EDGES MEMO #114

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To: EDGES Group

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Subject: Measurements of VNA noise and simulations of their effect on EoR estimation

Noise in the VNA measurements of S11 can result in a significant increase in the noise of the calibrated spectra. Especially serious is the noise in VNA measurement of the LNA S11 which has to be made at a low level to avoid errors due to saturation of the LNA.

1] Measurements of noise in S11 measurements in S11 measurements using the Hewlett Packard 85047A/8753C VNA.

Measurements were made using 201 spectral points from 50 to 200 MHz using an averaging factor of 100. S11 data was taken using a combination of the internal attenuator (from 0 to 20 dB) and the oscillator level (-10 to 0 dBm) to obtain output power in the range -30 dBm to 0 dBm . In addition data was taken over a range of S11 magnitude from -30 dB to 0 dB. The results are given in Table 1. These results are quite well fit by

Power level (dBm)	S11 (dB)	rms amp (dB)	rms phase (deg)
-30	-20	0.03	0.2
-20	-20	0.015	0.1
-10	-24	0.007	0.03
0	-24	0.002	0.015
-10	-30	0.015	0.07
-30	0	0.003	0.02

Table 1 VNA noise measurements

$S11\_rms = 10^{\alpha}$ in dB

$= 10^{\beta}$ in degrees of phase

Where $\alpha = -4 - 0.05(p\_dBm + S11\_dB)$

$\beta = -3.2 - 0.05(p\_dBm + S11\_dB)$

Where p_dBm is the power out of the VNA port in dBm

$S11\_dB$ is the reflection magnitude in dB

While these tests were being made it was noted that there are small shifts of about 0.001 dB the measurements with VNA oscillator power. This shift requires that VNA calibration should be repeated when the power level is changed even though the instrument doesn’t require this to be done.

2] Simulations of the effect of VNA noise on the calibrated spectra.

Following tests of adding a long cable between the reference plane at the antenna and the LNA (see memo #112) it was found that noise in the VNA measurements of the S11 of the LNR propagates into the calibrated spectra. Previously it was thought that the spectra averaging of the S11 data would be sufficient to reduce this noise but it was found that the long cable introduces fine structure in the S11 data due to deviation of the cable impedance from 50 ohms. While it might be possible to make corrections for the cable from separate VNA measurements it may be better to move the reference plane back to the input of the 3-position switch. In this case the S11 of the LNA has no fine frequency structure.

For simulations of the effect of VNA noise I used the basis functions given in memo 112.

The other parameters chosen were

a) smoothing of S11 of antenna	27 term Fourier series
b) smoothing of other S11 measurements	4 term polynomial
c) smoothing of noise waves	8 term polynomial
d) smoothing of calibration corrections	6 term polynomial
e) frequency range	90 to 195 MHz
f) Antenna S11	Data from Roberts Balun antenna
g) Noise wave parameters	Typical values from LNA
h) sky temperature	300 K at 150 MHz with 2.5 spectral index
i) EoR signature	20 mK, 50 MHz wide, centered at 145 MHz
j) Observation time	100 days.

The results of the simulations are given in Table 2. In this table n is the number of basis functions in the least squares solution. VNA noise has a value of 1 for the values given in Table 1. Reducing the noise to a value of 0.3 requires increasing the averaging factor to 999, which is the maximum available, using off-line averaging of several measurements. A calibration noise factor of 1 corresponds to 24 hours of data from the EDGES spectrometer for each of the hot, cold load and open cable spectra. Cable1 and Cable2 are the delays in the cable used to measure LNA noise waves and the delay in the cable from the antenna respectively. It should be noted that the covariance of the EoR estimate increases rapidly for n>7 when there is not significant delay to help decorrelate the EoR signature from noise or errors in the S11 measurements. The results in table 2 are for a Gaussian EoR signature with full width at half maximum of 50 MHz. Reducing the width to 40 MHz approximately doubles the EoR SNR for n>4. It should be noted that the calibration spectra, which will be produced in the laboratory, need to be made with about 10 days of integration for each spectrum to avoid significant additional noise in the calibrated spectrum. A more detailed examination shows that only the spectrum on the ambient (cold) load needs 10 days. The spectra on the hot and open cable can be reduced to 1 day each.

n	VNA noise	Covar ½	Calibration noise factor	Cable 1 (ns)	Cable 2 (ns)	EoR SNR	rms (mK)
2	0	1	0	200	60	200	0.4
7	0	10	0	200	60	30	0.4
14	0	14	1	200	60	7	1.0
14	0	14	0.3	200	60	16	0.5
14	0.3	14	0.3	200	60	10	0.7
2	0	1	0	200	0	200	0.4
7	0	9	0	200	0	15	0.4
8	0	18	0	200	0	15	0.4
9		42					
7	0.3	9	0.3	200	0	11	1.0
14	0.3	14	0.3	60	60	3	3.0

Table 2 – Simulations of the ability to extract an EoR signature from observations of 100 days of integration for various levels of noise in the VNA measurements and noise in the spectra used for calibration.

It is noted that performance improves with an open cable delay of more than 60 ns up to a delay of 200 ns. It was found that adding an additional spectrum with the end of cable 1 shorted reduces the delay required for best performance to about 60 ns.

In summary these simulations show that error in the antenna S11 can be removed by adding a delay between the antenna and the LNA. An advantage is that small changes in the antenna S11 can be observed in the calibrated spectrum and corrected using basis functions to allow a polynomial to be fitted to measure these changes. A disadvantage of the added cable is its contribution to the spectrum from its loss which has to be corrected to obtain the sky spectrum.

These simulations also show that significant integration times of up to 10 days are needed for the laboratory calibration. It is also noted that detection of an EoR signature as wide as 50 MHz is not ruled out provided the basis functions are sufficient to allow removal of the ionosphere and the foreground.