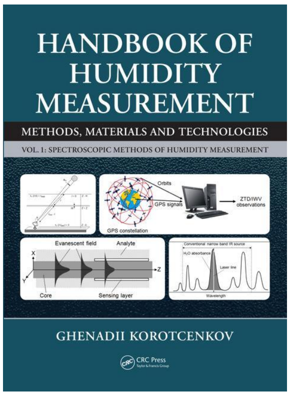

Handbook of Humidity Measurement
Methods, Materials and Technologies: Spectroscopic Methods of Humidity Measurement

Ghenadii Korotcenkov

Atmosphere Monitoring Using Methods of Absorption of Electromagnetic Radiation—Microwave Absorption

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5 Atmosphere Monitoring Using Methods of Absorption of Electromagnetic Radiation—Microwave Absorption

5.1 MICROWAVE RADIOMETRY

It is known that microwaves with wavelengths ranging from 1 m to 1 mm or with frequencies between 300 MHz (100 cm) and 300 GHz (0.1 cm) are absorbed by the water vapor in the material. But in contrast to the radiation from infrared (IR) spectral range, where absorption is limited by the surface, microwaves can penetrate into deeper thicknesses of material. This means that the tested materials can be transparent to microwaves and thus the intensity of transmitted radiation will carry information about the amount of moisture in the sample investigated. Therefore, currently, this method is widely used in determining the moisture content in various materials (Kraszewski 1973).

Two simple microwave moisture meters, utilizing the electromagnetic wave absorption in wet materials are shown in Figure 5.1. A microwave generator is mounted on one side of the material. On the opposite side, a receiver measures the change in microwave amplitude and the extent of the phase shift. The amplitude loss divided by the phase shift is proportional to the moisture in the material. Microwave and IR absorption techniques are equally accurate, but since IR instruments are generally less costly, microwaves are typically used in deep beds or dark materials where IR techniques have limitations. As high-power microwave sources could be used specialized vacuum tubes. These devices operate on different principles from low frequency vacuum tubes, using the ballistic motion of electrons in a vacuum under the influence of controlling electric or magnetic fields, and include the magnetron (used in a microwave ovens), klystron, traveling-wave tube (TWT), and gyrotron. These devices work in the density-modulated mode, rather than the current modulated mode. This means that they work on the basis of clumps of electrons flying ballistically through them, rather than using a continuous stream of electrons. Solid-state devices such as the field-effect transistor (at least at lower frequencies), tunnel diodes, Gunn diodes, and IMPact ionization Avalanche Transit-Time (IMPATT) diodes can be used as low-power microwave sources. Low-power sources are available as benchtop instruments, rackmount instruments, embeddable modules, and in card-level formats. A maser is a solid-state device, which amplifies microwaves using similar principles to the laser, which amplifies higher frequency light waves.

Various types of microwave antennas (Tsui 2008), tuned to the appropriate wavelength and coupled with the sensors of heat or microwave radiation such as bolometers, thermocouples, microwave diodes (Schottky diodes, tunnel diodes, etc.), Pyroelectric InfraRed (PIR) sensors, and superconductivity-based sensors can be used as receivers of microwave radiation. In most cases, microwave receivers are built on the superheterodyne scheme, because as usual, this scheme provides the highest sensitivity, and it is easier to implement it practically than a direct amplification circuit.

Detector microwave receivers are being applied mainly in the decimetric band and are based on cryogenically cooled bolometers and semiconductor detectors. In the centimeter and millimeter ranges (up to a frequency $f = 230$ GHz) in most cases uncooled detectors are used. Shorter microwave receivers, which are often cooled, are used only in research.

However, studies have shown that microwave techniques can be successfully used not only to control the moisture in solids but also for studies of atmospheric water vapor. Already, weather satellites using IR sensors have widened our knowledge of the mechanisms of cloud formations, and through the use of IR spectrometers the vertical profiles of temperature and water vapor above the clouds have been probed. Thus, a great volume of important information was gathered. However, this information does not provide the necessary data concerning the lower troposphere, which are necessary for numerical weather prediction. The cloud-top limit effectively shields the majority of the lower atmosphere from IR sensors. Even thin clouds are opaque to IR radiation and restrict the region of the troposphere, which is to be

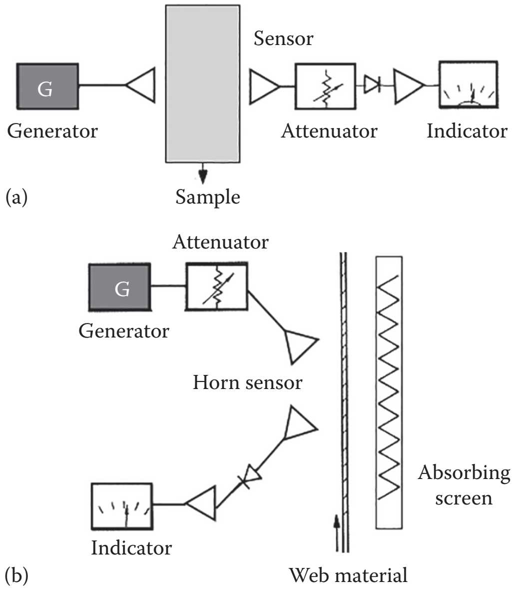

FIGURE 5.1 Two simple microwave moisture meters: (a) transmission measurement and (b) reflection measurement. (Idea from Kraszewski, A., *J. Microw Power*, 8, 323–335, 1973.)

explored by IR sensors. Analysis of hemispheric pictures of the Earth taken from space for percentage of cloud cover has revealed how much of a handicap this is.

Experiment and theoretical simulations have shown that the use of microwave region, which extends arbitrarily from millimeter to meter wavelengths, gives possibility to circumvent this limitation. Just in this range (22.235 and 183.31 GHz), it is being observed atmospheric absorption arising from pure rotational spectral lines of the water vapor (Van Vleck 1947; Payne et al. 2011). Research has shown that in the microwave spectral region, the principal sources of thermal radiation are atmospheric oxygen, the water vapor, and the liquid water within clouds. In the range between 20 and 200 GHz, emission is dominated by the oxygen complex from 50 to 70 GHz, the isolated oxygen line at 118.75 GHz, the water vapor lines indicated before at 22.235 and 183.31 GHz, and the so-called water vapor continuum arising from higher frequency lines contribution. Hydrometeors, forming clouds, contribute with the emission, absorption, and scattering, although for lower frequencies and for nonprecipitating clouds, the scattering effects can be considered negligible (Janssen 1993a).

The theoretical substantiation of possibilities of microwave radiometry for sounding of the atmosphere is represented in Gunn and East (1954), Staelin et al. (1973), and Karmakar (2012, 2014). It was established that the microwave region of the spectrum has a zone of frequencies within which clouds at the lower frequencies are essentially transparent, and at the higher frequencies opaque. Below approximately 30 GHz (1 cm) the clouds rapidly lose the ability to absorb and scatter radiation; at higher frequencies they rapidly become opaque. Quite fortuitously, the water-vapor resonance of lowest frequency is centered near 1.35 cm, and therefore is little affected by ordinary cloud cover. A total atmospheric attenuation of this band does not exceed 1.5 dB at resonance. Thus, there are important advantages in passively probing the atmosphere in this part of the electromagnetic spectrum rather than in the IR: (1) clouds are not opaque at these frequencies, thereby making it possible to study the cloud itself and the region below the cloud; and (2) instrumentation exists whose bandwidth is much smaller than the widths of spectral lines arising from several of the most important atmospheric gases. This last fact allows detailed analysis of line shape, which in turn facilitates the inference of the atmospheric conditions in which the lines arise. At the same time, the 183.3 GHz resonance line, which is a very strong spectral line, is subjected to strong attenuation in the atmosphere. In the moist tropical regions, the peak one-way attenuation through the atmosphere reaches more than 200 dB. In dry Arctic regions the peak attenuation falls below 20 dB, still, however, it is optically thick. This means that the measurements on two frequencies 22 and 183 GHz will contain information about the clouds. It is important to note that the resonant absorption bands related to the water vapor do not coincide with the absorption bands of oxygen (Figure 5.2), which simplifies the monitoring of the atmosphere. As it is seen in Figure 5.2, oxygen has an absorption band around 60 GHz. Although other atmospheric molecules have spectral lines in this frequency region, their expected strength is too small to affect propagation significantly (Meeks 1976; Raghavan 2003).

Also, due to the properties of the water vapor absorption bands in the microwave portion of the spectrum, it is possible to retrieve the profiles of humidity, rather than the column integrated humidity quantities that are derived from IR radiances (e.g., Blankenship et al. 2000). It is known that the intensity of radiation emitted at any altitude is proportional to the concentration of gases and hydrometeors, and to the local temperature. Thus, the principle of radiometric retrieval of the temperature and humidity profiles is based on the measurement of radiation generated at different atmospheric levels. This can be accomplished in part by measuring the emitted spectrum at frequencies conveniently distributed along the wing of an absorption line/complex, which correspond to different absorption and penetration depth (Rosenkranz 1998). For instance, temperature profiles can be estimated from

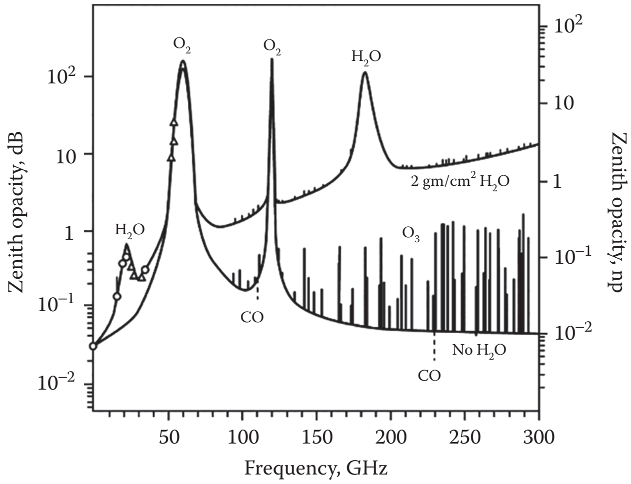

FIGURE 5.2 Atmospheric zenith opacity for H_2O, O_2, O_3, and CO. (Data extracted from Meeks, M.L., *Methods of Experimental Physics: Astrophysics*, Academic Press, New York, 1976, from Raghavan, S., *Radar Meteorology*, Kluwer Academic Publishers, Dordrecht, the Netherlands, 2003, and from Karmakar, P.K. *Microwave Propagation and Remote Sensing: Atmosphere Influence with Models and Applications*, CRC Press, Boca Raton, FL, 2012.)

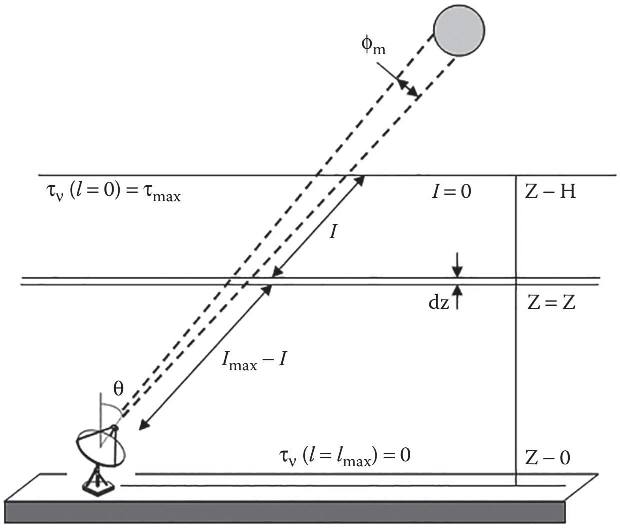

FIGURE 5.3 Schematic illustration of the passive microwave technique application for the study of atmospheric water vapor using solar radiation.

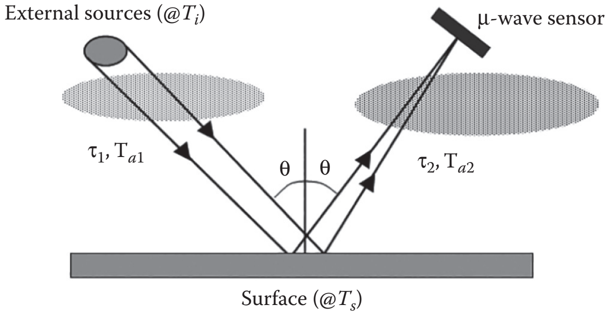

FIGURE 5.4 Combined influence of active (external) sources and atmosphere: T_i = brightness temperature from external sources. τ_1 = transmittance of the whole atmosphere in direction θ. τ_2 = transmittance of atmosphere between surface and sensor. T_{a1} = mean temperature of the whole atmosphere. T_{a2} = mean temperature of atmosphere between surface and sensor.

spectral measurements in the 50–60 GHz band, whereas the measurements around 22 GHz yield information on the water vapor profile (Cimini et al. 2006).

This is an important advantage of microwave radiometry, because the use of this approach for measuring atmospheric vertical profiles of temperature and humidity eliminates the need for probes. The probes are expensive devices and moreover they give a finite space/time resolution (routinely once or twice per day). So, they are inadequate for a detailed study of the diurnal evolution of the near surface atmosphere. At the same time, the study of the atmosphere using microwave radiometry can be carried out round-the-clock. Moreover, these studies can be organized using both satellites and aircrafts with generators or receivers of mircowave radiation, as well as passive microwave techniques, when the light source is the Sun (Figures 5.3 and 5.4), which significantly simplifies and reduces the cost of the research process. Advantages and disadvantages of such approach to the study of the atmosphere are shown in Table 5.1. Moreover, microwave radiometers can be operated in long-term unattended mode in nearly all weather conditions, with temporal resolution of the order of seconds. These features make a microwave radiometry very appealing for planetary boundary layer research (Ruffieux et al. 2006), where atmospheric processes can develop in a time scale of the order of minutes. Thus, a microwave technology can significantly enhance the ability to study atmospheric phenomena. Research has shown that microwave technique can also be used for analyzing the reflected radiation from the Earth's surface using satellites and aircrafts (Guan et al. 2011). It was found that the precipitation and the rain rates can also be estimated using microwave radiation (Chwala et al. 2012, 2014). However, accurate retrieval of humidity from the satellite microwave sensor requires accurate knowledge of the surface emissivity at the wavelength(s) to which the sensor is sensitive. Unfortunately, this information is only available for the oceans and therefore definitions

TABLE 5.1

Features of the Passive Microwave Remote Sensing from Space

Advantages	Disadvantages
• Penetration through nonprecipitating clouds • Radiance is linearly related to temperature (i.e., the retrieval is nearly linear) • Highly stable instrument calibration • Global coverage and wide swath	• Larger field of views (10–50 km) compared to VIS/IR sensors • Variable emissivity over land • Polar orbiting satellites provide discontinuous temporal coverage at low latitudes (need to create weekly composites)

TABLE 5.2

Microwave Radiometers Which Have Been Used for a Humidity Measurement in the Atmosphere

Microwave Radiometers	Producer
RPG–HATPRO, RPG–HUMPRO, RPG–LHUMPRO (Humidity and temperature profilers)	Radiometer Physics GmbH
MWRP, MWR3C (ARM microwave radiometers)	Argonne National Laboratory
RA-2 (Microwave Radiometer, MWR)	Envisat (European Space Agency)
AMSR-E (Advanced Microwave Scanning Radiometer)	Japan Aerospace Exploration Agency
Ground-based water vapor millimeter-wave spectrometer (WVMS)	The Naval Research Laboratory (NRL)
The MPAE ground-based microwave spectrometer (WASPAM)	Max Planck Institut für Aeronomie (MPAE)

for surface temperature, atmospheric water vapor, cloud liquid water, and rainfall rate when using Passive Microwave Remote Sensing from Space are possible only over the oceans. Other examples of using a microwave radiation for the study of the atmosphere and mathematical tools used for processing the information received one can find in Janssen (1993b), Westwater et al. (2003), Matzler (2006), Noam et al. (2011), David et al. (2012), Karmakar (2012, 2014), Kampfer (2013), Massaro et al. (2015), Roy et al. (2016), and Grankov and Milshin (2016). Unfortunately, a detailed discussion of these issues is beyond the scope of this book.

It should be noted that the use of microwave radiometry for studying the atmosphere increased sharply only after the appearance of commercial microwave radiometers, among which the most widely used are microwave radiometers, made by Radiometer Physics GmbH (Table 5.2). The appearance of these hygrometers is shown in Figure 5.5a. The microwave radiometers developed by Argonne National Laboratory (Figure 5.5b) (Candlish et al. 2012), are also widely used. Other radiometers were designed for large international projects related to the study of the atmosphere.

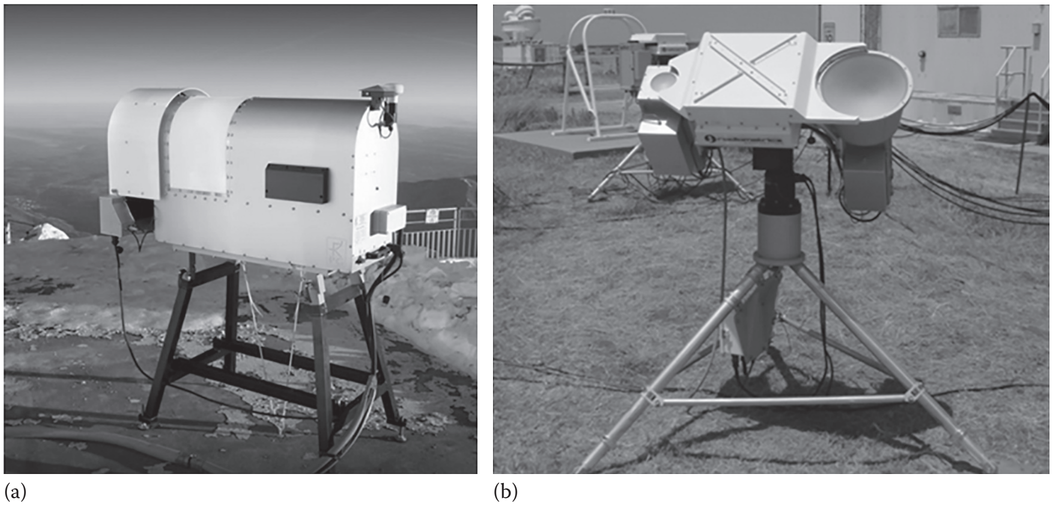
(a) (b)

FIGURE 5.5 (a) The humidity and temperature profilers RPG–HATPRO (Radiometer Physics GmbH) (From http://www.radiometer-physics.de/); (b) 3 Channel Microwave Radiometer MWR3C. (From the U.S. Department of Energy, http://www.arm.gov/.)

5.2 EXAMPLES OF MICROWAVE HYGROMETERS REALIZATION

Usually ground-based microwave spectrometers use passive microwave techniques and carry out measurements at 22.2 GHz, which corresponds to the emission frequency of the 6_{16}–5_{23} rotational line of H_2O. With regard to these differences in hygrometers, they are mostly associated with the use of either a variety of detectors, or various software (Kley et al. 2000). The ground-based Water Vapor Millimeter-wave Spectrometer (WVMS), designed by the Naval Research Laboratory (NRL), was based on a High Electron Mobility Transistors amplifier, which was refrigerated to 20 K and provided 30 dB gained more than a 500 MHz bandwidth. Radiation entered the radiometer through a scalar feedhorn that had a full width at half-maximum (FWHM) beam size of ≈8°, after being reflected from an elliptical aluminium plate. A stepper motor rotated the aluminium plate that was inclined at a 45° angle to the axis of the motor and the horn, thus allowing variation of the measurement elevation angle. The WVMS2 and WVMS3 instrument spectrometers consisted of a filter bank with thirty 14 MHz wide filters, thirty 2 MHz filters, twenty 200 kHz filters, and ten 50 kHz filters.

An estimate of the optical depth of the troposphere (τ_{trop}) was obtained by tipping the instrument through 11 angles from 45° to 75° from zenith, using a high density of angles near 75° where the rate of the change of the air mass (μ) as a function of angle is the highest. To solve for the tropospheric optical depth NRL used the measured system temperature from the widest filters (T_{sys}), estimated the receiver temperature and the atmospheric temperature (T_{rx} and T_{atm}), and then solved for the tropospheric optical depth using the best fit to the equation,

$$T_{\text{sys}} = T_{\text{rx}} + T_{\text{atm}}\left(1 - \exp\left(-\mu \cdot \tau_{\text{trop}}\right)\right) \tag{5.1}$$

Details of the measurement and retrieval technique are discussed in Rodgers (1976) and Nedoluha et al. (1995, 1996).

The WVMS instruments have been in operation, providing nearly continuous measurements of water vapor from ≈40 to 80 km (Kley et al. 2000). An integration time of ≈one week was required in order to achieve adequate signal-to-noise for retrievals at 80 km, while in the stratosphere daily retrievals were possible. For weekly retrievals the random error was estimated to be 4%–7%, with the largest error at the highest altitudes. The altitude resolution was ≈10 km, and systematic uncertainties were ≈5%–10%. The systematic uncertainties were arised primarily from errors in the calibration and pointing.

The ground-based microwave spectrometer of the Max Planck Institut für Aeronomie (MPAE), the WASPAM (Wasserdampf und Spurengasmessungen mit Mikrowellen) (Hartogh and Jarchow 1995; Kley et al. 2000) in addition to 22.235 GHz frequency observed also the water vapor continuum at 31.5 GHz. A rotating mirror reflected the microwave radiation of the atmosphere, a cold load and a hot load alternately to a polarization grid. While one polarization passed the grid into the horn antenna of the 31.5 GHz receiver, the other polarization was reflected via an elliptic mirror to the horn antenna of the 22 GHz receiver. The signal level was amplified by about 30 dB using three High Electron Mobility Transistors. The amplifier covered the frequency range of 20–24 GHz and was cooled to 20 K by a closed Helium loop. A steep low-pass filter at the output of the amplifier is cut off all frequencies above 22.5 GHz. The single sideband (SSB) receiver temperature was about 100 K. A Chirp Transform Spectrometer (CTS) with 2048 channels of 21 kHz resolution (i.e., 43 MHz bandwidth) performs the spectral analysis.

The atmospheric radiation was received with a fixed elevation angle of 18° and a beam width of 7° FWHM. The tropospheric transmission was derived from the measured brightness temperature in the line wings of the water vapor line, assuming that the troposphere is a single layer with a constant temperature. It can be shown that the error of this approach is negligible for low brightness temperatures of the atmosphere and small line amplitudes (Jarchow 1998). The retrieval techniques, which have been applied to determine altitude profiles of water vapor from the measured spectra, were described in Backus and Gilbert (1970) and Rodgers (1976). While the approach described by Rodgers (1976) gives the best results when retrieving single spectra, for instance for a weekly or monthly mean, the approach described in Backus and Gilbert (1970) has advantages for retrieving continuous data sets, especially when there are large variabilities in the tropospheric transmission (Jarchow and Hartogh 1995).

The altitude coverage of the data observed by WASPAM was 35–85 km (Kley et al. 2000). For weekly retrievals in the altitude range of 40–80 km the random error is estimated to be 0.15 ppmv. The altitude resolution was about 10 km. The systematic errors ranged between 0.1 ppmv at 80 km and 0.5 ppmv at 40 km. The main source of systematic errors, the so-called baseline, occurred due to reflections in the receiver. The contribution of pointing errors to the total systematic error was negligible for the system. A detailed error analysis was described in Jarchow (1998).

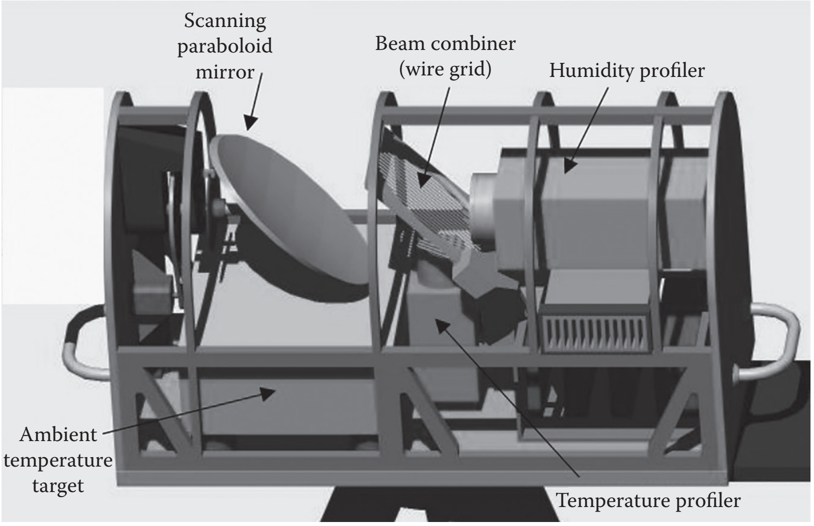

FIGURE 5.6 Internal structure of the RPG–HATPRO/RPG–LHATPRO radiometers designed by Radiometer Physics GmbH. (From ftp://ftp.radiometer-physics.de.)

The same frequency range of 22.24–31.4 GHz was used by Radiometer Physics GmbH when elaborating the RPG–HATPRO и RPG–HUMPRO Humidity and Temperature Profilers. A schematic drawing of the inner components of these radiometers is shown in Figure 5.6. The following functional blocks can be identified in this figure:

- Receiver optics comprising a corrugated feedhorn (encapsulated in thermal insulation) for each frequency band and off-axis paraboloid (scanning mirror).
- Two receiver units (22.24–31.4 GHz and 51.3–59 GHz) 51.3–59 GHz range were used for temperature profiling. Each channel has its own detector diode.
- The ambient load as part of the calibration system.
- The internal scanning mechanism.
- The instrument electronics sections.
- Data acquisition system.

One should note that discussed radiometers are based on the direct detection technique without using mixers and local oscillators for signal down conversion. Instead the input signal is directly amplified, filtered, and detected. The receivers are integrated with their feedhorns and are thermally insulated to achieve a high thermal stability. The zero bias highly doped GaAs Schottky detector diodes used in hygrometers can handle frequencies up to 110 GHz with a virtually flat detection sensitivity from 10 to 35 GHz. In addition, the detector diode offers superior thermal stability when compared to silicon zero bias Schottky diodes.

According to Operating Manual, RPG–HATPRO provides the construction of the tropospheric humidity profiles with the following vertical resolution:

- 200 m (range 0–2000 m)
- 400 m (range 2000–5000 m)
- 800 m (range 5000–10,000 m)

Accuracy of measurements is ~0.4 g/m^3 RMS (absolute humidity) or ~5% RMS (relative humidity).

As for the microwave hygrometers, operating at frequency of 183.31 GHz, they were developed for aircraft and satellite applications (Kley et al. 2000). The transition at 183.310 GHz is much better suited for these applications because its line strength is stronger by two orders of magnitude than the 22.235 transition. The brightness temperature for the 183 GHz line observed from aircraft is approximately 100 K in contrast to that measured from the ground at 23 GHz that is only a few tenths of a degree. Therefore, the integration time of a microwave receiver will be much shorter for the stronger line. This offers the opportunity to deduce latitudinal variations of water vapor if observed from a moving platform.

The microwave radiometer designed at the University of Bern, Switzerland is one of the examples of such devices (Peter et al. 1988; Peter 1998). The University of Bern system consists of a heterodyne receiver with an uncooled Schottky diode mixer that converts the high frequency signals to an intermediate frequency of 3.7 GHz. The radiometer has a single sideband system temperature of 4000 K. A Martin–Puplett interferometer acts as a filter to suppress the unwanted sideband. This sideband filter can be tuned to measure alternately in either of the two sidebands around 183.3 and 175.9 GHz that enables measurement of radiation in the very far wing of the water vapor line. Side band switching is controlled by the onboard computer. A rotating mirror switches the instrument's field of view approximately every 1.5 s between the atmosphere at an elevation angle of 15° and two microwave absorbers at temperatures of 77 K and 312 K that serve as calibration loads. The intermediate frequency signal is analyzed simultaneously with two acousto-optical spectrometers (AOS). One AOS has a large bandwidth of 1 GHz and a resolution of 1.2 MHz. It is well suited for the observation of spectral lines from the stratosphere. The second AOS has a total bandwidth of 50 MHz at a high resolution of 50 kHz. It is used for the analysis of narrow spectral lines emitted from the mesosphere. Furthermore, the instrument has its own independent global positioning system (GPS) receiver to record position and altitude for each measurement.

Water vapor profiles are retrieved between 15 and 75 km with an altitude resolution of approximately 8 km in the lower stratosphere and approximately 15 km in the upper mesosphere. The root sum square of all error contributions is below 0.6 ppmv.

Another example of a microwave hydrometers operating at frequency of 183.31 GHz is a LHUMPRO radiometer designed by Radiometer Physics GmbH. This device was designed for ultra-low humidity sites (IWV < 1.0 kg/m^2) such as high altitudes or arttic/Antarctic areas. LHUMPRO has a layout similar to the layout of the RPG-HATPRO/RPG-LHATPRO radiometers showed in Figure 5.5. The 183 GHz water vapor receiver is a DSB (double sideband) heterodyne radiometer with LO (local oscillator) tuned to the line center at 183.31 GHz. The mixer's lower/upper sideband response has been characterized by using a Rhode and Schwarz network analyzer plus frequency extension for the 170–220 GHz range.

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