NATIONAL RADIO ASTRONOMY OBSERVATORY

SUMMER LRCTURE ON "RADIOMETERS"

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The term radiometer generally refers to the electronics needed to convert electromagnetic energy into an interpretable record such as a chart recording. One of the simplest versions of a modern radiometer is shown in Figure 1. Basically it consists of an antenna, amplification and filter electronics, and a detector.

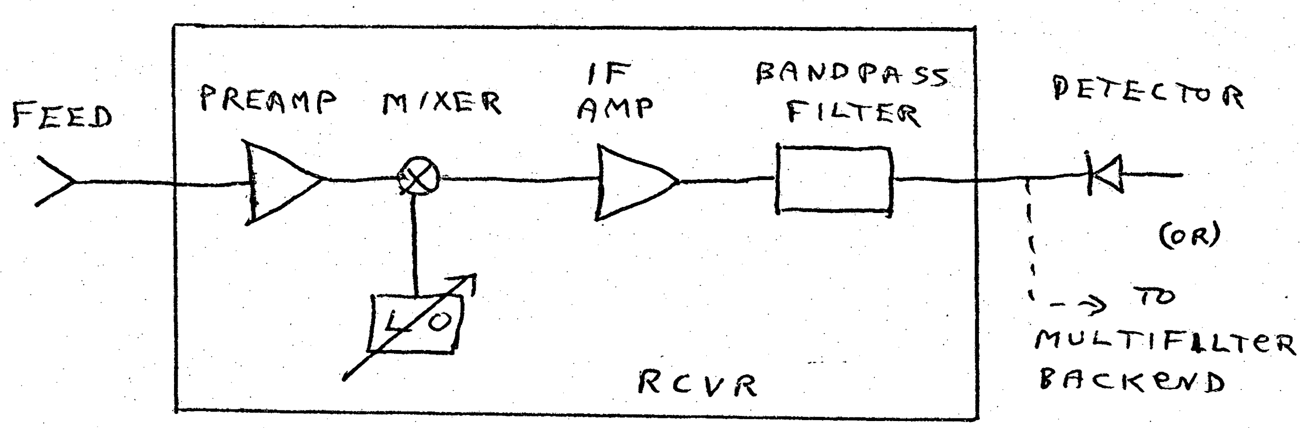

FIGURE 1

In the case of a reflector type antenna the receiver engineer is concerned only with the feed part of the antenna. Its purpose is to convert as much of the electromagnetic energy concentrated by the reflector into an electric signal on a coaxial cable. Looking at the antenna as a transmitter the feed is designed to illuminate the reflector as uniformly as possible without losing much energy past the edge of the dish. Below 1 GHz this is usually some sort of a half wave dipole while above this frequency various forms of waveguide horns are used.

The preamp in Figure 1 is designed to create as little noise itself while producing enough amplification to overcome the noise created by following stages. Below a few hundred MHz transistor amplifiers are generally adequate for this purpose. Between about 500 MHz and 30 GHz parametric amplifiers are most common while above these frequencies low noise amplification is difficult to achieve and the preamp is often omitted. Maser amplifiers have been around radio astronomy for many years, but their widespread use is just now beginning to be realized. The advent of low-temperature closed-cycle refrigerators and wideband maser designs are making them more attractive.

In principle enough gain could be provided by the preamp to drive a detector directly. In practice it is difficult to provide adequate filtering and flexibility in observing frequency at the signal frequency so at least one conversion is made to an intermediate frequency in a mixer. The mixer is driven by a local oscillator (LO), and its output is at the sum and difference of the LO and signal frequencies. Normally the lower or difference frequency is selected and further amplified before sending it down the telescope cables. The detector and associated equipment are then housed in the control room. For continuum observations the full bandwidth of the system is detected, but for spectral-line observations the IF signal is split up by a multi-filter system or autocorrelation receiver.

Since signals in radio astronomy are as much as 10^5 times smaller than the noise generated by the radiometer itself gain variations in the amplifier chain in Figure 1 would mask the small change in output due to the observed radio source. For this reason some sort of differencing technique is normally used to cancel out the receiver gain variations.

Continuum Radiometers

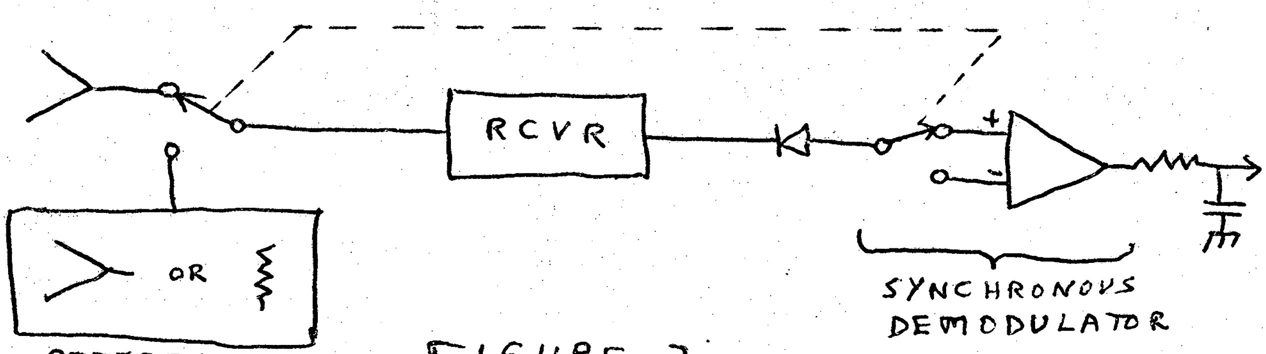

FIGURE 2

Figure 2 shows the most commonly used system for wideband continuum radiometry employing an RF switch ahead of the preamp and a synchronous demodulator after the detector. The RF switch and synchronous demodulator are run in step so that if the noise coming from the reference is equal to the noise from the feed the average output from the DC amplifier is zero. Gain variations in the receiver will not affect this zero level. Addition of a signal to the feed input will cause a net positive voltage to appear on the output integrator.

The reference can be either a resistive termination or an offset feed receiving radiation from a slightly different direction in the sky. The latter is commonly called beam switching and has the advantage that it tends to cancel variable thermal emission from the atmosphere, but if the radio source is extended and also falls in the reference beam it, too, will be cancelled. Atmospheric radiation (particularly from water droplets) is a problem above about 3 GHz. A more specialized form of switching uses the orthogonally polarized feed output as the reference so that the demodulator output will be non-zero only when a polarized source is in the beam.

In practice the noise power from the reference is not the same as that from the signal feed so an attenuator is normally switched in and out of the amplifier chain in synchronism with the RF switch to make the receiver output in the reference half of the cycle equal to that in the signal half.

A less commonly used technique for cancelling receiver gain fluctuations is through the use of a correlation receiver shown in Figure 3. In this case

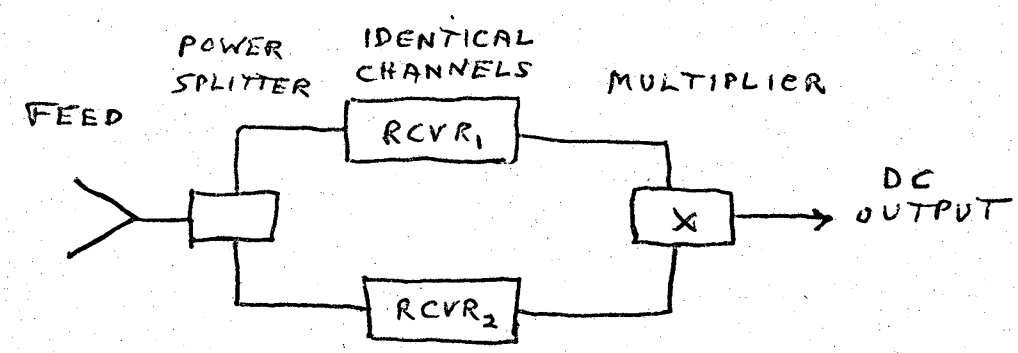

FIGURE 3

the incoming signal is split, and the two halves are separately amplified. The separate signals are combined in an RF multiplier. Noise from the two sets of RF amplifiers is uncorrelated so the average output from the multiplier will be zero with no signal present at the feed. A signal entering the feed will be coherent or correlated with itself at the two inputs to the multiplier and will produce a non-zero output. This type of system is somewhat more sensitive than the switched radiometer because full time is spent on the signal, but nearly twice as much electronics is required and the two signal paths must track in phase.

Another method of radiometer stabilization uses a gain compensation scheme to correct for electronic gain variations. This technique, called noise adding radiometry, injects a large noise signal into the input of the preamp and detects the resultant output change. By feeding the detected information back to an attenuator in the signal path the output change and hence receiver gain can be kept stable. The sensitivity of this method is about equal to the switched system because the signal is covered up by the added noise approximately half of the time.

Spectral Line Radiometers

Basically the only difference between continuum and spectral line receivers is that the latter splits the signal into a set of contiguous frequency channels so that the intensity versus frequency characteristics of a signal can be measured. In principle one could use the same sort of switching scheme with a synchronous demodulator for each frequency channel. However, for various reasons it is easier to use an adjacent frequency band as the reference and switch the first LO frequency. So long as the amplifiers ahead of the first mixer are relatively broadband as compared to the frequency switch change the signal and reference outputs of the detectors will be nearly equal. One must be very careful to design all channels to track in gain and detector characteristics to avoid spurious spectral features. Multifilter receivers are presently used for total frequency bandwidths greater than a few tens of MHz.

For total bandwidths less than 50 MHz or so autocorrelation receivers have generally replaced filter banks for spectral line work mainly because their resolution can be easily changed and they have less tendency to produce spectral anomalies due to gain drifts. This type of receiver works by sampling the IF signal in time and then searching the data for periodicities corresponding to different frequencies within the receiver passband. This search or conversion from time sampling to frequency samples is done through a Fourier Transform. The Fourier Transform concept tends to permeate all of radio astronomy with a slight tinge of the occult, but the idea is quite simple.

Take for example a relatively long time sequence sample of a sinusoidal voltage, V(t), as in Figure 4a.

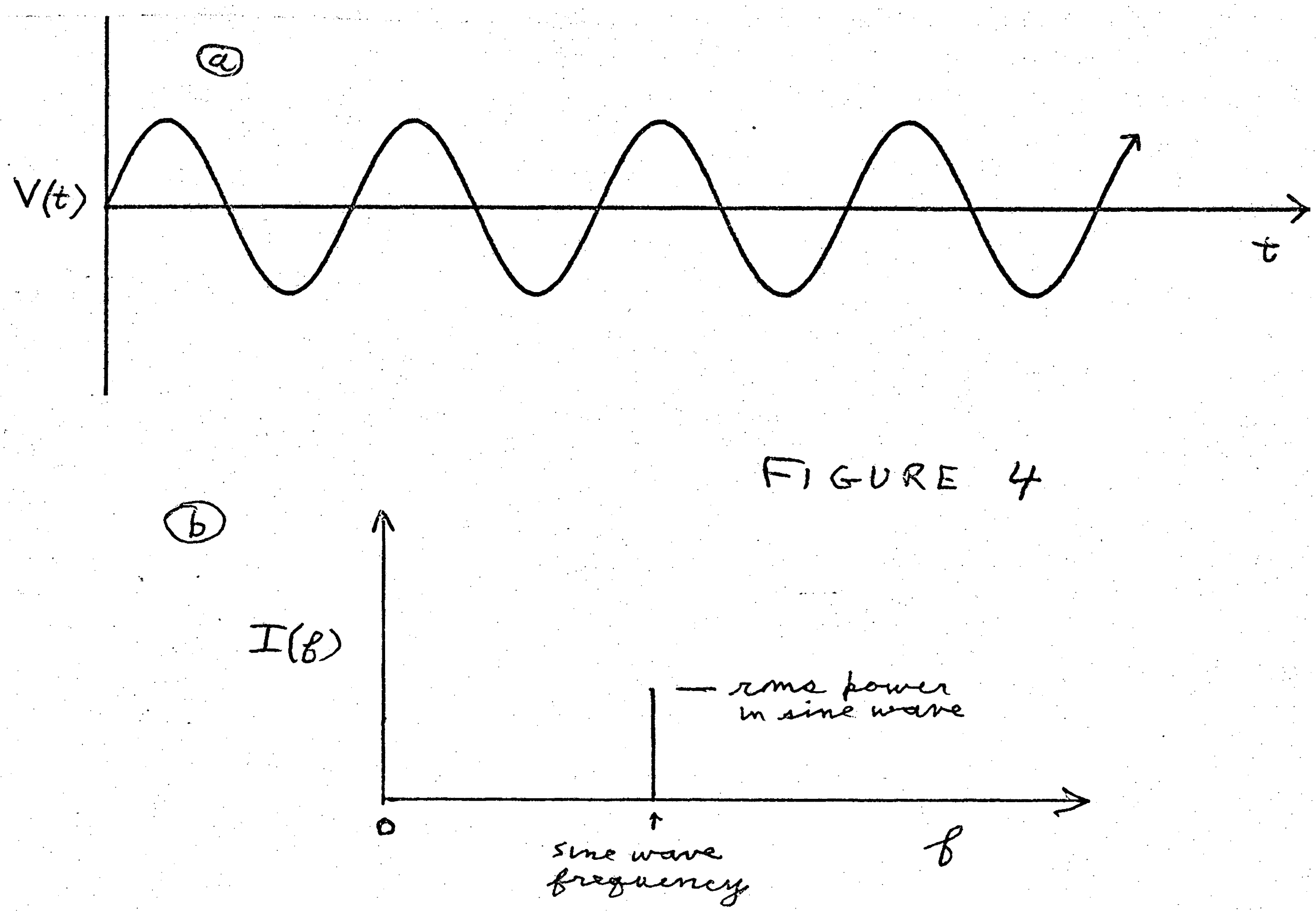

FIGURE 4

If one multiplies V(t) point for point by another sinusoid of unity amplitude and the same frequency and phase the average of the products will be the rms intensity of V(t). If V(t) is multiplied by a sinusoid of a different frequency the average product will be nearly zero so long as the sample is is long enough to allow V(t) and the test sinusoid to go in and out of phase many times. If we plot the average product

$$I(f) = \sum_{t=0}^{\infty} V(t)\sin(2\pi ft)$$

for frequencies from zero to f_1 we get Figure 4b. If several waves of different frequencies existed in V(t) there would be a corresponding number of spikes in the I(f) plot with the extreme being where V(t) is white noise, i.e., containing all frequencies, in which case I(f) would be a constant or a horizontal line in Figure 4b.

A more formal expression of the Fourier Transform is

$$I(f) = \int_{-\infty}^{\infty} V(t)\, e^{-i2\pi ft}\, dt$$

where $e^{-i2\pi ft} = \cos(2\pi ft) - i\sin(2\pi ft)$ is used instead of just sin $(2\pi ft)$ to account for periodicities of all phases. This transform has the interesting property that V(t) is the Fourier Transform of I(f).

Of course one cannot sample V(t) for an unlimited time with infinitesimal resolution, but some ground rules can be stated. First, the sample rate must be fast enough to take at least two points per cycle of the highest frequency wave present. Otherwise one cannot distinguish an undersampled wave from a properly sampled but lower frequency one. This is called aliasing. Second, the frequency resolution is determined by the length of the sample such that two frequencies separated by the resolution limit must go through one complete phase reversal in the total sample time.

One can actually do this sort of a transform in real time hardware, but a considerable savings in the cost of a high speed (say 100 MHz) system with a moderate number of channels (say 1000) can be had by not transforming the signal itself but its autocorrelation function. An autocorrelation function is simply the product of a signal V(t) times itself at a later time V(t + d) where d is the delay.

$$A(d) = V(t)\, V(t + d)$$

If you think about it for awhile you will realize that the autocorrelation of a sine wave is still a sine wave of the same frequency only d has been substituted for t. The advantage to be gained is that A(d) can be integrated for as long as desired before the transform is done. This allows the transform to be done fairly slowly in a small general purpose computer as opposed to once per sample string in the direct time sequence case which takes a lot of special purpose hardware.