EDGES MEMO #423

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To: EDGES group

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Subject: Tests of filtering parameters for optimum EDGES-3 calibration

While EDGES-3 has the advantage of being a self-contained instrument it has the disadvantage of having to use a compact Keysight N9923A Fieldfox VNA instead of a benchtop VNA which has lower noise and higher accuracy. Tests of the calibration accuracy made of the EDGES-3 in memo 361 were made in a very stable environment with long warm up as described in memo 363.

When EDGES-3 was installed at the MRO a study of the performance was made and a new averaging scheme described in memo 414 and evaluated in memos 412 and 416. Now that we have good data from day 54 to 210 of 2023 I have analyzed the Nature feature with different calibrations and used simulations and data to test different number of terms used for the calibration. Table 1 lists the terms, the number used, frequency range, temperature and the values of LNA s11 correction parameters used:

	2022_316	2023_020	2023_070	2023_082	082 test3	2023_210
cfit calibration	7	7	7	5	7	7
wfit noise wave	7	9	9	9	9	9
nfit3 LNA S11	10	10	10	10	6	7
Frequency range	50-190	50-190	50-190	50-190	50-120	50-190
Temperature deg C	30	30	30	30	30	30
cablen	4.26	4.26	4.26	4.26	4.26	4.26
cabdiel	-1.24	-0.9	-0.9	-0.9	-0.9	-0.9
cabloss	-91.5	-91.5	-91.5	-91.5	-91.5	-91.5
rms fit to open mK	384.7	429.5	320.6	665.2	253.8	368.5
rms 316 diff mK	ref	8.3	7.5	4.8	2.7	5.8

Table 1 Number of terms of filters used in calibration

Following the installation of EDGES-3 at the MRO in November 2022 as described in memo 406 some resonances were noticed (see memo 407) due to slots between bolts on the mounting of the baseplate. These were fixed and the first measurements of the 21-cm absorption were reported in memo 412 using data from day 54 to 65 for 60 to 100 MHz and day 54 to 71 for 53 to 100 MHz. The calibrations done on day 2022_316 was found to give low residuals and was used for the analysis of data into 2023. While calibrations on 2023_020, 2023_070 and 2023_082 produced reasonably consistent absorption results it was found that using as many as 10-terms to smooth the LNA S11 is probably not optimum and a simulation test was done using the 2023_210 calibration to test the sensitivity to changes in filter parameters. The rms fit to the "open" in table 1 is the rms residual with a constant removed from the calibrated noise from the open cable.

The last entry in table 1 is the rms residual with 5-terms removed when the calibrated sky spectrum data with the Nature feature added to the sky is simulated using a "reference calibration file" and then processed with a calibration file made from the same raw spectral and calibration data processed with different numbers of terms and LNA s11 correction parameters.

The simulation test is repeated using the 2023_210 calibration with the parameters listed in table 1 as the reference for changes in the calibration parameters listed in table 2.

case	cabdiel	cfit	wfit	nfit3	Freq MHz	SNR	amp	width MHz	rmsin mK	rms	rms3	amp db	phase deg
ref	-0.9	7	9	7	78.0	-	0.5	19.0	36	0	368		
	-1.24	7	9	7	78.1	215	0.51	18.9	37	1	353	0.46	2.3
	-0.9	7	9	6	77.7	16	0.32	19.7	44	22	369	0.82	3.8
	-0.9	7	9	8	77.7	127	0.49	19.7	37	2	365	0.38	2.4
	-0.9	7	9	10	77.7	132	0.51	19.8	38	2	379	0.41	2.4
	-0.9	7	8	7	78.1	135	0.46	19.1	35	1	406		
	-0.9	7	10	7	78.1	228	0.49	19.0	36	1	377		
	-0.9	6	9	7	78.1	222	0.48	19.0	36	1	370		
	-0.9	8	9	7	78.1	270	0.49	18.9	37	0	362		
					78.1	84	0.53	18.2	45	8			

Table 2 Results of simulation of changes to best fit absorption with change in calibration

The value of rms3 is the rms fit to the open as in table 1 and the last 2 columns are the peak to peak residuals to the nfit3 fit to the LNA s11 which shows that at least 7 terms are needed for the 50-190 MHz frequency range. The last entry in table 2 is for data simulated using the 2022_316 calibration processed with the 2023_210 calibration.

These results show that the filtering of the LNA s11 is critical to the reduction in the error in the determination of the parameters of the 21-cm absorption. This is consistent with the conclusion reached in memo 368 which points out from the equations of the calibrated sky temperature that the sensitivity to the phase of the LNA s11 is similar to the sensitivity on the antenna s11 phase. Achieving a low noise and a high accuracy LNA s11 is more difficult with a handheld VNA than with a benchtop VNA. The Fieldfox N9923A has 10 deg phase uncertainty at -20 dB while the P937XA and PNA-X N5249B VNAs have uncertainty is 2 degrees at -20 dB. Typical LNA s11 phase residuals were about 0.6 degrees using a benchtop compared with about 2 degrees with the Fieldfox.

The 10-term fit to the LNA s11 data for 2022_316 had peak to peak residuals of 0.25 dB and 1.2 deg. The corresponding residuals have increased a little for 2023_070,082,210 following the change in averaging described in memo 411, to reduce the effect of changes in VNA temperature, to 0.25 dB and 1.5 deg.

The effect of noise in the VNA s11 data was tested by adding gaussian noise in units of the fractional levels listed in Table 3.

Freq MHz	SNR	sig amp	Width MHz	rmsin mK	rms	Cal s11	LNA s11	Ant s11
77.7	98	0.57	20.0	51	7	1e-3	1e-3	0
77.7	134	0.48	19.3	34	4	1e-3	0	0
77.7	79	0.59	19.7	53	9	0	1e-3	0
77.7	38	0.40	19.2	36	13	0	0	2e-4

Table 3 Effect of added noise to s11 data

These simulations show that adding noise at the 1e-3 level has little effect on the calibration while adding noise to the antenna s11 has a significant effect. In the case of adding noise at the 2e-4 level to the antenna s11 results in an increase of the peak to peak residuals from 0.005 dB and 0.14 deg to 0.06 dB and 0.49 deg.

A test of the noise in the calibration spectra of day 2023_210 was made by cutting the time that was processed in half and this resulted in a difference of only 1K in the calibrated sky temperature, 5 mK in the absorption amplitude and 0.2 mK in the residuals rms fit to the absorption. This shows that there is unlikely to be any advantage of an increase in the time spent taking the spectra of the ambient load, hot load and open and shorted cables.

Test simulations of the numbers of terms in the filtering of the antenna s11 are listed in Table 4

Freq MHz	SNR	sig amp	width MHz	rmsin mK	rms	nfit4 ref	nfit4	freq range
78.1	71	0.56	19.1	43	10	11	10	51-110
78.5	57	0.57	17.8	49	14	10	9	51-110
78.5	46	0.54	17.8	47	16	12	11	51-110
78.1	325	0.47	18.9	35	0	11	10	56-104
77.7	266	0.48	19.2	34	2	12	11	56-104
77.7	15	0.38	15.7	57	35	9	8	56-104

Table 4 Simulation of the effects of filtering the antenna s11

These simulations show that for the frequency range of 60-100 MHz used for the absorption at least 10 terms are needed and even with 10 terms there is an improved accuracy in limiting the frequency range of the fit to only a little more than the frequency range for the absorption search. Limiting the number of terms to no more than 12 is also needed to avoid introducing significant fine frequency structure into the antenna s11.

Tests with data from day 54 to day 213 follow:

1] Effect of maxfm using calibration day =210 ant s11 filter nfit4 = 12 56 to 104 MHz

Freq MHz	SNR	sig amp	Width MHz	rmsin mK	rms	maxfm
78.1	27	0.50	19.7	70	17	2000
78.1	16	0.45	20.9	67	26	50
78.1	20	0.47	20.1	70	22	100
78.5	26	0.51	19.5	73	20	300
78.5	26	0.47	19.2	71	18	none

Table 5 Effects of fm threshold filtering

The last entry is without any acceptance threshold and just relies on filtering individual frequency channels.

2] Effect of different calibrations using ant s11 filter nfit4 = 11 50 to 100 MHz

Freq MHz	SNR	sig amp	width MHz	rmsin mK	rms	calibration
78.5	25	0.44	20.9	53	17	specals_2022_316.txt
78.7	27	0.41	18.4	74	18	specals_210opt.txt
78.1	24	0.47	20.9	44	19	specals_082.txt

Table 6 Effects of different calibrations

3] Effect of different antenna s11 filter using specals_210opt.txt calibration and 56 to 104 MHz

The grid search for the 21-cm absorption used tests used single data block for each day of GHA from 4 to 20 hours for which the sun was more 1 degree below the horizon. The results for 11 and 12 term filtering of antenna s11 and calibration from day 210 are given in table 7 below.

Freq MHz	SNR	sig amp	width MHz	rmsin mK	rms	nfit4
78.1	27	0.50	19.7	70	17	12
77.3	25	0.50	20.9	69	18	11
77.3	19	0.35	20.9	69	23	12 tau=7

Table 7. Results of a 21-cm absorption search on data from 2023 day 54 to 213
The last entry in table 7 is for the flattening parameter tau=7 while all other results are for tau=4 which results in a a better fit with lower residuals.

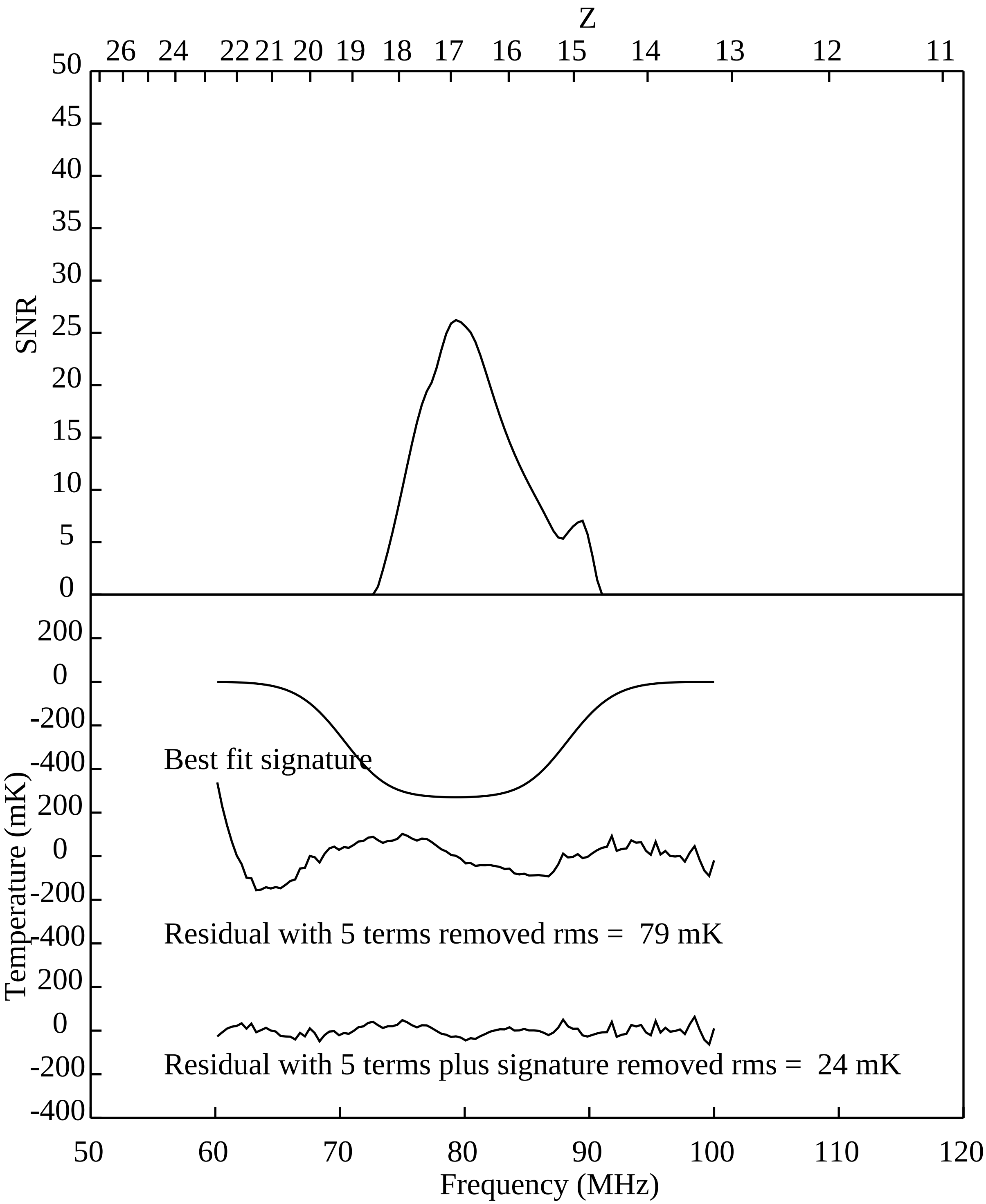
Another processing scheme which takes a little longer to run is to use all the 1 hour blocks from 4 to 20 hours for each day for which the sun was more than 1 degree below the horizon. The result of this method is in the last entry of table 8 with plots in Figures 1 and 2 of the first and second processing schemes.

Freq MHz	SNR	sig amp	width MHz	rmsin mK	rms	nfit4
79.3	26	0.53	18.1	79	24	12
80.1	23	0.42	17.0	78	26	11

Table 8. Results of a 21-cm absorption search on data from day 54 to 216

Summary of key calibration processing parameters:
Frequency range 50 – 190 MHz
cfit 7-terms
wfit 9-terms
nfit3 7-terms
Summary of key processing parameters:
maxrmsf 200
maxfm 2000
sunlim -1
Frequency range 50-120 MHz
wfstart 56 -wfstop 104 MHz
nfit4 11 or 12 terms

In overall summary the 21-cm center frequency, width and flatness from EDGES-3 at the MRO 2023 day 54 to 216 are consistent with the errors Nature 218 paper. The largest difference is a best fit flatness of tau = 4. A simultaneous absorption fit to lowband and midband data described in memo 286 also found that tau = 4 fits the data with lower residuals.



freq 79.3 snr 26.2 sig 0.53 wid 18.10 tau 4 rmsin 0.0790 rms 0.0237 60 - 100

Figure 1. Plot of 21-cm absorption for first entry in table 8.

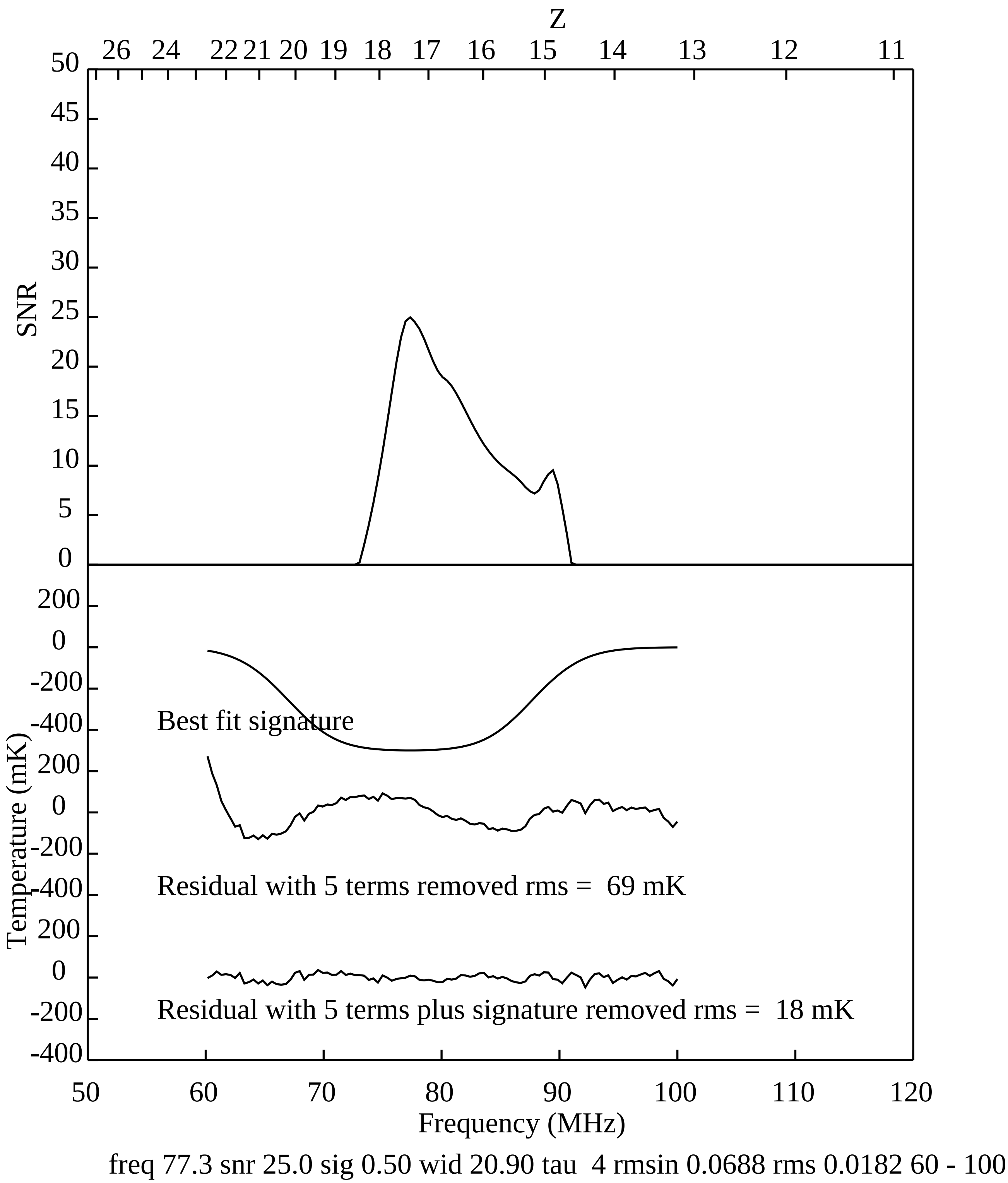


Figure 2. Plot of 21-cm absorption for second entry in table 8.