Toward an Accurate Calibration of EDGES Using Temperature References

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Description

This report describes two strategies for obtaining the quantities used to calibrate EDGES. The quantities are the scale and offset to correct the measured spectrum, and the noise wave parameters t_u, t_c, t_s.

This work is based on the material presented in memos 96[1] and 113[2], as well as the calibration equations presented in Rogers and Bowman 2012[3].

The methods are:

- METHOD 1: independent estimation of the quantities at each frequency.
- METHOD 2: interdependent estimation, subject to frequency-dependent polynomial modeling of noise wave parameters.

The results are compared to those obtained by Alan.

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[1] `http://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos/096.pdf`

[2] `http://www.haystack.mit.edu/ast/arrays/Edges/EDGES_memos/113.pdf`

[3] Rogers, A. E. E., and J. D. Bowman (2012), Absolute calibration of a wideband antenna and spectrometer for accurate sky noise temperature measurements, Radio Sci., 47, RS0K06.

Fundamental Equations

EDGES is internally calibrated using a load at ambient temperature, which is then connected to a noise source. This provides two reference points which allow to obtain a calibrated spectrum for the device connected to the receiver input, as follows:

$$sp = T_{cal}\left(\frac{P - P_{amb}}{P_{cal} - P_{amb}}\right) + T_{amb}, \tag{1}$$

where

- T_{amb}: ambient temperature
- T_{cal}: temperature of noise source, higher than ambient
- P_{amb}: power measured for load at ambient temperature
- P_{cal}: power measured for load connected to noise source
- P: power measured for the device connected to the receiver input
- sp: calibrated spectrum for the device at the receiver input

  However, sp represents an accurate calibrated spectrum only in case of perfect impedance match between blocks, and no noise emitted by the LNA in the direction of the input device.

Fundamental Equations

For the general case of imperfect impedance match between blocks, and non-negligible noise emitted by the LNA in the direction of the input device, the noise temperature of the input device is:

$$T = \frac{(1 - |\Gamma_l|^2)sp - t_u|\Gamma_d|^2|F|^2 - (t_c \cos\phi + t_s \sin\phi)|\Gamma_d||F|}{(1 - |\Gamma_d|^2)|F|^2} \tag{2}$$

with

$$F = \frac{\sqrt{1 - |\Gamma_l|^2}}{1 - \Gamma_d\Gamma_l}, \qquad \phi : \text{phase of } \ (\Gamma_d F) \tag{3}$$

where

- sp: spectrum obtained from equation 1
- Γ_d: reflection coefficient of input device
- Γ_l: S_{11} of LNA
- t_u, t_c, t_s: noise wave parameters

Calibration

The purpose of this work is to estimate the quantities t_u, t_c, t_s using measurements of the LNA performed by Alan in the lab.

In addition, the spectrum produced by equation 1 has to be corrected due to the use of incorrect assumptions for T_{amb} and T_{cal} during the processing of field data. A scale *sca* and an offset *off* are used for the correction,

$$sp_c = (sca \times sp) + off. \tag{4}$$

Therefore, in order to get an accurate noise temperature from equation 3, sp_c has to be used instead of *sp*.

Thus, five frequency-dependent quantities have to be computed from lab measurements: *sca*, *off*, t_u, t_c, t_s. The quantities computed using any method should satisfy equation 3 for devices of known reflection coefficient and temperature connected to the LNA input.

The lab measurements consisted of connecting to the input of the receiver a load at ambient temperature and a higher temperature (297 and 367 K respectively), and also a cable at ambient temperature (297 K) with its far end open and shorted. Measurements include the reflection coefficient of these devices, as well as their spectra (equation 1) assuming T_{amb}=300 K and T_{cal}=400 K for the internal references.

METHOD 1

Method 1 consists of the minimization of the difference $(T_{true} - T_{measured})$, simultaneously for the four input loads (cold, hot, open cable, shorted cable). $T_{measured}$ is the temperature obtained from equation 3 evaluated at a given set (scale, offset, t_u, t_c, t_s). The system could be solved only when the four equations are used.

The minimization is independent for each frequency channel. When a reasonable starting point is given to the algorithm, the solution converges reliably. However, at this solution only the scale and offset vary smoothly with frequency. The noise wave parameters (NWP) show an oscillatory response.

It was found that if the starting point was chosen from polynomial fits to these oscillatory responses, the solution of the NWP also became smooth. Thus, the starting point is refined iteratively by fitting a polynomial in frequency to the previous solution of the parameters. Convergence is achieved after 20 iterations. Finally, the solutions are modeled using polynomials.

Figure 1 shows the original and improved solutions of the parameter estimation through minimization.

METHOD 1

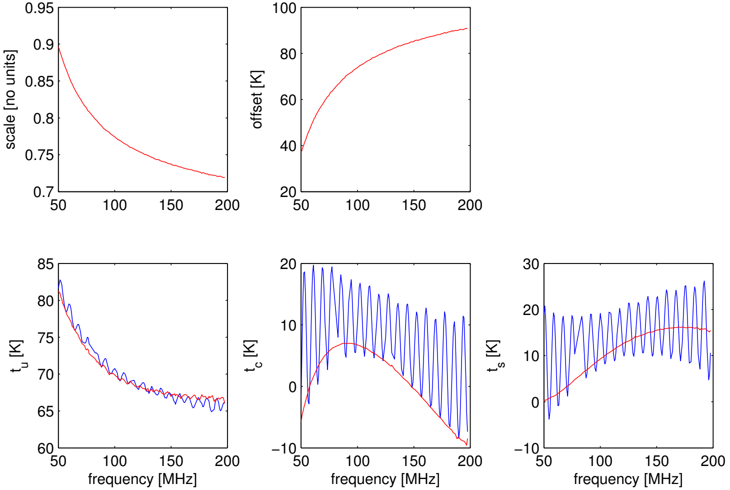

Figure : (1): Parameters obtained with Method 1. (BLUE) Solutions after using a generic starting point in the algorithm, flat in frequency. (RED) Solutions after improving iteratively the starting point of the algorithm. The improvement involves using a polynomial fit to the solutions of the previous iteration as the new starting point. For the scale and offset, the solution is not sensitive to the starting point, so the curves overlap.

METHOD 2

Method 2 is an implementation of the method introduced in memo 96. It involves the following steps:

1. Compute the scale and offset from the discrepancy between the true and measured temperatures of the cold and hot loads (assigning a value of zero to the NWP in the first loop).
2. Correct the spectrum for the cable (either open or shorted) using the computed scale and offset.
3. Obtain the NWP from polynomial fitting to equation 1, using the corrected cable spectrum and a temperature of 297 K.
4. Correct the spectrum of the cold and hot loads using all the parameters found in this iteration.
5. Go to step 1.

No more than 4 iterations are necessary, and the correction computed in the first iteration is by far the largest. The final scale and offset are obtained by combining the results of all the iterations:

$$sca = \prod_{i=1}^{N} sca_i, \qquad off = \sum_{i=1}^{N} off_i \prod_{j=i+1}^{N} sca_j. \tag{5}$$

Method 2 was evaluated using either the measurements of the open or shorted cable.

COMPARISON

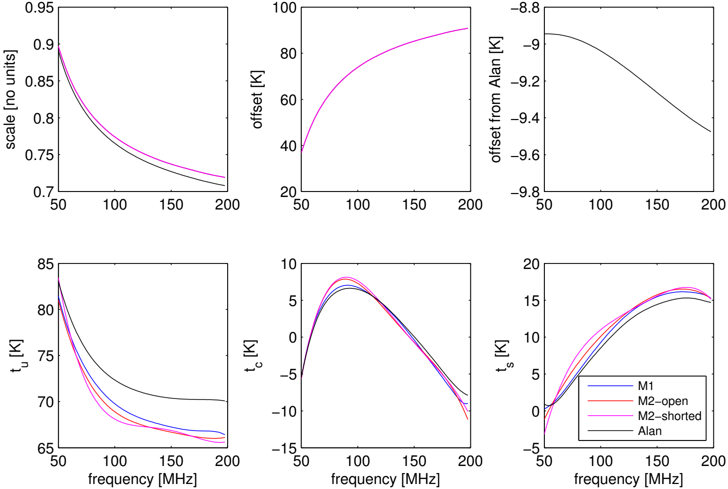

Figure : (2):Comparison of the recovered parameters using Methods 1 and 2 (open and shorted cable), as well as Alan's results from the specal.txt file. For the scale, the three results agree almost perfectly (they overlap in the figure), but differ from Alan's. For the offset they also agree and overlap, but Alan's has to be plotted in a different figure because he defines it differently (see memo 96). For t_u, the agreement is good but the difference with Alan's is significant. For t_c and t_s the agreement is better, even with Alan's.

EVALUATION

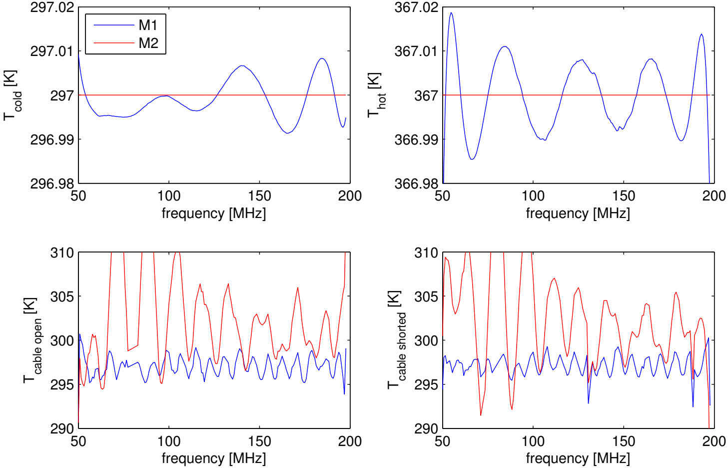

Figure : (3):Calibration of lab measurements using equation 3 and the parameters obtained with Methods 1 and 2 (from open cable data). Method 1 shows a peak-to peak ripple of ∼10 mK for the cold and hot loads, and of ∼3 K for the cables. Method 2 has a ripple better than 1 mK for the cold and hot loads, and of ∼10 K for the cables. Also, for Method 2 the averages of the cable results depart from 297 K by a few degrees.

EXAMPLES

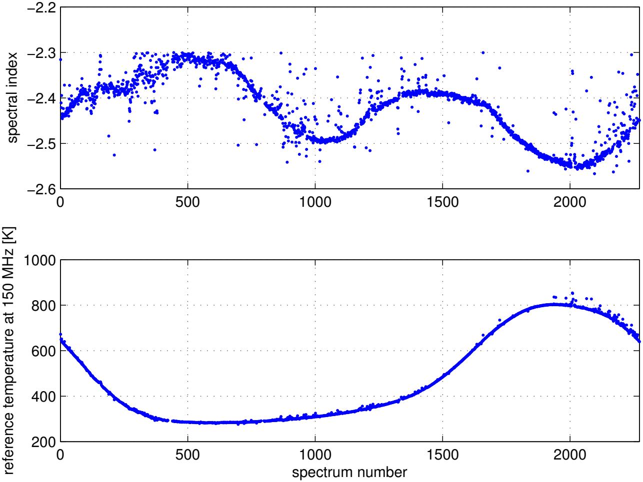

Figure : (4):Spectral index and reference temperature for day 96 (24 hours, starting at 8 am local time) obtained by fitting two parameters to the data calibrated with Method 1, after subtracting the CMB. Results for Method 2 are almost identical. The scatter is due to RFI which has not been filtered out at this point. The fits are done in the range 100-135 MHz, in order to avoid RFI and large features encountered above 150 MHz. On average, the spectral index is small (in absolute value), suggesting possible mistakes throughout the calibration.

EXAMPLES

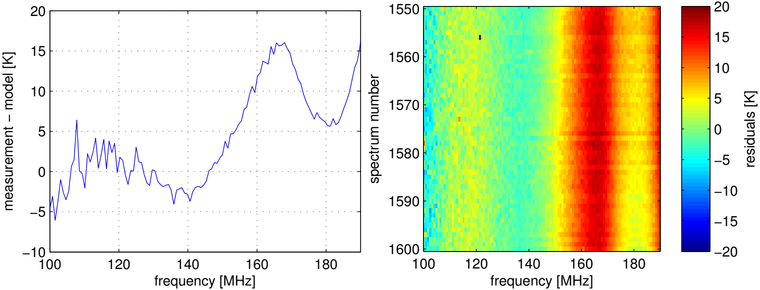

Figure : (5):Examples of residuals after subtracting a two-parameter model from the data calibrated using results from Method 1, and also subtracting the CMB. The left panel shows a single spectrum, while the right panel shows a continuous section of 50 spectra in a region with almost no RFI. The residuals are large, especially above 150 MHz since the model is obtained from fits to the 100-135 MHz range. Had the full frequency range been used for the fits, the spectral index would have been lower in absolute value, departing even more from expectations. The spectral features above ∼160 MHz can be attributed to the beam tilt.

Conclusion

This is clearly work in progress. The calibration process is still not well understood at ASU, and for this reason several strategies are being tested. Two of them are presented here.

Specifically, it has not been possible to obtain calibration parameters (scale, offset, t_u, t_c, t_c) that simultaneously correct the all the available lab data producing flat spectra to within reasonable margins. This could be due to impractical computation methods or due to incorrect procedures. More tests and cross-checks are necessary.