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A Miniaturized Water Vapor Profiling Radiometer for Network-based 3-D Measurements of the Tropospheric Water Vapor Field

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ABSTRACT:

Knowledge of the temporal and spatial distribution of water vapor and liquid water in the troposphere is fundamental for short- and medium-range prediction of precipitation and severe weather. Current measurements of these quantities in the troposphere are limited by optical extinction in clouds (lidar), in temporal resolution (radiosondes), in spatial resolution (GPS networks) and in spatial coverage (microwave radiometers). In order to facilitate three-dimensional (3-D) measurements of tropospheric water vapor with good temporal and spatial resolution, a new Miniaturized Water Vapor profiling Radiometer (MWVR) has been developed at Colorado State University and the University of Massachusetts Amherst. This new radiometer takes advantage of recent advances in Monolithic Microwave and Millimeter-wave Integrated Circuit (MMIC) technology to reduce substantially the mass, volume, power consumption and cost of passive microwave instruments. A second MMIC-based radiometer is under development to distinguish cloud liquid water from water vapor. A network of scanning MWVRs is planned to demonstrate 3-D measurements of both water vapor and cloud liquid water in near-real time.

INTRODUCTION:

Microwave radiometers deployed on ground-based and airborne platforms perform extensive measurements to calibrate and validate satellite sensors such as the DMSP SSM/I, NASA's TMI on TRMM, Navy/NPOESS WindSat, NOAA's AMSU-A and AMSU-B, and NASA's AMSR-E on Aqua. In addition, microwave radiometers are used for fundamental investigations to study the relationship of physical properties of the scene, i.e. land, atmosphere and oceans, to the brightness temperature incident on the aperture of a radiometer antenna. Results of these studies are used for improving retrieval algorithms of geophysical parameters from passive microwave data. Typical microwave radiometers for ground-based and airborne remote sensing are designed and built in a one-off manner. The RF and IF components in conventional radiometers are discrete components, connected by coaxial connectors or waveguides, depending on the microwave or millimeter-wave frequency range. Single frequency-band conventional radiometers typically have a mass of 20-70 kg and a volume of 0.1-0.3 m^3. Multiple frequency-band radiometers, such as the NOAA/ETL polarimetric scanning radiometer (PSR) and ground-based scanning radiometer (GSR), as well as the Naval Research Lab's APMIR, typically have mass and volume several times larger.

Microwave radiometers can be designed with substantially lower mass and volume by utilizing Monolithic Microwave and Millimeter-wave Integrated Circuit (MMIC) technologies. MMIC-based radiometers are excellent candidates for deployment on more readily available airborne platforms such as small, light UAVs. Currently, MMICs extend to at least 100 GHz in frequency [1] and are low-cost when manufactured in high volume. Consequently, commercial MMICs have typical retail prices of tens of USD per unit, in contrast to discrete packaged components that cost thousands of USD. In addition to reductions in mass, volume and cost, MMIC technology tends to decrease the power consumption of microwave radiometers, both by increasing component power efficiency and by reducing power requirements of heating/cooling systems. Since the RF and IF sections of MMIC-based radiometers can be designed with very small volumes, it is easier to keep their temperature stable, which is critical for gain stability. Finally, although MMIC-based radiometers are more readily reproducible than radiometers based on discrete components, they require specific skills and equipment in IC packaging and integration.

The Microwave Systems Laboratory at Colorado State University maintains an active collaboration with the Laboratory for Millimeter-Wave Devices and Applications at the University of Massachusetts Amherst, focused on the development of highly stable and easily reproducible microwave radiometers based on MMIC technology to measure the 3-D distribution of water vapor in the troposphere.

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RADIOMETER ARCHITECTURE:

Recent studies using a several different techniques of information content analysis have shown that approximately four frequencies near the K-band water vapor resonance at 22.235 GHz provide sufficient information for a retrieval of the altitude profile of water vapor density in the troposphere [2,3]. Redundant information is obtained if more than the optimum number of frequency channels is used [2]. Based on this result, the Miniaturized Water Vapor profiling Radiometer (MWVR) was designed and fabricated at Colorado State University and the University of Massachusetts Amherst with four frequency channels (22.2, 22.7, 23.3 and 24.6 GHz) chosen at nearly optimal frequencies for water vapor profile retrieval.

Since each radiometer channel has less than 1% relative bandwidth, a superheterodyne architecture was used to achieve this narrowband sensing with the constraints of small mass and volume. Internal calibration is achieved by observing a noise diode through an attenuator for short time intervals. When the noise diode is switched on, the hot calibration point is measured, and when the noise diode is switched off, a cold (ambient) calibration point is measured by viewing a matched load, i.e. the attenuator.

The principal challenge in utilizing MMICs to realize microwave systems is in their integration and packaging. This has been addressed through the design of multi-chip modules, e.g. [4,5]. The RF section of the MWVR operates over an 11% bandwidth centered and 23.4 GHz and is housed in a multi-chip module as observed in Figure 1. The RF section is 4 cm x 4 cm x 2.55 cm, has a mass of about 250 grams and consumes less than 0.8 W of power. This multi-chip module attaches directly to the radiometer antenna through a standard waveguide flange. The only RF component not in this multi-chip module is the commercially packaged local oscillator.

The output of the RF section is input to an IF amplifier section consisting of two separate, identical multi-chip modules, each providing about 34 dB of gain. Each of these modules is 2 cm x 1.25 cm x 0.45 cm with a mass of 50 grams, as shown in Figure 2. To achieve spectral filtering, the output of the IF amplifiers is divided four ways using a custom-designed two-stage Wilkinson power divider, shown in Figure 3. This power divider is fabricated in microstrip using a high permittivity substrate and thin-film resistors. The divider achieves low insertion loss over the 62% relative bandwidth of the four IF frequencies. The four outputs of the power divider are input into four commercially available filters packaged in separate housings, used to set the frequency range of each of the four channels. The outputs of the filters are then input to power detectors, followed by video-frequency signal conditioning and A/D sampling.

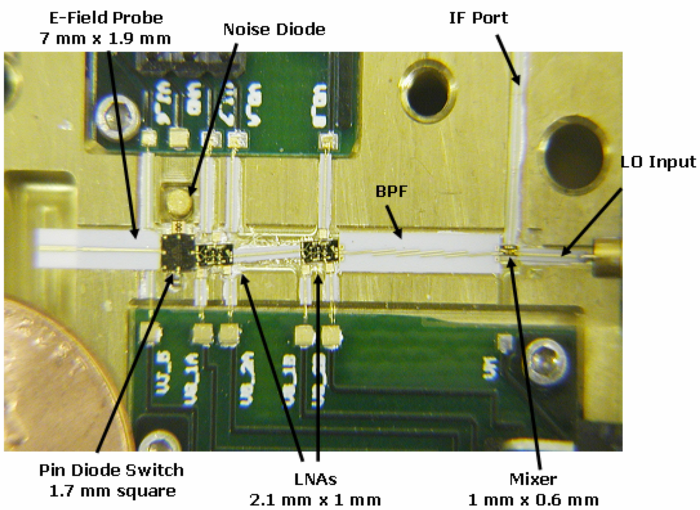

Fig. 1 RF section implemented in a multi-chip module.

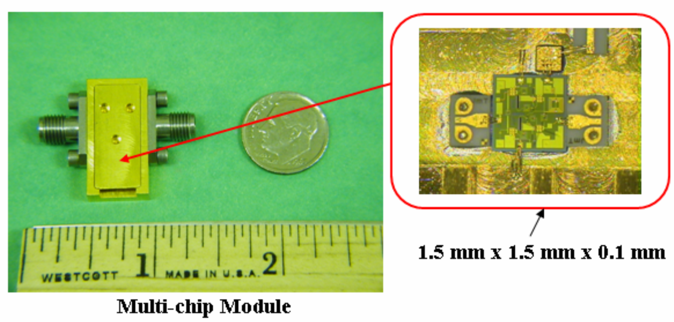

Fig. 2 Two-stage IF amplifier implemented in a multi-chip module.

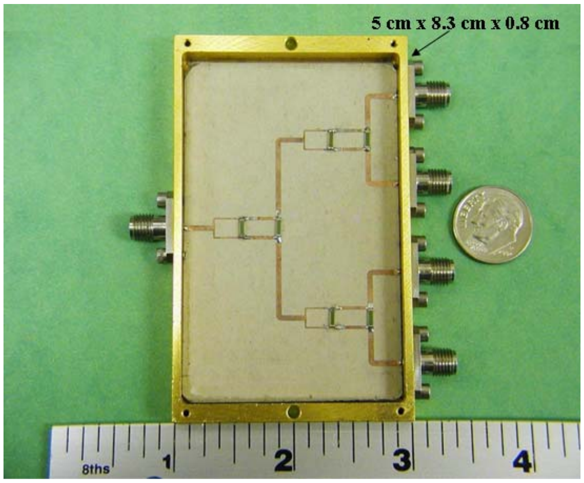

Fig. 3 Broadband Wilkinson power divider fabricated in microstrip using a high-dielectric substrate and thin-film resistors.

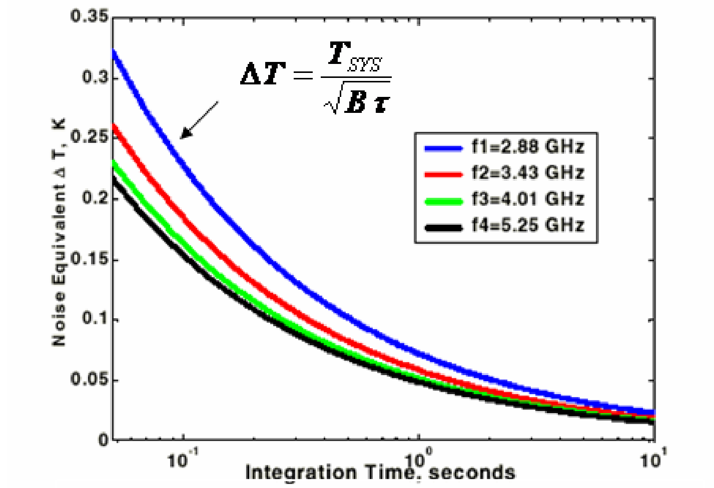

Fig. 4 Calculated sensitivity of the Miniaturized Water Vapor Radiometer (MWVR).

RADIOMETER SYSTEM:

The RF and IF sections of the MWVR were measured to find the equivalent noise temperature of the receiver, which varies with frequency, depending on filter bandwidth and mismatch of components. Measured equivalent noise temperatures of the first prototype MWVR range from 550 K to 750 K, depending on the drain current setting of the RF amplifiers. The noise-equivalent delta-T, i.e. the sensitivity of the MWVR, at each of the four channels is shown in Figure 4 as a function of integration time, assuming total power radiometer operation. From these measurements, the MWVR radiometer is predicted to have a sensitivity of better than 0.1 K for integration times of greater than 0.5 seconds, highly feasible for ground-based operation even when scanning a hemispherical volume of the troposphere. The MWVR will be calibrated using a combination of tipping curves [6] and internal calibration, as mentioned in the previous section. A 4 x 8 box horn array antenna is used to minimize the physical size of the radiometer while maintaining high performance for single-polarization measurements. The antenna and RF and IF sections of the MWVR are shown in Figure 5.

The complete radiometer system is shown in Figure 6. Except for the dc power supply box, which can be mounted near the radiometer but not on the elevation-over-azimuth positioner, the entire radiometer is 18 cm x 24 cm x 16 cm with a mass less than 4 kg. Preliminary tests have shown that the physical temperature inside the radiometer is stable to better than 0.1 °C over several hours when the ambient temperature is 12 °C below the internal temperature.

NETWORK OPERATION:

A small, 2-D prototype network consisting of three MWVR profilers will be used to demonstrate measurement of the 3-D distribution of water vapor in the troposphere. The scanning capabilities of the MWVR need to be considered, as in [7], including limitations of the antenna pattern when scanning at low elevation angles. Preliminary studies indicate that each radiometer can scan an entire hemispherical volume every three minutes. In addition, coordinated scanning of multiple MWVR profilers needs to be performed optimally to allow the inversion of brightness temperature measurements from multiple radiometers to retrieve the volume distribution of water vapor density in the coverage area of the MWVR profiler network.

SUMMARY:

A Miniaturized Water Vapor profiling Radiometer (MWVR) was designed and fabricated at Colorado State University and the University of Massachusetts Amherst. This new radiometer uses commercially available MMIC technology to reduce the mass, volume, power consumption and cost of passive microwave instrumentation. The MWVR is designed to profile the water vapor in the troposphere using four frequencies near the 22.235 GHz water vapor resonance. One principal advantage of

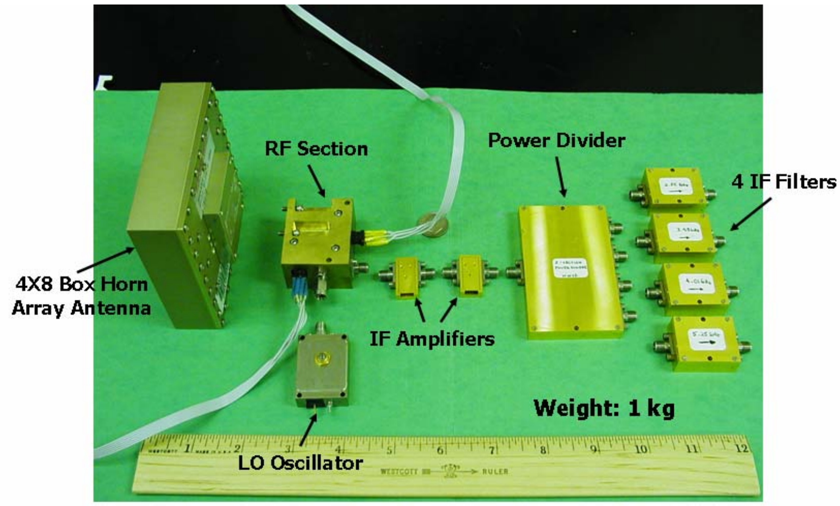

Fig. 5 Antenna and RF/IF sections of the MWVR.

Fig. 6. Complete MWVR radiometer.

the MWVR is that multiple units will be built and deployed to operate in a network using coordinated scanning to retrieve the 3-D distribution of water vapor in the troposphere with high temporal resolution.

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