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To: EDGES Group

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Subject: Tests of automated calibration self-checks using EDGES-3

A simplified approach to characterizing EDGES-3 is described in memo 303. In this approach the VNA reference plane is the plane of the internal contact of the female connectors on the 8-position switch on which the male connectors are connected. All 8 positions have the same delay to the switch input to within 1 picosecond. In this case the Keysight male SOL calibration parts are already at this reference plane and can be directly accessed by the VNA to measure the s11 of the antenna, hot load and open and shorted cables referred to the same reference plane. Loss corrections are only needed for the antenna, which includes the 1.5 inch cable to the antenna port between the antenna box elements, and the short cable to the hot load. When the VNA is used to measure the s11 of the LNA it is effectively about 5 inches of 0.141 semi-rigid cable closer to the reference plane which can be corrected using the S-parameters of the cable prior to performing the VNA calibration for the LNA s11. Any error in this correction will produce higher residuals to the calibration corrected spectra of the open and shorted cables for an automated “cross-check” of the calibration.

A fully automated check of the calibration can be made by running fastspec on the ambient load, hot load and open and shorted cables, and running the VNA to get the s11 of the hot load, open and shorted cables as well as the SOL. The s11 of the LNA and the SOL for the VNA calibration of the LNA s11 are run at -30 dBm. The SOL are needed again when the VNA is run for the LNA s11 measurement as there can be a calibration difference between high and low power states of the VNA. Tests show that -30 dBm is needed to avoid any evidence of saturation.

Figure 1 shows the results of using the calibrated spectrum on the open cable to assess the quality of the calibration. Figure 2 shows the calibrated spectrum if the correction for the 5 inches of semi-rigid for the change in path is made using only 3 inches. These tests were made with only 4 minutes integration per spectrum so in this case the sensitivity to the detection of systematics is limited by noise in the spectra. The results in figures 1 and 2 were made using the EDGES-3 prototype. Figure 3 is the result of the automatic calibration using the new EDGES-3 frontend, backend and Nuvo computer. Some RFI present as the components are not yet fastened down in the antenna box and is shown for comparison with Figure 1. In this case the rms difference between the s11 data and the fit is also given in fractional values of s11 following the rms differences in dB and degrees of phase on the plots.

Simulations of EDGES-3 compare the rms error observed in the fit to the open or shorted cable with the rms error in a 5-physical term fit to the foreground and a simulation of the rms error in the Nature absorption. These results are shown Table 1. These simulations have idealized approximations to the actual parameters of EDGES-3 to give an indication of the accuracy needed for S11 measurements.

EDGES-3 parameters	rms0 mK	Fcen MHz	amp	Width MHz	rms1 mK	rms2 mK
No offsets etc. ref. absorption	0.5	78.0	0.50	19.0	73	0
1 inch cable change in LNA path	900	79.5	0.55	19.1	99	37
1% dielectric change in LNA path	515	78.5	0.47	18.9	74	13
Added 100 mK noise to spectra	34.6	78.0	0.50	19.1	75	19
No hot load loss correction	0.5	78.0	0.52	19.0	73	0.1
No antenna cable loss correction	0.5	78.0	0.52	19.2	72	17
1 ohm error in calibration Load	261	77.8	0.52	19.0	74	6
30 ps error in calibration L O S	479	78.7	0.52	18.9	84	16
30 ps error in calibration Load	9	77.9	0.51	19.0	73	3
Added 5e-4 noise to VNA I/Q	227	79.3	0.53	17.4	101	35
Added 5e-4 noise to LNA s11	127	78.2	0.52	18.8	79	16
1 deg error in hot load temperature	0.5	78.0	0.50	19.0	76	2
LNA s11 filter 11 to 27-terms		77.3	0.56	18.6	74	24
Noise wave filter 6 to 7-terms		78.1	0.48	19.1	56	3

Table 1. Simulations of parameter changes and added noise. rms0 is the residual to the open cable fit over a frequency range 55 – 120 MHz. rms1 and rms2 are the residuals for a 5-physical term fit before and after including the absorption.

Owing to the filtering effects in the calibration the acceptable VNA noise depends on the frequency spacing of the VNA measurements. The effect of 5e-4 noise in the table is for 0.1 MHz frequency spacing. For 1 MHz spacing a level of 1.7e-4 of VNA noise has similar effects. These effects of noise which are for a LNA filter with 27 terms can be reduced with a 11 or 12 term filter. A VNA data frequency spacing of about 1 MHz is needed to provide enough frequency resolution to avoid the added systematics. The calibration is done for 50 -198 MHz and the absorption check is done for 55 -120 MHz. The results show that except for the cable loss corrections the sources of significant error can be detected in the residuals of the open and shorted cables. The path to the LNA can be verified by finding the path length that results in negligible residual ripple in the calibrated spectrum of the open and shorted cables. With EDGES-3 the calibration from 50 to 200 MHz provides a slightly more accurate result and a more accurate cross-check using the open or shorted cable as an artificial antenna. With EDGES-2, which has longer open and shorted cables calibration over a more limited frequency range is satisfactory.

Simulations show that 10 minutes on each of the 4 spectra leads due to noise of about 14 mK and more than 16 hours of integration is estimated to be needed for the antenna spectrum to get the noise below 20 mK for a sky noise level of 1700 K at 75 MHz. When measuring the LNA s11 an average of 100 traces of 151 frequencies from 50 to 200 MHz with bandwidth 300 Hz using the Agilent N9923A Fieldfox VNA are used which take about 4 minutes each. Acceptable filtering is 12 terms for antenna and LNA s11 and 6 to 9 terms for the LNA noise waves.

calibration	rms amplitude dB	rms phase deg
Receiver02_2019_12_10_040_to_200_25C	0.013	0.08
Lowband 2015	0.013	0.09
Lowband 2017	0.004	0.025
Lowband 25C_2018a	0.008	0.053

Table 2. Examples of noise in the LNA s11 from EDGES-2 calibrations. All of these are less than 1e-4 in fractional units of S11.

A test of the sensitivity of the new EDGE-3 frontend and its associated backend to changes in the filtering of the LNA S11 and the noise wave parameters is made by using a reference calibration and the antenna S11 from FEKO to simulate the antenna spectrum which is then processed with other calibrations made with different integration times for the spectra and S11 measurements. These results are shown in Table 3.

parameter changes	Fcen MHz	amp K	Width MHz	rms0 mK	rms1 mK
Ref.case 1hr spec 6m s11 55 – 100 MHz	78.0	0.50	19.0	73	0
30m spec 2m s11	78.1	0.51	19.2	73	4
3hr spec 12m s11	78.1	0.48	18.5	75	10
0.5 inch change in LNA path	77.7	0.37	20.1	50	13
SOL offset change 30 ps to 0 ps	77.7	0.57	18.8	85	9
Calibration 50-198 to 50-130 MHz	78.1	0.62	18.5	98	22
Noise wave filter wfit 10 to 7 terms	78.1	0.51	18.8	76	2
LNA s11 filter nfit3 10 to 7 terms	77.0	1.22	15.9	249	99
LNA filter 198 to 130 nfit3 10 to 12 terms	78.1	0.41	18.6	67	44
nfit3 10 to 12 terms	77.7	0.57	18.5	89	19
Fstop 198 to 130 wfit 10 to 7	78.1	0.57	18.2	93	16
Fstop 198 to 130 wfit 10 to 7 nfit3 12 to 10	78.1	0.58	18.3	93	15
Cal day 147 to day 146 55 – 120 MHz	78.1	0.59	19.1	87	13
Cal day 147 to day 146 55 – 100 MHz	77.7	0.58	18.9	87	11
day 147 to 146 55 – 120 MHz GHA=0	78.5	0.79	19.4	125	42
day 147 to 146 60 – 120 MHz GHA=0	78.1	0.54	19.2	63	5

Table 3. An automatic calibration using the new EDGES-3 frontend and backend. A reference calibration along with the antenna s11 and beam from FEKO is used for simulation of the spectrum with the Nature feature added to the sky using the Haslam map corrected for spectral index.

The results in Table 3 show that the number of terms used for the noise wave extraction, wfit, and the number of terms to fit the LNA s11, nfit3, need to be optimized. Also the results in the table show the effect of the use of another calibration or the reference calibration with the changes listed. All entries were for GHA=12 hours except the last 2 which were for GHA=0 hours. In this case the frequency range had to be reduced for the 5 physical terms used as the change in calibration is too large. In this case it may take a lower antenna s11 or more accurate calibration to get below 60 MHz.

	antenna	LNA	others
VNA noise 5e-4 with 10-term filter of antenna s11	52	26	2
VNA noise 5e-4 with 12-term filter of antenna s11	174	26	2
	ant	calib	
Spectrum noise 100 mK	30		
LNA 100 ps offset		60	
Ant 100 ps offset	90		

Table 4. Tests of added noise to the antenna and LNA and other s11 data on the residuals in mK to a 5-term fit to simulated data at GHA=0 55-120 MHz.

These simulations show that LNA s11 noise needs to be under 1e-4 for Galaxy up results. The validity of this conclusion is strengthened by comparing the results of automatic calibrations using spectra and s11 data taken overnight on 2021 days 145,146,147 and 148. These only show significant changes when using s11 data from different days. A closer examination shows that the calibration differences are dominated by the differences of the LNA s11 from one day to the next due to noise at the level of 1e-4 in fractional units.

GHA	change	Open cable ref.	Open cable	55 – 95 MHz	55 – 120 MHz
12	0.5 inch	403	599	13	35
00	0.5 inch	403	599	35	111
12	S11 from 147	403	463	15	41
00	S11 from 147	403	463	36	113

Table 5. Residuals in mK for reference case on day 148 for a change in LNA path and s11 from day 147. The last two columns are for the residuals to the simulated Nature feature as in Table 3 for the different frequency indicated and the middle two columns are for the rms residuals to the calibration corrected spectrum of the open cable.

In summary these initial tests of the repeatability and sensitivity of the automatic calibration show that a VNA noise level below 1e-4 in fractional units is needed which can be achieved in an hour. While noise in the calibration spectra is not a limiting factor a total of about 6 hours are needed to bring the residuals on the calibration corrected spectrum of the open cable down to about 400 mK which is sufficient to provide a good cross-check of the calibration. When the thermal control system is ready the new EDGES-3 will be moved into the screen room for tests of the temperature sensitivity and the performance using an artificial antenna.

These tests of automatic calibration show the source of change from one day's calibration to the next is dominated by the change in the S11 as there is little change in the calibration using the spectra from one day to the next using a common set of one day's s11 measurements. The VNA accuracy and repeatability can be improved by averaging many cycles of shorter VNA measurements so the SOL measurements are made closer in time to the LNA and antenna s11 measurements.

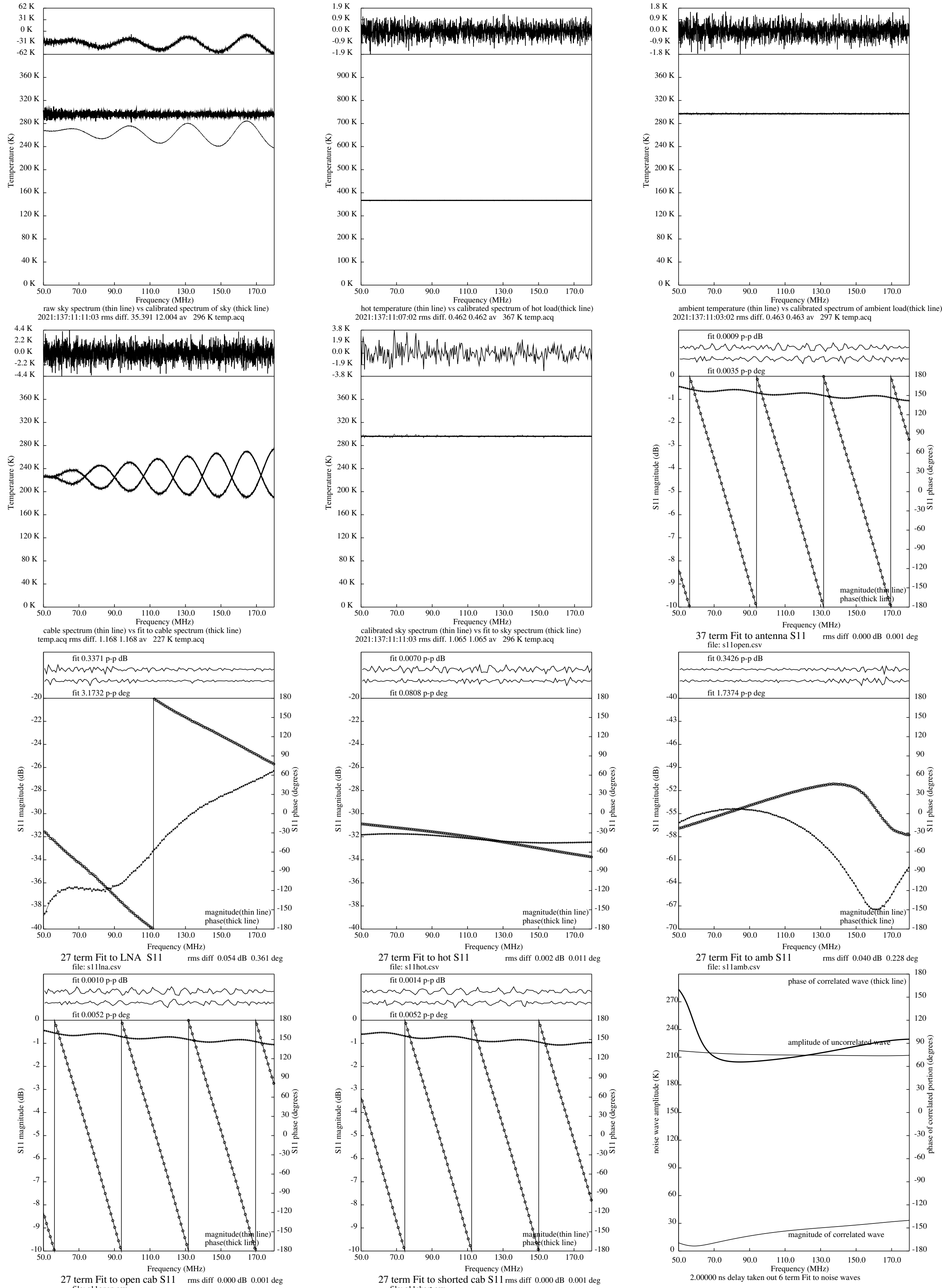

Figure 1. The results of the automated calibration for the EDGES-3 prototype with open cable as an "artificial antenna" to assess the quality of the calibration. The calibrated spectrum of the open cable (labeled sky spectrum) is treated as antenna to cross-check the quality of the calibration.

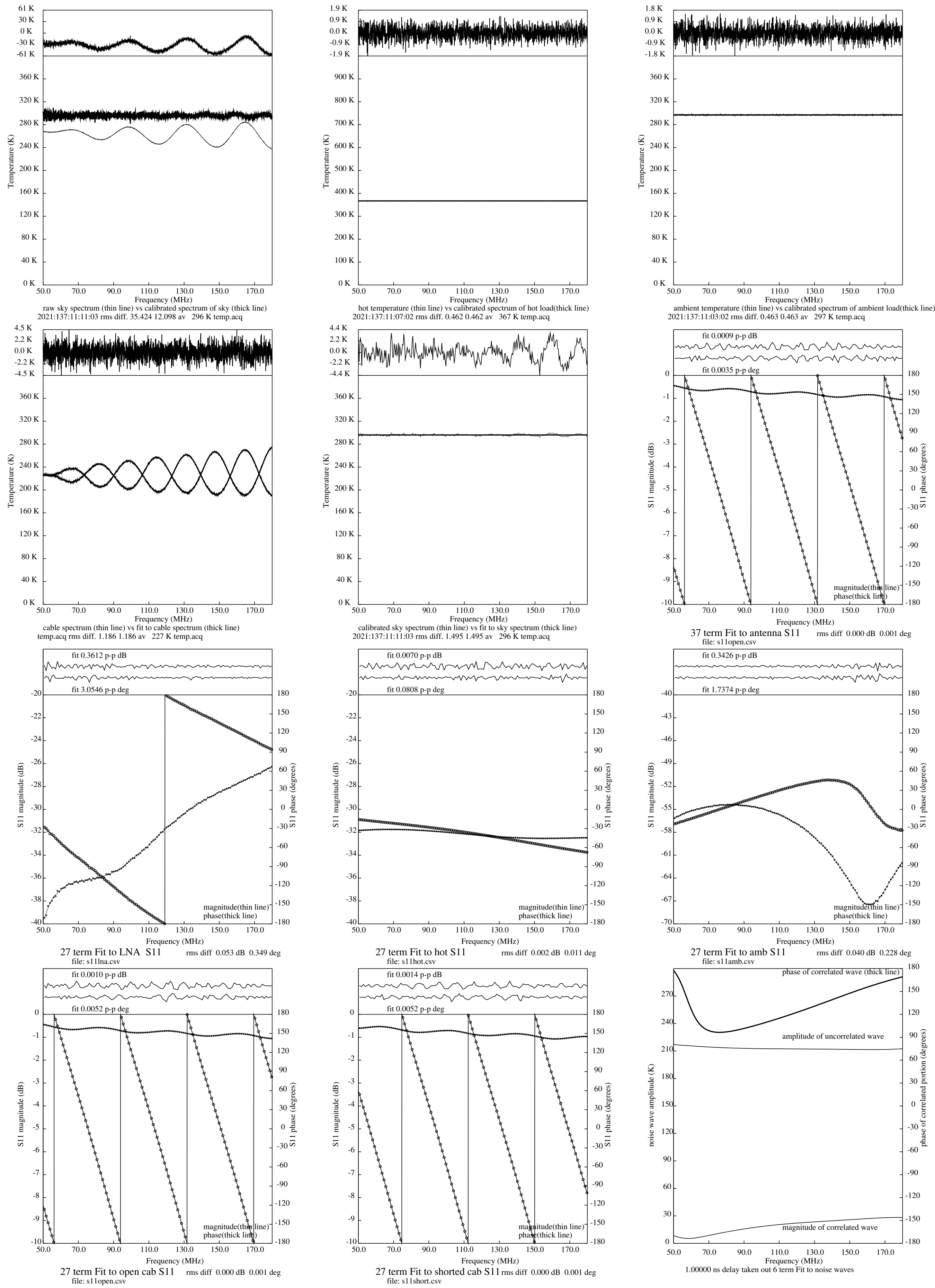

Figure 2. The results of the calibration when the correction for the 5 inches of semi-rigid used to obtain the s11 for the LNA referred to the reference plane of the 8 position switch is made using only 3 inches. Note the large residuals in the calibrated sky spectrum.

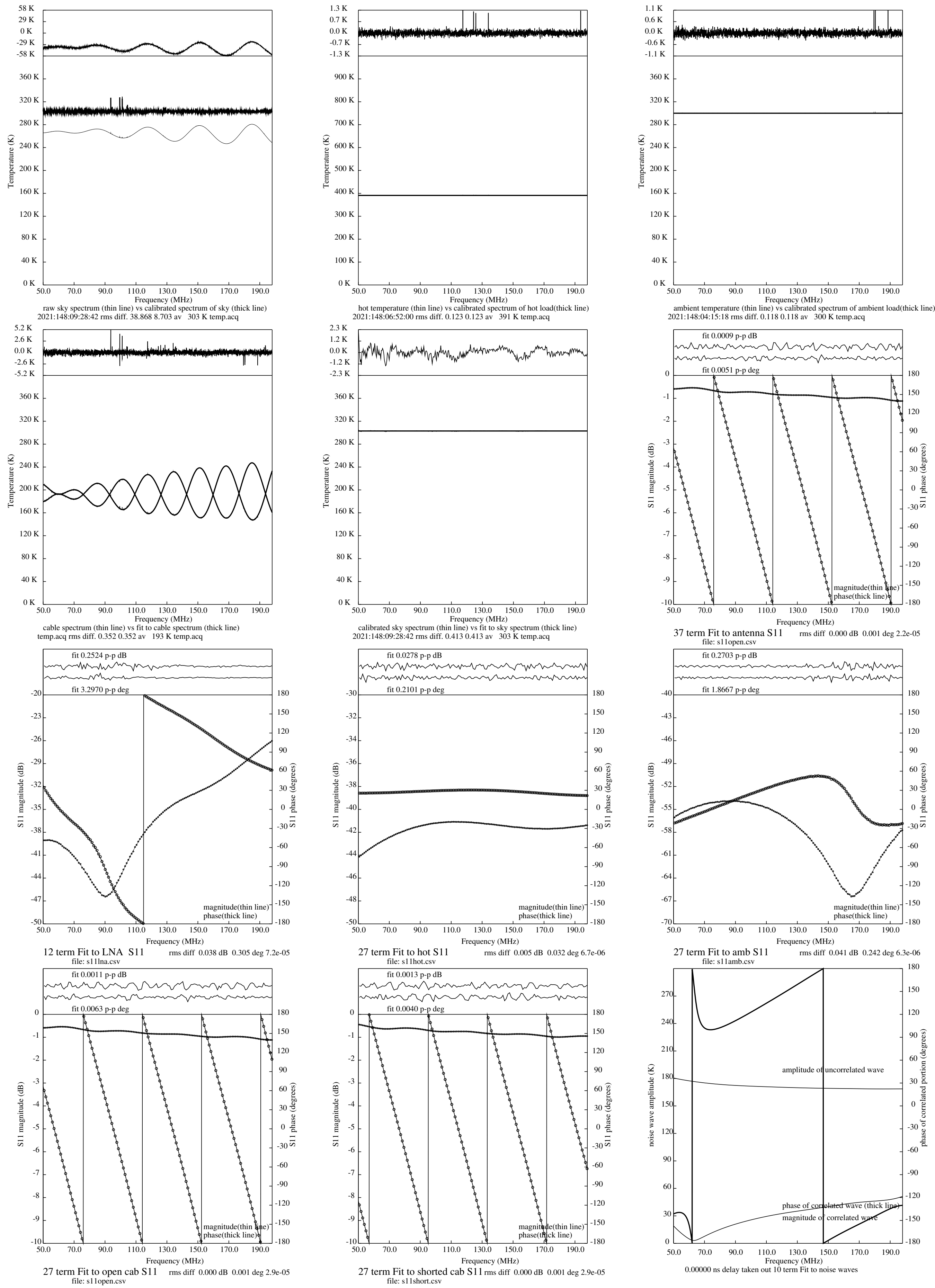

Figure 3. The results of calibration and open cable spectrum (labeled sky spectrum) as a cross-check for the new EDGES-3 frontend and backend.