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To: EDGES Group

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Subject: Extending the EDGES frequency range to cover 40 to 190 MHz

1] Introduction

Extending the frequency range of EDGES down to lower frequencies will allow observations of a region of red-shift which includes the range where the 21-cm line is expected to appear in absorption. While it may not be possible to design an antenna with fractional bandwidth greater than about 2:1 the electronics can easily be upgraded to cover more than 4:1.

2] Antenna design

The current "fourpoint" antenna covers about 110 to 220 MHz with a return loss below about -15 dB and has good pattern over this frequency range. With some "tweaks" in the design it may be possible to get the return loss below -20 dB over the 2:1 range but it is unlikely that we can cover a wider range because above 220 MHz the patterns degrade rapidly and below 110 MHz the VSWR degrades rapidly. There is a chance however that using a tapered ground plane which rises above the ground near the antenna terminals will improve the patterns at the high frequency end of the band without degrading the VSWR. If this turns out to be the case a single rescaled fourpoint might cover 45 to 190 MHz. Alternately 2 separate EDGES systems with separate antennas could over 45 to 90 MHz and 90 to 180 MHz.

3] Changes needed in the electronics

a) Low frequency cut-off

During the initial tests of the Deuterium array it was noticed that extremely strong signals can be present in the HF band. For example a typical path loss between the US and Europe at 14 MHz assuming an effective isotropic radiated power (EIRP) to a dipole is 130 dB so that a high power station with 3 Gw EIRP is received into a matched dipole at -5 dBm under the best conditions. This signal would be reduced by about 40 dB to -45 dBm when received by an EDGES antenna which extends down to 40 MHz. For this signal to average only 10^3 K over a 100 MHz bandwidth we need about 45 dB out of band rejection at the upper edge of the HF band, say at 30 MHz.

On the other hand we should not have significant attenuation of the 40 MHz signal prior to the gate of the LNA HEMT because this effects the input match and the sensitivity to antenna mismatch. In simulations and tests of the input filtering it was found that the input inductors should be increased from 270 nH to 4700 nH and the input coupling capacitor should be increased from $100\,pf$ to 470 *pf*.

b) Noise source injection

The current design has the noise diode coupled into the 30 dB attenuator via a 220 *pf* capacitor which results in significant roll-off at 40 MHz this capacitor should be increased to 47,000 *pf* and both the diode and the capacitor need to be moved closer to the attenuator connector. This has been done but further improvement is needed in the PC board layout planned for the next revision of the board.

c) Out of band noise injection

The out of band noise injection needed to improve the ADC linearity dynamic range and distribution of the quantization noise needs to be cut-off above 40 MHz to avoid degrading the performance at 40 MHz. Some changes in the noise generator have been made to ensure the added noise is limited to a band below 40 MHz.

4] Simulations of the detectability of an EOR signature centered from 60 to 170 MHz.

A simulation was conducted using a sliding window of 40 MHz. A weighted least squares fit was made using the following parameters (for a case of 4 polynomial terms):

1] Galaxy reference

2] A small change in sky noise spectral index

3] Polynomial starting at second order f^2 (i.e. curvature)

4] f^3

5] f^4

6] f^5

7] EoR model

In each case noise of 1 mK in 1 MHz was added to the simulated data and the data was constructed with deviations in the antenna impedance around a -15 dB return loss from those assumed for the reference. The circuit model parameters were not perturbed but in separate tests it was found that deviations in these parameters at the similar fractional level has a much smaller effect. An error in the assumed HEMT transconductance has the largest effect but a 10% error is still much smaller than a 10% error in the assumed antenna impedance.

The first test is to see how many polynomial terms are needed in addition to the first two and the last parameter to reach the level of 1 mK rms in systematic.

	Error in circuit parameters		
EoR freq (MHz)	10%	3%	1%
60	4	4	3
70	4	3	3
80	4	3	3
90	4	3	3
100	4	3	3

110	4	3	2
120	3	3	2
130	3	3	2
140	3	3	2
150	3	2	2
160	3	2	2
170	3	2	2

Table 1. Number polynomial terms needed to "soak-up" errors in antenna and circuit model. A sliding 40 MHz window is assumed.

The next table gives the achievable Δz assuming a noise level of 3 mK in one MHz above 80 MHz and 10 mK in a MHz at 80 MHz and below.

	Number of polynomial terms			
EOR Freq (MHz)	1	2	3	4
60	-	12 (3.5)	4.9 (2.0)	4.5 (2.0)
70	-	6.3 (2.6)	3.5 (1.5)	3.4 (1.5)
80	-	4.5 (1.9)	2.5 (1.1)	2.5 (1.1)
90	3.3	1.4	1.3	0.8
100	2.5	1.0	1.0	0.7
110	1.9	0.8	0.8	0.5
120	1.4	0.6	0.6	0.4
130	1.3	0.6	0.6	0.4
140	1.1	0.5	0.5	0.3
150	1.0	0.5	0.5	0.3
160	0.8	0.4	0.4	0.2
170	0.7	0.3	0.3	0.2

Table 2. Achievable delta_z vs frequency and the number of polynomial terms. Frequencies below 90 MHz assume an EoR absorption signature of 100 mK. A sliding 40 MHz window is assumed. Numbers in ( ) are for 20 MHz window.

a) *Tests of electronics systematic*

A constant 1200 K is placed on the EDGES input and 24 hours of data taken

	Number added polynomial terms		
Freq range	1	2	3
45-90	370	30	4
80-160	50	30	6
95-190	100	10	5

Table 3. rms error to fit in mK of data from "*ac240*" electronics with px14400 digitizer smoothed to 2 MHz resolution. The fits were done over the frequency range indicated using a polynomial. The number "added" terms is number beyond a constant and slope since the Galaxy and spectral index parameters provide the equivalent of a constant and slope.

The performance down to 40 MHz is limited by the roll-off of the coupling ahead of the HEMT. It is anticipated that the performance will improve with the circuit and PC board changes previously mentioned in this memo.

b) *The interpretation of tables 1 and 2*

The new proposed method of EDGES analysis described in memo 64 and expanded in this memo involves accurate measurements of the antenna impedance, using a network analyzer, and measurements of the LNA noise parameters using an open low loss cable. The advantage of this method is that the majority of the instrumental response is calibrated leaving fewer polynomial terms needed to soak up the errors and gives an estimate of the delta_z which might be reached as a function of frequency and number of polynomial terms.

c) *Method of searching for the EoR signature*

The EDGES data is fit using a weighted least squares over a sliding window centered on the EOR signature in which frequencies excluded owing to RFI are given zero weight. For each window the rms fit to the residuals are examined and a significant detection is flagged if the EoR signal to noise ratio, estimated from the covariance matrix, signal strength and rms residuals exceeds an appropriate threshold. If a detection is not flagged the delta_z of the EoR is excluded provided a significant detection is made when the model EoR signature is added to the data. This process of exclusion is iterated with increasing delta_z until either EoR is detected or a significant detection is not when the model is added.

Summary

These simulations suggest that following some simple circuit improvements EDGES should reach a level of cosmological interest in either detecting or setting important limits on the 21-cm absorption expected when the hydrogen kinetic temperature drops below that of the CMB just before reionization begins. However, while it is assumed that an antenna with return loss better than -15 dB can be built to cover 45-90 MHz, we have no experience of the RFI limits in this band. In one month of Galaxy down observing

EDGES should reach the 10 mK thermal noise level at 65 MHz assuming no significant loss to RFI. It is noted that the analogue channel 2 TV carrier at 64.25 MHz is frequently visible in the 2009 EDGES data despite the low antenna efficiency at 64 MHz.