Toward an Accurate Calibration of EDGES Using Temperature References: II

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Description

This report has two purposes.

First, it shows the level of accuracy achieved by Method 1, introduced in `http://loco.lab.asu.edu/memos/edges_reports/report_20140502.pdf`, which solves for the calibration parameters of the LNA (scale, offset, and noise wave parameters).

Second, it quantifies the effect of incorrect estimations of temperature for the references (cold load, hot load, and open and shorted cable), on the calibration parameters recovered by Method 1 and on the sky temperature ultimately computed.

PART 1: Method for Computing Calibration Parameters

Algorithm

The algorithm at the core of the method is the following:

```
-load lab data
-produce generic starting point for calibration parameters $\theta$
-for each frequency $i$

    -find solution $\theta_i^*$ by simultaneously minimizing:
        $\left[T_{true}^{cold}(i) - T_{eval}^{cold}(i,\theta_i)\right], \left[T_{true}^{hot}(i) - T_{eval}^{hot}(i,\theta_i)\right],$
        $\left[T_{true}^{open}(i) - T_{eval}^{open}(i,\theta_i)\right], \left[T_{true}^{short}(i) - T_{eval}^{short}(i,\theta_i)\right],$

-end

# The recipe above produces accurate results for the scale and offset, but the resulting noise wave parameters are
# oscillatory in frequency. Convergence to smoother shapes is achieved by improving iteratively the starting point
# with the additional steps below.

-for $j$ = 1 to 20
    -fit a 5th degree polynomial in frequency, $m(f)$, to the current solution of each parameter
    -for each frequency $i$
        -obtain the starting point by evaluating $m$ at $i$
        -find solution $\theta_i^*$ by simultaneously minimizing:
            $\left[T_{true}^{cold}(i) - T_{eval}^{cold}(i,\theta_i)\right], \left[T_{true}^{hot}(i) - T_{eval}^{hot}(i,\theta_i)\right],$
            $\left[T_{true}^{open}(i) - T_{eval}^{open}(i,\theta_i)\right], \left[T_{true}^{short}(i) - T_{eval}^{short}(i,\theta_i)\right],$
    -end
-end

-fit a 5th degree polynomial in frequency to the final solutions
```

Description of Tests

The method described in the previous page is tested as follows:

Input quantities:

- noise wave parameters and reflection coefficient of the LNA
- scale and offset that correct the 3-position switch spectra
- four temperature standards, and their reflection coefficient

Comparison of calibration parameters:

- using the input quantities, compute uncorrected 3-position switch spectra for the four temperature references
- using the method described in the previous page, recover the calibration parameters
- compare recovered parameters to originals

Comparison of sky temperatures:

- produce synthetic sky temperature with T_{150}=500 K, β=-2.5, and realistic antenna reflection coefficient
- compute uncorrected 3-position switch spectrum from the sky temperature using original calibration quantities
- compute sky temperature for the spectrum just obtained, using the recovered calibration quantities instead of originals
- compare input and output sky temperatures

Description of Tests

Four tests are used to determine how accurate and robust the recovery of calibration parameters is. They represent realistic or semi-realistic cases.

In all cases, the reflection coefficients of the temperature references are the actual ones, and not modified between tests. Only the spectra and cold/hot temperatures are varied.

Below, the phrase *input quantities* refers only to the spectra and hot/cold temperatures.

In all the tests except 4, the input quantities are fully determined by 5th-degree polynomials. For test 4, they are constant across frequency. In all cases, the outputs are recovered using 5th-degree polynomials.

- Test 1: input quantities are chosen as equal to actual calibration quantities obtained from the lab measurements. This has the purpose testing the method around a realistic operation point.
- Test 2: input quantities are scaled versions (60%) of those in test 1.
- Test 3: input quantities are scaled versions (150%) of those in test 1. Also, T_{cold}=197 K and T_{hot}=467 K, instead of the nominal values of 297 K and 367 K used in the other tests.
- Test 4: input quantities are flat in frequency.

Test 1

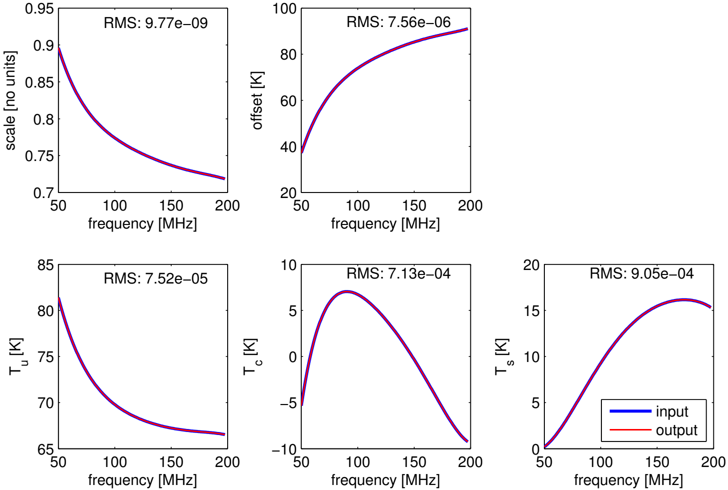

Figure : (1): Input and output values for test 1. They overlap and their RMS difference is very small, which validates the method.

Test 2

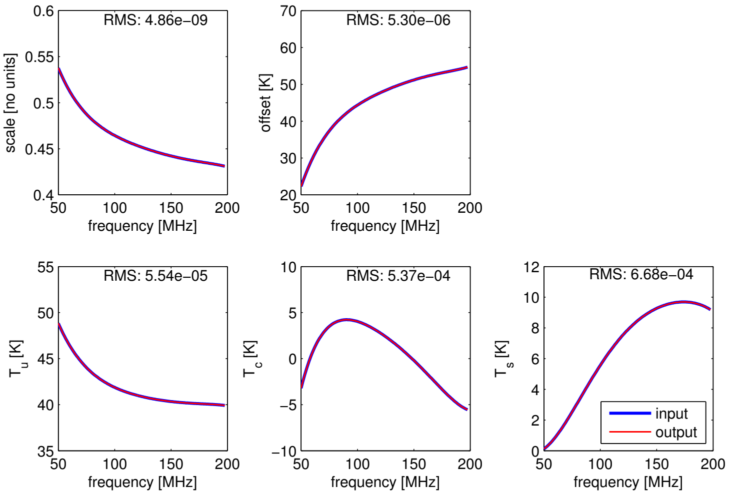

Figure : (2): Input and output values for test 2. They overlap and their RMS difference is very small, which validates the method.

Test 3

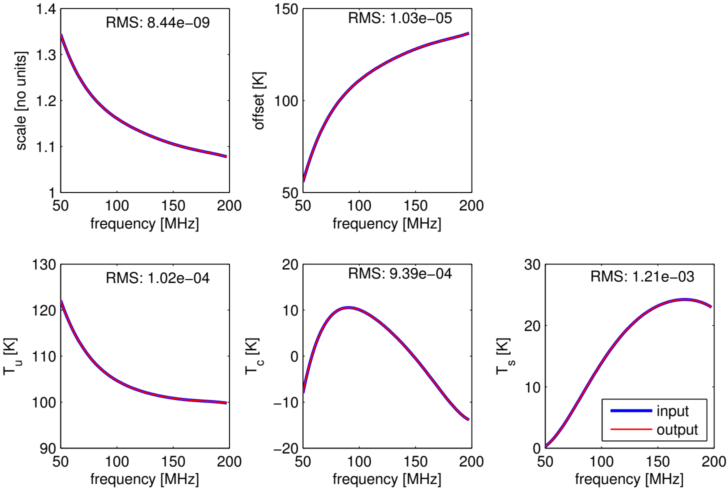

Figure : (3): Input and output values for test 3. They overlap and their RMS difference is very small, which validates the method.

Test 4

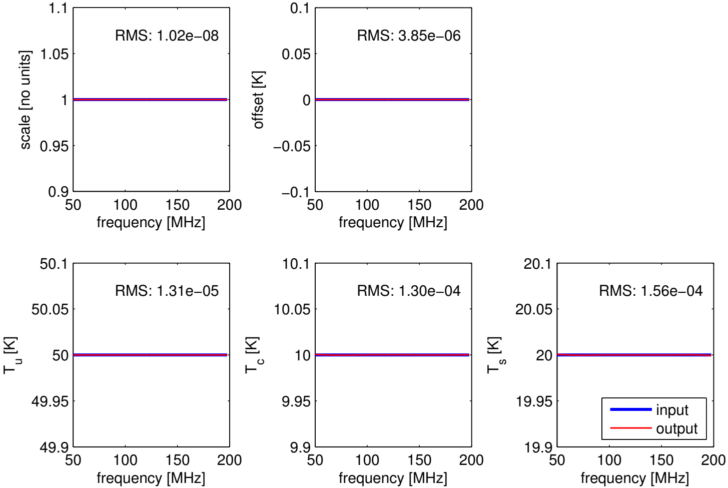

Figure : (4): Input and output values for test 4. They overlap, and their RMS difference is very small which validates the method. Even though the outputs correspond to 5th-degree polynomials, they capture very well the flat shape of the inputs.

Effect on T_{sky}

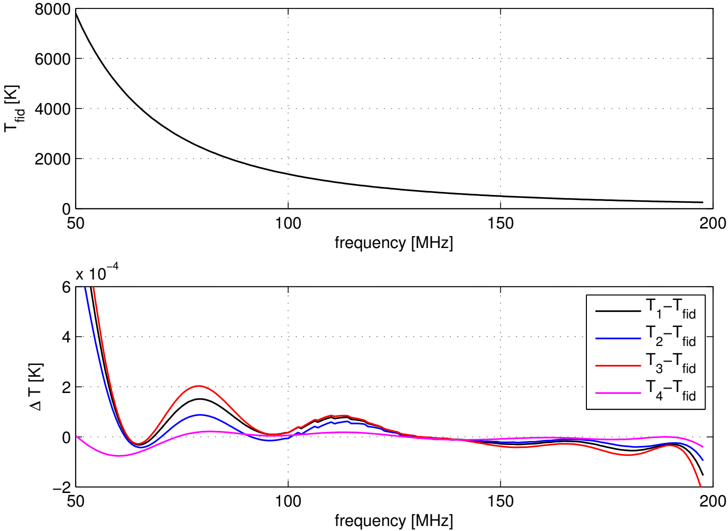

Figure : (5): TOP: Input or fiducial sky temperature. BOTTOM: Difference between sky temperature computed using with the calibration parameters returned by the tests, and the fiducial one. The differences are always lower than 1 mK, especially above 100 MHz.

Conclusions PART 1

The tests verify that the method used to compute the LNA calibration parameters is accurate in realistic scenarios. The RMS differences between input and output parameters are at most around 1.2 mK for T_s (see Figure 3, bottom right).

The recovered parameters produce errors in the sky temperature significantly better than 1 mK across the frequency range.

PART 2: Effect of Incorrect Assumptions for Reference Temperatures

Description of Tests

These tests investigate the sensitivity of the sky temperature to errors in the assumptions for the temperature of the four loads used to obtain the LNA calibration parameters.

In all cases, the input calibration parameters are those used for test 1 in Part 1 (figure 1). However, the temperature of the references relative to the nominal values change, one at a time. The nominal values are T_{cold}=297 K, T_{hot}=367 K, T_{open}=297 K, and $T_{shorted}$=297 K.

Comparison of calibration parameters:

- compute uncorrected 3-position switch spectrum for the four references, with one of their temperatures departing 1 K from its nominal value.
- from these four spectra, and using the method described in part 1, compute the calibration parameters assuming that the references are at their nominal temperatures
- compare recovered parameters to originals

Comparison of sky spectra:

- produce synthetic sky temperature with T_{150}=500 K, β=-2.5, and realistic antenna reflection coefficient
- compute uncorrected 3-position switch spectrum from the sky temperature using original calibration quantities
- compute sky temperature for the spectrum just obtained, using the recovered calibration quantities instead of originals
- compare input and output sky temperatures

Description of Tests

Four tests are performed, in which the actual temperatures are 1 K colder than assumed:

- using T_{cold}=297 K when the true value is T_{cold}=296 K. All the others equal to nominal.
- using T_{hot}=367 K when the true value is T_{hot}=366 K. All the others equal to nominal.
- using T_{open}=297 K when the true value is T_{open}=296 K. All the others equal to nominal.
- using $T_{shorted}$=297 K when the true value is $T_{shorted}$=296 K. All the others equal to nominal.

Error in T_{cold}

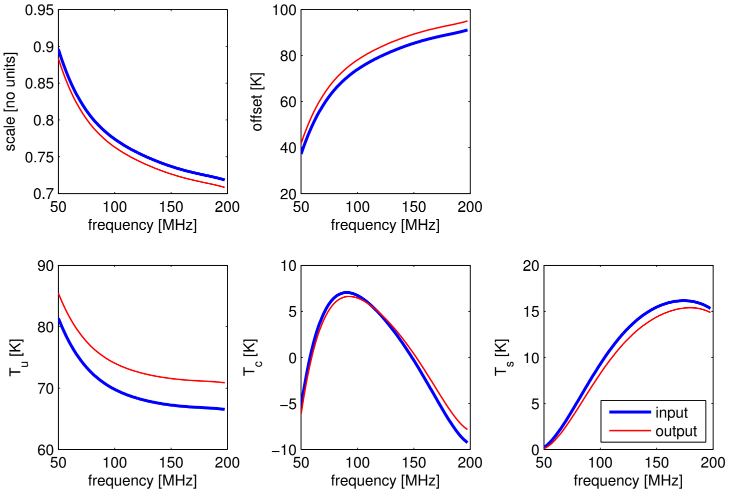

Figure : (6): Effect of error in T_{cold} on the calibration parameters. There are significant differences between inputs and outputs, but the shapes are similar and smooth.

Error in T_{hot}

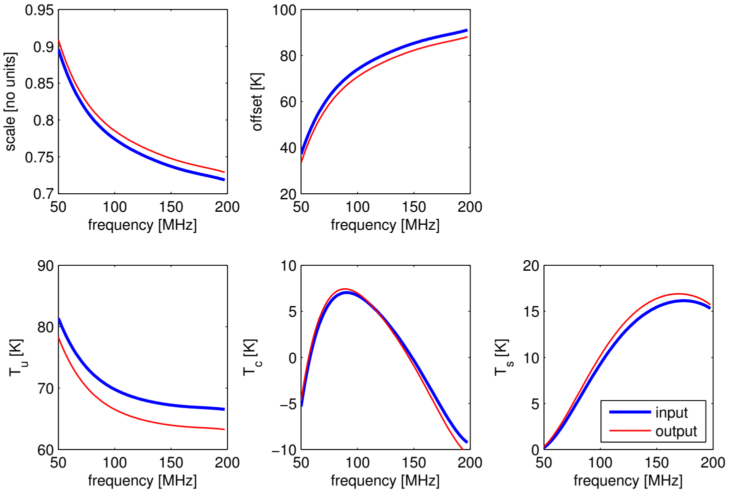

Figure : (7): Effect of error in T_{hot} on the calibration parameters. There are significant differences between inputs and outputs, but the shapes are similar and smooth.

Error in T_{open}

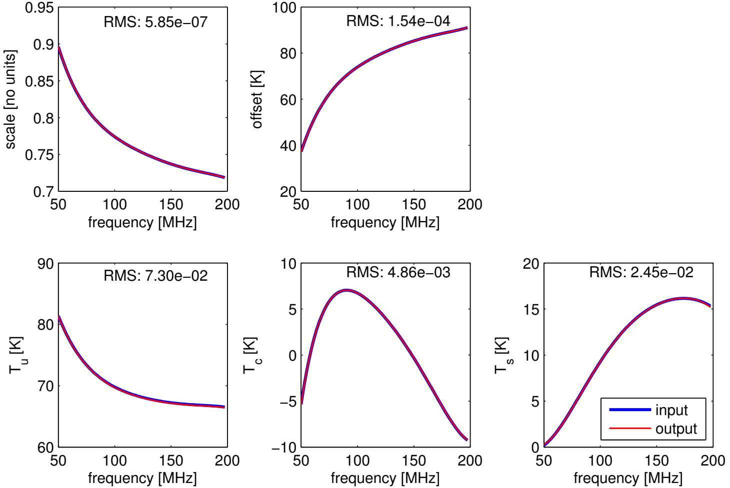

Figure : (8): Effect of error in T_{open} on the calibration parameters. The differences are not obvious. However, for T_u, T_c, and T_s the RMS differences are higher than those due to the limitations of the method alone, which are always lower than 1 mK (see figure 1).

Error in $T_{shorted}$

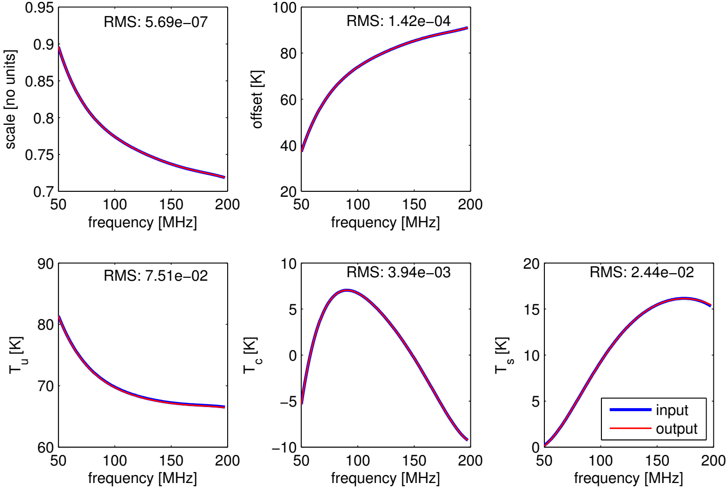

Figure : (9): Effect of error in $T_{shorted}$ on the calibration parameters. The differences are not obvious. However, for T_u, T_c, and T_s the RMS differences are higher than those due to the limitations of the method alone, which are always lower than 1 mK (see figure 1).

Effect on T_{sky}

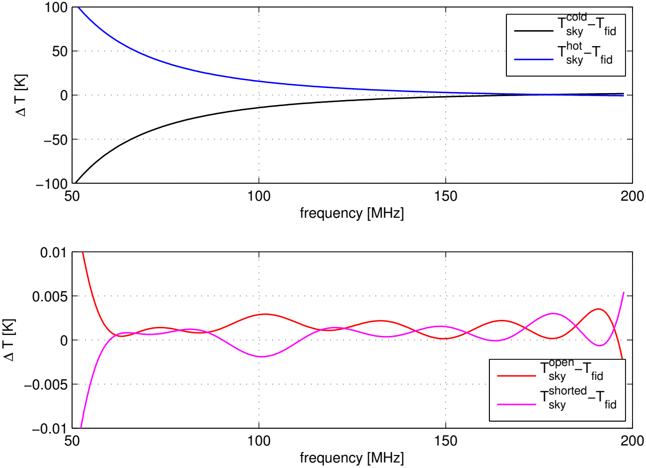

Figure : (10): Effect of error in the reference temperatures, on the recovered sky temperature. The fiducial sky temperature is that shown in the top panel of figure 5, with T_{150}=500 K and β=-2.5. This figure (10) shows a direct subtraction of the fiducial case from those recovered when assuming an error in each of the reference temperatures. For example, T_{sky}^{cold} corresponds to the sky temperature recovered when there is an error in the temperature of the cold load used to obtain the LNA calibration parameters. TOP: errors for the cold and hot loads result in smooth power-law-like residuals. BOTTOM: errors for the open and shorted cable result in ripples at the 2 mK-level on top of a flat baseline.

Effect on Sky Parameters and Residuals

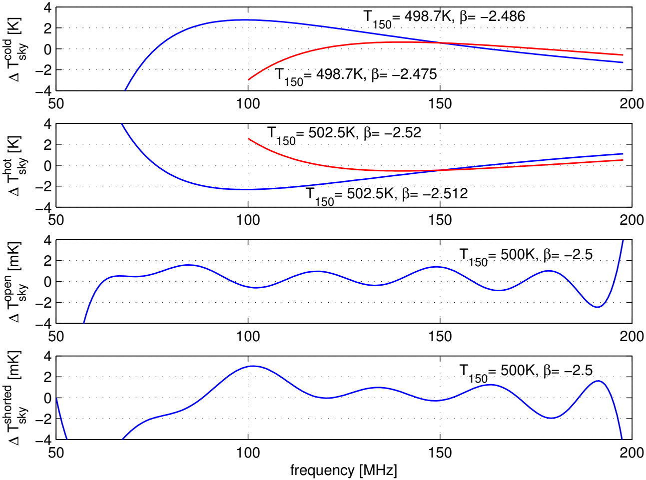

Figure : (11): Residuals after a two-parameter power-law model is fitted and removed from the sky temperature obtained using the *incorrect* calibration parameters. For example, ΔT^{cold}_{sky} is equal to T^{cold}_{sky} - best fit. Errors in the cold and hot load produce large smooth residuals. Blue lines represent fits and residuals in the 50-200 MHz range, while red lines correspond to fits in the 100-200 MHz range. For these two loads, errors in the parameters are of order 2 K and 0.014 for T_{150} and β respectively. Errors in the cable temperatures produce residuals with $\sim$ 2 mK ripples but no errors in the parameters of the power law.

Conclusions PART 2

Incorrect assumptions for the reference temperatures propagate to the LNA calibration parameters, and therefore to the recovered sky temperature. The amplitude and shape of the errors in the sky temperature are qualitatively different between effects from the cold/hot loads, and the cables.

Errors in the cold/hot loads produce errors in the sky temperature which are relatively large and smooth in frequency. This kind of error has the potential to become indistinguishable from the EoR signal, and therefore more exploration is necessary to determine an efficient way of identifying these effects in the data after an accurate removal of the beam effects.

Reasonable errors in the cable temperatures affect the sky temperature at a low level, and with a shape different from that of the EoR. Therefore, this can be considered a second-order effect, and the focus should be placed on the improvement of the cold/hot calibration.