MASSACHUSETTS INSTITUTE OF TECHNOLOGY
HAYSTACK OBSERVATORY
WESTFORD, MASSACHUSETTS 01886

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Telephone: 617-715-5533

To: EDGES group
From: Alan E.E. Rogers
Subject: Summary of tests of the sensitivity of EDGES-3 to systematics

The need for high accuracy VNA measurements was recognized in memo 90 and tests of VNAs reported in memos 97,120,122,124,130,131,133,134,135,333,351,369 and the need for more accurate VNA calibration in

Monsalve, R.A., Rogers, A.E.E., Mozdzen, T.J., and Bowman, J.D. (2016). One-port direct/reverse method for characterizing VNA calibration standards. *IEEE Transactions on Microwave Theory and Techniques* 64(8): 2631–2639. https://arxiv.org/pdf/1606.02446

Memo 363 discusses the need for VNA "warm-up" and memo 412 discusses the need to minimize the time from the measurement of the device and the SOL VNA calibration for high accuracy VNA measurements. In this memo the key characteristics are listed and tests of effects of errors are made on preliminary EDGES-3 data from the MRO following the fixing of the slot resonances in the ground plane (see memo 408) and the averaging of the VNA data to improve accuracy (see memos 411 and 412).

Key characteristics of EDGES-3 at MRO:

LNA uncorrelated noise 180 K
LNA correlated noise < 30 K 50 – 100 MHz
LNA input S11 < -39 dB 50 – 100 MHz
Fraction of power above out of band noise on load 3% 50 – 200 MHz 14-bit ADC Signatec PX14400A
VNA fractional error < 3e-4 Fieldfox N9923A
Antenna S11 < -10 dB 55 – 100 MHz
Antenna average rms beam chromaticity 67 mK for 1 hour blocks of GHA 53 – 100 MHz 5 physical terms removed using 408 MHz Haslam sky map scaled with -2.5 spectral index to 50 – 100 MHz
Antenna beam chromaticity 4 mK for 24 hours of GHA
Antenna plus 48.8x48.8m ground plane loss < 0.3% 50 – 120 MHz
Antenna gain at 1 degree elevation < -25 dBi horizontal polarization 50 – 120 MHz

test	Case 1	Case 2	rms1 3-terms mK	rms2 5-terms mK
Calibration S11	2023_070_11	2023_072_15	47	5
Calibration spectra	2023_070	2023_020	338	4
loss	0	0.3%	100	5
beam correction	applied	Not applied	3500	3

Table 1. Calculated estimates of the effect of different calibrations from the field at the MRO GHA=12

Table 1 shows the expected differences on the rms residuals in the calibrated sky noise spectra. rms1 and rms2 with 3-physical terms and 5-physical terms removed respectively in the absence of an absorption feature 53 – 100 MHz.

Data simulation:

A circuit model of the LNA is developed in memo 334 and then used in memo 380 to confirm the Meys noise wave analysis used in the EDGES calibration.

Simulations are used to derive the sensitivities of VNA errors in table 1 of memo 380, the noise in the VNA measurements and noise in the spectra in table 2, the effect of polynomial filtering in table 3 and the effect of the noise wave filter, wfiit, and scale filter, cfit, polynomials in table 4.

The overall conclusions of the simulations and the tests using an "antenna simulator" in memo 382 are that for the EDGES electronics the VNA noise needs to be less than 5e-4 fractional units and bias than 0.5 dB and 100 ps for the VNA measurement of the LNA S11.

Spectrum integration longer than about 2 hours is needed for each of the 4 calibration spectra and longer than 8 days for sky spectra for rms under 18 mK following the fit to the absorption spectra for sky noise of 300K at 150 MHz with -2.5 spectral index.

Table 1 of memo 380 shows that a 30 ps error on the VNA calibration short or open has a significant effect on the recovered amplitude of the absorption feature. The required accuracy of calibration and antenna S11 for "Galaxy up" data at the latitude of the MRO needs to be improved by a factor of about a factor of about 3.

Lab test using antenna simulator:

An important test of the receiver performance and calibration is to use a filtered noise source to simulate the sky noise spectrum as in memo 382. The first entry of table 1 and figure 1 of memo 382 show the results of an absorption search using EDGES-3 data using an "antenna simulator" to which the Nature (2018) absorption has been added to the calibrated spectrum.

Memo 367 shows the results using the antenna simulator, which provides 6000 K at 75 MHz, to assess the expected performance on "Galaxy up" data at the MRO in table 5 and plots in figures 1 through 4.

EDGES-3 relies on measurements of the calibration load resistance of the 49.994 and 49.962 ohms at 25 and 30 degC respectively made with an ohmmeter. The added path of the VNA connection to the LNA is discussed in memo 303 and the result measured for EDGES-3 and the prototype. The result of the measurement at the MRO on 2023_070 is given in the last entry in table 2 below:

EDGES-3	Length inches	Dielectric correction %	Loss correction %
Prototype 7000	4.68	-2.9	-93.0
New 7002 at 30C	4.46	-1.24	-91.5
MRO 2023_070 at 35C	4.34	-1.64	-90.6

Table 2. VNA to LNA path correction from prototype and lab from memo 367.

A plot of the calibration used for the correction obtained from the MRO is shown in Figure 1. In the current deployment when the temperature control of the inner box with the LNA, switches, hot and ambient loads plus the open and shorted cables deviates by more than 1degC from the set-point the repeatability of the calibration is not good enough and the rms with 5-terms removed can exceed 20 mK. In this case the frequency coverage has to be limited to 60 – 100 MHz. The extreme temperature in summer during which the temperature of the air being circulated through the antenna box with the electronics can exceed 50 degC make it difficult to maintain a constant temperature but hopefully a constant temperature can be maintained during the winter months.

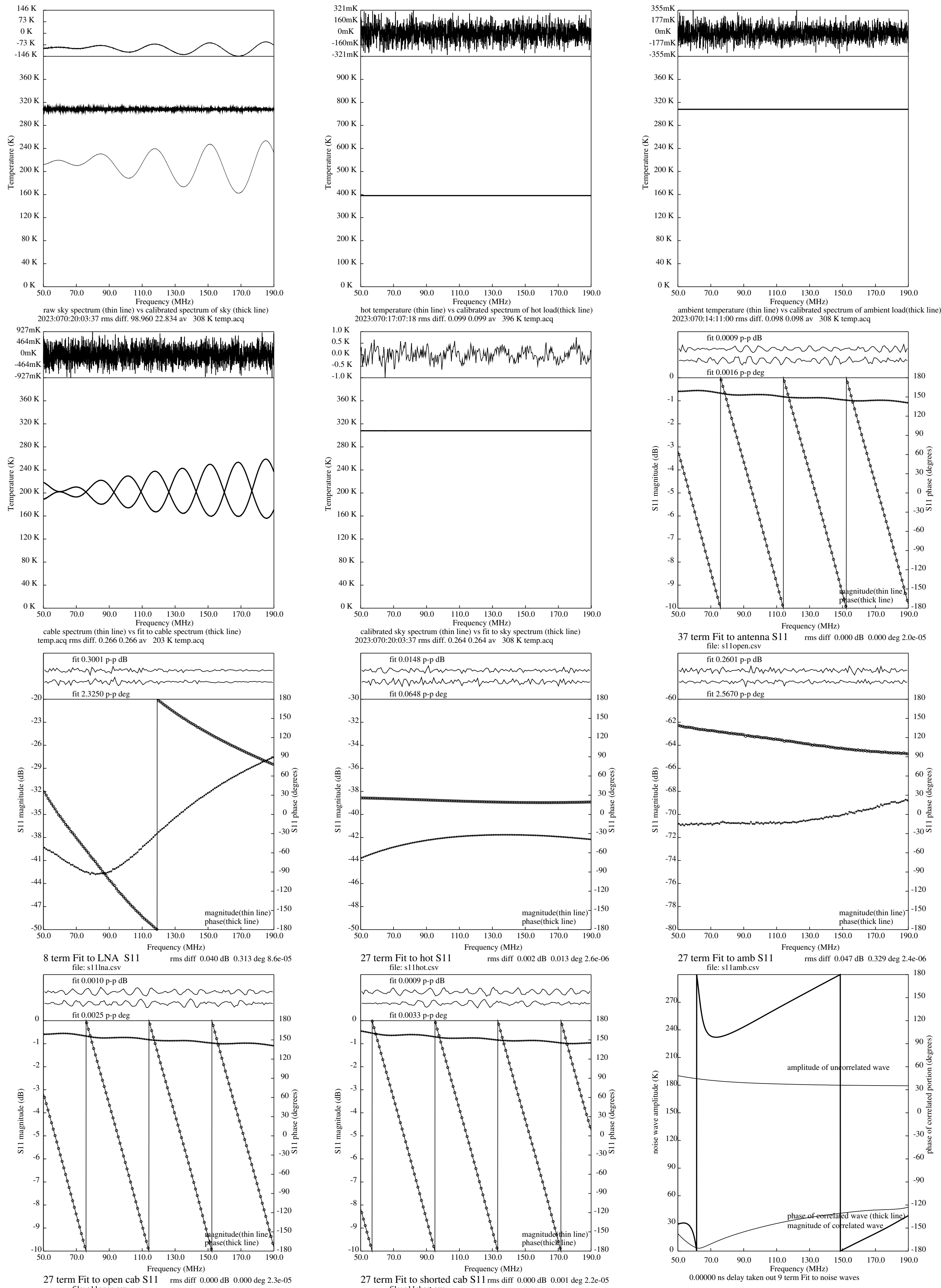

Figure 1. Plot the calibration of EDGES-3 from 2023_070.