EDGES-2 Calibration Limits

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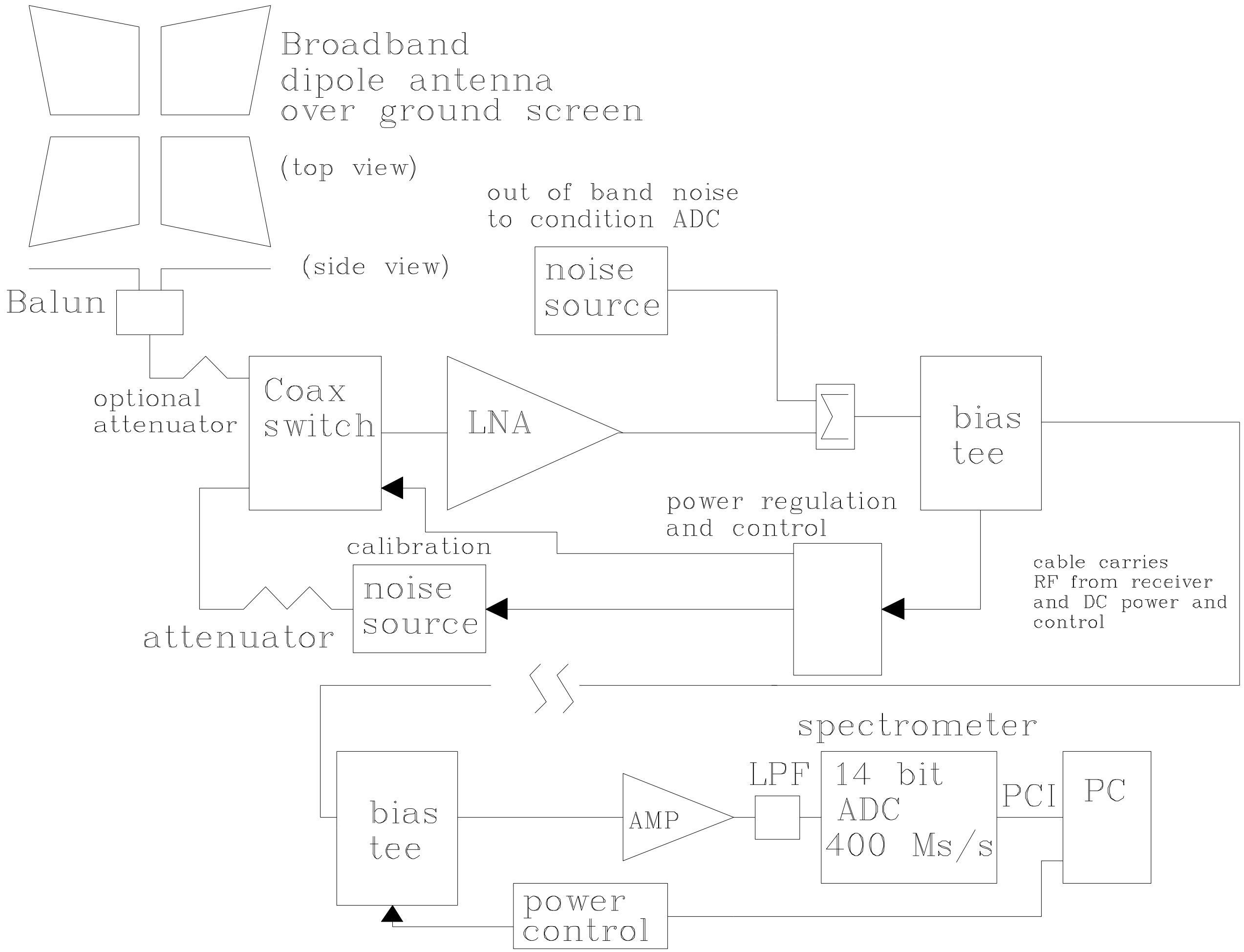
EOR Workshop 2012

Outline

- Absolute calibration method under development for EDGES-2
- Mathematical details
- Example of field test and lab test
- Estimates of accuracy



Simplified block diagram of EDGES

EDGES – “2” Calibration

In the Field:

- Broadband compact dipoles refl. < 10 dB, 50 – 100 and 100 – 200 MHz with separate antennas
- 3-position switched spectra from antenna, load, and load plus noise from diode for calibration and bandpass subtraction. S11 measurement of antenna (during installation) and ambient temperature measurements.

In the Lab:

- Ancillary 3-position switched spectra from ambient and hot loads for calibration of noise diode. In addition spectra are taken of an open cable for measurement of LNA noise waves.
- Ancillary S11 measurements of ambient and hot loads, LNA input and open cable used for noise wave measurements.
- Measurement are done at 2 temperatures for the derivation of temperature coefficients.
- Lab performance verification using “antenna simulator”

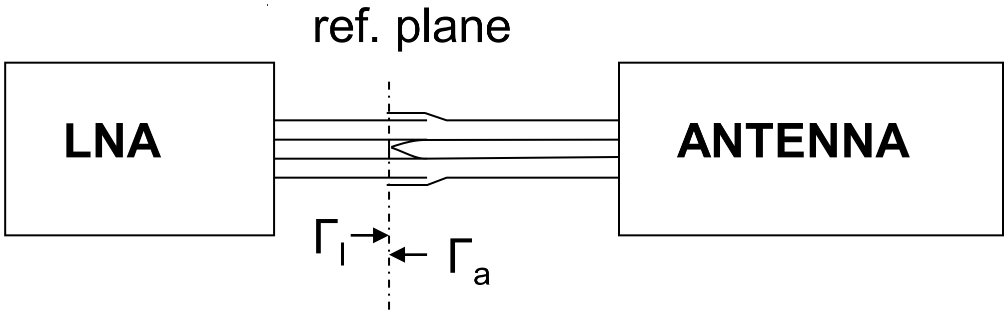
Additional calibration steps required

- Estimate antenna and balun ohmic loss and ground losses using EM simulation
- Measure change of antenna S11 with temperature to derive temperature coefficient. (New antenna design uses materials with low coefficients of expansion and change of dielectric constant).

For EOR

- Correct for antenna beamshape changes vs frequency using EM simulation and sky model
- Fit for ionosphere

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

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

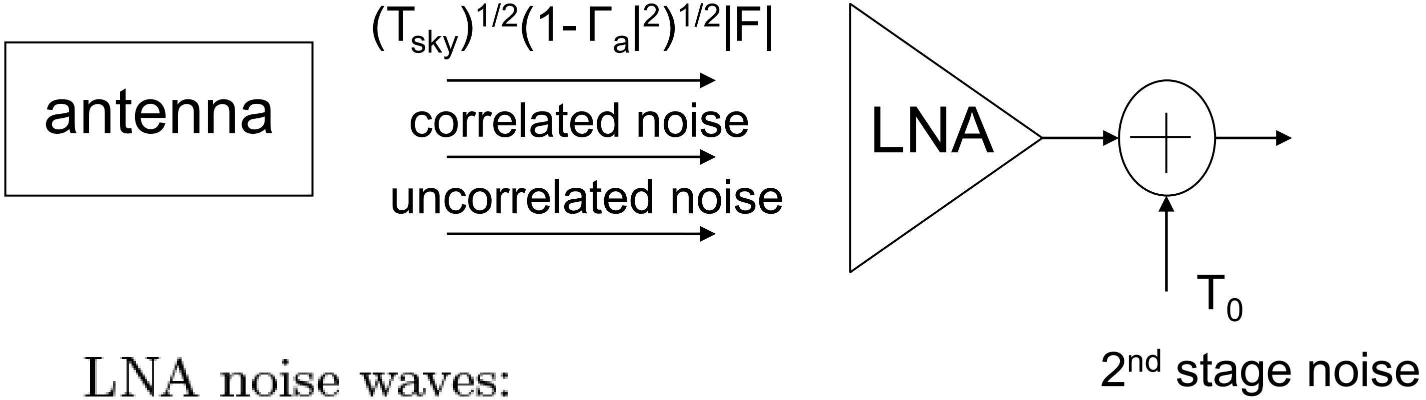
$$F=\frac{(1-|\Gamma_l|^2)^{1/2}}{1-\Gamma_a\Gamma_l}$$

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



antenna

$(T_{sky})^{1/2}(1- \Gamma_a|^2)^{1/2}|F|$

correlated noise

uncorrelated noise

LNA

T_0

2nd stage noise

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 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

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

Removing LNA noise waves – correcting for mismatch, antenna and balun loss

The calibrated sky noise is given by:

$$\begin{aligned} T_{sky} &= [T_{3p} - T_u|\Gamma_a|^2|F|^2G^{-1} \\ &- (T_c cos(\phi) + T_s sin(\phi))|\Gamma_a||F|G^{-1}] \\ &\times [(1 - |\Gamma_a|^2)|F|^2G^{-1}]^{-1} \end{aligned}$$

$T_{csky} = (T_{usky} - T_{amb}(L-1))/L$

where T_{csky} is corrected for antenna loss plus balun loss, $L = 10^{-l/10}$. The balun loss is

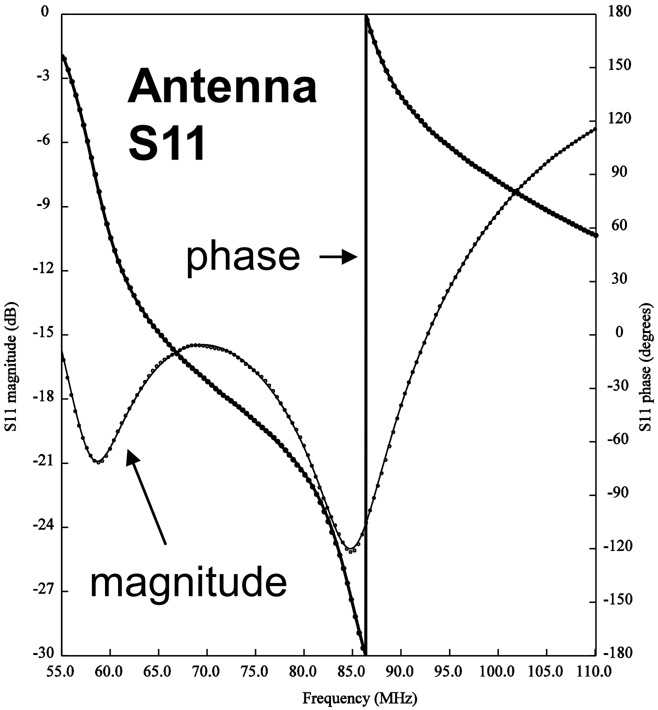
$L = \frac{Re(Z_a)|Z_f|^2}{(Re(Z_a)|Z_f|^2 + Re(Z_f)|Z_a|^2)}$

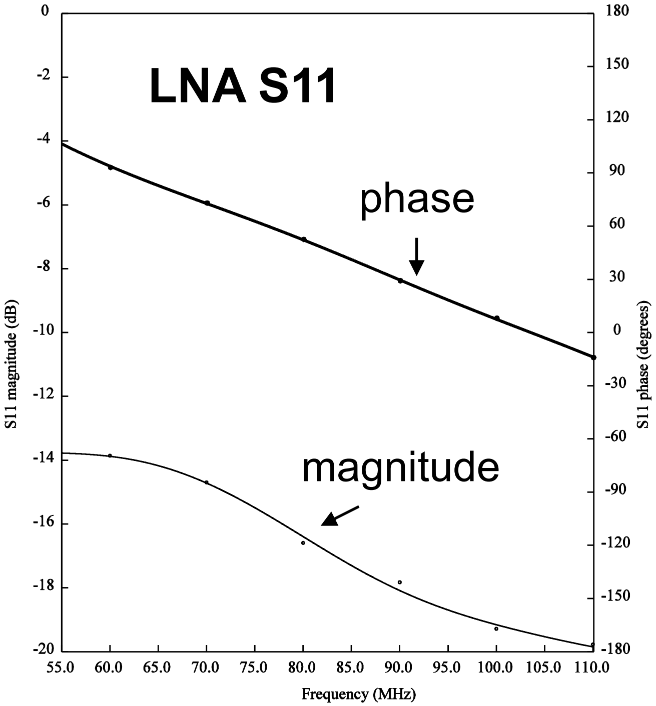
where Z_a is the antenna impedance corrected for the ferrite impedance, Z_f.

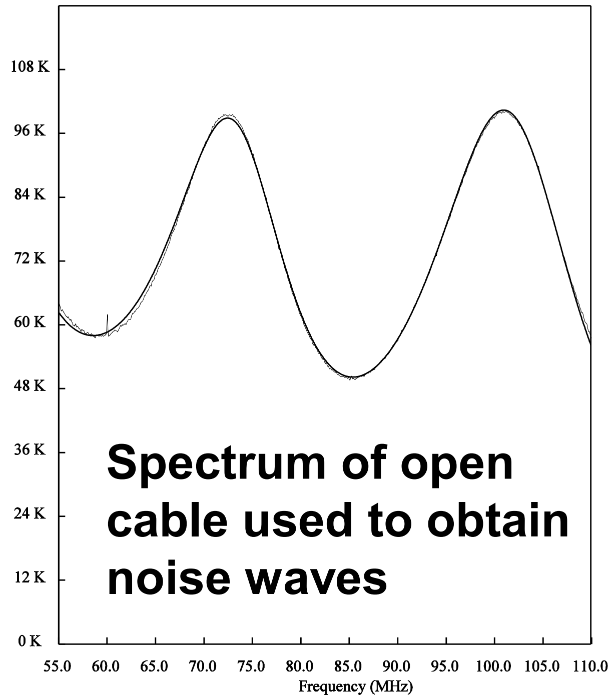
First “Field Test” of absolute calibration

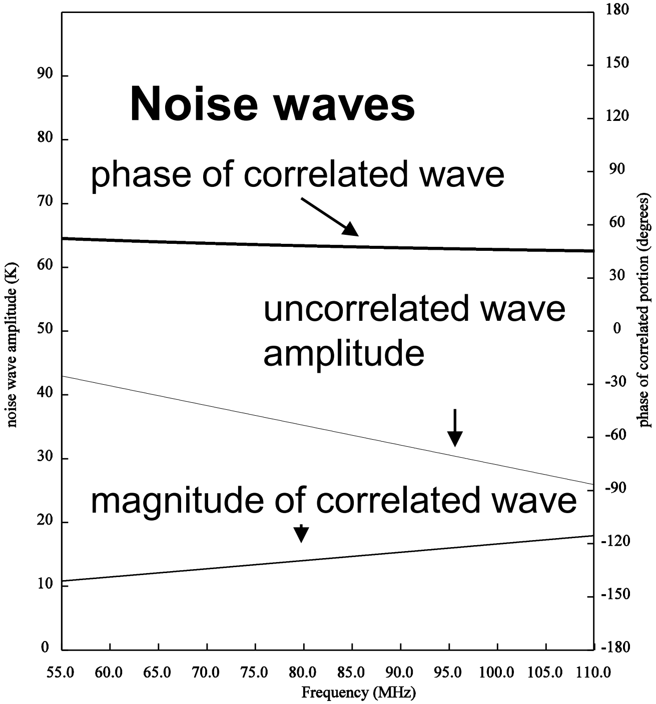
Rogers, A.E.E., Bowman, J.D., 2012 "Absolute calibration of a wideband antenna and spectrometer for accurate sky noise temperature measurements," *Radio Science*, **47**, RS0K06, doi: 10.1029/2011RS004962.

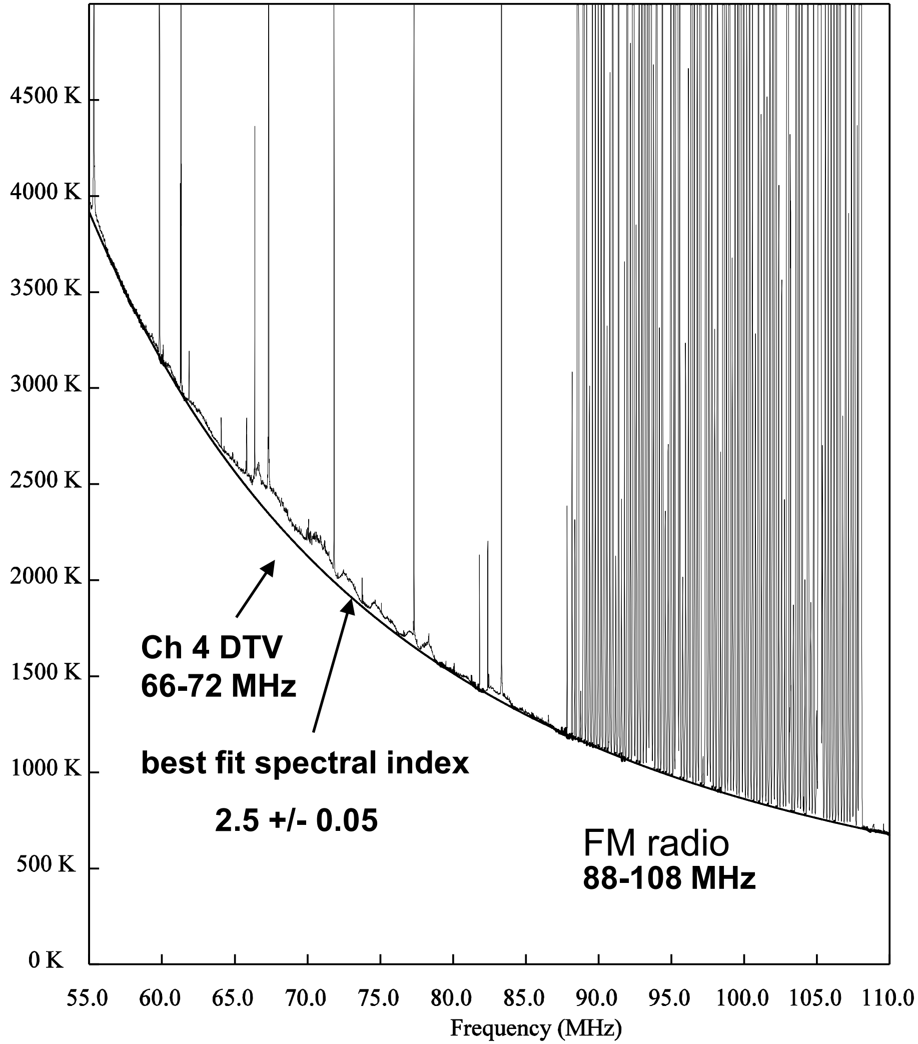
EDGES–2 test of absolute calibration at West Forks, ME


Antenna S11


LNA S11


Spectrum of open cable used to obtain noise waves


Noise waves



Ch 4 DTV
66-72 MHz

best fit spectral index

2.5 +/- 0.05

FM radio
88-108 MHz

Calibrated sky noise spectrum

Lab testing – work in progress

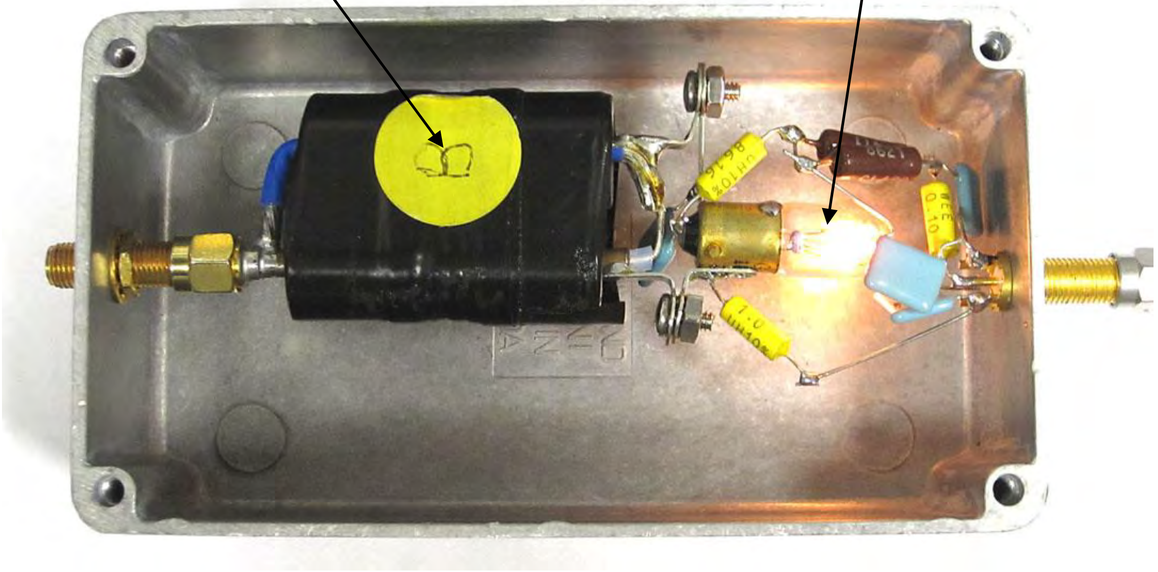
Use an “antenna simulator” to test the accuracy

Assumes:

- A mismatched load at uniform temperatures is precisely equivalent to a lossless antenna observing a uniform sky at the same temperature

Caveat:

- Corrections have to be made for the non-uniform temperature of a hot tungsten filament source (although corrections are small ~ less than 1 K – see EDGES memo 100)



balun at ambient temperature

Lamp filament of 1670K +/- 30K estimated from 8.26 fold increase in tungsten resistance

Simulator of antenna looking at sky temperature of 1670K +/- 30K

Primary calibration via thermal HOT load of known temperature

Heated 50 ohm load

Use current and/or temperature probe

Corrections required for high accuracy:

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

2] Input line loss – plus assumption of temperature gradient

R. Monsalve

Noise diodes have 1/f noise and need to be calibrated

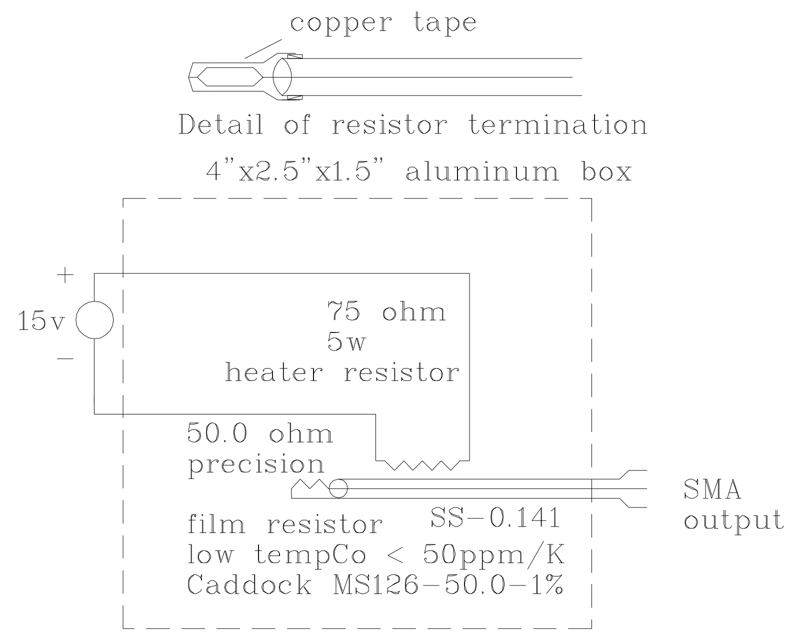
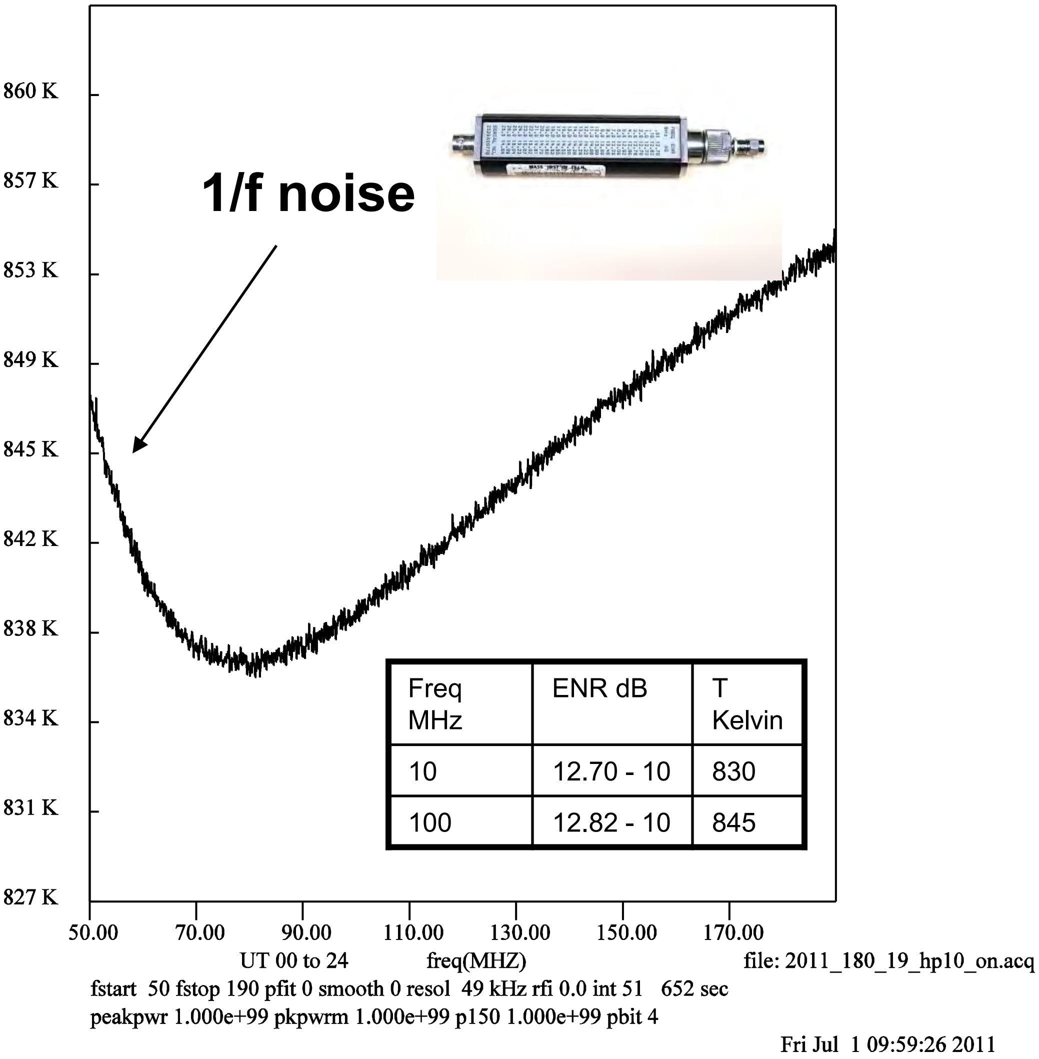
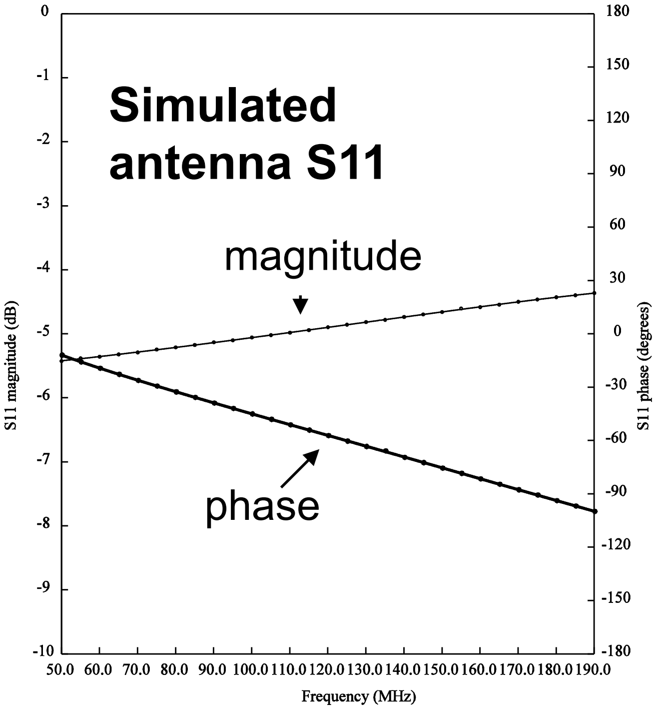


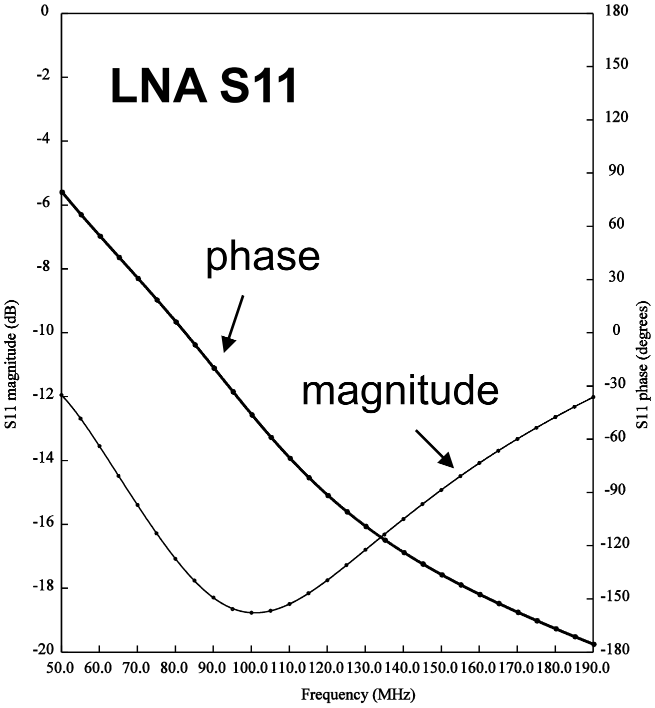
Figure 1 Heated resistor noise source

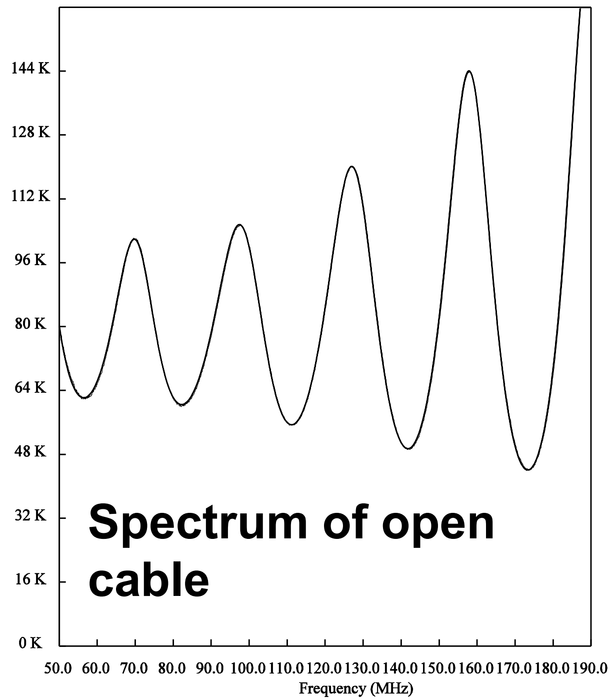


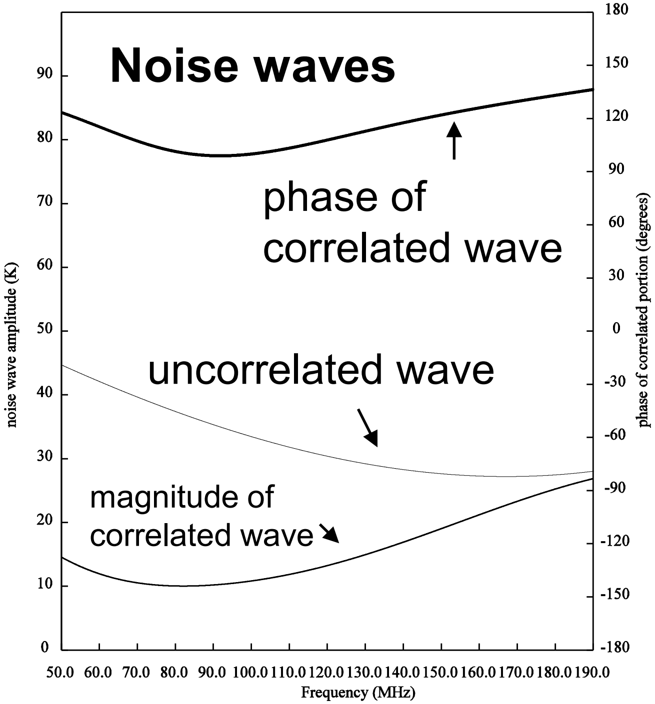
Freq MHz	ENR dB	T Kelvin
10	12.70 - 10	830
100	12.82 - 10	845

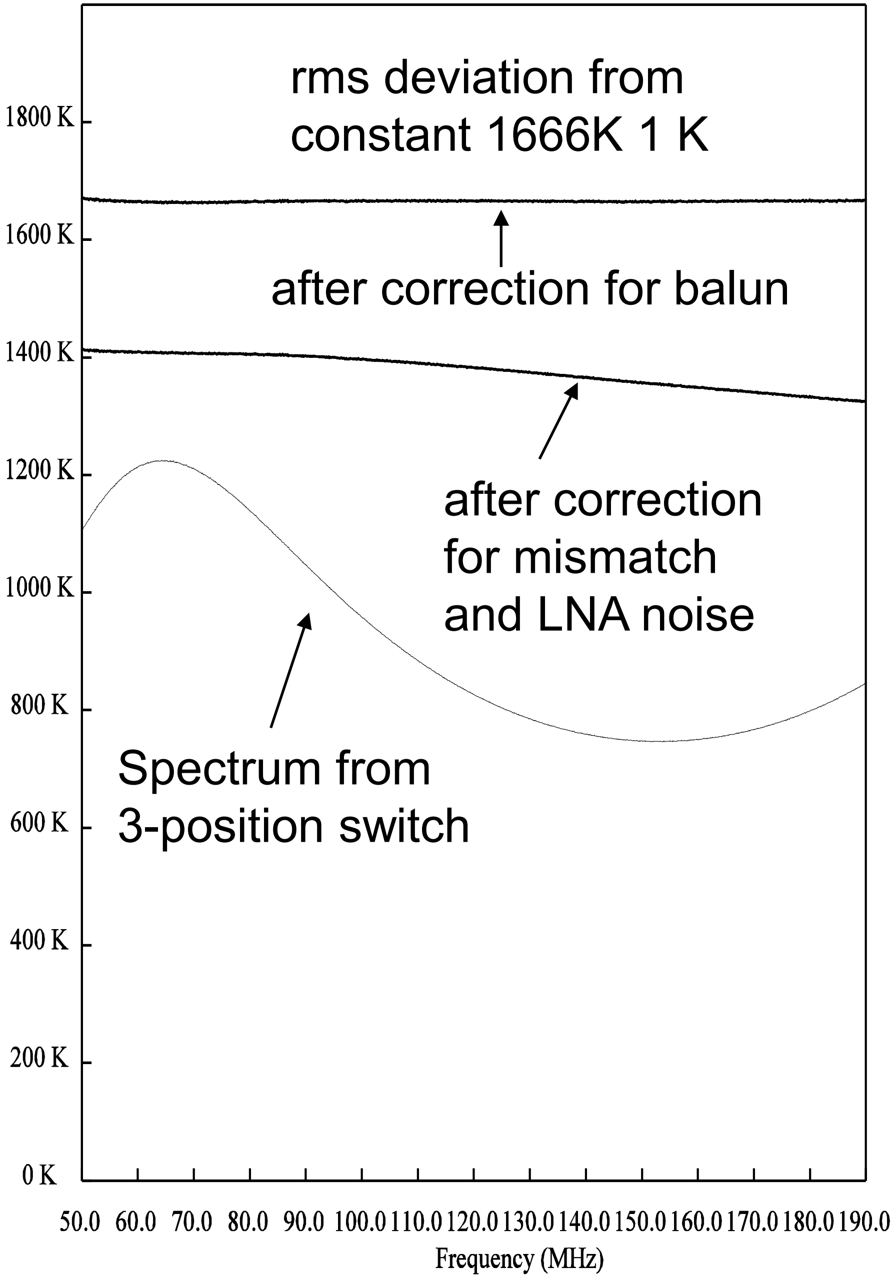
Spectrum of Hp 346C Noise Source (via 10 dB atten) measured with EDGES calibrated using a heated resistor noise source


Simulated antenna S11
magnitude
phase
S11 magnitude (dB)
S11 phase (degrees)
Frequency (MHz)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
50.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0 160.0 170.0 180.0 190.0


LNA S11
phase
magnitude
S11 magnitude (dB)
S11 phase (degrees)
Frequency (MHz)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
50.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0 160.0 170.0 180.0 190.0


Spectrum of open cable
Frequency (MHz)
144 K
128 K
112 K
96 K
80 K
64 K
48 K
32 K
16 K
0 K
50.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0 160.0 170.0 180.0 190.0


Noise waves
phase of correlated wave
uncorrelated wave
magnitude of correlated wave
noise wave amplitude (K)
phase of correlated portion (degrees)
Frequency (MHz)
90
80
70
60
50
40
30
20
10
0
180
150
120
90
60
30
0
-30
-60
-90
-120
-150
-180
50.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0 160.0 170.0 180.0 190.0


rms deviation from
constant 1666K 1 K
after correction for balun
after correction
for mismatch
and LNA noise
Spectrum from
3-position switch
1800 K
1600 K
1400 K
1200 K
1000 K
800 K
600 K
400 K
200 K
0 K
50.0
60.0
70.0
80.0
90.0
100.0
110.0
120.0
130.0
140.0
150.0
160.0
170.0
180.0
190.0
Frequency (MHz)

Sources of error from limited accuracy S11 and antenna loss

- For antenna reflection level of -15 dB an error of 0.01 dB corresponds to 70 mK out of 1000 K.
- For typical noise wave amplitude of 20 K and antenna reflection of -15 dB an error of 0.1 degree in S11 phase corresponds to 10 mK.
- An error of 0.1% in antenna/balun loss corresponds to 300 mK

S11 accuracy improvements

- Largest source of VNA error below 200 MHz is the assumption that the calibration load is exactly 50 ohms in the SOL cal procedure
- Fix is to make accurate DC resistance measurements of the calibration load and make corrections
- Level of better than 0.01 dB can be achieved
- Paper in preparation by Raul Monsalve of ASU

Estimates of the sources of error and their magnitude expressed as the residuals to fits with increased numbers of parameters along with the bias in EOR estimation

Parameters of 10 parameter solution:

1] **EoR signature** (30 mK, 50@145MHz)

2] **scale** (assumes spectral index of -2.5)

3] **constant** (ground emission)

4] **frequency $^{-2}$** (ionosphere emission)

5] **frequency $^{-4.5}$** (ionosphere absorption)

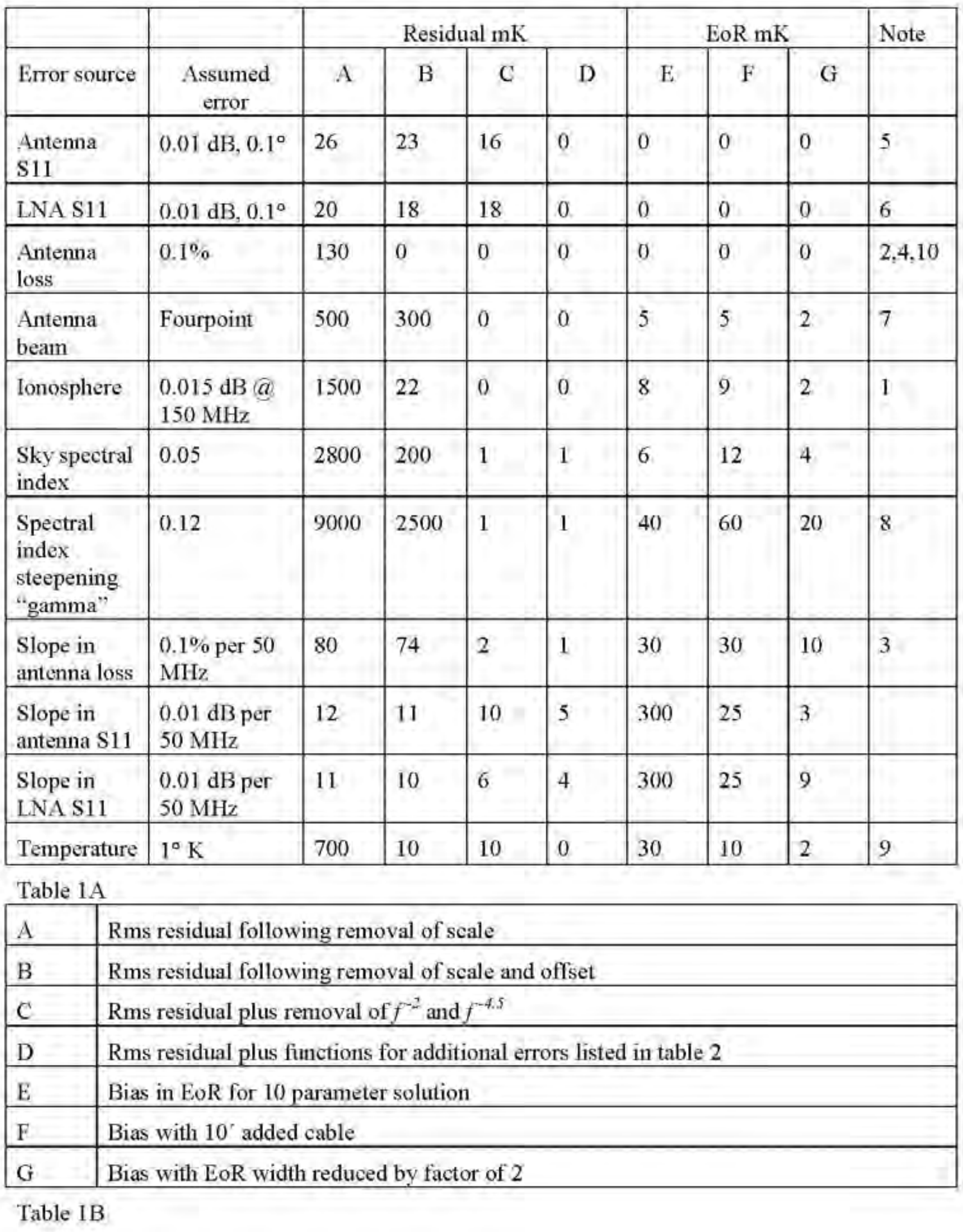
6] **Magnitude of antenna S11**

7] **Magnitude of LNA S11**

8] **S11 phase error**

9] **S11 delay error**

10] **temperature scale**



		Residual mK				EoR mK			Note
Error source	Assumed error	A	B	C	D	E	F	G	
Antenna S11	0.01 dB, 0.1°	26	23	16	0	0	0	0	5
LNA S11	0.01 dB, 0.1°	20	18	18	0	0	0	0	6
Antenna loss	0.1%	130	0	0	0	0	0	0	2,4,10
Antenna beam	Fourpoint	500	300	0	0	5	5	2	7
Ionosphere	0.015 dB @ 150 MHz	1500	22	0	0	8	9	2	1
Sky spectral index	0.05	2800	200	1	1	6	12	4	
Spectral index steepening "gamma"	0.12	9000	2500	1	1	40	60	20	8
Slope in antenna loss	0.1% per 50 MHz	80	74	2	1	30	30	10	3
Slope in antenna S11	0.01 dB per 50 MHz	12	11	10	5	300	25	3	
Slope in LNA S11	0.01 dB per 50 MHz	11	10	6	4	300	25	9	
Temperature	1° K	700	10	10	0	30	10	2	9

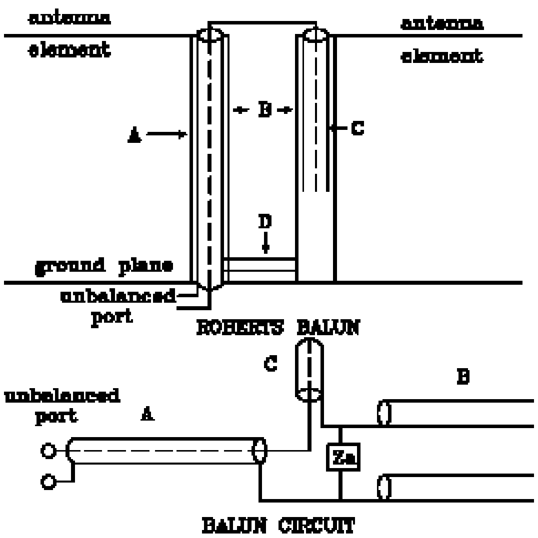
Table 1A

A	Rms residual following removal of scale
B	Rms residual following removal of scale and offset
C	Rms residual plus removal of f^{-2} and $f^{-4.5}$
D	Rms residual plus functions for additional errors listed in table 2
E	Bias in EoR for 10 parameter solution
F	Bias with 10′ added cable
G	Bias with EoR width reduced by factor of 2

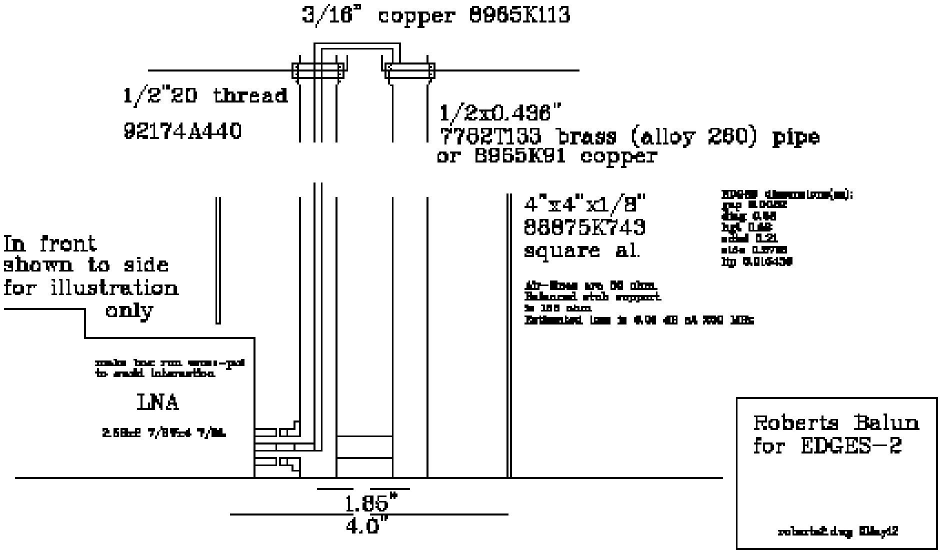
Table 1B

Estimate of errors using simulations – for more details see EDGES memo 99

Development of new antenna with very low loss Roberts balun

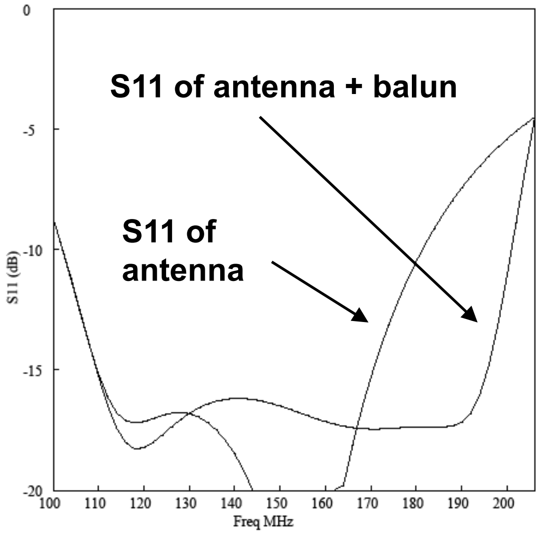


Equivalent circuit of Roberts balun



Mechanical details

Prototype of antenna under development



Roberts balun also results in larger bandwidth

CONCLUSIONS

- A smooth broadband response has been sufficient to start setting some limits on the red-shifted 21cm line in the early universe
- Absolute calibration presents extreme challenges to be able to reach the 10 milliKelvin level but much will be learned along the way and development will be beneficial for other projects

END