S-BAND RADIOMETER DESIGN FOR HIGH ABSOLUTE PRECISION MEASUREMENT

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ABSTRACT

A radiometer for the remote measurement of absolute sea surface temperature is described. Two requirements are necessary for the attainment of the desired goal of 1 or 2 degrees (K) in absolute accuracy. Although the first is inappropriate for discussion here, it is clear that corrections must be developed to account for perturbations caused by surface effects (roughness, foaming, and salinity changes) and for atmospheric effects (absorption and scattering). The second requirement, namely the development of an instrument capable not only of high relative accuracy (i.e., resolution) but also of high absolute precision, is the subject of this paper.

The concept underlying the design of an instrument capable of an absolute precision of a few tenths degrees Kelvin in the measurement of brightness temperature at S-band is described. The role of the antenna is discussed and the importance of high ohmic and beam efficiencies is stressed.

Finally, a description of the hardware itself is presented, along with the development of a unique cryogenically cooled termination used to calibrate the entire system, including antenna.

Introduction

A relative accuracy or resolution of 0.1°K is routinely achieved in microwave radiometers provided adequate predetection bandwidth and integration time are used. On the other hand, the attainment of absolute accuracy approaching this value is not easy and demands extreme care in system design. Consider, for example, the case where the antenna sees a brightness temperature of 100°K while it and its RF transmission line are physically at 300°K. Then each .001 db of loss increases the apparent antenna temperature by 0.05°K. It is clear that RF line losses must be minimized and that they must remain stable and constant to order .001 db between calibration cycles.

The instrument to be described operates at 2650 MHz, using a waveguide fed horn antenna (HPBW-20°) and integral transition to a microstrip RF front end. This technique eliminates the variable losses and instabilities associated with even the best coaxial connectors.

Design Concept

The radiometer is of the signal modulated type, due to Dicke[1], in the basic configuration shown in Fig. 1. It is designed around the following three basic ideas:

1. Use of a constant temperature enclosure for front-end RF components, including the circulator switch and its reference termination.
2. A null-balance mode of operation which, in conjunction with (1), avoids the effects of time dependent losses in the RF components.
3. Use of a stable, pulsed avalanche diode noise source to provide variable noise injection in the antenna arm. Constant pulse width is relatively easy to achieve so that the added noise is accurately proportional to the pulse repetition frequency.

The usual Dicke type radiometer, to which is added a noise injection arm and a constant temperature enclosure which includes the reference termination, is shown in Figure 1. If the output is amplified, detected and then demodulated at the switching frequency, then the condition for zero AC signal is exactly that $T_{in} = T_o$, the temperature of the enclosure. This result is completely independent of losses or reflections in the circulator switch, imperfections in the reference termination, finite switching times, etc., provided only that the isolator "isolates" well enough and that a single electromagnetic mode propagates in the input arm. The radiometer operates in a feedback mode whereby the input noise power level is adjusted to achieve a null at the output. Thus, because the feedback always ensures that $T_{in} = T_o$, the antenna temperature is given by $T_A = T_o - T_N$. T_o is, of course, measured thermometrically. In principle the added noise, T_N, can be determined from a knowledge of the loss in the variable attenuator. In practice, however, it is not possible to measure the loss of the variable attenuator with sufficient precision, so that another way of controlling and monitoring the injected noise T_N, has been devised. The details are shown in Figure 2. The noise diode is gated by means of a switch so that its output occurs in the form of 20 μsec wide pulses. Any error signal at the output of the demodulator and filter causes the frequency of the pulses to change, thereby varying the average injected noise in such a way as to reduce the error signal to the vanishing point. If the noise diode is switched with constant width pulses, then at null the antenna temperature T_A is related to pulse frequency f_p by

$$f_p = k\,(T_o - T_A) \qquad (1)$$

where k is the calibration constant for the noise injection system.

Resolution

The sensitivity of the nulling feedback radiometer is given by

$$\Delta T_{rms} = \frac{2}{\sqrt{B\tau}} \quad \frac{T_O + T_R}{1 - \ell} \qquad (2)$$

where T_R is the receiver noise temperature (including second stage contributions), ℓ is the total fractional loss (both reflective and dissipative) sustained by a signal in reaching the amplifier input, and B and τ are the predetection bandwidth and postdetection integration time respectively. The factor 2 obtains if both the switching and demodulation are square wave. For the present radiometer $T_o = 300°K$, $T_R = 70°K$, $\ell = 1$ db, and therefore

$$\Delta T_{rms} = \frac{925°K}{\sqrt{B\tau}} \quad (3)$$

A resolution of less than 0.1°K is achieved, for example, when B = 100 MHz and τ is one second or longer.

Instrumentation

RF Microwave Integrated Circuit (MIC)

The Dicke circulator switch and noise injection circuits are fabricated in microstrip on a substrate of high purity alumina. These microstrip circuits are built around a short length of WR 284 rectangular waveguide with integral probe coupling from microstrip to waveguide, as indicated schematically in Figure 3. The small size of this enclosure (3x4x5 inches) greatly eases the burden on design of a regulator capable of holding the temperature of the enclosure constant to within 0.03° at 303°K (i.e., about 10° above ambient).

The MIC is electrically connected to, but thermally insulated from, the antenna by means of a two section quarter-wave impedance transformer designed to create a match between the square waveguide of the antenna and the rectangular guide of the MIC transition. It is constructed of thin wall (.020 inch) stainless steel, internally gold plated to reduce ohmic loss. Calculations show that the heat flux through this transformer will amount only to 0.3 watts for a 10°C temperature differential between ends. Foam dielectric plugs inside the transformer effectively eliminate radiative and convective heat transfer, without creating mismatch.

Receiver

This rather conventional subsystem is comprised of a bandpass filter, degenerate parametric amplifier and associated stabilized pump circuitry, double balanced mixer with integrated IF amplifier, low pass filter, square law detector and low noise audio frequency amplifier. With the exception of the pump source, which dissipates several watts of power, these components are all mounted inside a thermally insulated, but non-regulated, enclosure.

A Schottky barrier diode has been chosen for the square law detector, due to the very low 1/f noise of these hot carrier devices. Unusually stringent requirements are placed on this detector and the following low noise audio amplifier, due to the low modulation frequency (50 Hz) and the need for accurate square law detection imposed by the use of pulsed noise injection. The latter requirement demands that RF (or IF) gain be carefully adjusted to ensure that deviation from square law response is negligibly small.

The Antenna

Low ohmic loss and high beam efficiency are of paramount importance, but aperture efficiency is of less concern. Circular polarization over the whole of the main beam is desirable as a convenient way of averaging the parallel and perpendicularly polarized components of sea emission.

The only antenna capable of meeting all of these requirements is some form of compensated horn, e.g., corrugated[2] or multimode[3, 4]. The latter type has been selected for this application and the hybrid TE_{12}/TM_{12} mode is generated, along with the dominant TE_{10} mode, by means of a discontinuous change in dimension of the square waveguide which feeds the square aperture pyramidal horn. When the modes are properly phased at the aperture, the beamwidths become essentially equal in all planes and E-plane side lobes are suppressed to -30 db or more. Beam efficiency between first pattern nulls exceeds 98%.

Calibration

Calibration of a microwave radiometer is normally done by replacing the antenna with a cooled reference termination, followed by application of corrections for ohmic and mismatch losses in the antenna. The uncertainty in these corrections is the dominant factor in the ultimate precision of the radiometer and, for many applications, is unacceptably large.

An alternative is to point the antenna at a target of known temperature. To the extent that this temperature is known, and the target is reflectionless and completely fills the antenna field of view, the calibration is exact. A target suitable for use with the previously described horn antenna is shown in Figure 4. It is basically a primary standard of brightness temperature, requiring only two small corrections which together add about 0.1°K to the target's temperature. One correction accounts for the small reflections which occur at the foam interface, and in the absorbing material itself. The other accounts for the fact that the antenna does not couple 100% to the target alone. It is estimated that the coupling to external space, however, is down by at least 40 db.

Conclusion

Preliminary tests indicate that the goal of a few tenths degree Kelvin has been reached in this instrument. For example, the temperature of the reference termination is controlled to better than 0.01°K and no gradients exceeding 0.03°K have been observed within the MIC.

The measured stability of the noise diode exceeds 0.1°K in 72 hours, while the pulsed noise injection technique results in an extremely linear relationship between the pulse frequency f_p and the average injected noise.

Possibly the largest single source of error is in the calibration technique, but this is believed not to exceed 0.1°K, as noted previously.

References

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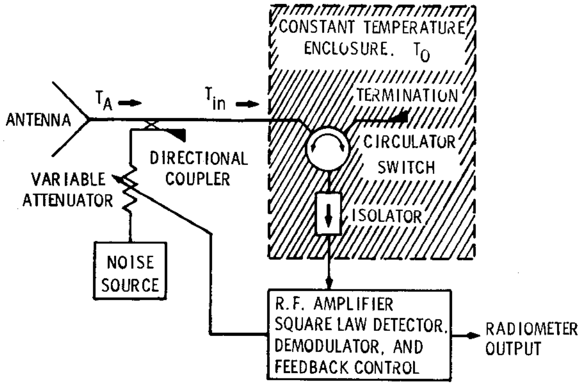

FIG. 1. BASIC RADIOMETER CONFIGURATION

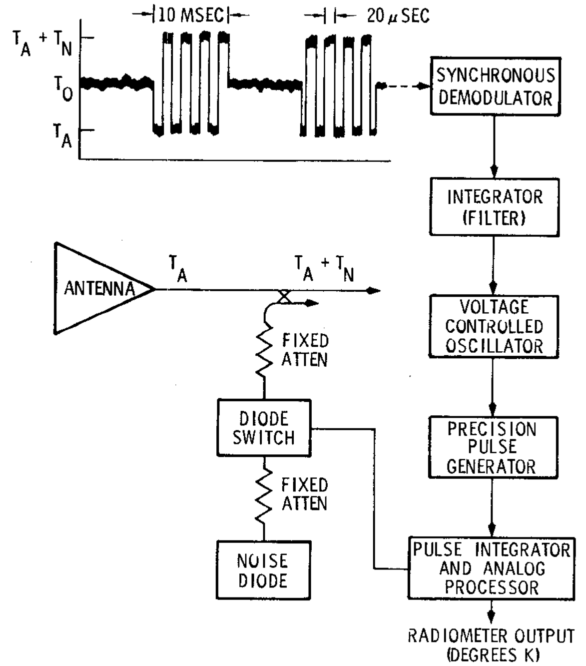

FIG. 2. NOISE INJECTION CONTROL CIRCUIT

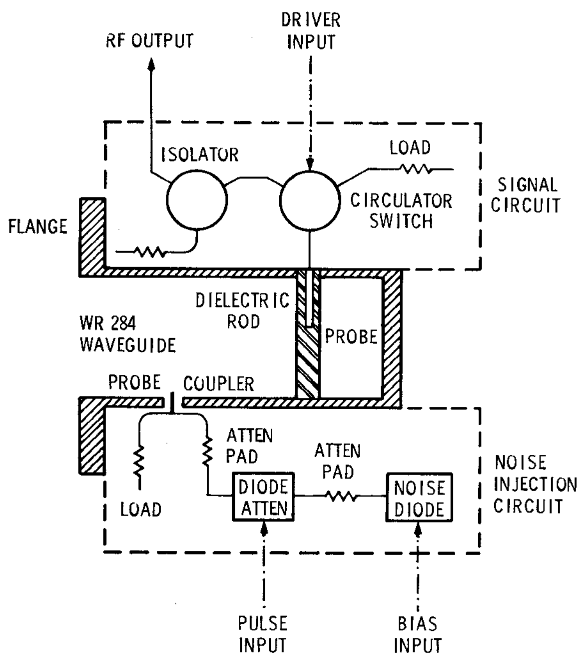

FIG. 3. MICROWAVE INTEGRATED CIRCUIT AND ENCLOSURE

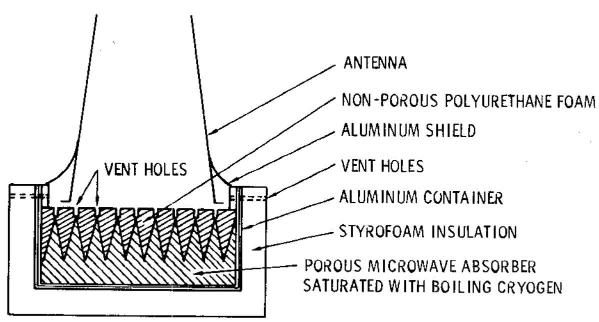

FIG. 4. CRYOGENIC ANTENNA LOAD