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December 21, 2011

To: EDGES Group

From: Alan E.E. Rogers

Subject: A laboratory test of the absolute calibration using an antenna simulator

1] Introduction:
EDGES Memo #80 described a method of absolute calibration (more details are in a paper "Absolute calibration of a wideband antenna and spectrometer for sky noise spectral index measurements by Rogers and Bowman recently submitted to Radio Science). Memo 81 outlines some initial tests of the method. A more complete test has now been made using a "hot filament" source which includes a balun.

2] Antenna simulator
Figure 1 shows the circuit diagram of the antenna simulator and Figure 2 is a photograph of the unit with the cover removed. The basic concept behind the "antenna simulator" is that the hot filament emulates the sky noise temperature presented to the EGES 3-position switched receiver via various stray reactance to which is added the loss and ambient thermal noise from the balun. The incandescent lamp provides a poorly matched source of noise at a temperature over 1000 K and should be spectrally flat once the mismatch and balun are taken into account although these remain an issue concerning the effects of the skin effect producing a frequency dependent weighting of the variations of temperature along the filament.
The use of the tungsten filament as a hot noise source can also be used to check or set the temperature scale since its temperature can be measured via the change in resistance. For the measured 8.26 ± 0.1 fold increase in resistance the temperature is 1670 ± 30 K from tables of tungsten resistance, assuming 294 K for the ambient room temperature.

3] Initial results
Figure 3 shows the antenna simulator reflection coefficient measurements and polynomial fits. While measurements could be made at more closely spaced frequencies a least squares fit using a smooth curve is needed to remove noise and allow interpolation to the precise frequencies of the spectrometer channels. These show that in general a polynomial can be fit with fewer free parameters than a Fourier series. Figure 4 is the measured LNA reflection coefficient rms and Figure 5 shows the spectrum of the noise wave calibration cable. Figure 6 shows the partially calibrated spectrum prior correction for the balun. Figure 7 shows the observed spectrum prior to correction for the mismatch and balun along with the corrected spectrum and the best fit constant. The rms deviation from a flat spectrum is 1 K and the constant is 1666 ± 0.5 K.

4] The Measurements needed are listed in the table below

Item	Measurement	Comments	Purpose
Antenna	Impedance	In field	Calibration
Antenna	Spectrum	In field	Observation
Balun	Impedance	In lab open	Calibration
Balun	Impedance	In lab shorted	Calibration
Hot load	Spectrum	In lab	Noise diode calibration
Open cable	Impedance	In lab	Noise wave calibration
Open cable	Spectrum	In lab	Noise wave calibration
Hot load	Impedance	In lab	Calibration check
Antenna simulator	Impedance	In lab	Calibration check
Antenna simulator	Spectrum	In lab	Calibration check

Note: If connector of the device under test doesn't match the SOLT calibration connector corrections for adapters need to be made. Also it is assumed that the SOLT offset delay correction has been entered in the VNA.

5] Sources of error

While initial results provide some confidence that the method is correct the rms deviation is more than an order of magnitude larger than the goal of under 100 milli K. The problem is largely lack of accuracy and attention to detail. For example, an error of about 0.1 dB or 5 degrees in phase in antenna reflection coefficient produces an error of about 20 K. the high sensitivity is due to the relatively poor match of the antenna simulator.

The following are some "lessons learned:"

1. Use sufficient averaging time when calibration and making measurements with VNA.
2. Use the appropriate sex of SOL (short open load) when calibrating the or correctly account for the use of a male to male adapter when measuring the LNA impedance at the female input. In each case the reference plane needs to be precisely at the interface of the LNA to the antenna. For example a 1 cm long adapter has a 2-way delay of 100 ps which corresponds to a phase shift of 7 degrees at 200 MHz.
3. Be careful to avoid flexing the cable to the VNA between calibration and measurement.
4. VNA measurements of the open cable used to measure the LNA noise waves, need to be made rather than assuming a delay and loss from cable datasheet. The VNA measurements are fit to model parameters of delay, impedance, and attenuation which depends on the square root of frequency. Alternately a polynomial fit could be made to the reflection magnitude and phase but the rapid variations due to a deviation from 50 ohms require a high order polynomial.

5. The hot load used to calibrate the internal noise diode needs to have a near perfect match of 50 ohms with 0.1 ohms at the operating temperature.
6. The ferrite impedance in the balun needs to be measured using VNA measurements with open and shorted balanced ports. It is not yet clear if the model of the balun as a perfect transformer with twice the ferrite impedance in parallel with the balanced port is sufficiently accurate. It is noted that while the ferrite chokes are largely resistive their stray reactance makes a transition from inductive to capacitive at about 100 MHz.
7. The EDGES electronics is not temperature controlled so that temperature coefficients of the change in LNA impedance, noise waves etc. will be needed so corrections can be made based on a measurement of the temperature. However these coefficients are quite small, for example, the temperature coefficient of LNA impedance is of the order of 0.01 Ω/K.

Summary

In summary a great attention to detail and care is needed to obtain accurate calibration. The table below summarizes the level of error measurement in current tests.

Measurement	Number of terms in fit	Rms
Antenna S11	9	5×10^{-4}
LNA S11	13	1×10^{-4}
Balun impedance	5	2Ω
Noise wave calibration spectrum	4	0.3 K
Noise wave calibration cable delay	1	50 ps
Noise wave calibration cable loss	1	0.1 dB
Noise wave calibration cable impedance	1	0.1Ω

280   0.02

1uH   0.02

Choke
Balun

1:1   0.02

0.1uH

SMA male

Zf
Zf

+28v

28v lamp
22 ohms cold
220 ohms
at 1794K

0.02

2 x Zf ~ 800   1uH

Tungsten rsistance
273 K   1.0
472 K   2.0
835 K   4.0
1485K   8.0
1794K   10.0
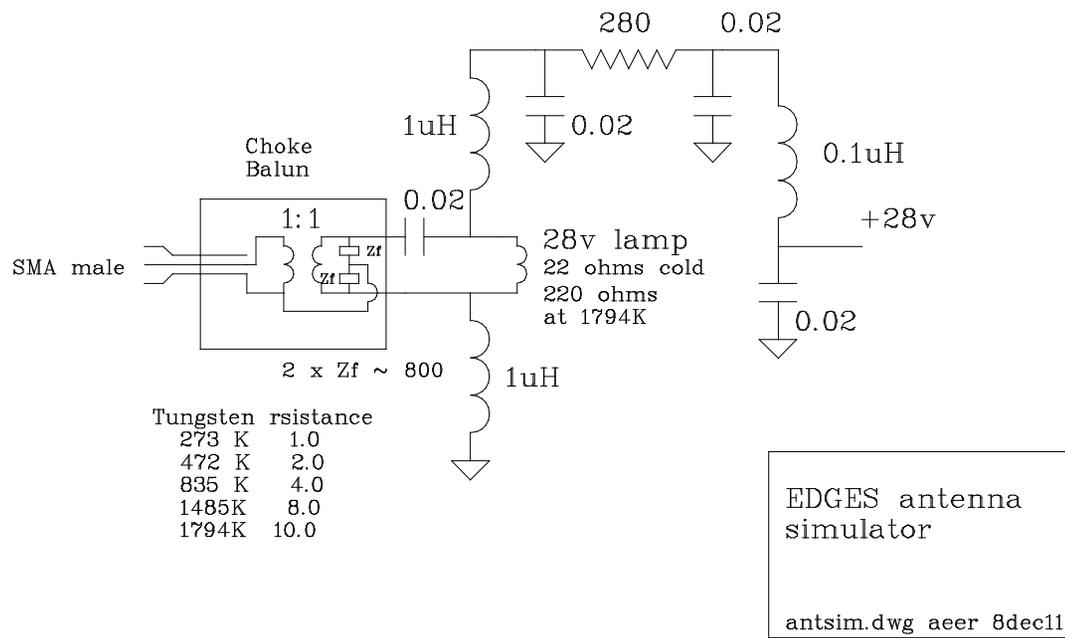
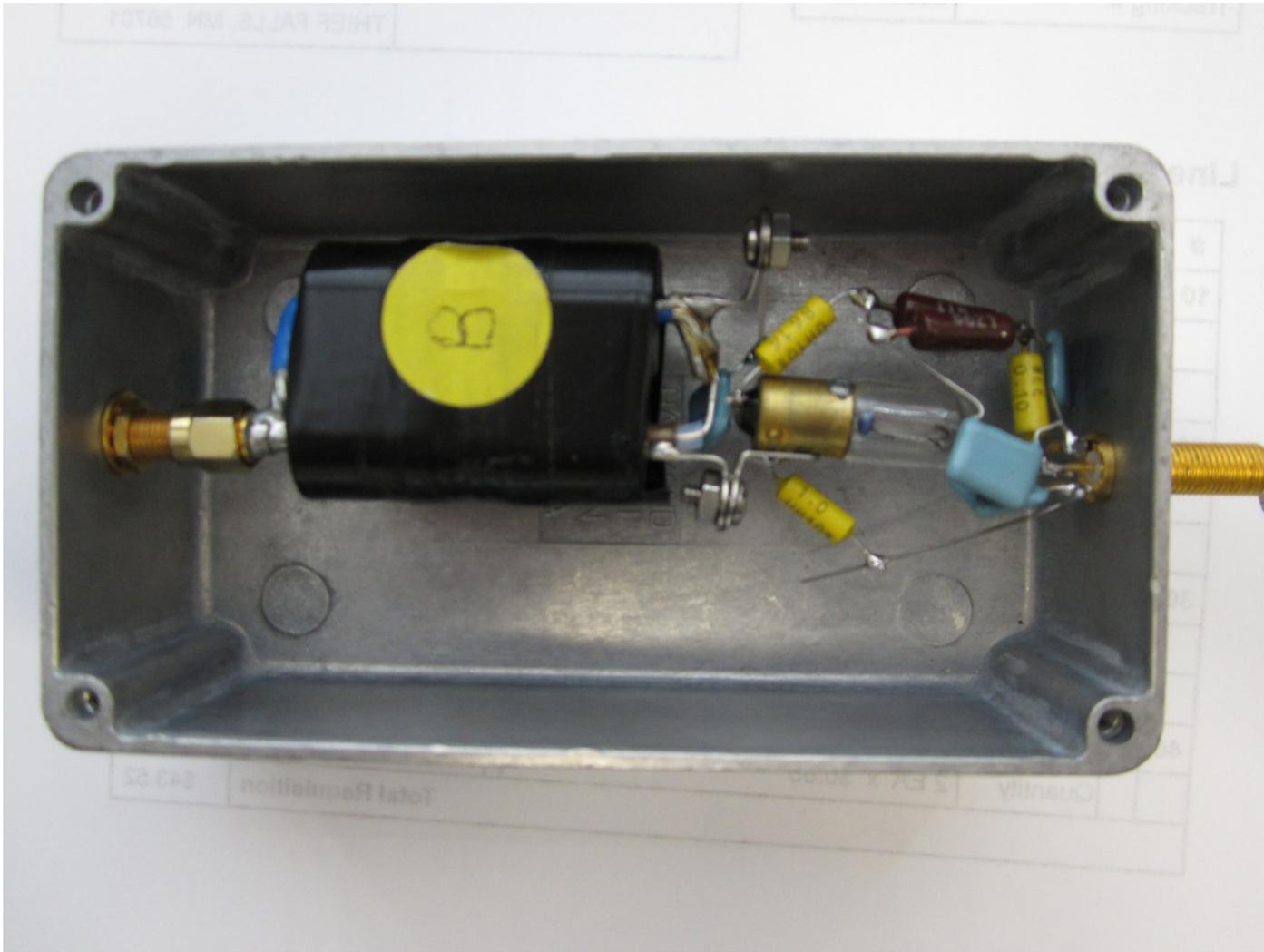EDGES antenna
simulator

antsim.dwg aeer 8dec11

Figure 1

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Figure 2. Antenna simulator with balun and hot filament noise source
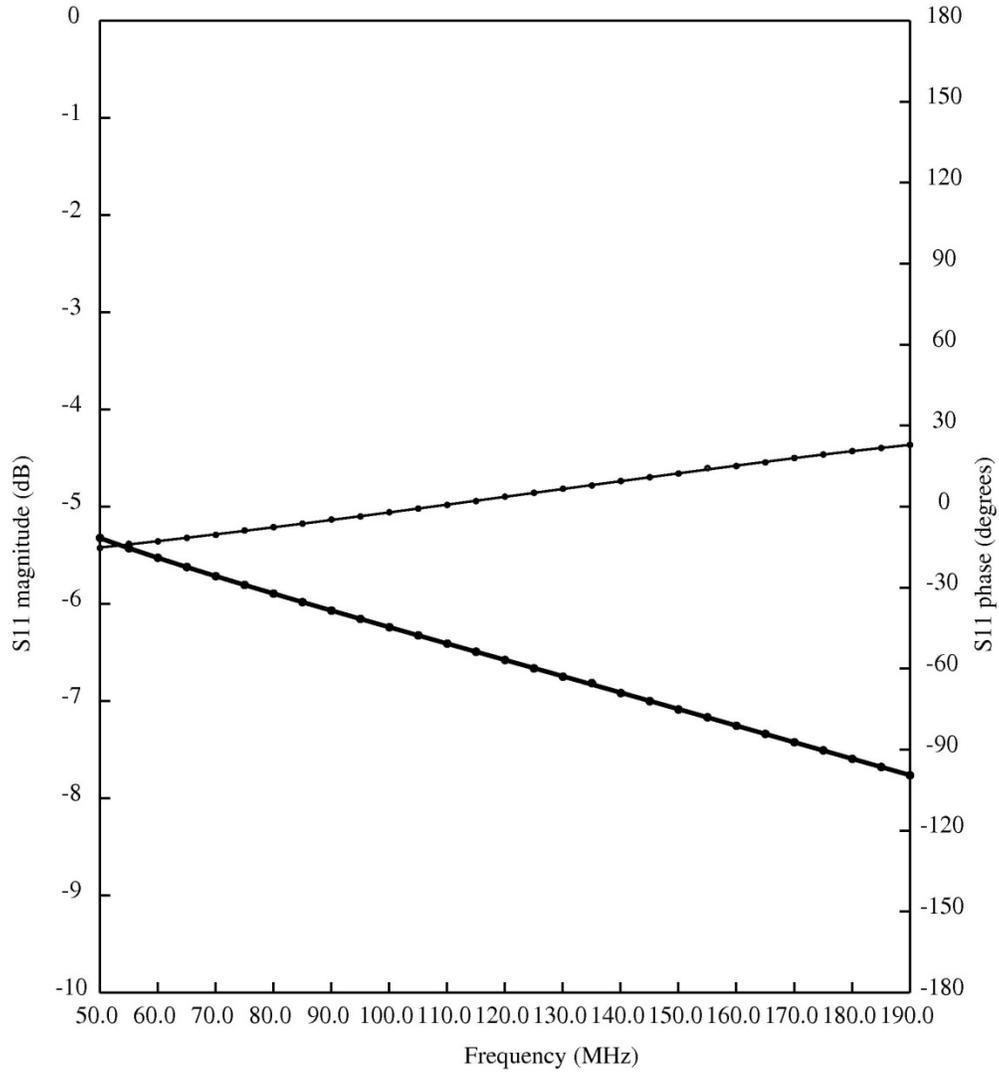
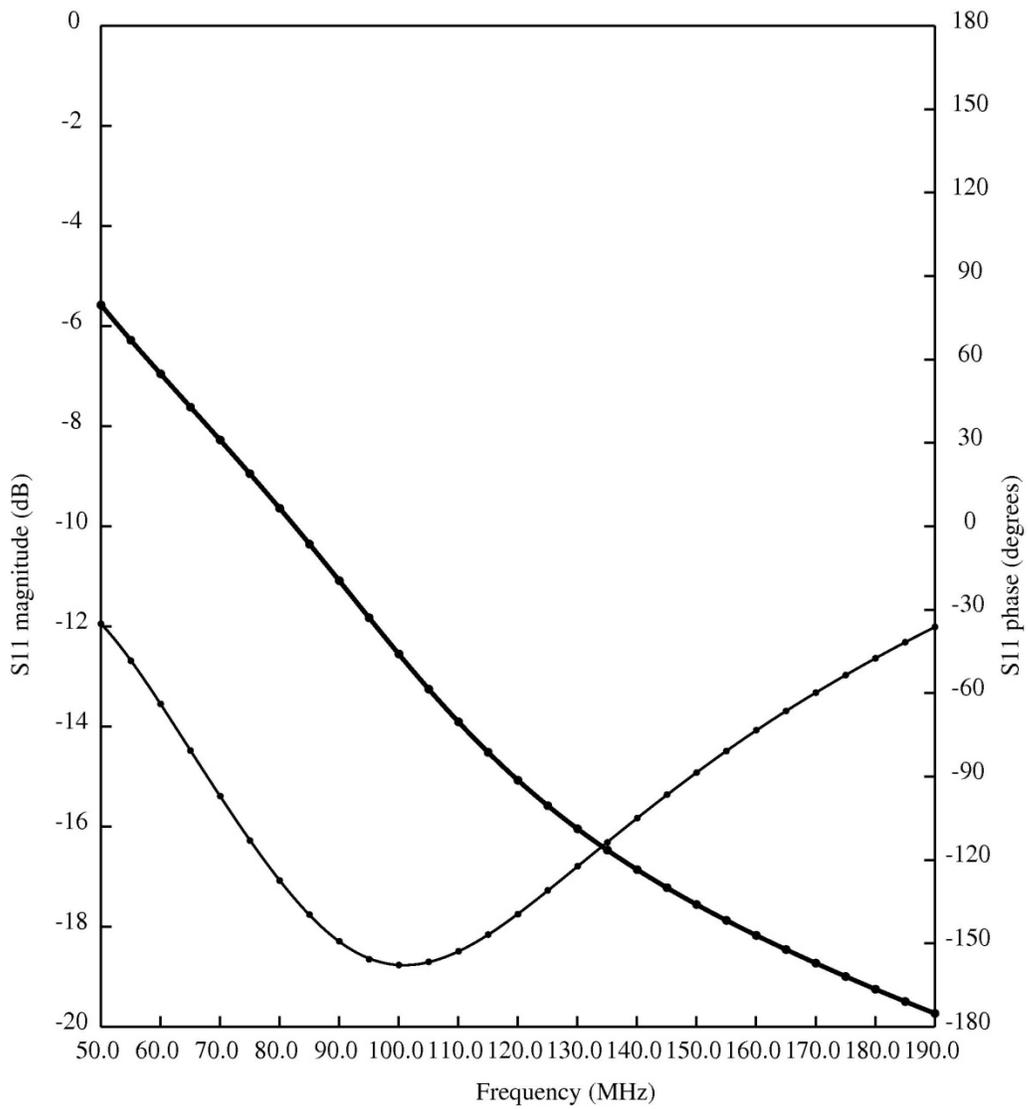Figure 3. Antenna simulator reflection coefficient. Thick line is the phase. Cures are a polynomial fit to the measurements.

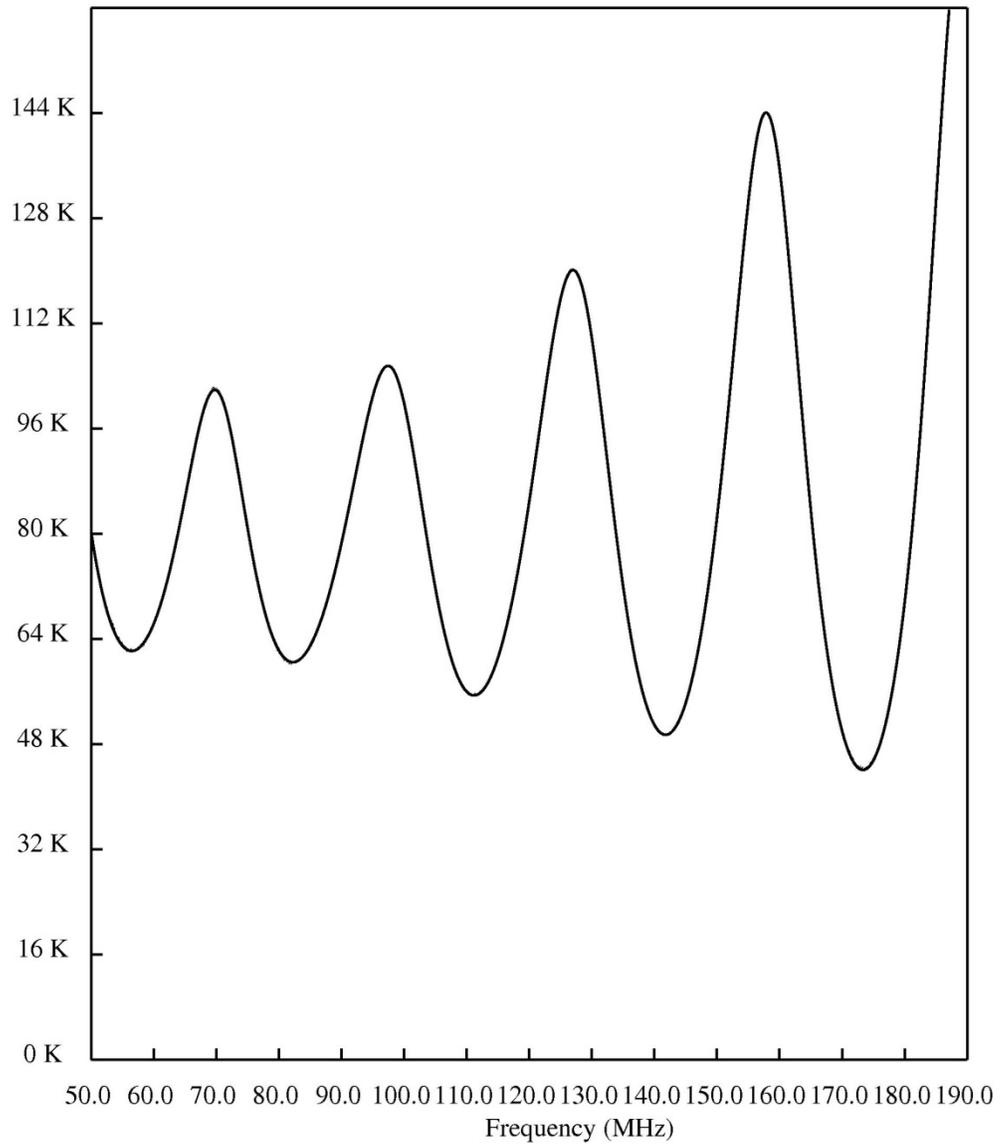Figure 4. LNA reflection coefficient. Thick line is the phase. Curves polynomial fits to the measurements.

Figure 5. Spectrum of the noise wave calibration cable and fit using 4 term polynomial for each of the 3 noise wave parameters.
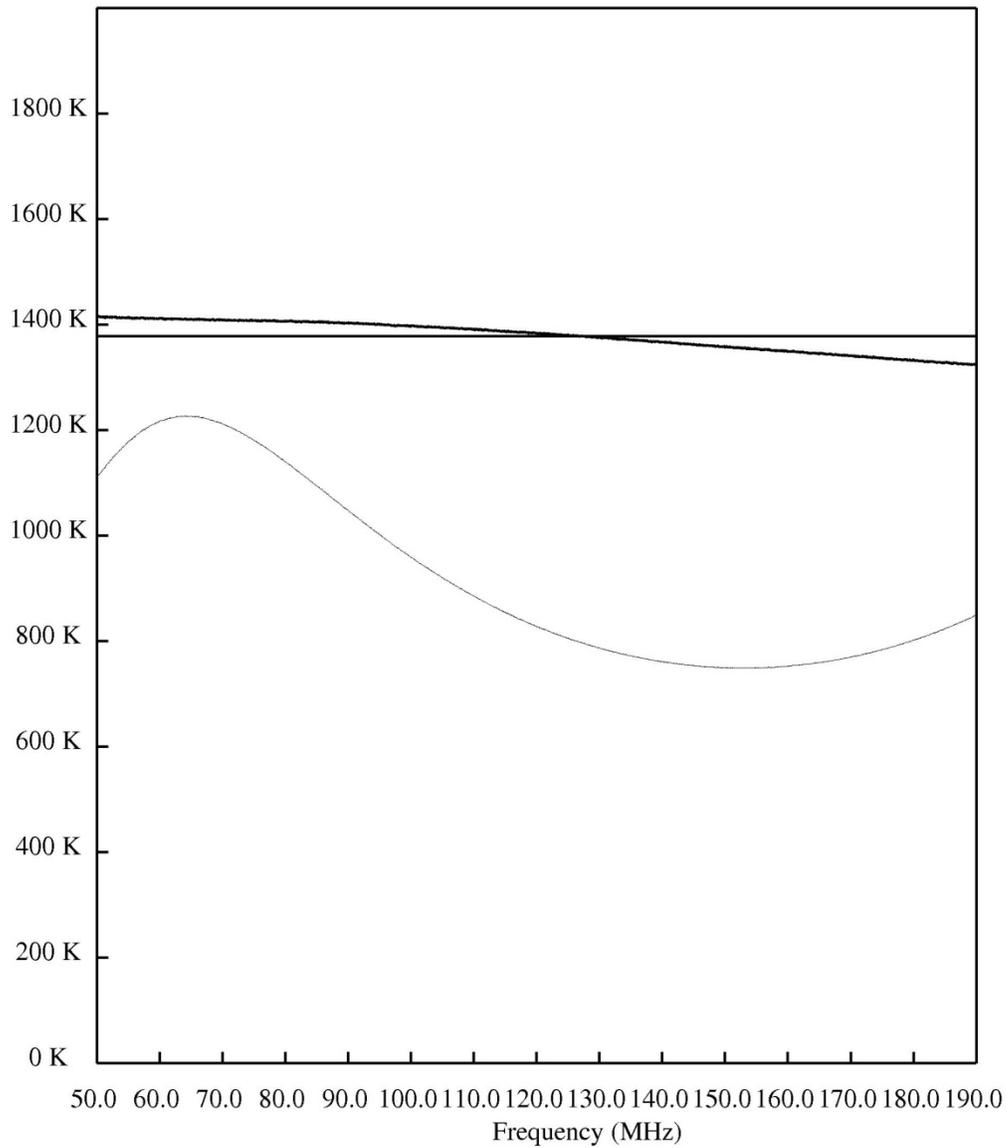
Figure 6. Partially calibrated spectrum prior to correction for the balun. The lower curve is the observed spectrum before calibration. The upper curves are the partially calibrated spectrum and best fit constant of 1377 K.
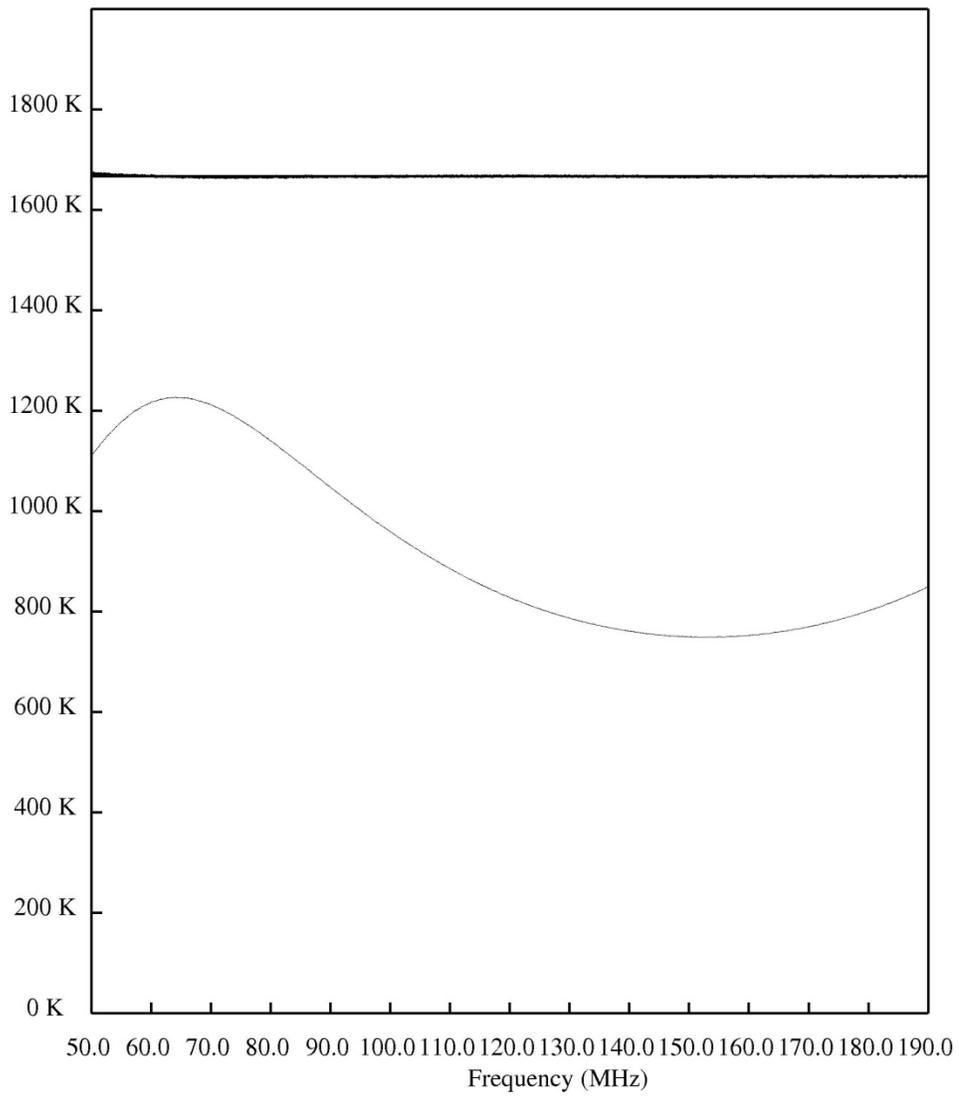
Figure 7. Calibrated spectrum. The average is 1666 K and the rms deviation from a constant is $1^{\circ}K$.