Study of Antenna S11 Variability in EDGES-3

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Introduction

EDGES-3 began operating in November 2022 and has been observing since then. The antenna S11 measurements are done periodically at a cadence of ∼37 hr, with a total of 227 measurements. The EDGES-3 observations are summarized in 1. This memo investigates daily antenna S11 variations, modeling errors and effects of the variations on the using a simulated sky signal.

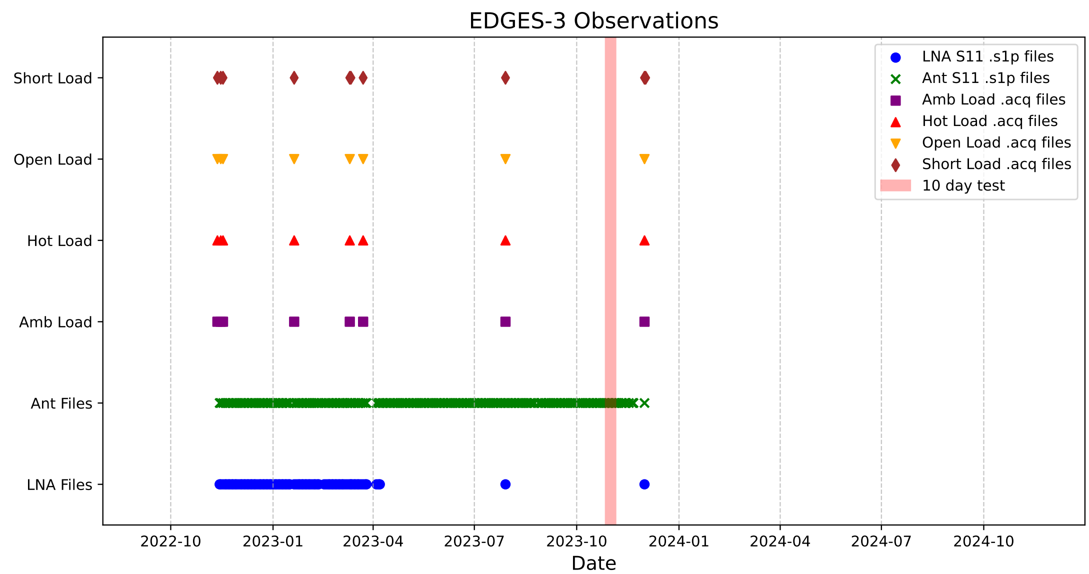

Figure 1: EDGES-3 observations since it began operating in Nov 2022. There are 227 antenna S11 measurements, 6 calibration measurements and 87 LNA S11 measurements. The 10 days used in validation tests discussed in previous memos is also highlighted.

Modeling in Antenna S11

Antenna S11 are modeled using a 12 term polynomial that fits the real and imaginary parts of the measured S11 (not magnitude and phase). The frequency is transformed on a logarithmic scale. To test the accuracy of the fits, residuals between the raw antenna S11 and the model is calculated (in linear units), which was found to be of the order of 10^{-5}, as shown in Figure 2.

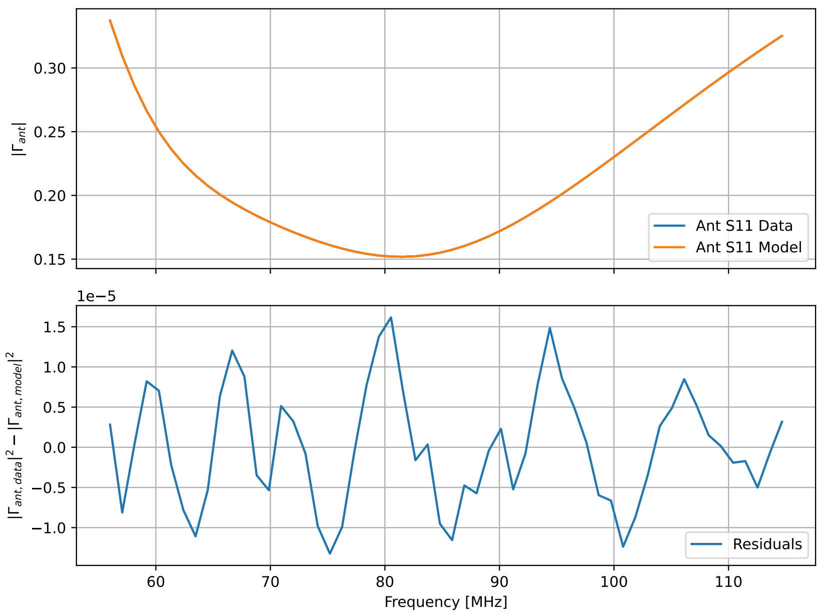

Figure 2: The measured antenna S11, model and the corresponding model residuals for a randomly chosen day of 2023_117.

Daily variations and data cuts

To study the daily variations in antenna S11, we choose a reference day and calculate the differences relative to the reference day. Most days show a variations of ±1dB relative to a randomly chosen reference day of 2023_070, with some crossing over 30dB, which can be attributed to to rain and/or solar activity. The magnitude variations are shown in Figure 3, and the phase variations are shown in 4.

A slice of the magnitude of antenna S11 at 75 MHz relative to day 2023_70 when plotted along with the measured thermal-controlled ambient temperature (Figure 5), shows a correlation of $|\Gamma_{ant}|$ with the T_{amb}. We note that, although thermal control is set-up to maintain a stable T_{amb}, due to large diurnal temperature fluctuations on-site, the set-up is inefficacious, especially in the Australian summer. Thus the set temperature is increased to 35° C in the summer instead of the desired 30° C throughout the year. Further, it is reported in

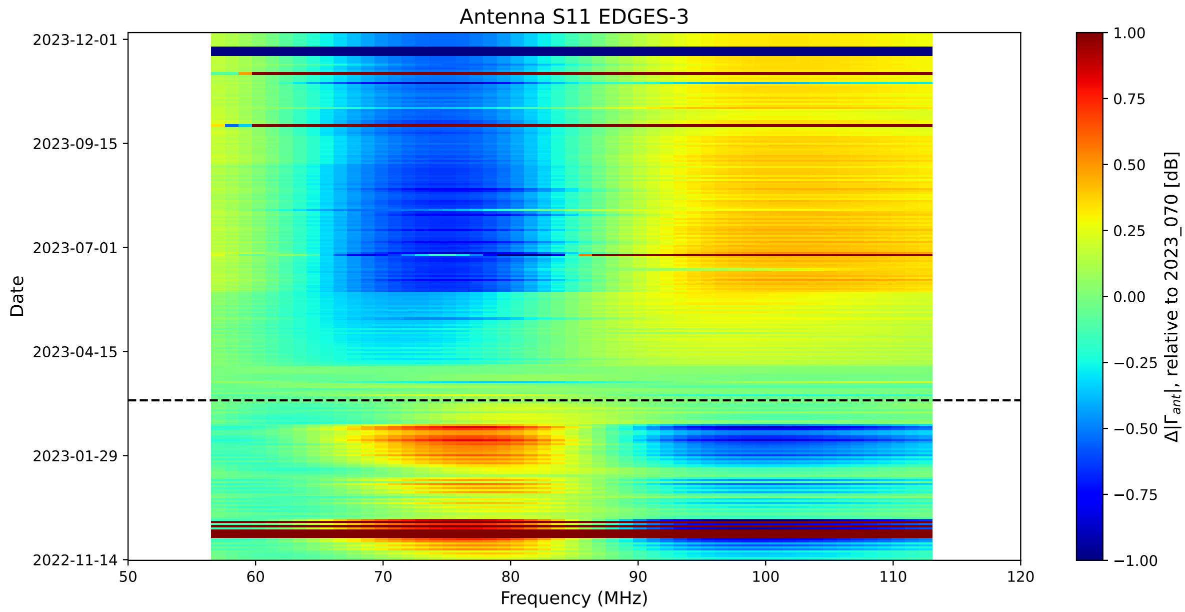

Figure 3: Daily variations in antenna S11 Measurements, relative to day 2023_070.

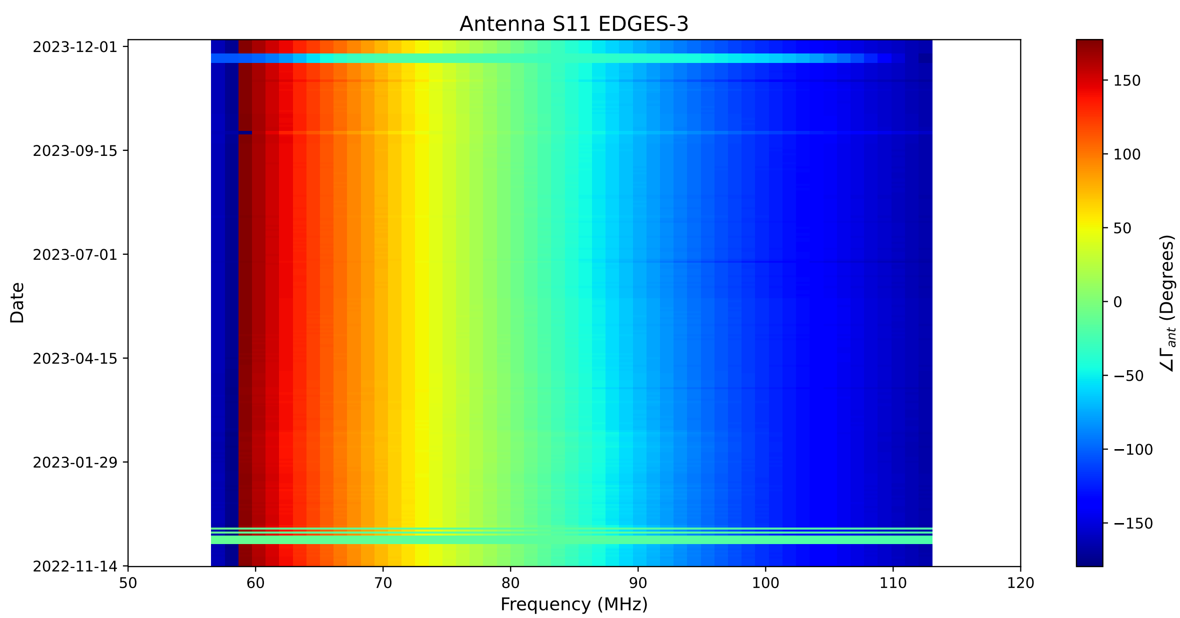

Figure 4: Daily variations in phase of antenna S11 measurements.

MIT Memo 412 that changing the VNA measurement scheme is necessary to maintain the accuracy in the absence of a reliable thermal control system. The details of the suggested change is laid out in MIT Memo 411, but mentioned here for brevity.

Original VNA measurement scheme: 400 VNA scans on each of amb hot ant open short S O L and then 400 VNA scans on each of lna S O L for a total of 12x400 = 4800 scans.

Updated VNA measurement scheme that maintains accuracy in the presence of temperature fluctuations: 5 VNA scans on each x S O L for x= amb,hot,ant,open,short calculates the calibrated for each and repeats 40 times and then averages calibrated results and then repeats LNA calibration of 5 VNA scans on LNA S O L 40 times to obtain the average for a total of 40x4x6x5 = 4800 scans.

This results in a lower error in measurements owing to shorter time difference between consecutive calibration load measurements, resulting in a factor of 10 improvement.

The suggested change in scheme is as follows: the averaging of VNA measurements is deemed necessary to reduce the effects of the large temperature fluctuations. shows that the VNA averaging was increased in March 2023, after which the antenna S11 measurements are more reliable and less noisy. This new scheme was implemented on March 9th 2023 (2023_068), which explains the drift in antenna S11 measurements in Figure 5, shown as the blue curve.

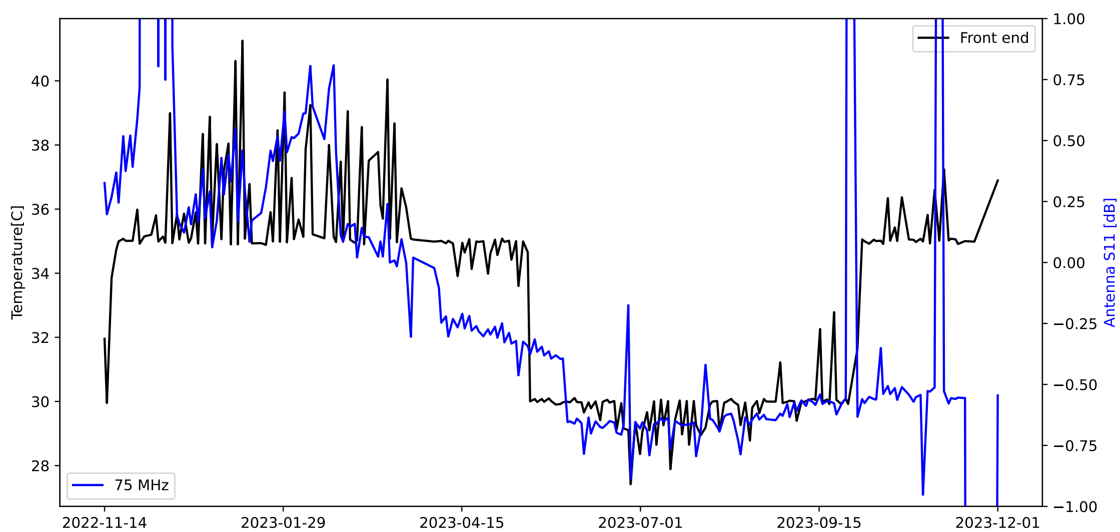

Figure 5: Daily variations in antenna S11 measurements at 75 MHz, relative to day 2023_70 plotted alongside the thermal-controlled measured ambient temperature.

To maintain data quality in the EDGES-3 science analysis, only the days with stable and reliable antenna s11 measurements should be selected. To achieve this, a night time cut is also applied that selects days when antenna S11 was measured between 23:00 and 07:00 local time. This results in 40 days of usable antenna s11 measurements. The temperature and antenna S11 at 75 MHz for the selected days is shown in Figure 6, and the daily variations relative to randomly chosen day 2023_266 are shown in Figure 7.

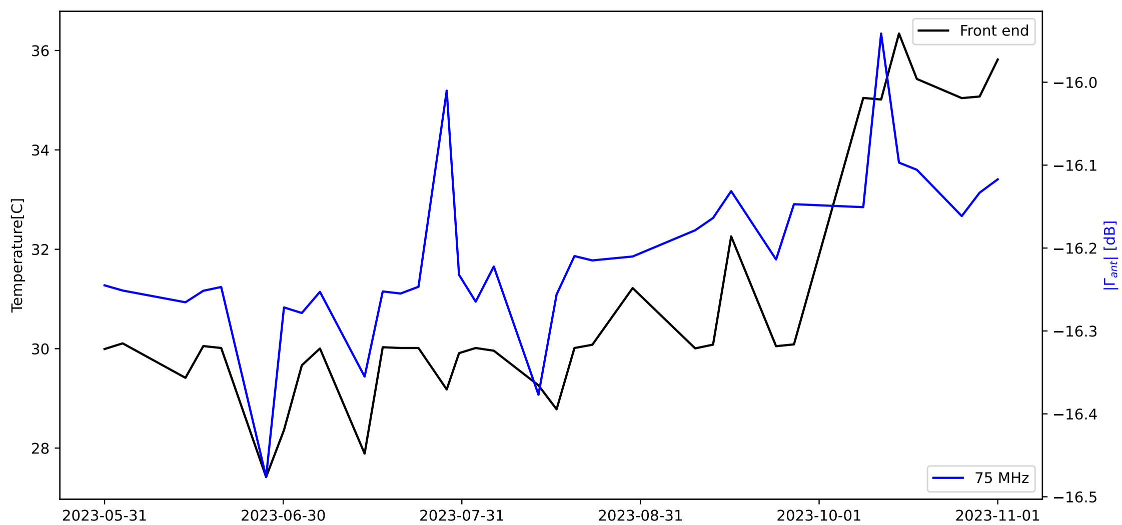

Figure 6: Daily variations in antenna S11 measurements at 75 MHz plotted alongside the thermal-controlled measured ambient temperature for measurements after the implementation of updated VNA scheme and only using night time measurements (2300 to 0700 local time). A total of 40 days are selected out of 227 measurements.

Frequency cuts

For the analysis of the global 21cm signal detection, a frequency selection is necessary. One agnostic way of doing the frequency cut is using antenna S11. For this, we choose a nominal -10 dB as the cut off in order to maintain good data quality. The magnitude and phase of antenna S11 is shown in Figure 8. This results in a usable frequency range of 57-114 MHz. For the science analysis, this frequency range will be used.

Simulated sky signal test

The biggest differences after the night time cut is about ±0.3 dB, and Figure 7 shows that these differences change with frequency. To quantify these effects on the sky signal, we employ an 'uncal-recal' test using simulated sky spectra. This test is described in LoCo EDGES Memo 206, but described here for brevity:

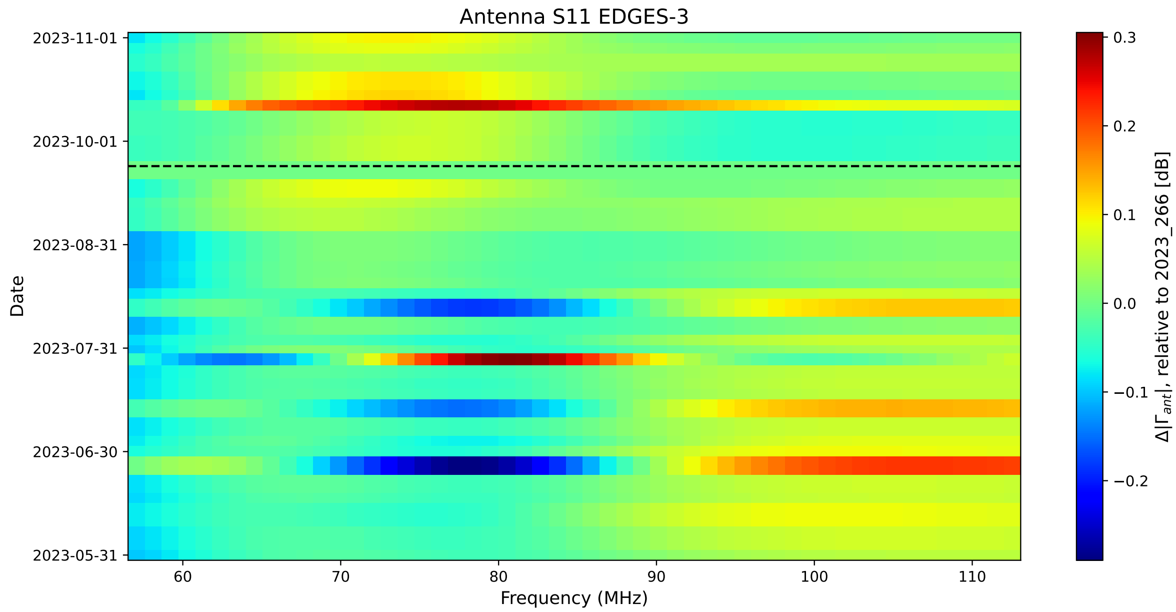

Figure 7: Daily variations in antenna S11 Measurements, relative to a randomly chosen day 2023_266.

1. Simulate a sky signal using a simple power law with fixed spectral index (in this test, $\beta = -2.55$, $T_{100} = 1110$ K)

2. Remove the calibration from the sky signal using calibration coefficients and antenna S11 from a chosen random day. This is somewhat un-intuitive, as such we are treating the simulated sky signal to be analogous to a measured sky signal. Thus the term 'removing calibration' is a misnomer in this context.

3. Apply the calibration using the same cal-coefficients as the previous step and antenna S11 from each measurement.

4. a difference between the obtained sky signal relative to the input simulated sky signal will show the level of error in antenna S11. Further, a difference between the obtained signal relative to the signal from the chosen reference day will quantify the effects of antenna S11 on the sky signal.

The results are shown in Figure 9.

The highest differences are noted to be ∼5 K for Γ_{ant} variations of ±0.3 dB at the level of ∼-16 dB. This can be quantified using the equation 7 of Monsalve et al. [2017].

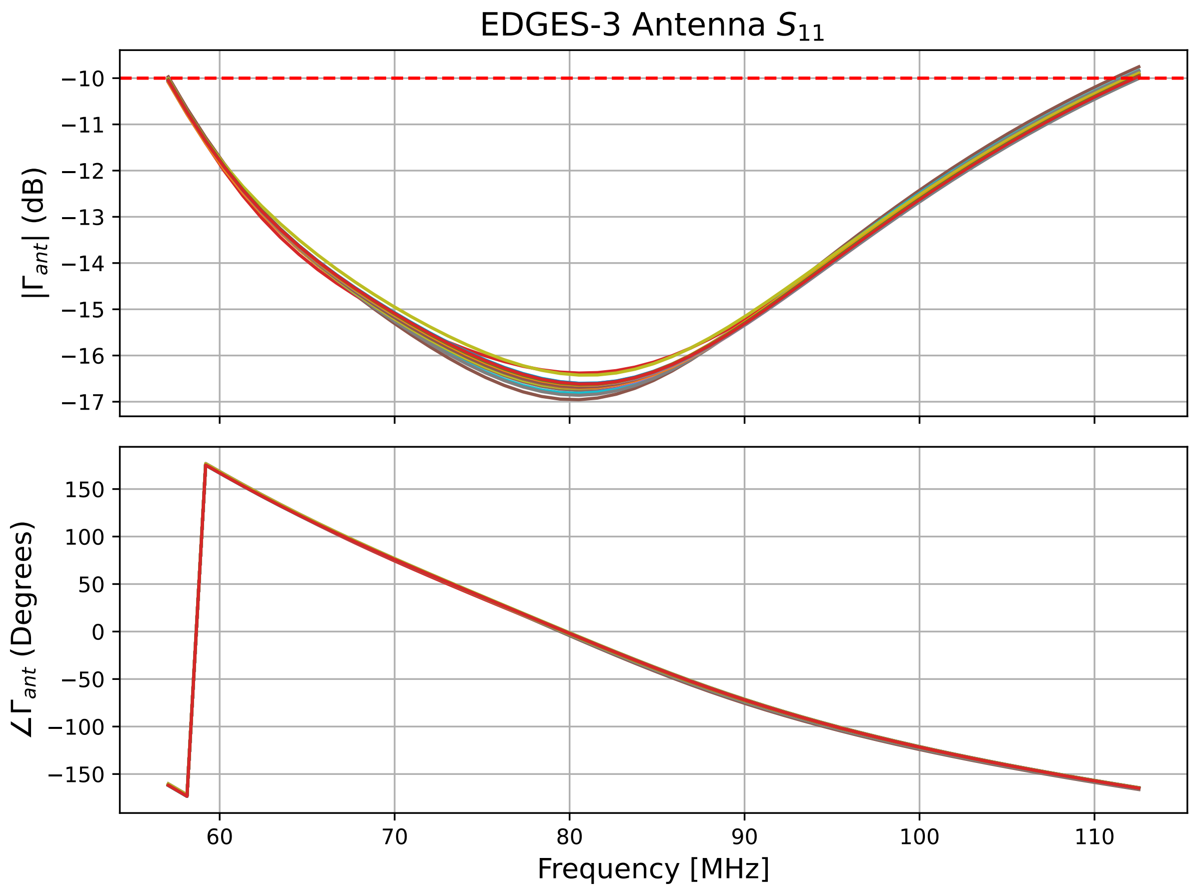

Figure 8: Magnitude and phase of the antenna S11. Frequency range based on -10 dB cut off results in 57-114 MHz, which will be used in the science analysis.

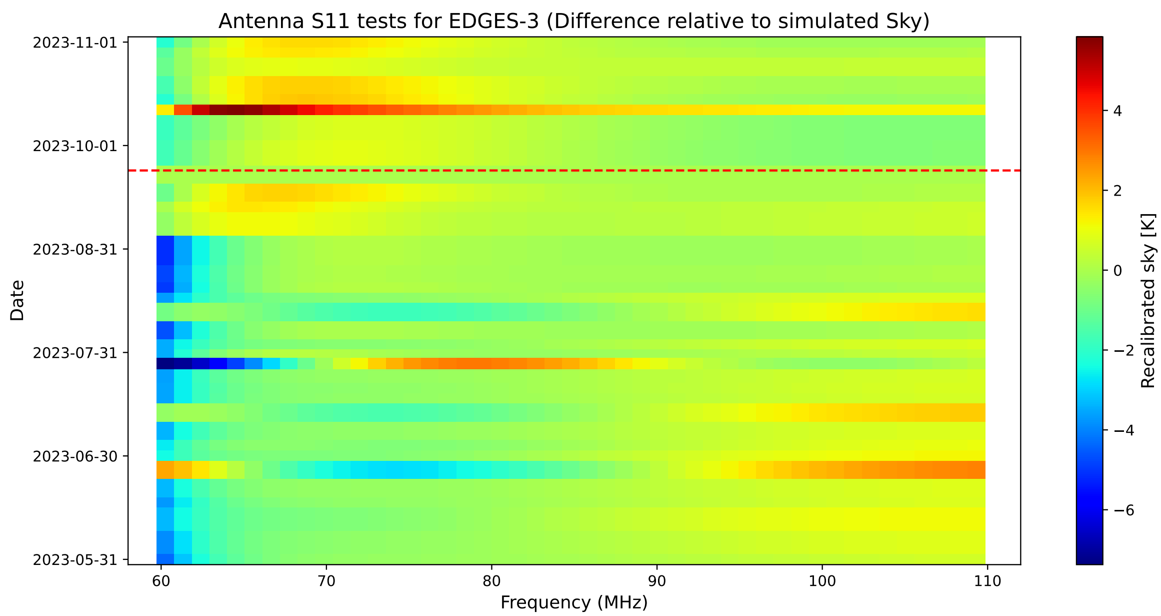

Figure 9: Results of simulated sky signal test. Differences of the obtained signal and the simulated sky signal are plotted relative to a randomly chosen day 2023_266. This ensures the only the only variable in each measurement is antenna S11, allowing quantification of effects of antenna S11 on the sky signal. Note that in this test, the differences relative to the simulated sky are identical to differences relative to day 2023_266.

$$(T^*_{ant} - T_L)C_1 + (T_L - C_2) = T_{ant}\left[\frac{(1-|\Gamma_{ant}|^2)|F|^2}{1-|\Gamma_{rec}|^2}\right] + T_{unc}\left[\frac{|\Gamma_{ant}|^2|F|^2}{1-|\Gamma_{rec}|^2}\right] + T_{cos}\left[\frac{(|\Gamma_{ant}||F|}{1-|\Gamma_{rec}|^2}\cos\alpha\right] + T_{sin}\left[\frac{(|\Gamma_{ant}||F|}{1-|\Gamma_{rec}|^2}\sin\alpha\right] \quad (1)$$

where T^*_{ant} is three-position switch corrected antenna temperature and T_{ant} is the calibrated antenna temperature, C_1, C_2 are calibration coefficients that represent scale and offset respectively, $T_{unc}, T_{sin}, T_{cos}$ are noise wave parameters. $\Gamma_{ant}, \Gamma_{rec}$ are antenna S11 and receiver S11 respectively. $T_L = 300$ K is the assumed noise temperature of the load. To evaluate the level of changes in $T_{ant}*$ as a function of Γ_{ant}, we use the results from the 'uncal-recal' test. We use the reference day and the day that shows the highest difference in antenna S11 relative to the reference day. This is day 2023_285. Under the assumption that all terms in Equation 1 are fixed other than Γ_{ant} and T_{ant}, the left hand side of the equation is invariant. So we calculate the right hand side of the equation for the reference day and day 2023_285.

$$\begin{aligned} T_{ant1}\left[\frac{(1-|\Gamma_{ant1}|^2)|F_1|^2}{1-|\Gamma_{rec}|^2}\right] &+ T_{unc}\left[\frac{|\Gamma_{ant1}|^2|F_1|^2}{1-|\Gamma_{rec}|^2}\right] \\ &+ T_{cos}\left[\frac{|\Gamma_{ant1}||F_1|}{1-|\Gamma_{rec}|^2}\cos\alpha_1\right] + T_{sin1}\left[\frac{|\Gamma_{ant1}||F_1|}{1-|\Gamma_{rec}|^2}\sin\alpha_1\right] \\ &= T_{ant2}\left[\frac{(1-|\Gamma_{ant2}|^2)|F_2|^2}{1-|\Gamma_{rec}|^2}\right] + T_{unc}\left[\frac{|\Gamma_{ant2}|^2|F_2|^2}{1-|\Gamma_{rec}|^2}\right] \\ &+ T_{cos}\left[\frac{|\Gamma_{ant2}||F_2|}{1-|\Gamma_{rec}|^2}\cos\alpha_2\right] + T_{sin}\left[\frac{|\Gamma_{ant2}||F_2|}{1-|\Gamma_{rec}|^2}\sin\alpha_2\right] \end{aligned} \quad (2)$$

Analytical approximations

For the purposes of easier estimation of effects of antenna S11 on the sky signal, we propose some analytical approximations.

(i)$T_{ant} >> T_x$, x= sin, cos, unc,
(ii) $|\Gamma_{rec}| << 1$, therefore $1 - |\Gamma_{rec}|^2 \approx 1$,
(iv) $|F| \approx 1$.

In its simplest form, we can estimate this effect as an approximation of equation 2:

$$T_{ant1}(1 - |\Gamma_{ant1}|^2) \approx T_{ant2}(1 - |\Gamma_{ant2}|^2) \quad (3)$$

$$\frac{T_{ant1}}{T_{ant2}} \approx \frac{(1-|\Gamma_{ant1}|^2)}{(1-|\Gamma_{ant2}|^2)} \tag{4}$$

$$\tag{5}$$

$$T_{ant1} - T_{ant2} = \Delta T_{ant} \approx T_{ant2}\left[\frac{(1-|\Gamma_{ant1}|^2)}{(1-|\Gamma_{ant2}|^2)} - 1\right] \tag{6}$$

At 75 MHz:

$T_{ant}, (2023\_266) = 2295.9768$ K and $T_{ant}, (2023\_285) = 2299.1658$ K, resulting in an effective difference of 3.1890 K. At this frequency, the difference in magnitude of antenna S11 is ∼0.27 dB at the level of ∼-16 dB, or 0.00492 at the level of 0.1655 in linear units. We also verify the effective difference using equation 6 yields 3.6538 K. The error due to assumed approximations is roughly 0.4 K (or roughly ∼10%). In other words, the effects are majorly driven by Γ_{ant}, and effects of T_x terms are less that ∼10%.

Further, to estimate the error in calibrated sky temperature due to error in modeling antenna s11, we use results from Figure 2 equation 5, and estimate the effects of errors in antenna S11 modeling. With modeling errors of the order of 10^{-5} for $|\Gamma_{ant}|$, at 75 MHz this corresponds to an error of roughly 0.71 mK (where T_{sky} or $T_{ant1} \approx 2296$ K, $|\Gamma_{ant2}| = |\Gamma_{ant1}| + 10^{-5}$). Therefore modeling errors in antenna S11 are not of concern in the detection of redshifted 21 cm signal.

Conclusion

In this memo the antenna S11 for EDGES-3 were studied, with an emphasis on daily variations, modeling errors, data cuts based on antenna s11 quality; and the analytical (and empirical) estimation of effects of antenna s11 variations on the calibrated sky signal. We find that data volume is limited by change in VNA averaging scheme in March 2023 and non-functioning VNA in Nov 2023, reducing the usable measurements to only ∼40 days after a conservative night time cut of 23:00 to 07:00 local time. We use a -10 dB cut-off to select frequency for the science analysis - 57-114 MHz. After the data cuts, we see maximum variations of the order 0.3 dB at the level of -16 dB that corresponds to ∼5 K in the calibrated signal. We propose analytical approximations to estimate the dependence of antenna S11 on the the calibrated sky signal. Using the analytically approximated equation 5, we estimate the errors in calibrated signal. When antenna S11 is modeled using a 12 term polynomial, the modeling errors are of the order 10^{-5} which result in an error of ∼0.7 mK in the calibrated signal. We thus conclude that modeling errors at this level are not of concern in the detection of redshifted 21 cm signal.

References

R. A. Monsalve, A. E. Rogers, J. D. Bowman, and T. J. Mozdzen. Calibration of the edges high-band receiver to observe the global 21 cm signature from the epoch of reionization. *The Astrophysical Journal*, 835(1):49, 2017.