EDGES MEMO #104

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
HAYSTACK OBSERVATORY

WESTFORD, MASSACHUSETTS 01886

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Telephone: 781-981-5400
Fax: 781-981-0590

To: EDGES Group

From: Alan E.E. Rogers

Subject: EDGES-2 Laboratory tests of absolute calibration

Following the initial tests given in memo 82 this memo gives more details of the method and corrections needed to get higher accuracy.

1] Review of fundamental algorithms (based on Rogers & Bowman 2012)

LNA power output P

$$
\begin{aligned}
P = {} & T_{ant}\left(1-|\Gamma_a|^2\right)|F|^2 \\
& + T_u |\Gamma_a|^2 |F|^2 \\
& + |\Gamma_a||F|\left(T_c \cos\phi + T_s \sin\phi\right) + T_0
\end{aligned}
$$

Where

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

ϕ = phase of $\Gamma_a F$

T_{ant} = temperature of sky for lossless antenna

Γ_a = antenna S11

Γ_ℓ = LNA S11

T_u = uncorrelated noise wave

T_s, T_c = sine and cosine components of correlated noise

T_0 = added noise which is independent of input

While the LNA noise parameters T_u, T_s, T_c and T_0 vary with frequency the expression above exactly predicts the dependence of the power output on the antenna reflection coefficient, Γ_a.

When the LNA is connected to any passive lossy load of uniform temperature T, T_{ant} = T and Γ_a is the S11 of the load. If the load has lossy components at different temperatures then a circuit model is required to estimate the equivalent temperature. For the case of a lossless antenna connected to a lossy 50Ω transmission line it can be shown that

$$T_{ant} = T_{sky}L + T_{amb}\left(1-L\right)$$

and $L = L_m \left(1 - |\Gamma_a|^2 / L_m^2\right) \Big/ \left(1 - |\Gamma_a|^2\right)$

where L_m is the line loss when matched and Γ_a is the S11 measured at the cable end connected to the LNA.

2] 3-position switch

In order to remove the bandpass and the effects of slow gain changes the LNA is switched between the "antenna," a load and a load plus noise from a diode. In order to calibrate the system is connected to the following:

a) Ambient load
b) Hot load
c) Open cable

Using the measured S11, temperature, loss estimates and 3-position switched spectra for these devices the following effects are removed:

a) Noise diode temperature errors
b) Offset due to different temperature and S11 of the internal load of the 3-position switch

and the noise wave parameter values are determined.

3] Calibration tests

Finally the system is connected to an "artificial" antenna made from a hot tungsten filament. The output of this test source can be estimated using a measurement of the filament resistance to estimate the temperature and a circuit model to estimate the relatively small losses.

4] Circuit model test of algorithms

A test of the algorithms can be made using the simple circuit in which power is proportional to the voltage across the LNA impedance, Z_ℓ, in which case

$$P \,\alpha \left(T_{sky}\left(R_e Z_a\right) + T_{\text{lna}}\left(R_e Z_\ell\right)\right)|Z_\ell|^2 \Big/ |Z_a + Z_\ell|^2$$

Where Z_a is the antenna impedance. In addition to the simple model. Data simulated using the full LNA circuit model given in memo 62 produced the expected temperature of the antenna simulator to within 1 mK from 50 to 200 MHz.

4] Test set-up

The EDGES-2 electronics was set-up on the bench shielded from the very strong local interference in the Haystack control room. These signals are so strong that they can leak into the input through the shield of the connections to the input. The open box shield in Figure 1A was found to provide adequate shielding so that it was not necessary to work in a screen room. A HP8753C vector network analyzer shown in Figure 1B was set-up close to the EDGES so that the input of the LNA could be reached with a 24" Gortex VNA cable. The 2 VNA ports were set-up and calibrated. Port A was set with a low enough power level (-10 dBm plus 10 dB attenuator) to avoid saturation of the LNA first and second stages. The effects of second stage saturation, which effect the LNA impedance, are evident above -17 dBm. Port B was set-up at 0 dBm with 0 dB attenuators for optimum accuracy in the measurement of S11 of the ambient hot load and antenna simulator shown in figures 1C and 1D respectively with covers removed. All VNA measurements were made with 100 point averaging with 201 spectral points from 50 to 200 MHz. All calibration was done using male short, open and load. Because the load was 50 ohms within 0.1 ohm it was not necessary to make the corrections described in memo 86 but it was necessary to remove the female to female adapter and make a delay correction when measuring the LNA S11 at the female input of the LNA.

5] Details for high accuracy

a) Calibration load S11 and loss

The calibration load S11 is measured at ambient (~298K) and hot (~368K). While the loss between the LNA and the load has no effect at ambient as the entire structure is at a uniform temperature the loss at the “hot” temperature estimated to be 0.02 dB at 100 MHz reduces the effective temperature from that measured by the Fluke thermocouple probe by about 0.5 K. In addition the loss puts a slope and curvature on the spectrum since the loss is resistive and increases with the square root frequency as a result of the decreasing skin depth. Corrections for the S11 and loss are made in the software which iteratively corrects measured spectra for error in the noise diode and comparison load offset as described in memo 96.

b) Temperature of LNA and comparison load.

Like a VNA EDGES-2 is assumed to remain at a constant temperature during calibration. Further the 3-position switch needs to be running for about 30 minutes prior to any measurement to ensure a repeatable temperature distribution within the front-end. The primary effect is the change of temperature the comparison loss which results in a constant offset. While EDGES-2 should be operated in a constant temperature environment the application of linear corrections based on calibration at 2 temperatures should allow accurate results to be obtained for operation in an environment in which the temperature changes slowly.

c) Calibration verification using “artificial antenna”

The tungsten filament hot load provides a near ideal “artificial antenna” since the load is mismatched, has low loss and has a high temperature that can be accurately estimated from the change in resistance between ambient when no current is applied and “hot” when current is applied. However several issues have arisen:

1) A filament with intermediate supports can produce changes in S11 and temperature with orientation or vibration. This problem is solved by using a “fuse style” lamp in which the filament is only supported at the ends.
2) It is not clear if the filament is made of pure tungsten or contains certain enhancing impurities like thorium which makes the filament less brittle. However experimental data on thoriated tungsten show that it has little effect on the resistance vs temperature. If impurities do effect the resistance curve then filament source still provides a check on the spectral flatness and not the temperature scale.
3) Loss in the inductor needed to isolate the power source
   In order to reduce the loss a handmade solenoid inductor made of 20 turns of 30 a.w.g. wire on a 5mm diameter rod. The loss of the parts of the filament load which remain at ambient can be measured from S11 measurements a unit in which a filament is absent and shorted.
4) Loss at ends of the filament

A small reduction of the effective temperature results from the ends of the filament. First this is very small, a few millimeters out of several centimeters and second the reduced temperature results in lower resistance so the effect on the temperature determined from the change of resistance is compensated. In the 50-200 MHz range the tungsten wire diameter is less than the skin depth so there is no effect on the spectral flatness.

6] S11 and temperature sensitivity from simulations

Data generated from the circuit model of the LNA was used to test the LNA optimization. For an antenna with S11 of -12 dB the rms deviation (after removal of scale) due to error in the measured temperature are relatively small at 13 mK per 1000K per K.

The results of errors S11 amplitude and phase are summarized in table below

	Amplitude	Phase
Antenna	70 mK/0.01 dB	400 mK/degree
Noise wave cable	16 mK/0.01 dB	50 mK/degree
LNA	30 mK/0.01 dB	400 mK/degree
Loads	30mK/dB	5 mK/degree

Table 1 Effect of error in S11 measurements

These results are for an optimized LNA with S11 about -20 dB and an antenna temperature of 1000 K. Improving the antenna match reduces the sensitivity to errors in S11 amplitude in proportion S11 power while the sensitivity to phase S11 errors are only reduced in proportion to S11 voltage. Errors which result from errors in the loss estimates are independent the LNA and its calibration.

7] Results of tests with “artificial antenna”

Measurements of S11 of the artificial antenna, LNA, cable used to calibrate noise wave parameters, hot load, and ambient load are shown in Figure 2A,B,C and D respectively. In each case the S11 data is fit with a Fourier series in a least squares sense. This reduces the noise in the measurements and allows accurate interpolation to be observed spectral frequencies which can have a different spacing than those of the S11 measurements. The 3-position switched spectra of the artificial antenna, hot load, ambient load, noise wave calibration are shown in Figures 3 A,B,C and D. In each case the residuals is to the fit to the spectrum is shown at the top.

Figure 4 shows the noise wave parameters derived from the data and Figure 5 shows the corrected spectrum of the artificial antenna and the residuals to a constant 1587 K. The rms deviation from a constant shown at the top of Figure 5 is 842 milli K. While this result is a long way from a goal of a few milli K the effect of errors in S11 are more than four times larger than expected for an antenna S11 magnitude of -15 dB compared with the artificial antenna S11 magnitude of about -5 dB.

8] Comments on results and plans for improvements

a) LNA noise and S11
The LNA noise is higher than expected at the low end of the 50-200 MHz band. This may be due to some losses in the 2μH ferrite core surface mount inductors used between the input and the HEMT. Tests are planned using air core inductors with lower loss. It also is expected that the variation of the LNA noise waves will be well represented by a lower order polynomial than the fifth order used to fit the spectrum shown in figure 3D so clearly there is some unwanted rapid frequency dependence in the LNA circuit which needs to be removed.

b) VNA accuracy
The sensitivity to the VNA phase error poses a challenge in the measurement of the LNA S11 which needs to be made at the low level to avoid saturating the 2^{nd} stage. Longer averaging times and more care is needed in this measurements. More tests and checks on the VNA calibration at these low levels are in progress

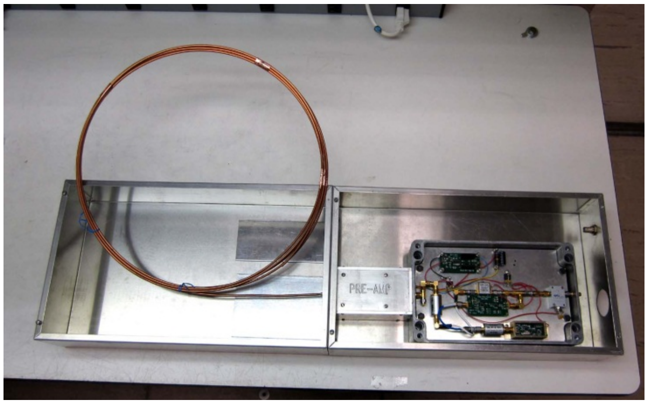

Fig. 1A Edges in open box shield connected to cable to calibrate noise waves.

Fig. 1B HP8753C VNA

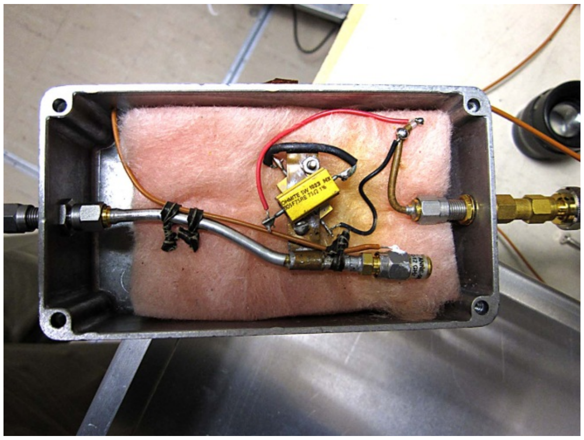

Fig. 1C. Hot/Cold load

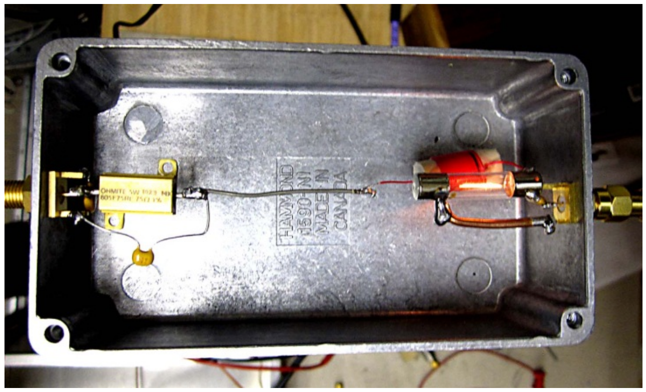

Fig. 1D. Filament load

Figure 1

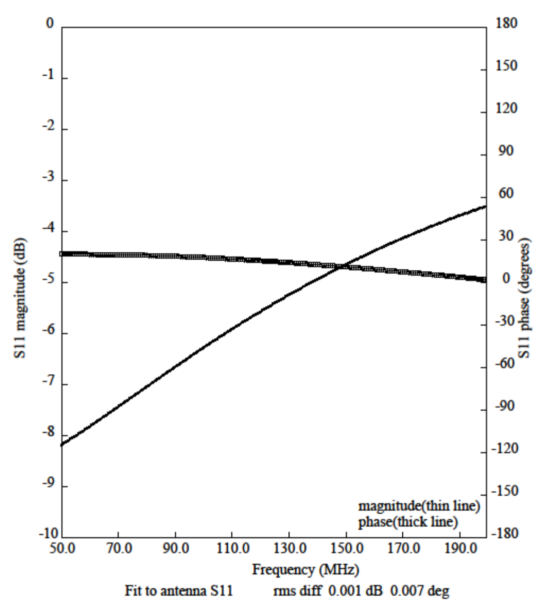

Figure 2A

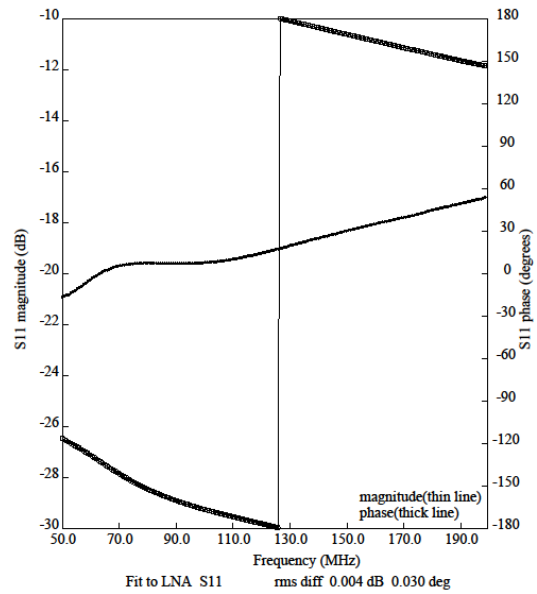

Figure 2B

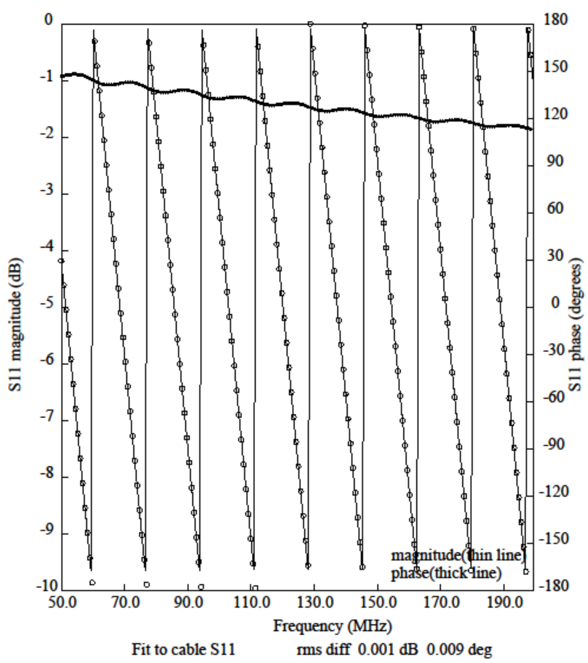

Figure 2C

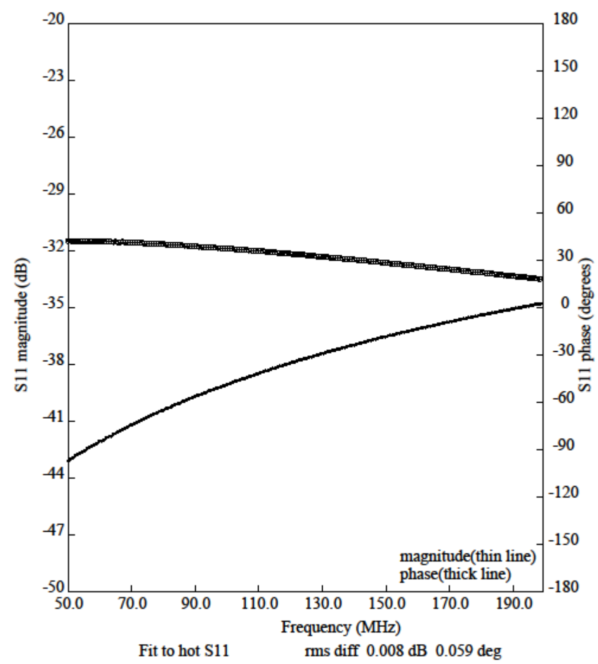

Figure 2D

Figure 2. S11 measurements of the "artificial antenna," LNA, cable used to measure the LNA, cable used to measure the LNA noise waves and calibration load at 100°C. The S11 of the calibration load at 25 C which is not shown is about -40 dB.

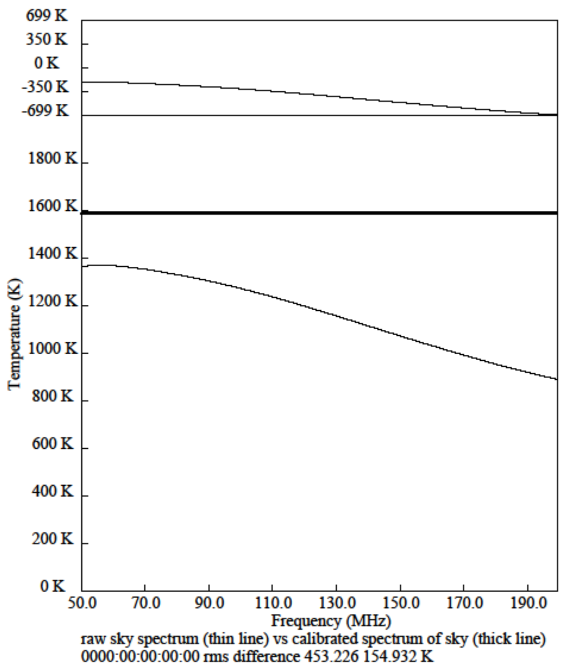

Figure 3A

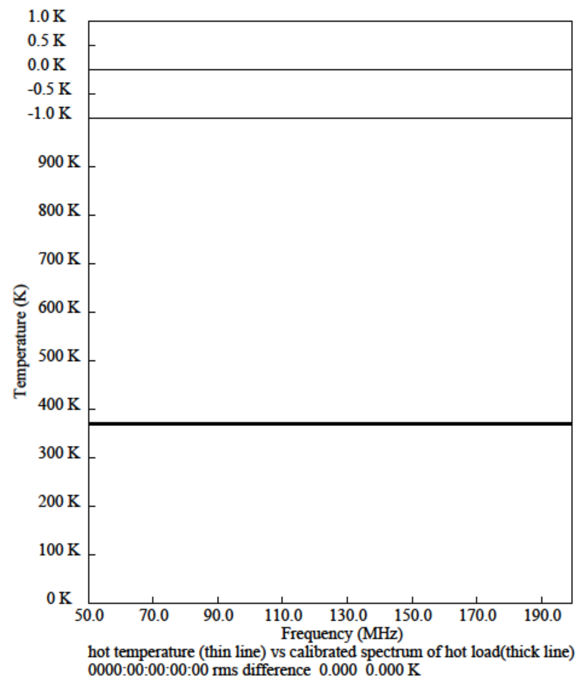

Figure 3B

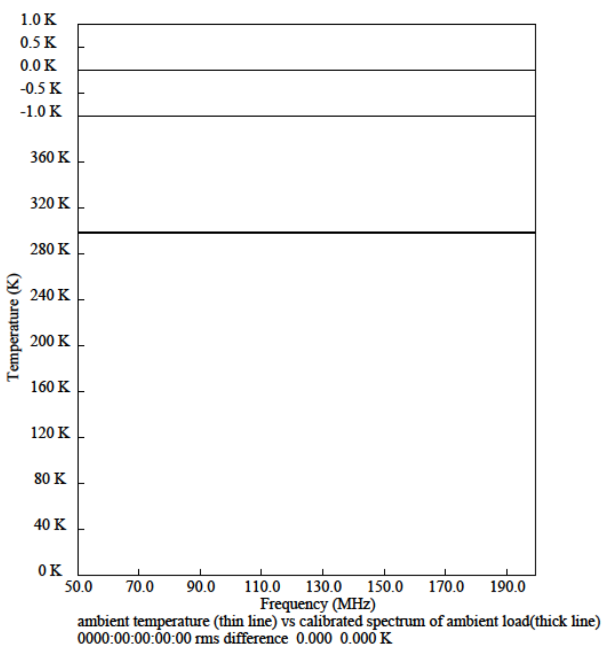

Figure 3C

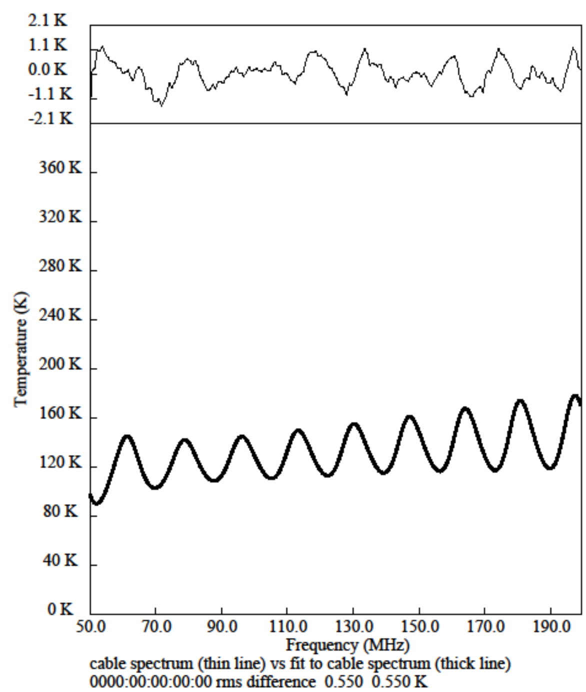

Figure 3D

Figure 3. The calibrated spectra of the artificial antenna hot and ambient loads and cable used to calibrate the LNA noise waves. The residuals to each fit are plotted at the top of each figure.

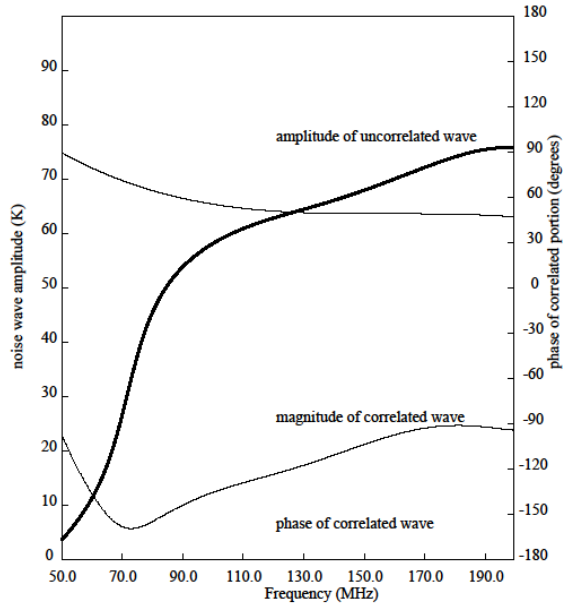

Figure 4. Noise waves. The thick line is the phase of the correlated wave.

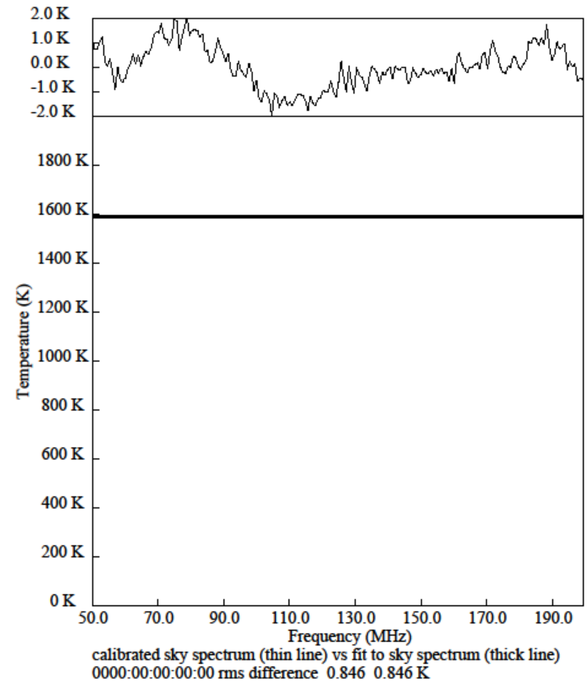

Figure 5 Calibrated spectrum of "artificial antenna" after corrected for losses of 0.008 dB.