7

Radio-Telescope Receivers

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7-1 General Principles of Radio-Telescope Receivers

7-1a. *Introduction.* The function of a radio-telescope receiver is to detect and measure the radio emission of celestial sources. In most cases the emission consists of incoherent radiation whose statistical properties do not differ from the noise originating in the receiver or from the background radiation coupled to the receiver by the antenna. The power level of the signal in radio-telescope receivers is usually quite small, of the order of 10^{-15} to 10^{-20} watt. The power received from the background (Fig. 7-1)‡ may be much higher than this, so that both high sensitivity and high stability of the receiver are important requirements. However, there are cases involving, for example, solar bursts or Jovian radiation, where the radiation is relatively strong, and other receiver characteristics, such as the ability to detect the signal spectrum as a function of time, become important.

7-1b. *Receiver Types.* Radio-telescope receivers are basically similar in construction to receivers used in other branches of radio science and engineering. The most common type is the superheterodyne receiver. Figure 7-2 gives the block diagram of a typical *superheterodyne receiver*. The signal power, having a center frequency ν_{RF}, is coupled to the receiver by an antenna and is first amplified in a radio-frequency (RF) amplifier with a gain of the order of 10 to 30 dB. The next stage is a mixer, where the weak signal is mixed with a strong local-oscillator signal at a frequency ν_0 producing an output signal on an intermediate frequency (IF), the IF signal power being directly proportional to the RF signal power. The IF signal is then amplified with a gain of the order of 60 to 90 dB. The largest part of the gain in a superheterodyne receiver is obtained in this IF amplifier, which also usually determines the predetector bandwidth of the receiver. The IF amplifier is followed by a detector, which is normally a

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square-law device in radio-telescope receivers (d-c output voltage proportional to the input-voltage amplitude squared). This means that the output d-c voltage of the detector is directly proportional to the output noise power of the predetection section of the receiver. Final stages may

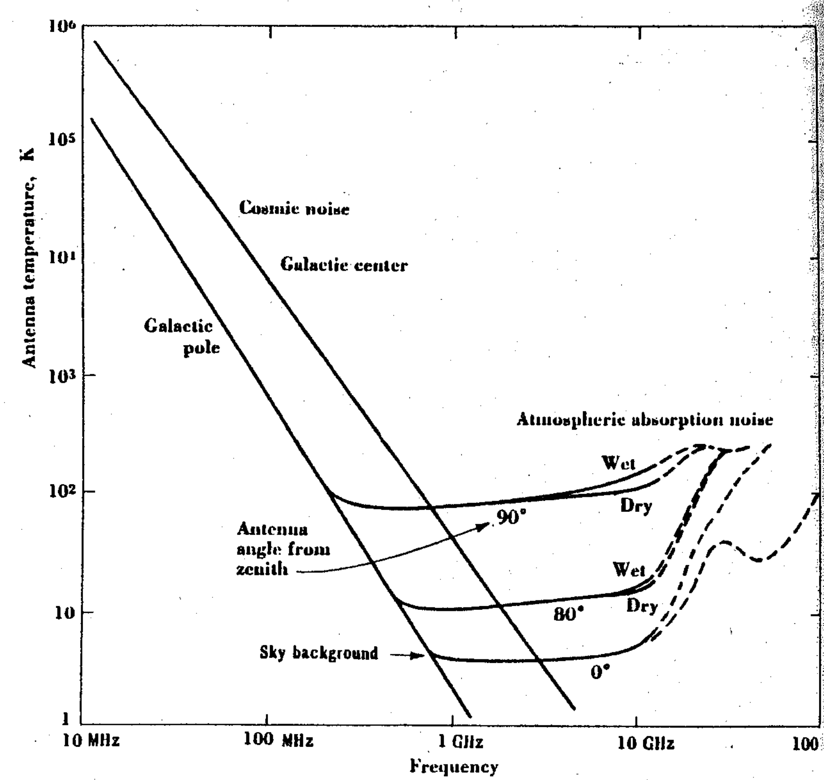

Fig. 7-1. Antenna sky-noise temperature as a function of frequency. A beam angle (HPBW) of less than a few degrees and 100 percent beam efficiency are assumed. (After *Kraus and Ko*. 1957 cosmic noise below 1 GHz: *Penzias and Wilson*. 1965. above 1 GHz: and *Croom*. 1964 atmospheric noise). Quantum-noise temperature $= h\nu/k = 0.048\ \nu_{\mathrm{GHz}}$. See also Figs. 7-25 and 8-3.

consist of a low-pass amplifier or integrator and a data-recording system, such as an analog recorder or a digital output system. The integrator integrates the observed signal power for a predetermined length of time. The actual value used, commonly of the order of seconds, is usually a compromise between too short a period, for which the output noise is excessive, and too long a period, causing excessive smoothing and loss of information.

In superheterodyne receivers (Fig. 7-2) the section after the mixer is the same for all frequencies. Only the RF amplifier, the mixer, and the local oscillator must be designed separately for each frequency range. The

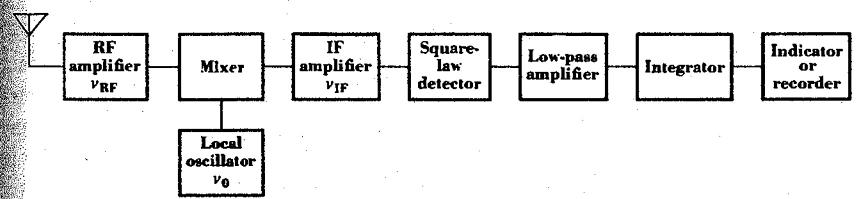

Fig. 7-2. A superheterodyne radio-telescope receiver.

section before the detector is usually called the high-frequency part of the receiver or the predetection section. The section following the detector is called the low-frequency part or the postdetection section.

Figure 7-3 shows a *two-channel superheterodyne receiver*. It was the standard receiver on microwave frequencies prior to the advent of low-noise microwave amplifiers, and it is still widely used, particularly in the milli-

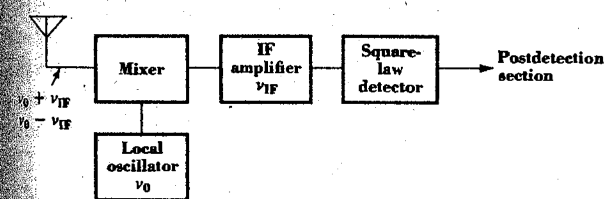

Fig. 7-3. Two-channel superheterodyne receiver.

meter range. If no filter is used between the antenna and the receiver, there is no RF selectivity before the mixer. In this case, the signal frequency

$$\nu_{RF} = \nu_0 + \nu_{IF} \tag{7-1}$$

and the image frequency

$$\nu'_{RF} = \nu_0 - \nu_{IF} \tag{7-2}$$

can be received. These two frequencies are usually equally effective in giving intermediate frequency power, and, hence, the receiver has two input channels separated in frequency by $2\nu_{IF}$. In continuum measurements signals in both channels may be practically equal in power and statistically

independent, resulting in a receiver which has a sensitivity of about twic that of the one-channel receiver.

The block diagram of the so-called *direct receiver* is shown in Fig. 7-4. This type is frequently used when very broad-band (of the order of 1 octave) measurements are made. The RF section might consist of a FET amplifier.

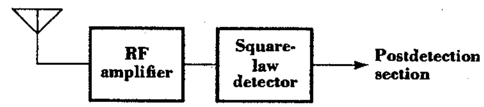

Fig. 7-4. Direct receiver.

Figure 7-5 shows the block diagram of a *video receiver*. The first active stage of this kind of receiver is the detector. Radio-frequency selectivity can be achieved by a suitable filter. The video receiver is mostly used in the sub–mm region, where standard superheterodyne receivers are more difficult to construct.

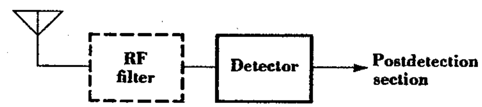

Fig. 7-5. Video receiver.

From a radio-astronomy point of view, receivers can be divided in two groups, *continuum receivers* and *spectral-line receivers*. In the former the *exact* frequency of operation is not critical, but in the latter the precise frequency of reception may be of paramount importance and may also need to be variable (tuning done by changing the local-oscillator frequency).

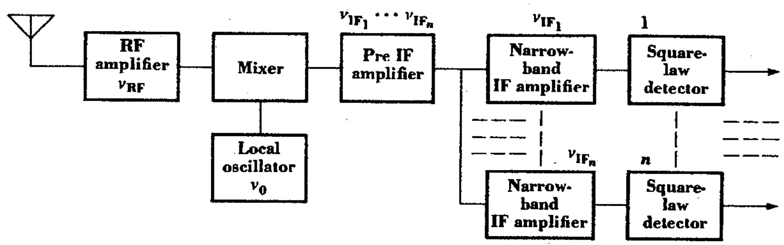

Fig. 7-6. Multi output-channel superheterodyne receiver.

An alternative scheme for spectral observations is to use a *multioutput-channel receiver*, as in Fig. 7-6. This type can be a normal superheterodyne receiver where a part of the IF amplifier and the rest of the receiver consist of several narrow-band stages in parallel. Multioutput-channel receivers are usually preferred in radio-astronomy work because it is easier to construct several equally sensitive channels than to keep the sensitivity constant when sweeping the local-oscillator frequency.

7-1c. *System Noise.* As has been discussed in Chap. 3, the noise power per unit bandwidth from an antenna is given by kT_A, where k is Boltzmann's constant and T_A is the effective noise temperature of the antenna radiation resistance. The noise power from the antenna is

$$W_{NA} = kT_A\,\Delta\nu \tag{7-3}$$

where W_{NA} = antenna noise power, watts
k = Boltzmann's constant ($= 1.38 \times 10^{-23}$ joule K^{-1})
T_A = antenna temperature, K
$\Delta\nu$ = bandwidth, Hz

The receiver also contributes noise due to the thermal noise in the receiver components, shot noise in the tubes or transistors, etc. In addition, losses in the transmission line (coaxial line or wave guide) between the antenna and receiver will add noise. Thus, the total or system noise power at the antenna terminals is

$$W_{sys} = W_{NA} + W_{NR} = k(T_A + T_{RT})\,\Delta\nu \tag{7-4}$$

and the total or system noise temperature referred to the antenna terminals (Fig. 7-7) is

$$T_{sys} = T_A + T_{RT} \tag{7-4a}$$

where T_A = antenna temperature, K
T_{RT} = receiver noise temperature (including transmission line), K
W_{NR} = receiver noise power referred to the antenna terminals, watts

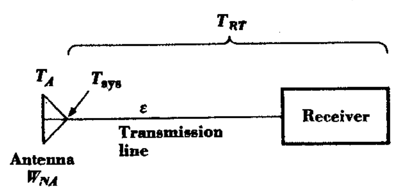

Fig. 7-7. The antenna, transmission line, and receiver contribute to the system temperature.

The system noise temperature T_{sys} of radio telescopes varies from ten or so degrees kelvin to thousands of degrees Kelvin, depending on the frequency and type of antenna and receiver. The signal temperature ΔT may be a small part of 1 K. Hence, the receiver must be able to detect small differences in the total noise. The basic theory of the noise temperature of receivers is discussed in more detail in Sec. 7-2.

7-1d. *Total-power Receiver and Its Sensitivity.* Any receiver which measures the total noise power from the antenna and from the receiver is called a *total-power receiver*. This is in distinction to receivers which measure, for example, the difference in powers from the antenna and a reference (see Secs. 7-1*f* and following). The characteristics and sensitivity of the total-power receiver will be analyzed in this section.

A block diagram of the total-power receiver is presented in Fig. 7-8. It is assumed that the amplifiers of the receiver are linear and have constant gain and that the bandpass characteristics are rectangular. The detector is assumed to be of the square-law type. The system noise temperature is taken to be T_{sys}, and ΔT is the signal noise temperature or change in

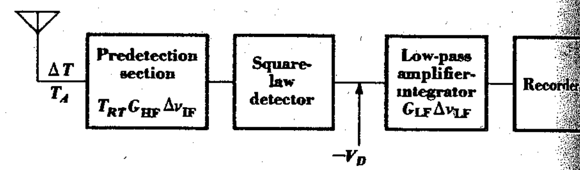

Fig. 7-8. Total-power receiver

antenna temperature to be measured. Figure 7-9 shows the voltage wave forms and power spectra at different parts of the receiver. The incident power consists of broad-band noise. The RF amplifiers and mixer accept only the frequency components around the signal frequency ν_{RF}, while the mixer converts this spectrum to the IF frequency ν_{IF}. The predetection part of the receiver is assumed to have a rectangular passband of width $\Delta\nu_{HF}$, determined effectively by the bandwidth of the IF amplifier. The filtered voltage V_{IF} at the IF amplifier output resembles a randomly modulated carrier wave of frequency ν_{IF} (Fig. 7-9). The amplitude v of the envelope of the wave form has a Rayleigh distribution, as shown in Fig. 7-10 (Rice, 1945):

$$P(v) = \frac{v}{V_{eff}}\, e^{-(v^2/2V^2_{eff})} \tag{7-5}$$

The most probable value of the envelope amplitude v is the rms value V_{eff} of the noise. The bandwidth $\Delta\nu_{HF}$ allows the envelope to have a rise time of approximately $1/\Delta\nu_{HF}$ sec. This means that after the square-law detector there are about $\Delta\nu_{HF}$ independent noise pulses per second. In practical receivers, $\Delta\nu_{HF}$ varies from a few kilocycles per second to tens of megacycles per second.

The IF amplifier output power W_{HF} is

$$W_{HF} = G_{HF}k(T_{sys} + \Delta T)\,\Delta\nu_{HF} \quad \text{watts} \tag{7-6}$$

where G_{HF} = power gain of predetection section

This power is fed to the square-law detector. The detector has an output voltage V_{det}, which varies with the input voltage v, according to

$$V_{det} = \alpha v^2 \tag{7-7}$$

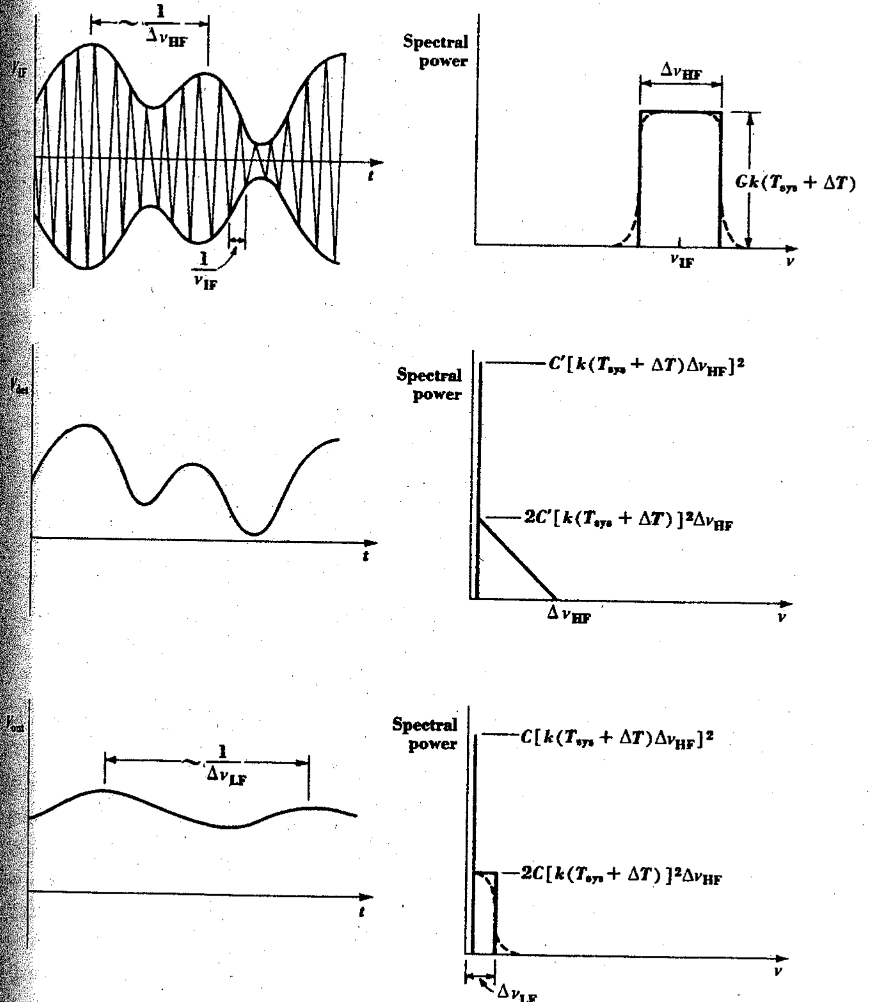

Fig. 7-9. Voltage wave forms and spectral power (watts cps⁻¹) spectra at different stages in a radio-telescope receiver.

where α is a constant. Hence, the detector d-c output voltage, $V_D + \Delta V$, is directly proportional to the input power, or

$$V_D + \Delta V = \beta G_{HF} k T_{sys}\,\Delta\nu_{HF} + \beta G_{HF} k \Delta T\,\Delta\nu_{HF} \tag{7-8}$$

where β is a constant. In most square-law detectors V_{eff}, and hence V_D, must be kept small (about 0.1 volt) in order to ensure proper square-law operation. Because $\Delta V \ll V_D$ ($\Delta T \ll T_{sys}$) high amplification of ΔV is needed in order to get an output indication on the recorder. To make the amplification easier the voltage V_D due to the system noise T_{sys} is now canceled by a d-c voltage $-V_D$, leaving ΔV as the output signal voltage from the detector. The corresponding signal power is equal to

$$W' = C'(k\,\Delta T\,\Delta\nu_{HF})^2 \quad \text{watts} \tag{7-9}$$

where C' is a constant, watt^{-1}.

In addition to ΔV, a noise voltage also exists at the detector output. The low-frequency components of this voltage from d-c to $\Delta\nu_{HF}$ cps are due to different IF noise-voltage components in the frequency range from

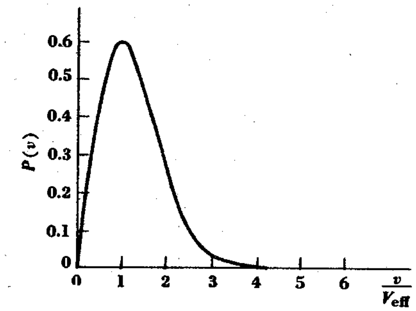

Fig. 7-10. Probability distribution of the amplitude of the envelope of the predetection output noise voltage. (*After Rice*, 1945.)

$\nu_{IF} - \Delta\nu_{HF}/2$ to $\nu_{IF} + \Delta\nu_{HF}/2$ beating with each other in the detector. The resulting low-frequency (LF) power spectrum is triangularly shaped, because the number of IF noise-voltage components giving a certain noise component at frequency ν_{LF} is proportional to $\Delta\nu_{HF} - \nu_{LF}$ (ν_{LF} varies from zero to $\Delta\nu_{HF}$). The maximum LF power density close to zero frequency is equal to (Tiuri, 1964)

$$W_{LF_{max}} = 2C'(kT_{sys})^2\,\Delta\nu_{HF} \tag{7-10}$$

assuming $\Delta T \ll T_{sys}$.

The detector output voltage is fed to the recorder through a low-pass filter amplifier in order to reduce fluctuations. The effect of a low-pass filter is often obtained by a long-time-constant (order of seconds) RC integrator circuit so that the effective bandwidth $\Delta\nu_{LF}$ of the low-pass filter is much smaller than the bandwidth of predetection section $\Delta\nu_{HF}$. If the low-pass amplifier filter has a rectangular passband from zero to $\Delta\nu_{LF}$ and a power gain G_{LF}, then the fluctuating noise power output is equal to

$$W_{LF} = G_{LF} 2C'(kT_{sys})^2\,\Delta\nu_{HF}\,\Delta\nu_{LF} \tag{7-11}$$