Microwave Radiometry – Laboratory Experiment

JEFFREY D. DUDA

Iowa State University Department of Geologic and Atmospheric Sciences

ABSTRACT

A laboratory experiment involving the use of a microwave radiometer to measure the brightness temperature of the sky and of the roof, as well as the emissivity, of Agronomy Hall on the Iowa State University campus is described in detail. An analysis of the data compares experimental brightness temperatures to those of a simple model of the atmosphere. The model is quite inaccurate, as the results will tell.

1. Introduction

On 9 April 2010, the students and faculty of a microwave remote sensing course at Iowa State University performed a simple experiment. In this experiment they compared the brightness temperature of the atmosphere obtained from a simple model to that obtained by an L-band radiometer. They also estimated the emissivity of the roof of Agronomy Hall. Some parameters characterizing the stability of the radiometer were also computed. This write-up details the investigation, including a description of the instrument used, initial data retrieved, an analysis of that data, a comparison between that data and that which would be expected from a model, and an estimation of the emissivity of the roof of Agronomy Hall.

2. The Radiometer

The instrument used was an L-band Direct-Sampling Digital Radiometer operating on a central frequency of 1.4 GHz. Figures 1 – 3 show selected components of the radiometer. Note in Fig. 2 that the radiometer actually consists of two, one for v-pol and one for h-pol radiation. These two radiometers were also termed channels A and B, one for each polarization. Although it had been a goal to identify which channel was v-pol and which was h-pol, as it turned out, one of the channels was bad, and therefore such an identification was not attempted.

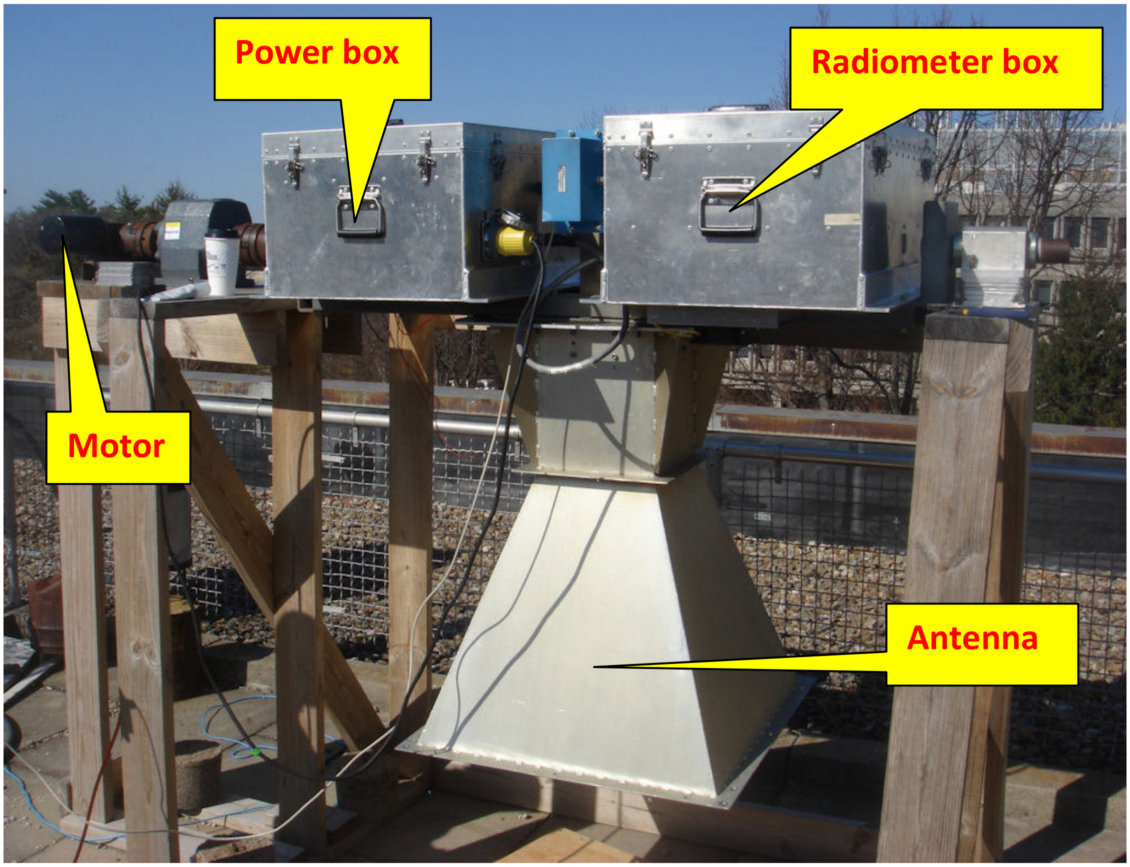

Figure 1. L-band radiometer: outer components

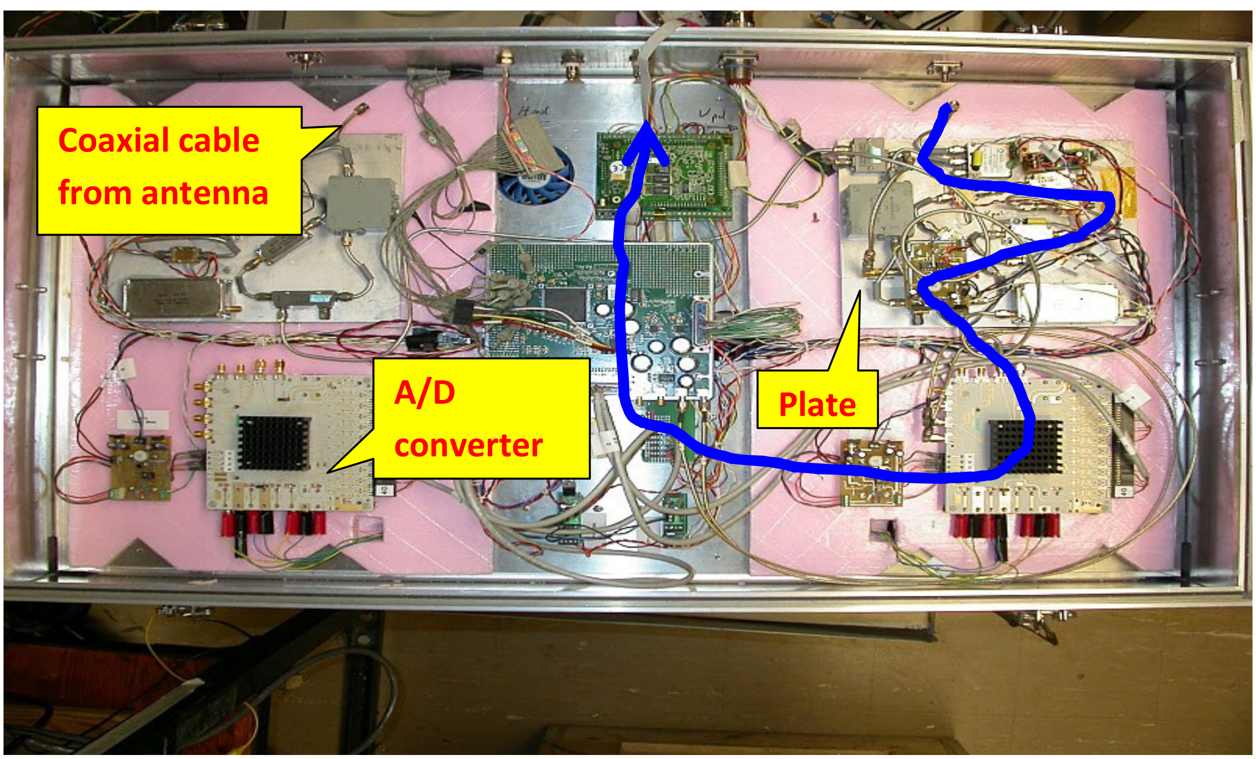

Figure 2. Detailed look of the radiometer box part of the L-band radiometer. The blue curvilinear arrow headed line shows the path through which the microwave signal travels from when it enters the horn antenna to when it goes to the software for storage.

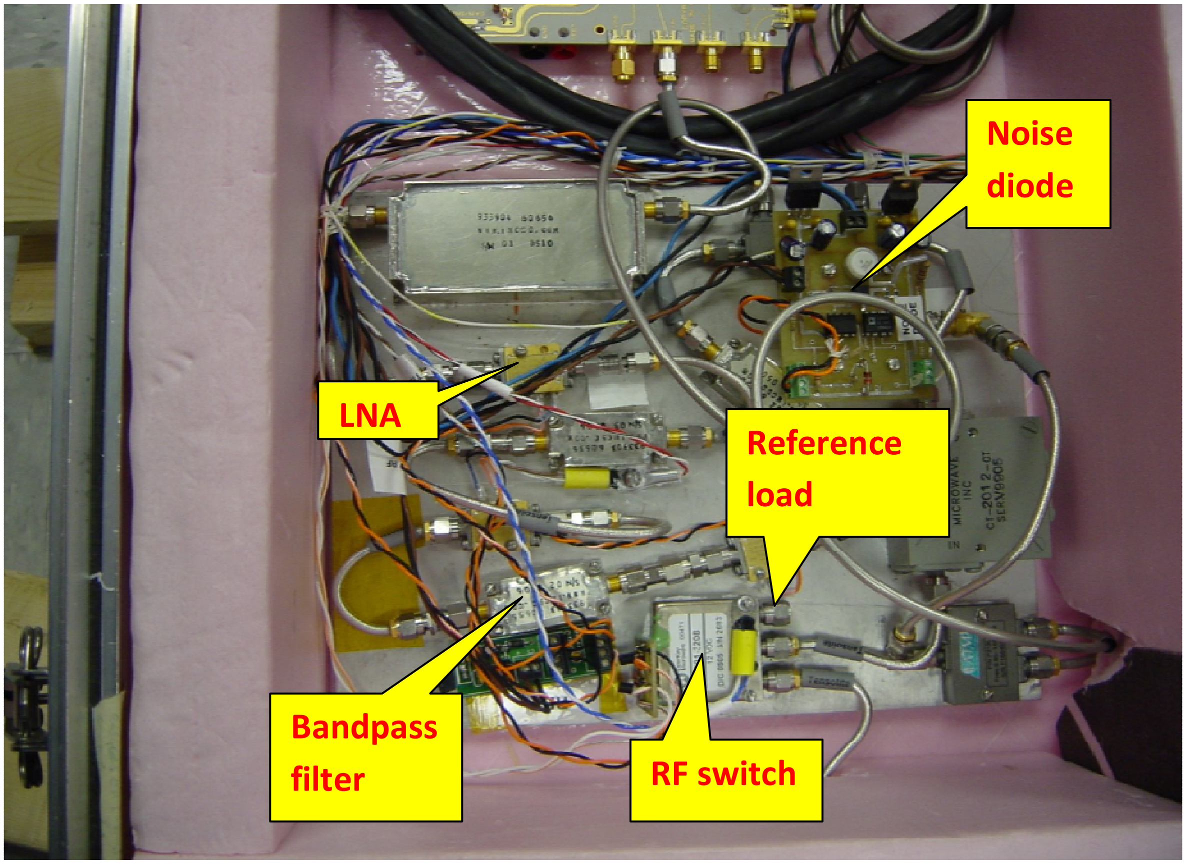

Figure 3. Detailed look at one of the sides/channels of the radiometer box.

3. Radiometer measurements

The goal of the experiment was to obtain brightness temperature measurements of the sky and of the roof of Agronomy Hall. Like nearly all electronic devices, the radiometer does not directly output the sought measurement, brightness temperature in this case. Instead, it outputs an analog voltage signal, which is digitized through an A/D converter. The converted digital signal then must be converted into a brightness temperature through a calibration. This calibration is sensitive to many things, including the temperature of the electronic components themselves and of their immediate ambient environment. Figure 4 illustrates the stability of that environment and of the electronics through a time series of plate temperature for the two radiometers. Figures 5 and 6 illustrate the stability of the calibration techniques used to obtain brightness temperature from the radiometer output.

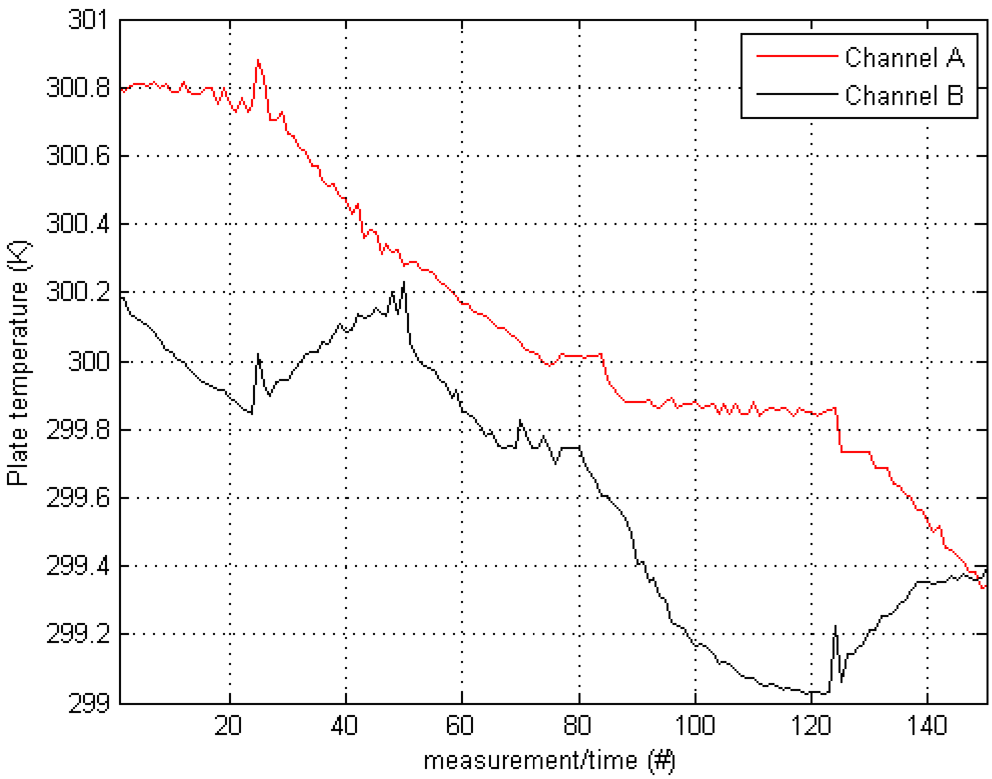

Figure 4. Time series of plate temperature for the two channels/radiometers.

Figure 4 shows that the plate temperature for both channels generally decreased throughout the experiment period, which was about 2.5 hours. However, the decrease was small, only about 0.8 – 1.4 K. The standard deviations of the plate temperatures are 0.424 K for channel A and 0.385 K for channel B. It is hypothesized here that this variability over the course of the experiment does not result in any significant error or difference between the brightness temperatures obtained in this experiment and those that would be obtained in an identical experiment given the exact same atmospheric and celestial conditions, but with more stable plate temperatures.

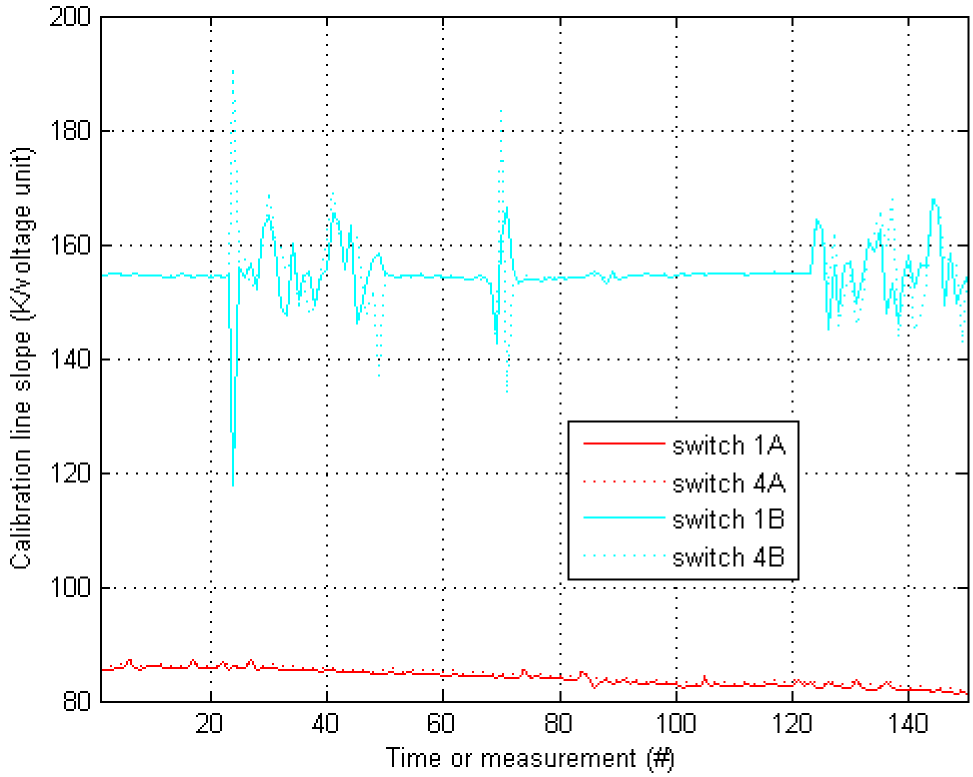

Figure 5. Time series of the slope of the calibration line used to obtain brightness temperature from the radiometer output.

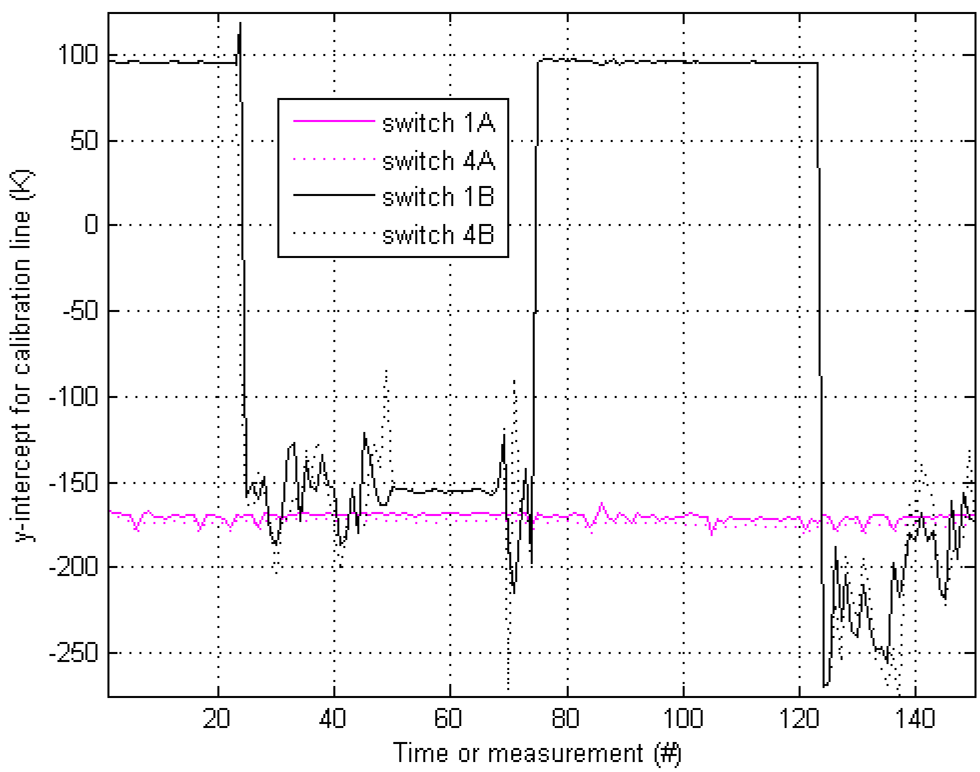

Figure 6. Time series of the y-intercept of the calibration line used to obtain brightness temperature from the radiometer output.

Actual brightness temperature was obtained from the radiometer through a calibration process that used radiometer output from two sources with known brightness temperature. The two sources are a reference load and a noise diode. Using the output voltage from these two sources, a series of calibration lines were made, one for each measurement (there were ~150 measurements made). Figures 5 and 6 show how the slope and y-intercept of those calibration lines changed throughout the experiment. It can be seen that the calibration for channel A was quite stable, whereas that for channel B was not. It is believed that hardware issues caused the radiometer that comprises channel B to malfunction during this experiment, and thus little useful data was obtained from it. The resultant brightness temperatures obtained from the calibration procedure is shown in Figure 7 below.

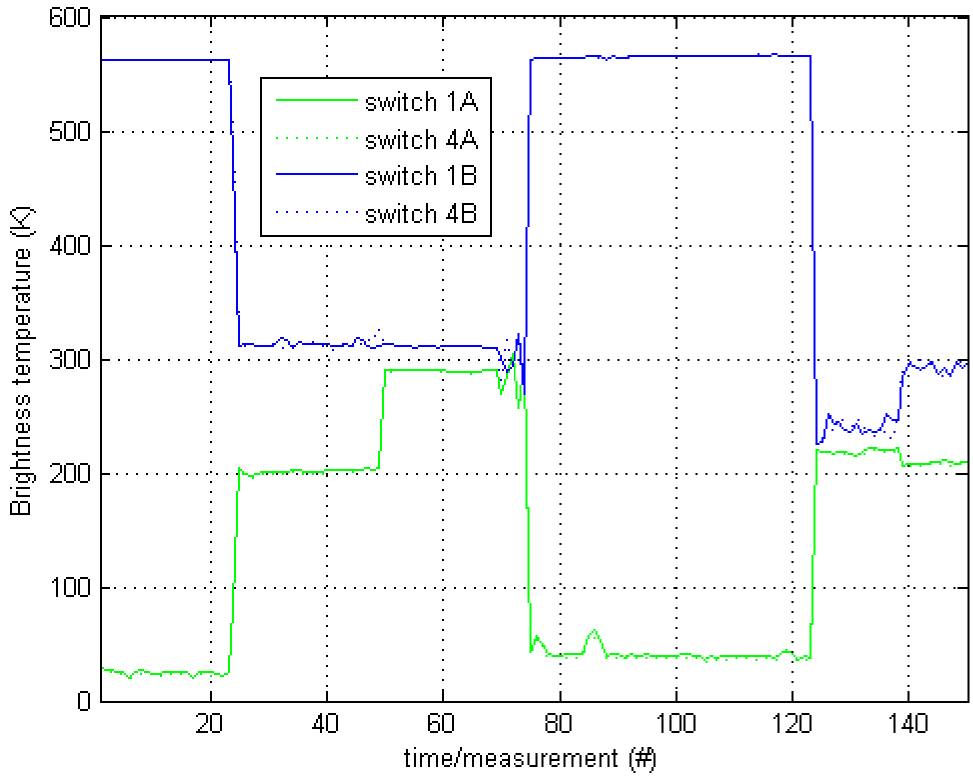

Figure 7. Time series of brightness temperature from the radiometer.

Measurements were made of two features: the sky when the radiometer was pointed more or less straight up at a zenith angle of 0°, and the roof of Agronomy Hall when the radiometer was pointed more or less straight down at an incidence angle of 0°. Brightness temperature measurements of these features is illustrated between measurement numbers (as indicated on the x-axis of Fig. 7) 50 – 70 for the roof and 80 – 120 for the sky, as well as measurements 130 – 150, at which time the radiometer was pointed at the roof of Agronomy Hall, but likely at an incidence angle of > 0°. Presumably, measurements 0 – 20 are also of the sky, and measurements 30 – 50 as well as 130 – 150 are of the roof of Agronomy Hall, although that can't be confirmed. By computing the mean of the brightness temperatures obtained from channel A, switches 1 and 4, the brightness temperature of the sky was estimated to be 40 K, while that of the roof of Agronomy Hall was 289 K. Note that these numbers were obtained using the values from measurements ~75 - ~120 and ~50 - ~70. The sky brightness temperature seems rather high compared to the expected value of 6 to 8 K. This disparity is probably due to bad parts in the radiometer, but could also be due to calibration errors. It was assumed that the radiometer is linear so that the calibration equation for each measurement is a line, when in fact it may not be. Also, for both the sky and roof measurements, the actual values of brightness temperature were *extrapolated*, rather than *interpolated*, from the calibration lines, because the brightness temperatures of the reference load and noise diode are about 299.5 K and 429.5 K, respectively, and since the measured brightness temperatures obtained from the calibration lines (at least for channel A) are never in that range, then the $r_{Q,a}$ (actual radiometer output) values used to obtain them were located *outside* the range of values used to obtain the calibration line (i.e., $r_{Q,r} \leq$

$r_{Q,a} \leq r_{Q,r+n}$ is false). Extrapolation of data can lead to inaccurate results. Figure 7 also reveals more evidence of the suspected malfunction of the radiometer that comprises channel B, given that measurements from that channel indicate sky brightness temperature between 500 K and 600 K, which is obviously not true (the atmosphere would have to be warmer than 500 K to 600 K for these measurements to be accurate, and we would obviously be burning in pain if it were really that warm).

Also monitored during the experiment was the precision of the radiometer, i.e., the consistency of its output for an unchanging input. For the radiometer used in this experiment, the term to describe its precision is called its noise-equivalent sensitivity, or NEΔT, which is essentially the standard deviation of the brightness temperatures obtained from it. The NEΔT for each channel was estimated by taking the mean of the standard deviation of the brightness temperatures during six specific periods during which a stable measurement was being made. These six periods are illustrated by the plateaus in brightness temperature in Fig. 7. There was some variability in brightness temperature measured in channel A, as the NEΔT of that radiometer was estimated to be about 2.4 K. This may be due to some of the large jumps in brightness temperature at various points during the experiment, such as around measurements 65, 75, and 85. The standard deviation of the brightness temperature for one of the sections was as low as 0.8 K, but as high as 5.3 K in another. Although the accuracy of the measurements from channel B is poor, the NEΔT of that radiometer could still be estimated. It was estimated to be about 3.1 K, for similar reasons as for channel A.

4. Comparison to theory

A simple model of the brightness temperature of the sky is given by the following equation:

$$T_B^-(0,\mu) = T_B^-(h,\mu)e^{-\tau(h,0)/\mu} + \int_h^0 \kappa_a(z')T(z')e^{-\tau(z',0)/\mu}\frac{dz'}{\mu},$$

where h represents the top of the atmosphere, which is approximated as 30 km, μ is the direction cosine, τ is the optical depth, κ_a is the water vapor absorption coefficient (the only atmospheric constituent assumed to have any significant effect on brightness temperature at 1.4 GHz), and z' is some height between h and 0. Using MATLAB and the vertical profile of temperature, pressure, and water vapor density from Ames that morning (Fig. 8), the brightness temperature of the sky from this model was computed to be about 2.71 K, which significantly differs from the values obtained in this experiment, and from expected values of the brightness temperature of the sky. This difference is probably due to several inadequacies of the model. For one, it is assumed that $T_B^-(h,\mu) = T_{cosmic} + T_{galactic}$, where T_{cosmic} = 2.7 K and is from the remnants of the Big Bang, and $T_{galactic}$ is nonthermal potential from the galaxy and is direction and frequency dependent. It turns out that $T_{galactic}$ can be neglected for frequencies greater than about 5 GHz, and it is neglected in this model. However, the radiometer in this study uses a wavelength of 1.4 GHz, and thus this assumption of negligence of $T_{galactic}$ is not valid. For another, this model assumes that the only atmospheric gas/constituent that significantly contributes to emission/absorption of microwave radiation is water vapor. This is not true, as other constituents, such as oxygen and nitrogen may very well contribute significantly to the absorption/emission of radiation at 1.4 GHz. One more inadequacy of this model is the exclusion of scattering from other particles in the atmosphere, such as dust or water vapor particles. Although the experiment was performed on a cloudless morning, there may have been enough particles in the atmosphere to scatter enough radiation to have some impact on the measured brightness temperature that isn't accounted for in this model.

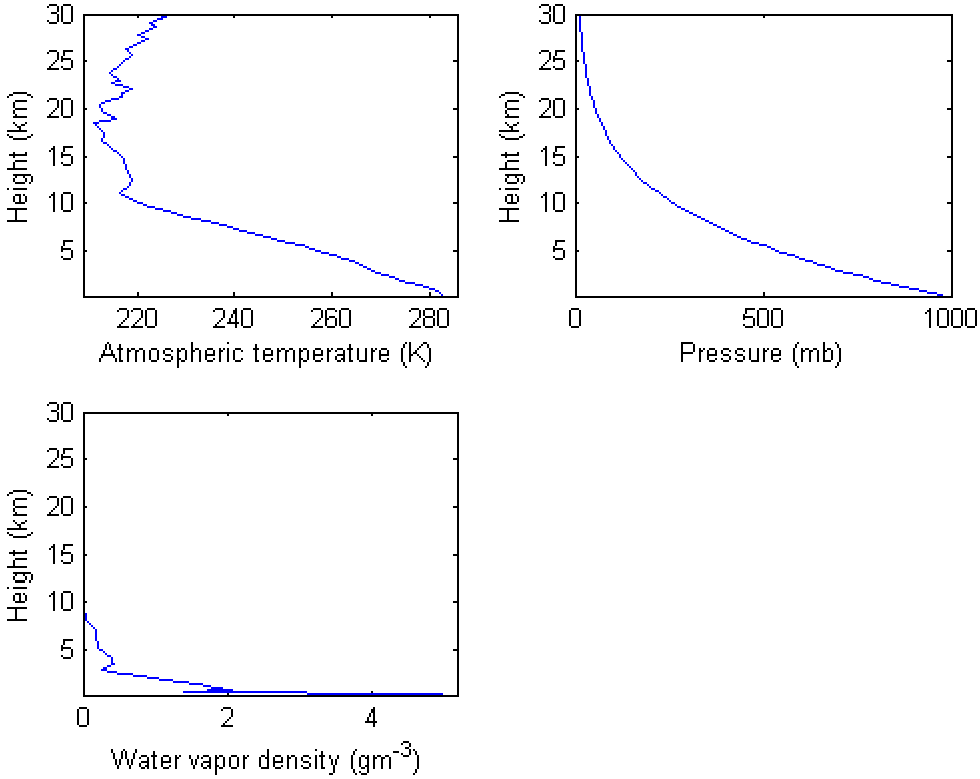

Figure 8. Vertical profiles of temperature (top left), barometric pressure (top right), and water vapor density (bottom left) from about 10 AM CDT 9 April 2010 in Ames, IA. Data was obtained from a combination of sources, but mainly from a 15Z RUC analysis sounding from a point very near Ames.

5. Emissivity of Agronomy Hall

Finally, the emissivity of the roof of Agronomy Hall was estimated using the simple computation

$$e = \frac{T_B}{T},$$

where e is emissivity, T is thermal temperature, and T_B is brightness temperature. The thermal temperature of the roof of Agronomy Hall was obtained using an IR radiometer. The roof temperature was changing greatly throughout the experiment, as it went from about 58°F at about 10:20 AM CDT to about 73°F at 11:02 AM CDT, to about 77°F at 11:32 AM CDT. However, the brightness temperature of the roof changed very little during this time, so the computed emissivities are strange. Using the three thermal temperature values above, the emissivity of Agronomy Hall was estimated to be 1.01, 0.98, and 0.97. This seems to imply that the roof of Agronomy Hall is approximately a blackbody! Obviously the emissivity of an object should not be greater than 1, so there must be some errors in measurement or in the assumptions made from the measurements obtained by the IR radiometer. The emitting depth of the roof at IR wavelengths is tiny compared to that at L-band wavelengths. The section of the roof that is below that measured by the IR radiometer but that is measured by the L-band radiometer used in this experiment probably has a much more stable temperature, and thus wouldn't change as readily as the sun rose through the sky that morning. The difference in wavelength used to make thermal temperature measurements and brightness temperature measurements probably is the cause of a computed emissivity greater than one. However, a minor amount of radiometer miscalibration may also contributed to some error.

6. Summary

The students of a microwave remote sensing course at Iowa State University performed an experiment on the morning of 9 April 2010. In this experiment, they used an L-band radiometer to measure the brightness temperature of the sky and of the roof of a campus building, Agronomy Hall. They then compared the measured brightness temperature of the sky to that from a simple model, only to find that the model (and the measured brightness temperature) does not match the typical values found for the brightness temperature of the sky. The students also used thermal temperature measurements of the roof of Agronomy Hall, made by an IR radiometer, to estimate the emissivity of the roof of Agronomy Hall. It is believed that hardware issues and calibration errors are the leading culprits of the errant brightness temperature measurements, and an inadequate model is responsible for the errant modeled brightness temperature of the sky.