1 Objectives

In this laboratory you will:

1. identify the main components of a ground–based microwave radiometer system and an individual microwave radiometer;
2. collect data using a microwave radiometer;
3. calibrate a radiometer;
4. produce a time–series of brightness temperature;
5. calculate the NE∆T (precision) of a radiometer;
6. determine a “mystery temperature;” and
7. produce a well–organized report that you can reference later in your career.

See the rubric at the end of this document to see how your report will be graded.

2 Microwave Radiometer Systems

2.1 Main Components

A ground–based radiometer system is shown in Figure 1. It has three main components.

a horn antenna that has a high main–beam efficiency. The horn antenna in Figure 1 has two outputs so that it can observe both horizontally– and vertically–polarized radiation.

electronics in a metal box mounted on the back of the antenna. The analog components are collectively called the “RF front end” where RF stands for “radio frequency” to distinguish it from typical lower–frequency electronics like what you would find in an off–the–shelf electronic device. The RF front end amplifies the extremely weak signal coming from the antenna so it can be reliably measured. Digital components sample the output of the RF front end. A microcontroller (mini–computer) manages the system, controls the temperature of the RF front end, and communicates with the user.

power supplies in a metal box that convert wall power (110 VAC) into various levels of DC power used by the analog and digital hardware.

Satellite microwave radiometers, like SMOS and SMAP, have roughly the same basic components.
2.2 Measurement Description

The power intercepted by a microwave radiometer’s antenna and delivered to the radiometer can be represented by an equivalent blackbody temperature since, according to the Rayleigh–Jeans law, there is a direct and linear relationship between the microwave power emitted by an object and its physical temperature (at typical Earth temperatures). Technically we call this the antenna temperature since it is composed of brightness potentially originating from multiple locations (the apparent temperature) plus a small contribution from the antenna itself (the antenna also emits!). Practically, we just call this the brightness temperature of the scene within the antenna’s field–of–view.

The input signal to a microwave radiometer is the time–varying antenna voltage (literally the voltage measured across the output of the antenna) associated with the intercepted power and thermal noise from the antenna. This voltage signal is essentially random noise and can be described by a zero–mean Gaussian (normal) probability distribution. Since power is directly proportional to the square of the voltage, the expected (average) value of the power (and hence brightness temperature) is directly proportional to the expected value of the square of the voltage, also known as the voltage’s variance.

In the past most radiometers used a mixer, a type of electrical hardware component, to convert the radio frequency (microwave) analog input signal into an analog signal at a lower frequency. At this lower frequency typical off–the–shelf electrical hardware can be used to measure the power associated with the analog signal and then it into a digital signal which can be understood by a computer. A Direct–Sampling Digital Radiometer (DSDR) (Fischman and England, 1999; Fischman and England, 1999; Fis-
on the other hand, employs a fast A/D (analog to digital) converter that can work at the original high frequency. Subsequent digital hardware then operates on the signal (which is now just a stream of numbers) to measure the input power. Digital radiometers are becoming more popular and can be used for higher frequencies than L–band because of the rapid increase in the capabilities of analog and digital electronics.

The output of a DSDR is a digital number that is the average of $N$ samples of the square of the quantized voltage signal, $Q[v(t_n)]^2$, sampled at time $t_n$. Fischman and England (1999) call it the $r_Q$ value:

$$r_Q = \frac{1}{N} \sum_{n=1}^{N} Q[v(t_n)]^2.$$  \hspace{1cm} (1)

The $r_Q$ value is simply a time–limited estimate of the variance of the quantized voltage, which is an estimate of the power captured by the radiometer’s antenna as discussed earlier. Hence the $r_Q$ value will be directly proportional to the antenna temperature, which is for all practical purposes equal to the brightness temperature of the scene within the field of view of the antenna if the radiometer system is linear.

### 2.3 Radiometer Calibration

In normal practice microwave radiometers are calibrated by filling the pattern of the antenna with objects of known brightness temperature. If the relationship between the radiometer output (the $r_Q$ value for a DSDR) and brightness is linear, only two calibration points are needed. To make an accurate calibration, the actual brightness of the calibration targets must be measured or found in some other way. It is also desirable to have distinct “cold” and “hot” brightness temperatures, to best estimate the calibration function.

The sky is a perfect calibration load at 1.4 GHz because it is very cold (about 5 K), occupies essentially the entire main beam of the antenna, and stable (does not vary quickly over time). At the top of the atmosphere, the brightness temperature of the sky has two components: $T_{\cos}$, the cosmic background (2.7 K); and $T_{gal}$, the direction–dependent brightness from our own galaxy. $T_{gal}$ can be significant at L–band. At Earth’s surface, a up–looking radiometer will also measure downwelling atmospheric emission, $T_{atm}$, as well as the extra–terrestrial radiation attenuated by the atmosphere:

$$T_{sky} = T_{atm} + (T_{\cos} + T_{gal}) \times e^{-\tau/\mu},$$ \hspace{1cm} (2)

where $e^{-\tau/\mu}$ is the atmospheric attenuation. At 1.4 GHz, atmospheric attenuation and emission are small (in the absence of hydrometeors) and does not vary much from day to day.

Usually a microwave absorber is used as the “hot” source. A microwave absorber consists of a high–loss material shaped into cones that produces a surface of nearly zero reflectivity (and consequently an emissivity near unity) at certain frequencies. Assuming that the absorber is approximately a blackbody, its brightness temperature is the same as its physical temperature. Hence a brightness temperature at ambient temperature ($\approx$ 300 K) can be obtained. Figure 2 illustrates an absorber calibration procedure and the piece of absorber used. Ideally the absorber must be the only thing that the antenna “sees” so it is desirable to fill the pattern of the antenna as much as possible. Filling the aperture of the antenna is typically adequate for horn antennas designed for radiometry. For L–band radiometers absorber calibration is difficult (simply because of the physical size of the aperture) and may not produce accurate results.

Instead of using the sky and an absorber a radiometer can also utilize an internal reference load and a noise diode for calibration. A reference load is a piece of hardware that produces a brightness temperature equal to its physical temperature and hence it acts like a blackbody inside
the radiometer. A noise diode is another piece of hardware that adds a known amount of power to the power emitted by the reference load. For example, the noise diode could increase the brightness temperature of the reference load by around 120 to 150 K. An RF switch is used to change the input to the radiometer: the antenna; the reference load with the noise diode off; and the reference load with the noise diode on. See Table 1 for an example.

An internal calibration is advantageous because it can be done during every measurement and we can therefore compensate for short- and long-term drifts in the gain of a radiometer, which result in changes in the slope of the calibration line. The radiometer itself emits radiation because the analog electronics that make up the radiometer emit and this emission changes over time as the temperature of the radiometer changes. This self-emission adds noise to the radiometer system. The RF front end is typically mounted on the same metal “plate” so that component temperatures can be tightly controlled (to within about 0.1 K) using some type of active control system like a thermo-electric cooler to reduce the variation in self-emission. However, other parts of the radiometer can experience changes in temperature. Slow changes in the overall temperature of the radiometer can be due to diurnal temperature fluctuations of the radiometer components. Sharp changes can result from changes in radiometer orientation. As coaxial cables and connectors warm and cool, their electrical properties and hence noise that they emit change slightly. Mechanical stress on cables, and thus their electrical properties, can change as the incidence angle of the radiometer is adjusted. Heat can also be redistributed within the radiometer through convection.
An A/D converter may also have a temperature dependence.

A simple calibration procedure (that does not utilize an internal reference load or noise diode) is illustrated in Figure 3. Two points are needed if the system is linear. One should be a “hot” source, like a microwave absorber that fills the aperture of the antenna (Figure 2). The other should be a “cold” source (like the sky).

The y–intercept is $-T_{rec}$, the negative of the radiometer “receiver temperature.” $T_{rec}$ can be thought of as the negative brightness temperature that would need to come from the antenna to cancel out the noise that is generated by the radiometer electronics themselves in order to make $r_Q = 0$. Hence $T_{rec}$ represents the noise temperature (thermal emission from the radiometer hardware itself) of the radiometer and it is typically around a couple hundred kelvins. After the calibration line has been defined, the radiometer is ready to be used to measure brightness temperature.

### 2.4 Radiometer Accuracy and Precision

Accuracy is a measure of how close a measurement is to the real value. Typical ground–based radiometer systems have an accuracy of ±2 K considering errors in the estimate of sky brightness temperature and uncertainties associated with the temperature, emissivity, and size of the hot absorber.

Precision is the closeness of agreement among several measurements of the same quantity. Precision can also be thought of as the reproducibility of a measurement or the sensitivity of the instrument in terms of the minimum detectable change. A radiometer’s precision is commonly called its noise–equivalent sensitivity, or NE∆T. The NE∆T is simply the standard deviation of the brightness temperature measurements reported by the radiometer. Theoretically there are three main sources of noise which determine the NE∆T of a DSDR:

1. Random DC bias fluctuations in the A/D converter, $\Delta T_L$;

2. The finite number of samples made during the measurement, $\Delta T_F$;
3. Gain change due to random temperature fluctuations, $\Delta T_G$.

Because these effects are independent,

$$\text{NEAT} \approx \sqrt{\Delta T_L^2 + \Delta T_F^2 + \Delta T_G^2}. \quad (3)$$

Typically $\Delta T_L \approx 0.01$ K. In the previous section the $r_Q$ value was described as a time–limited estimate of the expected voltage variance. The actual expected value can only be found after an infinite number of samples have been recorded. The sensitivity contribution due to a finite sampling time is

$$\Delta T_F = \frac{T_{\text{sys}}}{\sqrt{N}} \quad (4)$$

where $T_{\text{sys}} = T_{\text{ant}} + T_{\text{rec}}$ is the antenna temperature ($T_{\text{ant}}$) plus the noise–equivalent temperature of the analog hardware before the A/D converter ($T_{\text{rec}}$) and $N$ is the number of independent samples of the incident brightness that are averaged together to determine the final measurement. A typical radiometer observing the Earth’s surface has a $T_{\text{sys}}$ of $\approx 400$ K. $N = f_s \tau$, where the digital sample rate $f_s = 1/(t_n - t_{n-1})$, and $\tau$ is called the integration time, or period over which the antenna voltage is sampled. For example, if $f_s = 5 \text{ MHz}$ and $\tau \approx 1 \text{ s}$, $N = 5 \times 10^6$ samples, and $\Delta T_F \approx 0.2$ K.

Finally, the gain, $G$, of the amplifiers used to boost the antenna voltage to a measurable level is sensitive to changes in their temperature:

$$\Delta T_G = T_{\text{sys}} \left| \frac{\Delta G}{G} \right| \quad (5)$$

where $\Delta G$ is the change in gain that occurs as the RF front end component temperatures change. The real art of microwave radiometry is to keep the temperature of the radiometer hardware as constant as possible in order to limit the change in gain during the integration time. In a good radiometer the standard deviation of the temperature of the radiometer components is normally 0.1 K or less and a typical value of $\Delta T_G$ is $\approx 0.5$ K. Hence a typical total DSDR sensitivity, according to (3) is then:

$$\text{NEAT} \approx \sqrt{0.01^2 + 0.2^2 + 0.5^2} = 0.5 \text{ K}. \quad (6)$$

3 Laboratory Procedure

We will not use the horn antenna. Instead we will connect a matched load to the coaxial cable that normally connects the antenna output to the radiometer input. A matched load can be thought of as a blackbody. To calibrate the radiometer we will put the matched load in two known temperature baths. One bath will be liquid nitrogen (which boils at 77 K at sea–level) and the other will be liquid water (which boils at 373 K at sea–level). Consequently in Figure 3 $T_{\text{cold}} = 77$ K and $T_{\text{hot}}$ will be close to 373 K. We will perform two calibrations, one at the beginning of the laboratory and the other at the end. To test your calibrations we will use the radiometer to measure the temperature of a beaker of tap water by placing the reference load inside the beaker. The challenge will be to see if you can correctly determine the “mystery temperature” of the tap water.

Take careful notes during the laboratory. In particular, note the time at which the reference load “antenna” is initially placed in each bath. You will need these times: to interpret your data; and to calculate the rate at which the raw data is generated.
4 Report

Write a concise but thorough report that addresses each of the objectives in Section 1 (see the rubric on the last page for specific information).

To calculate the NEΔT do not use (3), which is the theoretical value for a DSDR. Instead, do the following. Determine the rate at which the raw data is recorded. Choose an integration time, perhaps between 1 and 5 s. Find the standard deviation of the raw data over your integration time. Divide this by the square root of the number of samples of raw data. Essentially this is the standard error, the uncertainty in the mean value of the data over your integration time. If you processed all of your raw data like this (averaged it over the integration time you chose) then the standard deviation of this processed data would be equal to the standard error over your integration time, which is equivalent to the NEΔT.

References


518 Laboratory Rubric

The total points available is 100.

1. Identify the main components of the Iowa State microwave radiometer system and an individual microwave radiometer. Use the pictures on the syllabus for the overall radiometer system. Take your own picture (or use a friend’s picture) of the RF front end. Be sure to capture at least one of the matched loads in your RF–front–end picture. Label the following. (10 items × 2 points = 20 points)
   (a) antenna of the radiometer system
   (b) power and radiometer boxes of the radiometer system
   (c) the plate supporting the RF front end components
   (d) a matched load
   (e) the isolator
   (f) a bandpass filter
   (g) a low–noise amplifier
   (h) the radiometer input
   (i) the square–law detector and analog–to–digital circuit
   (j) the path that the microwave signal travels through the radiometer

2. Create a figure of the raw $r_Q$ data and mark on the figure the periods during which the matched load was in different locations, and indicate the location of the matched load during each period. (15 points)
   (a) time series of $r_Q$ data (5 points)
   (b) N$_2$ A; H$_2$O A; mystery; N$_2$ B; H$_2$O B (5 items × 2 points = 10 points)

3. Determine two calibrations for the radiometer. Illustrate with a figure and report the slopes and y–intercepts. (4 items × 5 points = 20 points)

4. Determine the NE∆T of the radiometer. Use a period when the matched load is at a known and stable temperature. (10 points)

5. Use each of the calibrations to produce two records of the brightness temperature measured by the radiometer over the course of the laboratory. (10 points)

6. Determine the “mystery temperature” of the matched load (including its uncertainty) using the same integration time as in Part 4. (5 points)

7. Produce a well–organized, concise but thorough, report. (20 points)