Mini-Reviews

Ground-Based Remote Sensing and Profiling of the Lower Atmosphere Using Radio Wavelengths

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Abstract—From an all-weather point of view, radio waves appear to be most suitable for the remote sensing of winds, temperature, water vapor, and liquid of the troposphere. Some background is given on the measured data, and the physical principles involved are discussed.

INTRODUCTION

Sensing the variables in the lower atmosphere remotely and continuously has wide applications. The magnitude and distribution of temperature, humidity, liquid water, and wind in the troposphere are necessary ingredients for weather prediction and are also useful observables in weather modification, long-distance metrology, astronomy, communications, and beyond-the-horizon radar coverage. Although visible, infrared, and acoustic waves interact strongly with the atmospheric constituents [11], radio waves prove most useful for all-weather application because of relatively good transparency through clouds and precipitation. Observations can be made from either satellites [2] or from the surface of the earth; here we discuss only the latter. Both active and passive instruments are used depending on the atmospheric variable to be observed; active observations depend upon the refractivity fluctuations in air and passive upon molecular absorption.

I. PHYSICAL PRINCIPLES AND EXAMPLES OF DATA

A. Temperature Profiling

Passive radiometric techniques at millimeter wavelengths are used to profile temperature. When a wavelength is chosen such that there is significant absorption [3] by one of the atmospheric gases, a sensitive receiver (similar to those used in radio astronomy [4]) with the antenna beam oriented toward the zenith will respond to the black-body radiation emitted by the gas; this radiation is proportional to a brightness temperature

\[
T_b = \int_{h=0}^{h=\infty} a(h)T(h)e^{-\int_0^h a(h)dh}dh,
\]

(1)

where \(a\) and \(T\) are the absorption and temperature of the gas (oxygen, for example) at altitude \(h\).

The amount and distribution of oxygen in the troposphere is quite constant. Therefore, according to (1), if the absorption is known, a measure of the temperature of the troposphere is obtained by inverting the integral. Moreover, the absorption \(a\) can be quite a strong function of wavelength, for example at frequencies on the “side” of the oxygen band at 60 GHz [3]. Thus for a radiometric channel at a frequency with relatively small absorption, (1) is automatically weighted such that the temperature through the whole troposphere is sensed. On the other hand, a frequency with high absorption only senses the air temperature near the earth’s surface. It is in this way, by measuring brightness temperatures from several channels on the “side” of the oxygen line, that profiles of temperature can be obtained [5], [6].

The right side of Fig. 1 shows an example of a temperature profile (the dashed curve) retrieved at the Wave Propagation Laboratory, National Oceanographic and Atmospheric Administration (NOAA), using data from a system1 that includes five radiometric channels, three on the side of the oxygen band. It is compared with a profile measured at the same time by a temperature sensor on a radiosonde balloon (the solid curve). The radiometric profiles are retrieved using a process known as statistical inversion [7] that employs computations using a historical set of radiosonde data for a given location. Comparisons of this type, at locations with different climatologies, show that the root mean square (rms) differences between the radiometric and radiosonde measurements are less than 2°C over most of the profile. The method used in obtaining the dotted profile in Fig. 1 will be discussed later.

The remaining two of the five channels mentioned above are at approximately 20 GHz (primarily for sensing water vapor) and 30 GHz (primarily for liquid-bearing clouds). The brightness temperatures from these channels are used to minimize the degrading effect of water vapor and liquid in clouds on the 60-GHz brightness temperatures. Indeed, the

1 Built and operated by the Jet Propulsion Laboratory, Pasadena, CA.

Manuscript received June 11, 1979; revised July 28, 1979.

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retrieved temperature profile in Fig. 1 was obtained during the presence of a cloud [8] which transported about 0.3 mm of liquid into the antenna beam. This correction procedure is an important ingredient in the "all-weather" capability for the measurement of temperature profiles; it also points to the superiority of microwaves over infrared sensors in that respect.

B. Water Vapor and Liquid

The amount of water vapor integrated along a path through the atmosphere is quite variable. The amount is significant not only in meteorology but also in determining phase shifts caused by changes in refractivity in long baseline-radio interferometry [9] and in millimeter-wave astronomy, so it will be discussed in some detail.

A measure of integrated vapor can be obtained by observing brightness temperatures at a single frequency on the peak of a water vapor absorption line, for example at 22.2 or 183 GHz. In fact, Dicke’s measurements [10] that first employed his switched-radiometer principle were of this type, but these were pressure-broadened lines, and since the pressure and amount of water vapor vary with height, errors arise in the derived precipitable water vapor. However, there are more suitable frequencies off the peak of the line, for example 20.6 rather than 22.2 GHz, at which the absorption (and therefore the derived vapor) is relatively independent [11] of pressure.

Precipitable water vapor and integrated cloud liquid are measured more accurately by dual-frequency radiometry [12] rather than single-frequency only when the system must operate in the presence of liquid-bearing clouds. Many clouds are formed of ice particles, but these have a negligible effect because absorption by ice is insignificant. Using frequencies of 20.6 and 31.6 GHz in a zenith-pointing mode, the vapor \( V \) and liquid \( L \) are written in linear relationship to the respective measured brightness temperatures (in K) \( T_2 \) and \( T_3 \):

\[
V = a_1 + a_2 T_2 + a_3 T_3 \text{ cm,}
\]

\[
L = b_1 + b_2 T_2 + b_3 T_3 \text{ cm,} \tag{2}
\]

where the \( a \) and \( b \) are constants, derived by statistical inversion, for a given climate.\(^3\) The \( a_1 \) and \( b_1 \) primarily offset the effect of oxygen absorption and the cosmic background radiation [13].

Equations (2) for the climatology of Denver, CO, for example, become

\[
V = -0.18 + 0.11 T_2 - 0.053 T_3 \text{ cm,}
\]

\[
L = -0.017 - 0.0011 T_2 + 0.0027 T_3 \text{ cm.} \tag{3}
\]

Fig. 2 shows a two-week analog example of the comparison of precipitable water vapor retrieved using the first of (3) (the continuous plot) with vapor obtained by integrating radiosonde observations (the triangles spaced at 12-h intervals). It is found from an eight month sample of such data [12] that the rms difference between the two methods of measurement is 0.17 cm, with a short-term (hours) stability of 0.007 cm for the radiometric system. Output from the liquid channel, the second of (3), has proven useful in the sensing of super-cooled water that was associated with icing of aircraft. It is this function that is of main interest in weather modification.

Although good measurements of precipitable water vapor are obtained in the presence of clouds, such is not the case during rain which is a strong absorber. If rain in the antenna beam is too intense, the radiometer noise temperature saturates [14]. This limitation does not apply for low rain rates (depending on the operating frequency of the radiometer), but low rain rates are notorious [15] for variability of drop-size distribution and therefore variability of the absorption produced which complicates the procedure of writing algorithms analogous to (3).

Although conventional weather radar is used for locating and tracking precipitation, radiometers operating at centimeter (rather than millimeter) wavelengths can also be designed to measure rain on an earth-space path. Since the absorption and therefore the brightness temperature produced by rain depends on the path length through the rain as well as on the rain rate, at least two frequencies must be employed [14] to estimate the extent and intensity of the rain. In cases where measurement over an area is involved, the antenna beams must be scanned in a conical fashion, or a fixed antenna with an area-coverage beam must be employed.

C. Wind

Radar is used to measure the profile of wind both during clear conditions and in the presence of cloud and precipitation. The measurement relies upon the Doppler shift \( f_d \) in the backscattered signal due to the motion of the scatterers produced by the wind. Thus if an antenna beam (wavelength \( \lambda \)) is pointed at an elevation angle \( \theta_1 \), the radial velocity (along the beam) of the scatterers, \( V = (f_d \lambda / 2) \), is comprised of three
components:

\[ V = u \cos \theta_1 \sin \beta + v \cos \theta_1 \cos \beta + w \sin \theta_1, \]

where \( u \) and \( v \) are components of the horizontal wind, \( w \) is the vertical component, and \( \beta \) is the azimuth of the beam. \( \theta_1 \) is typically 50° to 75°.

Under clear conditions inhomogeneities in the refractive index of the lower atmosphere provide the scattering mechanism. At radio wavelengths these are caused primarily by variations in water vapor density which have a scale size (along the beam) of \( \lambda/2 \). For horizontal flow, \( w = 0 \) in (4); the horizontal components \( u \) and \( v \), and therefore the magnitude and direction of \( V \), are then determined by either rotating the beam in azimuth (\( \beta \)) or by utilizing two or more fixed beams at different azimuths. Accuracies of about 1 m/s are achieved.

An example of a wind velocity profile measured by a pulsed L-band radar [18] is shown in Fig. 3 (the dots and crosses) in comparison with data measured using a windsonde balloon (the solid curve). In this example the jet stream is situated at an altitude of about 8 km; the data were obtained by continuous scan in \( \beta \) (see (4)). CW microwave radar using FM has also been demonstrated to measure wind accurately [19], especially at low altitudes. Similar good agreement has been obtained by the Aeronomy Laboratory/NOAA, with VHF systems [18] using arrays that produce fixed orthogonal beams some tens of degrees off zenith.

This simplified discussion has assumed zero vertical velocity of the scatterers, but during precipitation, especially using microwave radar, the prime scatterers can be snow and rain, which have significant fall velocity. Thus the vertical component of velocity must be measured and eliminated from (4); this can be done by interrupting the continuously scanned beam for a short dwell in the zenith or by switching to a fixed zenith beam in the component system. By measurement of the width of the Doppler spectrum turbulence fields are also detected.

II. A PROFILING SYSTEM

There are advantages to be gained in combining data from the radiometers and radars discussed above. In clear air, radars measure, in addition to the fine-scale refractive-index inhomogeneities, persistent layers which produce a strong backscattered signal [20]. These layers, in turn, are often associated with turbulence and with large gradients in the refractive index which is determined by pressure, temperature, and primarily humidity (see Fig. 1). Thus the backscattered power reveals the height of levels of strong and persistent refractive turbulence. These heights can be included as additional information in the retrieval of the radiometric temperature profiles. Such an exercise has been carried out for the dotted temperature profile in Fig. 1, where it has been assumed that radar backscatter would have provided a measure of the inversion height. Note that the inversion at about 1 km altitude is represented much more faithfully by the dotted curve than by the dashed curve retrieved from radiometric data alone.

We have not yet discussed humidity profiling; it has purposely been avoided because the five-channel system discussed above is not designed to profile humidity. Nevertheless, the 20-, 30-, and 60-GHz frequencies all respond to water vapor independently, and therefore, a coarse humidity profile is obtained using statistical methods. An example is shown on the left side of Fig. 1 (the dashed curve); it does not represent the humidity profile measured by the radiosonde (the solid curve) very well, but by inclusion of inversion height (the dotted curve), agreement is somewhat improved. A multichannel radiometer operating on the “side” of a fairly strong water vapor absorption line, such as at 183 GHz [2], will be required for accurate humidity profiling. Much more detailed discussion of remote-sensing techniques and measurements can be found in [22], [23], and [24].

REFERENCES