A Multi-Channel Microwave Radiometer Uses Reference Averaging For Calibration: Precision Approaches That Of A Total Power Radiometer

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ABSTRACT

A seven channel microwave radiometer has recently been developed for the Department of Energy Atmospheric Radiation Measurement Unmanned Aerospace Vehicle program. The instrument is designed to measure precipitable water vapor and cloud liquid water from board a DHC-6 (Twin Otter), chase plane for a remotely piloted vehicle. Five of the seven channels are centered about the 22.235 GHz water vapor absorption line. The other two channels are centered about 36.5 GHz and 89.0 GHz. Four calibration references exist for each channel within the radiometer. A digital computer is used to synchronize the switching of the circulators to the sampling of the analog-to-digital converters, thus, the timing of the data acquisition is programmable. By shortening the duty cycle of the calibration sequence and averaging the reference samples over an extended period of time radiometric precision approaching that of a total power radiometer is achieved. The channel selection along with its novel calibration scheme make this instrument a unique research tool.

THE DEPARTMENT OF ENERGY MICROWAVE RADIOMETER (DoER)

A seven channel microwave radiometer has been developed in support of the Department of Energy Atmospheric Radiation Measurement Unmanned Aerospace Vehicle (DoE ARM/UV) program. The DoE microwave radiometer (DoER) is designed to fly aboard a Twin Otter, chase plane for the unmanned aircraft. Zenith viewing microwave radiance measurements are used to derive precipitable water vapor (PWV) and liquid water path (LWP) above the aircraft. In a typical measurement scenario, the unmanned aircraft flies above a cloud layer while the Twin Otter flies in stacked formation below the cloud deck. Bi-directional broadband flux measurements from both aircraft are compared to quantify the cloud and clear air extinction. Funding limitations have delayed the deployment of the DoER on the Twin Otter. However, ground-based measurements were made with the DoER during the 1997 ARM Water Vapor Intensive Observation Period at the Southern Great Plains Cloud and Radiation Test (SGP CART) facility.

The locations of the seven channels are indicated in Fig. 1. The channel locations are plotted onto the absorption spectra of atmospheric constituents: water vapor, cloud liquid water, and oxygen. As illustrated, the seven channels are centered about three frequencies, 22.2 GHz, 36.5 GHz, and 89.0 GHz. The 36.5 GHz and 89 GHz channels use double-side-band mixers with IF frequencies of 100 - 500 MHz and 100 - 1500 MHz, respectively. A low noise amplifier and a single-side-band mixer provide independent sampling of both sides of the 22.2 GHz absorption line. A 5-channel multiplexer is used to separate the 3500 MHz intermediate frequency bandwidth into five equally-spaced 500 MHz pass bands. Hence, the effective detection bandwidth is 2500 MHz.

Calibration is obtained by switching between four calibration references. Each receiver is switched between the scene and calibration references using three junction (five port) ferrite latching circulators. Two of the references are waveguide terminations encased in thermally controlled copper blocks. Each block with a mass of approximately 2.0 kg is embedded in a well-insulated housing for optimum thermal stability. One block is heated to 340 K and the other is chilled to about 250 K using a sterling cycle cooler. A nitrogen purge prevents condensation on the cold reference. A noise source connected through a waveguide attenuator provide the other two references. With the noise source off, the attenuator appears like a waveguide termination at ambient temperature; with the noise source energized, the attenuator has an equivalent noise temperature in excess of 500 K.

This work was funded by the Department of Energy's Atmospheric Radiation Measurement Unmanned Aerospace Vehicle Program.

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Two references are required to determine the response of a linear radiometer system. Additional references are necessary to infer information on the quality of the calibration coefficients. In an aircraft environment external conditions affecting system calibration are difficult to control, e.g. temperature, vibration, power supply fluctuations. Comparisons of calibration coefficients obtained with permutations of the four references can be used to identify anomalies in the references such as errors in the thermometry or spurious changes in their mean values. However, such comparisons will not include factors affecting calibration beyond the reference plane, i.e. system components not included in the calibration path. Thus it is important to stabilize those elements, e.g. waveguide coupling to the antenna, which affect system calibration beyond the reference plane. For this reason, we have chosen to integrate the antenna system into the radiometer housing.

Sixteen-bit analog-to-digital converters (A/D's) are used for sampling the detected signal. The sixteen bit converters have sufficient dynamic range to eliminate feedback often needed to compensate for drifts in receiver gain. Software control of the switching circulators and the sampling of the A/D's eliminate the need for analog demodulation of the detected signal. Switching between the references and synchronous demodulation are programmable, thus duty cycles other than 50%, utilization of multiple references, and time-weighted averages of the reference samples are easily implemented. A novel modulation scheme combining techniques using multiple references developed by Hach [1] and reference averaging proposed by Bremer [2] yields radiometric precision approaching that of a total-power radiometer.

**FREQUENCY SELECTION**

The 5 channels around 22.235 GHz result in an increased retrieval certainty over a single channel in this region. The use of five channels was inspired by the need to compensate for the shorter integration time which is limited by the aircraft motion. Much of this improvement is due to the statistical improvement of making five independent measurements rather than one. In addition to the improved retrieval certainty, we see an important use of the 5 channel configuration as confirming current models of the spectroscopy, specifically the continuum contribution. While the strength of the 22.235 GHz line is known to high precision, the effects of the continuum absorption are not as well defined. By operating the DoER on the ground, or more usefully on the Twin Otter flying a stepped-altitude pattern in stable clear air conditions, and with high-quality temperature and humidity profiles (such as from the Twin Otter meteorological instrumentation) absorption models may be tested against high quality observations.

**REFERENCE AVERAGING**

The radiometric precision of a total power radiometer is commonly approximated by

$$T_{\text{sys}}(B\tau)^{0.5}$$

where $T_{\text{sys}}$ is the sum of the receiver and measurement noise equivalent temperatures and $B\tau$ is the integration time bandwidth product of the receiver. However as Hersman [4] and Bremer [2] noted, the actual precision is degraded when system calibration is included in the analysis. Bremer [2] approximates the degradation in precision by the factor $K$ given by

$$K = \sqrt{\frac{\tau}{\tau_r} + \frac{\tau}{\tau_s}}$$
where \( t \) is the measurement cycle period, \( \tau_s \) is the time calibrating, and \( \tau_r \) is the time observing the scene. This expression for \( K \) assumes that low frequency noise, e.g. slow gain fluctuations, at and above the calibration frequency is negligible.

For the classical balanced-Dicke radiometer with a 50% duty cycle, \( \tau_r = \tau_s = 0.5 t \), the factor \( K = 2 \). The radiometric precision of a Dicke radiometer is half that of a total power radiometer with no calibration. However, for a typical total power radiometer system, a substantial fraction of the measurement cycle is allocated to calibration. In a total power system such as the Millimeter-wave Imaging Radiometer (MIR) described by Racette et al. [5], nearly 25% of the measurement time is allocated to calibration. The measurement cycle period for the MIR is \( t = 2.9 \text{s} \) during which time \( N = 30 \) independent measurements of the scene, i.e. pixels, are obtained. The effective cycle period per pixel is \( \tau_{ef} = \frac{t}{N} \). During each cycle, 800ms is allocated to calibration and the time to scan the scene is \( \tau_s = 2.1 \text{s} \); two calibration references are sampled for 150ms each, i.e. \( \tau_{cal} = 300 \text{ms} \), the other 500ms is required to move the scan mirror between the references and the scene. Assuming the calibration references are averaged using uniform weights over \( M = 3 \) measurement cycles

\[
K = \sqrt{\frac{\tau_{ef}}{M \tau_{cal}} + \frac{\tau_{ef}}{\tau_s \cdot N^{-1}}}
\]

yielding \( K = 1.22 \).

Two periods of the modulation cycle used by the DoER are illustrated in Fig. 2. Samples of the four calibration references are interleaved with samples of the scene. The scene is viewed 80% of the time with measurements of the calibration references being made during 20% of the observation time, i.e. \( \tau_r = 0.8 t \) and \( \tau_s = 0.8 t \). The switching time of the ferrite switches is negligible. Averaging over 16 cycles (64 reference measurements) yields \( K = 1.23 \). Thus, the reference averaging scheme used in the DoER has nearly the same \( K \) factor as that of the MIR. \( K \) factors approaching 1.0 may be achieved by further reducing the calibration duty cycle and increasing the number of calibration reference samples averaged.

The digitized calibration samples are stored and averaged. By storing the calibration samples, the optimum integration period and weighting for each reference can be determined in post processing of the sample statistics. The calibration coefficients relating the measured counts to the scene brightness temperature are then obtained by performing a weighted least squares regression on the calibration samples.

CONCLUSION

The demand for improved measurement accuracy is accompanied by the necessity to improve measurement precision. Two techniques have been implemented in the DoER to improve measurement precision. Five frequency bands are measured near the 22.235 GHz absorption line, thereby maximizing the detection bandwidth while maintaining the resolution of the spectral feature. Four references are used to obtain system calibration. A modulation scheme is employed where the references are observed only 20% of the time. By averaging the reference samples over multiple observations radiometric precision approaching that of a total power system is achieved.

REFERENCES