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To: EDGES Group

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Subject: Comparative tests of EDGES-2 electronics

EDGES-2 electronics serial #s 1, 2 and 3 have been calibrated and tested using one hour integration times for the hot filament hot, cold, open/shorted cable spectra along with the S11 measurements made at 0 dBm and no attenuation for all except the LNA which was measured with -10 dBm signal attenuated by 20 dB. In each case 999 sample averaging was used to minimize the noise (see memo #114).

Table 1 gives the values of filament temperature and the rms residuals after removing the best fit constant and after removing the 8 basis functions listed 0 through 7 in memo #118. In the first case the values of filament loss, hot load loss, and delay correction for a removal of a female to female adaptor during the S11 measurement of the LNA, had to be slightly adjusted to get the residuals into the millikelvin range.

Serial #	terms removed	filament loss dB	hot load loss dB	delay ns	T K	rms mK
1	1	0.020	0.044	0.088	1563	236
2	1	0.019	0.049	0.082	1548	289
3	1	0.017	0.049	0.100	1575	345
1	8	0.02	0.05	0.08	1562	177
2	8	0.02	0.05	0.08	1539	166
3	8	0.02	0.05	0.08	1571	168

Table 1. Tests of EDGES-2 electronics measurements of hot filament test source. The measured loss values at 100 MHz and adapter delay are 0.02 dB, 0.05 dB and 0.08 ns. The losses are assumed to increase with the square root of frequency and the values in the table are for 100 MHz. Spectral data was smoothed to 0.7 MHz resolution prior to calibration processing.

These adjustments are under 0.01 dB and 0.02 ns of the nominal values. In the second case the residuals are derived from the least squares solution for the best of the 8 basis functions found capable of removing the foreground and ionosphere. Fortunately these basis functions also remove the effects of monotonic errors in S11 and loss. The rms values of about 170 mK are close to the value of 150 mK expected for a spectral resolution of 0.7 MHz, antenna temperature of 1550 K, 40 % spectral processing efficiency and one hour integration.

The measured hot/cold resistance ratio for the filament source was 7.6 ± 0.05 corresponds to a temperature of $1565 \pm 10\ K$ assuming a filament of pure tungsten. It noted however that there is some added uncertainty in the "effective" temperature of the filament because there is a region close to the terminals where the temperature drops rapidly. The effect is added loss at some temperature between the filament and the ambient temperature. A good approximation for constant loss vs distance is the average temperature but the loss per unit length depends on the filament resistance which in turn depends on the temperature. More study is needed to make a better estimate of the loss and its effective temperature. A similar uncertainty exists for the hot load. In this case the spectrum can change since the loss depends on the square root of frequency.

Repeated calibrations of unit #2

While the results of the test of the 3 separate units given in show some difference between units these differences are mostly due to noise owing to the relatively short 1 hour integration times. This will be discussed in the next section. Three separate tests of unit #2 were made with the results shown in Table 2. The 3rd test was done at elevated temperature. For this test the peak and average increases in the measured LNA S11 were 0.26 and 0.17 dB respectively.

Date	Temp	Filament loss dB	Hot load loss dB	Delay ns	T K	rms mK
20 June 13	25	0.019	0.049	0.082	1548	289
28 June 13	25	0.015	0.049	0.090	1526	264
21 June 13	35	0.013	0.049	0.094	1558	448

Table 2. Tests of serial #2

Noise simulations

Longer integrations are needed for further tests of the electronics and calibration. Simulations show that to reach the theoretical noise levels in the integration times needed to detect or set limits on the EoR signatures significant integration times are needed for the S11 data and calibration spectra. In addition the S11 data for the LNA input reflection needs to be smoothed to avoid the need for integrations (averaging) that are too long to be practical. Further the calibration scale and offset data also need to be smoothed to avoid the need for calibration spectra integration times as long as the observation times.

The results in Table 3 show that the following integration times and smoothing are needed to avoid adding significant noise to observations of about 300 hours.

1] S11 averaging of 999 traces the longest supported by the HP85047A/8753C VNA (see memo #114).

2] Integration times of calibration spectra of 24 hours for the ambient and hot loads and at least 4 hours for the noise wave spectra.

3] Spectral smoothing of the LNA S11 data using 5 term complex polynomials fit to the data using least squares.

4] Spectral smoothing of the calibration scale and offset with 5 term polynomials.

5] Spectral smoothing of noise wave parameters with 6 term polynomial

Also shown in Table 3 are the signal to noise ratio for Gaussian EoR signatures of 100 mK 16 MHz wide and 30 mK 40 MHz wide at the 55-95 and 110-190 MHz bands respectively. The rms residuals are the values after removal of the 8 basis functions listed in memo #118.

The VNA noise on the LNA S11 data is the dominant contribution from the VNA. It noted that the VNA is a noisy instrument especially at the low signal levels needed to measure the LNA S11. In theory an impedance analyzer using a broadband noise source, resistance network, ADC sampling of the voltage and current followed by complex Fourier transform and some arithmetic to get the amplitude and phase could have much lower noise since a -30 dBm signal is 60 dB above the thermal noise in a 200 MHz bandwidth.

It is also noted that the noise using the Agilent N5222A PNA with the same power level, resolution and integration time of 240 seconds is about a factor of 2 to 3 times lower than the older HP85047A/8753C.

			1550 K	Sky 55-95	EoR SNR 16	Sky 110-190	EoR SNR 40
Contributor	Integrations Time (hrs)	Filter	rms mK	rms			
LNA S11	0.02	None	35	100		15	
LNA S11	0.1	None	13	30		7	
LNA S11	0.1	5	2	2		0.3	
Calibration	1	7	49	5		2	
Calibration	1	5	44	2		1	
Calibration	24	5	11	0.5		0.3	
Observation	1	-	152	230		25	
Observation	300	-	9	14		1.5	
All	1	-	155	230		25	
All	300	-	10	14	8	1.5	10

Table 3. Results of noise simulations to show the need for sufficient integration and smoothing of S11 measurements and calibration scale and offset. Simulations were run with temperatures of a constant 1550 K, foreground at 55-95 MHz and 110-190 MHz. The EoR signatures were assumed to have widths of 16 and 40 MHz in the “low” and “high” bands respectively.

As a check on the actual noise levels 2 test cases were ran. In the first case a 24 hour observation of the 1565 K artificial antenna in the 55-95 MHz band resulted in a residual rms of 40 mK and in the second a 24 hour observations of a 400 K artificial antenna in the 110-190 MHz band resulted in a residual rms of 8 mK. The expected rms values are 46 and 6 mK for the low and high bands respectively. Longer integrations are planned for a more complete test to demonstrate the levels needed to detect or set limits on the EoR. In both test cases the 8 basis functions were sufficient to absorb all the residual systematics using the nominal values of filament loss, load loss and delay correction.