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MICROWAVE RADIOMETRY FOR SURVEILLANCE FROM SPACECRAFT AND AIRCRAFT

by

A.W. Adey

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(Radio Research Directorate)

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ABSTRACT

The report reviews the status of current airborne and satellite remote-sensing programmes based on microwave radiometers. It provides details of instrumentation capabilities and limitations and outlines some research areas and problems where these devices appear to have application.

A bibliography is included.

1. INTRODUCTION

The primary aim of this report is to draw the microwave radiometer, in the role of a remote-sensing device, to the attention of those concerned with surveys of the earth and near-earth environment. The method adopted has been to identify a number of major application areas and to provide information on some primary sources of published literature. While the review should not be considered to be exhaustive in depth or scope of coverage, it should still comprise a very useful statement of the status of an important and rapidly-developing area of remote-sensing activity and should serve as a broad basis for any planned more-comprehensive and detailed study.

Radiometers operating in the microwave region of the frequency spectrum possess a number of inherent advantages as remote-sensing devices. They can function during periods of darkness and, if the frequencies are chosen appropriately, can operate through meteorological obscurants and precipitation such as fog, snow and rain, and can be used to study the sub-surface properties of structures and terrain.

Angular resolution is inferior to that normally obtained in the case of sensors operating in the visible and IR parts of the frequency spectrum because of limitations in terms of the maximum practical antenna dimensions at the longer wavelengths.

This report first presents a short discussion of some basic principles of radiometry. A number of general radiometer design factors based on those principles then follow. The report continues with a review of the status of current airborne and satellite remote-sensing programmes based on microwave radiometers. It provides details of instrumentation capabilities and limitations and outlines some research areas and problems where these devices appear to have application.

The final section comprises a bibliography. In the choice of the references the emphasis has been on details of programmes, applications, operational factors and results, rather than on specific hardware.

2. GENERAL RADIOMETRY PRINCIPLES*

All matter radiates electromagnetic energy. The microwave radiometer combines a sensitive receiver and a directive antenna designed to accept that energy contained in a certain range of frequencies and from a specific set of directions as determined by the characteristics of the antenna. By Kirchoff's law a body in thermal equilibrium emits or radiates energy at the same rate as that at which it absorbs energy. A 'black' body, or one which is perfectly absorbing (i.e. all the energy incident on it is absorbed) radiates as a function of frequency in accordance with the following relation -

$$P_\lambda = \frac{c\psi_\lambda \Delta\lambda}{4\pi} \qquad \text{.....(1)}$$

where P_λ is the power (in watts) emitted, in the wavelength range $\Delta\lambda$ meters about the wavelength λ, per steradian per square meter of surface area; c is the velocity of light in meters per second and ψ_λ expresses Planck's radiation law -

$$\psi_\lambda = \frac{8\pi ch}{\lambda^5[\exp(ch/\lambda kT)-1]} \qquad \text{.....(2)}$$

where k is Boltzmann's Constant, h is Planck's Constant and T is the temperature of the body in °K.

The curve of radiation intensity vs. wavelength for any temperature has a maximum at a wavelength λ_m given by the Wien relation -

$$\lambda_m T = 0.00294 \text{ meter degrees} \qquad \text{.....(3)}$$

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* The references listed on p. 14 are especially useful in providing background to this section.

For the relatively-long wavelengths exploited in microwave radiometry, and except when extremely-low temperatures are involved,

$$\frac{ch}{\lambda k} << T$$

An approximation of the series expansion of the right side of (2) is then given by the Rayleigh-Jeans equation -

$$\psi_\lambda = \frac{8\pi kT}{\lambda^4} \quad .....(4)$$

Then (1) becomes -

$$P_\lambda = \frac{2\ kT\ c\ \Delta\lambda}{\lambda^4} \quad .....(5)$$

By use of the standard relations for the effective area and the power gain ($G(\theta,\phi)$) of an antenna, (5) can be transformed to give -

$$P = \frac{kt\ \Delta f}{4\pi} \int_\Omega G(\theta,\phi)\ d\Omega \quad .....(6)$$

for the power in watts (in the frequency interval Δf) received by an antenna, from a source at temperature T and subtending an angle Ω at the antenna. This is seen to be independent of frequency except for the frequency - dependence of G.

Three special cases of the general situation covered by (6) can be recognized -

(a) If the source is much smaller than the main beam of the antenna, so that the gain is essentially constant over the solid angle Ω, equation (6) reduces to -

$$P = kT\ \Delta f\ G\Omega \quad .....(7)$$

(b) If the source completely encloses the antenna, (6) becomes -

$$P = kT\ \Delta f \quad .....(8)$$

When the antenna has high gain, so that the beam is confined almost entirely to a small solid angle about the forward direction, (8) holds as long as the angle subtended at the antenna by the source is two or three times that of the main beam.

(c) When the angle subtended by the source is comparable to that of the beam, the antenna is less efficient than in (8), and (6) becomes -

$$P = E\,kT\,\Delta f \qquad .....(9)$$

where E is of the order of 0.5 for a tapered-feed paraboloid antenna. It is seen that the received energy is independent of the gain of the antenna for the cases given by (b) and (c).

Thus far we have considered only "black" bodies. Most bodies are not perfect absorbers, and for them the right-hand side of all the above relations must be multiplied by the factor η, an overall emission factor, which is a function of not only the material of the body but also the boundary geometry, and is always less than unity.

If energy is incident on a body, then by the principle of the conservation of energy the material emissivity, e, is given by -

$$e = P_\alpha = 1 - P_r - P_t \qquad .....(10)$$

where P_α = the fraction of energy absorbed (absorption coefficient)

P_r = the fraction of energy reflected (reflection coefficient)

P_t = the fraction of energy transmitted (transmission coefficient).

The absorbing (and emitting) properties of a medium are a volume, or bulk, phenomenon, while the reflection from the medium depends on both the bulk properties and the state of the surface. For a diffuse medium such as the atmosphere (or one for which there is impedance matching at the boundary), $P_r = 0$, and -

$$P_\alpha = 1 - P_t \qquad .....(11)$$

For such a medium, with an attenuation constant α and a thickness ℓ,

$$P_\alpha = 1 - e^{-2\alpha\ell} \qquad .....(12)$$

Similarly, for a semi-infinite medium such as the earth, for which all the incident power is either reflected or absorbed, $P_t = 0$, and

$$P_\alpha = 1 - P_r \qquad .....(13)$$

From the relations (8) and (10) - (13) we can now determine the energy received in the bandwidth Δf from a source that fills the antenna pattern, when an absorbing medium that also fills the antenna pattern lies between the source and the antenna.

If the absorption coefficient and temperature of the source are $P_{\alpha 1}$ and T_1 and of the absorbing medium are $P_{\alpha 2}$ and T_2, the energy emitted by the source into the acceptance angle of the main beam of the antenna is -

$$P_1 = kP_{\alpha 1} T_1 \Delta f \qquad .....(14)$$

where k is Boltzmann's Constant. After passage of the wave through the absorbing medium (e.g. the atmosphere, so that $P_r = 0$),

$$P_1 = kP_{\alpha 1} (1 - P_{\alpha 2}) T_1 \Delta f \qquad .....(14b)$$

The absorbing medium itself radiates (into the same solid angle as that appropriate to (14)) the energy -

$$P_2 = k P_{\alpha 2} T_2 \Delta f \qquad .....(15)$$

The total energy received by the antenna is thus given by -

$$P_R = P_1 + P_2 = k\Delta f [P_{\alpha 1} (1 - P_{\alpha 2}) T_1 + P_{\alpha 2} T_2] \qquad .....(16)$$

Corrections have to be made if the absorbing medium has reflecting surfaces or if either the source or the absorbing medium does not fill the antenna pattern.

The discussion on which Equations (10) - (16) are based can be used to determine the effect of other lossy instrumentation components, such as transmission lines, attenuators, etc.

For convenience, it is customary to express the received power in units of temperature and to designate it as the antenna temperature. Thus in equation (8) the temperature would be -

$$T_B = T = \frac{P}{k\Delta F} \qquad .....(17)$$

for a 'black' body, and -

$$T_B = \eta T = \frac{P}{k\Delta f} \qquad .....(18)$$

for a "non-black", or "grey" body. T_B is the brightness temperature, or antenna temperature. It is the temperature that a "black" body would have in order to radiate the same power as the "grey" body.

In practice, an antenna will have side and back lobes, and one must therefore be prepared to correct experimental data for known spurious background radiation, such as certain types of sky noise, and to accept possible intermittent interference.

Interfering or spurious background noise is made up of five factors. These are as follows -

(1) A nominally steady background of galactic noise with a dependence on direction and with a spectrum that decreases in intensity with frequency. The levels at 200 MHz and 1500 MHz are approximately 100°K and 10°K respectively.

(2) Noise from discrete sources, such as the sun and radio stars. The noise can be thermal or non-thermal and, particularly in the case of the sun, the level can vary with time.

(3) Noise due to atmospheric components such as rain, snow, water vapour and oxygen.

(4) Ionospheric noise, including the aurora.

(5) Manmade interference which is seldom predictable and can vary over wide ranges in level and frequency. It is often of paramount importance in choosing a measuring site.

3. RADIOMETER DESIGN FACTORS

Microwave radiometers possess certain inherent advantages in surveillance. These include (a) enhanced ability (over devices operating in the visible and IR parts of the frequency spectrum) to operate through meteorological obscurants such as clouds, fog, snow and rain, (b) operation through darkness, (c) capability of providing information on sub-surface characteristics, (d) passive operation and (e) lower power consumption (no transmitter required). The emission factor of terrain and other targets is generally dependent on frequency, angle of incidence, polarization and surface geometry and structure, providing the designer and operator with additional degrees of freedom for the detection of, and discrimination among, various targets, and in the interpretation of data. However, certain of these advantages can be exploited only by careful selection of frequencies. In the same manner, ambiguities in the interpretation of data can be eliminated or minimized. In general, frequencies should be as low in the microwave range as possible to minimize absorption and scattering by the atmospheric components. It is also necessary to avoid the resonance frequencies of water vapour and oxygen (i.e. 22 and 60 GHz respectively), unless one is specifically attempting to measure or identify these components. For lower frequencies, limitations are imposed by the large antennas required for adequate angular resolution and by the increased levels of galactic noise. One chooses frequencies, whenever possible, in the radio astronomy bands, where interference from extraneous operations is likely to be a minimum.

Two further factors involved in the choice of frequencies when designing a radiometer for a particular application should be stressed. First, if one wishes to interpret radiometric data in terms of the sub-surface properties of a medium, the electric and magnetic properties of the medium must be considered when the frequencies are being chosen. The reason for this is that the received radiation will, in most cases, contain information about the sub-surface regions only if the radiation from those regions can penetrate to the surface with sufficiently low attenuation to be detected by the radiometer. The correct choice of frequencies implies that the electromagnetic properties of the medium, particularly of the absorption coefficient, are adequately known. Secondly, determination of a particular property or characteristic of a terrain or body is enhanced if data on a number of appropriately-spaced frequencies are available. This is particularly true if there are other properties which influence the radiation but whose values are known only approximately.

The design of the antenna involves a number of factors that are important in both the gathering and the interpretation of radiometric data. The design must always represent a compromise between the weight and volume constraints imposed by the vehicle carrying the antenna and the requirements for sufficient gain to provide the necessary angular resolution. The level of the side and back lobes must be made as low as practicable to reduce the power received from extraneous sources such as the sun. In some cases measurements may have to be corrected for interference from these extraneous sources.

Even with the antenna pointed vertically downward there will be some reception at oblique angles. The magnitude of this extraneous power will depend on the beamwidth and the polarization of the antenna, the variation of the transmission coefficient of the material-air interface with angle of incidence and polarization and the propagation properties of the terrain material itself.

As examples of frequency considerations, a moderate rain that would result in an attenuation of 5 - 10 db/km at 30 GHz would produce an attenuation of only 0.01 db/km at 3 GHz. For a heavy fog the corresponding losses might be 1 and 0.01 db/km respectively. Furthermore, both the depth in a given lossy material or structure from which emissions can be effectively monitored, and the antenna dimension required for a specified angular resolution, show an approximately inverse dependence on frequency.

A potentially-useful concept that warrants more-extensive investigation is that of integrating the radar and the radiometer into a single remote-sensing system. Each device has advantages that can complement the other. Thus, the radar can provide range information, while the radiometer can take advantage of the wide range of emission factors of terrestrial materials to aid in detection and identification. Applications include precipitation studies in meteorology and studies of targets against a water background, particularly under conditions of high sea state. Some specific possible applications are suggested in Section 6.

Radiometers are normally operated in the single-antenna and single-receiver mode. However, other configurations, such as interferometers and various forms of correlation radiometers, have proved to be powerful devices in the field of radio astronomy in studying the direction, extent and movement of radiating sources and of the existence, movement and the reflecting and scattering properties of bodies in the source-earth space. Related applications have been exploited in ionospheric physics. The potential of such special radiometer configurations should be examined, for possible application in surveillance and other terrain and atmospheric remote-sensing investigations.

4. SATELLITE INSTRUMENTATION

The U.S. has not yet flown an unclassified spacecraft microwave radiometer for Earth studies, although a 2-channel set operating at 1.35 and 1.90 cms. was flown on Mariner II in a Venus flyby in the early 1960's. Extensive operations have, however, been conducted on the ground and from aircraft. The USSR started their satellite operations in November 1968, with a 4-channel system on Cosmos 243. The wavelengths are 0.8, 1.35, 3.4 and 8.5 cms. Sensitivities are 2 K° at 0.8 and 1.35 cms. and 0.7 k° at 3.4 and 8.5 cms. Antenna beamwidths are 9 degrees at 8.5 cms. and 3.5 degrees at the other wavelengths. The orbit is inclined at 71.3 degrees, with major and minor axes of 319 and 210 Km, respectively.

It is not planned to include a microwave radiometer in either the ERTS A or B satellites. They are both terrain-oriented. ERTS E and F, however, which are oceanographic-oriented and scheduled for the mid-70's, will employ mainly microwave and visible-optics instrumentation. An L-band radiometer is planned for the first SKYLAB, scheduled for the 1973-74 period. A 1.55 cm. scanning radiometer, which has been flown extensively for several years in an aircraft programme (primarily in an oceanographic role), is being considered for a NIMBUS installation. The prototype of a 5-channel microwave spectrometer, scheduled for installation in NIMBUS E, has been undergoing aircraft flight tests. It operates at frequencies of 22.2, 31.4, 53.7, 54.9 and 58.8 GHz and is designed to determine atmospheric temperature and water content.

5. AIRCRAFT INSTRUMENTATION

Both the US and the USSR have had extensive programs using airborne and ground-based radiometers and, from the published results and from theoretical considerations, a fairly good understanding of the limitations and potential is becoming established.

The main US aircraft program is now based on a series of multi-frequency radiometers with wavelengths covering the range 0.31 - 21.2 cms. The NASA P3A and CONVAIR 990 are the main sensor aircraft. The projects are designed to gather basic ground (or near-ground) data and to test and evaluate equipment and techniques. Radiometer operation is being extended to still lower and higher frequencies. The lowest frequencies in current use are still too high to permit significant penetration of lossy materials such as sea ice. Polarization flexibility and scanning capability are incorporated in some of the current radiometers.

The USSR have reported research results from several comprehensive aircraft programs (including a 4-channel radiometer on 0.8, 1.35, 1.6 and 3.2 cms and another on 3, 10 and 30 cms). The aircraft is an Il-18 with measurement altitudes reported up to 30,000 ft. The former studies included determination of precipitation cells, thick cloud cover, water surface temperature - in the Baltic and Caspian Seas and in Lake Ladoga -, terrain material emissivities and the distribution of ice cover. The latter equipment was used mainly for lake and sea-ice studies, with thicknesses up to 2 meters. Sensitivities were in the range 1 - 2 K°.

6. ENVIRONMENTAL STUDIES

This section will provide details of microwave radiometric studies of a number of important parameters of the environment. These illustrate the state of development, the limitations and the wide range of application of the technique and suggest both areas for further exploitation and those where operational and interpretation difficulties justify increased research and development effort.

Environmental parameters being studied include -

6.1 SEA STATE

One attempts to interpret the radiometer data in terms of sea state and then to infer wind speed. The measurement is based on the increase in brightness temperature with sea roughness or sea state (a temperature change of the order of 1 K° per knot change in wind speed). There are a number of complicating factors that require further clarification before data can be properly interpreted -

(1) Clouds can cause a brightness temperature rise equivalent to that of a rough sea (e.g., 30 - 50 K°).

(2) Foam and spray on rough seas can cause spurious rises in brightness temperature. The error due to a specific area of foam is determined by the angular resolution of the radiometer antenna.

(3) The brightness temperature rise is sensitive to not only the sea state but also the spectra of the waves (i.e., to the fetch or to the presence of shoals, small islands, etc.).

When one is designing a radiometer experiment to determine sea state, there are some precautions to be taken, and phenomena that can be exploited. They include -

(a) Frequencies should be chosen outside of those ranges where brightness temperature is sensitive to changes in ocean temperature and salinity (i.e., frequencies in the region of 5 GHz and 1 GHz are to be avoided).

(b) Measurements should be made at as many frequencies as possible, and preferably at both orthogonal polarizations, to take advantage of the dispersive and polarization characteristics of the emitting medium as an aid in the interpretation of data.

(c) Vertically polarized emissions are relatively insensitive to sea state changes for incidence angles near 40°.

(d) Horizontally polarized emissions are sensitive to changes in sea state and incidence angle, but not to ocean temperature.

(e) Foam and atmospheric losses are not polarization-sensitive.

6.2 OIL POLLUTION

Laboratory measurements have been made at wavelengths of 0.8 and 2.2 cms, on a variety of oil types. The shorter wavelength was more sensitive to the presence of a surface oil film. Films of the order of 0.1 mm thickness could be detected at a wavelength of 0.8 cm. Measurements were made at sea at 0.8 cm wavelength. The oil signature (the effect on the antenna temperature of the presence of the oil) appeared to intensify with higher sea states. Time of day and aging did not affect the oil-to-water contrast. All the types tested, except gasoline which is essentially transparent at these frequencies, gave a positive brightness temperature signature (an increase).

More experience is needed to assess the technique, particularly with regard to the effect of wavelength, sea roughness, aging and film thickness. A 0.3 cm radiometer for this application is under development in the USA, since the preliminary measurements suggest that still shorter wavelengths might be more appropriate.

6.3 SURFACE TEMPERATURE AND MAPPING

Microwaves have potential advantages for this role, not so much for determining the thermometric temperature, as for discriminating among surface materials on the basis of varying emission factors and sensitivities to polarization. In principle, ocean surface temperature can be determined if a proper choice of frequency is made, but variations in apparent temperature can be masked by a number of other effects, such as foam, clouds, sea roughness, etc.

Terrain materials vary widely in emission factor, and some discrimination and identification is possible from temperature anomalies, given sufficient background emission data. Grain size is a characteristic of materials that affects the brightness temperature and therefore could be used as a basis for discrimination among materials, such as, for example, sand and gravel, etc. Surface roughness is another relevant characteristic, somewhat related to graininess, with smoother surfaces (such as roads) appearing colder than rougher areas (grass fields, shrubbery, rough hillsides, etc.). The sensitivity of brightness temperature to both grain size and surface roughness is accentuated for the shorter wavelengths. Some interesting results, with good spatial resolution, have been obtained with a 3 mm. scanner for terrestrial targets such as cars, roads, etc. Good penetration of 900 feet of fog, which obscured the view in the visible and IR regions, was achieved.

The mapping of snow cover is an important potential application area that has received very little attention. The measured characteristics include the density, water content and graininess of the snow. Some analytical work has been done on the microwave emission from metallic structures covered by layers of snow, soils, etc., and some field data have been obtained, mainly from ground-based measurements.

Theoretical studies suggest that the radiation from ocean surfaces in the VHF-UHF bands should be sensitive to the water salinity and relatively insensitive to water temperature. There has been some experimental verification of the prediction from 1.4 GHz data. But the experiments should be extended to lower frequencies.

6.4 ICE MAPPING

This role is an attractive one for a microwave device, on an essentially day-night and all-weather basis. A sea ice-water boundary exhibits a significant emissivity change, such that a brightness temperature change of the order of 100 K° is expected at the boundary for a measurement at 15 GHz. A very thin sea-ice sheet (a few mm thick) shows this behaviour for the shorter wavelengths (approximately 1 - 2 cm). Such short wavelengths have very little potential for measuring the thickness of sea ice, although they are useful for the measurement of the thickness of relatively transparent, fresh-water ice. Operation at lower frequencies (of the order of 300 - 1000 MHz) is necessary if the thickness of sea ice is to be measured. For measurement of the thickness of either fresh-water or sea ice, the radiometer should have a multi-frequency capability.

The microwave radiometer has been used for some time in an aircraft installation as an iceberg-detecting device. The contrast between water and ice is expected to be better in the passive mode than in the radar mode, particularly for rough seas and smooth ice, and there is some evidence to support this. In addition, because of the wide difference between the emission factors of ice and metal structures, the radiometer should provide an effective capability of discriminating between icebergs and ships. But experience in this area is limited and the problem deserves further study.

This general problem of detecting, locating and identifying structures in a water-ice environment illustrates an area where a complementary radar-radiometer sensor should possess a special effectiveness. The radar provides range and direction measurement capability and the radiometer offers special potential detection and identification advantages.

Determination of the presence of melt water on the surface of permafrost, and of the fraction of ice in permafrost, are subjects of current interest and study. The former application of the microwave radiometer depends on the marked difference in emission factors of water and ice. The latter application depends on penetration of the sub-surface structure by the radiation or emission from depth and thus on some knowledge of the dielectric constant at microwave frequencies. Such data are scarce.

6.5 SEA ICE THICKNESS

There have been extensive US laboratory and, more recently, aircraft studies of the application of microwave radiometers to this role. But the results have been very limited, and confined mainly to ice sheets for which the thickness did not exceed 20 - 30 cms, because of the short wavelengths used and the correspondingly small depth penetration. The USSR workers have been more successful, with their airborne surveys using wavelengths up to 30 cms. Their most recent ground work has involved wavelengths up to 100 cms. Canadian workers have recently reported promising results from initial airborne and ground tests of a multi-channel radiometer operating in the wavelength range of 14 - 75 cms. A multi-frequency system with a shortest wavelength range of about 20 cms is necessary to achieve penetration and to provide sufficient channels of independent data to ensure a fair probability of resolving the ambiguities due to the unknown and uncertain factors such as snow cover, profiles of temperature and salinity, boundary conditions, etc.

The implementation of such a radiometer concept in a spacecraft installation raises severe technological problems with respect to the antennas that would be necessary to achieve a satisfactory directivity and surface resolution for wavelengths as large as 75 - 100 cms. This would be so particularly in the case of the smaller, ERTS-type satellites intended for polar orbit. A current discussion involves putting a 21 cms radiometer on the larger SKYLAB or AAP satellites. Unfortunately, these spacecraft will be in low-inclination orbits, thus severely limiting their application for Arctic surveying.

6.6 METEOROLOGY

A number of important problem and application areas in meteorology have been identified, in which the remote-sensing potential of the microwave radiometer has been, or could be, exploited. These include the detection, measurement and classification as rain, snow or hail of precipitation cells, the determination of the elevation profiles of water vapor and temperature in the atmosphere and the location and determination of the water content of clouds. The data have direct application not only in meteorology but in the design of radio communication systems.

This is another research area where the radar and the radiometer complement each other in a powerful fashion as remote-sensing devices, in enhancing the value of data and in easing many of the problems of interpretation.

7. SUMMARY

A considerable background of experience and information has evolved from microwave radiometer programs so that, for many purposes, the requirements in terms of optimum wavelengths, minimum sensitivity and resolution, etc. are becoming established. The principal problems remaining in designing hardware, making measurements and processing and interpreting data have been defined.

One can identify a class of less-demanding roles involving a gross discrimination with a less-rigorous requirement for spatial and temperature resolution. These include the identification of water-land or water-ice boundaries. When closer discrimination is required in determining the type of terrain cover, structures - covered and otherwise -, cloud vs rain cells vs sea roughness vs sea surface temperature, etc, the problem of data interpretation is more complicated. This is due not only to limitations of instrumentation, but also to a limited knowledge of relevant signature data. The experience with spacecraft, although limited, has been encouraging.

It is feasible to instrument a spacecraft with a multi-channel instrument for a broad range of frequencies, with the lowest frequency such that information can be expected on sub-surface characteristics of low-loss materials and structures. Further extension of the low-frequency limit through significant developments in scanning antenna design and signal processing techniques should be expected in the next five years or so.

The most promising areas for investigation in the near future appear to include -

(a) oil pollution detection and mapping

(b) distribution and thickness of sea ice

(c) sea state

(d) snow cover, including density and water content

(e) detection of surface and, to a lesser extent, sub-surface, anomalies such as roads, metal structures, under-ground excavations, objects under snow cover, etc.

(f) presence of rain cells and moist clouds

(g) salinity of ocean water.

The microwave radiometer is not an exclusive, all-powerful device. Neither is any other sensor. Thus complementary information will often be necessary to aid in data interpretation including visible, IR, radar and lidar methods. It does possess the advantages of full-time operation, except for the intense absorbing conditions, with no transmitter and hence low power requirements and no identifying signal and capability of discrimination between targets on the basis of angle of incidence, polarization, emissivity and frequency. Because of its close relation in operation to the microwave radar, it has been suggested that the active and passive microwave sensors be combined in one instrument.

Spatial resolution is usually envisaged solely in terms of the frequency, the antenna dimensions and scanning rates. This is probably a restricted point of view when considering the maximum spatial resolution possible with an aircraft or spacecraft radiometer. Signal processing and, to some extent, antenna developments, have enabled workers in radio astronomy and radar to achieve higher resolutions. Considerations such as the maximum allowable integration time, the requirement to work with incoherent signals, and restrictions on the space available for mounting hardware tend to invalidate the complete analogy between radiometry and radio astronomy and radar. However, there is sufficient common ground to justify the expectation that certain relevant developments in the latter areas might result in the improvement of the spatial resolution in radiometry.

Much more research is required on the emitting properties of terrestrial materials, atmospheric components and meteorological elements. These properties are related to the complex dielectric constant and structure (anisotropy, graininess, roughness, etc.) of the material. The structure influences the scattering behaviour of the material or surface.

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12. Seling, T.V., and D.K. Nance. *Sensitive microwave radiometer detects small icebergs.* Electronics, 34, p. 72, 12 May, 1961.

    Discusses application by U.S. Coast Guard, using initially a 9 GHz line profiler and later a 35 GHz scanning instrument. The special capability of the radiometer (relative to radar) for detecting and identifying icebergs and ships is emphasized.

13. Chen, S.N.C., and W.H. Peake. *Apparent temperatures of smooth and rough terrain.* IRE Trans. on Antennas and Propagation, AP-9, p. 567, November 1961.

    Data are presented for the following ranges of parameters - frequencies of 1-75 GHz, angles of incidence of 5-80° and observation altitudes of 2-32 Km.

14. Wortendyke, D. *A memorandum on an X-band radiometer study.* Report No. 1041-3, AFCRL-62-74. The Antenna Lab., Ohio State University, Contract AF-19(604)-6134, 15 December 1961.

    Discusses types of radiometers, including methods of calibration. Includes details of experiments on antennas and reflecting screens to illustrate application of the radiometer.

15. McGillem, C.D., and T.V. Seling. *Influence of system parameters on airborne microwave radiometer design.* IEEE Trans. on Military Electronics, MIL-7, p. 296, October, 1963.

16. Barath, F.T., *et al. Mariner II microwave radiometer experiment and results.* The Astronomical Journal, 69, No. 1, p. 49, February 1964.

    Describes the 13.5 and 19.0 mm dual-channel radiometer used in a Venus flyby in 1962 and discusses the results.

17. Tiuri, M.E. *Radio astronomy receivers.* IEEE Trans. on Military Electronics, MIL-8, p. 264, July-October 1964.

    A general survey of the principles involved.

18. Jones, D.E. *The Mariner II microwave radiometer experiment.* Jet Prop. Laboratory, Tech. Report No. 32-722 for NASA, 1 January 1966.

    Related to No. 16.

19. Strangway, D.W., and R.C. Holmer. *The search for ore deposits using thermal radiation.* Geophysics, 31, p. 225, February 1966.

    Examines the feasibility of using microwave radiometers to achieve penetration of sub-surface structures. Concludes that depths of observation depend mainly on water content of soils and that wavelengths used should be as long as possible.

20. Chalfin, G.T., and W.B. Ricketts. *3.2 mm thermal imaging experiments*. Proc. of the 4th Symposium on Remote Sensing of the Environment, Univ. of Michigan, December 1966.

21. Peake, W.H., *et al. The mutual interpretation of active and passive microwave sensor outputs*. Proc. of the 4th Symposium on Remote Sensing of the Environment, Univ. of Michigan, December 1966.

    Results are given for two series of measurements made with radar and radiometer sensors at 10.0 & 35.0 GHz.

22. Shifrin, K.S., *et al. Some results of measurement of microwave radiation in a free atmosphere*. Meteorologiya i Gidrologiya, 7, p. 17, 1967.

    Discusses some of the USSR airborne, remote-sensing activities (based on a four-channel radiometer operating at 0.8, 1.35, 1.6 and 3.2 cms).

23. Goggins, W.B., Jr. *A microwave feedback radiometer.* IEEE Trans. on Aerospace and Electronic Systems, AES-3, p. 83, January 1967.

    Presents the details of the design of two L-band self-balancing radiometers (riometers).

24. Voss, K. *Coast Guard discovers that AN/AAR-33 Sperry iceberg tracker system aids mapping*. Technology Week, 20, p. 38, 16 January 1967.

    Discusses U.S. Coast Guard test-flights of a scanning radiometer operating in the frequency range 13.5 - 16.5 GHz.

25. Taylor, H.P. *The radiometer equation.* The Microwave Journal, 10, p. 39, May 1967.

    Re-examines the radiometer equation to emphasize the conditions and assumptions on which it is based.

26. Thomas, P.G. *Global weather forecasting.* Space/Aeronautics, p. 76, October 1967.

    A review of meteorological satellite programmes and plans.

27. Clark, H.L. *Some problems associated with airborne radiometry of the sea.* Applied Optics, 6, p. 2151, December 1967.

    A very detailed presentation. While reference is made to IR systems, most of the points raised apply to microwave radiometry.

28. Shifrin, K.S. *ed. Transfer of microwave radiation in the atmosphere*. NASA, Washington, July 1969. Translated from Tr. Gl. Geofiz. Observ. (Leningrad), NO. 222, 1968. (NASA-TT-F-590; N69-31851).

    A collection of papers emphasizing applications in oceanography and meteorology.

29. Schlude, F. *Some results of passive microwave groundmapping*. AGARD Conference on Advanced Techniques for Aerospace Surveillance, 1968. (AGARD Conference Proceedings No. 29.)

    Describes the use of a 35.0 GHz line-scanning radiometer to map terrain from altitudes in the range 2000-7000 ft.

30. Falco, C.V., and W.J. Johnson. *Passive microwave sensing of the atmosphere and earth surface environments.* AGARD Conference on Advanced Techniques for Aerospace Surveillance, 1968. (AGARD Conference Proceedings No. 29.)

    A general review of the state-of-the-art and areas of application.

31. Kreiss, W.T. *Meteorological observations with passive microwave systems.* Boeing Report No. D1-82-0692 for NASA, February 1968.

    A Ph.D. dissertation. Extensive bibliography.

32. Edgerton, A.T., *et al. Passive microwave measurements of snow, soils and snow-ice-water systems.* Report No. 4 (SGD-829-6), Aerojet-General Corp., El Monte, Calif. (Contract NOnr 4767(00), NR 387-033), 15 February 1968. (AD-669923).

    Reports theoretical and experimental work on the brightness temperature above a cover of ice. Frequencies used were 13.4, 37.0 and 94.0 GHz.

33. Barringer, A.R., and J.D. McNeill. *RADIOPHASE - A new system of conductivity mapping.* Proc. of 5th Symposium on Remote Sensing of the Environment, University of Michigan, April 1968.

    Describes an airborne radio propagation technique for the VLF and HF ranges.

34. Singer, S.F., and G.F. Williams. *Microwave detection of precipitation over the surface of the ocean.* Jour. Geophys. Res., 73, p. 3324, 15 May 1968.

    Considers the effects on the indicated brightness temperature of a precipitation volume between a radiometer and a surface or other objects being sensed.

35. Kennedy, J.M. *A microwave radiometric study of buried karst topography.* Geol. Soc. of Amer. Bull. 79, p. 735, June 1968.

    Reports theoretical and experimental studies on sensing of sub-surface structures with radiometers operating in the range 13.4 - 94.0 GHz.

36. Edgerton, A.T. *Passive microwave measurements of snow, ice and soil.* Progress Report on Contract No. NOnr 4767(00), NR 387-033, Aerojet-General Corp., El Monte, Calif., August 1968. (AD-674927).

    Describes theoretical and experimental work; 13.4 and 37.0 GHz used. Reports on radiometers for 1.4 and 5.0 GHz under development.

37. Crane, R.K. *Simultaneous radar and radiometer measurements of rain shower structure.* Mass. Inst. of Tech. (Lincoln Lab.) Tech. Note No. 1968-33, September, 1968.

    Describes the use of experimental X-band sky temperature data from a radiometer to estimate the validity of computing atmospheric attenuation and sky temperature from weather radar data.

38. Oliver, T.L. *A mobile facility for measuring the backscattering and brightness temperature of terrain at microwave frequencies.* Thesis, Ohio State University, under NASA Contract No. NSR-36-008-027. (NASA-CR-100544; Report-1903-6), October 1968. (N70-27032).

    Describes a truck-mounted facility. Doppler radar at 1.8, 10.0, 15.0 and 35.0 GHz and radiometer at 10.0 and 35.0 GHz.

39. Blinn, J.C., *et al. Airborne multifrequency microwave radiometric sensing of an exposed volcanic province.* Jet Propulsion Lab. Tech. Memo. No. 33-405, for NASA, 15 October 1968.

    Description of the MR-62 and MR-64 four-channel radiometer in the NASA Convair 240A aircraft (9, 15, 22 & 34 GHz) and its application.

40. Nordberg, W., *et al. Microwave observations of sea state from aircraft.* Report No. X-620-68-414 (TMX-63391), NASA (Goddard), November 1968. (N69-11537).

    Describes results obtained from flights with a 1.55 cm scanning radiometer for altitudes up to 12 Km.

41. LeFande, R.A. *Attenuation of microwave radiation for paths through the atmosphere.* Report No. 6766, U.S. Naval Research Lab. 29 November 1968. (AD-686664).

    Data for frequencies 10 - 100 GHz and elevation angles of 0 - 90°.

42. Peake, W.H. *The microwave radiometer as a remote sensing instrument.* Tech. Report No. 1903-8, Ohio State University, 17 January 1969. (N-69-15767).

    The report reviews the fundamentals of microwave radiometry and discusses the role of the parameters of a body that determine its emission properties, e.g., the nature of the boundaries, the complex dielectric constant. Samples of observed data are presented and discussed as illustrating applications of the technique.

43. Paris, J.F. *Microwave radiometry and its application to marine meteorology and oceanography.* Texas A&M University Report No. 69-IT under Project 286-13, funded by NASA through the ONR, January 1969.

    A detailed review.

44. *Atmospheric exploration by remote probes.* VOLS. I & II. Final Report of the Panel on Remote Atmospheric Probing to the Committee on Atmospheric Sciences, Nat. Acad. of Sci., Nat. Res. Counc., Washington, D.C., January 1969.

    An extensive review.

45. Nordberg, W., *et al. Microwave observations of sea state from aircraft.* Quart. Jour. Roy. Met. Soc., 95, p. 408, 1969.

    Reports measurements at 1.55 cm, from the NASA Convair 990 aircraft, at altitudes up to 12 Km.

46. Moore, R.K., and F.T. Ulaby. *The radar-radiometer.* Proc. of the IEEE, 57, p. 587, April 1969.

    Discusses the potential of the radar-radiometer as a remote-sensing system and illustrates its application in terms of some typical design and operational specifications and parameters.

47. Kreiss, W.T. *The influence of clouds on microwave brightness temperatures viewing downward over open seas.* Proc. IEEE, 57, No. 4, p. 440, April 1969.

48. Stehling, K.R. *Remote sensing of the oceans.* Astronautics & Aeronautics, 7, p. 62, May 1969.

    A review of U.S. programmes and plans.

49. Shimabukuro, F.I. *Optical display of millimeter-wavelength radiometric maps with good spatial, temporal and temperature resolutions.* IEEE 1969 G-MTT International Microwave Symposium, Dallas, Texas, May 1969.

    The paper discusses the inter-relations among the several radiometer parameters that determine mapping efficiency and the generation by computer of the display of the radio map. The discussion is illustrated with results from an operating 3.3 mm wavelength system.

50. Richer, K.A. *Near earth millimeter wave radar and radiometry.* IEEE 1969 G-MTT International Microwave Symposium, Dallas, Texas, May 1969.

    The paper discusses possible military applications. These include target acquisition, tracking and identification. Some 35 GHz radiometer data are presented.

51. Copeland, W.O., *et al. Millimeter-wave systems applications.* IEEE 1969 G-MTT International Microwave Symposium, Dallas, Texas, May 1969.

    System parameters of radiometers built for operation at frequencies of 35 GHz and higher are given. Applications include communications, missile guidance against ship targets and ship detection. Data obtained at 35 GHz in support of the last two applications are presented.

52. Spacecraft Oceanography Project (SPOC) of the U.S. Naval Oceanographic Office. *Microwave observations of the ocean surface.* Analyses of the NASA/Navy Review, 11-12 June 1969. (SPOC Report No. SP-152).

    An extensive review that includes several papers on radiometry. Some areas covered are - (a) calculated radiation from the sea surface as a function of temperature, salinity, frequency, angle of incidence and polarization and (b) experimental data obtained with radiometers operated at frequencies in the range 9 - 94 GHz and installed on towers or piers or in aircraft.

53. Basharinov, A. Ye., *et al. Determining geophysical parameters from thermal emissions obtained by the "KOSMOS 243 artificial earth satellite".* Transl. by Joint Public. Res. Serv. (JPRS No. 49474, 18 December 1969) from Dokl. Akad. Nauk SSSR (Moscow), 188, No. 6, 1969. (N-70-18303).

    Details of the programme using a four-channel, spacecraft radiometer operating at 0.8, 1.35, 3.4 and 8.5 cms.

54. Ewen, H.I., and A.H. Barrett. *Optimization of microwave radiometric systems for earth resource surveys.* Report No. NASA-CR-86316, Ewen-Knight Corp. Final Report on Contract No. NAS-12-2047, June 1969. (N70-17428).

    Extensive survey of applications. Emphasizes the requirements to use low frequencies if data on sub-surface properties and structures are to be obtained.

55. Pascalar, H.G. *Microwave radiometric instrumentation for remote sensing applications.* 14th Annual Technical Symposium, Soc. Photo. Instrument. Eng., San Francisco, August 1969.

    A general review of instrumentation and applications.

56. Haroules, G.G. and W.E. Brown. *The simultaneous investigation of attenuation and emission by the Earth's atmosphere at wavelengths from 4 centimeters to 8 millimeters.* Jour. of Geophys. Res., 74, No. 18, p. 4453, 20th August 1969.

57. Hovis, W. *Passive microwave sensors.* Proceedings of the Princeton University Conference on Aerospace Methods for Revealing and Evaluating Earth's Resources, Princeton, N.J. Editor - J.P. Layton. (Conference held September 1969). June 1970.

    A review of NASA's airborne programme.

58. Edgerton, A.T. and D.T. Trexler. *Oceanographic applications of remote sensing with passive microwave techniques.* Proc. of 6th Symposium on Remote Sensing of the Environment, University of Michigan, October 1969.

    Reports on measurements of emission above simulated-sea-ice sheets grown in the laboratory. Wavelengths used are in the range 3-5 cms.

59. Sherman, J.W. III. *Passive microwave sensors for satellites.* Proc. of 6th Symposium on Remote Sensing of the Environment, University of Michigan, October 1969.

    A general review.

60. Dees, J.W. and J.C. Wiltse. *An overview of millimeter wave systems.* Microwave Journal, 12, p. 42, November 1969.

61. Conway, W.H. and G.A. LaRocca. *Effects of the atmosphere on passive microwave sensing in the 20-100 GHz region.* AIAA 8th Aerospace Sciences Meeting, New York, (Paper No. 70-198), January 1970.

62. Gaut, N.E. and E.C. Reifenstein. *Degradation by the atmosphere of passive microwave observations from space in the frequency range 0.5 to 20 GHz.* AIAA 8th Aerospace Sciences Meeting, New York, (Paper No. 70-197), January 1970.

63. Droppleman, J.D. *Apparent microwave emissivity of sea foam.* Jour. Geophys. Res., 75, p. 696, 20th January 1970.

    Calculation of effect of a layer of foam.

64. Richer, K.A. *Comments on "A microwave radiometric study of buried karst topography".* Geol. Soc. of Amer. Bull., 81, p. 585, February 1970.

    Questions the results of Kennedy (June 1968), on the basis that radiation of such high frequencies would not be able to penetrate to the surface of the types of soil discussed.

65. Aukland, J.C. *et al. Remote sensing of the sea conditions with microwave radiometer systems.* Proceedings of AIAA Earth Resources Observations and Information Systems Meeting, Annapolis, Md., (Paper No. 70-318), March 1970.

    Emphasizes importance of ground-truth information in attempts to interpret satellite sea-surface-temperature data in terms of foam, spray, surface ripples, etc.

66. Hieronymus, W.S. *Use of microwave sensing grows*. Aviation Week and Space Technology, p. 44, 30th March 1970.

67. Porter, R.A. *et al. Degradation by the atmosphere of microwave radiometric observations from space - 0.5 to 20 GHz*. Final Report (2 volumes), NASA CR-86384 and CR-86385, Radiometric Tech. Inc. and Envir. Res. and Tech. Inc., under Contract NAS-12-2120, 30th April 1970. (N70-27290 and N70-27291).

    Data calculated to show atmospheric contribution to observations over ocean surfaces, as a function of viewing angle and for four weather models.

68. Capurro, L.R.A. *Oceanographic experiment support (remote sensing of coastal oceans)*. Annual Report of Texas A&M University Project 658, under U.S. Naval Oceanographic Office Contract No. N62306-69-C-0263, for NASA, May 1970. NASA No. CR-117316. (N71-20422).

    Includes an extensive review of the status of the uses of microwave radiometry in oceanography.

69. Steinbracher, E.E. and L.F. Gray. *A computer-controlled frequency-shift radiometer for satellite power monitoring*. Paper No. 70-CP-341-COM, Convention Record (Vol. VI), IEEE International Conference on Communications (1970), San Francisco, (IEEE Cat. No. 70C21-COM), June 1970.

    General discussion of radiometers as basis for decision on choice of instrument.

70. *Sensors pose earth satellite challenge*. Aviation Week & Space Technology, 92, p. 124, 22 June 1970.

    A review of NASA s remote sensing plans.

71. Hidy, G.M. *et al. Measurement of sea surface temperature by microwave radiometry*. Proc. of 6th Annual Conference, Marine Technology Society, Washington, D.C. June 1970.

72. Johnson, W.A. *et al. Design, development and initial measurements of a 1.4 mm radiometric system*. IEEE Trans. on Antennas and Propagation, AP-18, p. 512, July 1970.

    Includes data from measurements of atmospheric attenuation, using the sun as a source.

73. Shimabukuro, F.I. and E.E. Epstein. *Attenuation and emission of the atmosphere at 3.3 mm*. IEEE Trans. on Antennas and Propagation, AP-18, p. 485, July 1970.

    Describes the development of empirical relations for use in estimating atmospheric attenuation when the sun is not available as a source.

74. Toong, H.D. and D.H. Staelin. *Passive microwave spectrum measurements of atmospheric water vapor and clouds*. Jour. of Atmos. Sci., 27, p. 781, August 1970.

    Describes the use of a 5-channel radiometer operating in the frequency range 19-32 GHz to determine integrated water vapour abundance in the atmosphere and the liquid content of clouds under varying meteorological conditions.

75. Decker, M.T. and E.J. Dutton. *Radiometric observations of liquid water in thunderstorm cells.* Jour. of Atmosph. Sci., 27, p. 785, August 1970.

    Describes the use of a 10 GHz radiometer and correlates data with those from radar, radiosonde, etc.

76. Droppleman, J.D. and R.A. Mennela. *An airborne measurement of the salinity variations of the Mississippi River outflow.* Jour. Geophys. Res., 75, p. 5909, 20th October 1970.

    Reports measurements made at four frequencies in the range 1.4-31.4 GHz. The results support the prediction that a radiometer operating at frequencies near the low end of the range can be used to measure salinity variations of smooth water.

77. Strickland, J.I. *Simultaneous measurement of attenuation, emission and backscatter by precipitation along a satellite-to-Earth path.* Paper presented at the 14th Radar Meteorology Conference(American Meteorological Society), Tucson, Arizona, November, 1970.

    Describes the use of measurements of sky temperature at a frequency of 15.3 GHz to predict the radiowave attenuation for a satellite-earth path.

78. Adey, A.W. *A survey of sea-ice-thickness measuring techniques.* Report No. 1214, Communications Research Centre, Department of Communications, Ottawa, December 1970.

79. Basharinov, A.E. *et al. The results of microwave sounding of earth surface according to data experiments on earth satellite Cosmos 243.* Space Research XI (COSPAR), Akademie-Verlag, Berlin, p. 713, 1971.

    Further results from the 4-channel system - Antarctic ice distribution, humidity effects and sea surface temperature and roughness.

80. Aukland, J.C. *et al. Remote sensing of sea conditions with microwave radiometer systems.* J. Hydronautics, 5, p. 15, January 1971.

    See his March 1970 report.

81. Edgerton, A.T. *et al. Microwave emission characteristics of natural materials and the environment (A summary of six years research).* Aerojet-General Corp. Final Tech. Report No. 9016R-8 under US Navy Contract No. N00014-70C-0351 (Formerly No. NOnr-4767(00), NR 387-033), February 1971. (AD-720388).

    The summary includes the results of theoretical and experimental studies in areas including oceanography (sea temperature and salinity, ocean waves, foam and pollution), hydrology(snow and ice), sediments(soil, moisture content, roughness, layering) and atmospheric effects. Investigations were made in the wavelength range 0.32 - 21 cm.

82. Alishouse, J.C. *et al. Potential of satellite microwave sensing for hydrology and oceanography measurements.* U.S. Dept. of Commerce(NOAA) Tech. Memo No. NESS 26, March 1971. (COM 71-00544).

    The report reviews the U.S. radiometry projects, plans for satellite installations and the principal terrain and atmospheric parameters influencing the design of radiometric sensing systems.

83. Adey, A.W. *et al. Theory and field tests of a radiometer for determining sea-ice thickness.* Paper presented at Symposium on Remote Sensing and Earth Resource Satellites, Canadian Aeronautics and Space Institute. Toronto, March 1971. See, also. *Gauging sea ice thicknesses remotely.* Canadian Shipping and Marine Engineering, 42, p. 27, April 1971.

Initial results of ground and airborne tests with a four-channel microwave radiometer operating in the frequency range 400-2200 MHz. Tests were conducted in the Canadian Arctic in February-March 1971.

84. Falcone, V.J., Wulfsberg, K.N. and S. Gitelson. *Atmospheric emission and absorption at millimeter wavelengths.* Radio Science, 6, p. 347, March 1971.

The paper summarizes the theory relating to the absorption and emission of microwaves by the atmosphere and presents radiometer data for the frequency range 15 - 35 GHz.

85. Nordberg, W. *et al. Measurements of microwave emission from a foam-covered, wind-driven sea.* Jour. of Atmosph. Sci., 28, p. 429, April 1971.

Reports aircraft measurements using 1.55 cm and 3 cm radiometers. Further attempts to clarify differences between theory and experience as to relation between brightness temperature, angle of incidence and surface conditions (e.g., wind speed, surface roughness, foam coverage).

86. Lepley, L.K. and W.M. Adams. *Direct determination of the electromagnetic reflecting properties of smooth brackish water to the continuous spectrum from 10^8 to 4×10^9 Hertz.* Tech. Report No. 48, Water Resources Research Center, University of Hawaii, May 1971.

Describes reflection from a water-air interface computed for salinities up to those for ocean water and for the temperature range 0 - 40°C. (Reflectance measurements were made using both a coaxial line cell and a freewave reflection spectrometer.)

The results suggest that, in the VHF-UHF frequency ranges, the reflectance is highly sensitive to salinity and relatively insensitive to temperature. It is suggested that the reflectance technique offers potential in remote sensing for determination of salinity.

87. Hartz, T.R. *A radiometer method for determining the thickness of sea ice.* Report No. 1217, Communications Research Centre, Department of Communications Ottawa, May 1971.

The report examines the concept of applying the multi-channel, UHF radiometer to the problem of measuring the thickness of sea ice.

88. Kondratyev, K. Ya., *et al. On the feasibility of determining surface soil characteristics from remotely sensed microwave radiation.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

A radiometric technique is proposed which involves a scanning antenna and operation at three wavelengths. It is suggested that, from radiation data obtained by this technique, one should be able to determine moisture content, temperature profile, absorption coefficient and surface reflectance.

89. Rabinovich' Yu. I. *et al. The determination of the meteorological characteristics of the atmosphere and the earth's surface from airborne measurements of passive microwave radiation.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

    USSR program reported on includes - (a) Calculations of radiation from a water surface as a function of temperature and salinity and from surfaces such as sand (with a range of moisture percentages), clay, rock and snow, (b) Calculations of the radiation properties of the atmosphere for a range of wavelengths and of profiles of temperature and humidity, (c) Laboratory measurements of the radiation properties of fresh and sea water and (d) Data collection with a four-channel airborne radiometer system, for wavelengths in the range 0.8 - 3.2 cm; scanning capability was available for certain of the channels. In addition to the subjects noted in (a) and (b), distribution of ice cover is also included.

90. Gray, K.W. *et al. Microwave measurement of thermal emission from the sea.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

    The paper reports on theoretical and experimental studies of the radiation from the sea. The experiments were conducted at a frequency of 2.69 GHz.

    A design of an aircraft-satellite compatible radiometer is presented. It has an absolute measurement accuracy of better than 0.3 K° and operates in the nulling feedback mode.

91. Jean, B.R. *et al. Experimental microwave measurements of controlled surfaces.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

    Describes experiments performed at a frequency of 31.4 GHz, to determine the radiation from a smooth sand surface as a function of moisture content and from water with a thin film of crude oil. (Both situations were modelled theoretically, with atmospheric effects included. The data were obtained for both orthogonal polarizations and for several angles of incidence. Laboratory measurements of the dielectric properties of the sand as a function of moisture content were made.)

92. Aukland, T.C. *et al. Multi-sensor oil spill detection.* Proc. of the 7th International Symposium on Remote Sensing of Environment, Univ. of Michigan, May 1971.

    The paper summarizes results of experiments designed to detect and classify oil spills from moving ships at sea.

93. Rosenkranz, P.W. *et al. Indirect sensing of atmospheric temperature and water vapor using microwaves.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

    The paper reports on aircraft flights of a prototype of the NIMBUS E microwave spectrometer which has five channels at the approximate frequencies of 22.2, 31.4, 53.7, 54.9 and 58.8 GHz. (The flights were made over various types of surface - land, smooth and rough water - and for various atmospheric conditions. The aim was to determine the effectiveness of the radiometer for measuring atmospheric temperature and water content and the magnitude of possible uncertainties in these data introduced by the various terrestrial surfaces.)

94. Kunzi, K.,*et al. Passive microwave remote sensing at the University of Bern, Switzerland.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

Reports on a program that is divided into two parts - research on radiometer components and systems (e.g., imaging systems, antenna design, radiometer stability) and field studies aimed at measuring the radiating properties of surfaces of natural and artificial materials (including anisotropically radiating samples).

95. Hruby, R.J. and A.T. Edgerton. *Subsurface discontinuity detection by microwave radiometry.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

Describes tests performed at wavelengths of 0.8, 2.2 and 21 cm, to determine the possibility of detecting the presence of under-ground voids such as tunnels and caverns on the basis of changes in surface radiation.

Some correlation is indicated between the 21 cm data and near-surface moisture level, but none for the shorter wavelengths. There is no correlation between the existence of voids and the moisture content or the brightness temperature. It is emphasized that the results might be sensitive to local precipitation history.

96. Meier, M.F. and A.T. Edgerton. *Microwave emission from snow - a progress report.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

Involves a program for theoretical modelling of radiation from snow-packs, measurements on natural and artificial snow and studies of snow electrical properties. (The field measurements were made at wavelengths of 0.8, 2.2, 6 and 21 cm, with snow depth, temperature and water content as variables.)

97. Kazel, S. and R.J. Serafin. *Sidelooking radiometry: A new approach to passive mapping of terrain.* Proc. of the IEEE National Aerospace Elect. Conference, Dayton, Ohio, May 1971.

Describes an approach that is somewhat analogous to that of synthetic aperture radar. Range resolution is enhanced by data storage and subsequent optical processing.

98. Hodarev, Yu. K., *et al. Some possible uses of optical and radio-physical remote measurements for earth investigations.* Proc. of the 7th International Symposium on Remote Sensing of the Environment, University of Michigan, May 1971.

This review paper discusses the role of the radio-frequency radiometer in earth resources studies from both aircraft and spacecraft and presents data from USSR programs. Application to determination of ice thickness, sea surface temperature and vertical profiles of atmospheric temperature and water content receives special mention.

The desirability of obtaining data simultaneously in a number of spectral bands, the potential role of the radar-radiometer sensor and problems involved in developing radio-frequency scanning (mapping) systems for spacecraft operations are among the points raised.

99. Basharinov, A.E., *et al. Features of microwave passive remote sensing.* Proc. of the 7th International Symposium on Remote Sensing of Environment, University of Michigan, May 1971.

The paper provides data obtained with the USSR multifrequency radiometer (apparently from Cosmos 243), and other results for ice at longer wavelengths of 30 and 50 cms. Data are provided for the shorter wavelengths (0.8 - 8.5 cms) on ice cover, sea surface temperatures, soil moisture and atmospheric water content.

100. Paris, J.F., *Transfer of thermal microwaves in the atmosphere.* Texas A&M University (Dept. of Meteorology) Report, 2 Volumes, May 1971. NASA Grant No. NASA NGR-44-001-098; ONR Contract No. NOnr 2119(04); Water Resources Inst. Proj. No. 5013 and DoD.

An expansion and extension of his January 1969 review.

101. Hollinger, J.P. *Passive microwave measurements of sea surface roughness.* IEEE Trans. on Geosci. Elec., GE-9, p. 165, July 1971.

Radiometer data are presented for frequencies in the range 1.4 - 19.3 GHz and for wind speeds in the range 0 - 15 meters/sec.

102. Wermund, E.G. *Remote sensors for hydrogeologic prospecting in arid terrains.* IEEE Trans. on Geosci. Elec., GE-9, p. 120, July 1971.

Reviews remote sensing work in water prospecting. Presents results of an aerial survey using an IR scanner, a 13 GHz microwave radiometer and multiband photographic system.

103. Edgerton, A.T., *et al. A study of the microwave emission characteristics of sea ice.* Tech. Rep. No. 1741 R-2, Aerojet-General Corp., July 1971.

The report discusses the mathematical modelling of the emission from a sea-ice sheet and presents calculations for a range of the ice dielectric properties, of the ice temperature and of frequency. Aircraft observations for a number of frequencies in the range 9-60 GHz are presented. The main result from these observations is the fact that the younger ice gives a significantly higher brightness temperature than the older, and weathered ice.

104. Strong, A.E. *Mapping sea-surface roughness using microwave radiometry.* Jour. Geophys. Res., 76, p. 8641, 20 December, 1971.

The paper reviews the application of the technique to this problem area and presents further 1.55 cm experimental data. These tend to emphasize the significance of capillary-wave effects and the sensitivity of this radiometer to short-wave surface roughness. It is concluded that both points need further theoretical and experimental study. The potential roles of the multi-frequency radiometer and the radar-radiometer are noted.

ADEY, A. W.
--Microwave rasiometry for surveillance from spacecraft and aircraft.