Technical Report RSC-03

PASSIVE MICROWAVE SENSING OF THE EARTH'S ENVIRONMENT: A BIBLIOGRAPHY WITH ABSTRACTS

compiled by
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TEXAS A&M UNIVERSITY
REMOTE SENSING CENTER
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PASSIVE MICROWAVE SENSING OF THE EARTH'S ENVIRONMENT:

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This bibliography presents a collection of articles on the topic of passive microwave sensors. The main emphasis of the bibliography is on the application of passive remote sensing in the microwave region and the interpretation of the results. The theory of passive microwave radiometry is not covered completely, however, some articles on the theory of operation of the equipment and the theory of radiation by certain bodies are included to give a background for the study of applications of passive radiometry. A bibliography covering atmospheric absorption and attenuation of microwaves is included. The bibliography is only a representation and more complete references can be found in Townes and Schawlow, Microwave Spectroscopy, and Rosenblum, "Atmospheric Absorption of 10-400 KMCPS Radiation: Summary and Bibliography to 1961," The Microwave Journal, March 1961.

The bibliography is divided into three sections. First is a listing of books and symposium proceedings. The books give the general theoretical aspects of microwave radiometry. The listing of symposium proceedings in this division is for the purpose of providing information to aid in the location of these publications. Their basic topic is the application of passive microwave systems.

Second is a listing of articles covering the topic of passive microwave sensors. The emphasis of this section is on the application of microwave sensors, but some theory on microwave emission and factors effecting the microwave noise level is also included. In this section an abstract of each article is included.

The final listing is a representation of articles concerning microwave absorption and attenuation.

BOOKS AND SYMPOSIUM PROCEEDINGS

Beckman, P. and A. Spizzichino, *The Scattering of Electromagnetic Waves from Rough Surfaces*, Pergamon Press, Oxford, 1963.

Chandrasekhar, S., *Radiative Transfer*, Clarendon Press, Oxford, 1950.

Ewing, G. (ed.), *Proceedings of the Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories* (short title: *Oceanography from Space*), Reference No. 65-10, Woods Hole Oceanographic Institute, Woods Hole, Massachusetts, April 1965.

Gille, J.C. (ed.), *Proceedings Third Interdisciplinary Workshop on Inversion of Radiometric Measurements*, Technical Report No. 68-2, Department of Meterology, Florida State University, Tallahassee, 1968.

Goody, R., *Atmosphere Radiation*, Clarendon Press, Oxford, 1964.

Gordy, W., W.V. Smith and R.F. Trambarulo, *Microwave Spectroscopy*, John Wiley and Sons Inc.,New York, 1953.

Jordan, E., *Electromagnetic Waves and Radiating Systems*, Prentice-Hall Inc., New York, 1950.

Katz, Y. (ed.), *The Application of Passive Microwave Technology to Satellite Meteorology: A Symposium*, Memorandum RM 3401-NASA, Rand Corporation, Santa Monica, 1963.

Kondratyev, K., *Radiative Heat Exchange in the Atmosphere*, Pergamon Press, Oxford, 1965.

Kerr, D.E. (ed.), *Propagation of Short Radio Waves*, McGraw-Hill Book Co., New York, 1955.

Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, 1965.

Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, 1966.

Proceedings of the Fifth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, 1968.

Townes, C. and A. Schawlow, *Microwave Spectroscopy*, McGraw-Hill Book Co., New York, 1955.

Zirkink, R. (ed.), *Symposium on Electromagnetic Sensing of the Earth from Satellites* (Sponsored by University of Miami, 1965), Polytechnic Press, Brooklyn, 1967.

PUBLICATIONS

Aagard, R.L., "Measurements, By Two Methods, of the Equivalent Black-Body Radiation Temperature in the Atmosphere," Journal of Meteorology, Vol. 16, No. 3, 1959, pp. 340-343.

This article describes and compares simultaneous measurements, taken with a black ball and an infrared radiometer, of an equivalent black-body radiation temperature. The infrared radiometer is used since its measurement is independent of convection while the measurement using the black ball depends on convection.

Abbott, R.L., "Width of the Microwave Lines of Oxygen and their Relationship to the Thermal Noise Emission Spectrum of the Atmosphere," Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, November 1965, pp. 257-269.

Calculations of the thermal noise emitted by the atmosphere using values of the line widths of O_2 from measurements of the line widths at very low and at atmospheric pressure, are presented. The approximate calculation of line widths of previous investigations are described briefly. Some modifications necessary to calculate the anomalous behavior of the line widths of O_2 at atmospheric and lower pressures are given. These modifications enable many calculations to be made which were previously not feasible, and the results are much more precise than previous calculations. An example of such a calculation is presented. A brief view of the kinds of atmospheric probing information which are expected to result from the investigation is given. A brief comment will be given on how atmospheric probing can help in improving our understanding of molecular collision processes.*

Anway, A.C., "Millimeter-Wave Atmospheric Emission Measurements and their Relation to Meterological Conditions," Eleventh Weather Radar Conference, Boulder, Colorado, 1964, pp. 208-211.

This article describes and discusses an experimental investigation of atmospheric thermal emission symmetry at a wavelength of 5.94 mm. performed during November 1962 at Cedar Rapids, Iowa.

* Written by Author

Barath, F.T., "Microwave Radiometry and Application to Oceanography," Oceanography From Space, Woods Hole, Mass., 1965, pp. 235-239.

This article presents a brief description of the characteristics of microwave radiometers along with a description of the parameters of the ocean which affect the measured temperature of the target. A brief summary of the application of microwave radiometers is also included.

Basharinov, A.E., A.B. Gorelile, V.V. Kalashnikow, and B.G. Kutuza, "The Determination of Cloud and Rain Characteristics by Means of Simultaneous Microwave Radiometric and Radar Measurements," Proceedings of the Thirteenth Radar Meteorological Conference, McGill University, Montreal, August 1968, pp. 536-539.

Radar and radiometric investigations of the atmosphere are described in this article. An explanation of how the radio thermal method of investigation gives the possibility of determining the integral parameters of clouds and rain such as integral water content of clouds and dropping precipitation, and moisture content of the atmosphere.

Basharinov, A.E., M. Kolosov, A. Kurstaya and L. Tutchkov, "Microwave Radiation of Ice Cover," Proceedings of the Thirteenth Radar Meteorological Conference, McGill University, Montreal, August 1968, pp. 544-545.

Microwave emissivity of ice cover is discussed. Included is an observation of microwave radiation of ice cover in the centimeter and decimeter range in fresh and salt water. The results of these observations are also included.

Buettner, K.J., "Microwave Emission of Raining Clouds", Oceanography from Space, Woods Hole, Mass., 1965, pp. 287.

Rain showers attenuate radio signals of cm microwaves in a roughly known manner. The attenuation is due to scattering and absorption. The ratio of these two effects is known for D. Deirmendjan's application of the Mie theory to a polydisperse cloud. Accordingly, heavy rain clouds for $\lambda > 1.4$ cm emit substantially more than the ocean for the same λ. Inclusion of the unknown, but likely, effect of multiple scattering increases the signal difference between ocean and a cloud. The counteracting temperatures effect is small. It should therefore be possible to discriminate between raining clouds and ocean. Optimal wavelength seems to be 1.6 cm. A passive system receiver could also be used to discover sea state, icebergs, and openings in Arctic ice fields.*

Catoe, C., W. Nordberg, P. Thaddeus and G. Ling, "Preliminary Results from Aircraft Flight Tests of an Electrically Scanning Microwave Radiometer," Report No. X-622-67-352, Goddard Space Flight Center, Greenbelt, Maryland, August 1967.

The Electrically Scanning Microwave Radiometer, which was flown on NASA's Convair 990 aircraft proved the feasibility of extending the spectral range of meteorological satellite radiation measurements from the infrared regions to much longer microwave wavelengths (1.55 cm). The radiometer consists of a microwave receiver and a two dimensional, 18 x 18 inch, phased-array antenna. The phased array antenna was designed to scan a beam, 2.7 degrees wide, electrically through an angle of $\pm 50^{o}$ from nadir. The direction of beam scan is perpendicular to the direction of the aircraft motion so that two dimentional maps of the earth's brightness temperature are made.
Flights were conducted over Arctic Ocean ice, Alaskan tundra and snow, Southwestern U.S. deserts, Eastern and Mid-west U.S. farmland, Yucatan tropical forests, and storms and rain clouds over land and water. Data have not been completely reduced; however, preliminary indications from qualitative, real time displays (facsimile printer), over selected areas, demonstrate that this radiometer performed as expected.
Indications are that mapping was achieved with the desired spatial resolution (2.7^{o} beamwidth), and with useful radiometric accuracy. Land-water and ice contrasts were mapped with outstanding clarity in clear atmosphere as well as under all conditions of cloudiness, and rain clouds and storm activity over oceans could be positively identified even, and especially, when other cloudiness obscured such identification visually or by infrared techniques. The aircraft tests proved that scanning microwave radiometry will be an extremely useful sensor for mapping areas of heavy rainfall and the extent and thickness of sea ice ultimately from spacecrafts in orbit, and independent of cloud conditions.*

Chen, S.N.C., and W.H. Peake, "Apparent Temperatures of Smooth and Rough Terrain," I.R.E. Transactions on Antennas and Propagation, Vol. AP-9, November 1961, pp. 567-572.

The apparent temperatures of smooth and rough terrain surfaces are calculated for frequencies between 1 and 75 kMc, for angles of incidence between 5^{o} and 80^{o}, and for observation altitudes between 2 km and 32 km. The attenuation and thermal radiation caused by the atmosphere are accounted for by an experimental model atmosphere, and the surface emissivities are based on measured complex dielectric constants (for the smooth surfaces) and measured radar return (for the rough surfaces). It is found that perpendicular polarization provides the greatest temperature contrast between rough and smooth surfaces, and that the contrast decreases as the altitude of observation increases; at f = 75kMc (approximately the resonant frequency of the oxygen molecule), there is likely to be little, if any, contrast between rough and smooth surfaces.*

Conway, W.H., and R.T. Sakamoto, "Microwave Radiometer Measurements Program," Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, April 1966, pp. 263-271.

An experimental passive microwave radiometer measurements program is described. This discussion concerns itself primarily with the nature of the experiments, the equipments used, and, above all, the resulting data. The primary objective of the program was to obtain accurate microwave measurements of the characteristics of a selected set of material surfaces, e.g., various soils, vegetation, etc., under rigorously controlled conditions. Measurements have been made at a variety of frequencies, e.g., 13 kMc, 18 kMc, 35 kMc, and 70 kMc, and have also included effects of the depths of the surface material as well as the material itself. Multilayer effects with layers of different materials have also been included. Atmospheric measurements are also included.
A second prime objective of the program was to provide data to be used for analysis of the characteristics of the various surfaces. Much of the data is presented compared to the predicted values.*

Croom, D.L., "The Possible Detection of Atmospheric Water Vapor From a Satellite By Observation of the 13.5 mm. and 1.66 mm. H_2O Lines," Journal of Atmospheric and Terrestrial Physics, Vol. 28, No. 3, March 1966, pp. 323-326.

Calculations of the atmospheric noise temperature spectra that would be expected to be observed from an Earth satellite at wavelengths near the 13·5 mm and 1·64 mm rotational lines of the water-vapour molecule, indicate that although both of these lines would be detectable at the satellite, very little useful information on the total vertical water-vapour content of the atmosphere could be obtained from the results. If ground measurements show a central enhancement of the spectra as predicted by Barrett and Chung (1962) for the case of an increasing stratospheric mixing-ratio, then this could be detected from a satellite, though even over the most favourable surface (water) the increase at 13·5 mm is only 5°K. The corresponding value at 1·64 mm is about 45°K and is independent of the type of surface, though it is very dependent on the temperature structure of the atmosphere.*

Cummings, C.A. and J.W. Hull, "Microwave Radiometric Meteorological Observations," Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, April 1966, pp. 263-271.

Microwave radiometric observations of various meteorological conditions were undertaken in the summers of 1964 and 1965. Data were collected in the 35- and 23-GHz regions of the frequency spectrum. Observations in the 23-GHz region were made at the center of the water vapor absorption band, resulting in a high degree of resolution of changes in cloud mass, fog, and rain.
A simple twin-horn antenna technique was used, with one antenna oriented vertically and the other oriented 45 degrees from the vertical. The input to the radiometer was alternately switched between the two antennas, with a 2-minute exposure for each antenna. This technique provided the following information: (1) the apparent temperature as viewed by each antenna, and (2) the difference in apparent temperature between the two antennas. The microwave radiometer was found capable of sensing direction of cloud mass movement, as well as discerning between and measuring degrees of cloudiness, rain, and fog. The meteorological parameters measured with the 35- and 23-GHz radiometers were:
Cloud mass.
Cloud conditions (scattered, broken, overcast).
Humidity (moisture density depending on background).
Fog.
Rain.
Direction of cloud mass movement.
Complete weather reports were received from the U.S. Weather Bureau. Temperature, humidity, wind speed, and direction were also monitored on site.
This paper describes the radiometer, antenna system, and technique used in collecting and analyzing the meteorological data.*

Decker, M.T. and E.J. Dutton, "Radiometric Observations of Thunderstorm Cells," Proceedings of the Fifth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, April 1968, pp. 617-629.

Decker, M.T. and E.J. Dutton, (cont'd)

The thermal noise emission from Colorado thunderstorms has been measured using a 10.7 GHz radiometer and a 18-meter diameter steerable parabolic antenna. These measurements have been used to prepare contours of integrated liquid water content along radio rays passing through the storm. The analytical method used involves the following steps:
The experimental data consists of horizontal radiometric scans across the thunderstorm which permit measurements of the difference in antenna temperature when pointing at the clear atmosphere and the storm. Using radar, radiosonde and surface meteorological data, estimates were made of the absorption that must have been occurring along a line-of-sight toward the clear sky and also when looking toward the storm. Subtracting the absorption due to the clear sky from that occurring when looking at the storm resulted in an estimate of the absorption due to the storm itself. Since the storm absorption is proportional to the liquid water content with a known constant of proportionality dependent upon the temperature, it is possible to estimate water content of the storm along the line-of-sight. The technique is illustrated by contour diagrams showing liquid water content of a small storm system and its changes over a period of 2 hours.*

Dedman, E.V., J.L. Calver and F.J. Janza, "Computer Simulation of Remote Sensing By Microwave Radiometers," Ryan Aeronautical Co., San Diego, California, August 12, 1968.

This paper presents the concept of simulation by digital computer techniques. The advantages and limitations of simulations and the development of mathematical models are discussed.
A computer simulation of airborne microwave radiometers as remote sensors for mapping thermal upwellings in the ocean is described. The importance of correlating "ground truth" data to radiometer brightness temperature for deriving and validating mathematical models is pointed out. Methods of studying system characteristics using simulations are proposed and the value of such studies in reducing the cost of expensive field testing is emphasized. The benefits in utilizing analogous experience gained in the development of large space systems in evaluating remote sensing for Hydrology are enumerated and specific analogies discussed.*

Dicke, R.M., "The Measurement of Thermal Radiation at Microwave Frequencies," The Review of Scientific Instruments, Vol. 17, No. 7, July 1946.

The connection between Johnson noise and blackbody radiation is discussed, using a simple thermodynamic model. A microwave radiometer is described together with its theory of operation. The experimentally measured root mean square fluctuation of the output meter of a microwave radiometer (0.4°C) compares favorably with a theoretical value of 0.46°C. With an r-f band width of 16 mc/sec., the 0.4°C corresponds to a minimum detectable power of 10^{-16} watt. The method of calibrating using a variable temperature resistive load is described.*

Dutton, E.J., B.R. Bean and E.R. Westwater, "Brightness Temperature of the Atmosphere Using a Bi-Exponential Model In the 6-45 GHz Frequency Range," Eleventh Weather Radar Conference, Boulder, Colorado, September 1964, pp. 212-216.

In order to estimate the brightness temperature contributed by the atmosphere knowing only surface conditions, the absorptive properties of the atmosphere are discussed. The use of the bi-exponential model for predicting the brightness temperature is also discussed.

Edgerton, A.T., "Engineering Applications of Microwave Radiometry" Proceedings of the Fifth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, April 1968, pp. 711-724.

Recent research concerning the utilization of microwave radiometers for terrain analysis suggests a number of engineering applications for these instruments. This work, performed under sponsorship of the Office of Naval Research, Air Force Cambridge Research Laboratory, and the Army Cold Regions Research and Engineering Laboratory, has been conducted to establish the microwave characteristics of a number of natural materials. Materials examined include a number of soils.
These studies show that measured microwave temperatures are dependent on sensor frequency and polarization, and that sizable differences in radiometric response occur for the soils investigated. These variations are primarily attributed to differences in soil moisture content, particle size and surface roughness. Particle size and surface roughness variations influence the general shape and slope of the radiometric temperature versus antenna viewing angle plots, whereas moisture content variations cause the curves to shift along the temperature axis. The dielectric properties (both real and imaginary) of soils are strongly dependent on soil moisture content. Changes in the dielectric constant result in major changes in the emissivity and radiometric brightness temperature. Microwave temperature differences between saturated tidal mud and soils of low water content are on the order of 120°K. Experiments were also

conducted on a playa surface wherein soil bearing strengths were compared with microwave brightness temperatures. These measurements clearly demonstrate that a useful qualitative relationship exists between the radiometric brightness temperature and bearing strengths of soils. This relationship has particular significance in the field of soil engineering.*

Edgerton, A.T., R. Manl, G.A. Poe, J.E. Jenkins, F. Soltis and S. Sakamoto, "Passive Microwave Measurements of Snow, Soils, and Snow-Ice-Water Systems," Technical Report No. 4, SGD 829-6 Space Division, Aerojet-General Corporation, El Monte California, February 15, 1968.

The basic objectives of this program are to measure the microwave brightness temperatures of snow, soils, sediments, and snow-ice-water systems, both in the field and the laboratory and to relate these measurements to the corresponding material properties and environmental conditions. The major portion of this study has been devoted to field measurements. A few mathematical models were developed and compared to measured data. These have been useful in attaining a better understanding of the physics of microwave emission of natural materials.*

Edison, A.R., "Calculated Cloud Contributions to Sky Temperatures at Millimeter-Wave Frequencies," National Bureau of Standards Report 9138, U.S. Department of Commerce, Boulder Laboratories, Boulder Colorado, February 1966.

The contribution of water and ice clouds to zenith sky temperatures in the frequency range from 10 to 100 Gc/s is calculated using reasonable models. It is shown that radiation due to absorption by water vapor and cloud droplets may contribute from 1 to over 200°K to the apparent sky temperature. Scattering from cloud droplets is of negligible importance over the frequency range considered. A cloud droplet size distribution of the form $ar^6 \exp(-br)$ is used in the calculations. The droplet radius is critical because of the r^3 and r^6 variation respectively in the absorption and scattering cross sections.*

Eppler, W.G. and R.D. Merrill, "Relating Remote Sensors Signals to Ground-Truth Information," Proceedings of the I.E.E.E., Vol. 57, No. 4, April 1969, pp. 665-675.

This paper describes two computer-based methods for data handling and display which significantly simplify the task of relating remote sensor signals to that ground-truth information which can be derived from aerial photographs of the ground scene. These techniques have been applied successfully to microwave radiometer and infrared spectrometer flight-test data. Results indicate that the digital computer, with its associated storage and display capabilities, makes possible systematic and accurate analysis of remote sensor data in large volume at low cost. In one approach, the computer is used to determine and display, on aerial photographs, the exact path of the sensor boresight over the ground scene. Using this display, an investigator can observe visually certain simple correlations between the sensor return and the ground scene. In the second approach, the analyst uses a special light-pen console to put ground-truth information (in graphical form) into the computer. Using techniques described here for storing, retrieving, and processing graphical data, the computer automatically converts the ground-truth information into a form where it can be correlated directly with the remote sensor signals.*

Ewen, H.I., F. Haneman, R.M. Kalafus, M.E. Louapre, R. Mailloux and D.G. Steinbrecher, "Microwave Radiometric Capabilities and Techniques," Proceedings of the Fifth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, April 1968, pp. 9-58.

The principles of operation and present capabilities of microwave radiometric sensors are presented. Separate sections are devoted to a discussion of antennas and radiometric receivers as the two major functional subsystems of the sensor. Projected capabilities offered by near future solid state component advances are included in the section on receivers.*

Falco, C.U. and W.J. Johnson, "Passive Microwave Sensing of the Atmosphere and Earth Surface Environments," Thirteenth Technical Symposium of the Avionics Panel Advisory Group for Aerospace Research and Development, Milan, Italy, September 4-7, 1967.

The potential utility of microwave radiometry for satellite surveillance of the atmosphere and earth environments is examined in this paper. Some experiments and theory which have lead to space experiment development are also covered. A large portion of this paper is devoted to the generalized discussion of the relations between electromagnetic radiation in the microwave spectral region and the effects of changing physical parameters. However, since the extensive theoretical efforts gathered to date cannot possibly be covered, representative examples of experiments are presented.*

Falcone, V.J., Jr., "Calculations of Apparent Sky Temperatures at Millimeter Wavelengths," Radio Science, Vol. 1, No. 10, October 1966, pp. 1205-1209.

Apparent sky temperatures measured at 15, 17, and 35 Gc/s over a period of a year are compared with values calculated from the radiative transfer equation. Temperature, pressure, and relative humidity profiles, which are necessary to solve the radiative equation, are obtained from radiosonde data which are taken simultaneously with radiometric measurements. It is found that apparent sky temperatures calculated using the presently accepted line breadth constant for oxygen are not in good agreement with measured values. It is shown that by increasing the oxygen line breadth constant, calculated values within experimental error of measured apparent sky temperatures are obtained.*

Grossman, R.L. and W.E. Marlatt, "A Method of Showing what a Radiometer 'Sees' During an Aircraft Survey," Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, June 1966, pp. 571-574.

The aircraft-borne infrared technique of conducting a surface temperature survey is gaining wide popularity. Over wide areas, even though the flight path is known, it is difficult to assess exactly the surface conditions during the flight. It would be convenient sometime after the run to go back and carefully observe what surface conditions were present during the flight in hopes of relating surface conditions to radiation temperature (or other radiation parameter) measured. This paper presents a simple method of obtaining such a record. This method involves the use of a camera along with the radiometer. A list of equipment used is included in the article.*

Gunn, K.L.S. and T.W.R. East, "The Microwave Properties of Precipitation Particles," Quarterly Journal of the Royal Meteorological Society, Vol. 80, 1954, pp. 522-545.

The theory of scattering and attenuation by rain, snow and cloud is reviewed and theoretical results are presented in the form of equations, tables and graphs, so that the radar response to meteorological particles can be calculated at six wavelengths (10, 5·7, 3·2, 1·8, 1·24 and 0·9 cm) and various temperatures. Particular emphasis is placed on developments since Ryde's comprehensive paper in 1946. Published experimental results are compared with the theory.
All results computed from the theory are contained in Tables 4 and 5. The attenuation by water vapour and oxygen is given in an Appendix.*

Hagfors, T. and J. Moriello, "The Effect of Roughness on the Polarization of Thermal Emission from a Surface," Radio Science, Vol. 69D, 1965, pp. 1614-1615.

The basic procedure of the theory for the emission of electromagnetic waves from a dielectric medium with an undulating boundary surface is presented. The several simplifying assumptions used are stated and some numerical results presented in the form of diagrams in order to show the effect of surface roughness on the emission.

Hogg, D.L., "Effective Antenna Temperature Due to Oxygen and Water Vapor in the Atmosphere," Journal of Applied Physics, Vol. 30, No. 9, September 1959, pp. 1417-1419.

Calculations of the effective noise temperature at the terminals of a high gain antenna due to oxygen and water vapor in the atmosphere are given for the frequency range 0.5 to 40 kmc. In the 1 to 10 kmc band, the effective temperature increases from about 3° to 100°K as the zenith angle is increased from 0° to 90°. Calculated values of the total attenuation through the atmosphere are given.*

Hogg, D.C. and R.A. Semplak, "Estimated Sky Temperatures Due to Rain for the Microwave Band," Proceedings of the I.E.E.E., Vol. 51, March 1963, pp. 499-500.

Previous measurements of sky noise due to rain at 6 Gc are used to calculate that effect at other frequencies in the microwave band.

Hogg, D.C. and R.A. Semplak, "Measurement of Microwave Interference at 4 Gc Due to Scatter by Rain," Proceedings of the I.E.E.E., Vol. 51, March 1963, p. 500.

This communication discusses an observation in which transmissions from ground based transmitters, operating in the 4160 to 4180 Mc band, were being scattered into a low noise receiving system, operating at 4 Gc., during rainstorms.

Hogg, D.C. and R.A. Semplak, "The Effect of Rain and Water Vapor on Sky Noise at Centimeter Wavelength," Bell Systems Technical Journal, Vol. XL, No. 5, September 1961, pp. 1331-1348.

Measurements of sky noise temperature at a frequency of 6.0 kmc have been made for various conditions of absolute humidity and precipitation. For an antenna beam position 5° above the horizon, the sky noise temperature was found to increase about 15°K from winter to summer due to the change in absolute humidity. During periods of rain, with the antenna beam pointed to the zenith, sky noise temperatures as high as 130°K have been observed, compared with the usual background value of 3° due to oxygen and water vapor. Theoretical calculations of sky noise temperature for typical dry and humid summer days are presented.*

Hyatt, H.A., "Airborne Measurements of Microwave Emission from the Earth's Surface and Atmosphere," _Symposium on Electromagnetic Sensing of the Earth from Satellites_, University of Miami, 1965.

This paper reveals the results of a theoretical and experimental investigation of the microwave radiation emitted by the earth's surface and atmosphere. The study objective was to evaluate the potential application of microwave radiometry to weather satellite reconnaissance. Measurements were obtained by flying an aircraft-mounted radiometer (sensing fluxes at frequencies 22.235 and 15.78 Gc) at high and low altitudes over the Pacific Ocean and Southern California terrain. Average emissivities of 0.85 for the land and 0.53 for the ocean were computed from these measurements. The measurements indicated an average emission line amplitude of 20 ± 2°K over oceanic areas at both high (35,800 ft) and low (1600 ft) altitudes, while the average emission measured over the land was 12± 2°K. Small nonprecipitating clouds had very little effect on the outgoing radiation field. The data trends in this experiment agree with theory, but the effects of changes in surface emissivity and reflectivity, and in the atmosphere's vertical structure, cannot be explicitly separated for interpretation.*

Kaplan, L.D., "Inference of Atmospheric Structure from Remote Radiation Measurements," _Journal of the Optical Society of America_, Vol. 49, No. 10, October 1959, pp. 1004-1007.

A detailed analysis of the structure of the atmosphere, including the three-dimensional distribution of temperature and water vapor, can be obtained from the spectral variation of its thermal radiation as viewed from a reconnaissance aircraft or earth satellite. In order that the measurements be capable of unambiguous interpretation, however, it is essential that the selection of spectral intervals to be used are based on a carefully planned interpretation scheme.

A possible program is outlined, in which the temperature distribution is obtained by measurements in the 15-μ CO_2 band and the water vapor distribution obtained by simultaneous measurements in the rotational band. The temperature-and-pressure dependence of the absorption coefficients must be taken into account.
The instrument should be a multiple-slit or multiple-detector grating spectrometer, capable of resolving 10 cm^{-1} at 15 μ. Spectral models and methods of analysis of the spectra are discussed briefly.*

Kennedy, J.M. et al., "Passive Microwave Measurements of Snow," Technical Report No. 1, Space General Corporation SGC 829 R-3, El Monte, California, December 15, 1965.

This report documents the radiometric and geophysical measurements that were made during the spring of 1965 at Crater Lake, Oregon, and the reduction of the preliminary data to determine the feasibility of using passive microwave radiometers for discerning existing in situ conditions of snow-ice-water systems. Radiometric measurements at several frequencies were taken simultaneously and related meteorological, geophysical and geological data were also obtained. The radiometer frequencies were 13.5 Gc, 37 Gc, and 94 Gc. The data and analysis of data in the report is concerned primarily with "old" snow, snow that has undergone metamorphism.

Kennedy, J.M., "Passive Microwave Measurements of Snow and Soil," (Volumes I and II), Technical Report No. 2, Space-General Corporation SGC 829 R-4, El Monte, California, November 5, 1966.

The basic objectives of this program are to measure the radiometric brightness temperatures of snow, sand, soil, mud and rock, both in the field and in the laboratory, and to relate these measurements to physical parameters, changes in environment and sensor frequencies. The major effort during the period covered by this report was devoted to field measurements of in situ, undisturbed material.*

Kennedy, J.M., "A Microwave Radiometric Study of Buried Karst Topography," Geological Society of America Bulletin, Vol. 79, June 1968, pp. 735-742.

Theoretical studies and some microwave measurements of soil penetration capabilities suggested that microwave radiometers may be able to detect subsurface voids associated with karst development beneath relatively thick soil cover. However, from a theoretical aspect, it is difficult to model the effects of surface roughness, moisture content, vegetation coverage, and a nonhomogeneous sky. To prove the potential of microwave surveys in locating and mapping subsurface voids, a mobile laboratory unit was used to obtain in situ data. This unit is equipped with passive microwave radiometers operating at 13.4 GHz (2.22 cm), 37 GHz (8.1 mm), and 94 GHz (3.2 mm), as well as geophysical support equipment.

An area near the town of Cool, El Dorado County, California, was used to obtain data. This area is known to have well-developed subsurface karst development and has been surveyed by both the California Highway Department and the California Rock and Gravel Company.

The microwave survey showed significant radiometric "cold" anomalies associated with void-space development beneath several tens of feet of soil cover. Detection was positive in almost all cases, evidence of the strong probability that microwave systems may be used to detect and rapidly map karst systems from a remote platform. This will greatly reduce surveying and construction costs in areas where caves and sink holes have developed beneath obscuring soil cover.*

Kennedy, J.M., and A.T. Edgerton, "Microwave Radiometric Sensing of Soils and Sediments," American Geophysical Union 48th Annual Meeting, Washington, April 1967.

A field and laboratory measurements program sponsored by the Office of Naval Research, Air Force Cambridge Research Laboratories, and the Army Cold Regions Research and Engineering Laboratories has been conducted to determine the response of microwave radiometers to various soils and sediments. The materials investigated include beach sand, unconsolidated tideland mud, playa sediments, basalt, and two varieties of loam. Dual polarization measurements were taken at frequencies of 13.5 GHz and 37 GHz, with aspect angles ranging from nadir to zenith sky.

The results of these studies show that measured microwave responses are dependent on sensor frequency and polarization, and that sizeable differences in radiometric response occur for the materials investigated. These differences are primarily attributed to differences in moisture content, particle size, and emissivity of the various materials studied. Particle size variations influence the general shape and slope of radiometric temperature versus aspect angle plots, whereas moisture content variations cause the curves to shift along the temperature axis.*

Kennedy, J.M., and A.T. Edgerton, "Microwave Radiometric Sensing of Solid Moisture Content," International Association of Scientific Hydrology, Extract of Publication No. 78, General Assembly of Bern, 1967.

A field measurements program sponsored by the Office of Naval Research and the Air Force Cambridge Research Laboratories has been conducted to determine the response of microwave radiometers to moisture content in soils. Materials investigated include beach sand, unconsolidated tideland mud, playa sediments, and loam. Dual polarization measurements were made at frequencies of 13.5 GHz and 37 GHz (one GHz = 10^9 cps), with aspect angles from nadir to the local horizon.

All objects with temperatures above absolute zero emit electromagnetic energy. The intensity of this radiation depends on the temperature and emissivity of the object, and on the frequency of observation. Consideration of the radiation characteristics of soils shows that the emitted energy can be separated into two components; the emitted energy, and the reflected energy. Emitted energy is the product of thermometric soil temperature T_G, and soil emissivity ε. Reflected energy is the product of microwave sky temperature T_S and material reflectivity p. Antenna brightness temperature (measured in degrees Kelvin) can be expressed as $T_A = \varepsilon T_G + QT_S$ where $Q = 1 - \varepsilon$.

The dielectric properties (both real and imaginary) of soils are strongly dependent on soil moisture content. Changes in the dielectric constant result in major changes in the emissivity and radiometric brightness temperature. Microwave temperature differences between saturated tidal mud and ocean water covering the mud were found to be about 20°K. Much larger temperature differences are noted when soils of low water content are compared to the saturated muds. Soils and sediments containing 1 to 7 percent water were found to be 120°K warmer than the saturated muds.

Flat, uniform, argillic playa sediments, where only the moisture content varied were also studied. The radiometric temperature difference between playa sediments containing twelve and thirty percent moisture content was found to be 60°K. Polarization effects also changed drastically depending on the viewing angle (angle of incidence) at which measurements were made.

These measurements demonstrate that microwave radiometric surveys can aid hydrologists in many investigations. The instruments may be particularly useful for airborne applications when hydrological studies of large tracts of land are being performed.*

Kennedy, J.M., A.T. Edgerton and R.T. Sakamoto, "Microwave Radiometric Sensing of the Physical Parameters of Snow," Western Snow Conference, Boise, Idaho, April 1967.

A field and laboratory measurements program sponsored by the

Office of Naval Research, Cambridge Research Laboratory and Cold Regions Research and Engineering Laboratory is being conducted to determine the response of microwave radiometers to various snow conditions. The field portion of the program was carried out within the confines of Crater Lake National Park, with data obtained from new fallen powder snow and old metamorphosed snow. The measurements were made at three frequencies, 13.5 GHz, 37 GHz, and 94 GHz, (one GHz = 10^9 cycles per second), with microwave temperatures recorded for both horizontal and vertical polarizations at viewing angles ranging from nadir to the local horizon. Similar laboratory measurements were made of artificial snow manufactured in an environmental chamber in which snow temperature and moisture content can be controlled.
The results of these studies show that different microwave frequencies do not behave in the same manner as the moisture content of the snow varies. This is due to the frequency dispersive properties of water in the microwave region. By making measurements with suitable combinations of frequency, polarization, and incidence angles, the melt condition of snow, and possibily the density, may be determined from a remote sensing platform. At the present time, these parameters are obtained from limited ground surveys using snow tube techniques. The measurement of these parameters from a remote sensing platform over broad areas of major water sheds would greatly aid in the management of water resources.*

Kennedy, J.M., and R.T. Sakamoto, "Passive Microwave Determinations of Snow Wetness Factors," Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, June 1966, pp. 161-173.

A mobile field unit, designed and constructed by Space-General Corporation, was utilized to measure the microwave radiometric emission characteristics of snow at 13.5 GHz and 37 GHz. Analyses of the data and theoretical considerations show that variations in free water content affect significant changes in the radiometric brightness temperatures of snow. By making measurements with suitable combinations of frequency, polarization, and incidence angles, the free water content of natural snow may be determined.*

Ketchum, R.D., V.E. Noble and D.B. Ross, "Some Aspects of Remote Sensing as Applied to Oceanography," Proceedings of the I.E.E.E., Vol. 57, No. 4, April 1969, pp. 594-605.

Limitations in the state-of-the-art of remote sensing instrumentation and restriction of experimental ground truth, imposed by the inaccessibility of the oceanographic environment, have inhibited the application of remote sensing techniques to oceanographic research and the implementation of operational environmental monitoring programs. However, preliminary experiments are demonstrating the application of infrared sensors, surface mapping radars, radar scatterometers, surface profiling lasers, passive microwave radiometers, pulsed laser depth-finding systems, and optical scanners, cameras, and television systems to the problems of sea surface temperature measurement, sea state determination, sea ice surveillance, fisheries research, and subsurface reef detection. Data obtained from recent experiments are presented herein. It is concluded that particular attention should be paid to the development of microwave sensors to obtain an all-weather capability. Intensive research programs should be established to develop techniques for interpretation of subsurface phenomena based on surface measurements. This would enable construction of three-dimensional models describing the dynamic characteristics of the ocean.*

King, J.I.F., "Deduction of Vertical Thermal Structure of a Planetary Atmosphere from a Satellite," Planetary Space Science, Vol. 7, 1961, pp. 423-436.

An inversion technique is developed for deducing the temperature stratification of a planetary atmosphere from the variation of the emission spectrum with air mass. This is a planetary application of the well-known solar limb-darkening effect. Mathematically, the emergent intensity is an integral transform of the Planckian temperature taken as a function of optical depth. The solution therefore consists in devising a scheme for inverting the transform.
Pending satellite observations, the following approach is used for the verification of the theory. Ground observations of the emission of the 9·6 μ ozone band as a function of air mass thickness have been taken. These radiative data provide information on ozone "at a distance", in a manner similar to the remote satellite viewing from above. Four sets of ozone emission data have been analysed and the vertical thermal structure of the ozonosphere deduced therefrom. A critique of the method together with future research directions is given.*

Kinsman, Frank E., "Some Fundamentals in Non-Contact Electromagnetic Sensing for Geoscience Purposes," Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, October 1964.

This paper presents some conventional and non-conventional airborne sensing techniques used for geophysical data collection. State-of-the-art and developmental types of sensors which may become standard tools of the future are described. The value of data collected in various portions of the spectrum is demonstrated and some critical problems awaiting solution are identified. Pertinent geophysical data collected by some of the newer types of sensors are also presented.*

Kreiss, W.T., "Meteorological Observations with Passive Microwave Systems," Boeing Research Laboratories Document DI-82-0692, Boeing Aircraft Company, Seattle, Washington, February 1968.

This investigation concerns the use of passive microwave systems for collecting meteorological data. It was initiated primarily for the purpose of developing new methods of acquiring useful meteorological information from weather satellites. Analysis is confined to the wavelength range 1 - 2 centimeters where a single, weak, collisionally broadened, purely rotational absorption line of the water vapor molecule is the dominant feature which permits remote sounding of the atmosphere in this wavelength range. A method of solving the equation of radiative transfer which is direct, accurate, and meaningful is developed in detail and the resulting numerical expressions are employed for computations with atmospheric models. Calculations of upward and downward viewing brightness temperatures over land and water for clear and clouded atmosphere are presented. Design details of a radiometer constructed specifically for this study and operating at 1.6 cm wavelength are described. Selected data collected with this instrument viewing upward from the ground are presented and interpreted along with selected 1.55 cm downward viewing data obtained from an extensive aircraft meteorological flight test program carried out by NASA personnel. It is concluded that absorption theory can explain many observations, that significant tropospheric measurements can be made with passive microwave systems, and that such systems can become important meteorological tools if properly exploited. A number of suggestions for continued research are presented.*

Kreiss, W.T., "The Influence of Clouds on Microwave Brightness Temperatures Viewing Downward Over Open Seas," Proceedings of the I.E.E.E., Vol. 57, No. 4, April 1969, pp. 440-446.

Microwave brightness temperatures for the case of downward viewing from above the earth's atmosphere over water for the 1- to 2-cm wavelength range are calculated for comparison with observations. A model of the troposphere which contains homogeneous layer clouds of varied thickness and liquid water content is used to compute estimates of the influence which clouds would have on real observations. It is assumed that only pure absorption is important for the cloud droplet-size distributions and droplet densities used. Results of the computations indicate that most water clouds will contribute a measurable amount to the microwave emission of the atmosphere and, in some cases, can be the principal source of received radiation. Comparisons of the computed cases with measurements obtained with a high flying aircraft are shown to be in reasonable agreement. These results are significant because they demonstrate that water clouds cannot be neglected in the application of passive microwave techniques to remote probing of the earth's atmosphere and because they indicate that quantitative measures of cloud liquid water contents and cloud thickness might be acquired through multifrequency measurements.*

Kutuza, B.G., "Investigation of Radiowave Attenuation and Radiation of Rain in the Microwave Range," Proceedings of the Thirteenth Radar Meteorological Conference, McGill University, Montreal, August 1968, pp. 540-542.

An investigation of radio attenuation and atmosphere radiation during rain was carried out by the radio astronomy method. The reception of self emission of the atmosphere at waves of 0.82, 1.6, and 3.3 cm. was fulfilled with an immobile antenna. The wavelengths of 0.41, 0.82, and 1.6 cm. were used for measurements of attenuation over radioemission of the sun. Accompanying the radiometric observations were the temperature, rain intensity and other weather parameters at the experiment station.

Ladley, A.E., "Radiometry for Ice Detection," The Engineer's Digest (U.S.C.G.), No. 154, January - March 1967.

This article is a description of the AN/AAR-33 microwave radiometer and its use in detecting targets, especially icebergs, against a saltwater background. The article discusses basic theory of operation and gives the results of several runs made over a 600' cargo ship.

LaRocca, G.A., and G.T. Chalfin, "Microwave Thermal Imaging - A Remote-Sensor Technique for Geophysical Investigations," Space-General Division, Aerojet-General Corporation, El Monte, California.

Microwave radiometry has for several years been regarded as a promising technique for obtaining data on the surface and near sub-surface properties of terrain -- particularly over wide areas and under all-weather and day-night conditions. However, only recently have instruments been available with sufficient angular and thermal resolution and a sufficiently wide field of view to be practical for these applications. Such an instrument has been constructed for the 19 GHz (15.5 mm) region of the spectrum. Imagery has been obtained of a wide variety of areas including open water, coastlines, farmland, snow-covered mountains, river valleys, deserts and cities. Certain preliminary conclusions can be drawn from the imagery that has been obtained. First, image quality through clouds is essentially the same as during clear-weather conditions. Water features are quite prominent. Lakes and rivers are nearly always seen and low areas of the terrain where water has accumulated following a rain are usually distinguishable. Snow-covered areas are readily distinguished from non-snow-covered terrain. Vegetated areas are distinguished from non-vegetated areas and urban areas have a characteristic appearance.*

Mardon, A., "Application of Microwave Radiometers to Oceanographic Measurements," Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, 1965, pp. 763-779.

The following material is intended to discuss more specific application possibilities of radiometers to oceanographic measurements. Fortunately, the experimental and analytical work already cited can be directly related to such a possibility. Parameters of specific interest to oceanographers which we are confident will be ultimately measured with radiometers include: (1) Thermometric temperature of the sea (through fog), (2) distribution of water vapor above the sea, (3) determination of the sea state and sea swell vector, (4) distribution of ice (through fog), (5) thickness of level ice over water, (6) distribution of condensed water vapor over the sea, (7) atmospheric temperature as a function of altitude.*

Marsh, H.W., "Exact Solution of Wave Scattering by Irregular Surfaces," Journal of the Acoustical Society of America, Vol. 33, No. 3, March 1961, pp. 330-333.

The problem which Lord Rayleigh considered (reflection from a corrugated surface) and which several have treated approximately in recent years, is developed in a general form. An exact solution is obtained by extensive use of Wiener's generalized harmonic analysis. This solution is readily extended to include electromagnetic waves, general elastic waves, and nonplanar, nonharmonic sources. Numerical evaluation of the formulas is considered by means of an operational representation, from which various types of successive approximations can be constructed. Applications can be of special interest in scatter communications and in underwater sound transmission and reverberation. Experimental evidence from the latter area indicates that a rather detailed theory is necessary for an adequate account of the situation.*

McAlister, E.D. and W.L. McLeish, "A Two Wavelength Microwave Radiometer for Temperature and Heat Exchange Measurements at the Sea Surface of Possible Use in Manned Satellites," Oceanography from Space, Woods Hole, Massachuetts, 1965, pp. 189-214.

A part of the experimental study program at the Applied Oceanography Group of the Scripps Institution of Oceanography is to describe the infrared radiance of the sea surface, its variation in time and space -- the noise background of the sea -- and relate it to the ocean factors producing the variation. Infrared radiometers, a sanner, and meteorological equipment installed in a DC-3 and a surface vessel for simultaneous oceanographic measurements are the essential equipment used. This paper shows that is theoretically possible to construct a two wavelength microwave radiometer that will duplicate the results of the present infrared instrument.*

Meeks, M.L., "Atmospheric Emission and Opacity at Millimeter Wavelengths Due to Oxygen," Journal of Geophysical Research, Vol. 66, No. 11, November 1961, pp. 3749-3757.

The theory of Van Vleck and Weisskopf has been used to compute the emission and opacity of the earth's atmosphere in the wavelength region from 7.5 to 3.7 mm. Equal pressure broadening was assumed for the 25 oxygen transitions which occur in this spectral region. The line-broadening parameter Δv was set equal to 600 Mc/s for $T = 300^{o}K$ and $P = 1$ atmosphere, and the temperature dependence was assumed to be proportional to $T^{-0.85}$. Digital computer calculations were made of t_o, the total zenith opacity of the atmosphere as a function of frequency v. In these computations the ARDC model atmosphere was used, and excellent agreement was found with measured values of t_o at 6-mm and 4.3-mm wavelengths. Emission was computed similarly in terms of T_o (θ), the antenna temperature contributed by oxygen for observation at a zenith angle θ. Computations were made of t_o and T_o for elevations of 0, 2.5, 3.5, 8, and 30 km above the earth in order to determine the advantages of various sites for astronomical observations in this wavelength region. The radiation from the atmosphere into space was also computed, and the oxygen lines were found to appear in emission.*

Meeks, M.L. and A.E. Lilley, "The Microwave Spectrum of Oxygen in the Earth's Atmosphere," *Journal of Geophysical Research*, Vol. 68, No. 6, March 1963, pp. 1683-1703.

Space probe techniques open the possibility of radio and microwave spectroscopic investigations of planetary atmospheres through the study of resonant transitions in gaseous constituents. Computations were undertaken to determine the opacity and the thermal emission produced by the millimeter-wavelength complex of oxygen lines in the earth's atmosphere. The calculations predict line profiles of individual oxygen transitions in emission or in absorption against the sun. Potential experimental observation heights were assumed: sea level, aircraft heights (5 and 8 km), a typical high-altitude balloon height (30 km), and earth-satellite heights. The computed spectrums are based on the Van Vleck-Weisskopf theory of oxygen absorption combined with the ARDC model atmosphere. The transfer equation for the oxygen line complex is complicated by the Zeeman splitting produced by the earth's magnetic field, but this effect is significant only in spectrums predicted for satellite observations and is neglected here. Computed values of the zenith opacity from the earth's surface are in good agreement with measurements that extend down to about 1 Gc/s. The depths of absorption lines observed against the sun are predicted to be greater by a factor of 20 than the intensity of the same lines in emission. Satellite observations of microwave brightness temperature as a function of frequency around 60 Gc/s can yield information about the vertical thermal structure of the atmosphere; this technique, undertaken with a polar satellite, offers the possibility of a global determination of the approximate vertical temperature distribution in the earth's atmosphere. The relationship between the emission spectrum and the temperature as a function of height demonstrates that the emission at a given frequency represents the average temperature in a layer of air roughly 10 km deep. The mean height of these layers depends on frequency and varies between 0 and 40 km. It may be possible to increase this height considerably by taking the Zeeman effect into account. Specifications are estimated for the aircraft, balloon, and satellite radiometric systems that would be required to undertake the research program defined in this paper.*

Merritt, E.S. and R. Wexler, "Radiometric Detection of Clear Air Turbulence," Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, October 1964, pp. 125-140.

The mesoscale nature of clear air turbulence (CAT) makes it unlikely that any technique developed from synoptic scale observations will prove generally effective to predict the occurrence of significant turbulent areas in the upper troposphere. An airborne passive detecting system is, therefore, required.
CAT often occurs in regions of strong horizontal and vertical wind shears which are associated with strong horizontal temperature gradients; the detection of these temperature gradients and turbulence-related temperature microstructure might provide the means to sense the turbulent area.
A passive airborne radiometric technique is suggested to accomplish this thermal sensing.
In the suggested technique an aircraft mounted radiometer would scan the atmosphere ahead of the aircraft. In each scan the radiant energy of the background will be sensed. In those scans when CAT-associated temperature gradients or micro-structure are occurring there may be a variation in the detected radiant energy. Sinceethe amount of radiant energy present in most spectral regions at the pressures and temperatures where CAT is a significant problem is limited, a spectral region is required which will provide detectable radiant energies within the state-of-the-art of radiometer technology. The following intervals are suggested:
(1) the 2.7 micron region, containing strong CO_2 and H_2O bands.
(2) the 6.3 micron H_2O band.
(3) the 15 micron CO_2 band.
The emissivities of a representative turbulent cell and the transmissions of the intervening atmosphere at about 35,000 ft. are evaluated in each of the suggested spectral intervals. From these evaluations, selection of an optimum spectral interval is accomplished. The selected interval will provide detectable energies within the state-of-the-art of infrared radiometric technology.*

Moore, R.K. and F.T. Ulaby, "The Radar Radiometer," Proceedings of the I.E.E.E., Vol. 57, No. 4, April 1969, pp. 587-590.

Addition of a radar to a scanning microwave radiometer is shown to be simple and to consume little power. Since both the radar and the radiometer receive signals having the statistical properties of noise, both receivers may use the Dicke synchronous detection system, provided the radar receives enough independent samples. Application of the combined instrument to spacecraft measurement both of oceanic winds and waves and of precipitation has more promise than the use of either instrument alone, since they can, in part, calibrate each other. An aircraft imaging radar radiometer has potential for applications where superposition of the thermal radiometer image on a relatively static radar image will aid in interpretation.*

Paris, J.F., "Investigations into the Applications of Passive Microwave Radiometry to Oceanographic and Meteorological Problems," Technical Papers Ninth AD HOC Spacecraft Oceanography Advisory Group, Spacecraft Oceanography Project, U.S. Naval Oceanographic Office, Washington, D.C., January 23-25, 1968.

The Spacecraft Oceanography Project (SPOC) is committed to the task of identifying spectral signatures which determine air-sea interaction and energy exchanges to establish the utility of remote sensing for gathering data of functional use to oceanographers and meteorologists. The goal of SPOC at Texas A&M University is to determine remotely sensed signatures associated with interactions between river and Gulf of Mexico water and between the atmosphere and the Gulf of Mexico. Primarily the work has been confined to the ultraviolet, visible and infrared portions of the electromagnetic spectrum. In July 1967, Dr. Huebner and the author became interested in the possibilities of passive microwave radiometry. This paper's purpose is to review the past, present and future activities at Texas A&M University in Applied Passive Microwave Radiometry.*

Paris, J.F., "Microwave Radiometry and its Application to Marine Meteorology and Oceanography," Reference No. 69-1T Department of Oceanography, Texas A&M University, College Station, Texas, January 1969.

Past developments in microwave radiometry, a discipline of remote sensing, are reviewed comprehensively to establish a continuity between microwave physics, microwave engineering, and applications to marine meteorology and oceanography. Molecular oxygen, water vapor, and liquid water absorb, emit, and scatter microwave radiation. The ocean reflects or scatters a majority of the microwave radiation incident upon its surface and emits microwave energy. The functional relationships between these interactions and the physical state of the atmosphere and hydrosphere are described in detail.
The emission of sea water is almost constant with temperature and salinity for frequencies of 8 GHz to 30 GHz, is linearly proportional to temperature for frequencies near 5.4 GHz, and is strongly dependent upon salinity for frequencies near 1 GHz. Sea foam causes the microwave emission of the sea to increase

greatly for all microwave frequencies and angles of viewing. The natural variability of water vapor in the atmosphere affects the absolute value of upwelling microwave radiation greatly for frequencies near 22.235 GHz. The attenuation and emission of the atmosphere are predictable for frequencies less than 8 GHz.
Microwave measurements near 5.4 GHz and 1 GHz may be used to survey, remotely, the temperature and salinity of coastal water. Microwave measurements near 22.235 GHz may be used to measure the precipitable water in the atmosphere.
It is recommended that (1) electric properties of sea water be measured precisely, (2) controlled environmental tests of current microwave theory be conducted, (3) the problem of the microwave emission and extinction of raining clouds over water be studied in great detail using realistic models of clouds and using the Mie theory, and (4) the emissive properties of sea foam, bubbles, and rough sea surfaces be determined through empiricism.*

Paris, J.F., "Oceanography Using Remote Sensors," Reference No. 69-2F Department of Oceanography, Texas A&M University, College Station, Texas, January 15, 1969.

In general, this study is concerned with the planning, execution, and evaluation of environmental tests of certain oceanographic and meteorological applications of multispectral remote sensors flown over portions of the Gulf of Mexico from aircraft or spacecraft. The general objective of this project was to investigate the uses of remote sensors in surveying ocean features and air-sea interactions.*

Paris, J.F., "Preliminary Results from Convair 240A Mission 50, 12 June 1967, Over Mississippi Delta Area," Reference No. 68-6T Department of Oceanography, Texas A&M University, College Station, Texas, May 3, 1968.

On June 12, 1967, Test Site 128 (Mississippi Delta) was overflown on three flights by the NASA Convair 240A aircraft equipped with multispectral sensors as a part of Mission 50. The data obtained were studied to determine their quality and scientific value. Twenty-seven percent of the color photography taken by the RC-8 metric camera was judged to be useful. Many potentially useful photographs were lost due to untimely film changes. The sediment-boundary could easily be seen in the RC-8 photography.
Data from Mission 50 has been either late in arriving at the user agency or has never arrived.

The photographs obtained by the Itek 9-lens multiband camera show serious discrepancies and do not offer any advantages over the RC-8 photography.
The Reconofax IV infrared imager is judged to be the most useful of the remote sensors used on Mission 50. Water-mass boundaries and the surface flow field could be deduced from the infrared image in the area between South Pass and Southwest Pass. Recommendations are made to conduct missions only when ground support is available, to place marker buoys at the outer ends of the radial flight lines and to set aside blocks of aircraft time for ocean studies.*

Pascalar, H.G., "Microwave Radiometric Terrain Mapping from Space Vehicles," Space-General Corporation, 'l Monte California, 1966.

The discussion in this paper is solely confined to radiometric microwave sensing. While this discussion is immediately concerned with terrain mapping, a more general perspective is achieved by initially reviewing the results of microwave radiometric sky mapping. Several examples of microwave radiometric mapping applications are also included.*

Pascalar, H.G. and R.T. Sakamoto, "Microwave Radiometric Measurements of Ice and Water," Proceedings of the Third Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, November 1965, pp. 803-812.

This paper describes an experiment of ice measurements with a passive microwave radiometer. The discussion concerns itself with measurements of ice, the equipments used, and the data obtained. In addition, the theoretical basis for the observed phenomena including both multilayer and wave dependence is given. Consideration is given to attenuation, apparent temperature and interference effects, etc. The paper also indicates the possible utility of microwave radiometry in various ice applications.*

Peake, W.H., "Interaction of Electromagnetic Waves with some Natural Surfaces," I.R.E. Transactions on Antennas and Propagation (special supplement), AP-7, December, 1959.

The problem of the interaction of electromagnetic radiation with nonuniform surfaces (terrain, roadways, etc.) is of interest for predicting the apparent temperature of radiometers or radio telescopes. In this paper, the interaction is described by the differential scattering coefficients of the surface, in terms of which one may express such parameters of the surface as the radar cross section, the absorption coefficient, the albedo, etc. By making use of the reciprocity properties of the differential scattering coefficients, Kirchhoff's radiation law is derived in its most general form, which takes account of both the angular dependence and the polarization properties of the emitted radiation. Thus, the emissivity of the surface can also be expressed in terms of the scattering coefficients. General formulas for apparent surface temperature are obtained and are used to calculate the apparent temperature of an asphalt roadway and a vegetation-covered surface. The predicted temperatures are found to be in reasonably good agreement with measurements of Britt, Tolbert and Straiton[1] at 4.3 mm wavelength.*

Peake, W.H., "The Microwave Radiometer as a Remote Sensing Instrument," Contract Number NSR-36-008-027 (NASA-CR-99102; TR-1903-8), January 17, 1969. (Abstracted: Scientific and Technical Aerospace Reports, Vol. 7, No. 5, March 1969, p. 828.)

The fundamentals of microwave radiometry are reviewed including radiation theory, antenna effects and instrument design. The parameters of a surface which control its brightness temperature at microwave frequencies are reviewed and related to other parameters whihh characterize the surface. Among these, the role of the complex dielectric constant and its dependence on moisture and ion content, and the effects of surface roughness are discussed. A number of observations of the brightness temperature of terrestrial surfaces are reviewed, interpreted on the basis of model surface properties, and considered as potential applications of the instrument as a remote sensor.*

Peake, W.H., "The Microwave Radiometer as a Remote Sensing Instrument with Applications to Geology," Notes prepared for a short course on Geologic Remote Sensing, Stanford University, December 4 - 8, 1967.

These notes, it is hoped, will provide the kind of background information that will allow the geoscientist to make more effective use of the forthcoming imagery. The first sections review the nature of thermal radiation at microwave frequencies, and the characteristics of the instrument used to measure it. We have then tried to show how the attenuation in and thermal emission from the atmosphere degrade the imagery, and how the surface roughness and dielectric constant (particularly the dielectric constant of water) determine the radiometer output. A final rather brief section is concerned with the applications of the imagery.*

Peake, W.H., R.L. Riegler and C.H. Schultz, "The Mutual Interpretation of Active and Passive Microwave Sensor Outputs," Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, April 1966, pp. 771-777.

The interpretation of surface characteristics from microwave sensor outputs alone is more effective when data is available from both active (radar) and passive (radiometer) sensors. This is because both outputs are determined by the complete scattering pattern of the surface; of which one aspect (back-scatter) is estimated by the radar and another (albedo) is estimated by the radiometer. However, because the radiometer output is the convolution of the desired radiation temperature of the surface and the antenna pattern, it is first suggested that this instrumental bias be removed (a simple "bootstrap" method is outlined).
An example is given, used to show that the correction is a significant one for current radiometer performance, and should be applied by those investigators wishing to make quantitative interpretations of apparent surface temperatures.
As examples of the interdependence of active and passive sensor outputs, and their relation to significant surface properties, results are given for two series of measurements, made almost simultaneously with radar and radiometer sensors (at 10 GHz and 35 GHz) over well controlled terrain (vegetation - Purdue Agronomy Farm Indiana; pumice - Mono Crater, California). In each case the data from one sensor is used to give a more detailed explanation of the output of the other, and the combined sensor outputs interpreted in terms of measurable surface characteristics (roughness scale, dielectric-constant, density, water content).*

Pearson, M.D. and W.T. Kreiss, "Ground-Based Microwave Radiometry for Recovery of Average Temperature Profiles of the Atmosphere," Boeing Scientific Research Laboratories Document D1-82-0781, Geo-Astrophysics Laboratory, December 1968.

Calculations and analyses are presented to demonstrate the feasibility of inverting multi-frequency brightness temperature measurements obtained with an oxygen-band radiometer to recover the average kinetic temperature profile of the atmosphere. Special attention is given to cloud effects, radiation from above the atmospheric model, radiative-transfer equation solutions, effects of radiometer measurement errors on the profile recovery accuracy, and the selection of optimum observing frequencies. Recovered temperatures could be used to calculate pressure altitudes, which for a network of ground stations would provide the pressure gradient for calculating winds aloft. Such information is required for long-term numerical weather forecasting.

This paper uses a linear analytical approach for inversion. It is based on the assumption that an average Planck radiance exists for an atmospheric layer and has associated with it an average kinetic temperature. To illustrate the method, a computer program has been used to perform inversions for thick, multi-layered models of a standard atmosphere and to demonstrate the convergence properties of the Newton-Raphson iterative method used for solving the set of nonlinear transcendental radiative transfer equations.
It has been found:
1. Accurate recoveries are possible when errors in the measured frequency dependent brightness temperature are less than 0.1^{O}K.
2. For a given atmospheric model there exist certain sets of frequencies which lead to maximum accuracy and a minimum number of iterations for recovery of the atmospheric temperature profile.
3. Clouds lead to a serious limitation in the use of any kind of inversion technique.
The results of this study provide insight into the inversion process and point out certain design criteria that must be considered in constructing a multi-channel oxygen-band radiometer for atmospheric temperature recovery.*

Porter, R.A., "Microwave Radiometric Measurements of Sea Water, Concrete and Asphalt," Raytheon Company, Space and Information Systems Division, Sudbury, Massachusetts, June 20, 1966.

Under contract to the Jet Propulsion Laboratory, the Raytheon Space and Information Systems Division has been conducting extensive microwave radiometric field measurements on a variety of homogeneous, naturally occurring materials including ocean surfaces, dry salt lake beds, quartz sand and crushed marble. These measurements have been performed at frequencies of 9.5, 16.5 and 94 GHz (wavelengths of 3.2 cm, 1.8 cm and 3.2 mm). Samples of the measured data, together with correlative information, are presented in this preliminary report. These data include the results of measurements of ocean surfaces as well as concrete and asphalt, Measurements on the latter materials were performed to provide a "calibration" check on the measurement techniques and on radiometer performance. In addition to the basic apparent temperature data,plots of the emissivities of sea water, concrete and asphalt are presented in this report. This information includes emissivities deduced from the radiometric measurements as well as those calculated from dielectric constant data.
The apparent temperature and emissivity data presented in this report is considered to be rather unique in that it stems from very carefully performed measurements under known conditions. This type of measured radiometric data has not been available

heretofore. There is every expectation that the techniques and equipment used in obtaining the data presented in this report will provide the basis for continued valuable contributions to the Earth Resources Survey Program.*

"Presentation of Basic Microwave Radiometry," Report No. SG P-6668, Space-General, A Division of Aerojet-General Corporation, El Monte, California, November 3, 1967.

These notes are intended to introduce the physical principles involved in microwave radiometric sensing. The use of the principles in designing operational systems will be discussed and illustrated by consideration of specific systems intended for aircraft and satellite applications.*

Rice, S., "Reflection of Electromagnetic Waves from Slightly Rough Surfaces," Communications on Pure and Applied Mathematics, Vol. 4, 1951, pp. 351-378.

This paper deals with reflections of plane electromagnetic waves from a surface which is assumed to be a perfect conductor, except in the last section of the paper, and is almost but not quite flat. The reflected field is determined and two special cases corresponding to horizontal polarization and vertical polarization are considered. After expressions for the components of the field are obtained, various averages are computed, in particular the average value of the reflected field which leads to an expression for reflection coefficient. In the last section of the paper the method used to study reflection from a slightly rough but perfectly conducting surface is extended to take into account the electrical properties of the reflecting medium.

Roedar, R.S., "Airborne Measurements with the AN/AAR-33 Radiometric Search Set," Sperry Microwave Electronics Company, Division of Sperry Rand Corporation, January 10, 1967.

The AN/AAR-33 Radiometric Search Set is a fully operational iceberg detection and identification system. This paper describes the characteristics and operation of the system. The uses and capabilities of the radiometer are briefly discussed.

Saunders, P.M. and C.H. Wilkons, "Precise Airborne Radiation Thermometry," Proceedings of the Fourth Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor, June 1966, pp. 815-826.

Measurements with radiation thermometers suffer from the imperfect transparency of atmospheric windows and the non-blackness of the surface. By vertical sounding the importance of atmospheric absorption and emission can be estimated: effects of up to 1°C arise at altitudes of only 1000 ft. Estimates of the energy reflected from the ocean have been made employing a statistical description of the slopes on its surface: it is shown that in the 8 - 12μ window sun glitter is unimportant and that except for a near horizon strip sky radiation reflected from its surface does not change appreciably with roughness. A normal-oblique method for interrogation of the sea surface is proposed which yields directly the magnitude of the absorption-emission and reflected energy corrections from flight level.*

Singer, S.F. and G.F. Williams Jr., "Microwave Detection of Precipitation Over the Surface of the Ocean," Symposium on Electromagnetic Sensing of the Earth from Satellites, University of Miami, 1965.

This letter is a preliminary report on the detection of precipitation over the ocean by means of passive microwave radiometry. The measurements were made from an aircraft and are part of a larger program of oceanographic remote sensing research. They are reported here because of their important implications to satellite oceanography, to tropical meteorology, and to gaging the rate and geographic distribution of sea-to-air energy transfer (Buettner, 1963).
The observations were made in October 1966 and February 1967. Although the Jet Propulsion Laboratory radiometers have four channels (Blinn, 1967), only the results at 15.8 gHz (1.9 cm) will be discussed. The aircraft, NASA 926, was at an altitude of 3 km, looking down in the Florida Straits over test site 99 (see Flight Research Projects Branch, 1966).*

Sirounian, V.A., "Effect of Temperature Angle of Observation, Salinity, and Thin Ice on the Microwave Emission of Water," Journal of Geophysical Research, Vol. 73, No. 14, July 15, 1968, pp. 4481-4486.

Numerical computations of the polarized emissivity of smooth water for various nadir angles of observation and different water temperatures, in the 0.1- to 10-cm region of the microwave spectrum, indicate that the polarization of the emitted microwave radiation of water is negligible for small angles of observation, increases with the increase of the angle of observation, and has a maximum that shifts toward larger angles for

longer wavelengths. The changes of polarized emissivity with temperature are especially strong in the 0.2- to 2-cm region and for large nadir angles of observation; however, the changes become negligible for wavelengths greater than 3 cm. Numerical computations of polarized emission of water with various salinities indicate a 4°K change of brightness temperature for an equivalent salinity change from 6.7 to 32.3 parts per thousand in the wavelength region of 10 cm. The effects are smaller at shorter wavelengths; the polarized emission also decreases with increasing angles of observation. The polarized emissivity of thin ice on top of water calculated for various angles of observation indicates a considerable change in the emissivity of water when the ice thickness is of the same order of magnitude as the wavelength of the microwave radiation. When the ice thickness is small in comparison to the wavelength, a systematic change of the polarized emissivity is observed, which suggests the possibility of determining ice thickness by airborne passive microwave radiometry.*

Staelin, D.H., "Measurements and Interpretation of the Microwave Spectrum of the Terrestrial Atmosphere Near 1-Centimeter Wavelength," Journal of Geophysical Research, Vol. 71, No. 12, June 15, 1966, pp. 2875-2881.

Solar extinction measurements of the atmospheric absorption spectrum near 1-cm wavelength were made on 10 days during 1964. The 1.35-cm water vapor resonance varied in intensity and shape, and this variation can be correlated with simultaneous radiosonde measurements. The spectrum can be interpreted theoretically in terms of the water vapor content of the atmosphere with an altitude resolution of 15 km or less. The integrated water vapor content of the troposphere can be determined with an accuracy of approximately 5%, including uncertainties in the measurements and the atmospheric model. Theoretically, the integrated liquid water content of heavy clouds can be measured simultaneously with an rms accuracy of approximately 0.004 g/cm^2, or 15%.*

Staelin, D.H., "Passive Remote Sensing at Microwave Wavelengths," Proceedings of the I.E.E.E., Vol. 57, No. 4, April 1969, pp. 427-440.

Passive remote sensing at microwave frequencies has applications which range from meteorology to oceanography and geology. The meteorological applications are the most fully developed and include measurements of the temperature profile of the atmosphere and of the atmospheric distribution of H_2O and O_3. Such measurements can be made from space or from the ground by utilizing the microwave resonances of O_2, H_2O, and O_3 which occur near 1-cm wavelength. Although infrared observations permit similar meteorological measurements, such optical devices are much more sensitive to aerosols and clouds. The small but finite nonresonant attenuation of most moderate clouds at microwave frequencies also permits their liquid water content to be estimated.

At wavelengths longer than 2 cm the microwave properties of the terrestrial surface dominate observations from space, and measurements as a function of polarization and viewing angle yield information about surface temperature and emissivity. Such measurements of the ocean should also permit the sea state to be inferred.

The review has two major parts. The first part reviews the physics of the interactions, the mathematics of data interpretation, and the instrumentation currently available. The second part is applications-oriented and emphasizes the types, accuracy, and relevance of possible meteorological measurements.*

Stogryn, A.P., "Effects of Scattering by Precipitation on Apparent Sky Temperature in the Microwave Region," Space-General Corporation, Report No. SGC 613TM-1, September 1964.

It is the purpose of this paper to evaluate the influence of scattering by precipitation on sky temperature for some representative cases.

In Section 2 of this report, the basic equations taking scattering and polarization effects into account are formulated. This is followed in Section 3 by a discussion of the various cross-sections and parameters which occur in the transfer equations. Representative weather conditions are considered in Section 4. A method for solving the transfer equations numerically is discussed in Section 5. Results are given in Section 6.*

Stogryn, A.P., "Electromagnetic Scattering from Rough, Finitely Conducting Surfaces," Radio Science, Vol. 2, No. 4, April 1967, pp. 415-428.

The problem of electromagnetic scattering from a statistically rough surface bounding a uniform, finitely conducting medium of infinite extent is treated in the Kirchhoff approximation. Both intensity and polarization of the scattered wave is considered. Explicit formulas are obtained for the special case of a normally distributed surface. Comparison is made with previous results obtained by other authors under the assumption of infinite conductivity.*

Stogryn, A.P., "The Apparent Temperature of the Sea at Microwave Frequencies, Part II," Space-General Corporation, El Monte, California, December 21, 1966.

A study is made of the effect of atmospheric conditions on the apparent temperature of the radiation emitted by the sea in the frequency range 11-30 KMC. It is found that, for clear sky conditions, the only variable which significantly effects the temperature is the total water vapor content of the atmosphere. If clouds are present, the apparent temperature also depends on the cloud water droplet content and, to a lesser extent, on the ambient air temperature and cloud structure.*

Stogryn, A.P., "The Determination of Synoptic Weather Data by Use of Satellite Mounted Radiometers," Space-General Division, Aerojet-General Corporation, August 1, 1967.

A computer study of the feasibility of determining atmospheric conditions from an analysis of microwave radiometric data obtained from a satellite is made. A detailed consideration of an eight frequency experiment with simulated experimental errors of the order of 1-2^{o}K in the "measured" data has shown that useful determinations can be made of the atmospheric water vapor and cloud water droplet content with no a priori assumptions concerning atmospheric conditions. Air temperature profiles have also been derived from an analysis of the data. Although good results have been obtained under some conditions, some combinations of errors in the "measured" radiometric temperatures can lead to predictions of air temperatures which are not adequate for use in weather forecasting. It is believed that the quality of the air temperature predictions can be significantly improved by a systematic optimization procedure in the analysis.*

Stogryn, A.P., "The Apparent Temperature of the Sea at Microwave Frequencies," I.E.E.E. Transactions on Antennas and Propagation, Vol. AP-15, No. 2, March 1967, pp. 278-286.

A discussion of the apparent temperature of the sea at microwave frequencies is presented using a theory based on the Kirchhoff approximation for scattering from rough, finitely conducting surfaces. Detailed numerical results on the variation of the temperature with wind speed are discussed for a frequency of 19.4 GHz. The dependence of the rms slope of the sea on wind speed, which is needed in the theory, is based on experimental measurements. It is found that significant temperature changes occur with increasing wind speed for horizontally polarized radiation. The temperature of vertically polarized radiation is much less affected by the wind and, at an angle of 50° (at 19.4 GHz), is almost independent of the state of the sea.*

Stogryn, A., "The Brightness Temperature of a Vertically Structured Medium," Space Division, Aerojet General Corporation, El Monte, California, March 27, 1969.

Exact equations are derived for calculating the brightness temperature of a medium which is bounded by a plane surface and whose properties (dielectric constant and thermometric temperature) vary only with depth. Although no approximations are made in the development of the principal results, the final equations are presented in a form most convenient for use in the area of microwave radiometry - that is, in the limit where the Rayleigh-Jeans approximation to the Planck black body radiation law is valid.
Some special cases in which the differential equations arising in the theory can be solved analytically are presented as examples. A practical numerical method for evaluating the exact equations by use of a digital computer is also discussed.*

Straiton, A.W., C.W. Tolbert and C.O. Britt, "Apparent Temperatures of some Terrestial Materials and the Sun at 4.3-Millimeter Wavelengths," Journal of Applied Physics, Vol. 29, No. 5, May 1958, pp. 776-782.

This paper describes a 4.3-mm radiometer and measurements made with it of the apparent temperature of various terrestrial materials, the attenuation through the atmosphere and the temperature of the sun. Materials whose apparent temperatures were measured included water, wood, metal, grass, asphalt, gravel and asbestos. Since their apparent temperatures are dependent upon their reflectivity, these data are interpreted in terms of the background reflected by the materials. The attenuation vertically through a clear sky ranged between 1.6 and 2.3 db. The sun, of optical disk size, was found to be between 10^4 and 1.2×10^4 °K on May 3 and June 17, 1957.*

Strum, P.D., "A Note on Noise Temperature," I.R.E. Transactions on Microwave Theory and Techniques, Vol. MTT-4, July 1956, pp. 145-151.

The effective noise temperature of the output impedance of a lossy passive network at an arbitrary noise temperature connected to one or more resistive loads at arbitrary noise temperature set between the highest and the lowest of these noise temperatures, is determined by the losses between the output terminals and the loads. The determination of the effective noise temperature of a gas-discharge noise generator over a wide frequency range is simplified by the substitution of a loss measurement for the more difficult noise temperature measurement. For minimum-noise radar applications this must be used in considering the excess noise of crystal mixers for gas-discharge duplexers. The influence of galactic radiation on a receiving system is such that there is an optimum frequency in the region of 200 to 600 mc for minimum "operating noise figure." Typical examples of radio-astronomy measurements are amenable to analysis of the type given. Finally, several corrections to measured noise figure are analyzed.*

Strum, P.D., "Considerations in High-Sensitivity Microwave Radiometry," Proceedings of the I.R.E., Vol. 46, No. 1, January 1958, pp. 43-53.

This paper discusses considerations in high-sensitivity microwave radiometry, especially as applied to systems having temperature thresholds significantly less than 1°K. Many considerations that have been ignored in previous analyses are shown to be prominent. The influences of the background radiation from space, atmospheric oxygen, atmospheric water vapor, and earth-bound radiators are shown to set a threshold level. Fluctuations in gain and temperature of the antenna, the waveguide system, the comparison source, the noise balancer, the receiver, and other amplifying components are shown to set another threshold. Impedance-modulation effects set still another threshold. The intrinsic internal receiver noise establishes an irreducible threshold. Continuous nonswitched types of radiometers usually are not suited for high-sensitivity applications because the present state of the art in gain stability is not adequate. The square-wave switched system is most likely to yield satisfactory results. In these systems the optimum performance is obtained when the magnitude of the signal within the system is minimized at approximately the level at which measurements will be made. This result establishes the requirement for noise balancing which may be either continuously adjusted or adjusted once for each measurement.*

"Useful Applications of Earth-Oriented Satellites," (Prepared by Panel Six of the Summer Study on Space Applications, Division of Engineering, NASA.) National Academy of Sciences, Washington, D.C., 1969.

This report constitutes the National Academy of Sciences study for NASA on the future usefulness of Earth-oriented satellites. The main emphasis is in the area of sensor techniques. This area covers radar, television, photography, radiometry and lasers. Data systems and data processing is also discussed somewhat, Several appendixes cover specific topics in the sensor and data areas.

Wark, D.Q., "On Indirect Temperature Soundings of the Stratosphere from Satellites," Journal of Geophysical Research, Vol. 66, No. 1, 1961, pp. 71-82.

Outgoing radiation from the atmosphere is calculated at several frequencies in the 15-μ carbon dioxide band according to the random Elsasser band model and the Curtis-Godson approximation to the mean line width. From the resulting values, an inversion of the problem is performed, with simplifying assumptions, to recover the temperature structure of the upper part of the atmosphere. This abbreviation of the experiment proposed by Kaplan would yield the temperatures and the lapse rates in two layers of the atmosphere from three measurements of the outgoing radiation. Results from three model atmospheres indicate that calculated mean lapse rates and mean temperatures in the two layers, as they might be deduced from measurements made from a satellite, are in good agreement with actual temperature structures.*

Weger, E., "Apparent Sky Temperatures in the Microwave Region," Journal of Meteorology, Vol. 17, April 1960, pp. 159-165.

The problem of atmospheric radiation over narrow bands in the microwave region is considered. Equations for the radiation received at a point on the earth's surface for a particular angle of observation, and also for the integrated average over the whole sky, are presented. For convenience, the results are expressed as "apparent sky temperatures" - the comparison being a black body. The dependence of the sky temperatures on wavelength and weather conditions is brought out by a discussion of the absorption of radiation by oxygen, water vapor and condensed water droplets. Calculated sky temperature data are presented for three typical weather conditions at wavelengths of 0.30, 0.43, 0.86, 1.25, 1.80 and 3.00 cm. The causes of the wide range of temperatures encountered at these wavelengths for various sky conditions are discussed.*

Weger, E., "Apparent Thermal Noise Temperatures in the Microwave Region," I.R.E. Transactions on Antennas and Propagation, Vol. AP-8, No. 2, March 1960, pp. 213-217.

The necessary equations are presented for obtaining the noise temperature due to thermal radiation which would be sensed by a receiver with an antenna located at some altitude above the earth. Emission and absorption of radiation by the atmosphere is considered. Calculated over-all absorptivities and apparent atmospheric temperatures are given as a function of antenna observation angle for beam paths through the atmosphere. Six wavelengths in the microwave band and three types of weather conditions were chosen for the calculations. Some typical antenna temperatures are presented as examples of the magnitudes of the effects to be expected as a function of the type of surface being viewed, the weather, and polarization.*

Wells, D.R., "The Apparent Temperature of the Ocean at Microwave Frequencies," Space-General Corporation, El Monte, California, January 17, 1967.

A method is developed for measuring the state-of-the-sea using microwave radiometry from a remote platform. Computations for various illustrative cases indicate feasibility in the region of 19 GHz.*

Williams, G.F., "Microwave Radiometry of the Ocean," Technical Papers, Ninth AD HOC Spacecraft Oceanography Advisory Group, Spacecraft Oceanography Project, U.S. Naval Oceanographic Office, Washington, D.C., January 23-25, 1968.

This work is directed at exploring the feasibility of microwave radiometry for determining from spacecraft such sea-surface and atmospheric parameters as sea state, surface wind velocity, and rainfall. Potential advantages of the microwave region include capability in light or in darkness and (at the longer wavelengths) penetration of the densest cloud cover; response to rainfall can be governed by selection of wavelength.
Early flight experience was obtained from a rather primitive radiometer flown over the ocean in a Goodyear blimp. Large apparent temperature changes were noted in passage over a white-capped wave and over the wake of a high-speed boat. Work has continued under Navy/NASA SPOC sponsorship, using data from four radiometers (9.4, 15.8, 22.2, and 34 Ghz) mounted in a NASA Earth Resource aircraft; effects of rainfall have been delineated, but rough-sea measurements have not been made due to a crowded aircraft schedule and absense of timely high seas in the near-by area.
Data from an imaging radiometer in a U.S. Coast Guard aircraft showed several lines of surf off a North Carolina beach, supporting early indications of response to foam. This was studied further by parking the NASA aircraft over a wading pool, and recording radiometer response to an artifically generated layer of foam. First-order analyses of the results are compared with relations between sea foam and local wind velocity derived earlier by Munk and Blanchard, and with some U.S. Navy aerial photos; it appears that the percentage of the sea covered by foam will be a function of the local wind field and, under some conditions, of sea state.
It may eventually be possible to determine wind speeds of > 15 knots to an accuracy of a few knots from satellite-mounted microwave radiometers; wind-direction determination may be possible from, say, assymmetries when looking at angles from the vertical. Data obtained at two or more frequencies should permit separation of the effects on apparent temperature of rainfall and sea roughness. The above possibilities lead to the need for an extensive measurement program and associated analyses to understand the physical meaning of the results.*

Wulfsberg, K.N., "Apparent Sky Temperatures at Millimeter Wave Frequencies," Physical Sciences Research Papers, No. 38, Air Force Cambridge Research Papers, No. 38, Air Force Cambridge Research Laboratories, U.S.A.F., Hanscom Field, Massachusetts, July 1964.

Measurements of apparent sky temperatures taken over a one-year period at 15, 17 and 35 Gc are summarized. Sky temperature profiles for various meteorological conditions are presented as well as curves showing the percentage time distributions for various zenith angles. Such factors as absorption and radiation by oxygen and water vapor, extrapolation of the data to other geographical areas, and the relation between total attenuation of the atmosphere and sky temperature are discussed. A description of the radiometers and the calibration techniques are included.*

Wulfsberg, K.N., "Sky Noise Measurements at Millimeter Wavelengths," Proceedings of the I.E.E.E., Vol. 52, No. 3, March 1964, pp. 321-322.

This article discusses sky noise measurement which is a result of water vapor and oxygen, in the absence of precipitation, in the X band. A plot of percentage time distributions of sky noise statistics for the months of February through July for various antenna elevation positions at 15 to 35 Gc for climates comparable to the Boston area is included.

Yamamoto, G., "Numerical Method for Estimating the Stratospheric Temperature Distribution from Satellite Measurements in the CO_2 Band," Journal of Meteorology, Vol. 18, October 1961, pp. 581-588.

Based on Kaplan's idea that the temperature structure of the upper atmosphere may be inferred from satellite measurements, new methods of estimating the temperature distribution are presented and sample calculations are made assuming observations in four intervals of the 15-micron CO_2 band.*

SYSTEMS INFORMATION PUBLICATIONS

"Earth Resources Aircraft Program Flight Requirements," Science and Applications Directorate, Earth Resources Division, Manned Spacecraft Center, Houston, Texas.

The purpose of this document is to indicate the capabilities of the NASA-MSC earth resources aircraft and to serve as the official document for specifying the flight requirements for test sites scheduled to be overflown.*

"Instructions for Multifrequency Airborne Microwave Radiometer System, Vol. I - III," Aerojet General Report No. 9088 M-1, El Monte, California, March 1969.

This manual gives the information about the Microwave Radiometer System and its design theory, maintenance and detailed operation. The overall system and its operation is presented in Volume I. Information pertaining to the overall maintenance of the system with specific consideration given to bench check procedures, installation instructions, maintenance and trouble shooting, calibration curves, as well as a parts list, is given in Volume II entitled "System Maintenance". Information pertaining to the detailed operation of the system, including procedures, special instructions and calibration curves may be found in Volume III entitled "Operation". Engineering drawings and schematics, wire lists and an illustrated parts breakdown are also included in this volume.*

PAPERS ON MICROWAVE ABSORPTION AND ATTENUATION IN THE EARTH'S ATMOSPHERE

Anderson, L.J., J.P. Day, C.H. Freres and A. Stokes, "Attenuation of 1.25-Centimeter Radiation through Rain," Proceedings of the I.R.E., Vol. 35, No. 4, April 1947, pp. 351-354.

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