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Passive ground-based remote sensing of atmospheric temperature, water vapor, and cloud liquid water profiles by a frequency synthesized microwave radiometer

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Summar . An advanced microwave radiometer for profiling atmospheric parameters is described in this paper. The method accomplishing profiling is described. The innovations of the radiometer system, including utilization of a stable frequency synthesizer and the calibration system are described. The performance of several mathematical retrieval methods and representative profiles are presented, as well as several comparisons with radiosondes.

Passive bodengebundene atmosphaerische Fernkundung von Temperatur-, Wasserdampf-, und Wolkenwasser-profilen mit einem frequenzsynthetisierten Mikrowellen Radiometer

Zusammenfassung. In diesem Beitrag wird ein neuentwickeltes Mikrowellen Radiometer fuer die Fernerkundung von atmosphaerischen Profilen beschrieben. Die Methode der zur Vervollstaendigung der Profile wird dargestellt. Die Innovationen dieses Radiometersystems sind der Einsatz eines hochstabilen Frequenzsynthesizers und eine speziell entwickelte Kalibrierung. Das Leistungsvermoegen von verschiedenen mathematischen Inversionsmethoden, typische Profile und verschiedene Vergleiche mit Radiosonden werden vorgestellt.

1 Introduction

In spite of their cost, sparse temporal sampling, and logistical difficulties, radiosondes are still the fundamental method for atmospheric temperature, wind, and water vapor profiling. A better technology has been pursued for decades, but until now, no accurate continuous all-weather temperature and water vapor profiling technology has been demonstrated. Laser radars (LIDARS) and Fourier transform infrared spectrometers can profile temperature and water vapor, but not beyond cloud. RASS can profile virtual temperature, but is limited in height. The radiometric temperature and water vapor profiler described herein gives continuous unattended profile measurements in all sky conditions, and also has the capability to profile cloud liquid water, a capability absent in radiosondes. Except for *in situ* aircraft measurements and values inferred from radar reflectivity by estimating droplet distribution, there are no other sensor systems that can profile cloud liquid water.

Under funding from the Department of the Army and the Department of Energy we have developed an advanced passive profiling microwave radiometer design based on a highly stable tunable synthesized local oscillator in the receiver. This design overcomes errors induced by receiver frequency drift in other current generation designs, while allowing observation of a large number of frequencies across wide tuning ranges. The number of eigenvalues in the radiometer observations, and therefore the information content, is thereby maximized. The result is more accurate and resolute atmospheric temperature, pressure, water vapor, and cloud liquid profiles than currently deployed microwave radiometers. Temperature profile rms errors are nearly halved relative to 4-channel Gunn-based radiometers (SOLHEIM, 1995; HAN AND THOMSON, 1994; ASKNE AND WESTWATER, 1986).

Various mathematical retrieval methods for temperature, water vapor, and cloud liquid water profiles were tested based on these radiometer designs. These include neural networking, Newtonian iteration of statistically retrieved profiles, and Bayesian “most probable” retrievals. Based on realistic radiometer errors and performance, very good retrieval capability is demonstrated. The performance of the various retrieval methods are presented and compared. Examples of actual profile retrievals concurrent with radiosondes are also presented.

Applications for this passive profiling capability include weather forecasting and nowcasting, detection of aircraft icing and other aviation related meteorological conditions, determination of density profiles for artillery trajectory and sound propagation determinations, refractivity profiles for radio ducting prediction, corrections to Very Long Baseline Interfermoetry (VLBI) and GPS measurements, atmospheric radiation flux studies, and measurement of water vapor densities as they affect hygroscopic aerosols and smokes.

2. Radiometric profiling of atmospheric parameters

Microwave radiometers are receivers that measure the power emitted the atmosphere at selected frequencies. The atmospheric emission spectrum in the millimeter waveband contains resonance lines of oxygen and water vapor as well as continuum emission by water vapor and liquid water (if clouds are present). Profiling of temperature, water vapor, and cloud liquid water can be accomplished by a radiometer as follows.

The microwave profiling methods discussed herein make use of atmospheric radiation measurements in the 20 to 75 GHz region. The zenith path atmospheric absorption spectrum at sea level for a typical mid latitude atmosphere with a 1 km thick, 0.5 g/ ^{3} cloud in this frequency range is shown in Figure 1. The feature at 22.2 GHz is a water vapor resonance that is pressure broadened according to the pressure altitude of the water vapor distribution, while the feature at 60 GHz is an atmospheric oxygen resonance. The liquid water emission increases approximately with the second power of frequency in this region.

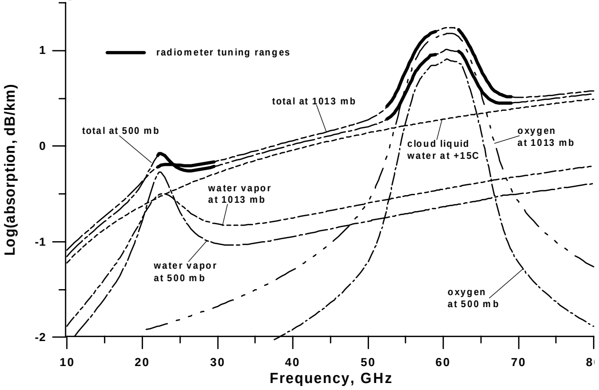

Fig. 1. Contributions to atmospheric absorption by oxygen, water vapor, and cloud liquid water droplets. Radiometer tuning ranges are shown by the broadened traces. Absorption at two altitudes is shown to demonstrate pressure broadening.

Temperature profiles can be obtained by measuring the spectrum of radiation intensity, "brightness" spectrum, at points along the side of the oxygen feature at 60 GHz [WESTWATER, 1965]. By scanning outward from line center, where the opacity is so great that all signal originates from just above the antenna, onto the wing of the line, where the radiometer "sees" deeper into the atmosphere, one can obtain altitude information. Emission at any altitude is proportional to local temperature; thus the temperature profile can be retrieved. Either shoulder of this feature is suitable for retrieval of temperature profile information.

Water vapor profiles can be obtained by observing the intensity and shape of emission from pressure broadened water vapor lines. The water vapor line at 183 GHz is used for water vapor profiling from satellites. The high opacity of this line hides the unknown emission emanating from the earth's surface, eliminating this error source but precluding profiling to low altitudes. The line at 22 GHz is too transparent for effective profiling from satellites but is suitable for ground based profiling. In this feature, the emission from water vapor is in a narrow line at high altitudes and is pressure broadened at low altitudes. The intensity of emission is proportional to vapor density. Scanning the spectral profile and mathematically inverting the observed data can therefore provide water vapor profiles.

While profiling of water vapor and temperature are accomplished utilizing resonances, cloud liquid has no spectral features, but instead contributes to the brightness temperature in the microwave region as *(frequency)*^{2}. To obtain altitude information, profiling of cloud liquid must therefore be accomplished by measuring its contribution to known (or measured) atmospheric spectral features whose opacity varies with frequency. For instance, as described above, the atmospheric temperature profile can be obtained by scanning either side of the 60 GHz oxygen feature. Scanning from line center outward onto either of the wings of the feature moves the observation deeper and deeper into the atmosphere, yielding altitude information on atmospheric temperature. Cloud liquid water, if present, contributes more to the high frequency side (60 to 75 GHz) of this feature than to the low frequency side (45 to 60 GHz) and skews the line shape. Therefore, scanning *both* sides of the line yields information on the temperature *and* cloud liquid profiles. There is also liquid profile information in the 22 to 29 GHz + 52 to 59 GHz tuning bands.

3. Receiver design, specification, and advantages

he radiometer design is an advance over other current designs in several respects. The previous state of radiometric art was to employ Gunn oscillators as the local oscillators for the receiver mixer. A separate oscillator was generally utilized for each frequency to be observed, imposing a practical limit on the number of frequencies observed. Additionally, Gunn oscillators drift in frequency, even when temperature stabilized, and can induce errors in the retrieved temperature as large as 1C (Fig. 2). The highly stable frequency synthesizer utilized here eliminates frequency drift, and allows a large number of frequencies to be observed. The number of eigenvalues, and therefore the information content of the observations, is thereby maximized.

Dicke-switched hot and ambient temperature loads are commonly used in radiometers as a calibration reference. This system switches from antenna to reference load, thereby excluding the antenna from the calibration. Dicke switches are ferrite waveguide devices with imperfect switching qualities, having isolation of about 20 dB and an “on” insertion loss of about 0.4 dB. They can therefore be a source of receiver noise and error. Hot loads are generally operated at 100 to 150C above ambient, with an ambient load giving a second measurement for determining the gain and offset of the receiver. As shown in Fig. 3, although the load temperatures can be known very accurately, non-square-law behavior of the detector and signal compression of the receiver at higher antenna temperatures (higher signal values) can cause nonlinear behavior that can induce an error when the calibration is extrapolated to the range of sky observables.

We utilize a highly stable noise diode and an ambient target as a calibration reference. Although the noise diode raises the antenna temperature to well above ambient by injecting power into the antenna circuit, we utilize tipping curves or a second liquid nitrogen target at 77K for calibration of gain and offset of the radiometric receivers. This calibration is then transferred to the highly stable noise source for field use. The nonlinearity of the receiver is present in both this calibration transfer and in sky observations, is common-mode to both measurements, and is therefore cancelled. The antenna system is included in the calibration, and the fundamental calibration spans the range of sky observables rather than being extrapolated.

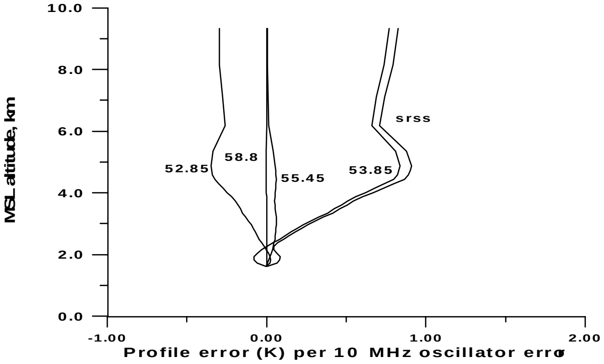

Fig. 2. Errors generated by local oscillator drift in a 4-channel Gunn-based temperature profiler

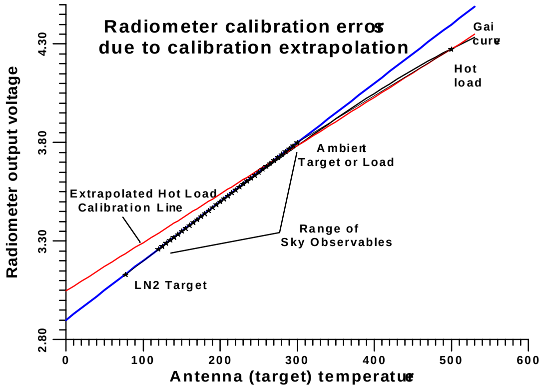

Fig. 3. The liquid nitrogen calibration target reduces extrapolation error.

4. Mathematical inversion (retrieval) methods

The fundamental observable of the radiometer is “brightness temperature,” the temperature of a blackbody of equivalent radiated power, as a function of frequency. The observables are then mathematically inverted to yield the vertical distribution of atmospheric temperature (Westwater, 1993; Rodgers, 1976; Keihm and Marsh, 1997), water vapor (Han and Westwater, 1995), and cloud liquid water. This inversion of observables to obtain atmospheric parameters is called “retrieval” of the parameters.

Performances of a number of inversion methods were tested. These methods were: neural network, Newtonian iterative, linear regression, and Bayesian maximum probability. As a first step, the radiometer observing frequencies containing independent information, were determined from 2000 radiosondes with eigenvalue analysis. The brightness temperatures for these frequencies from 13 years of radiosondes at 3 sites were forward modeled utilizing the National Oceanic and Atmospheric Administration Environmental Technology Laboratory radiative transfer software (Schroeder and Westwater 1991, 1992). The first 10 years were used as the training set, and the subsequent 3 years were utilized as the test (verification) set.

Year round retrievals were utilized in all cases to conserve computing time. Had the retrievals been binned into seasons or months, we would expect some improvement in the rms retrieval errors and in the individual profiles. The performance of the various inversion methods were found to be roughly equivalent. The rms errors for the three profile types for Norman Oklahoma are shown in Fig. 4 A more complete description of the eigenvalue analysis, the inversion methods, and the performance results can be found in SOLHEIM ET AL.,. 1997

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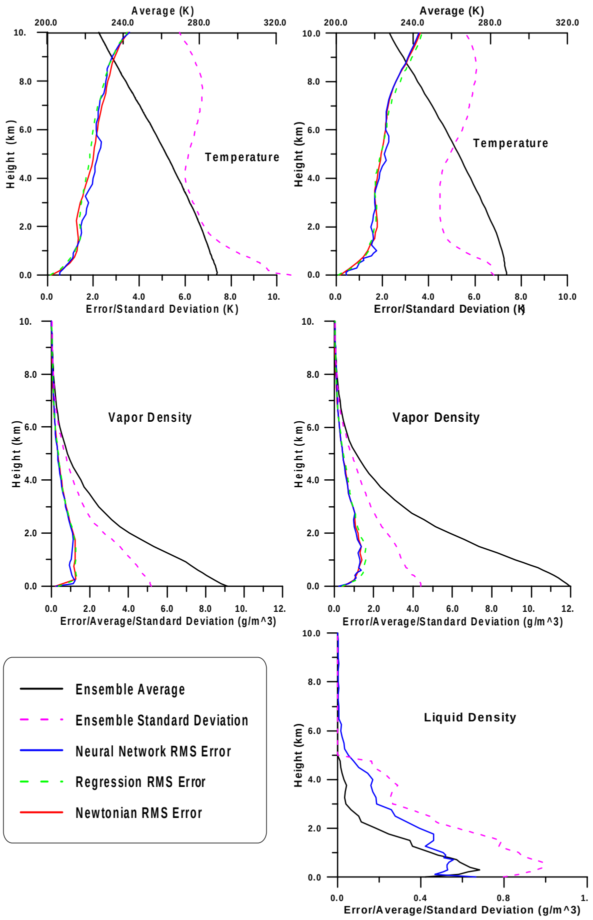

Fig. 4. Comparison of neural network, Newtonian, and statistical regression rms errors for Norman Oklahoma all-season retrievals. Clear condition results are shown on the left, and cloudy condition results on the right. The profile variances from the RAOBs and the average profile are also shown. Note that the cloud liquid retrieval rms errors are high because the retrieval did not define the cloud bases and tops very accurately in this study. We feel that this retrieval method can be improved with better implementation of cloud base data in the retrieval method.

4.1. Modeled profile results

Several profiles retrieved from the modeling effort are shown Fig. 5 Note that, although surface inversions are well resolved, passive remote sensing will not resolve elevated inversions very well. Also, sensitivity is greatest near the surface, and diminishes with altitude, with the practical altitude limitation of 7 to 10 kilometers.

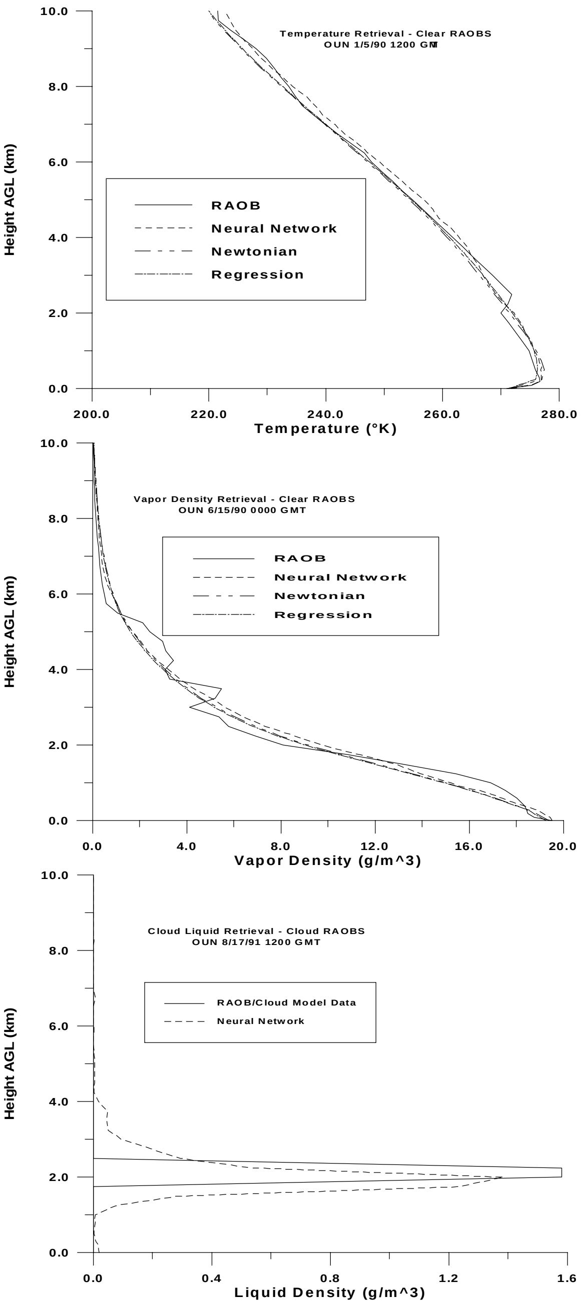

Fig. 5. Profiles retrieved by the various mathematical methods as compared with radiosonde soundings.

4.2. Comparisons with radiosondes

Shown in Figs. 6 and 7 are examples of comparisons of the temperature and water vapor profiles retrieved by our prototype radiometer compared with concurrent radiosondes at the National Weather Service site in Denver Colorado.

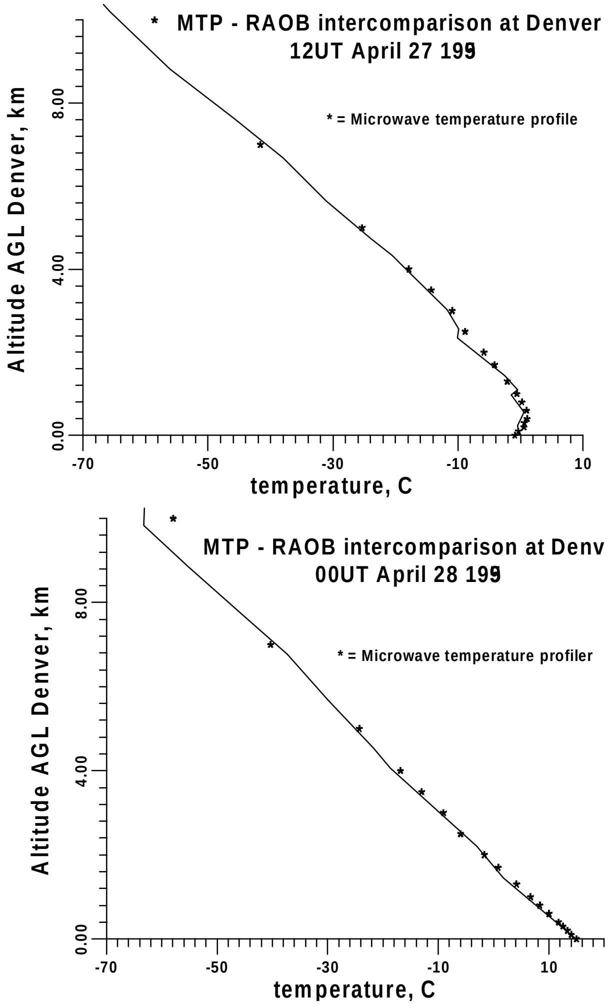

Fig. 6. Radiometric temperature profiles compared with concurrent radiosonde soundings at the national Weather Service site in Denver Colorado.

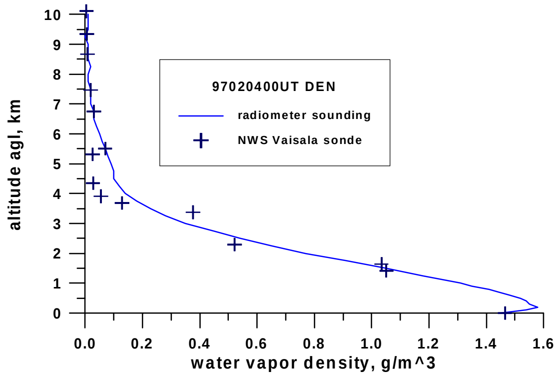

Fig. 7. Radiometric water vapor profile compared with radiosonde at the National Weather Service site in Denver Colorado

5. Aircraft icing detection

One of the capabilities of a multifrequency multiwaveband microwave radiometer is the detection and profiling of supercooled liquid water. Aircraft icing occurs in the presence of supercooled liquid water droplets. Because such droplets are generally very small in size, they are not easily detected by radar. Because this radiometer can profile temperature, water vapor, and cloud liquid, it can determine the presence and location (altitude) of supercooled liquid water by two separate mechanisms:

(1) The saturation vapor pressure can be calculated fro the temperature profile, and when the measured vapor pressure goes to saturation, cloud liquid is present.

(2) The cloud liquid profiling capability defines the region of liquid water, while the temperature profile determines if the water is supercooled.

If the measured temperature profile shows that the water is below freezing, it is an aircraft icing hazard. Shown in Fig. 8 is a case of aircraft icing wherein the pilot lost control of the aircraft and crashed into Denver Colorado. National Center for Atmospheric Research aircraft were probing this winter storm and defined the icing layer between 2400 and 3300 meters above sea level. The RAOB did not accurately define the cloud layer because of deficiencies in the humidity sensor; the measured water vapor density should have been at saturation. Additionally, radiosondes cannot detect liquid water.

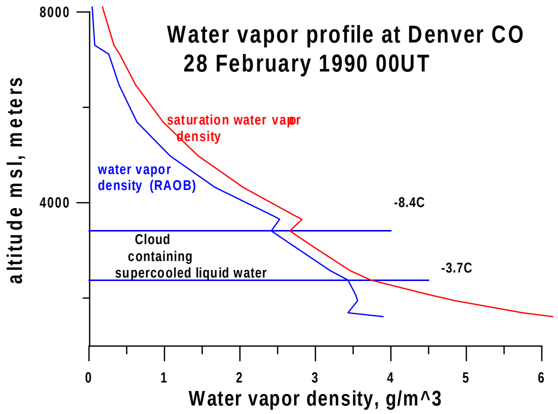

Fig. 8. Supercooled liquid water observed at Denver Colorado near the time of an aircraft accident caused by aircraft icing.

6. Conclusions

We have described an advanced radiometer for passive remote sensing of atmospheric temperature, water vapor and cloud liquid profiles. We have shown that the radiometric observations can be inverted into accurate tropospheric profiles using a variety of mathematical methods. The radiometer is based on a highly stable synthesized local oscillator that allows a large number of frequencies to be selected. The atmospheric profiles are useful for weather and artillery trajectory prediction, aircraft icing hazard and radio ducting detection, astrogeodetic measurements, and atmospheric radiation flux studies.

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