PASSIVE MICROWAVE SENSING OF THE EARTH

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Abstract

Passive microwave radiometers have found varied geophysical applications, particularly the remote sensing from satellites of atmospheric temperature and humidity profiles, clouds, soil moisture, snow and ice type and coverage, and other parameters.

Basic Principles

Passive microwave sensors can measure the natural thermal radio radiation emitted by the terrestrial atmosphere and surface. Their capabilities have been reviewed by several authors.[1,2,3] The microwave power P (watts) received is kT_AB, where k is Boltzmann's constant (1.38×10^{-23}), T_A is the effective temperature, or antenna temperature, of the source (°K), and B is the system bandwidth (Hz). T_A equals the kinetic temperature T_S for a blackbody source with emissivity $\varepsilon = 1$; and more generally it is $T_A = \varepsilon T_S + (1 - \varepsilon)T_o$, where $(1 - \varepsilon)$ is approximately the surface reflectivity and T_o is the effective temperature of any signal incident upon the surface being viewed. An atmosphere between the surface at z = 0 and the sensor at z = P can absorb some of the surface radiation and emit additional thermal radiation of its own, so that T_A at position P becomes:

$$T_A = [\varepsilon T_S + (1 - \varepsilon)T_o]e^{-\int_o^P \alpha(z)dz} + \int_o^P T(z)\alpha(z)e^{-\int_z^P \alpha(z)dz}dz$$

where $\alpha(z)$ and $T(z)$ are the atmospheric absorption coefficient and kinetic temperature profiles, respectively, and T_o includes contributions from the atmosphere too. This equation of radiative transfer becomes more complicated if there is scattering from atmospheric inhomogeneities or aerosols.

Receivers and Antennas

Microwave receivers are sensitive versions of systems commonly used for communications, radar, or similar applications. They are designed for the lowest possible noise levels (∿50-2000°K receiver noise temperatures T_R), typically have broad bandwidths (∿1-2000 MHz), and generally have elaborate provisions for precise calibration (∿0.1-2°K rms absolute accuracy). The power received in any bandwidth B (Hz) is averaged for a time τ(sec). The receiver output is proportional to the antenna temperature T_A and fluctuates randomly with an rms deviation

$$\Delta T_{rms}(°K) \simeq \frac{\beta(T_A + T_R)}{\sqrt{B\tau}}$$

where β is a constant ∿1-3, depending on the calibration configuration and signal processing. Typical rms sensitivities are ∿0.1-2°K.

Spectrometers with two or more frequency bands are useful for observing spectral properties of atmospheric resonances and the non-resonant behavior of aerosols and the terrestrial surface. Polarimeters separately observing vertical and horizontal polarization have yielded surface information.

Imaging has been achieved with both electrically and mechanically scanned antennas, the former being more rapid, and the latter offering greater bandwidths. Angular resolution is approximately λ/D, where λ is wavelength and D is antenna diameter. Antennas with beamwidths larger than one arc minute are generally feasible, over ten arc minutes is straightforward, and 2-10 degrees is typical.

Geophysical Information Obtainable

Satellite microwave observations near nadir can yield atmospheric temperature profiles 0-80 km having ∿1-6°K rms accuracy, with ∿2°K being typical. Each frequency in the semi-opaque 60 and 118 GHz oxygen bands intercepts thermal radiation originating in a layer ∿7-20 km thick, with ∿10 km resolution in most of the troposphere and stratosphere. Limb scanning sensors could, in principle, yield stratospheric and mesospheric temperature profiles with ∿3 km vertical resolution.

Observations near the 22 and 183 GHz H_2O resonances can yield over ocean the integrated water vapor abundance and perhaps 1-4 other parameters describing the H_2O altitude distribution. Stratospheric ozone is the other atmospheric species with important millimeter wave spectra, and its profile can also be sensed. Limb sounding of H_2O and O_3 can improve the sensitivity and altitude resolution for stratospheric and mesospheric observations.

The liquid water content of the atmosphere can be measured separately, and the drop-size spectrum can be crudely sensed too. The temperature and humidity data have sufficient accuracy to be useful inputs into global numerical weather prediction systems.

Surface information is obtainable from the observed spectral and polarization data. Sea state, ice type, snow cover, surface temperature and subsurface temperature gradients, soil moisture, and other parameters can all be inferred in appropriate circumstances.

Satellite, Aircraft, and Ground-Based Observations

Extensive microwave observations of the terrestrial atmosphere and surface have been made by many experimentors over the past several years from trucks, elevated platforms, radio telescopes, aircraft, and spacecraft. Much of this work has been reviewed by Basharinov et al.,[1] Tomiyasu,[2] and Staelin.[3]

Perhaps of greatest current interest are observations from spacecraft. The first satellites with earth-viewing passive microwave sensors were Cosmos-243,[4] Cosmos-384,[5] Nimbus-5, and Skylab I. The two Cosmos spectrometers viewed the earth for about two weeks in

September, 1968, and two days in December, 1970 respectively. They observed nadir at frequencies of 3.5, 8.8, 22.235, and 37 GHz, and yielded information about the columnar integrated abundances of water vapor and liquid water over ocean, sea surface temperatures, and the microwave spectra of land and ice.

The Nimbus-5 instruments were launched in polar orbit on December 11, 1972 and have operated continuously for over two years. They include the NEMS 5-channel microwave spectrometer operating near 22.235, 31.4, 53.65, 54.9, and 58.8 GHz,[6] and the ESMR[7] electrically scanned imager operating near 19.35 GHz.

NEMS views nadir with 200 km resolution, and observes brightness temperatures with 0.1-0.2°K rms noise for 16-sec integration. The absolute accuracy is ∿2°K. One major result of the experiment was that only about 0.4 percent of the temperature profile soundings were perturbed by clouds more than 1°K, and of these half were within 15 degrees of the equator. No such perturbation in brightness temperature exceeded 5°K, and 54.9 and 58.8 GHz were never affected. Most cloud-affected soundings can be identified from the data itself and thus be discarded. The rms accuracy of the 0-20 km temperature profile determinations is approximately 1-7°K, and 2°K is typical.

The abundances of water vapor over ocean inferred by NEMS agree with values reported for nearby radiosondes with rms errors of ∿0.1-0.45 g cm^{-2}, with greater accuracies in January and less in June, when the atmosphere contains more small scale inhomogeneities. These inferences are not greatly affected by clouds or precipitation, even in the ITCZ.

The NEMS data indicate that liquid water abundances over ocean can be inferred with ∿0.01 g cm^{-2} rms error, and that sea state effects can spuriously increase the determinations by as much as 0.035 g cm^{-2}. Errors at large concentrations, say 0.2 g cm^{-2}, might be as much as 50 percent, but are difficult to assess without valid ground-truth data.

Observations of snow and ice reveal spectral variations at 22.235 and 31.4 GHz which are uncorrelated with the average brightness temperature, and thus provide additional information. Surfaces with unique signatures include deep dry snow, sea ice, ocean, land, and highland ice and snow as in Greenland and Antarctica. Observations of deserts also suggest the diurnal variation of subsurface temperature gradients can be monitored.

The ESMR images have ∿25 km resolution at nadir and ∿2°K rms sensitivity. ESMR scans every 4 seconds ±50° from left to right in 78 slightly overlapping steps, thus forming continuous images of the strip beneath the satellite.

Over ocean the images clearly delineate bands of water vapor and precipitation that are generally obscured for infrared sensors because of overlying clouds.[8] They differ from infrared water vapor and liquid water, particularly in the lower 1-2 km of the atmosphere where infrared sensors suffer insensitivity due to lack of contrast. The ability to delineate rain bands in tropical cyclones is another unique capability.

Two prominant ESMR features over land are soil moisture and snow cover which perhaps can be studied quantitatively. River basins like the Mississippi and the Yangtze River valley are particularly evident. Land surface temperatures are also evident, but the surface emissivity must be considered in any interpretation.

In polar regions the evolution of the ice caps can be continually montored, both at the edge where the sea ice boundary is particularly striking, but also in the interior where different ice and snow characteristics are evident. Comparison of the high resolution monochromatic ESMR images with the polychromatic NEMS data yields additional information, and it is clear that much remains to be learned from improved systems in the future. Examples of NEMS and ESMR data are contained here in Figure 1.

Skylab I, lauched May 14, 1973, carried a 13.9 GHz radiometer-scatterometer altimeter and a 1.4 GHz nadir-viewing radiometer.[9] More satellites carrying microwave radiometers are planned for launch over the next several years, and the ultimate potential will not be reached for at least a decade.

Acknowledgements

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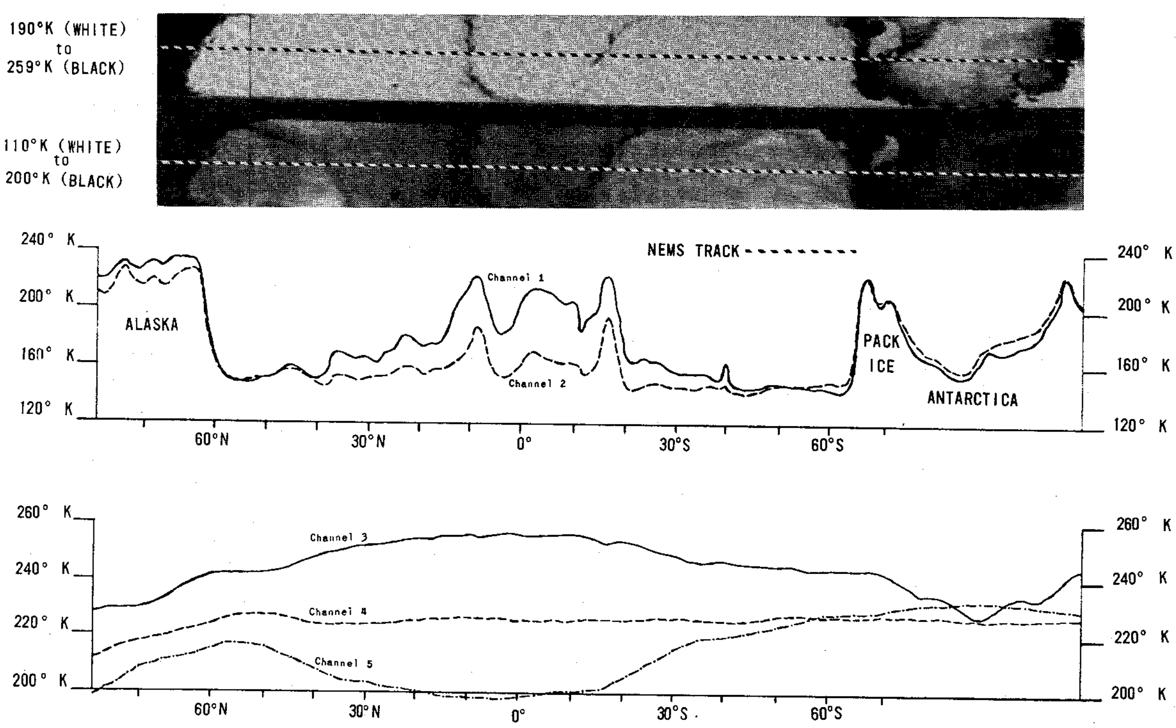
CORRELATION OF NIMBUS 5 ESMR IMAGERY AND NEMS BRIGHTNESS TEMPERATURE PROFILES



Displayed is brightness temperature data for 23 December 1972 from the two Nimbus 5 microwave experiments. Both detect atmospheric water vapor and rainfall areas over oceans. In the Electrically Scanning Microwave Radiometer (ESMR) images, rainfall areas over oceans appear quite dark, while the areas of atmospheric water vapor have intermediate shades of gray. Channel 1 of the Nimbus E Microwave Spectrometer (NEMS) is used to estimate the water vapor density over oceans; channel 2 is used to estimate the atmospheric liquid water content over oceans. NEMS channels 3, 4, and 5 are used for temperature sounding, and peak near 4, 11, and 18 km altitudes, respectively. Note that clouds have almost no perturbing effect on the atmospheric temperature values sensed by these three channels. In these channels temperatures vary smoothly along the orbit.

The coverage here is from Alaska, through the Pacific Ocean, to Antarctica. Of special interest is the response of channels 1 and 2 to water vapor and rain clouds over the tropical ocean, and the high response of both channels to the pack ice near Antarctica.

Figure 1