CHALMERS – Space, Earth and Environment

RRY100 – Satellite Communications – 2024 – LAB-1

Microwave radiometry for atmospheric measurements

1 Introduction

The earth's atmosphere plays an important role in satellite communications since it impacts the signal propagation between the communication satellites and the corresponding ground stations. The radio frequency signals are attenuated on their way through the atmosphere, and at the same time, the atmosphere contributes with additional noise. Thus, the radio frequency performance of a satellite link (up-link or down-link), which is usually expressed as carrier-to-noise-ration C/N, is impacted.

A simple way to look at this is to regard the earth's atmosphere as a waveguide, i.e. a passive device that (a) attenuates the signals passing through it, and (b) contributes with additional noise. Concerning the first aspect (a), let us regard a signal that is expressed by a noise temperature T_{in}. When this signal is passing through the waveguide, it will be attenuated due to the loss L of the waveguide. At the output of the waveguide, the signal will have noise temperature $T_{out} = T_{in}/L$. Concerning the second aspect (b), you are familiar with the equation for the noise contribution of a waveguide. For a waveguide with loss L and physical temperature T_{phy}, the effective noise temperature at its output is $T_{wg.out} = T_{phy} \cdot (1 - 1/L)$.

This can be directly applied to the earth's atmosphere, where the loss L corresponds to the atmospheric attenuation, usually denoted by A, and the physical temperature corresponds to the atmosphere's effective temperature T_{eff}. In a down-link situation, the antenna of a ground station will thus have an antenna temperature T_{ant} that is composed by the sum of (a) the attenuated input temperature and (b) the noise contribution originating from the atmosphere:

$$T_{ant} \quad = \quad \frac{T_{in}}{A} + T_{\text{eff}} \cdot (1 - \frac{1}{A}) \tag{1}$$

The purpose of this lab exercise is to measure the atmospheric attenuation A using a microwave radiometer.

Expected learning outcome:

- Measure the receiver noise temperature T_{rec} of a heterodyne radiometer.
- Determine the antenna temperature T_{ant}.
- Understand the relationship between absorption, transmission, opacity, and attenuation.
- Estimate the total tropospheric zenith opacity from an elevation scan (tipping curve).
- Analyse the data and present the results, preferably during the lab time.
- Report your results and main lessons learned in the combined "lab report".

2 Theory

2.1 Objective and motivation

Measurements at several different elevation angles are commonly used by ground-based radiometer systems in order to derive the opacity (and thus the related attenuation) of the troposphere for a given observation frequency. Such a sequence of observations is often referred to as a tipping curve, or just tip curve. The main task of this exercise is to estimate the tropospheric opacity (low opacity is high transparency) at 31 GHz as accurate as possible using tipping curve measurements.

Figure 1 shows model calculations for zenith opacities and brightness temperatures as observed both from the tropopause (15 km altitude) and from the ground for low and high tropospheric water content. The high opacities at 50–70 GHz and 119 GHz are due to absorption of O_2. The peak at 22 GHz comes from absorption of H_2O and the 75–115 GHz peaks are due to absorption of ozone, O_3. The large differences in zenith opacities as observed from the ground compared to observations from the tropopause is explained by absorption of tropospheric H_2O. It is possible to estimate the total water column, and the signal propagation delay due to water vapour, in the troposphere from opacity measurements. Onsala Space Observatory operates two dual channel (21 and 31 GHz) radiometers dedicated for this purpose.

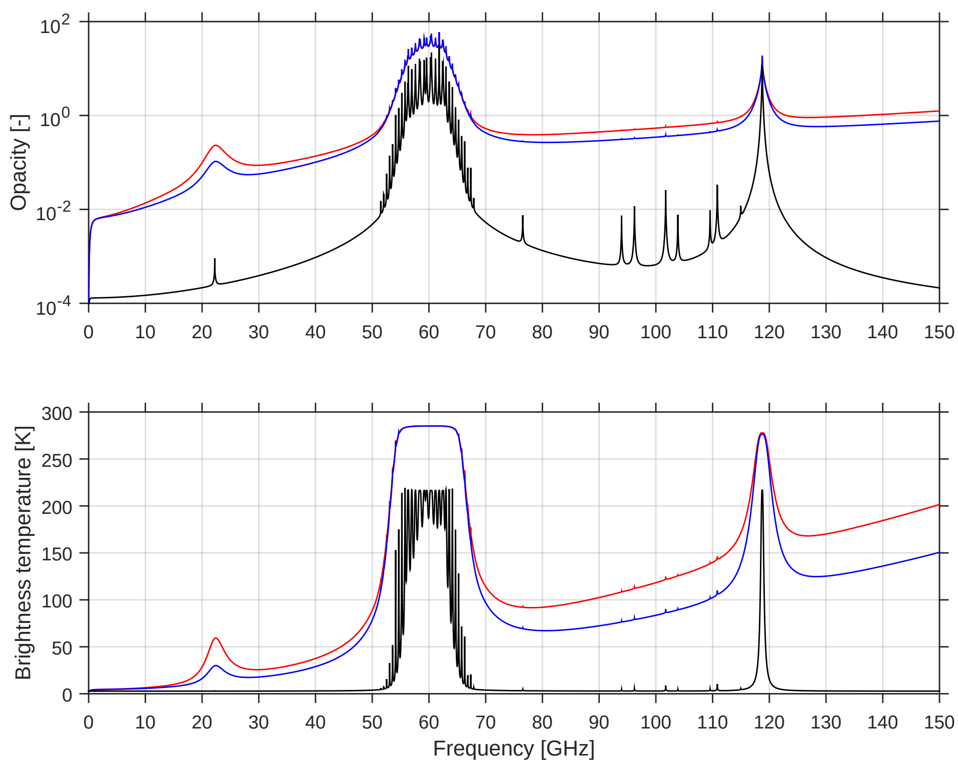

Figure 1: Zenith opacity (upper) and brightness temperature (lower) of the atmosphere versus frequency as observed from the ground for low (blue) and high (red) tropospheric water vapor content. The black curves show the zenith opacity and the brightness temperatures as observed from the tropopause (above the troposphere, altitude 15 km).

2.2 Model of the tropospheric radiative transfer

If the radiation from the middle and upper atmosphere is negligible, as at 31 GHz (see Fig. 1) the received radiation from the troposphere for a zenith-observing, ground-based radiometer with narrow beam ("pencil beam"), is given by

$$T_{ant} = T_{bg}\, e^{-\tau_Z} + \int_0^{z_T} T(z)\, \alpha(z)\, e^{-\tau(z)} dz \quad , \tag{2}$$

where T_{bg} is the cosmic background temperature ($\approx$ 2.8 K at 31 GHz), z_T is the altitude of the tropopause, $T(z)$ is the altitude dependent temperature, α is the atmospheric *absorption coefficient* [m^{-1}], which depends on frequency, temperature, pressure, number densities of oxygen and water vapor and the amount of liquid water in the troposphere. The first term in Eq. 2 is the cosmic background radiation times the *tropospheric zenith transmission factor*, $e^{-\tau_Z}$. The second term is the sum of the tropospheric sources. The radiation emitted at one altitude, z, is given by $T(z)\,\alpha(z)dz$. This radiation times the transmission factor, $e^{-\tau(z)}$, gives what reaches the ground. The relation between the *zenith opacity*, τ, and α is given by $d\tau = \alpha dz$. The *tropospheric zenith opacity*, τ_Z is defined by:

$$\tau_Z = \int_0^{z_T} \alpha(z)\, dz \tag{3}$$

Introducing T_{eff}, the *effective temperature of the troposphere*, the integral in Eq. 2, can be simplified:

$$\int_0^{z_T} T(z)\, \alpha(z)\, e^{-\tau(z)} dz = T_{\text{eff}} \int_0^{z_T} \alpha(z)\, e^{-\tau(z)} dz = T_{\text{eff}} \int_0^{\tau_Z} e^{-\tau(z)} d\tau = T_{\text{eff}} \left(1 - e^{-\tau_Z}\right) \tag{4}$$

T_{eff} can be approximated with $T_{\text{eff}} = 0.95 \cdot T_{ground}$ where T_{ground} is the temperature at the ground. Finally, Eq. 2 can be expressed as:

$$T_{ant} = T_{bg} e^{-\tau_Z} + T_{\text{eff}} \left(1 - e^{-\tau_Z}\right) \tag{5}$$

To be able to estimate T_{ant} for different elevations (i.e. not only the zenith direction) the airmass factor (or mapping function) $m(\epsilon)$ is introduced. An expanded version of Eq. 5 can be derived as:

$$T_{ant}(\epsilon) = T_{bg} e^{-m(\epsilon)\tau_Z} + T_{\text{eff}} \left(1 - e^{-m(\epsilon)\tau_Z}\right) \tag{6}$$

For observation elevation angles $\epsilon > 20°$, $m(\epsilon)$ can be well approximated by:

$$m(\epsilon) = \frac{1}{\sin(\epsilon)} \tag{7}$$

Note that $m(90°) = 1$ (one airmass in the zenith direction) and $m(30°) = 2$.
$e^{-m(\epsilon)\tau_Z}$ is denoted the *tropospheric transmission*, where $0 < e^{-m(\epsilon)\tau_Z} \leq 1$. Another way to formulate Eq. 6 is to use the expression

$$T_{ant} = \frac{T_{bg}}{A} + T_{\text{eff}} \left(1 - \frac{1}{A}\right), \tag{8}$$

where the *tropospheric attenuation*, A, is given by $A = e^{m(\epsilon)\tau_Z}$. We now have an intuitive explanation of Eq. 6. The 2.7 K background radiation is attenuated during the transmission through the troposphere. The attenuation is due to absorption in the troposphere and the troposphere finally re-emit at a higher temperature T_{eff}. This is analogous to a waveguide which both attenuates the transmitted signal and adds noise, see Eq. 8. The expression $m(\epsilon)\tau_Z$ can be derived from Eq. 6:

$$m(\epsilon)\tau_Z = -\ln\left(\frac{T_{\text{eff}} - T_{ant}}{T_{\text{eff}} - T_{bg}}\right) \tag{9}$$

3 The instrumentation, measurements and calibration

A 31 GHz heterodyne radiometer, a digital voltmeter and a thermometer are available to preform the lab exercises.

3.1 Description of the 31 GHz heterodyne radiometer

The heterodyne radiometer used in this exercise operates around 31.6 GHz. The incoming radio signal (RF), acquired by a horn antenna, is down-converted by a mixer to an intermediate frequency signal (IF) around 600 MHz. The IF power is measured with a square-law detector and displayed by a voltmeter. Additionally, ferrite switches (circulators) make it possible to select the input to the mixer between the antenna, a warm internal calibration load at ambient temperature, and a heated internal calibration load. A block-diagram of the radiometer is shown in Fig. 2. A mirror in front of the radiometer horn can be adjusted to perfrom observations at different elevation angles.

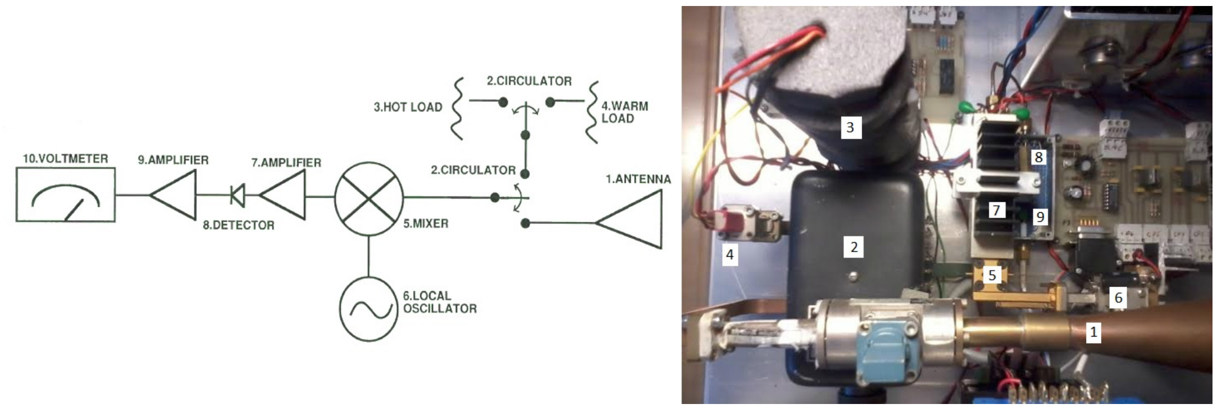

Figure 2: Block diagram (left) and photo (right, with marked components) of the 31 GHz radiometer.

3.2 Measurements and calibration

For our radiometer measurements the Rayleigh-Jeans approximation is valid: the received radiation is proportional to an equivalent black body temperature. The receiver produces an output voltage, V_{ant}, proportional to the input power, which, in its turn, is proportional to the sum of the receiver temperature, T_{rec}, and the temperature of a black body that covers the antenna beam, T_{ant}. The sum $T_{rec} + T_{ant}$ is denoted the system temperature T_{sys}. The measured voltage V_{ant} is hence given by:

$$V_{ant} = G\,(T_{rec} + T_{ant}) \tag{10}$$

Here we have only one observable V_{ant} and three unknown parameters: the net gain G of the radiometer system, the noise temperature of the receiver referred to the antenna input T_{rec}, and the antenna temperature, T_{ant}, that we like to measure. In order to determine all the parameters we can add two additional measurements replacing the unknown T_{ant} by two known reference load temperatures. We refer to these as one warm and one hot load and obtain the following three equations for the three measured voltages, i.e.

$$V_{ant} = G\,(T_{rec} + T_{ant}), \tag{11a}$$
$$V_{warm} = G\,(T_{rec} + T_{warm}), \tag{11b}$$
$$V_{hot} = G\,(T_{rec} + T_{hot}), \tag{11c}$$

where T_{warm} is the ambient temperature of the warm load and the hot load temperature, T_{hot}, is approximately 70 °C. When observing the sky, T_{ant} is the sky brightness temperature, T_b, convolved with the antenna beam pattern. In this exercise, a directive antenna with one narrow main-lobe is assumed, a so-called ”pencil beam antenna”, which gives that $T_{ant}(\epsilon) = T_b(\epsilon)$, where ϵ is the observation elevation.

3.2.1 Determining T_{rec} using the Y-factor method

The Y-factor method, derived from Eq. 11b and Eq. 11c, is often used to calculate T_{rec}:

$$Y = \frac{V_{hot}}{V_{warm}} \tag{12a}$$

$$T_{rec} = \frac{(T_{hot} - Y \cdot T_{warm})}{Y - 1} \tag{12b}$$

3.2.2 Calibration and determination of T_{ant}

Provided that these measurements are made reasonably fast, so that temporal variations in the system parameters G and T_{rec} can be ignored during the measurement period, we can use Eq. 11a – Eq. 11c to calculate T_{ant}. If we form the differences Eq. 11b − Eq. 11a and Eq. 11b − Eq. 11c we get:

$$V_1 = V_{warm} - V_{ant} = G\,(T_{warm} - T_{ant}) \tag{13a}$$

$$V_2 = V_{warm} - V_{hot} = G\,(T_{warm} - T_{hot}) \tag{13b}$$

In the block diagram in Fig. 2 the voltages V_{ant}, V_{warm} and V_{hot} are measured by using the waveguide switch. The unknown antenna temperature, T_{ant} is found by dividing Eq. 13a by Eq. 13b:

$$T_{ant} = T_{warm} - \frac{V_1}{V_2}\,(T_{warm} - T_{hot}) \tag{14}$$

However, the accuracy of T_{hot} is not good enough. Due to losses and temperature gradients in the waveguides we need to estimate an empirical correction, ΔT_{hot}, to the hot load temperature:

$$T_{ant} = T_{warm} - \frac{V_1}{V_2}\,[T_{warm} - (T_{hot} + \Delta T_{hot})] \tag{15}$$

4 Experiment description and data analysis

Record V_{ant}, V_{warm}, V_{hot}, T_{warm}, T_{hot} and T_{ground} for elevations from 90° to 30°, see Tab. 1. All subsequent calculations can in psinciple be done using a simple calculator, but are preferably done by writing small progams in *MatLab* or *Phython* (see Sec. 4.1). First determine receiver temperature T_{rec} and antenna temperature T_{ant}. Then, both the hot load correction, ΔT_{hot}, and τ_Z, can be found by plotting, $m(\epsilon)\tau_Z$ as a function of airmass, $m(\epsilon)$, for different elevations, ϵ. Make a linear fit to the data and extrapolate it to zero airmass. At zero airmass the transmission is 1, i.e. $m(\epsilon)\tau_Z = 0$. If this is not the case, adjust ΔT_{hot} until this is accomplished. Finally, τ_Z is given by the slope of the fit and can be used to calculate also attenuation A and transmission.

Table 1: Your measurements.

Elevation, ϵ [°]	$m = 1/\sin\epsilon$ [-]	V_{ant} $[V]$	V_{warm} $[V]$	V_{hot} $[V]$	T_{warm} $[K]$	T_{hot} $[K]$	T_{ground} $[K]$
90.0	1.000						
65.0	1.103						
55.0	1.221						
45.0	1.414						
40.0	1.556						
35.0	1.743						
30.0	2.000						

4.1 Analysis with *MatLab* or *Python*

- Save the elevation angles of the observations and the corresponding voltages (proportional to the power and brightness temperature) in a text file e.g. elev_power.txt, with four columns: ϵ [deg], V_{ant} [V], V_{warm} [V], and V_{hot} [V]).
- Use the Y-factor method (Equations 12a and 12b) to derive the receiver temperature T_{rec}.
- Use the measured temperatures for T_{warm} and T_{hot}. The ground temperature, T_{ground}, can be assumed to be the outside air temperature.
- Use Eq. 15 to calculate T_{ant}. Start with $\Delta T_{hot} = 0$, use Eq. 7 to get $m(\epsilon)$ and Eq. 9 to get $m(\epsilon)\tau_Z$.
- Plot $m(\epsilon)\tau_Z$ as a function of $m(\epsilon)$. Adjust ΔT_{hot} in the script until the extrapolated $m(\epsilon) - m(\epsilon)\tau_Z$ plot intercepts origo. Then τ_Z is given by the slope of the final fit.
- In addition to τ_Z, the *tropospheric zenith opacity*, also calculate A, the *tropospheric attenuation*, and $e^{-m(\epsilon)\tau_Z}$, the *tropospheric transmission*.

5 Feed back

Comments and suggestions for improving this lab exercise are much appreciated and can be sent to:
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