Reflections in long cable calibration source

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Motivation

Murray et al. (2022) reported higher RMS ($\sim 20\sigma$) in the residuals of long cable open and short calibration sources. This memo is an investigation into cause of such high residuals, and to check if they exist in the EDGES-3 data.

As a first order test, six days of recorded calibration data were calibrated using `edges-cal`. This calibration was done with the following settings:

Table 1: Calibration choices

	Parameter	Value set
Int. load model	c terms	7
Noise wave model	w terms	9
Frequency	f_{low}	50 MHz
	f_{high}	190 MHz
Noise temperature of load	T_L	300
Noise temperature of noise	T_{NS}	1000
LNA path correction	Cable Length	4.32 inches
	Cable dielectric	1.64
	Cable loss	90.6%
	Temperature	From logger

Figure 1 shows the temperatures obtained from the temperature logs that are used in calibration. Figure 2 shows the calibration coefficients (scaling and additive factors) for six days of calibration observations. Figures in Section A show the plots of calibrated temperatures of each load. Each day is calibrated with the settings shown in Table 1 (right panels in

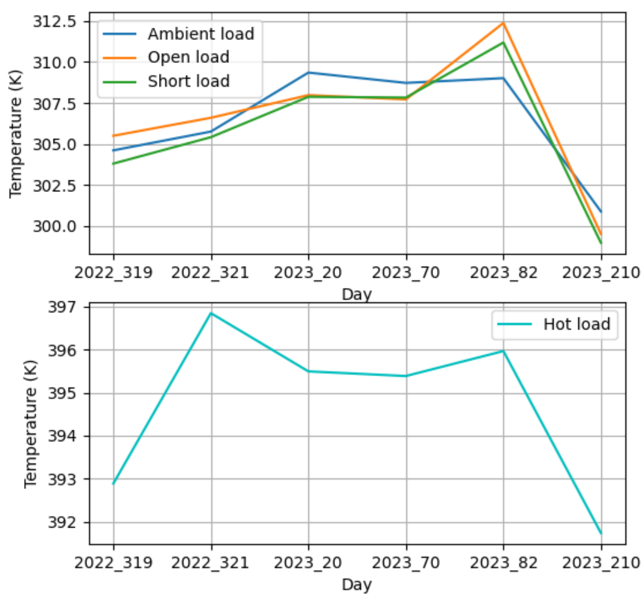


Figure 1: Temperature of calibration loads, obtained by calculating the mean of the temperatures recorded between the timestamps of when the calibration spectra is recorded. Temperatures of `amb, long cable open, long cable short` loads are plotted in the top panel. `hot` load temperature is plotted in the bottom panel.

the plots), and an additional analysis using the calibration choices used from Bowman et al. (2018) (c terms =6, w terms =5, frequency range of 50-100 MHz).

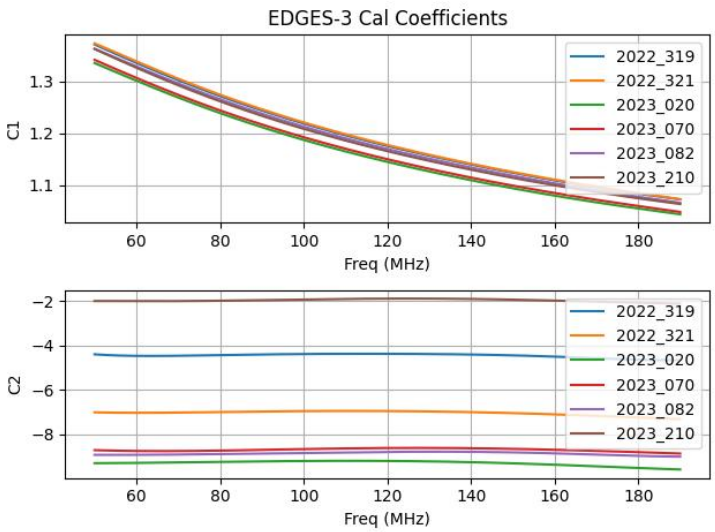


Figure 2: Cal-coefficients for six different days when calibration data was recorded.

It is evident from the different days of calibrated temperatures shown in Figure A that the long cable calibration sources show sinusoidal structures in the residuals, especially at higher frequencies. A smaller frequency cut as the left panel of plots show lower RMS but issue with long cable calibration remains significant in the full frequency range analysis.

This could be due to various reasons currently unknown. A few hypotheses could be:

- Issue in S11 modelling
- Issue in noise-wave formalism used
- Issue in how the two stage LNA is modeled
- Something else...

In this memo, we explore the possibility of error in S11 modeling.

S11 modeling of long cable

MIT EDGES Memo #269 elaborates on the cable tests performed in the lab. It is reported that a 10 ft SiO2 cable gives a loss of 0.6dB and two-way delay of 24 ns. This corresponds to about 15% loss in speed of light relative to free space. This is comparable to the 87% velocity propagation value reported in the WM10479-nd data sheet. Ideally, computing the power spectrum (Fourier transform) of long cable S11 should let us retrieve a delay of 24 ns. We employ the following analysis to calculate the delay:

- Multiply the S11 with a Blackman-Harris window, independently for real and imaginary part of S11
- Subtract the mean
- Compute FFT
- Identify the FFT peak that corresponds to the cable delay

We repeat this analysis for a few different cases to identify the potential issue in the modelling. First, we compute power spectrum of raw S11. We then repeat this analysis for the modelled S11, at the same spectral resolution as raw S11 and at a spectral resolution identical to the recorded spectra. Corresponding results are shown in Figures 3, 4 and 5.

Raw S11:
The Fourier analysis of raw S11 shows one dominant peak at 24 ns, and a few sub-dominant delays due to reflections. This is as expected, indicating a two-way cable length of 20.6 ft. The second peak corresponds to reflections with two-way cable length of 25.8 ft. Refer Figure 3 for plots.

Modeled S11, at the spectral resolution of raw S11:
The Fourier analysis of modeled S11 at the spectral resolution of raw S11 performs identical to the raw S11 case, with a dominant peak at 24 ns, indicating a two-way cable length of 20.6 ft. Refer Figure 4.

Modeled S11, at the spectral resolution of spectra:
The Fourier analysis of the modeled S11 at the spectral resolution of spectra (which is used in the calibration pipeline) shows slightly different results. The peak is at a delay of 28.5 ns corresponding to two-way cable length of 23.8 ft. Refer Figure 5.

Alan's Modeled S11: The Fourier analysis of Alan's modeled S11 shows a peak at the delay of 28.5 ns, corresponding to two-way cable delay of 23.8 ft. Refer Figure 6.

This indicates that the interpolation function that lets us change the spectral resolution of S11 model could be one of the issues of how we are handling the S11. Additional tests were performed to compare the S11 models obtained from `edges-cal` with those from Alan's pipeline (refer LoCo EDGES Memo #203 for details). Currently, the differences in modeled S11 between the two pipelines remain at the level of 10^{-4} for long cable calibration sources.

Note on delay analysis in S11 modeling:
As detailed in Memo #203, S11 is modeled using the delay corresponding to the dominant sin wave. This involves finding the delay corresponding to the dominant sin wave and subtracting it from the raw S11. The residual is then fit with the chosen model, and the delay corresponding to the dominant sin wave is added back to obtain the S11 model. A similar Fourier analysis as described in this memo was performed on the S11 model obtained each with and without the delay subtraction. No noticeable differences were seen in these two cases.

Effects of differences in modeled S11 on cal coefficients
From Memo #203, the differences in cal-coefficients still remain significant (order of 10^{-3} to 10^{-2}). To test if these could be due to differences in modeled S11s between the two pipelines, we do an injection test. We take modeled S11s from Alan's pipeline and overlay them on `CalibrationObservation` object in `edges-cal`. This makes sure that the modeled S11s used in both the pipelines are identical. Recalculating calibration coefficients should quantify the effects of differences in modeled S11s on calibration. Figure 7 shows the differences in modeled S11s after injection and Figure 8 shows corresponding differences in cal-coefficients. This test shows that differences in modeled S11s of long cables at the order of 10^{-4} are not sensitive to cal-coefficients.

Conclusion

General calibration outputs from all six days of recorded calibration observations are shown in this memo. An attempt to narrow down issues with the structures in long cable calibration sources is shown, in particular issues involving S11 modeling. Raw S11 and the S11 model at the original spectral resolution of raw S11 show identical results in Fourier domain, retrieving a delay of 24 ns corresponding to two-way cable length of ∼20 ft. However, when the S11 model is interpolated at a different frequency resolution (such as the resolution of the spectra), the model fails to retrieve the expected delay in the Fourier domain. We note that there are still differences in modeled S11 obtained from `edges-cal` and Alan's pipeline (order of $\sim 10^{-4}$), however these differences are not the cause of issues in differences in calibration solutions. Further investigation is needed to narrow down the issues about structures in long cable S11s.

References

Bowman J. D., Rogers A. E., Monsalve R. A., Mozdzen T. J., Mahesh N., 2018, Nature, 555, 67

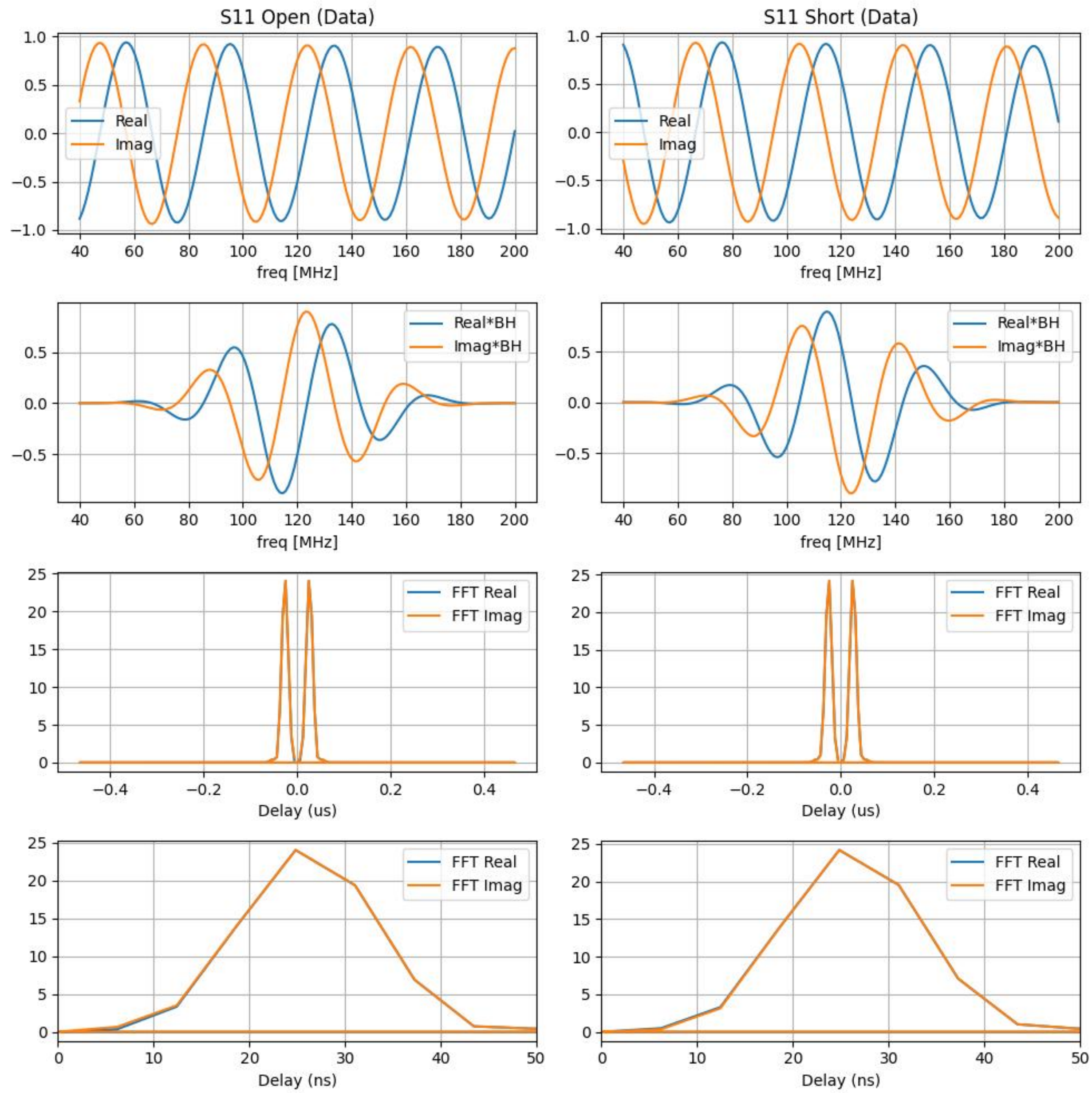


Figure 3: Cable delay analysis of raw S11 data. Left panels show the `open` load, and right panels show the `short` load. (Row-1): Raw S11 real and imaginary. (Row-2): Raw S11 multiplied by Blackman-Harris window. (Row-3): FFT of Row-2. (Row-4): Zoomed-in window of Row-3

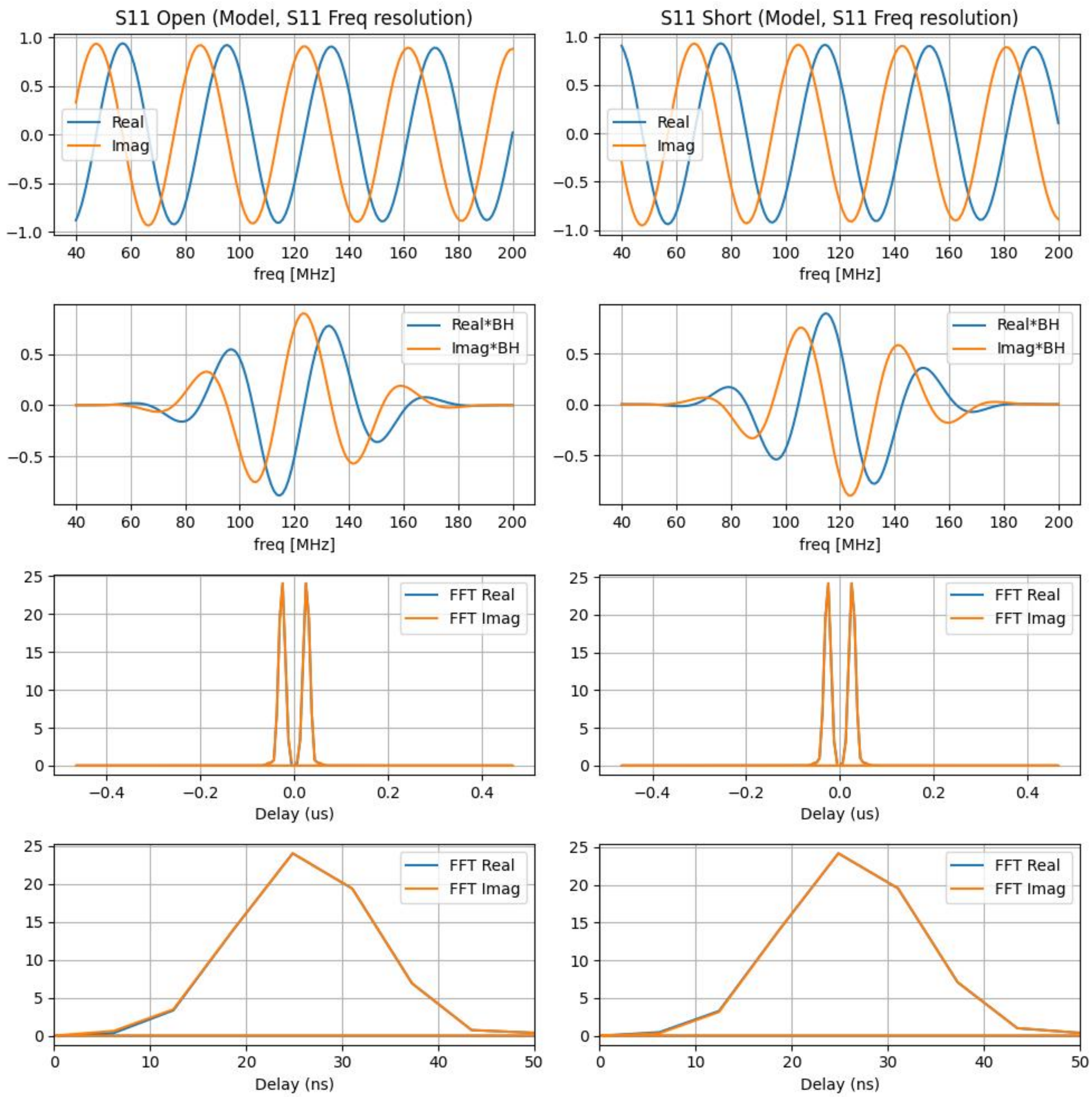


Figure 4: Cable delay analysis of S11 model, at the spectral resolution of raw S11. Left panels show the `open` load, and right panels show the `short` load. (Row-1): Modeled S11 real and imaginary. (Row-2): Modeled S11 multiplied by Blackman-Harris window. (Row-3): FFT of Row-2. (Row-4): Zoomed-in window of Row-3

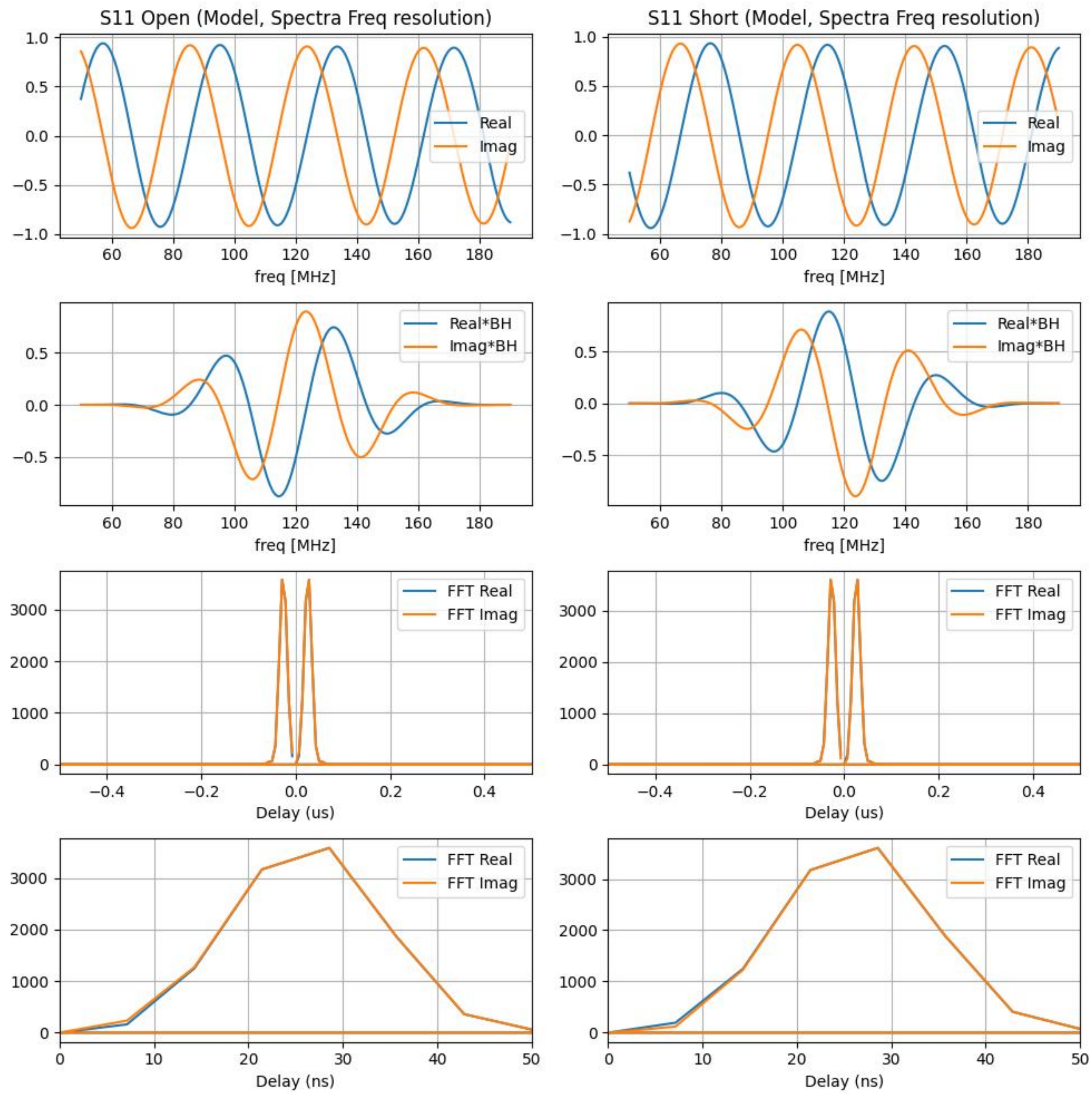


Figure 5: Cable delay analysis of S11 model, at the spectral resolution of spectra. Left panels show the `open` load, and right panels show the `short` load. (Row-1): Modeled S11 real and imaginary. (Row-2): Modeled S11 multiplied by Blackman-Harris window. (Row-3): FFT of Row-2. (Row-4): Zoomed-in window of Row-3

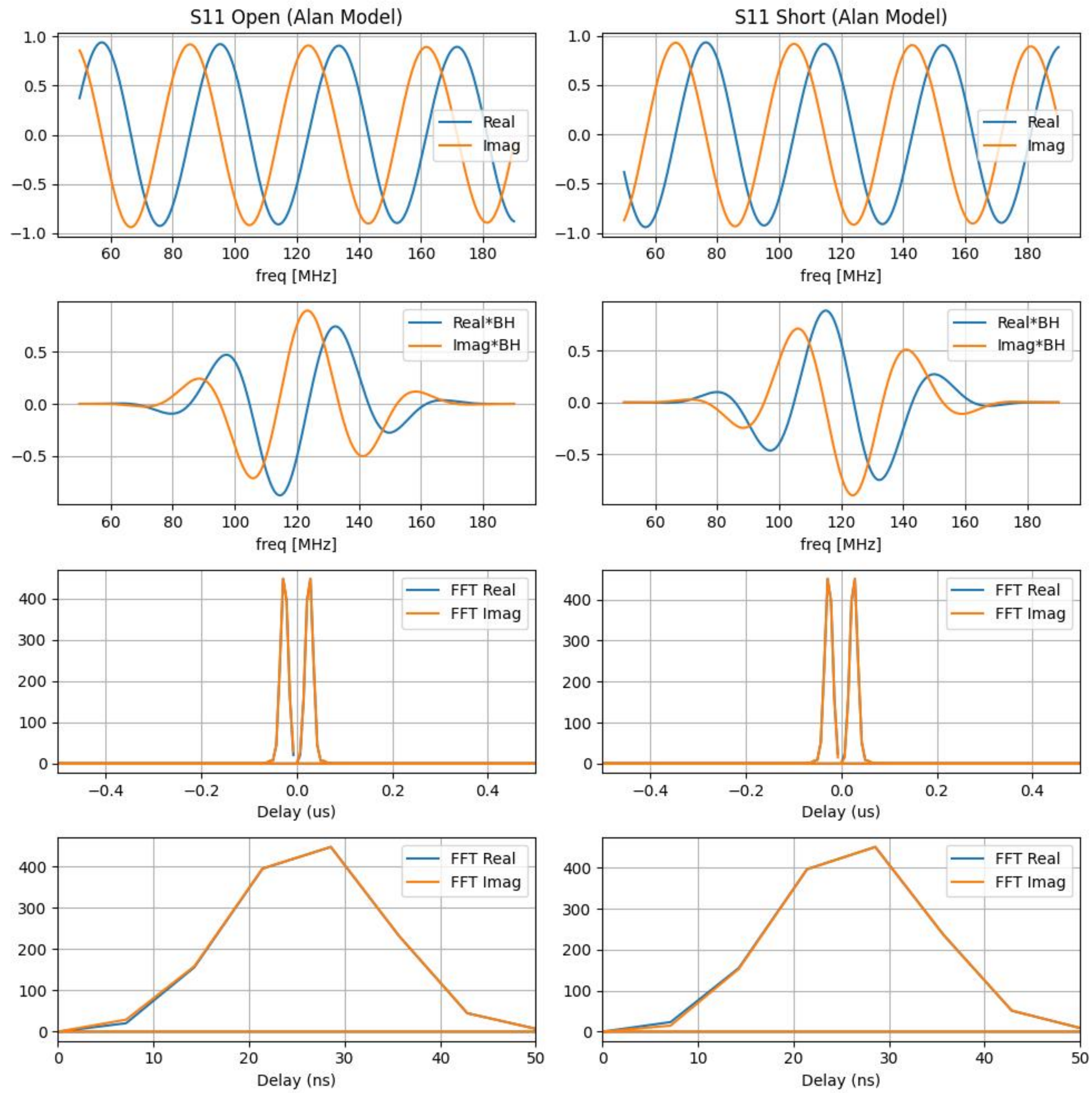


Figure 6: Cable delay analysis of Alan's S11 model. Left panels show the `open` load, and right panels show the `short` load. (Row-1): Modeled S11 real and imaginary. (Row-2): Modeled S11 multiplied by Blackman-Harris window. (Row-3): FFT of Row-2. (Row-4): Zoomed-in window of Row-3

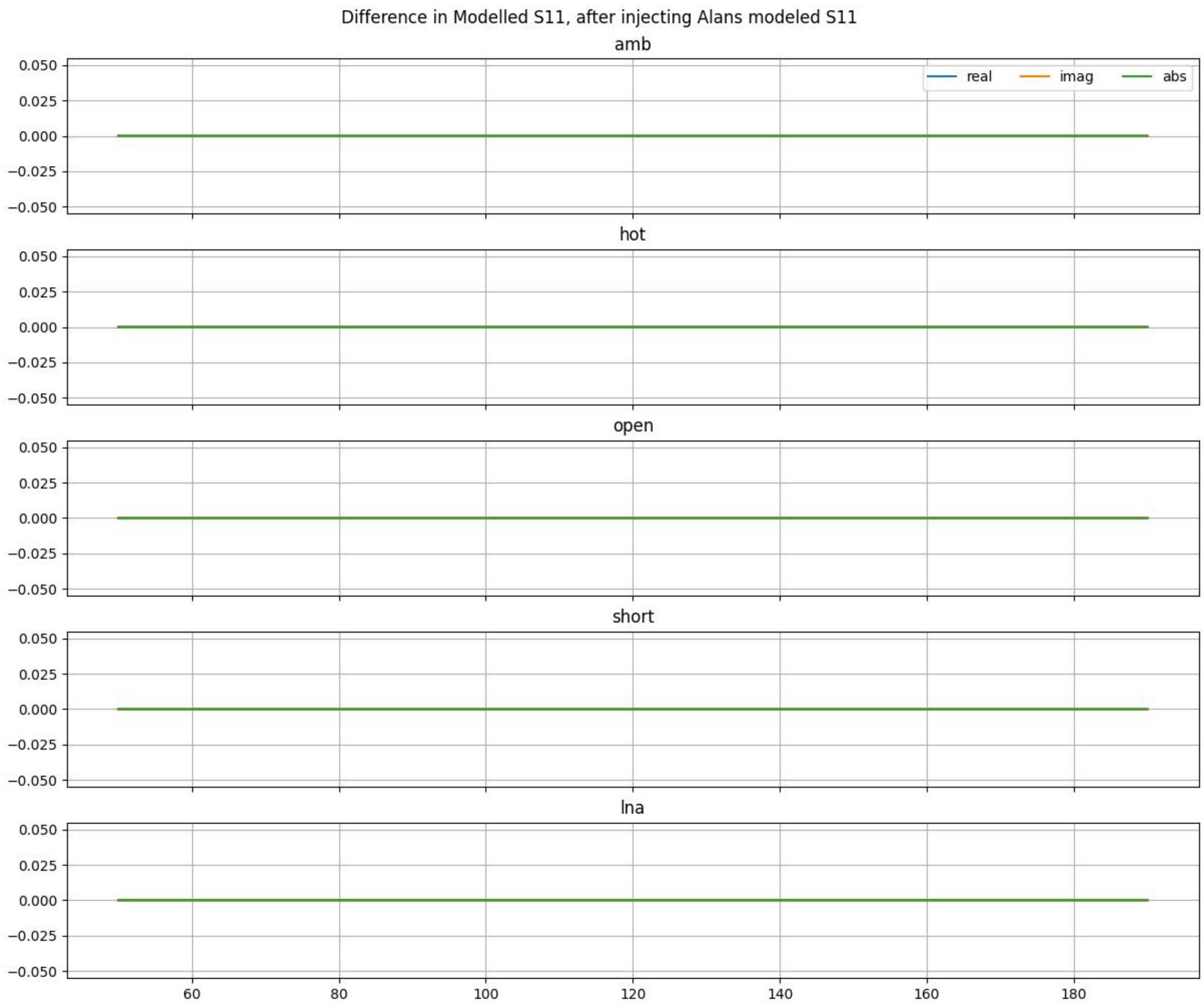


Figure 7: Differences in modeled S11s after injecting Alan's modeled S11s. This is overlaying on the `edges-cal` modeled S11s.

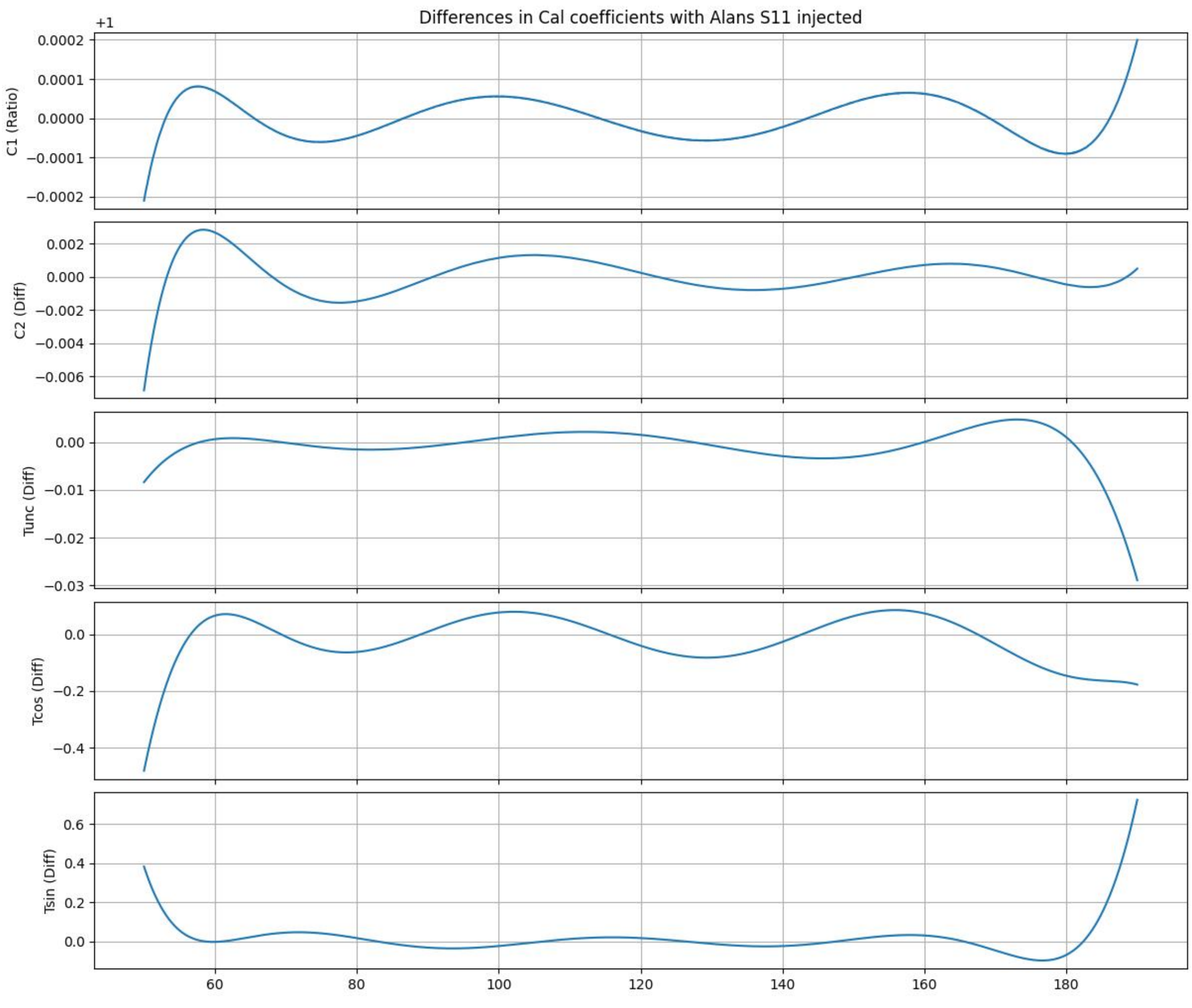


Figure 8: Differences in cal-coefficients between Alan's code and `edges-cal` after injecting modeled S11s. This shows that calibration is not sensitive to differences in modeled S11s shown in Memo #203.

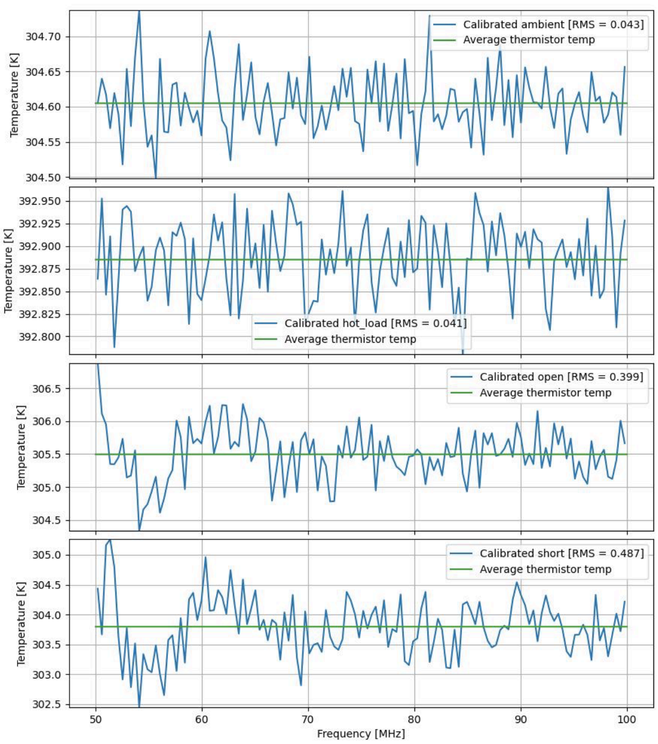
Murray S. G., Bowman J. D., Sims P. H., Mahesh N., Rogers A. E., Monsalve R. A., Samson T., Vydula A. K., 2022, Monthly Notices of the Royal Astronomical Society, 517, 2264

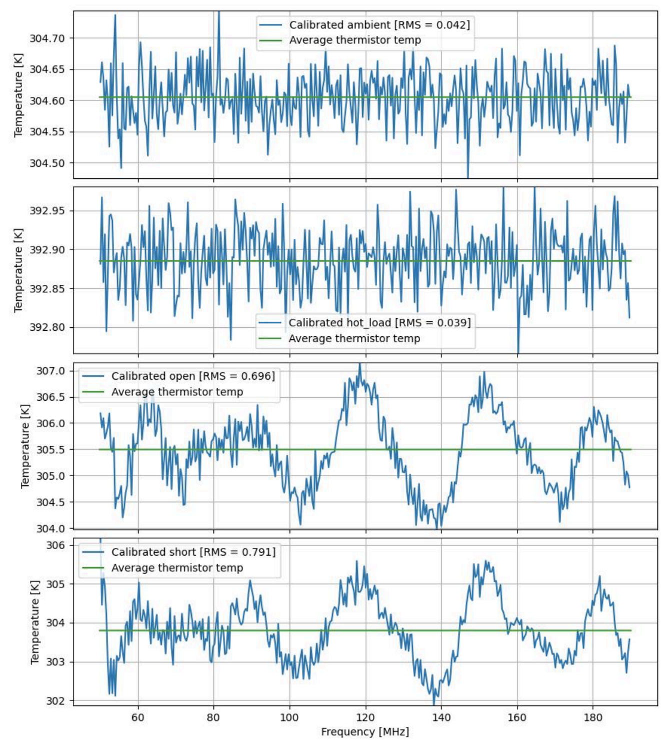
A Calibrated temperatures of each load for six days of calibration observations.

All days: edges-2 settings:
cterms=6, wterms=5, frequency range: 50-100 MHz

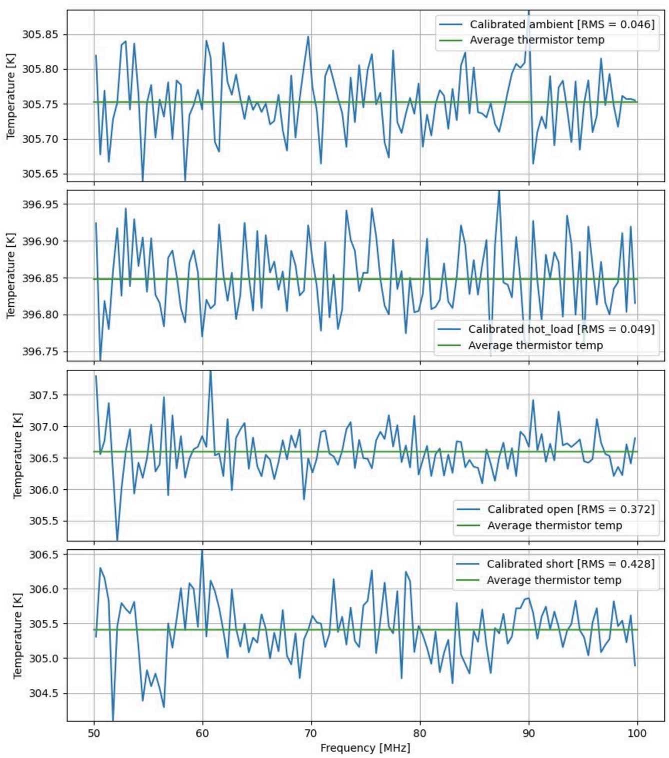
New settings: cterms=7, wterms=9, freq: 50-190 MHz

Day: 2022_319

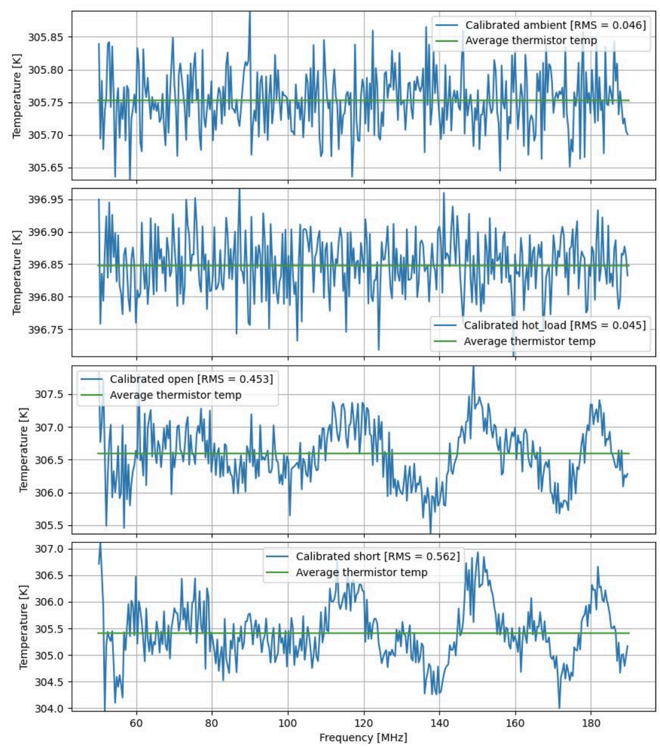




Day: 2022_321

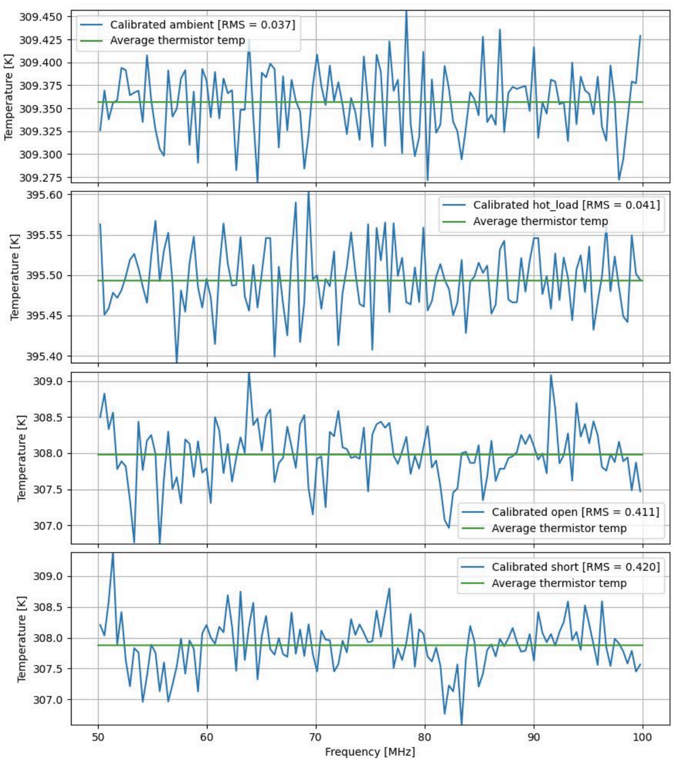


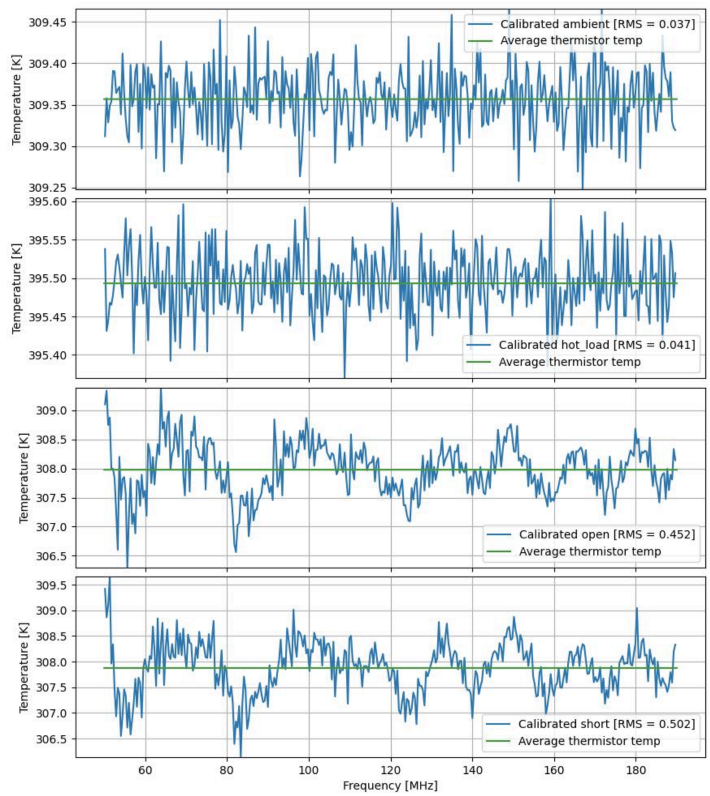
Calibrated ambient [RMS = 0.046]
Average thermistor temp
Calibrated hot_load [RMS = 0.049]
Average thermistor temp
Calibrated open [RMS = 0.372]
Average thermistor temp
Calibrated short [RMS = 0.428]
Average thermistor temp
Temperature [K]
Frequency [MHz]



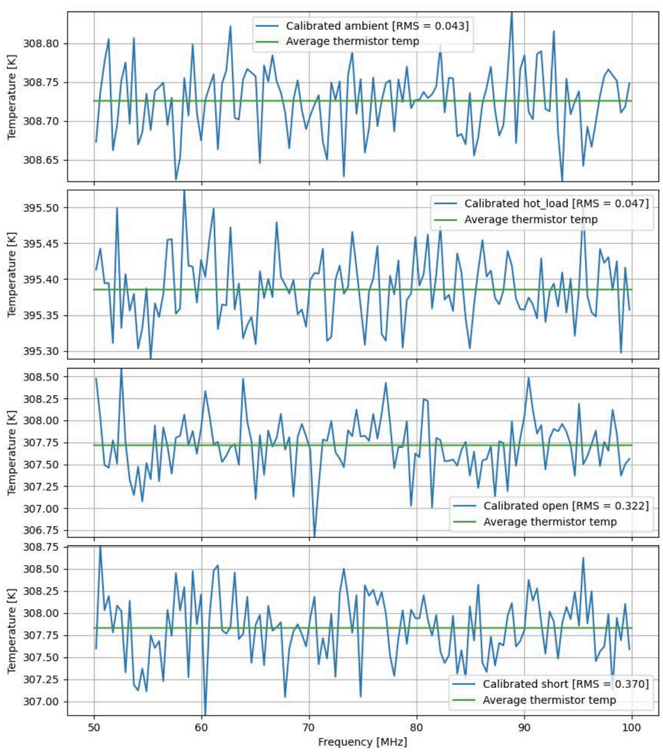
Calibrated ambient [RMS = 0.046]
Average thermistor temp
Calibrated hot_load [RMS = 0.045]
Average thermistor temp
Calibrated open [RMS = 0.453]
Average thermistor temp
Calibrated short [RMS = 0.562]
Average thermistor temp
Temperature [K]
Frequency [MHz]

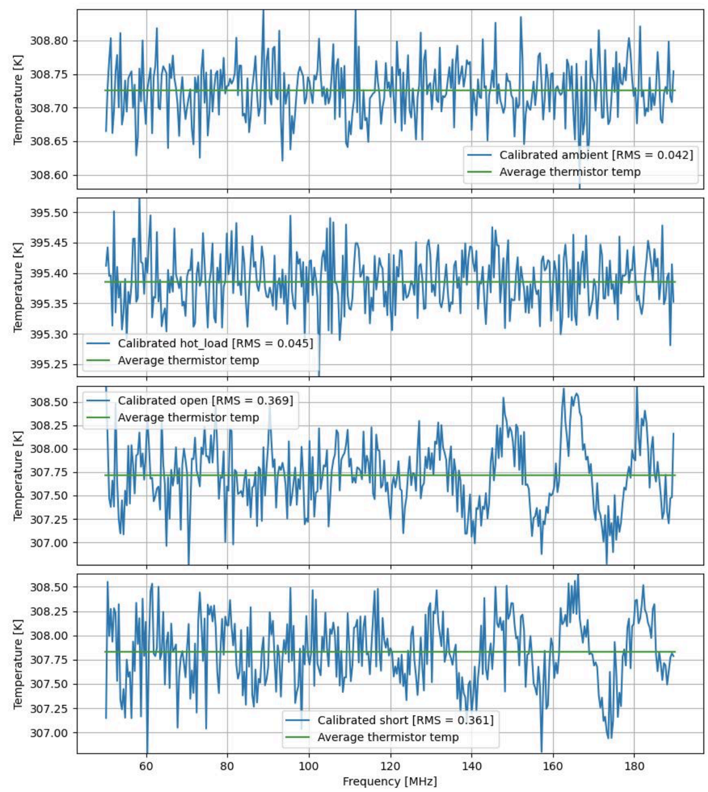
Day 2023_020


Calibrated ambient [RMS = 0.037]
Average thermistor temp
Calibrated hot_load [RMS = 0.041]
Average thermistor temp
Calibrated open [RMS = 0.411]
Average thermistor temp
Calibrated short [RMS = 0.420]
Average thermistor temp
Temperature [K]
Frequency [MHz]

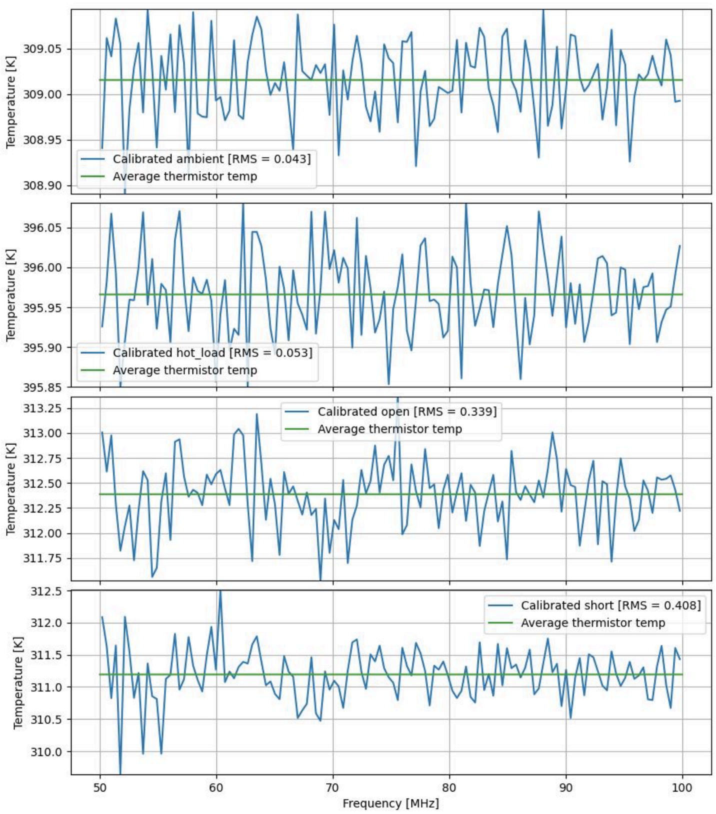

Calibrated ambient [RMS = 0.037]
Average thermistor temp
Calibrated hot_load [RMS = 0.041]
Average thermistor temp
Calibrated open [RMS = 0.452]
Average thermistor temp
Calibrated short [RMS = 0.502]
Average thermistor temp
Temperature [K]
Frequency [MHz]

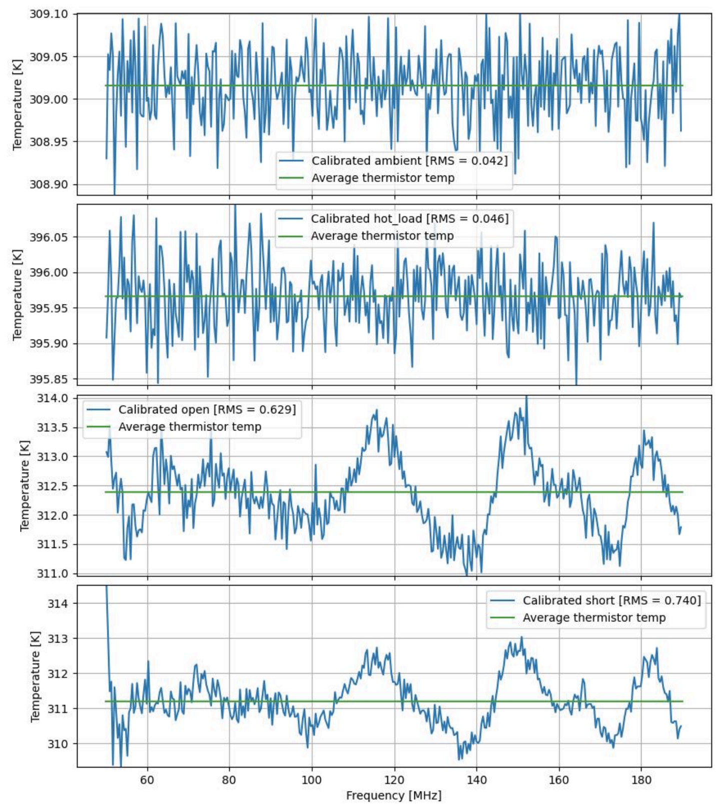
Day 2023_070:


Calibrated ambient [RMS = 0.043]
Average thermistor temp
Calibrated hot_load [RMS = 0.047]
Average thermistor temp
Calibrated open [RMS = 0.322]
Average thermistor temp
Calibrated short [RMS = 0.370]
Average thermistor temp
Temperature [K]
Frequency [MHz]


Calibrated ambient [RMS = 0.042]
Average thermistor temp
Calibrated hot_load [RMS = 0.045]
Average thermistor temp
Calibrated open [RMS = 0.369]
Average thermistor temp
Calibrated short [RMS = 0.361]
Average thermistor temp
Temperature [K]
Frequency [MHz]

Day 2023_082:


Calibrated ambient [RMS = 0.043]
Average thermistor temp
Calibrated hot_load [RMS = 0.053]
Average thermistor temp
Calibrated open [RMS = 0.339]
Average thermistor temp
Calibrated short [RMS = 0.408]
Average thermistor temp
Temperature [K]
Frequency [MHz]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Average thermistor temp
Calibrated hot_load [RMS = 0.046]
Average thermistor temp
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Average thermistor temp
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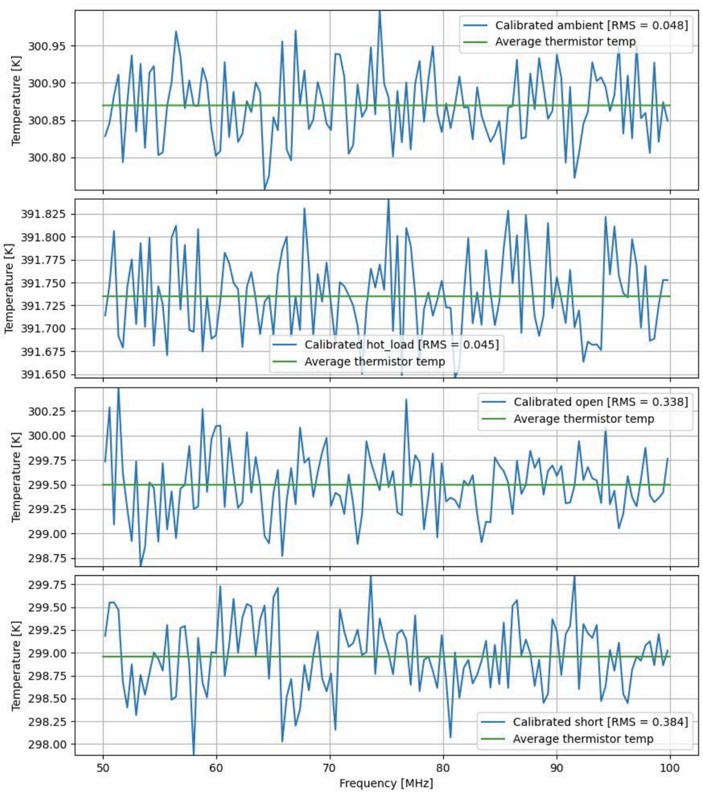
Average thermistor temp
Temperature [K]
Frequency [MHz]

Day 2023_210: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Average thermistor temp
Calibrated hot_load [RMS = 0.045]
Average thermistor temp
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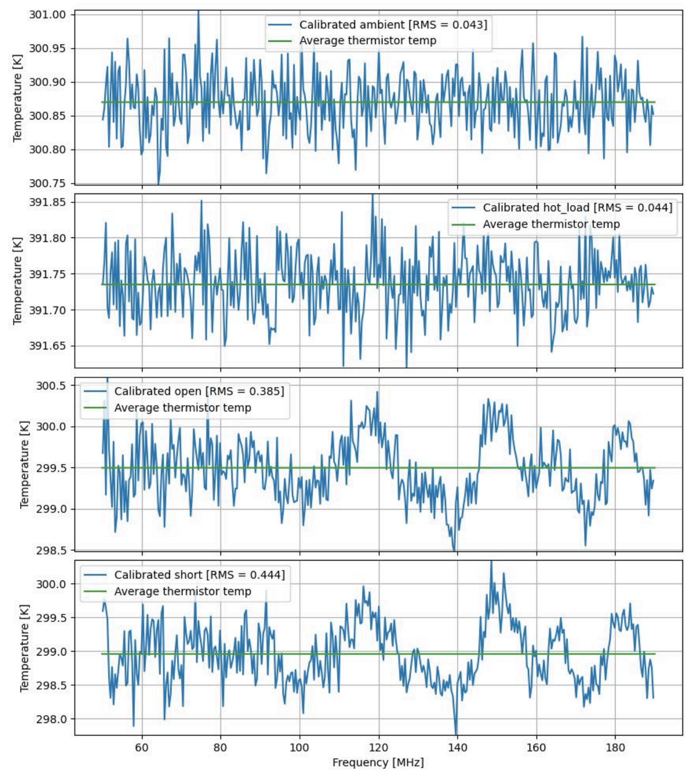
Average thermistor temp
Calibrated short [RMS = 0.384]
Average thermistor temp
Temperature [K]
Frequency [MHz]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Average thermistor temp
Calibrated hot_load [RMS = 0.044]
Average thermistor temp
Calibrated open [RMS = 0.385]
Average thermistor temp
Calibrated short [RMS = 0.444]
Average thermistor temp
Temperature [K]
Frequency [MHz]