COMBINED MICROWAVE AND OPTICAL ATMOSPHERIC REMOTE SENSING TECHNIQUES: A REVIEW*

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Abstract

Remote sensing of atmospheric parameters with space-based passive microwave and optical sensors matured from research experiments in the 1960's and 1970's to operational systems in the 1970's and 1980's. Atmospheric temperature and humidity profiles can be retrieved using the infrared carbon dioxide resonances, the microwave oxygen resonances, and the water vapor resonances in both spectral bands. Superior retrievals can be obtained by combining these sensors, taking advantage of the superior ability of microwaves to penetrate many cloud types and to respond better to low temperatures and negative lapse rates, while simultaneously taking advantage of the high spatial resolution, channel count, and sensitivity of modern infrared sensors, together with their reduced sensitivity to surface effects. Microwave and infrared soundings from satellites have been combined since their operational introduction in the 1970's, and progress continues to be made. These evolving techniques are reviewed here.

I. Physical Issues

The infrared and microwave atmospheric remote sensing bands differ in their spectroscopic characteristics, propagation characteristics through clouds and other aerosols, and surface emission characteristics. The instruments designed for each band also differ. The much shorter wavelength and higher sensitivity of most practical infrared sensors permit many more spectral channels to be combined in a small infrared instrument having very high angular resolution. Thus the next-generation NASA-developed infrared sounder AIRS has over 2,000 channels and 15-km spatial resolution at nadir, compared to twenty channels and 50-km resolution for the corresponding microwave instrument, AMSU. Although the use of more infrared channels and higher spatial resolution is partially at the expense of channel sensitivity, the net result is that the infrared channels, particularly in the 4-micron band, are relatively more sensitive for warmer targets and the microwave channels are relatively more sensitive otherwise; this increased thermal sensitivity at 4- and 15-micron wavelengths results largely from the Planck function $B(T,\nu)$.

The spectral differences between the microwave and infrared channels result principally from: 1) the more-nearly monochromatic character of the microwave channels, 2) the stronger temperature dependence of the infrared channels, particularly near 4.3 microns, 3) the presence of more interfering species in the infrared bands, such as H_2O, N_2O, and O_3, and 4) the slightly greater variability in the CO_2 resonances due to annual CO_2 variations in the lower troposphere, related to vegetative cycles. Some consequences of these spectral differences are evident in Figures 1 and 2. Figure 1 shows the temperature weighting functions for the microwave channels of AMSU and the 15- and 4.3-micron channels of AIRS. The weighting functions in Figure 1 do not include the Planck function but are defined instead as $d\tau/d(\ln p)$, where τ is transmittance and p is pressure. Note that the more monochromatic character of the microwave channels relative to the molecular spectral linewidths gives AMSU sharper weighting functions for altitudes above 100 mbar; the corresponding AIRS channels have bandwidths which smear the infrared spectral lines sufficiently to degrade the altitude resolution. Figure 2 shows the contribution functions for these same sets of channels for the model atmosphere. Note that the microwave contribution functions are essentially unchanged because of the linearity of the Planck function $B(T,\nu)$ in the microwave region. In contrast, the 15-micron channels, and particularly the 4.3-micron channels, show increased vertical resolution in the warmer portions of the atmosphere where the lapse rate is greater, and degraded vertical resolution near the tropopause and at altitudes where the lapse rate is negative. These differences lead any integrated retrieval system to rely more heavily on the 15- and 4.3-micron channels in the lower troposphere where strong positive lapse rates are more common, and to rely more heavily on the microwave channels above 100 mbar. These weighting functions for AMSU correspond to frequencies ranging between 50.3 and 56.964 GHz and, for AIRS, to wave numbers between 667.948 cm^{-1} and 723.278 cm^{-1}, and between 2363.66 and 2393.39 cm^{-1}.

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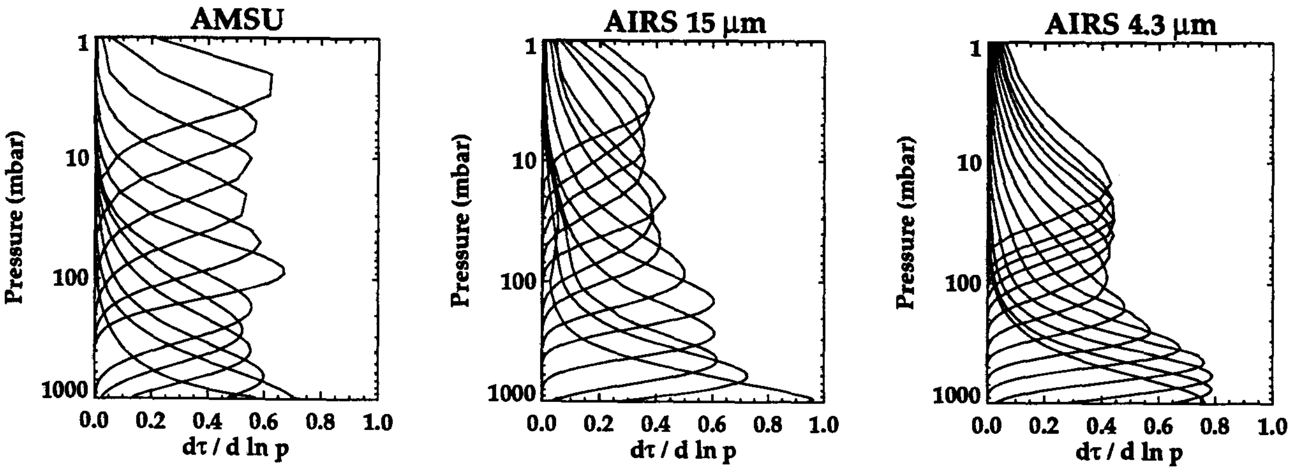

Fig. 1. Temperature weighting functions for a selection of AMSU and AIRS spectral channels.

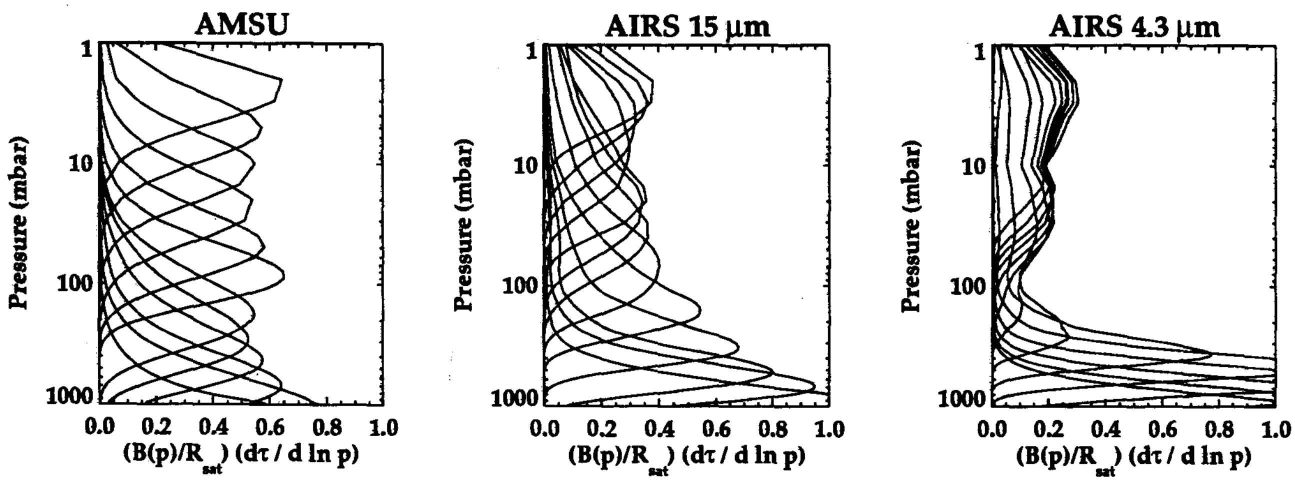

Fig. 2. Normalized contribution functions for the same AMSU and AIRS channels as in Fig. 1.

The different behavior of these bands in the presence of typical clouds (the heaviest being a cumulus) and other aerosols is suggested in Figure 3, developed from theoretical computations by Deirmendjian (1) and from Gasiewski and Staelin. (2) The two most important critical factors are the diameter of the droplets or dust particles compared to the wavelength λ, and whether the particles are water, ice, or a material like quartz. In general, the extinction coefficients are nearly wavelength independent for particle diameters larger than a quarter-wavelength; this situation generally exists for the optical and infrared wavelengths of interest here. One consequence is that some thin cirrus can noticeably perturb even the 15-micron channels, motivating use of the holes between clouds for deriving the best infrared temperature and humidity profiles. In the microwave region, except for large precipitating particles or hail, the absorption cross section drops as λ^{-2}, and the scattering cross section drops even faster, being roughly proportional to λ^{-4} in the Rayleigh limit where the wavelengths are much larger than the particles; for many clouds both microwave cross sections are negligible. At visible and infrared wavelengths small differences between the behavior of ice and water are suggested in the figure for different cloud models. Much larger differences exist in the scattering and absorption cross sections for ice and water particles in the microwave region. In addition, clouds can also reflect enough 4.3-micron solar radiation to confuse daytime soundings at these wavelengths if corrections are not made. As discussed in the next section, improved retrievals can be made when infrared and microwave soundings are combined. Even microwave soundings become invalid below the tops of precipitating clouds, although microwave soundings through nonprecipitating clouds can usually be obtained with little or no error.

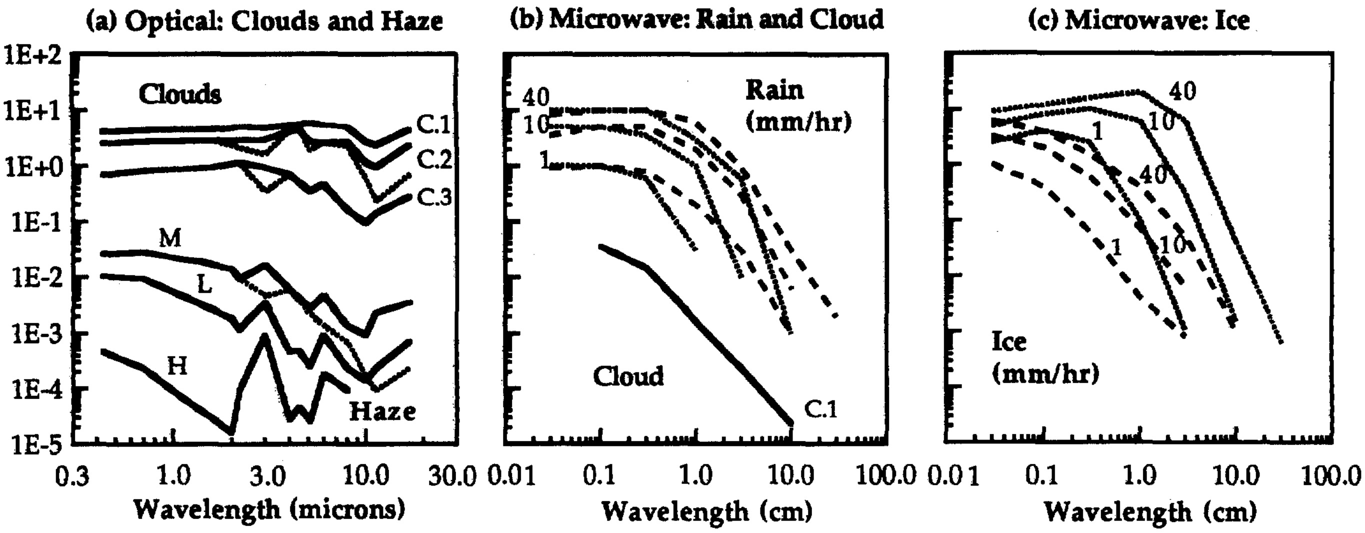

Fig. 3. Atmospheric attenuation in dB/km (solid - total extinction, dashed - absorption, dotted - scattering) for several types of atmospheric particles. The cloud and haze data were adapted from Deirmendjian (1), and the rain and ice data were from Gasiewski and Staelin (2).

The enhanced microwave sensitivity to large particle sizes, particularly the high scattering coefficient and albedo of large ice particles aloft over strong convection cells, improves cell location, cell characterization, and precipitation estimation.

The microwave emissivity of the terrestrial surface varies substantially, particularly over ocean or other water surfaces where it changes from roughly 35 percent to over 60 percent as the wavelength decreases from 10 centimeters to a few millimeters. The emissivity of deep, dry snow or firn at low temperatures can rival these low numbers. As a result, microwave observations at frequencies penetrating to the surface become increasingly dependent on these emissivities, which vary enough over wavelength intervals of an octave or more to introduce errors into temperature and humidity retrievals immediately above such surfaces. This is a problem for altitudes within a few kilometers of the surface if the areal coverage of snow, water, and other surface types is sufficiently uncertain within the antenna beamwidth to prevent calibration of these effects using the microwave window channels. In contrast, the infrared surface emissivity is close to unity, particularly for ocean surfaces. This fact also typically makes infrared determinations of surface temperature more reliable than those at microwave wavelengths, although temperature gradients within vegetative canopies can confuse some infrared measurements.

II. Retrieval Issues

Information from different spectral bands can be combined in several ways: 1) data from one band can be used to determine the geophysical situation and then dictate which processing procedures are used on data in other bands, 2) estimates of a retrieval parameter of interest are made independently in the two bands, and the results are averaged or combined in some way, and 3) the bands can be interpreted jointly. For example, in the updated operational processing system for the polar NOAA satellites, few-km resolution AVHRR images will be used to detect and correct cloud-contaminated HIRS temperature and humidity soundings. Microwave temperature sounding channels can be used for the same purpose, as well as contributing their own unique information to the retrievals. Early techniques compared infrared spectra in adjacent fields of view in order to observe the differential effects of clouds; now microwave channels are also used in this process to estimate cloud-free radiances and to provide improved corrections for cloud-contaminated infrared soundings.

In addition to the cloud-flagging and cloud-clearing roles of microwave soundings in supporting infrared retrievals, the microwave and infrared data can also be combined directly in nonlinear fashion to produce superior retrievals that capitalize on the differing characteristics of these spectral bands. An example presented by McMillan et al. (3) is shown in Table 1, where the rms retrieval accuracies of pure HIRS infrared spectral data are compared to pure AMSU data, all simulated. Note the higher performance of microwaves in and above the tropopause where the Planck function degrades the infrared response. More modern infrared sensors with better spectral resolution and sensitivity permit better retrievals at all altitudes. Progress continues to be made in this area, with the most encouraging results coming from use of neural networks and comparable situation-sensitive algorithmic approaches. Alternative techniques include 1) climate determination followed by an optimum linear retrieval for that climate set, and 2) retrievals which iteratively subtract from the observed radiances the current best retrieval-based predicted radiances; this residual radiance error is used to linearly predict corrections to the current retrieved temperature or humidity profile. Statistics relevant to regional climate can improve these estimates. An advantage of feed-forward neural-network estimators is that the same network can operate on all the data in one or a few steps, while still responding to all the nonlinear physics and statistical anomalies which may exist.

Table 1. Simulated RMS Retrieval Accuracies (°K), Clear Mid-latitude Winter

	OCEAN		LAND	
Pressure (mb)	HIRS	AMSU	HIRS	AMSU
1000	1.3	2.1	2.3	3.0
600	1.3	1.7	1.2	1.6
400	1.8	1.8	1.5	1.7
200	2.6	2.2	2.4	2.1
100	2.2	1.0	2.2	0.9
50	2.7	1.0	1.9	1.0

Simulations have shown the benefits of merging infrared and microwave spectral data in next-generation temperature and humidity AIRS/AMSU profile sounders. Rms 1-4 km layer-mean temperature errors of ~0.7 - 1.6 K, and rms 2-km layer-mean precipitable water errors of ~2-20 percent of mean values have been predicted by simulations for cloud fractions as high as seventy-five percent (4). Another example of how combined observations can enhance imagery of atmospheric humidity is the merger of microwave spectral measurements from SSM/I and the geosynchronous infrared VAS data from polar satellites. The SSM/I observations of humidity have large gaps between orbital swaths and are largely useless over land due to surface emissivity variations and low values, while the VAS data are degraded or useless over clouds; when combined, only cloudy soundings over land are lost (5). Another example is the combination of microwave window-channel observations responsive to humidity low over the ocean, with infrared observations of opaque water vapor at multiple atmospheric levels higher in the atmosphere; the low microwave emissivity of ocean provides a cold background contrasting sharply with water vapor 1-2 km above, whereas the high infrared emissivity of ocean provides relatively little contrast.

III. Future Directions

The opportunities for synergism between infrared and microwave atmospheric sounders increase with each succeeding generation's improvements in spatial and spectral resolution and number of channels. This is because the fundamental physical limitations inherent in each spectral band impose their own points of diminishing returns, which only combinations of instruments can overcome. The next important step forward will occur with the launch of AMSU on U.S. operational satellites beginning in 1996, and another major step forward will occur after the turn of the century when AIRS and AMSU fly together on the NASA EOS.

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