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To: EDGES Group
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 Subject: Measurement of the loss of SOL standards

A method of checking the accuracy of a VNA was described in memo #131. This method was used to check and potentially correct errors in the data provided for the SOL standards. The results of an attempt to measure the loss of the SOL standards was given in memo #133. In order to resolve the different values of the skin loss factor normalized at 1 GHz of 1.33 Gohms/s by Maury and the value of 2.3 Gohms/s given by Agilent for similar SOL standards the measurements have been extended from 200 to 500 MHz.

These tests have been made using a 2-port SMA tee with a short with 330 ps 2-way delay shown in Figure 1. While this is a symmetric 2-port within the mechanical tolerance of the tee a simulation shows that this 2-port is more sensitive to the loss of the calibration short than the 2-port used in the earlier tests. In addition to using a different 2-port the tests were made from 100 to 500 MHz. In going to 500 MHz it is noted that there is a significant imaginary impedance of the load owing to the internal inductance of the transmission and consequently, contrary to common practice, the offset delay of the load needs to be included in the calibration kit data. The calibration load used had a one-way delay offset of 33 ps (obtained from a mechanical inspection) which results in a S11 of 1×10^{-4} and 5×10^{-4} at 50 and 500 MHz respectively even though the measured DC resistance of the load is 50.02 ± 0.05 ohms. It is noted that the internal inductance normally ignored for the load reaches a maximum on this load of about 2×10^{-3} at about 7 GHz. For 33 ps offset.

The results of these tests are given in Table 1

Test #	Offset correction ps	Conductivity % Cu	Sum
1	0.05	16	0.002
2	0.03	14	0.002
3	0.02	11	0.002
4	0.03	12	0.002
5	0.06	16	0.001
6	0.05	18	0.001
7	-0.02	15	0.001
8	0.01	19	0.001

Table 1.

These results give a conductivity 15 ± 2 (1σ) which is now significantly in favor of a normalized resistive loss about twice the 1.3 Gohm/s. Tests 5 through 8 used the Agilent N5222A which has lower noise which accounts for the lower value for the sum at the best value of conductivity.

Tests 1 through 4 used the HP85047A/8753C. The value of 10^{-3} for the sum is not limited by noise and implies a fundamental limit to VNA accuracy of about 5×10^{-3} due to additional errors in the reflection coefficients of the calibration kit or defects in the VNA like deviations from linearity.

Figures 2 and 3 show the forward-reverse differences and total S parameters for test 5 as an example.

The effect of various small errors in linear units of S11 in the calibration kit are summarized in table 2 below:

Error	Frequency (MHz)					
	50	200	500	7,000	22,000	
A	2×10^{-4}	4×10^{-4}	7×10^{-4}	2.4×10^{-3}	1.7×10^{-3}	Load
B	1×10^{-4}	3×10^{-4}	5×10^{-4}	2.0×10^{-3}	1.5×10^{-3}	Load
C	2×10^{-5}	8×10^{-5}	2×10^{-4}	6.0×10^{-3}	1.2×10^{-2}	Open
D	1×10^{-4}	2×10^{-4}	4×10^{-4}	1.0×10^{-3}	1.0×10^{-3}	Short
E	1×10^{-9}	4×10^{-8}	4×10^{-7}	2.4×10^{-4}	1.5×10^{-3}	Open

Table 2.

The errors are as follows:

- A The effect of conductivity 15% of copper (IACS) on load
- B The effect of conductivity 33% of copper (IACS) on load
- C Difference between male and female open
- D Difference between 16% and 33% IACS on short
- E Difference between 16% and 33% IACS on open

The effects on the open and short are well described by the “standard” model used by Maury and Agilent in the characterization of their calibration kit. However for some unknown reason the effect of a physical offset on the load is ignored and in doing so sets a fundamental limit on VNA accuracy of 4×10^{-4} at 200 MHz. This is equivalent to 0.015 dB in magnitude and 0.08 degrees of phase at an S11 of -15 dB. Consequently it is essential for the VNA measurement accuracy needed for the EDGES project to know the offset delay of the load and to account for its effect in the model of the load.

An alternate method of processing the S11 data was investigated. In this method linearized least squares is used to find the conductivity which minimizes the rms residuals of the best fit to the actual measurements. The design matrix is calculated starting with the best “Apriori” model for the observed S11 data, then adding a small perturbation to each of the 3 real and 3 imaginary values of VNA correction 2-port, each of the 3 real and 3 imaginary values of asymmetrical 2-port and to the apriori value of conductivity. The design matrix times its transpose is then inverted to get the covariance matrix based on these numerically calculated partial derivatives. In this case we have 9 real and 9 imaginary measurements and only 13 unknowns. In order to judge the power of each asymmetric 2-port to measure the conductivity a simulation which assumed a measurement noise of 10^{-4} in linear S11 for each real and imaginary value.

Freq (MHz)	2-port	(covar) ^{1/2} ×10 ⁻⁴
200	A	0.1
500	A	0.07
200	B	0.1
500	B	0.05
500	C	0.02

Table 3.

Where A is a 2-port made with 50 ohms between ports and 30 *pf* to ground. B is 2-port used in the measurements of table 1 and C is a 2-port like A but with 120 *pf*. The values of the 3rd column are the expected 1-sigma error in the determination of the fractional IACS starting with a Apriori value of 0.15. Its noted that while 2-port C should in theory be more sensitive to the loss in the calibration short, it was noted that the 120 *pf* must have a very small series inductance which may set a practical limit.

Using this alternate method of calculation the following results were obtained:

Test #	Conductivity %	Estimated EoR %
1	14	7
2	12	7
3	9	7
4	10	7
5	10	6
6	14	5
7	18	4
8	18	4

Table 4.

The estimated error in the conductivity as a percentage of that of copper is derived from the square root of the covariance times the rms residual for each set of 18 measurements at a given frequency. The number is an average for all frequencies. In principle this number could be divided by the square root of the number of frequencies if the residuals were just due to noise but it is clear that the presence systematics are present and the assumption of independent random noise from each frequency is not justified.

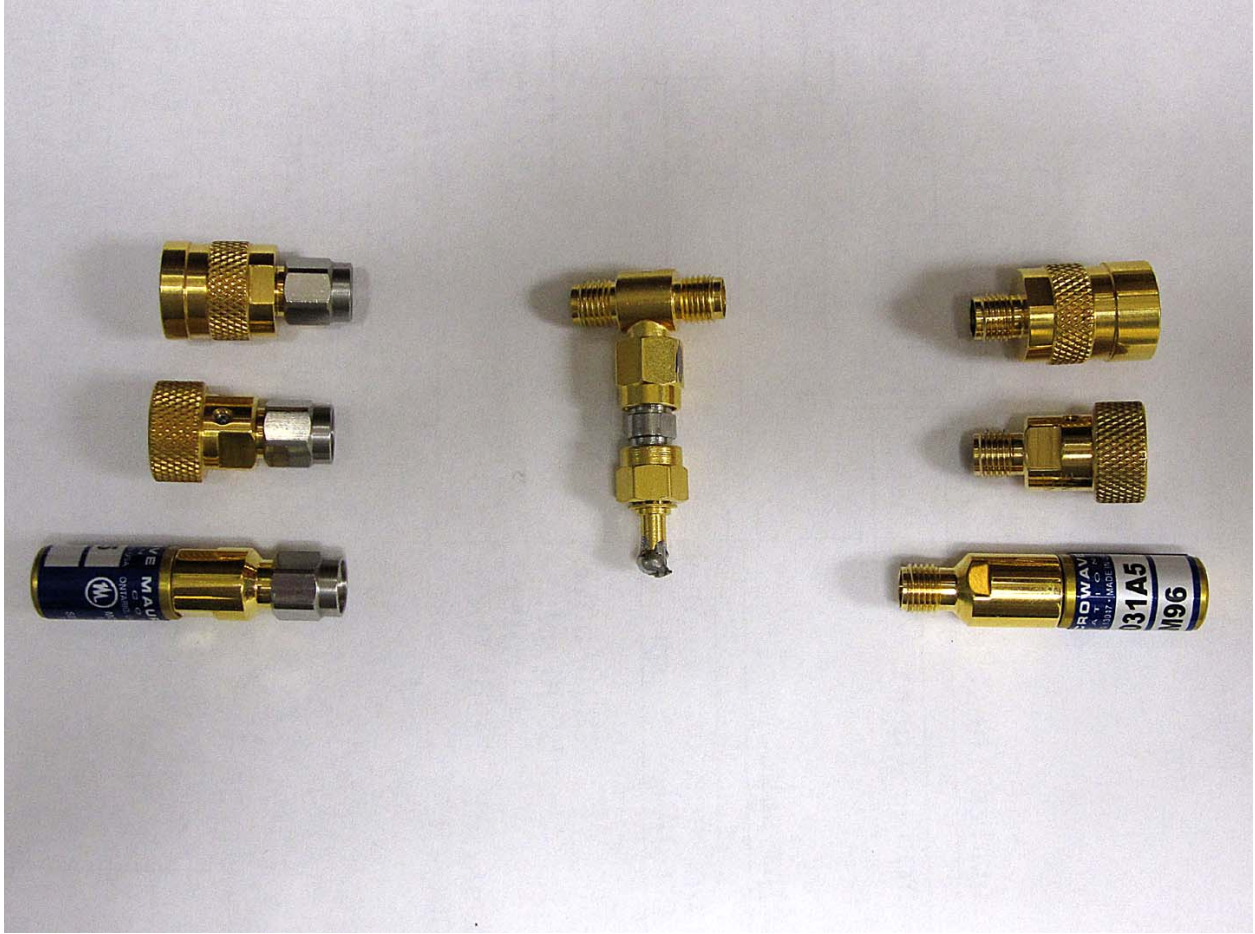


Figure 1. SOL calibration kit and 2-port network for test. Some tests also used an Anritsu load not shown.

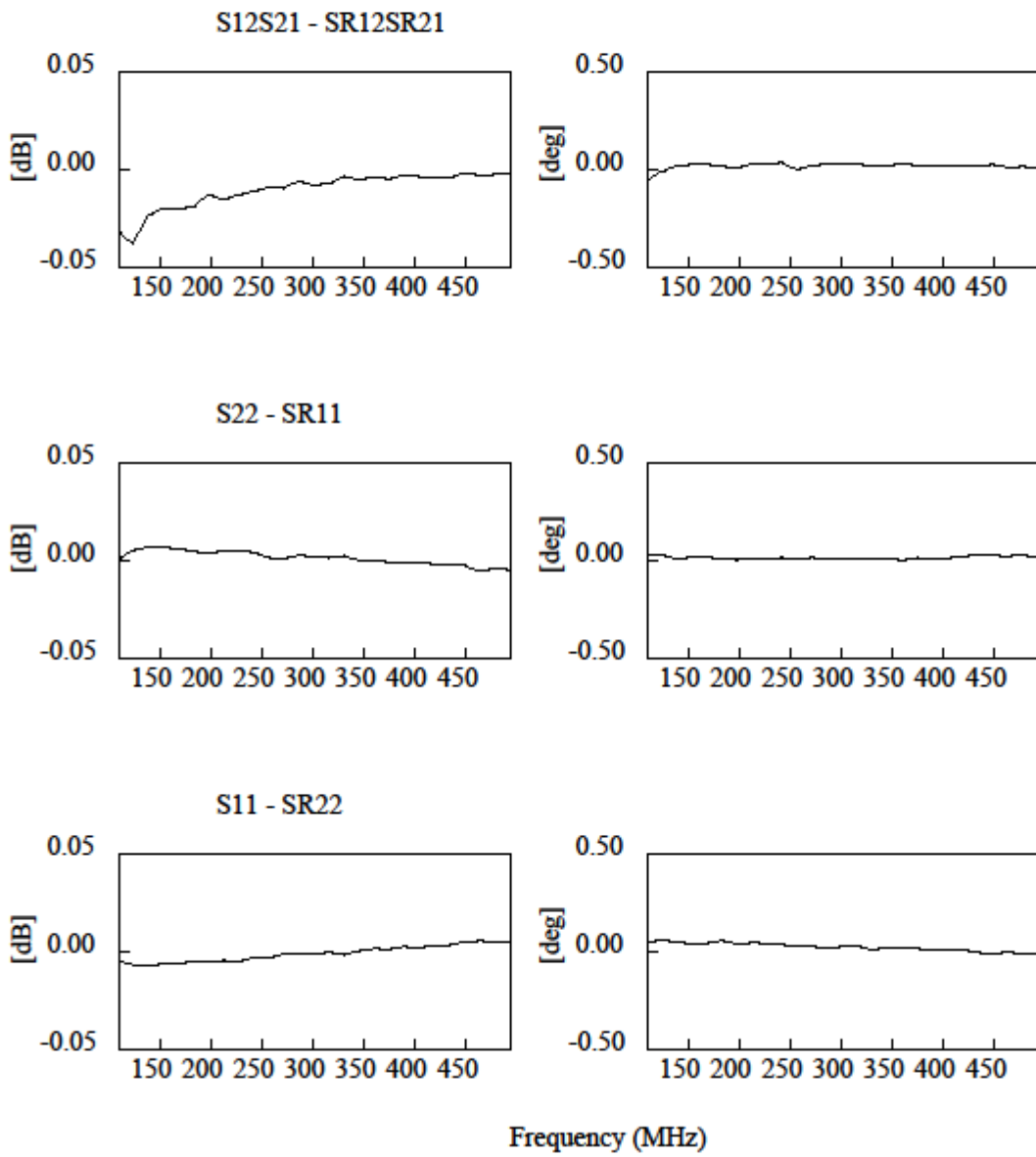


Figure 2. Forward-reverse differences for best fit SOL corrections in test 5.

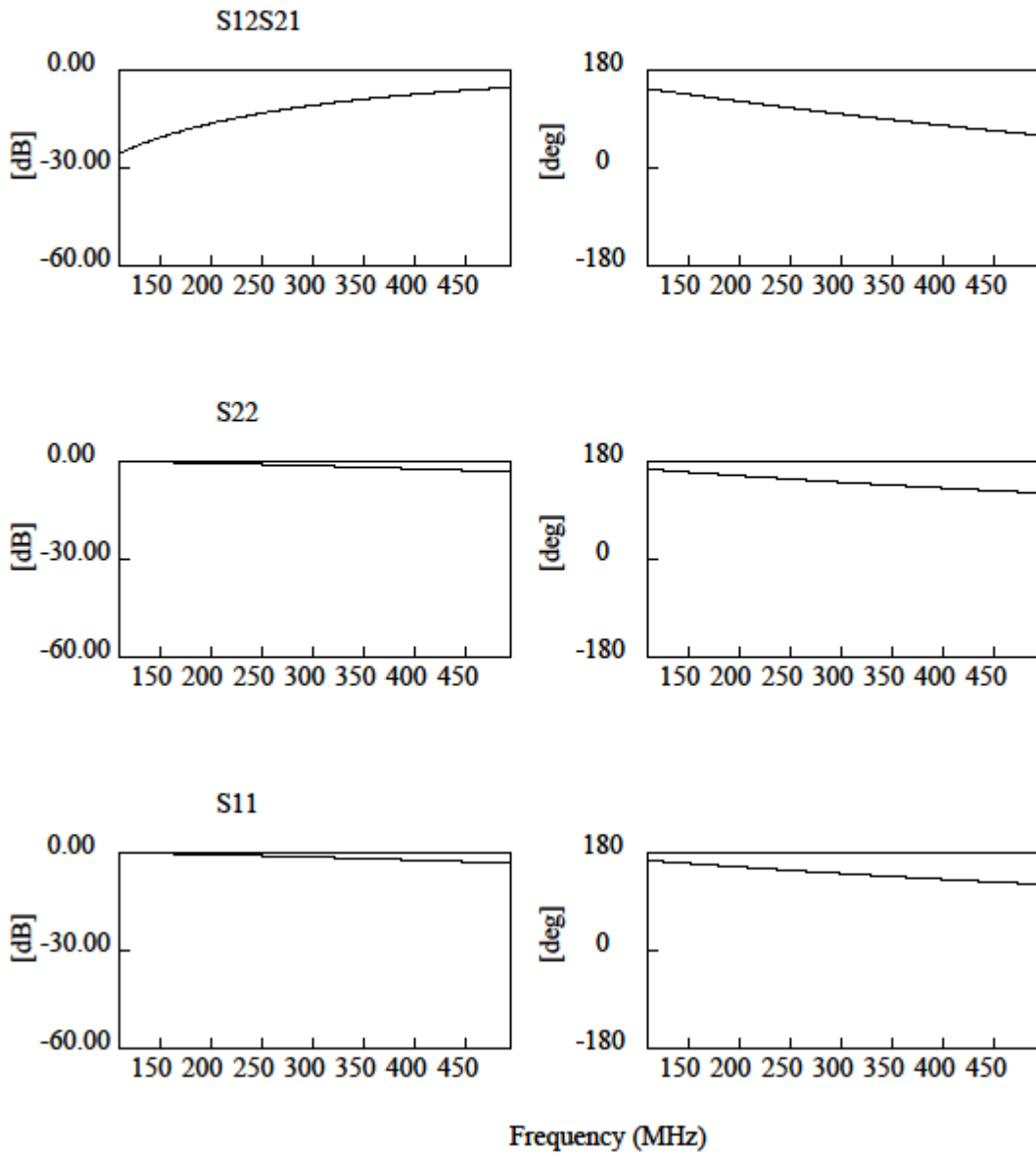


Figure 3. 2-port S-parameters.