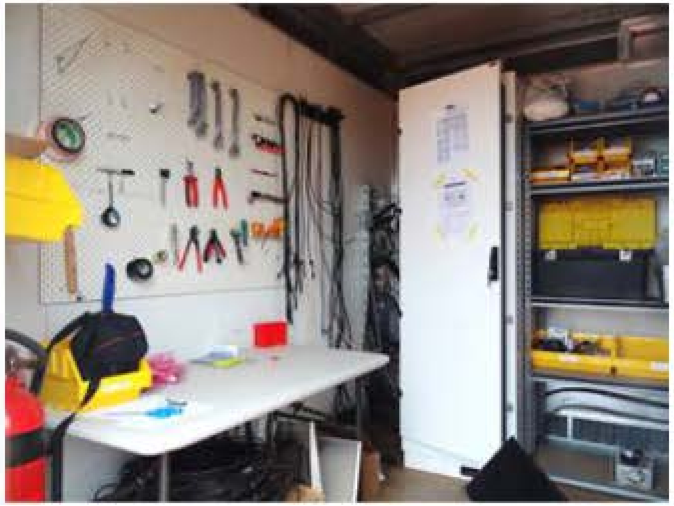
Experiment to Detect the Detect the Global EoR Signature (EDGES) at the MRO in Western Australia

High band 100 – 200 MHz

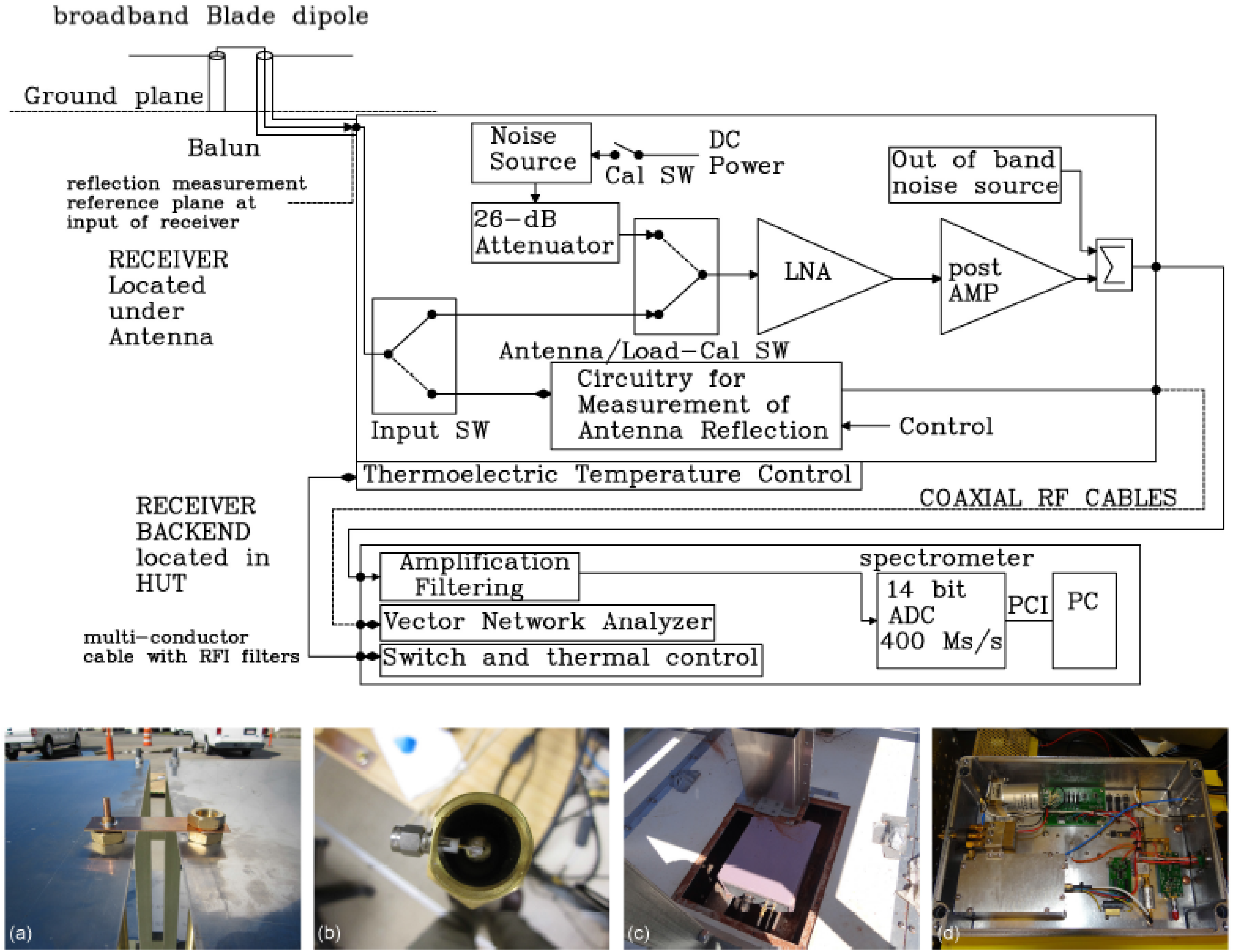
Low band 50 – 100 MHz







EDGES-2 installation at the MRO


broadband Blade dipole
Ground plane
Balun
reflection measurement reference plane at input of receiver
RECEIVER Located under Antenna
Noise Source
Cal SW
DC Power
26-dB Attenuator
Out of band noise source
LNA
post AMP
Input SW
Antenna/Load-Cal SW
Circuitry for Measurement of Antenna Reflection
Control
Thermoelectric Temperature Control
COAXIAL RF CABLES
RECEIVER BACKEND located in HUT
multi-conductor cable with RFI filters
Amplification Filtering
Vector Network Analyzer
Switch and thermal control
spectrometer
14 bit ADC 400 Ms/s
PCI
PC
(a)
(b)
(c)
(d)

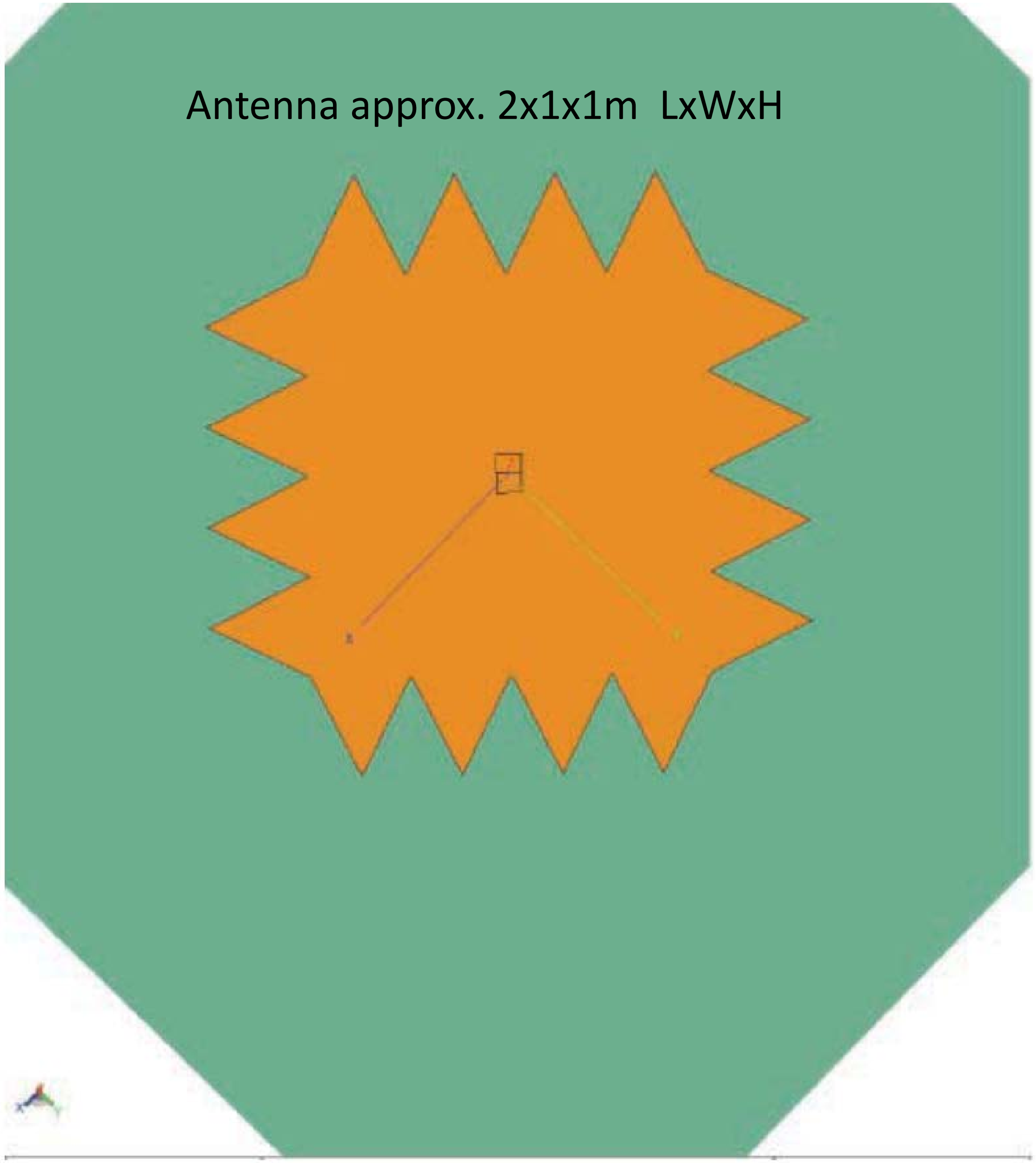
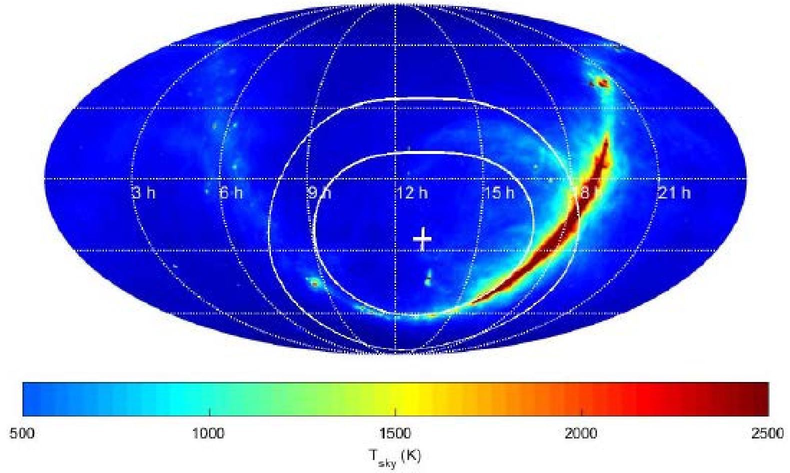
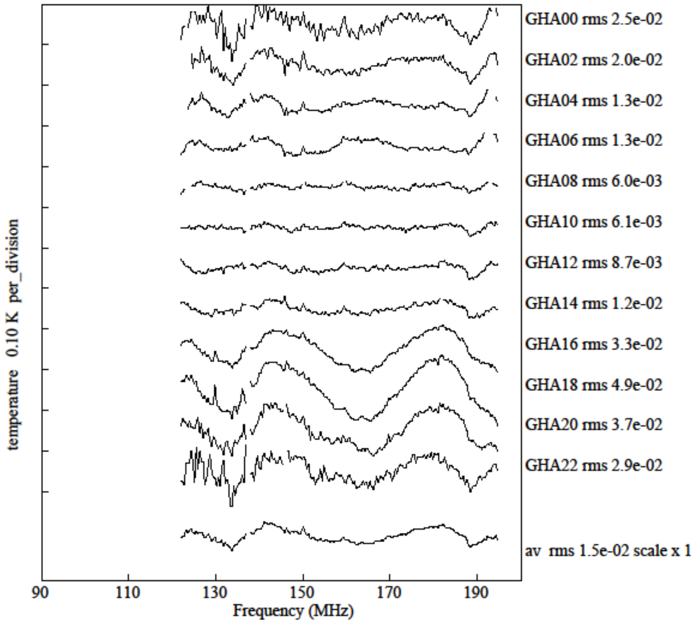


Figure 1. Proposed low band ground plane.

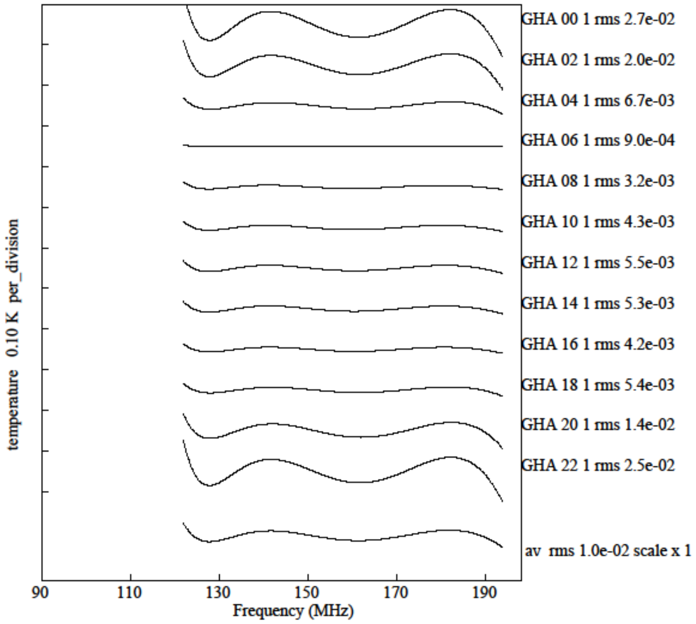
Low Band Antenna on large 30x30m ground plane



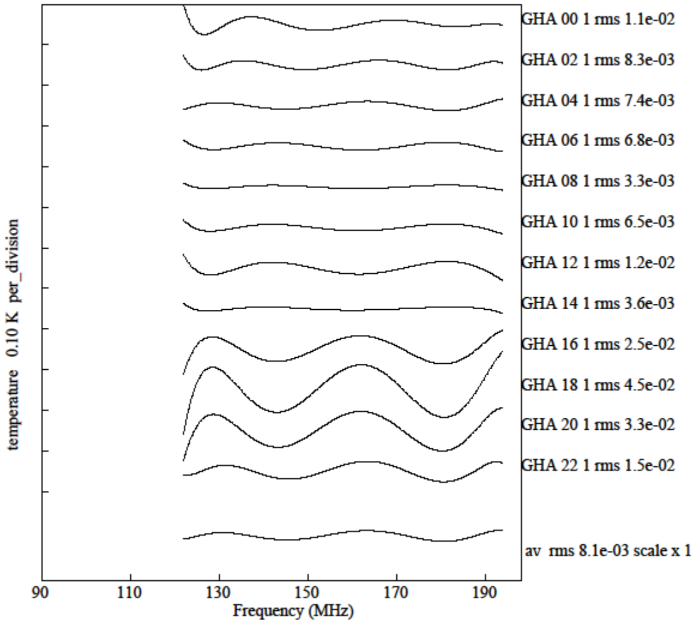
EDGES beam -3 and -10 dB at 75 MHz



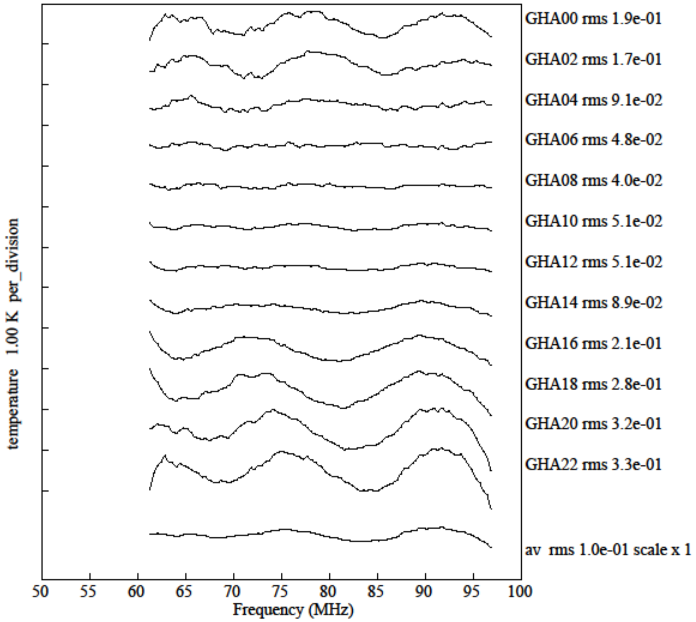
High band 5-terms removed



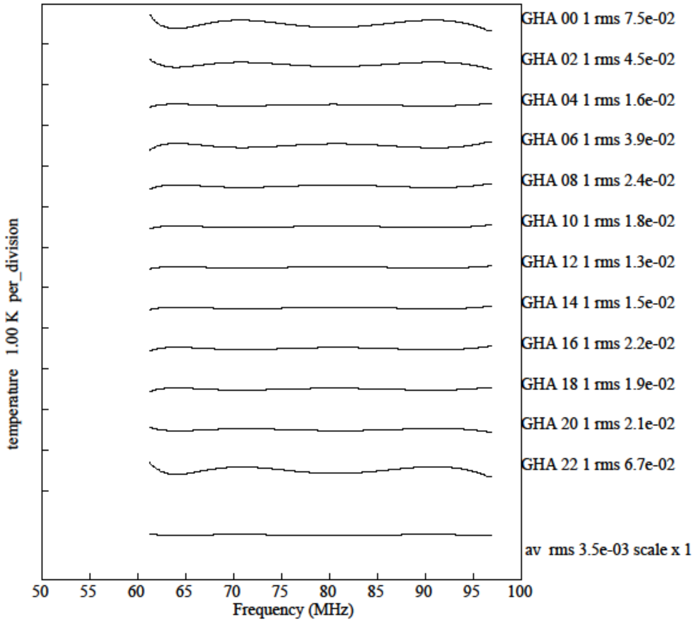
Simulated beam effect



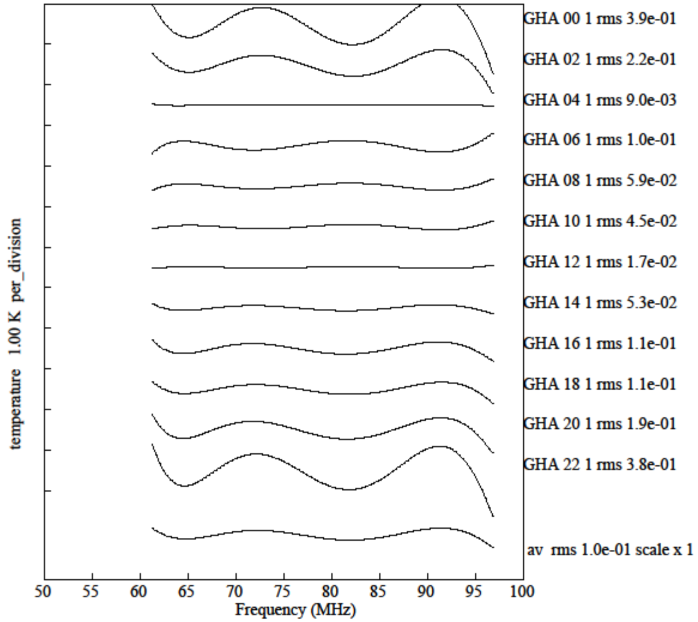
Simulated GF beam effect



Low band 5-terms removed



Simulated beam effect



Simulated GF beam effect

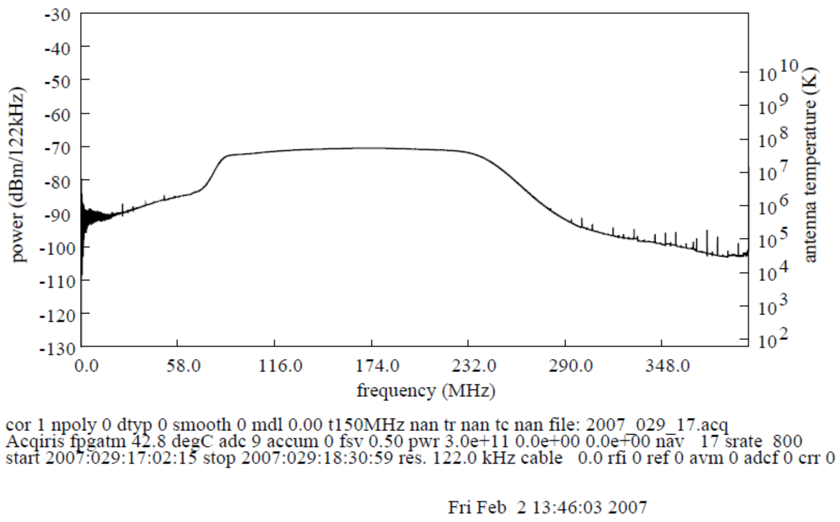


Figure 1. Spectrum of noise source from AC240 with 800 Ms/s. Note the spurs and steps in the spectrum beyond the edge of the analog filter at about 280 MHz.

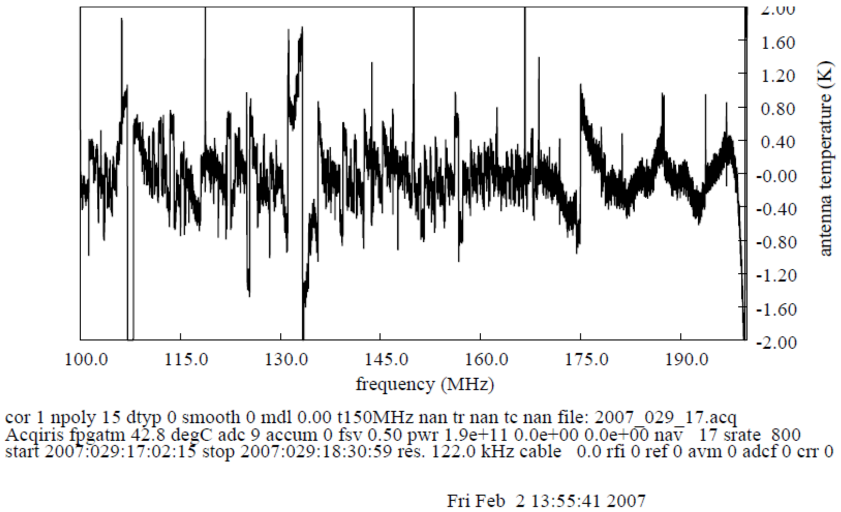


Figure 2. The spectrum from 100 to 200 MHz of the data in figure 1 after the removal of a polynomial. The vertical scale is now expanded to a linear temperature.

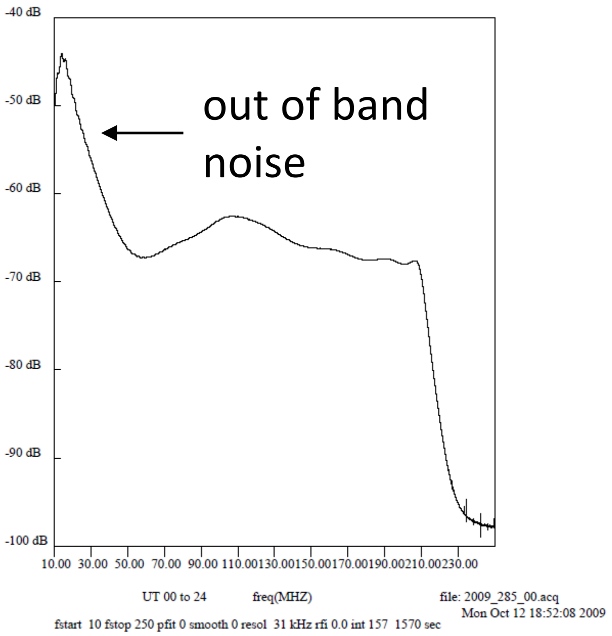


Figure 1. Spectrum of the added out of band noise peaking below 30 MHz, the simulated antenna spectrum peaking at about 110 MHz and the filter cut-off at 210 MHz.

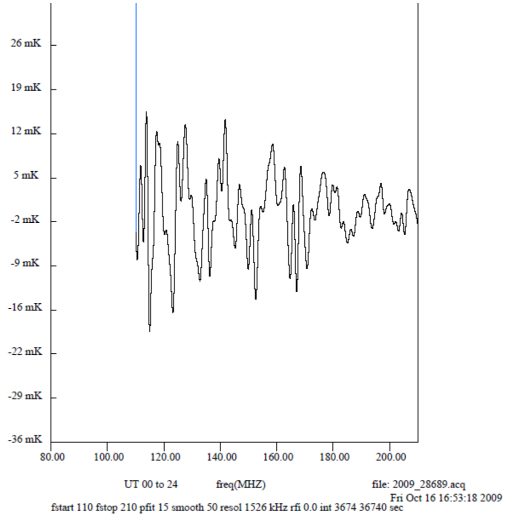


Figure 2. Spectrum of antenna ports using 3-position switching after removal of 15 term polynomial. The signal from the antenna port is 8% of the total power and the full-scale voltage setting on the AC240 was 0.5 volts. The rms is about 6 mK.

The need for “out of band noise” to improve the linearity and dynamic range of the ADC

Technical Innovations

Improved VNA calibration

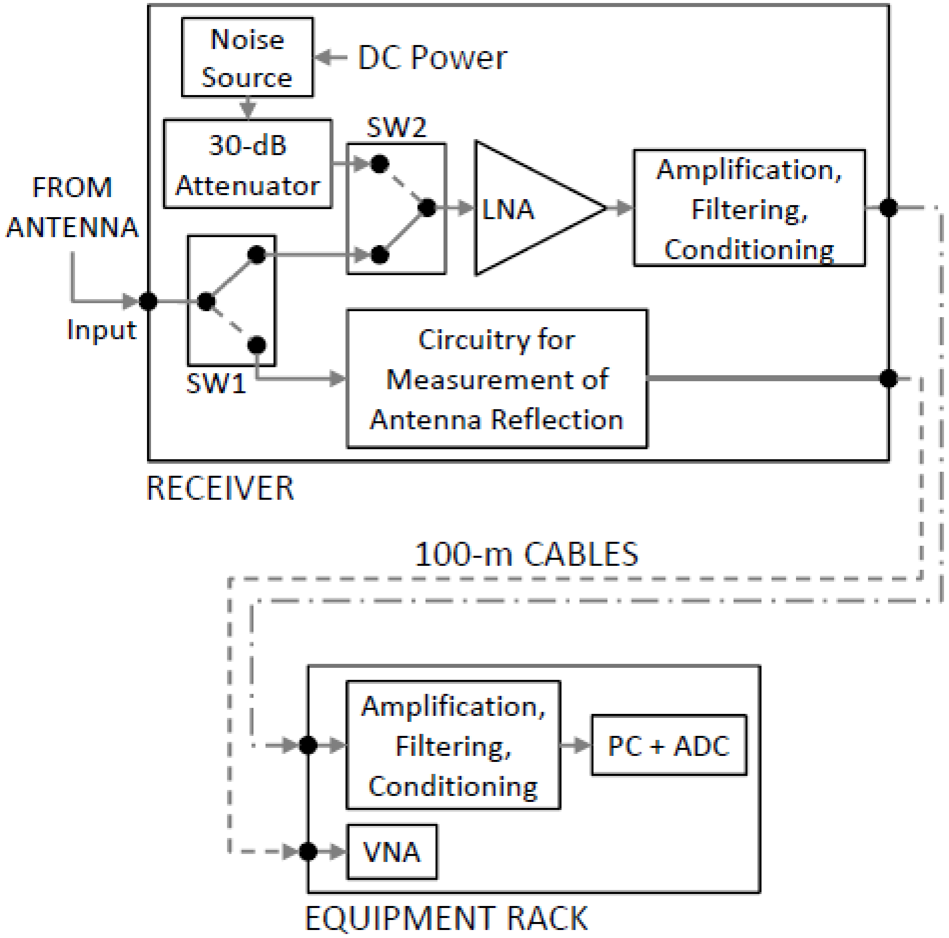
Uses VNA plus asymetric 2-port network to make measurements of

1] Short, Open, Load
2] SOL on asymmetric passive 2-port
3] SOL on asymmetric passive 2-port reversed
4] DC resistance of Load
 9-complex measurements + 1 real measurement to solve for
 3 complex unknowns of SOL
 3 complex unknowns of 2-port S11,S22,S12=S21
 3 complex unknowns of VNA calibration

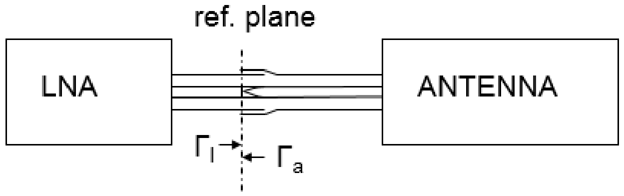
"One-Port Direct/Reverse method for Characterizing VNA Calibration Standards" Monsalve et al. (2016) IEEE Transactions on Microwave Theory and Techniques 64(8): 2631-2639

Automated S11 measurement of antenna

0.01 dB error in antenna S11 of -10 dB results in ~0.5 K out of 2000 K



Antenna to Low Noise Amplifier mismatch



Compensating for the antenna mismatch
$T_{sky}(1-|\Gamma|^2) = T_{sky}(1-|\Gamma_a|^2)|F|^2$

where Γ is the reflection from the LNA and

$\Gamma = \frac{Z_a - Z_l^*}{Z_a + Z_l}$

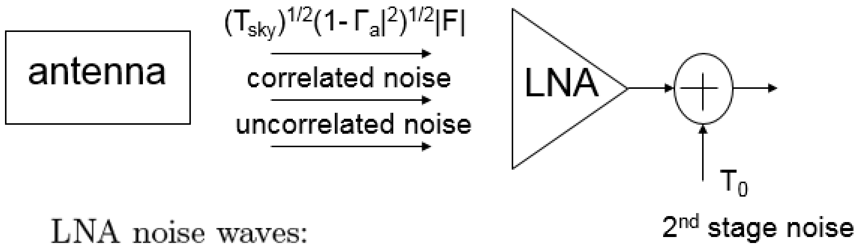
$F = \frac{(1-|\Gamma_l|^2)^{1/2}}{1-\Gamma_a\Gamma_l}$

where Γ_a and Γ_l are the reflections at 50 ohms ref. point

$\Gamma_a = \frac{Z_a-50}{Z_a+50}$

$\Gamma_l = \frac{Z_l-50}{Z_l+50}$

LNA noise waves reflected back from antenna



LNA noise waves:

$$T_{rec} = T_{sky}(1-|\Gamma_a|^2)|F|^2 + T_u|\Gamma_a|^2|F|^2 + (T_c cos(\phi) + T_s sin(\phi))|\Gamma_a||F| + T_0$$

T_u is the uncorrelated wave

$T_c cos(\phi)$ and $T_s sin(\phi)$ are the correlated portions which depend on the phase, ϕ, of the reflected wave.

ϕ is the phase of $\Gamma_a F$

T_0 is the "second stage noise".

3 – position input switching – antenna, load, cal to take out "bandpass" and set temperature scale

$$P_{ant} = gT_{rec}$$
$$P_{load} = g(GT_{amb} + T_0)$$
$$P_{cal} = g(G(T_{amb} + T_{cal}) + T_0)$$

where g is the receiver gain and G is $G = 1 - |\Gamma_l|^2$

$Tamb$ is the ambient temperature and T_{cal} calibration noise

The calibrated receiver output, T_{3p}, is

$$\begin{aligned} T_{3p} &= \frac{T_{cal}(P_{ant} - P_{load})}{(P_{cal} - P_{load})} + T_{amb} \\ &= T_{sky}(1-|\Gamma_a|^2)|F|^2G^{-1} \\ &+ T_u|\Gamma_a|^2|F|^2G^{-1} \\ &+ (T_c cos(\phi) + T_s sin(\phi))|\Gamma_a||F|G^{-1} \end{aligned}$$

Calibration requires measurements of antenna and LNA reflection coefficients as well correlated and uncorrelated LNA noise

Correction for losses

$$T = T_{sky}L + T_{amb}(1-L)$$

$$L = (1 - |\Gamma a|^2)^{-1}|S21|^2(1-|\Gamma|^2)/|1-S22\Gamma|^2$$

where:

Γa = reflection coefficient on antenna measured from reference plane at LNA input

Γ = antenna reflection = $(\Gamma a - S11)/(S12S21 - S11S22 + S22\Gamma a)$

S11,S22,S12,S21 = antenna balun scattering coefficients

Calibration and processing procedure

In the Lab:

- Measure S11 of LNA, hot and ambient loads, and open/shorted cable
- Measure 3-position switched spectra of hot and ambient loads and open/shorted cable
- Use the data above to calibrate internal noise diode and measure LNA noise waves
- Measure the antenna balun loss

In the field:

- Measure the antenna S11 and 3-position switched spectrum

Using EM simulations

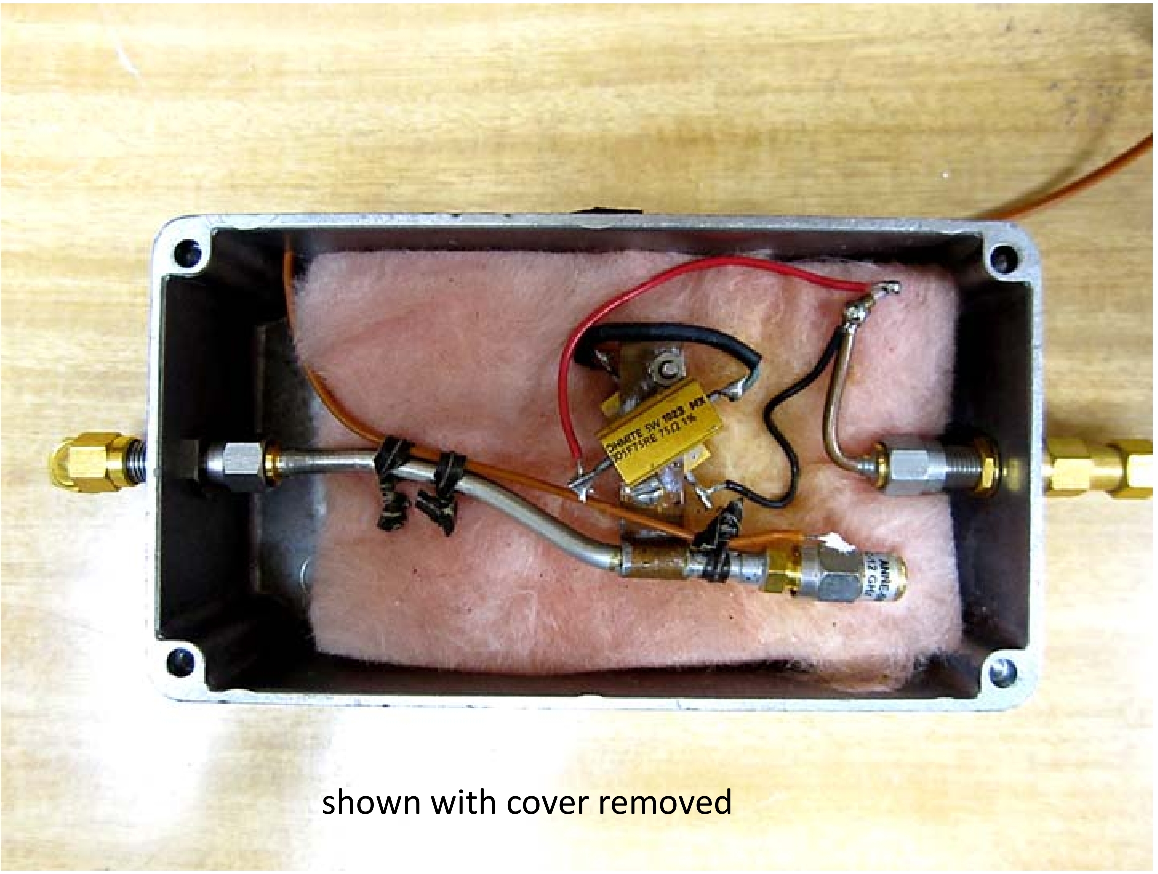
- Estimate the antenna and ground plane loss

Obtain absolute calibration of sky spectrum processing

- Using lab calibration data, antenna S11 and losses obtain sky spectrum
- Use weighted least squares with up to 6 physics based “basis” functions to remove foreground, ionosphere and solve for hydrogen line signature
- Error estimates from covariance matrix

Calibration HOT load of known temperature

Heated 50 ohm load with temperature probe



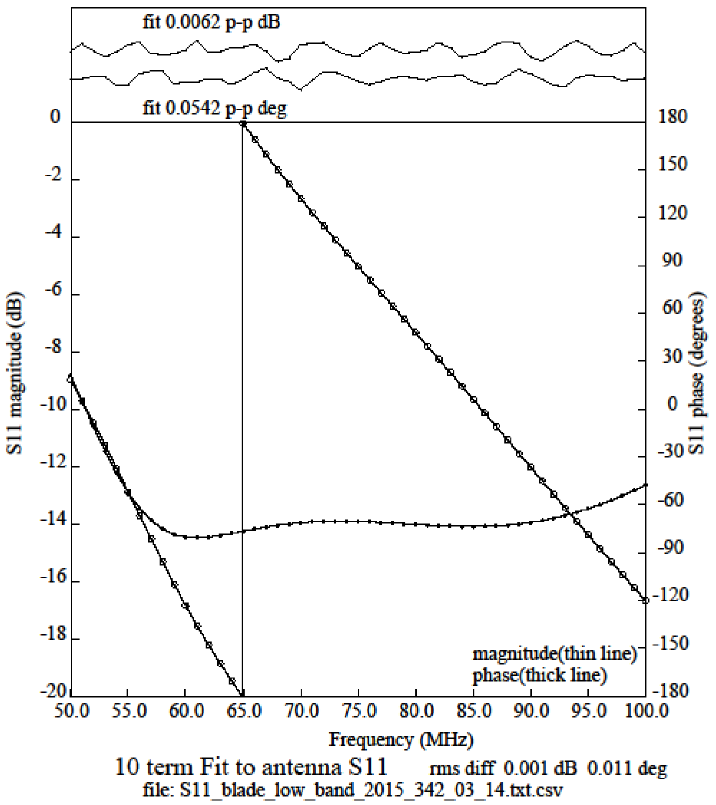
shown with cover removed

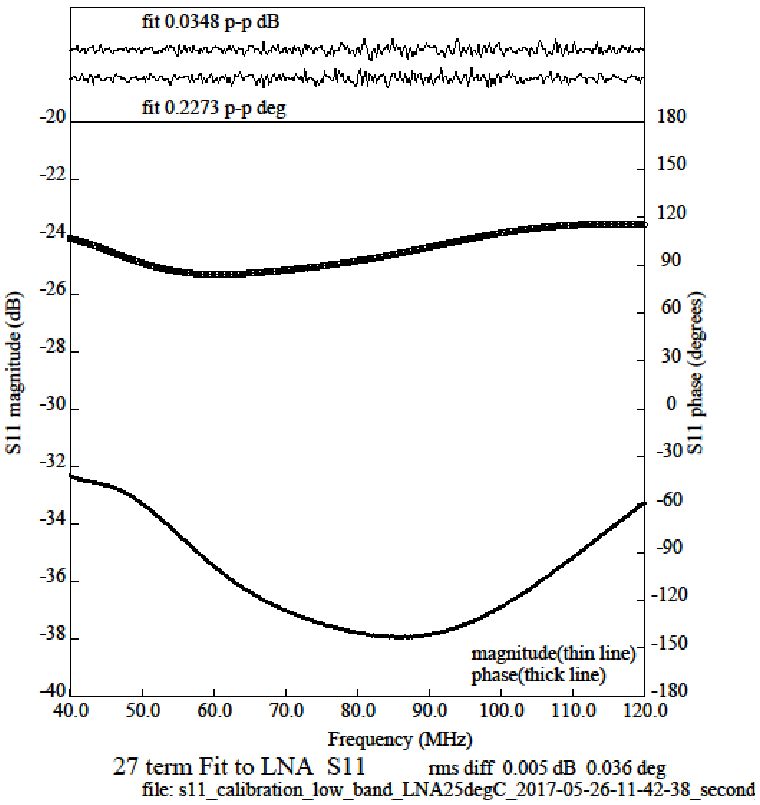
Corrections required for high accuracy:

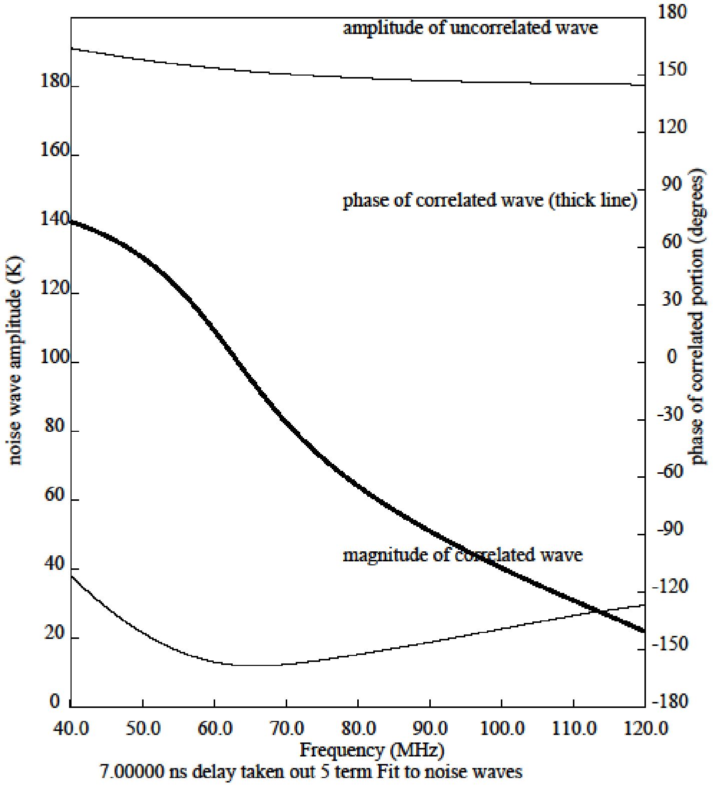
1] S11 measurement vs temperature – as load changes with temperature

2] Input line loss – plus assumption of temperature gradient

Open/shorted cable used to calibrate LNA noise waves





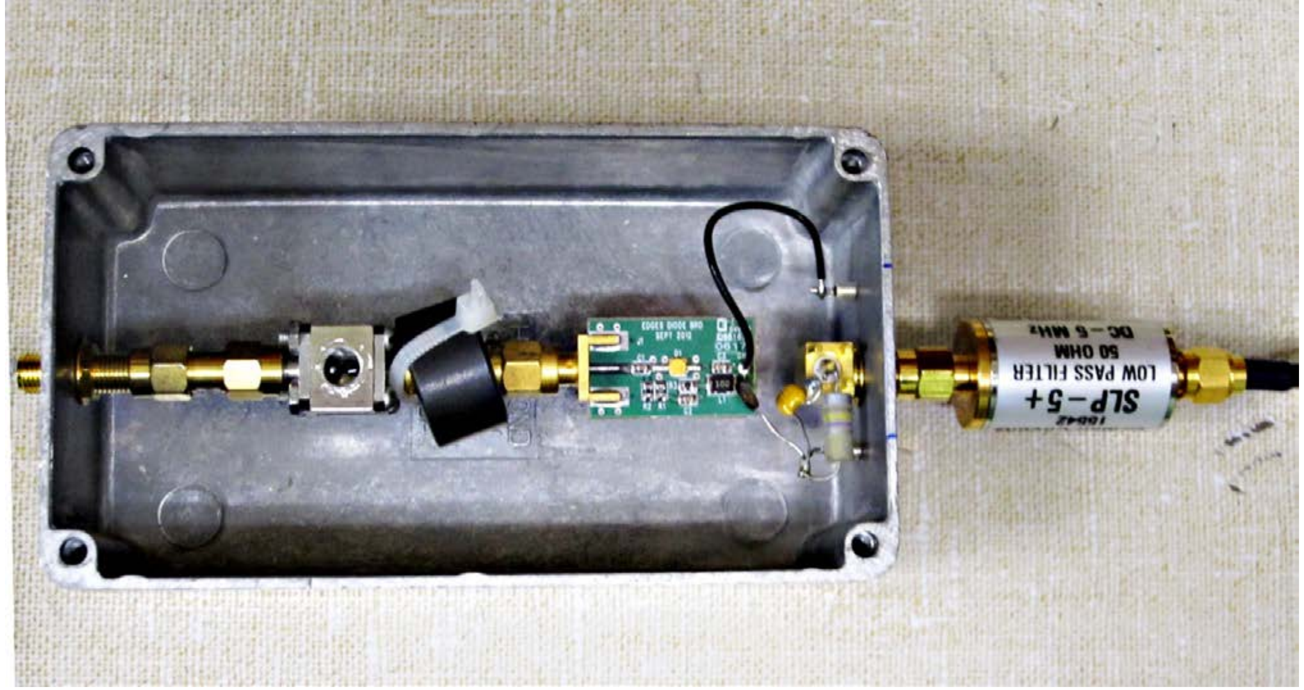


Antenna S11

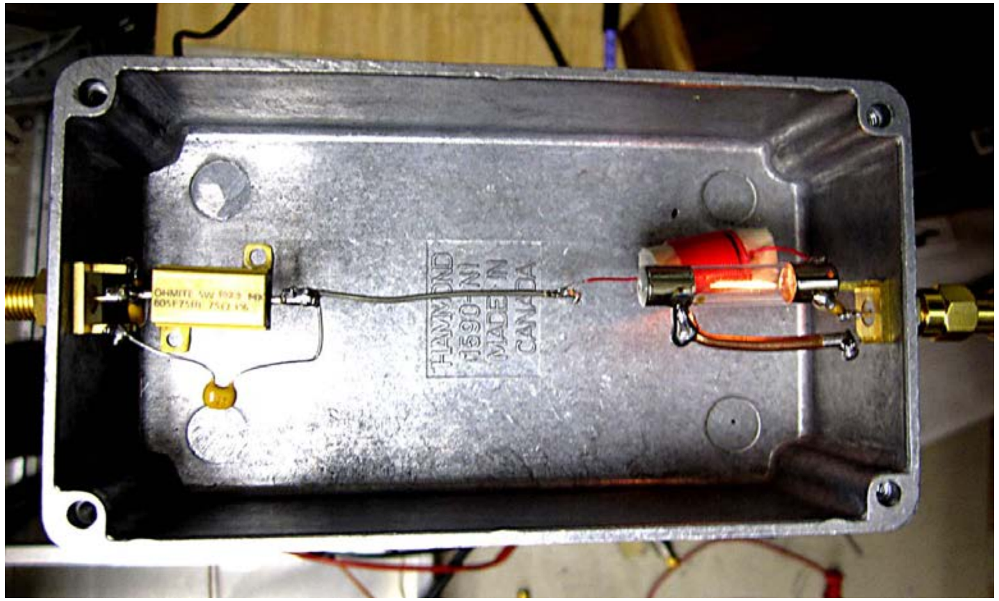
LNA S11

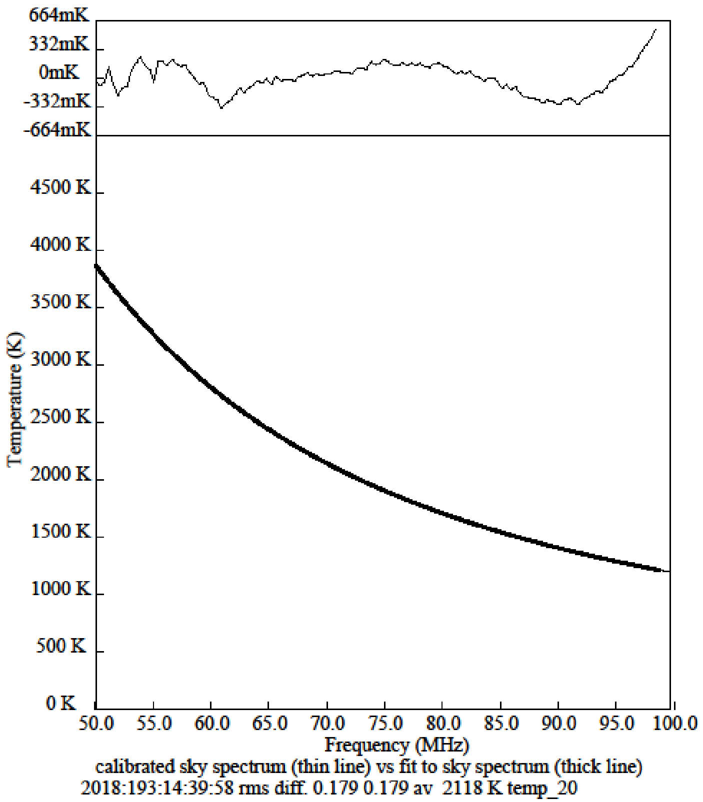
LNA noise waves

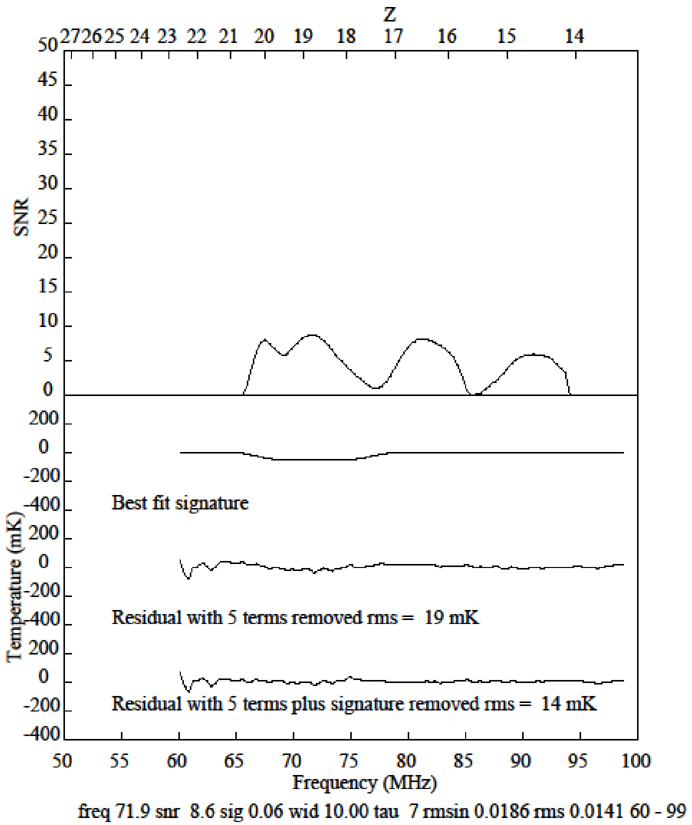
Noise source with filter used as "artificial" antenna

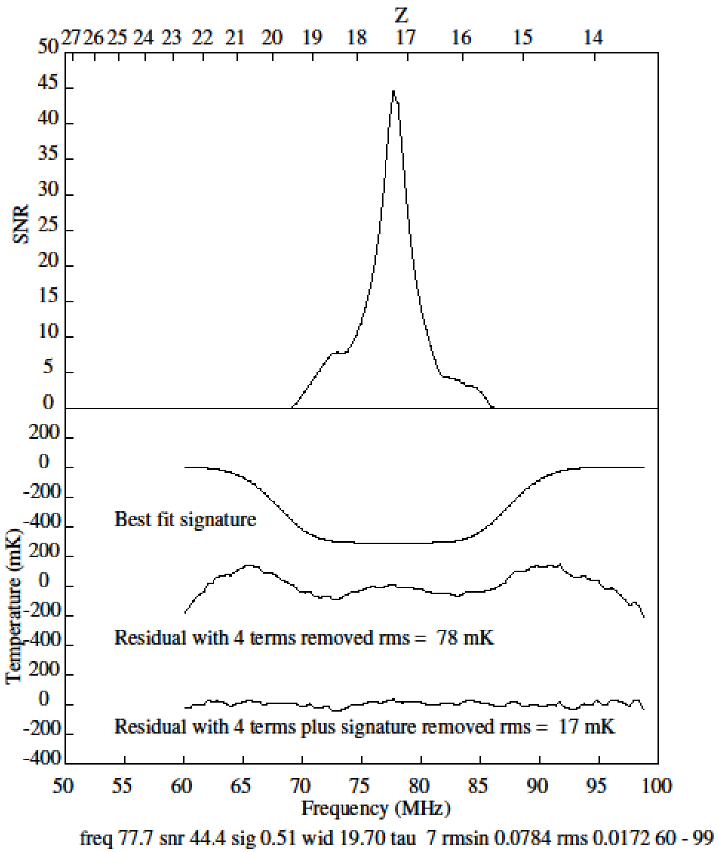


Tungsten lamp load for check of calibration – resistance is measured to obtain temperature of filament









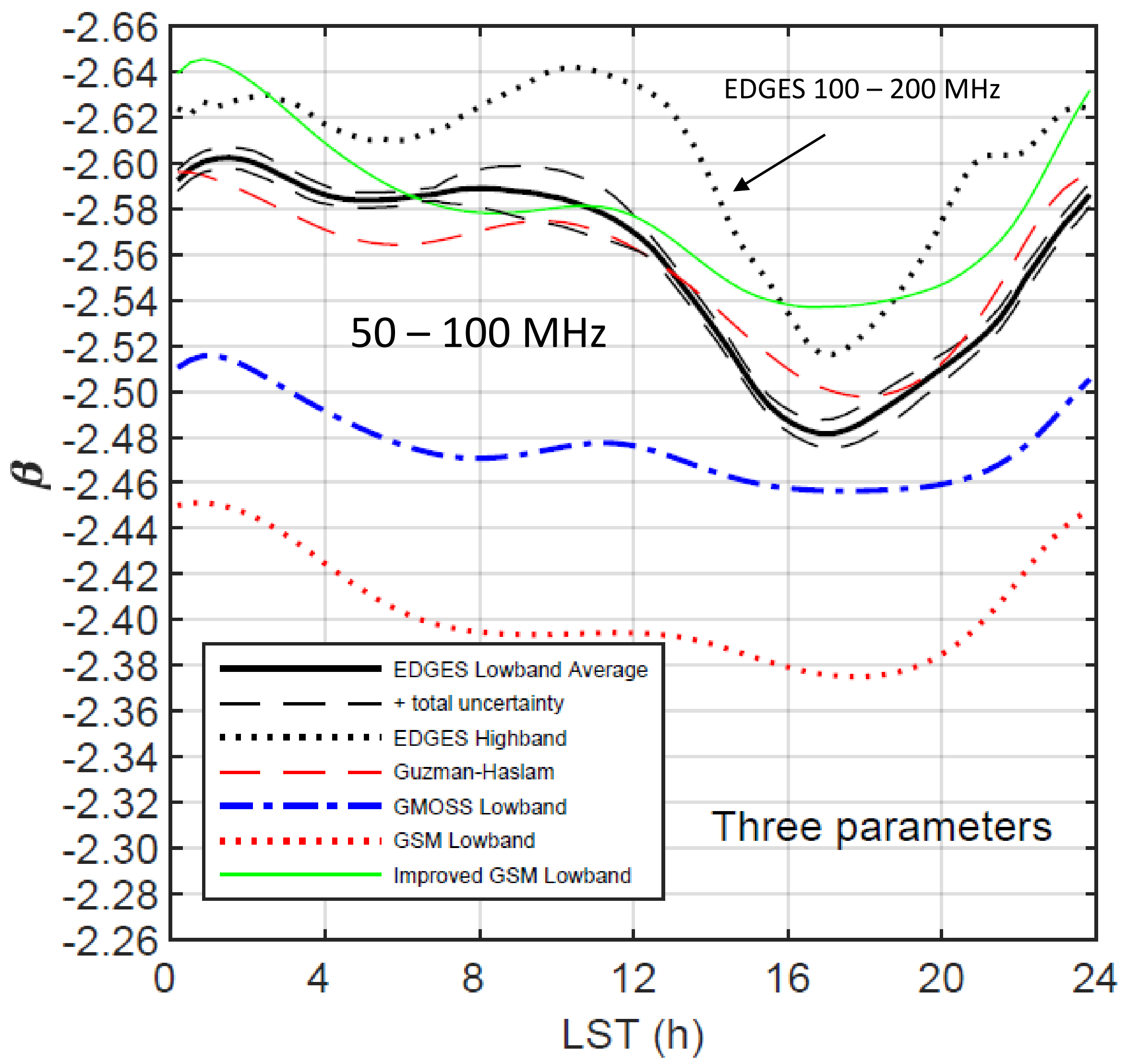
Spectrum from Antenna simulator
Top plot are residuals to 5-term fit

Signature search
using simulator

Signature search
using lowband data

Basis functions used to remove foreground and ionosphere and make estimates of the spectral index, curvature in the spectral index as well as the ionospheric absorption and emission

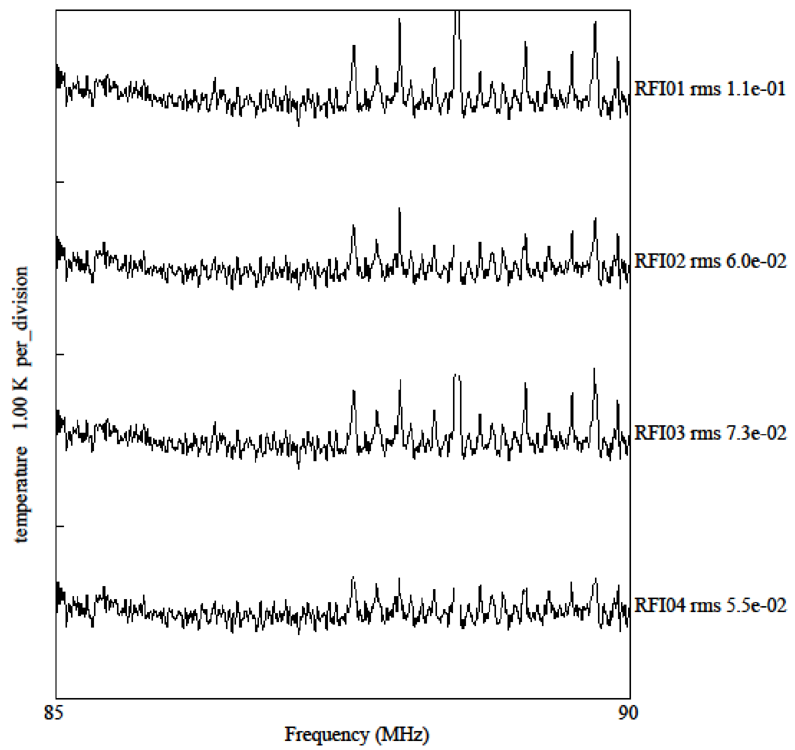
	function	Purpose
0	$f^{-2.5}$	Scale
1	$\log(f)\, f^{-2.5}$	Spectral index
2	$(\log(f))^2 f^{-2.5}$	foreground gamma
3	$f^{-4.5}$	Ion absorption
4	$f^{-2.0}$	Ion emission



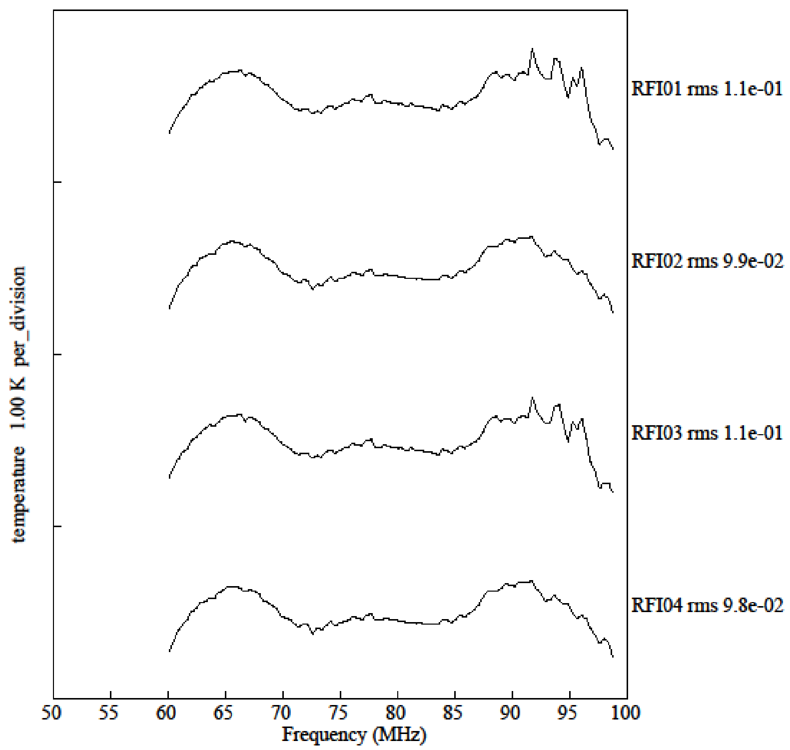
Mozdzen et al. 2018
Mon. Not. RAS

Foreground spectral index from EDGES compared with results from sky maps

RADIO FREQUENCY INTERFERENCE (RFI)



Relative sparseness of RFI from FM radio

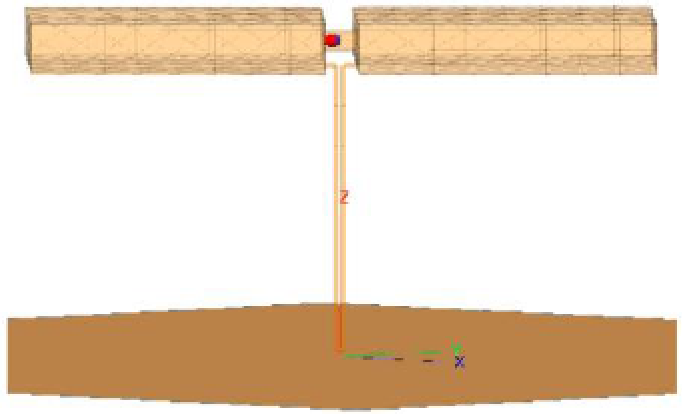


Effects of FM radio on absorption signature

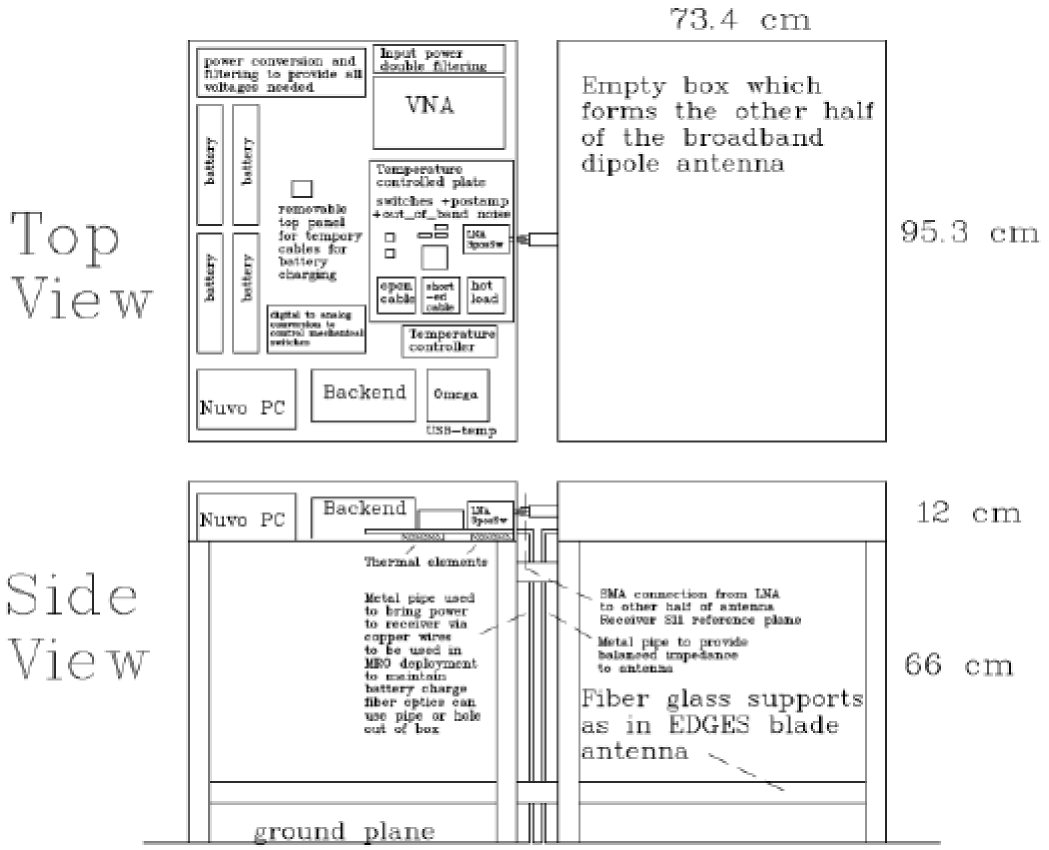
RFI from FM radio signals reflected from meteors which burn up at about 100 km. Sites need to be more than 2000 km from FM radio to completely avoid this source of RFI. Effects of FM radio reflected from the moon about 0.05 K max when moon is close to the zenith.

TESTS and CHECKS performed with EDGES-2

- Sensitivity to receiver calibration and S11 error
- Performed receiver recalibration – test suggested by Irwin Shapiro
- Changed antenna orientation
- Data from 2 separate lowband antennas on different ground planes
- Changed ground plane size
- Removed balun shield and other checks for possible resonances
- Measured absorption over full range of LST
- Checked for effects of ionosphere absorption and emission
- Checked for RFI effects on absorption including reflection from moon
- Checked sensitivity to foreground fitting
- Have 2 independently developed processing pipelines Haystack’s and ASU’s
- Checked effects of processing data with calibration at made at different temperatures
- Checked effects of beam correction with FEKO & HFSS and effect of no beam correction
- Checked effect of making no balun and other loss corrections



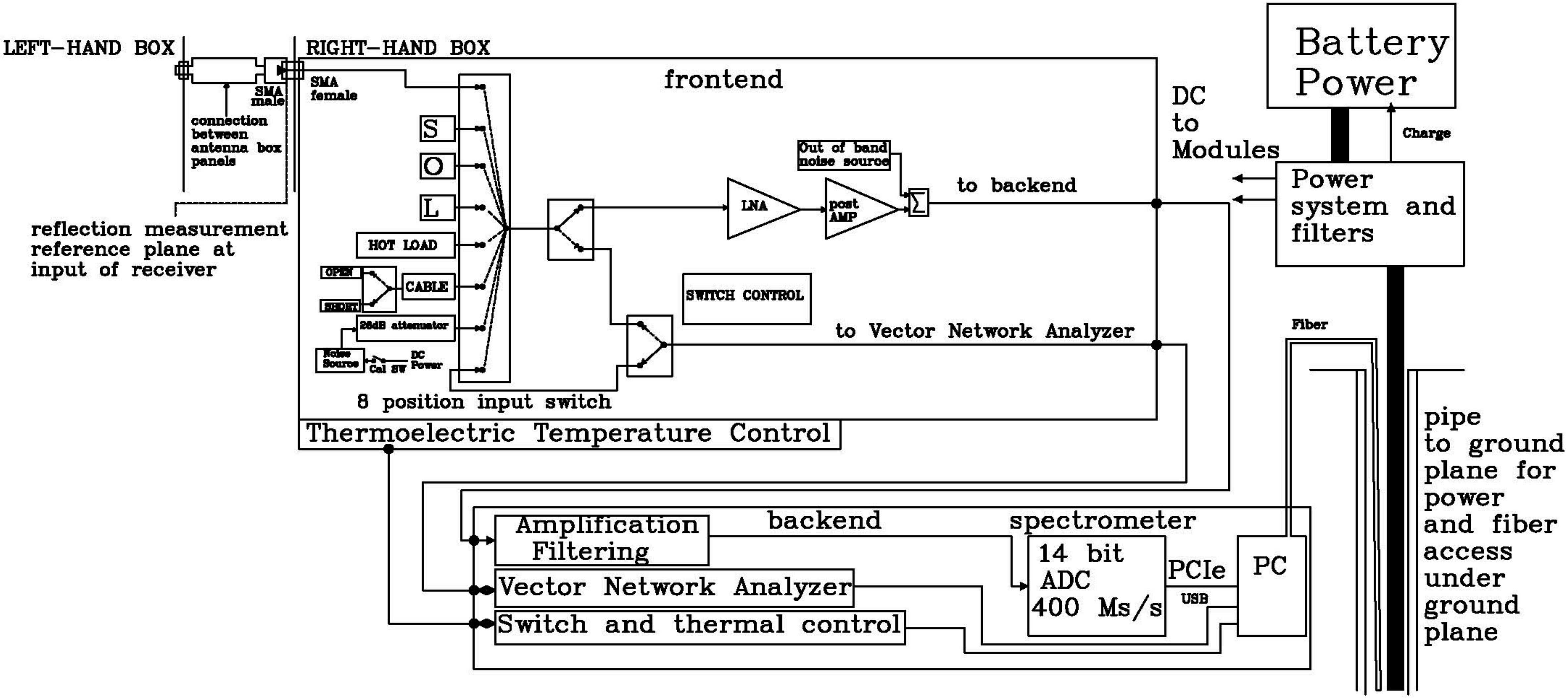
Horizontal profile view of the box-blade antenna design with same dimensions as the planar mid-band blade antenna, except 12cm panel height so that receiver can be located inside an antenna panel.



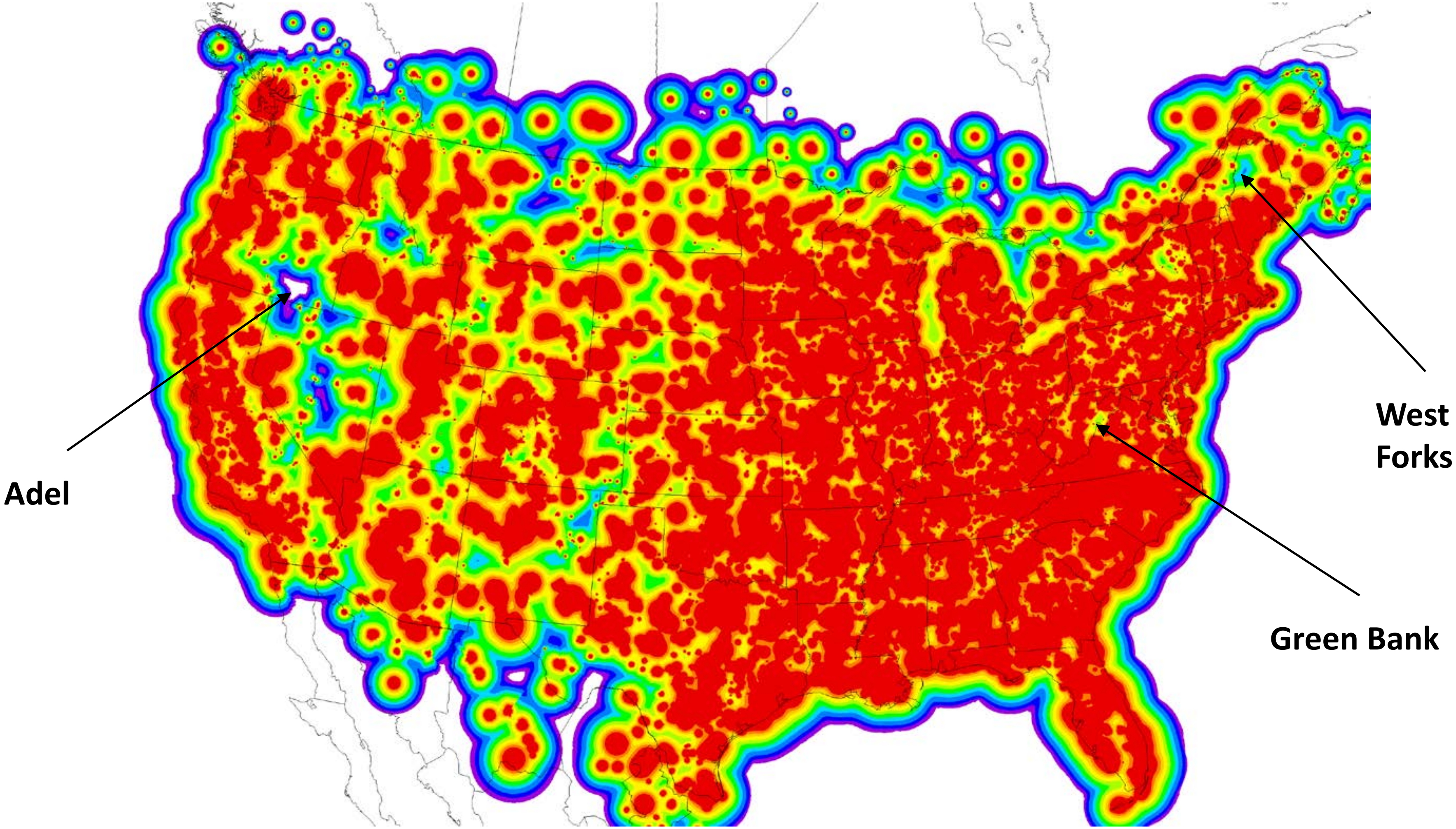
Layout of components inside antenna panel. Shown with optional batteries for field campaigns.

EDGES 3 system with built-in Calibration and all electronics in antenna proposed in November 2018. The advantages are:

- **Reduced loss and less delay in antenna S11 – since balun is not needed**
- **Automated Calibration**
- **Easier deployment**



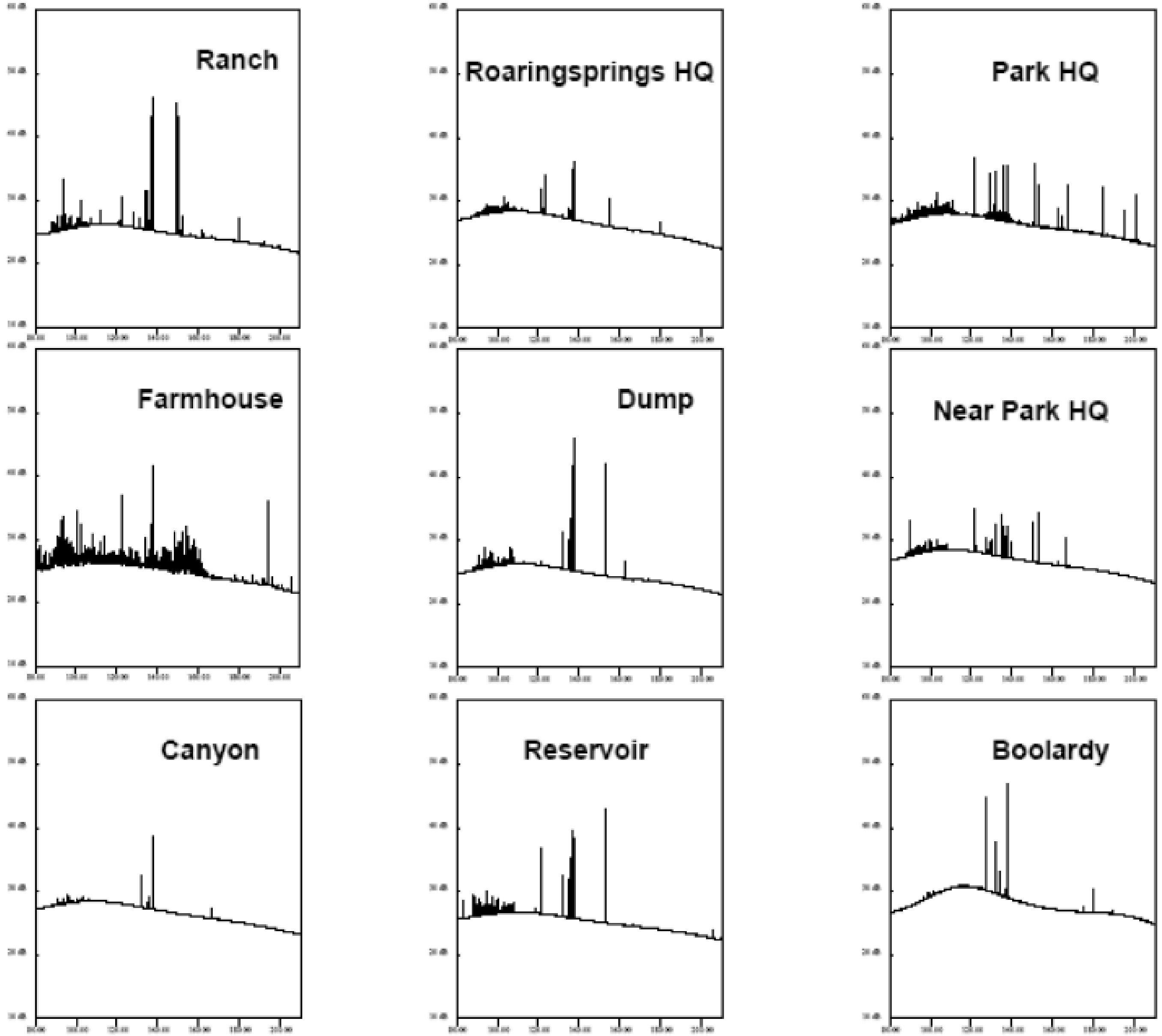
Block diagram of EDGES 3 system with built-in Calibration and all electronics in antenna

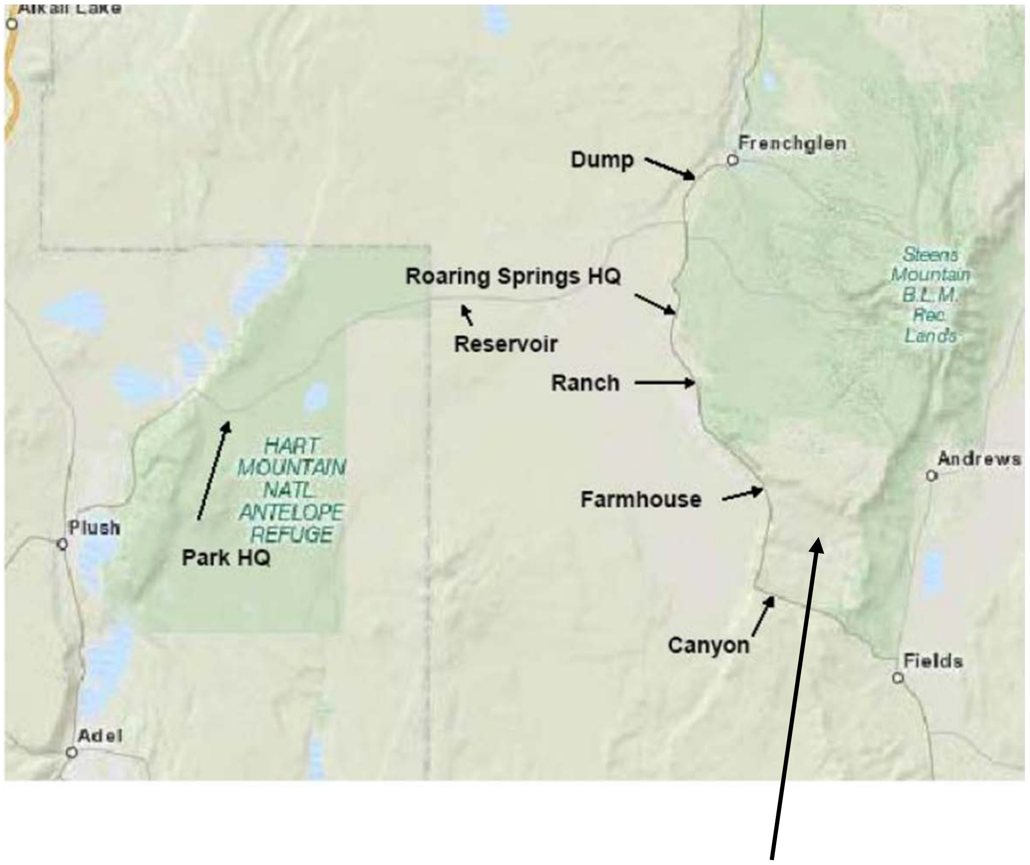


Integrated strength of FM radio for continental USA from radio-locator.com

Quietest regions: West Forks, ME Adel, Oregon -better than Green Bank

SPECTRA using EDGES-1 in 2009

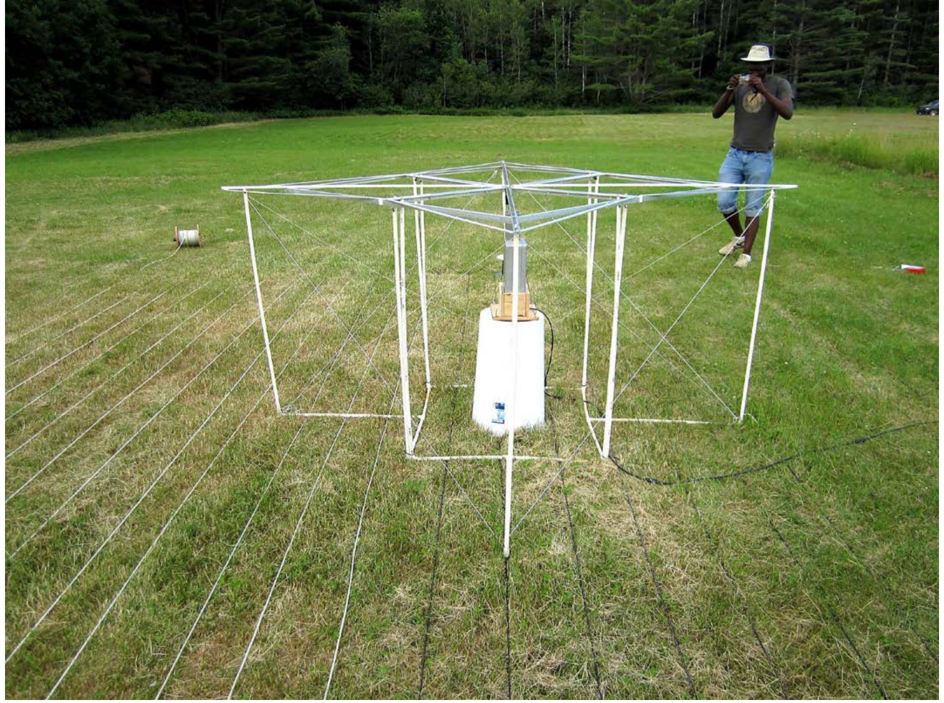




Skull Creek Reservoir
not visited in 2009

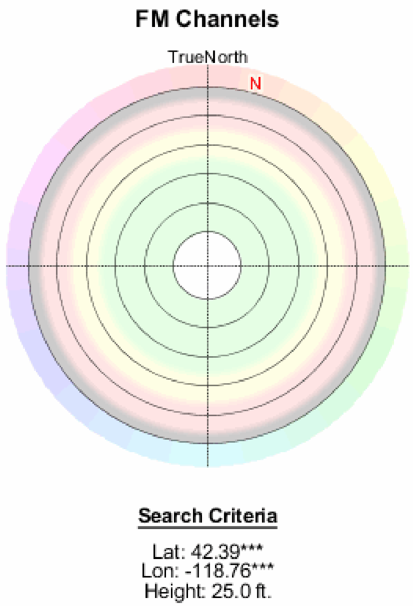
Figure 4. Spectra from the Catlow Valley sites with Boolardy for reference. The vertical scale is from 10 to 60 dB above 1 Kelvin.

Skull Creek from exploratory visit in January 2019



Wire grid ground plane used during EDGES-2 test at West Forks Maine 2011

	Signal					Azimuth		ft AGL
Callsign	Channel	Xmit(kW)	Rx(dBm)	Path	Dist(mi)	True	(Magn)	LOS
KAWS	89.1	8.75	-108.0	2Edge	113.1	67°	(54°)	---
KCNU	103.9	100.00	-109.9	2Edge	97.7	52°	(38°)	---
KSQB	92.7	10.00	-115.7	2Edge	84.0	347°	(334°)	---



Radio quiet site in the Catlow Valley region of Oregon

Lat 42.3870 Long -118.7614 deg. – different longitude checks absorption not RFI from synchronous satellite

Tentative plan to deploy in late June 2019 using 30x16m wire grid 12cm spacing ground plane

Estimated ground loss ~ 0.5 %

Beam chromaticity ~ 80 mK 5-terms 60 – 120 MHz average 2hr blocks over all LST

Loss chromaticity ~ 20 mK 5-terms 60 – 120 MHz average 2hr blocks over all LST thank you

Questions?

Comments?

EDGES memos are at
www.haystack.mit.edu/ast/arrays/Edges
loco.lab.asu.edu/memos