

Radio astronomy receiver overview

The noise temperature concept

Before covering the basics of a receiver, let's look at one of the fundamental units of power commonly used in radio astronomy, noise temperature in Kelvins. The ultimate goal is to measure the strength (*flux density*, S) of radio sources in the sky in $Watts/(meter^2 Hz)$, the energy in a one Hz bandwidth falling on one square meter per second. If we know the collecting area of our antenna, A , we can convert the flux density to a power per unit bandwidth appearing at the antenna terminals or feed output.

$$P_{radio\ source} = \frac{S A}{2} \text{ Watts/Hz} \quad (1)$$

The factor of two comes from the fact that an antenna receives only have the power from a radio source in each of two possible polarizations.

In principle, we could measure the power from a radio source by measuring how much it raises the temperature of an energy absorber tied to the antenna. However, radio sources are much too weak to do this directly. We need to amplify the radio source signal enough to drive a power detector. This adds an unknown, the gain of the amplifier, that must be calibrated. We calibrate the amplifier gain by looking at the output of a resistor at a known temperature since its output power can be computed from the first principles of physics.

We know that, at radio frequencies, the electrical power produced by a resistor is proportional to its physical temperature. In a one Hz bandwidth that power is

$$P_{resistor} = k T \text{ Watts/Hz} \quad (2)$$

where k is Boltzman's constant, 1.38×10^{-23} joules per Kelvin or Watt seconds per Kelvin, and T is the physical temperature of the resistor in Kelvins. Notice that the power does not depend on the resistance of the resistor and that the difference in powers from a resistor at two temperatures is proportional the the *difference* in temperatures, independent of what those temperatures actually are.

To show that a resistor produces a signal of reasonable strength for comparing to the signal from a radio source, let's compute the power difference from a one Kelvin change in resistor temperature and the power output of the 140-ft telescope from a one-Jansky source in its beam. From the resistor

$$P_{resistor} = 1.38 \times 10^{-23} \times 1.0 \quad (3)$$

$$= 1.38 \times 10^{-23} \text{ Watts/Hz} \quad (4)$$

One Jansky equals $10^{-26} \text{ Watts}/(meter^2 \text{ Hz})$, and the effective collecting area of the 140-ft is about 715 square meters, so from the telescope we get

$$P_{radio\ source} = \frac{1.0 \times 10^{-26} \times 7.15 \times 10^2}{2} \quad (5)$$

$$= 0.36 \times 10^{-23} \text{ Watts/Hz} \quad (6)$$

We see that a one-Jansky radio source produces a power equivalent to about a quarter-Kelvin change in resistor temperature. One figure of merit for a radio telescope is its “gain” expressed in Kelvins/Jansky. For the 140-ft it is about 0.25, and for the GBT it will be something over 1.5. At Arecibo, values around 8 are common.

An example receiver

Figure 1 shows a diagram of one of the three receiver channels for the Cas A measurement antennas. If you are not familiar with all of the symbols in this diagram, see Figure 2.

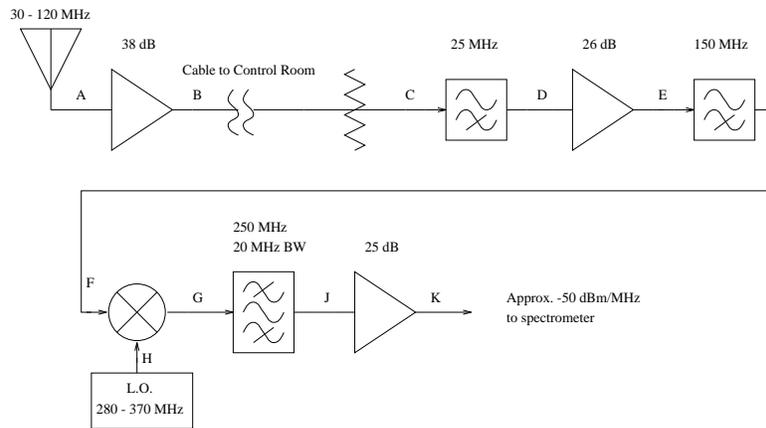


Figure 1:

This receiver is designed to tune anywhere in the 30 to 120 MHz range and to convert a 20-MHz portion of this spectrum to a center frequency of 250 MHz for analysis by the spectral processor. There are many strong man-made radio signals in this frequency range, so the filters and amplifier gains are arranged to minimize the chance of overload of any of the amplifiers in the system.

Since the antennas used in this experiment have very broad beams (more than 60 degrees), they see the average effective noise temperature of the sky. This ranges from about 30,000 K at 30 MHz to 800 K at 120 MHz. The radiation from our own galaxy is quite strong at these low frequencies and dominates the system temperature of our receiver. Ordinary, uncooled amplifiers are quite adequate.

The primary properties of the radio noise signal anywhere in the receiver are its intensity and frequency range. In this case we have the added complication that the signal intensity is quite dependent on frequency. To avoid this complication we will restrict our description to a small frequency range around 50 MHz at the antenna. For convenience, let’s use a 1-MHz bandwidth for computing noise power.

The pivotal element in this receiver for determining the measured frequency range is the mixer. There are four combinations of input and output frequency ranges that can be passed by the mixer for any given L.O. frequency. The filters in the receiver are selected to eliminate all but one of these possibilities. More on this later.

At 50 MHz the effective antenna temperature is about 8000 K. In our 1-MHz bandwidth at point A in Figure 1 we have, using Equation 2 and converting from one Hz to one MHz bandwidth,

$$P_A = 1.38 \times 10^{-23} \times 8000 \times 1.0 \times 10^6 \quad (7)$$

$$= 1.10 \times 10^{-13} \text{ Watts/MHz} \quad (8)$$

$$= -99.6 \text{ dBm/MHz} \quad (9)$$

In Equation 7 we have converted to the units, dBm, which is dB above or below one milliWatt. This is a very common unit in receiver design, and it is convenient in that amplifier gains in dB can be *added* to input signal levels to get output levels. The conversion to dBm is $10 \log(P_A) + 30$, where 30 comes from the change from Watts to milliWatts.

At the output of the first amplifier, point B, we have $-99.6 + 38 = -61.6$ dBm/MHz. At 50 MHz the loss in the transmission line from the antenna that is furthest from the control room is about 15 dB, and we shall assume the attenuator shown in Figure 1 is 0 dB. This produces -76.6 dBm/MHz at point C.

The 25 MHz highpass filter sharply attenuates the intense interference and increasing galactic background noise below its cutoff frequency. This reduces the chance of overloading the amplifier and mixer following this filter.

The first two amplifiers in our receiver have nearly full gain up to 300 MHz and beyond, and the attenuation of the cable for the antennas near the control room will be relatively small. Although there will be very little noise from the antenna at high frequencies, the noise from the first amplifier, ~ 300 K, and any very strong signals entering the antenna could produce a significant amount of power above 300 MHz. This could produce an unwanted signal at the output of the mixer at 250 MHz. The 150 MHz lowpass filter is added to remove this possibility.

The mixer is a frequency converter. Its output frequencies are the sum and difference of the signal and L.O. frequencies. From our 50 MHz signal and an LO frequency of 300 MHz we can get either 250 MHz or 350 MHz. The 250 MHz bandpass filter passes the former and rejects the latter. In addition, mixer input frequencies of both 50 and 550 MHz will produce an output frequency of 250 MHz. The 150 MHz lowpass filter rejects the higher frequency.

The conversion loss of the Mixer is about 7 dB. If we assume 1 dB loss in each filter, the signal level at point K will be about

$$-36 = -77 - 1 + 26 - 1 - 7 - 1 + 25 \text{ dBm/MHz} \quad (10)$$

This is 14 dB more than is required by the spectrometer so we can make the attenuator between points B and C 10 dB to further reduce the possibility of

overload of the amplifiers and mixers following it. At an observing frequency of 120 MHz this attenuator must be removed because the cable attenuation is 8 dB greater, and the sky temperature is 10 dB lower.

Block Diagram Symbols

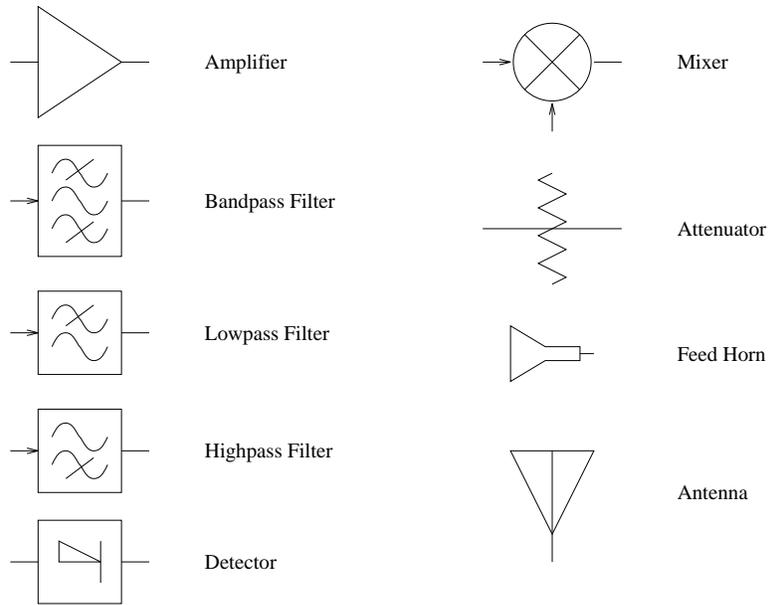


Figure 2: