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BASIC DATA REQUIREMENTS FOR MICROWAVE RADIOMETER SYSTEMS

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Microwave Radiometry has emerged over the last two decades to become an integral part of the field of environmental remote sensing. Numerous investigations have been conducted to evaluate the use of microwave radiometry for atmospheric, oceanographic, hydrological, and geological applications. Remote sensing of the earth using microwave radiometry began in 1968 by the Soviet satellite Cosmos 243, which included four microwave radiometers (Ulably, 1981). Since then, microwave radiometers have been included onboard many spacecraft, and have been used to infer many physical parameters.

The development of the required algorithm to determine these physical parameters from radiometric measurements is clearly an extremely broad area and is beyond the scope of this paper. Rather, in this paper, some of the basic concepts of radiometric emission and measurement will be discussed. Several radiometer systems will be presented and an overview of their operation will be discussed. From the above description of the radiometer operation the data stream required from the radiometer and the general type of algorithm required for the measurement will be discussed.

As noted above the radiometer has been shown to be useful in the measurement of many physical properties. This is accomplished by measuring the energy the object emits. All substances at a temperature above absolute zero radiate electromagnetic energy. Atomic gases radiate electromagnetic energy at discrete frequencies according to specific transition of an electron from one energy level to another. For liquids and solids, the increased particles interaction results in a continuous spectrum. A radiometer is simply a very sensitive receiver which can be used to accurately measure this radiated energy and thus infer physical properties.

The power P emitted by an object in thermal equilibrium is a function of its physical temperature T and in the microwave region P is directly proportional to T. The maximum power an object can emit for a given T is given by P_{bb}, the ideal black body radiation. If a microwave radiometer is completely surrounded by perfectly absorbing material, i.e. a black body, the power received by the antenna would be

$$P_{bb} = kTB \qquad (1)$$

where k is Boltzmann's constant and B is the noise bandwidth of the radiometer. The term *brightness* temperature T_b can be used to characterize the energy emitted by a material of constant physical temperature by the following equation

$$T_b = \frac{P}{k\ B} \qquad (2)$$

where P is the power emitted by the material over the bandwidth B. For materials that are not perfect absorbers (not black bodies) the power received will be less than the maximum P_{bb}, and the material is said to have an emissivity $e = T_b/T$. The radiometers measurement of T_b can then be used to determine the emissivity of an object which may be related to physical parameters.

The radiometer must estimate the power P radiated from an object. The power level of this received signal may be lower than the receiver noise level. Thus, a radiometer must make a very precise measurement of a very small signal. Clearly this requires the gain and receiver noise to be well known and very stable. Several radiometer systems have been developed to facilitate this measurement and will be discussed below.

The *total-power radiometer* is a straightforward configuration consisting of an antenna, amplifier stages, a detector, and a low-pass filter or integrator. An ideal system is shown in figure 1. Here the system is dependent on the receiver noise and gain to be stable between calibrations. The internal receiver noise is represented as an additive noise source and the front end amplifier stage is considered noise free. If the detector is assumed to be a square law device, then the voltage out of the detector will be proportional to the noise power at the input. That is,

$$V_{out}(t) = V_{dc} + V_{ac}(t) \tag{3}$$

where

$$V_{dc} = G_s(T_A + T_{REC}) \tag{4}$$

where G_s is the system gain. The dc portion is a measure of the power into the square law device, i.e. a measure of the input noise temperature. The ac portion represents the statistical uncertainty in the measurement. The low-pass filter (or integrator) will reduce this uncertainty. It can be shown [Ulably, 1981] that integrating a random process with a noise bandwidth B for a time τ will reduce the variance of the output process by $B\tau$. Therefore,

$$\frac{\{V_{ac}\}_{rms}}{V_{dc}} = \frac{1.}{\sqrt{B\tau}} \tag{5}$$

If the term ΔT is defined as the standard deviation of the output in terms of the input antenna temperature measurement

$$\Delta T = \frac{\{V_{ac}\}_{rms}}{G_s} \tag{6}$$

Then,

$$\Delta T = \frac{T_A + T_{REC}}{\sqrt{B\tau}} \tag{7}$$

where ΔT can be considered as the minimum detectable change in the radiometric antenna temperature. In the above expression, ΔT is defined as the radiometric sensitivity of an ideal total power radiometer. Uncertainty in the measurement because of gain fluctuations can be written

$$\Delta T_G = \frac{\Delta G_S}{G_S} \tag{8}$$

then the total uncertainty can be written

$$\Delta T = T_{sys}\left[\frac{1}{B\tau} + \left(\frac{\Delta G_S}{G_S}\right)^2\right] \tag{9}$$

Equation 9 is the radiometric sensitivity of a total power Dicke radiometer including the effects of noise and gain fluctuations.

One method to reduce the effect of gain fluctuations was developed by Dicke in 1946 using a modulation technique to reduce these effects. Figure 2 shows a simplified block diagram of a *Dicke radiometer.* The system is essentially a total power radiometer with the addition of two switches (often called Dicke switches). This allows the input to the radiometer to be alternately switched from the antenna to a reference load of known noise temperature. The output for these two switch positions are subtracted before averaging. If the switches are operated at a rate in excess of the highest component of the spectrum of the gain fluctuation, then the effective system gain G_s can be considered constant for both switch positions. Since the gain is identical for each half cycle, the average voltage out of the square law detector can be written

$$\bar{V}_{d_{ant}} = G_s kB(T_A + T_{REC}) \quad \text{for } 0 \le t \le \tau_s/2 \tag{10a}$$

$$\bar{V}_{d_{REF}} = G_s kB(T_{REF} + T_{REC}) \quad \text{for } \tau_s/2 \le t \le \tau_s \tag{10b}$$

where T_{REF} is the known reference noise source and τ_s is the period of the switching cycle. The average output voltage, V_{out}, can be written

$$\bar{V}_{out} = \frac{1}{2} G_s (T_A - T_{REF}) \tag{11}$$

The ΔT of the Dicke radiometer will be determined by first finding the ΔT for each half cycle. The noise uncertainty during the antenna portion

$$\Delta T_{ANT} = \frac{T_A + T_{REC}}{\sqrt{\frac{B\tau}{2}}} \tag{12}$$

For the reference portion

$$\Delta T_{REF} = \frac{T_{REF} + T_{REC}}{\sqrt{\frac{B\tau}{2}}} \tag{13}$$

The effect on gain fluctuations

$$\Delta T_G = (T_{REF} - T_A')(\Delta G_S / G_S) \qquad (14)$$

Since these fluctuations are independent the total uncertainty or ΔT for the Dicke radiometer can be written

$$\Delta T = \left[\frac{2(T_A + T_{REC})^2 + 2(T_{REF} + T_{REC})^2}{B\tau} + \left(\frac{\Delta G_S}{G_S}\right)^2 (T_A - T_{REF})^2 \right]^{1/2} \qquad (15)$$

If the antenna temperature, T_A, equals the reference temperature in equation 15 the effects of gain fluctuations are virtually eliminated. The ΔT for this *Balanced Dicke radiometer*, shown in figure 3, then becomes

$$\Delta T = \frac{2(T_{REF} + T_{REC})}{\sqrt{B\tau}} \qquad (16)$$

or

$$\Delta T = 2\Delta T_{IDEAL}$$

There are several techniques which may be used to ensure the above condition is met and the radiometer is balanced. These techniques use a control loop such that the error signal adjusts the system gain during one half cycle, varies the reference temperature, or adds noise to the antenna port to balance the loop. These approaches have various advantages and disadvantages and the specific approach is not important to this discussion.

The sensitivity for the *Total Power, Dicke (unbalanced)*, and *Balanced Dicke* is shown in equations 9, 15, and 16 respectively. The sensitivity is important to the information scientist since the required precision or word length is dependent on the sensitivity of the radiometer. These expressions allow the information scientist to determine the likely digital word length requirements from either the science requirements or from a hardware description of the proposed radiometer system.

In the above discussion, the RF components in the radiometer front-end have been assumed to be perfectly impedance matched, that is, no reflections exits between components. In actuality, although these reflections can be minimized they can never be completely eliminated and, as will be shown, their effect on radiometer performance can be significant.

If the radiometer measurement is assumed to be linear over the range of interest, then the output of the radiometer (counts, volts, duty cycle, etc.) can be expressed as

$$N_{counts} = M\, T_A + b \qquad (17)$$

For the ideal (perfectly impedance matched) case the intercept, b, can be calculated from system parameters for some radiometer configurations. The slope M can then be found by calibration. In practice, accurate characterization of the instrument including the effects of mismatch requires calibration at two reference temperatures. This allows the independent determination of M and b. To the extent that the reflection coefficients of the radiometer front end remain constant, their effect can, in principle, be accounted for by the calibration of the effects of the reflection coefficients.

The effect of impedance mismatch and loss in the radiometer front end can be understood by the analysis of the simplified front end network shown in figure 4. The effective noise temperature at the input to the receiver T_{IN} can be shown to be [Ulably, 1981], [Kerns, 1967]

$$T_{IN} = \alpha_m Y\, T_{ANT} + \alpha_m (1-Y) T_o + (1-\alpha_m) T_{REC} \qquad (18)$$

where

$$\alpha_m = \frac{(1-|R_{2S}|^2)(1-|R_R|^2)}{|1-R_R R_{2S}|^2}$$

$$Y = \frac{1}{L_S}\left[\frac{(1-|R_G|^2)(1-|S_{11}|^2)}{|1-S_{11}R_G|^2(1-|R_{2S}|^2)}\right]$$

and

$$R_{2S} = S_{22} + \frac{S_{21}S_{12}R_G}{1-S_{11}R_G}$$

$$L_S = \frac{Z_{02}}{Z_{01}}\frac{(1-|S_{11}|^2)}{|S_{21}|^2}$$

The first term in equation 18 is the net-delivered noise temperature from the antenna; the second term is the net-delivered noise temperature generated by the losses in the network; the third term is the net-delivered noise temperature emitted by the receiver itself. The purpose of the calibration, in addition to compensating for gain constants, etc. in the receiver, is to allow the extraction of T_{ANT} from the measurement of T_{IN}. Fortunately, the calibration can be performed, and an algorithm to convert from the indicator (counts) to engineering units (T_A) developed without knowledge of the specific relationship between the various reflection coefficients and the factors of equation 16. However, equation 16 indicates the dependence of the calibration constants on temperature. Clearly, the second term is directly a function of temperature and all the reflection coefficients could be temperature dependent.

For this reason, radiometric front ends are generally temperature stabilized, and the algorithm from counts to T_A will be temperature dependent. Although the method used to include this temperature dependence is hardware specific, a technique commonly used for thermally controlled systems is to perform calibrations at operating temperatures, and correct only for temperature dependence of significant losses as shown below.

$$T_{ANT} = \sum_i \alpha_i (T_{PHY_i} - T^{CAL}_{PHY_i}) + M\, N_{counts} + b \qquad (19)$$

The information scientist wanting to provide estimates of T_A must extract from the data stream the measured T_{IN} for the available calibration sources or ground truths. From the "known" noise temperatures of the sources the coefficients M and b are then found for one set of physical temperatures within the front end. For small changes in physical temperatures and for time periods for which the radiometer system is stable T_A can be estimated from equation 17. The required precision of the operation of equation 17 would be similar to those found for N_{COUNT}. Required data rate and calibration intervals are again instrument/mission specific; however, some "typical" values are shown in table 1.

Thus far, the discussion has focused on transforming the radiometer output to antenna temperature T_A (noise temperature delivered by the antenna). Although not discussed here, for completeness it should be noted that a second transformation is generally required to convert the antenna temperature to the scene brightness temperature. This transformation is dependent on detailed antenna characteristics and the incidence dependence of the brightness temperature.

This transformation from T_A to T_B is closely related to the spatial resolution and antenna pattern of the radiometer. The spatial resolution of a microwave radiometer is often specified by its *instantaneous field of view* (IFOV). The IFOV is defined as the area on the ground contained by a specified portion of the antenna pattern (often the 3 dB contour). Of course the actual antenna temperature is a weighted average of the noise temperature received over the entire antenna pattern. In general, careful antenna design and definition of the IFOV will ensure that the transformation from T_A to T_B can be performed separately for each pixel or IFOV. However, if there is enough spatial sampling it may be possible to partially deconvolve the antenna pattern and brightness temperature to improve the trade off between spatial and temperature resolution. This could be of interest to onboard real-time users of radiometric data. In developing such an algorithm, the information scientist would require very specific information about the imaging aspects of the instrument. A possibly more trackable problem would be to develop a deconvolution algorithm that could correct the radiometric image for larger antenna side lobes. This may allow processing of nearest cells only.

In summary, although this paper is clearly not an in-depth study of possible applications of onboard processing in radiometry, it is hoped that it does provide the information scientist with an appreciation of the general data requirements for radiometric systems. An overview of general radiometer concepts has been presented with hopes that the information scientist can estimate the type of algorithms or processing which could be required in a generic sense for various applications.

REFERENCES

1. Ulably, S. T., Moore, R. K., and Fung, A. K.: Microwave Remote Sensing, Volume I, Addison Wesley Publishers, Reading, Massachusetts, 1981.

2. Kerns, D. M., and Beatty, R. W.: The Basic Theory of Waveguide Junctions and Introduction To Microwave Network Analysis, Volume III, Pergammon Press, New York, 1967.

Table 1. Data Rates and Calibration Intervals

DATA RATE

• T_A	> INTEGRATION TIME – 47 ms ESMR(NIMBUS 5) – 32 ms RADSCAT(SKYLAB) – 128 ms – 256 ms
• PHYSICAL TEMPERATURES	> THERMAL TIME CONSTANT
• CALIBRATION	> TOTAL POWER - SECONDS > DICKE - MINUTES > DICKE BALANCED - HOURS ⇒ DAYS

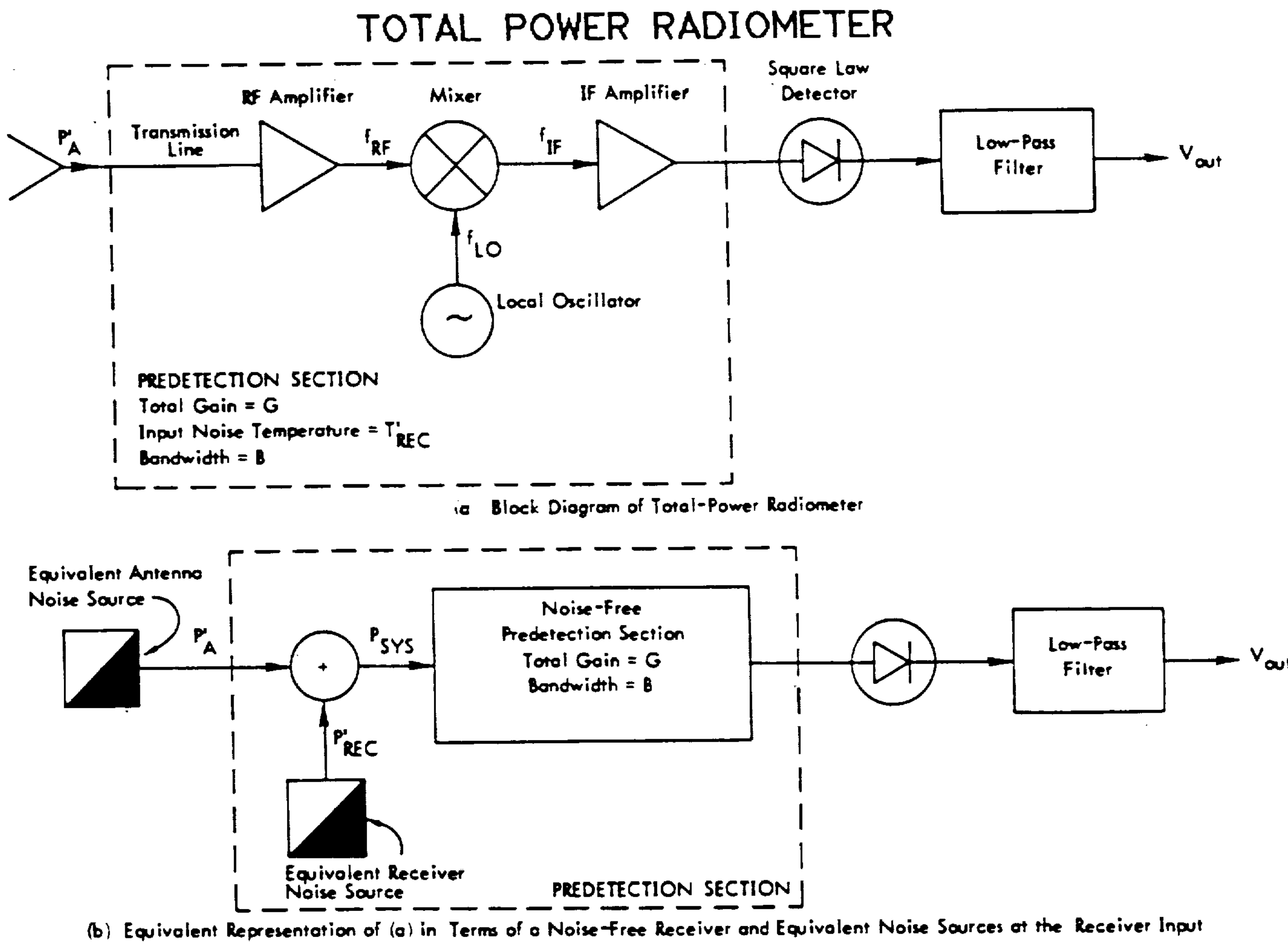

Figure 1. Total power radiometer.

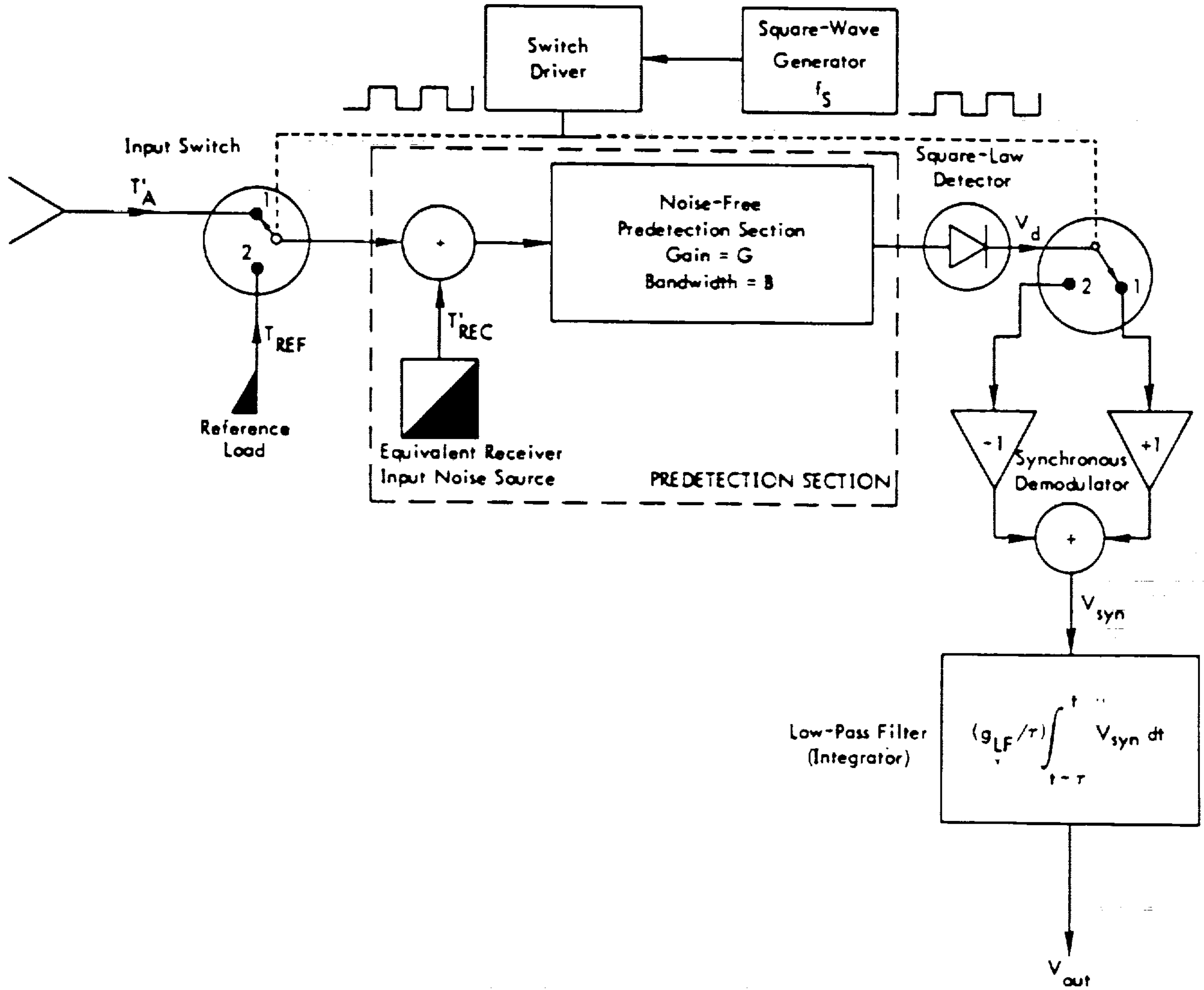

Figure 2. Dicke radiometer.

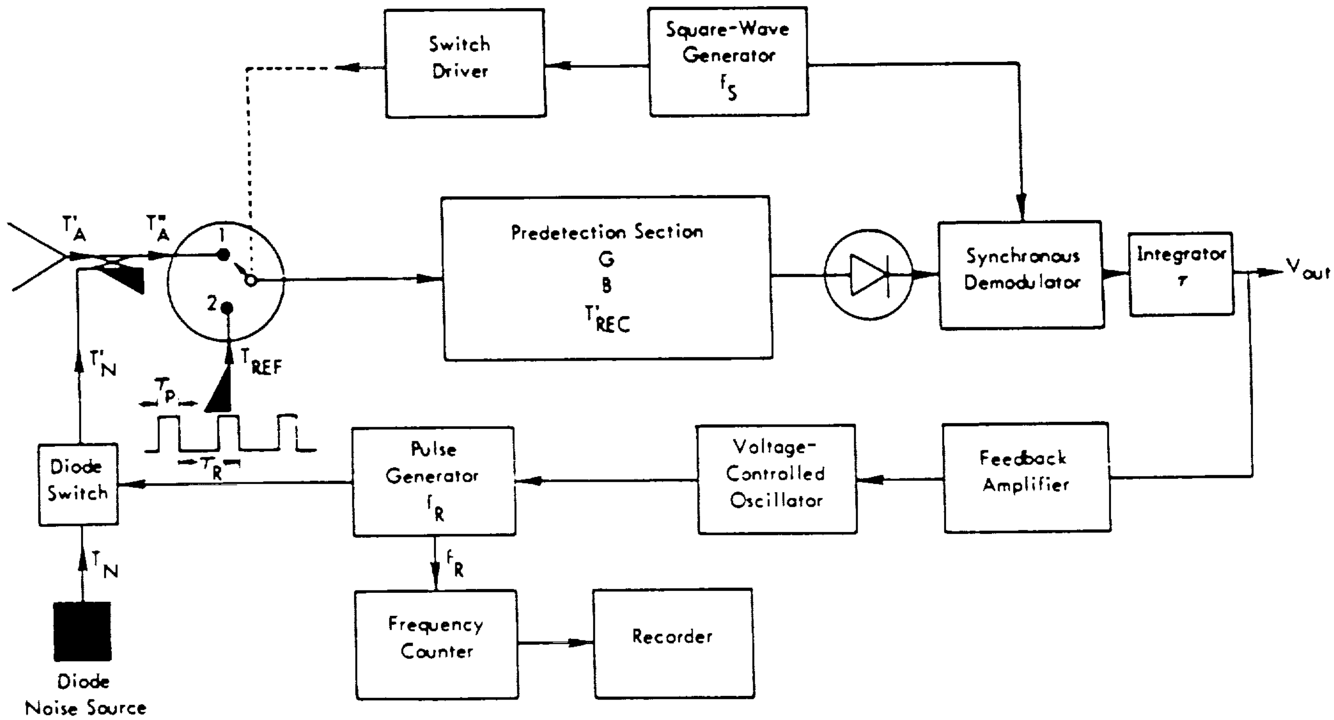

Figure 3. Dicke radiometer (noise injection).

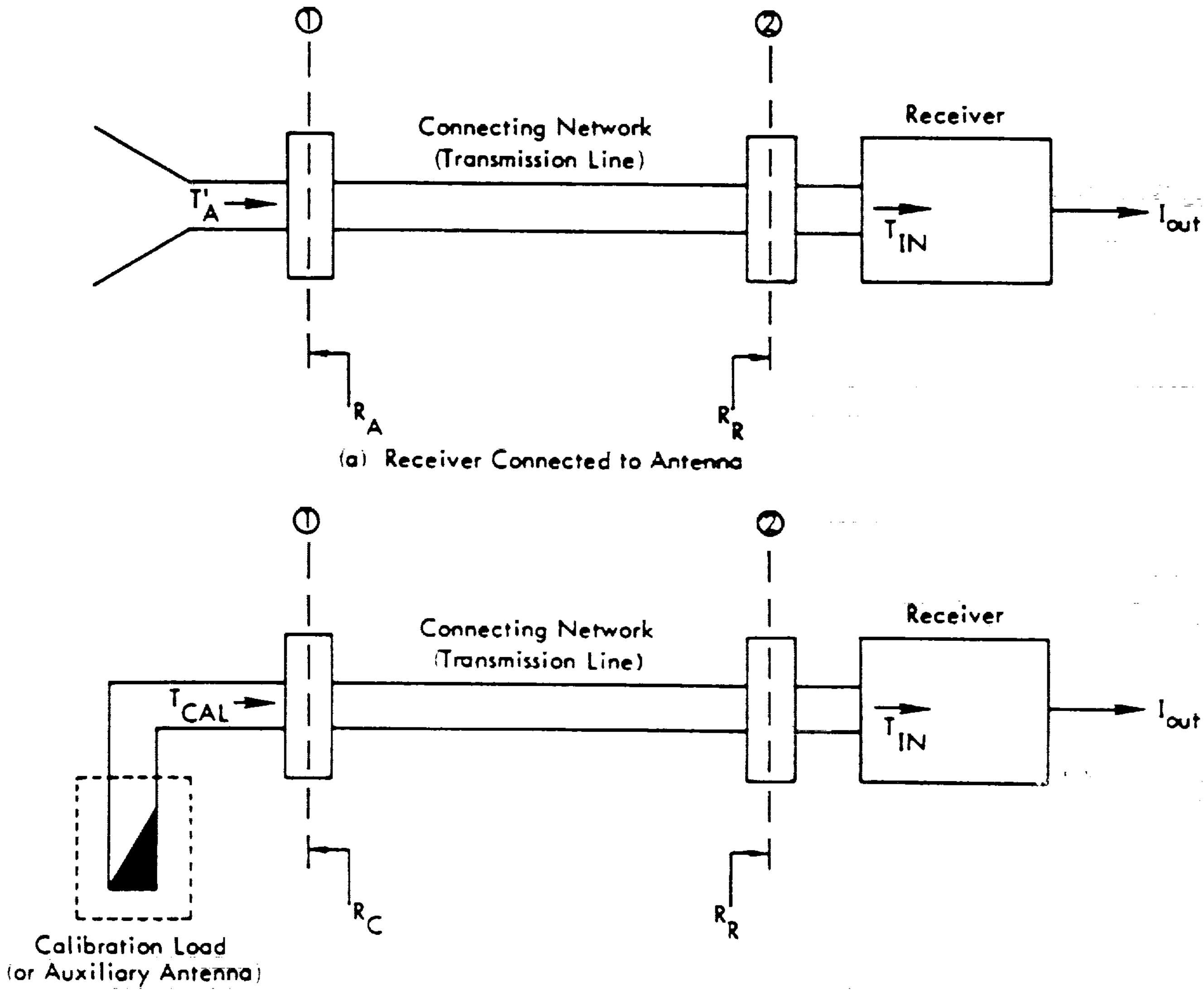

Figure 4. Effects of impedance mismatch.