EDGES MEMO #113

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April 7, 2015

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To: EDGES Group

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Subject: Summary EDGES processing software

1] Processing of raw spectrum

The real time software acquires spectra from the Signatec PX14400 ADC card at 400 Ms/s rate. The 14 bit real data is transformed to the frequency domain using FFTs running in the multi-core CPU and spectra are accumulated for each position of the 3-position switch. These data are time tagged and stored to disk. The first "post" processing step is to read this data and compute the sky spectrum from

$$t_{sky}(f) = \frac{t_{cal}\left(p_{sky}(f) - p_{load}(f)\right)}{\left(p_{cal}(f) - p_{load}(f)\right)} + t_{load}$$

At this stage the values of t_{cal} and t_{load} are only approximate and are taken as constants independent of frequency. The approximate sky temperature (t_{sky}) for each 3 position cycle is examined for RFI and may be discarded if contaminated with a strong signal. The sky spectra are then accumulated over a longer period of several hours and the average spectrum is examined for spectral RFI using a sliding window to pick-out regions of the spectrum which need to be given a zero weight in the spectrum which is written to disk for the next stage of post processing. This output file has the format of frequency (MHz), sky temperature, weight (0 or 1) with spaces as delimiters. Smoothing in frequency can be used to reduce the number of spectral points to the resolution required for the next stage of processing. In computing the weight for a given frequency bin of lower resolution than in the raw data need not be assigned to a zero if only a few of the original bins are contaminated with RFI.

2] Processing to calibrate the spectrum

This step requires the following data files:

a) Spectra of antenna, hot load, ambient load, open and shorted cable. The hot load, ambient load and open and shorted cable data have been derived in the laboratory and are assumed to be valid for an extended period of observations.

b) S11 measurements of antenna, hot load, ambient load, open and shorted cable and LNA.

The S11 data is in the "csv" format with frequency (Hz), real, imaginary (or magnitude (dB), phase (deg)) with commas as delimiters. The number of frequencies and their spacing need not be the same as for the spectra as the S11 data is smoothed and interpolated to the same frequency bins as in the antenna spectrum.

The integration times required for the calibration spectra on the hot, ambient and cable loads is discussed in section 6.

For a check of the consistency of the calibration the “antenna” spectrum can be one of the calibration spectra so the calibrated spectrum should agree with the temperature of the hot, ambient and cables, which ever one is chosen. The same results should also be obtained as a “cross-check” when the calibration spectra are calibrated using the calibration output file.

In addition to these 11 files (5 spectra plus 6 S11) a number of additional parameters are needed as listed in Table 1.

Parameter	Description	Default
tload	temperature of load in LNA	298 K
thot	temperature of hot load	368 K
tcold	temperature of cold load	298 K
nfit1	number terms in Fourier series fit to ant S11	27
nfit2	number of terms in series fit to LNA, hot, cold, open and shorted cable S11	27
mfit	number of basis function in fit to sky spectrum	1
wfit	number of terms in polynomial fit to noise wave	7
cfit	number of terms in fit to calibration constants	7
nloss	flag to turn off antenna loss correction	1 (off)
nbeam	flag to turn off antenna beam correction	1 (off)
fitmode	Determines choice of basis functions	0
smooth	number frequency bins to be averaged	1
aloss	antenna loss	0 dB
wfstart	start of weighting	50 MHz
wfstop	stop of weighting	200 MHz
delayant	adapter delay on antenna S11	0
delaylna	adapter delay on LNA S11	0
delaycab	Apriori delay of noise wave cal cable	60 ns
Lh	hot load loss	0 dB
eorcen	EoR basis function center	0
eorwidth	EoR basis function width	0

3] Fundamental equations

The absolute calibration is based on the following fundamental equations

a) Power from a LNA connected to a mismatched load

$$P = \left[T_a\left(1-|\Gamma_a|^2\right)+T_u|\Gamma_a|^2\right]|F|^2+|\Gamma_a||F|\left(T_c\cos\phi+T_s\sin\phi\right)+T_\ell$$

where $F = \left(1-|\Gamma_\ell|^2\right)^{1/2} \Big/ \left(1-\Gamma_a\Gamma_\ell\right)$

and $\phi =$ phase of $\left(\Gamma_a F\right)$

T_a = input noise temperature

T_u = reflected uncorrelated LNA noise

T_c = cosine component of LNA correlated noise

T_s = sine component of LNA correlated noise

T_ℓ = portion of LNA noise independent of input match

Γ_a = reflection coefficient (S11) of input

T_ℓ = reflection coefficient (S11) of input

T_ℓ is mostly 2nd stage noise and is not important as it cancels out in the 3-position switch. T_u, T_c and T_s are slowly varying functions of frequency after the removal of phase due to a large delay in Γ_ℓ. The correlated noise wave can also be written as

$$|\Gamma_a||F|T\cos\left(\phi+\theta\right)$$

Where T and θ are the magnitude and phase of the correlated noise wave. The phase, ϕ, determines how the phase depends on the input reflection Γ_a.

b) Contribution of ambient temperature noise to the input noise

$T_a = TL\phi + T_{amb}\left(1-L\phi\right)$

Where $L\phi = L\left(1-|\Gamma|^2/L^2\right)\Big/\left(1-|\Gamma|^2\right)$

T = input noise temperature to lossy transmission line

L = loss factor in line without mismatch (1 = zero loss)

Γ = reflection magnitude at the reference plane.

If S-parameter measurements are available for the transmission limit or for parts of the transmission from the loads or antenna to the calibration reference plane then the loss theory given in memo 132 is available in the calibration software and can be selected for specific cases using the "*l*mode" number. For example *l*mode = 0 for hot load loss using S-parameters of the coaxial line from the reference plane to the heated load.

4] Calibration

The spectra of hot load, cold load, open and shorted cable in conjunction with S11 measurements of hot, cold load and LNA are used to simultaneous determine the calibration corrections and noise waves the iterative algorithm described in memo #96. This process corrects for errors in the noise diode as well as offsets in the 3-position switch. Noise is reduced by fitting the S11 data and calibration constants with a series. To avoid limiting accuracy by over smoothing the LNA electronics is made to be as broadband as possible. These calibrations corrections are applied to the antenna spectra. In addition corrections are made for antenna losses.

5] Fitting of basis functions to calibrated spectra.

The basis functions are given in Memo 112. These include the polynomials used to correct errors in the antenna S11.

The calibration results of processing of data taken in the laboratory are compressed in a single file which contains the following data for each frequency:

a) Frequency MHz
b) LNA S11 (real, imaginary)
c) Calibration scale (ratio)
d) Calibration offset (K)
e) noise waves (T_u, T_c, T_s) (K)
f) Calibration weight

This enables rapid calibration of the observations from the raw uncalibrated antenna spectrum. A zero weight indicates frequencies without calibration.

6] Test of performance

The processing software was first tested with simulations and then using the EDGES-2 hardware with a hot filament as an “artificial antenna.” The simulations were used to determine how to optimize the smoothing and interpolation of the S11 measurements and the calibration corrections.

7] Tests of performance with revised configuration

Following the proposal to add delay to the LNA tests and simulations show that there are difficulties with moving the reference plane away from the 3-position switch owing to non-uniformity in coax cable. Simulations reported in memo 114 show that the following changes are needed.

1) Move reference plane to input of 3-position switch.
2) Use open and shorted cable of at least 60 ns 2-way delay to measure LNA noise waves.
3) Make S11 measurements with averaging as discussed in memo #114.

The processing software generates 12 plots:

a) Antenna spectrum
b) Hot load spectrum
c) Ambient load spectrum
d) Open and shorted cable spectrum with fit
e) Calibrated sky spectrum
f) Fit to antenna S11

g) Fit to LNA S11
h) Fit to hot load S11
i) Fit to ambient load S11
j) Fit to open cable S11
k) Fit to shorted cable S11
l) LNA noise waves

These are produced as separate Postscript files and as a pdf file (via gs and psnup) with all plots on a single page.

Figure 1 is a single page plot of a test using an artificial source using a tungsten filament (as per memos 82, 100 and 104). The error in the calibrated spectrum shown in the upper portion of the "calibrated sky spectrum" has an rms of 346 mK. Figure 2 shows the calibrated spectrum of the open cable as an example of a check of the consistency of the calibration processing.

In general the calibrated spectrum of any of the open closed cable, ambient, hot loads should yield the assumed temperature of cable or loads respectively. The values of the loss taken for the hot load and hot filament were 0.05 and 0.02 dB respectively. The temperatures of the ambient and hot loads were 297 and 367 K. The measured temperature of the hot filament was 1575 K which is within 1% of the value of estimated from the ratio of hot to cold D.C. resistance of 7.6. The rms of 346 mK is not unreasonable for the typical error in S11 of 0.01 dB which corresponds to 900 mK for 1600 K source with -6 dB reflection coefficient.

8] Test of the required integration of calibration spectra.

Tests of the calibration show that about 2 hours of data in each calibration spectrum is sufficient to reduce the noise in the calibration discussed in section 4 to a level of about 10 millikelvin. Longer integrations may not be useful as systematics are the dominant source of error. However repeated calibrations may be useful in reducing the systematics. The reason the noise is not a problem in the calibration is due to smoothing that results from the low order polynomial fitting of the calibration constants.

Simulations of 2 hours integration for the calibration spectra gave the following

Noise added to	rms (mK)
All	13
Hot	12
Ambient	9
0pen	0.2
Short	0.3

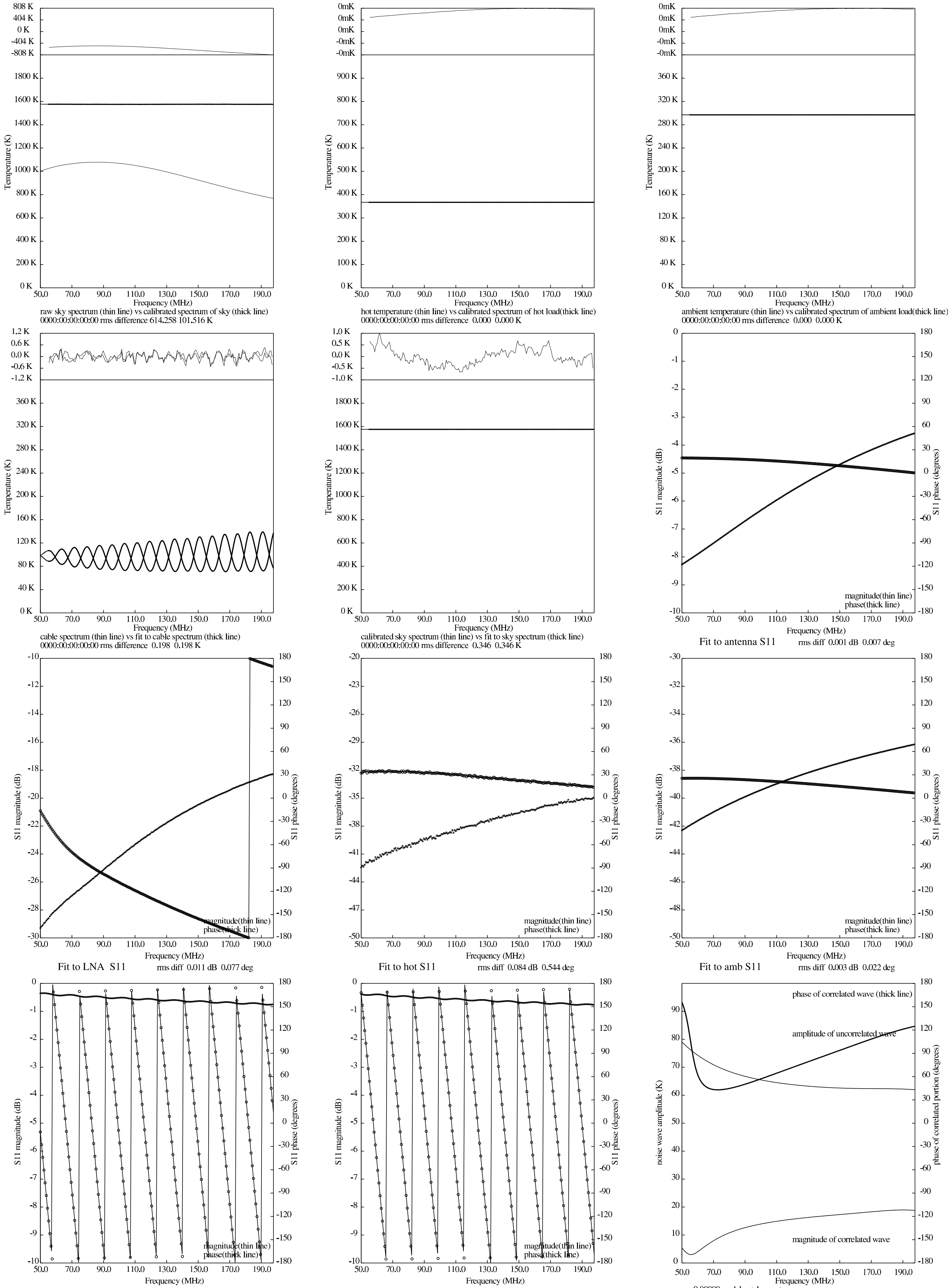

Figure 1. Spectra and S11 measurements along with calibrated spectrum of tungsten filament source.

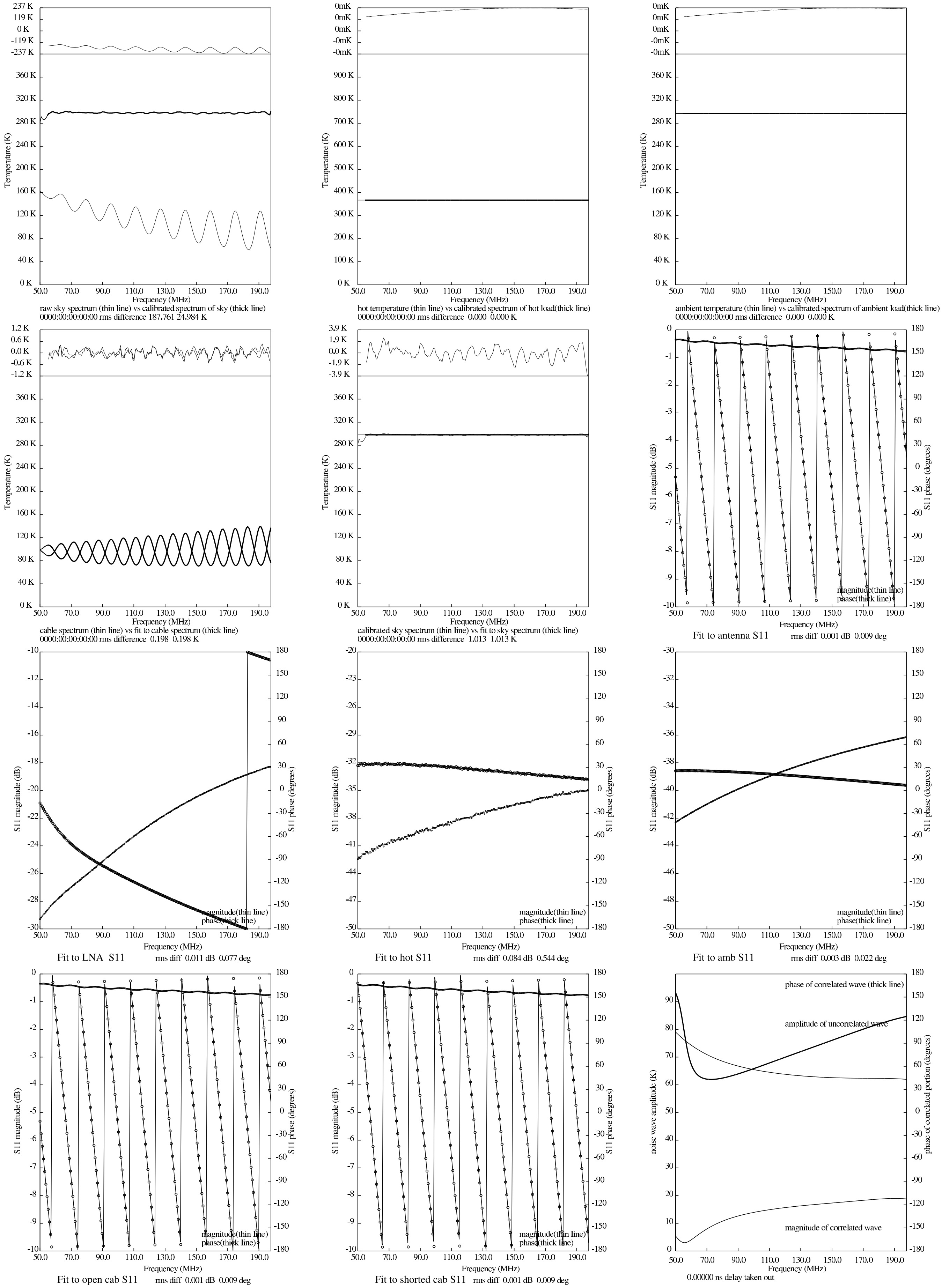

Figure2. Same processing but open cable as test source.