Frontiers in Surface-based Microwave and Millimeter Wavelength Radiometry

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***Abstract*—Surface-based radiometric sensing of atmospheric parameters has a long history of providing useful measurements of temperature, water vapor, and cloud liquid. In this Special Tributary Session to Professor Calvin Swift, several contemporary instruments are discussed and representative results are presented. Recent and promising developments include new absorption models, improved retrieval techniques, multi-frequency radiometers, scanning observations of clouds, and combined active-passive remote sensing.**

I. Introduction

Surface-based radiometric measurements of atmospheric thermal emission have proven useful in a variety of geophysical applications, including meteorological observations and forecasting, communications, geodesy and long-baseline interferometry, satellite validation, climate, air-sea interaction, and fundamental molecular physics. One reason for the utility of these measurements is that with careful design, radiometers can be operated in a long-term unattended mode in nearly all weather conditions. The measurements also enable the continued development of absorption and radiative transfer models in both clear and cloudy atmospheres. This development has been greatly aided by long-term, carefully calibrated radiometer measurements, supplemented by frequent radiosonde releases using active sensors for cloud identification. Last, but not least, is the development of retrieval and data assimilation algorithms with which radiometer data can be combined with external data sources, such as forecasts or soundings from active sensors. In this overview of recent developments in surface-based radiometry, we confine our attention to radiometric soundings of water vapor, temperature, and clouds in the troposphere.

II. THEORETICAL DEVELOPMENTS

A. Gaseous Absorption Models

To take advantage of continued improvements in radiometric techniques, it is important to provide such quality measurements with algorithms to calculate brightness temperature (T_b), given the state of the atmosphere. In the clear atmosphere, this requires calculating absorption as a function of frequency from given vertical profiles of pressure, temperature, and water vapor density. Currently, there are three absorption models that are widely used in the propagation and remote-sensing communities. H. Liebe developed and distributed two versions of the computer code of his Microwave Propagation Model (MPM) [1], [2]. More recently, Rosenkranz [3] developed an improved absorption model that also is frequently used in the microwave propagation community. However, there are still many issues in the determination of parameters that enter into water-vapor-absorption modeling. Another model that is used extensively in the US climate research community is the Line by Line Radiative Transfer Model (LBLRTM) by S. Clough and his colleagues [4]. In addition, P. Rosenkranz has modified several parameters to provide an updated model [5]. Finally, [6] has modified the parameters of [5] to portray a 5 % decrease in the line width parameters of the 22.235 GHz water vapor line. With the development of models [4], [5], and [6], we believe that over the frequency range of 20 to 300 GHz, that clear sky T_b can be calculated with an accuracy of 1 to 3 %, and in the 20 to 30 GHz region to about 0.5 K.

B. Cloud Liquid Dielectric Constant Models

An important physical property for the calculations of cloud liquid absorption is the complex dielectric constant of water. This dielectric constant is described by the dielectric relaxation spectra of Debye. The strong temperature dependence of the relaxation frequency is linked to the temperature-dependent viscosity of liquid; therefore the cloud-absorption coefficient also shows significant temperature sensitivity. Above 0 °C, the dielectric constant can be well measured in the laboratory, and a variety of measurements have been made from 5 to 500 GHz [6]. However for super-cooled water, below 0 °C, the situation is less certain, and, for example, models of [7], [8], and [9] differ by 20 to 30% in this region [10]. This is relevant for cloud remote sensing, because measurements of super-cooled liquid are important for detection of aircraft icing. Currently, [7] represents the state-of-the-art in modeling of the dielectric constant of clouds.

C. Retrieval Techniques from Passive instruments

Techniques to derive meteorological information from radiation measurements are generally based on numerically solving the radiative transfer equation. Because only a finite number of imperfect radiation measurements are available, and a continuum of parameters is needed to describe profiles of temperature, water vapor, and cloud liquid, a rigorous mathematical solution does not exist and the inverse problem is said to be ill-posed. Therefore, it is better to regard the measurements as constraints and to blend them with supplementary sources of information or to drastically reduce the dimensionality of the inverse problem by projecting the profiles onto their linear functionals. Useful supplementary information can be provided by numerical meteorological forecasts, or by a priori information obtained from past radiosonde data. For mildly nonlinear problems, a perturbation form of the radiative transfer equation (RTE) is frequently used as the basis of subsequent iterations. An excellent review article discussing optimal estimation techniques for solving the RTE was written by Rodgers [11]. Other frequently used methods in radiometry include neural network inversion [12] and Kalman filtering [13].

D. Integrated Profiling By Sensor Synergy

Microwave radiometer measurements are often combined with simultaneous cloud radar observations which provide the radar reflectivity factor Z with a vertical resolution of approximately 50-100 m. Since Z is proportional to the sixth moment of the drop size distribution and the cloud liquid water content *LWC* is proportional to the third, a direct conversion of Z to *LWC* results in large errors. Thus, a common approach scales the radar reflectivity profile to the *LWP*. A more sophisticated, physically based technique combines the microwave brightness temperatures, the attenuation-corrected radar reflectivity profile, the lidar-ceilometer cloud base, ground temperature and humidity, and the nearest operational radiosonde profile within an optimal estimation retrieval. The Integrated Profiling Technique (IPT) [14] can simultaneously derive profiles of temperature, humidity, and *LWC*. The retrieved IPT profiles are characterized by their physical consistency with respect to the microwave radiometer and cloud radar measurements. Additional constraints guarantee a match with the ground-level measurements, saturation within the cloud boundaries, and statistical consistency with the radiosonde temperature and humidity profiles. Error covariances of all measurements are required, such that all constraints can be met within an iterative optimal estimation procedure. The solution is interpreted as a probability density so that a retrieval error estimate is inherently given. A further advantage of the IPT is that, in contrast to the LWP scaling methods, the *LWC* profiles are independent of errors of an *LWP* algorithm. The IPT is a first step toward an “all-encompassing” profiling algorithm which combines measurements from all available instruments to derive the atmospheric state as accurately as possible. Since this task should ideally be accomplished in a physically consistent way, knowledge of all involved forward models is required. Future extensions will include infrared and ceilometer forward models to further constrain cloud microphysical parameters, especially in the lower part of the cloud.

III. INSTRUMENTS

In this section, we describe briefly some state-of-the-art instruments for surface-based remote sensing of temperature and moisture.

A. Meteorological Temperature Profiler MTP5

Kipp & Zonen BV is now marketing a radiometer that was originally designed and deployed by the Russian firm ATTEX [15]. This radiometer is designed to measure temperature profiles in the boundary layer from 0 to 600 m AGL. The radiometer is a single-channel (61 GHz) solid-state Dicke-type super-heterodyne receiver that is electronically chopped at 1 KHz between the sky and a reference noise source. The antenna is a scalar horn with a FWHP beam width of 6 º and scans by viewing a flat reflector at each of 11 scanning angles. Because of the 2 GHz bandwidth and a low receiver noise temperature of 600 K, a high sensitivity of 0.04 K is achieved. Calibration of the receiver is achieved by 0.1 °C temperature control and a switched internal noise generator. A one-point absolute calibration is achieved either by viewing an external target or by knowing the emission temperature in the horizontal direction. A variation of this radiometer scans continuously in a 360 º vertical plane, and, in addition to temperature profiles, can also be used to measure air-sea temperature difference [16].

B. Radiometrics Corporation Microwave Profiler

Radiometrics Corporation has developed a multi-frequency microwave radiometer that is based on a highly stable, tunable, and synthesized, local oscillator in the receiver. This design overcomes errors caused by receiver frequency drift, while allowing observation of a large number of frequencies across wide tuning ranges. The total power receiver has a highly stable noise diode that is used as a gain reference. The radiometer observes atmospheric brightness temperatures in five frequency bands from 22 to 30 GHz, and in seven bands from 51 to 59 GHz [17]. It also measures zenith infrared temperature, surface temperature, humidity and pressure. The radiometer has automated elevation- and azimuth-scanning capability, and the observation interval can be as short as several seconds. The instrument is relatively portable, with 0.12 m^3 volume and 32 kg weight.

C. All Sky Multi-Wavelength Radiometer (ASMUWARA)

The ASMUWARA is a radiometer system designed for remote sensing of tropospheric water vapor, cloud liquid water, and temperature profiles [18]. It was designed and built at the Institute of Applied Physics (IAP) at the University of Bern. The instrument consists of nine microwave channels in the frequency range from 18 to 151 GHz, a broad-band thermal infrared radiometer (wavelength band: 8 to 14 μm), meteorological sensors, including a rain detector, and an optional camera. The radiometers are housed in a temperature-controlled cylinder with all beams aligned in a horizontal direction pointing to a rotating mirror scans the sky and two calibration loads. The entire instrument can be rotated around its vertical axis. The beams perform a rosetta-like pattern to map the sky hemisphere within 20 minutes. All channels have the same view and a common full beam width of 9°, formed by corrugated horns. A planned extension to all weather operability will include a movable roof with a limited sky view during periods of rain.

D. Microwave Radiometer for Cloud Cartography (MICCY)

MICCY is a 22-channel radiometer operated by the University of Bonn [19] which is capable of high temporal (0.1 s) and spatial (< 1°) resolution. The radiometer has 10 channels on the high-frequency side of the 22.235 GHz water vapor line, 10 channels on the low-frequency side of the 60 GHz O_2 absorption band, and two channels at 90 GHz; at each frequency of operation, both H and V polarization are measured. MICCY is a single sideband total power radiometer that is based on a heterodyne receiver filter-bank design (parallel detection of all frequency channels). A Dicke modulation scheme is not foreseen for the system since the thermal stability of the receivers is less than 20 mK, which implies that the instrument is capable of maintaining its radiometric accuracy for several minutes without recalibration. Both targets and inserted noise from highly stable diodes are used in calibration. With FWHP beam widths of about 0.9 º the radiometer is capable of full 360 º scanning in azimuth and a zenith scan of 0 to 90 º. For mapping of clouds the entire system can be scanned in azimuth and elevation. The latter is performed by a planar mirror that reflects the incoming radiation into a fixed 1 m Cassegrain system. The system comprises a quasi-optical multiplexer for the three frequency bands. External ambient and cold blackbodies are used for absolute calibration, while internal noise calibration standards are used in between absolute calibrations. The entire system is mounted on a transportable trailer, and all parts are enclosed in a radome.

E. Radiometer Physics GmbH-Humidity and Temperature Profiler (RPG-HATPRO)

Because the implementation of an operational network of microwave radiometers is presently hampered by the cost and complexity of the available instruments, it was a major objective of the European CLIWA-NET project [20] to develop a network-suitable low-cost microwave radiometer. This radiometer – RPG-HATPRO – has been built by the German company Radiometer Physics GmbH (http://www.radiometer-physics.de/html/RPG_home.html). It fulfills the requirements defined within CLIWA-NET: e.g., the maintenance interval is two months, the outside temperature range is from –30°C to +45°C, and the following features are available: rain detection and protection by a shutter system, a GPS clock, measurements of environmental temperature, pressure and humidity, possible internet connection, and portability. The radiometer avoids lossy components such as lenses in the optical section. Instead, an off-axis paraboloid is used for both beam imaging and elevation scanning. The RPG-HATPRO comprises total-power radiometers utilizing direct detection receivers at all frequencies (14 channels up to 60 GHz). This approach avoids any problems that might arise from mixers or local oscillators (standing waves, frequency drifts, insufficient isolation, sideband suppression, higher system complexity and cost). Thus, the stability and accuracy of the system are drastically improved. Furthermore, possible IF interferences caused, e.g., by communication systems, are eliminated. The receivers of each frequency band are designed as filter-banks in order to acquire each frequency channel in parallel. In addition, the flexibility to adjust each channel bandwidth individually allows for optimizing temperature profiling for both boundary layer and full troposphere.

F. NOAA/ETL Ground-based Scanning Radiometer (GSR)

The NOAA/Environmental Technology Laboratory (ETL) designed and constructed a multi-frequency scanning radiometer operating from 50 to 380 GHz. The radiometers are installed into a scanning drum or scanhead. The GSR uses a sub-millimeter scanhead with 11-channels in the 50-56 GHz region, a dual-polarization measurement at 89 GHz, 7-channels around the 183.31 GHz water vapor absorption line, a dual-polarized channel at 340 GHz, and three channels near 380.2 GHz. It also has a 10.6 micrometer infrared radiometer within the same scanhead. All of the radiometers use lens antennas and view two external reference targets during the calibration cycle. In addition, each of the radiometers' design includes two internal reference points for more frequent calibration. The GSR instrument is a modification of a similar instrument that operated at the North Slope of Alaska/Adjacent Arctic Ocean site in 1999. A substantial improvement in radiometer calibration for ground observation in the Arctic environment has been achieved. Based on experience from the 1999 experiment, a new set of thermally stable calibration targets with high emission coefficients were also designed, constructed, and deployed. The primary use of the instrument is to measure temperature, water vapor, and clouds, at cold (-20 to -55 °C) and dry (PWV < 5 mm) conditions. The beam widths of the GSR channels are 1.8 ° and can be averaged to given beam-widths that are consistent with the MWR (4.5 to 5.5 °). The GSR was deployed in the NSA/AAO Arctic Winter Radiometric Experiment that was conducted in Barrow, Alaska, USA, during March-April 2004 [21].

IV. SELECTED EXAMPLES

A. Temperature Profiling

Radiometric temperature profiling can be accomplished by measuring the spectrum of radiation intensity at points along the side of the oxygen feature at 60 GHz. By scanning outward from band center, where the opacity is so great that all of the received signal originates from just above the antenna, onto the wing of the line, where the radiometer "sees" deeper (higher) into the atmosphere, altitude information is obtained. Emission at any altitude is proportional to local temperature; thus, the temperature profile can be retrieved. Either shoulder of the band center is suitable for retrieval of temperature profile information. Temperature profiles have been derived from all of the instruments discussed in Section III. As an example, using data from ASMUWARA, the temperature profile is retrieved by optimal estimation using Channels 5 through 8 using a climatology that is derived from radiosonde data as described in [18]. Temperature profiles of September 18, 2002 are shown in Figure 1. The profiles nicely follow the temperature development measured at the meteorological station Bantiger on the nearby TV tower.

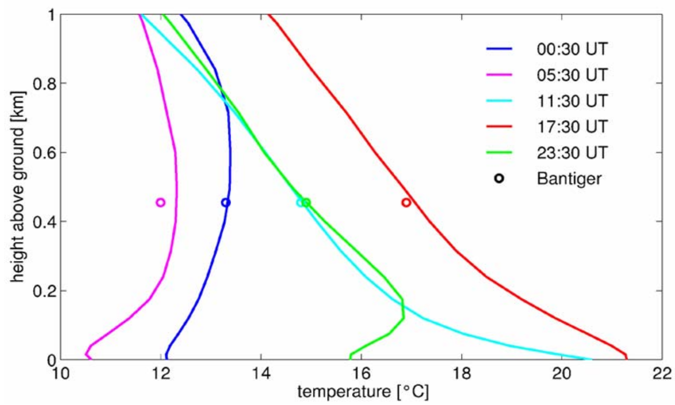

Figure 1. Temperature profiles in the lowest km above ground at 5 different times on September 18, 2002 in Bern measured with ASMUWARA and comparison with data from a meteo station (circles) located on a nearby TV tower. After [18].

B. Angular Scanning of Cloud Liquid

As discussed in Section III, the ASUMUWARA is capable of hemispheric imaging of clouds and water vapor. For channels with optically thin radiation, measured T_b can be accurately converted to opacity τ. In turn, equivalent zenith values of IWV and LWP can be derived from τ. Based on local climatology and simulations based on MPM-93 [2], regression coefficients relating τ at 23.6 and 31.4 GHz to IWV and LWP were derived and applied to angular scanning data. A snapshot of the partly cloudy sky is depicted by the LWP data derived from channels 3 and 4 and the thermal infrared channel (see Figure 2). Clear sky is represented by LWP = 0; liquid-water clouds with LWP up to 0.1 kg/m^2 are apparent.

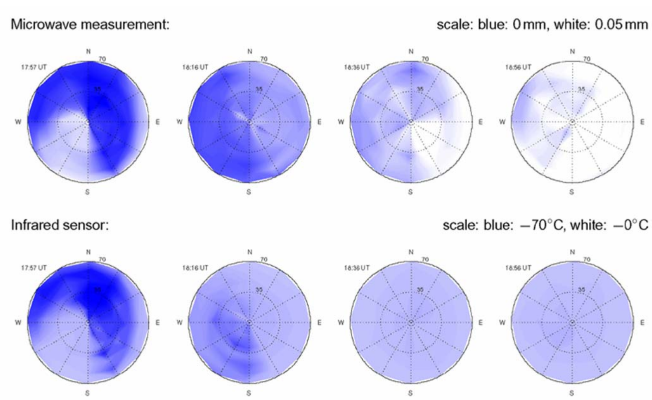

Figure 2. Hemispheric Integrated Liquid Water and Infrared Cloud Temperature distributions above Bern on April 8, 2003 as derived from ASMUWARA. After [18].

While the ASUMUWARA antenna beam width and scan patterns are optimized to provide a fast overview of the entire hemisphere, small scale information on the cloud structure is measured by the MICCY-see Section III) [19]. Figure 3 shows several azimuth scans observed by MICCY, made at an elevation angle of 30 °.

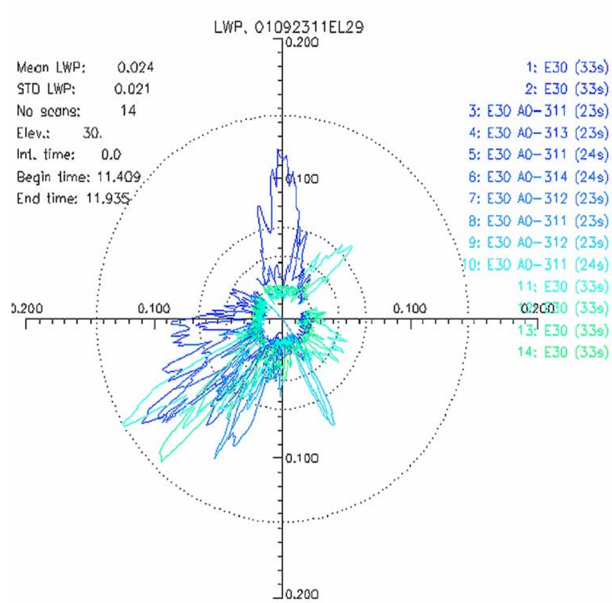

Figure 3. Series of 14 successive azimuth scans at 30 deg elevation with the multi-channel microwave radiometer MICCY having a beam width of less than 1 deg in all channels. Liquid water path was derived using a regression algorithm employing four frequency channels. Venema [Private communication].

C. Cloud Classification and Profiling By Sensor Synergy

Presently, the IPT has been developed only for cases when the radar reflectivity is solely caused by liquid-water drops. This means that the occurrence of mixed phase clouds within the vertical column above the instruments will make IPT application impossible. However, the presence of pure ice clouds above one or more liquid cloud layers will not influence the IPT because ice clouds do not contribute to the microwave

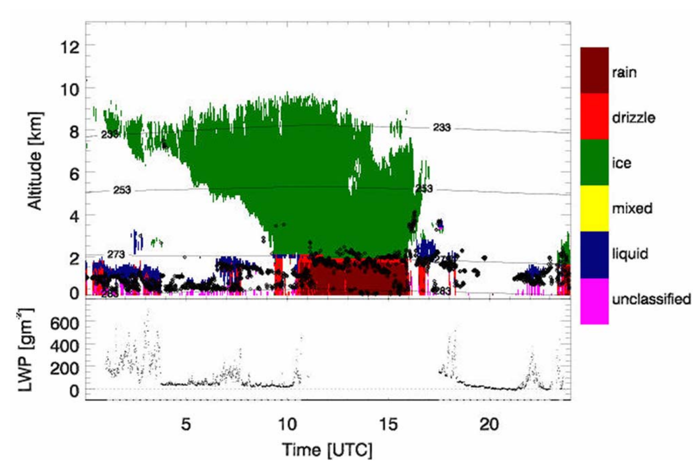

Figure 4. Cloud classification and LWP for May 19, 2003 at Cabauw. Temperature is derived from interpolated radiosondes. The classification is performed for each individual cloud radar range gate. Black dots indicate the cloud base height as observed by lidar ceilometer.

signal in the frequency range below 90 GHz. Furthermore, insect- and precipitation-dominated radar pixels need to be removed. Thus, to be able to apply the IPT automatically, a cloud classification was developed that distinguishes between six phases/regimes (pure ice, mixed-phase, pure liquid water, drizzle, significant precipitation and unclassified). The classification makes use of cloud radar, lidar-ceilometer, the nearest operational radiosonde temperature profiles, and microwave-radiometer-derived *LWP*. An example of the cloud classification for one day is shown in Figure 4. Obviously, the ice- and mixed-phase- clouds dominate the radar signal. Although the classification suggests that water clouds play a minor role, their strong influence on the solar radiation makes them of utmost importance for climate research.

V. OUTLOOK

For the past 35 years, surface-based microwave radiometers operating below 60 GHz have provided useful data on temperature, water vapor, and clouds. Steady progress has been made in the development of robust, sensitive, and accurate radiometers. This has been accompanied by continued development of forward models for the accurate calculation of brightness temperature, although there is still some concern about cloud liquid characterization below freezing temperatures. The development of suitable inverse models has also occurred, but, it now seems likely that assimilation of data with forecast models is the most promising technique for exploiting radiometer data [22]. Of equal promise, is the synergism of active and passive sensors, as has been achieved in cloud sensing [23]. Finally, another promising area of research is the development of scanning radiometers that can measure horizontal gradients in water vapor and cloud liquid.

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