EDGES MEMO #132

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Subject: Measurement of cable loss between LNA and antenna.

The tests of the performance of the EDGE-2 electronics on the bench using an artificial antenna described in memo 126 used a lossy cable between the hot filament source and the EDGES reference plane at the input of the LNA module. This test allows a more realistic simulation of EDGES connected to an antenna because the S11 of the artificial antenna formed by the combination of the hot filament and the cable has significant delay and structure. A significant difficulty with this test is that it relies on a model of the cable to estimate its loss. This model is unable to account for the imperfections present in a real cable due to deviations in the concentricity of the center conductor, and deviations from uniformity of the dimensions etc. If the cable is attached to the antenna via a connector it is possible to completely characterize the cable from measurements of S11, S12, S21, S22. Further, since the cable is a reciprocal 2-port network S12 equals S21 and the cable can be measured with VNA one port measurements provided both ends of the cable can be accessed.

Measurements of the cable from one end with known S11 of an open, short and load at the other end provides knowns for the solution of 3 unknowns S11, S12, S21 and S22 from the relation.

$$\Gamma_{meas} = S11 + S12S21\Gamma_{\ell} / (1 - S22\Gamma_{\ell})$$

Where Γ_{meas} is the reflection coefficient measured by a calibrated VNA and Γ_{ℓ} are the known reflection coefficient of the open, short and load.

If the S parameters of a cable are measured the loss can be computed from

$$L = \left(1 - |\Gamma_{in}|^2\right)^{-1} |S21|^2 \left(1 - |\Gamma_a|^2\right) \Big/ |1 - S22\Gamma_a|^2$$

Where $\Gamma_{in} = S11 + S12S21\Gamma_a / (1 - S22\Gamma_a)$

It is noted that for a reciprocal network, like a cable, $S12 = S21$ so that the loss can be calculated from measurements with a one port VNA made at each end of the cable. In general $S12 \neq S21$ owing to asymmetries in cable. Γ_a in the expression above is the antenna reflection coefficient at the input of the cable so that if the antenna is connected to the balun Γ_a can be calculated from

$$\Gamma_a = (\Gamma_{in} - S11) / (S12\,S21 - S11\,S22 + S22\,\Gamma_{in})$$

In practice using a one port VNA to measure a cable from one end only results in a large error for the determination of S22. For example a 1 ps error in the open or short one-way delay results in an error of about 10^{-3} in the S22 which corresponds to about 0.3 dB error at -30dB. Moreover an error this large results in an antenna S11 phase dependent error in the loss estimate of the balun equivalent to about 50 mK in the high band. The solution is to be able to measure the balun from both ends (to obtain S22 from SR11) which in turn requires a connector on the antenna or a method of being able to separate the balun from the antenna for a separate measurement. Adding a connector increases the loss and decreases reliability. The addition of a connector will make it more difficult to obtain very low loss in the top cap. Another possibility is to assume the balun is symmetrical in which case it can be assumed that $S11 = S22$ thereby allowing S22 to be estimated from S11 without the need to reverse the cable.

In memo 105 the advantage of adding attenuation was considered for the low band. Adding an attenuator on the antenna improves the match into the balun and reduces the influence of the antenna S11 phase on the balun loss while adding an attenuator at the input to the 3-position switch is equivalent, for the strong signals in the band, to improving the LNA input match. Another option considered was increasing the length of the cable from the LNA to the antenna. While this has the advantage of reducing the period to the ripple so that it is no longer highly correlated with the EoR signature. However a long cable is likely to have imperfections like those discussed in memo 126. In addition the longer cable will be less stable with temperature which might not be a problem of EDGES electronics could be installed in a vault under the antenna where the cable could be maintained along with electronics at a constant temperature.

Simulations using the calibration data and antenna S11 measured at the EDGE-2 deployment in November 2013 were used to make estimates in Table 1 of the sensitivity to a 1 ps bias error in antenna S11, a 0.01 dB bias error in antenna S11 and 100 ps bias error in the balun cable length used to estimate the loss.

	EoR bias (mK)	
Bias source	High band	Low band
1 ps	3	80(20)
0.01 dB	60	100
100ps	70	110(60)

Table 1.

The EoR signatures were Gaussians at 150 and 75 MHz with 32 and 16 MHz full width at high and low band respectively. The numbers in parentheses are for 6 dB added attenuation which clearly improves performance in the low band. The balun was taken to be the current design at high band and a scaled version for low band. Reducing the balun loss is a clear advantage (see memo 127) unless the balun loss can be accurately measured or modeled. It was determined that placing an attenuator, at a low band, on the antenna offers no advantage over placing the attenuator at the end of the balun cable. These simulations emphasis the need for VNA accuracy better than 0.01 dB and 3 ps which is 0.16 degrees at 150 MHz. In the low band the need for extreme phase accuracy is ameliorated by the use of attenuation. In addition the use of a longer cable is under consideration to reduce the correlation between the EoR signature and effect of phase error in the antenna and LNA reflection coefficients.

Summary of algorithms

$$P = \left[\left(T_{sky} L + T_{amb} \left(1 - L\right) \right) \left(1 - \left| \Gamma_a \right|^2 \right) + T_u \left| \Gamma_a \right|^2 \right] \left| F \right|^2 + T_c \operatorname{Re}\left(\Gamma_a F \right) + T_s \operatorname{Im}\left(\Gamma_a F \right)$$

Where $F = \left(1 - \left| \Gamma_\ell \right|^2 \right)^{1/2} \Big/ \left(1 - \Gamma_a \Gamma_\ell \right)$

$$L = \left(1 - \left| \Gamma_a \right|^2 \right)^{-1} \left| S21 \right|^2 \left(1 - \left| \Gamma \right|^2 \right) \Big/ \left| 1 - S22\Gamma \right|^2$$

Where $\Gamma = \left(\Gamma_a - S11 \right) / \left(S12S21 - S11S22 + S22\Gamma_a \right)$

Where Γ_a, Γ_ℓ = reflection coefficients from reference plane in opposite directions with Γ_a towards the antenna

T_c, T_s = LNA correlated noise wave components

T_u = LNA uncorrelated noise wave component

S11, S22, S12, S21 = antenna cable scattering coefficients where S11 is towards antenna

T_{sky}, T_{amb} = sky and ambient noise

P = noise temperature calibrated by loads of known temperature and reflection coefficient at reference plane.

The terms which depend strongly on reflection phase are $\left| 1 - \Gamma_a \Gamma_\ell \right|, \left| 1 - S22\Gamma \right|$, $T_c \operatorname{Re}\left(\Gamma_a F \right)$ and $T_s \operatorname{Im}\left(\Gamma_a F \right)$. In the low band the first of these is dominant amounting to 25 mK peak for Tsky=3000K, $\left| \Gamma_a \right| = \left| \Gamma_\ell \right| = 0.1$ and a 1 ps error at 70 MHz.