NOAA Technical Memorandum NESS 26

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite Service

Potential of Satellite Microwave Sensing for Hydrology and Oceanography Measurements

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WASHINGTON, D.C.

March 1971

NOAA TECHNICAL MEMORANDA

National Environmental Satellite Service Series

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POTENTIAL OF SATELLITE MICROWAVE SENSING FOR HYDROLOGY AND OCEANOGRAPHY MEASUREMENTS

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UDC 551.507.362.2:551.578.46:556:631.432:
551.46:535.214.4

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POTENTIAL OF SATELLITE MICROWAVE SENSING FOR HYDROLOGY AND OCEANOGRAPHY MEASUREMENTS

ABSTRACT. NOAA's hydrologic or oceanographic use of visible or infrared radiation measurements from earth satellites is seriously limited by the opacity of clouds at these wavelengths. Microwave radiation at frequencies which are subject to relatively small attenuation by clouds and other atmospheric constituents offers a means to circumvent this limitation. Microwave sensors that can be carried on unmanned satellites should be able to provide measurements usable for the delineation of snow and ice cover and the detection of precipitation; also, there is considerable promise that soil moisture measurements that are quantitative to some degree can be made. Requirements for spatial resolution by the sensor are usually lower for oceanographic than for hydrologic needs. Microwave radiometers on unmanned satellites appear usable for detecting sea-ice boundaries through clouds and for obtaining information of sea-surface roughness and temperatures. With the increasing tempo of theoretical and experimental studies in microwave sensors and antenna technology, there appears to be considerable potential for microwave measurements from earth satellites applicable to NOAA's hydrologic and oceanographic services.

1. INTRODUCTION AND BASIC CONSIDERATIONS

General

Among the environmental services for which NOAA has responsibility are Weather and Ocean Forecasts and Warning Services; Marine Description, Mapping, and Charting Services; and River and Flood Prediction and Warning Services. Although NOAA's National Environmental Satellite Service (NESS) has been making important contributions to most of these service programs from a meteorological standpoint for over 5 years, the direct application of environmental satellite data to problems in hydrology and oceanography is relatively new.

Advanced Vidicon Camera System (AVCS) data from NOAA's Environmental Survey Satellites (ESSA) and High Resolution Infrared Radiometer (HRIR) measurements from the National Aeronautics and Space Administration's (NASA) NIMBUS satellites are being studied by NESS to develop methods for application of the data to snow surveying, sea-surface temperature mapping, sea-ice surveillance, and the charting of certain sea-roughness conditions. Because these visual and infrared sensors were designed primarily for meteorological purposes, the data obtained have many limitations from the standpoint of hydrologic or oceanographic use. Among the main limitations are the inability of the sensor to "see" through cloud cover or to obtain information from below the earth's surface, and the coarse spectral and spatial resolution of the data. Radiation in microwave regions is characterized by relatively small attenuation by clouds and other atmospheric constituents. For a clear sky and zenith viewing angle, the attenuation is 1 db or less for frequencies less than the O_2 complex at 60 GHz. There also exists the possibility of detecting microwave radiation originating from subsurface layers under certain circumstances.

Although it appears there will be difficulties in obtaining data with high-spatial resolution by microwave sensors, especially with the constraints on the size of antennas that can be carried on unmanned earth satellites, these measurements should have considerable potential for use in hydrology and oceanography. This report attempts to assess this potential on the basis of past and current work in the field.

Attenuation of Microwave Radiation

The microwave region of the electromagnetic spectrum includes wavelengths ranging from near 30 cm to somewhat less than 1 mm (frequencies of about 1 to 300 GHz). The emission, transmission, scattering, and absorption of microwave radiation are governed by the same physical laws as radiation in the visible and infrared spectral bands.

In hydrology and oceanography, research is focused upon the microwave radiation emitted by natural substances on the earth's surface. Specifically, NESS research is directed toward satellite detection and measurement of microwave radiation emitted naturally from the earth's surface (generally expressed as the "brightness temperature, T_B," of the surface). Passive sensors used for this purpose are microwave radiometers. Active microwave systems, on the other hand, are radars because they transmit energy at these wavelengths and measure the reflected or scattered return; these systems are often called microwave or radar "scatterometers." Scatterometer system signals returning to the spacecraft detector are generally several orders of magnitude stronger than the naturally generated signals detectable by passive radiometer systems.

Whether an active or passive system is used, microwave radiation still must pass through the soil, snow, water, or other earth materials, and also through the atmosphere (including water vapor and other gases, cloud droplets and ice crystals, precipitation, suspended dust, and other particulate matter) before reaching an aircraft or satellite platform. Calculations and measurements for zenith viewing have shown (summarized in Haroules and Brown 1969) that there is little or no atmospheric attenuation (fig. 1) at frequencies lower than about 10 GHz

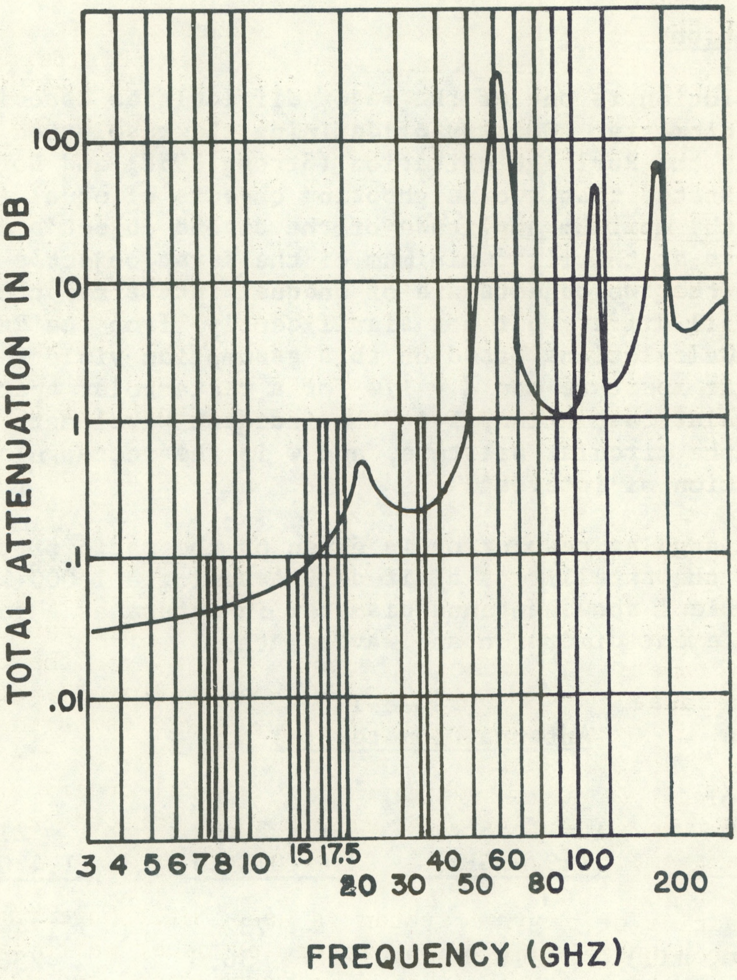

Figure 1.--Typical atmospheric attenuation for a clear sky and zenith viewing (After Haroules and Brown 1969)

(3 cm). Attenuation increases fairly slowly with increasing frequency in the range from near 1 GHz to about 30 GHz (1 cm); above 30 GHz, the rate of increase is much more rapid. A fairly narrow but significant water vapor absorption band appears between 20 and 25 GHz (1.5 and 1.2 cm), and a broader and far stronger oxygen absorption band is found between 50 and 75 GHz (6 and 4 mm). Further attenuation takes place in the presence of clouds; the effect becomes greater with increasing microwave frequency and mass of liquid water in the column. Attenuation is more pronounced when precipitation is present; here absorption, emissivity, reflectivity, and scattering are important.

Areal Resolution

Spatial resolution is one of the major difficulties associated with microwave radiometry. One way of defining the resolution of an instrument is the Rayleigh criterion (Strong 1958; and Born and Wolf 1959) which states that two neighboring objects of equal intensity are resolved if the maximum amplitude of the second object's diffraction pattern occurs at the first minimum of the first object's diffraction pattern. If the two objects are of unequal intensity, the angular resolution will differ, but not significantly, from the Rayleigh criterion. Calculations based on this assumption yield $\alpha = 1.22\ \lambda/D$ for a circular aperture and $\alpha = \lambda/w$ for a rectangular aperture, where α is the angular resolution, λ is the incident wavelength, D is the diameter of the circular aperture, and w is the rectangular dimension in the direction of interest.

The required angular resolution is given by the ratio of the desired spot size to the satellite's altitude. Assuming a 1,000-km orbital altitude, table 1 shows antenna diameter in meters as a function of resolution element dimension and wavelength.

Table 1
Antenna Diameter (m)

Dimension of resolution element	λ = 1.55 cm (19.4 GHz)	λ = 3 cm (10 GHz)	λ = 21 cm (1.4 GHz)
50 m	378	732	5.124×10^3
1 km (0.5 n. mi.)	18.9	36.6	256.2
1.8 km (1 n. mi.)	10.5	20.3	143.3
9.3 km (5 n. mi.)	2.03	3.9	27.5
18.0 km (10 n. mi.)	1.0	2.0	14.2

The problem of how large an antenna can be flown must also be considered. It has been proposed than an erectable 30-m antenna could be flown on an

Apollo Applications mission (General Dynamics 1967); a 10-m antenna is proposed for the Applications Technology Satellite, ATS-G. Utilizing General Dynamic's formula, the package containing the 30-m antenna in stored form would be 5.1 m long, be 3 m in diameter, and would weigh more than 750 lbs. Such antenna packages are too large for use with NIMBUS; Improved TIROS Operational Satellite (ITOS), or Earth Resources Technology Satellite (ERTS)-type vehicles. Antennas with erected diameters of about 6 to 8 m appear realistic for the typical unmanned spacecraft.

2. APPLICATIONS OF MICROWAVE SENSING TO HYDROLOGY

Snow Measurements

Passive sensor

The *areal extent* of snow could be mapped with a microwave radiometer quite reliably, although resolutions better than 3 to 6 n. mi. are likely to be unobtainable without going to large spacecraft such as NASA's Skylab. Practically, one might expect maximum achievable resolutions on the order of 1 n. mi. The 19.3-GHz imaging radiometer which has been aircraft-tested appears to be good for this purpose (Catoe et al. 1967). Measurements at this frequency indicate very little about the water equivalent of the snow or its depth.

Marked diurnal and snow morphology effects complicate the snow problem. Measurements made a short distance above the snow indicate that at higher frequencies (about 37 GHz and above) brightness temperatures for the snowpack are about 130°-150°K higher in the daytime than at night (Edgerton et al. 1968). At lower frequencies (13.4 GHz), these effects are much less pronounced. These fluctuations in brightness temperature are thought to be emissivity variations caused by interference effects and scattering (Edgerton et al. 1968). These, in turn, seem to be a function of granularity, ice layering, etc., or in fact, the general morphology of the snowpack. As yet, very little of a *quantitative* nature can be inferred about the snowpack from microwave measurements.

Soil Measurements

Measurements of *soil moisture* in the uppermost several centimeters would seem to be one of microwave radiometry's most promising areas. In contrast with the infrared where the emissivity is essentially independent of soil moisture, significant variations of brightness temperature occur with fluctuations in soil moisture content.

Microwave measurement of the water content of the soil at levels below the surface is less well defined. From near-surface measurements, it has been found that a 13.4 GHz radiometer "sees" down to a depth of

5 cm into dry soil (Edgerton et al. 1968). The need to sense radiation originating deeper in the soil leads to consideration of lower frequencies. In preliminary data taken at L-band frequencies [1], 1.4 GHz, penetrations of up to 76 cm in very dry, low-density soil (pumice) have been achieved. A multichannel radiometer for determining soil moisture profiles analogous to the Satellite Infrared Spectrometer (SIRS) temperature profiles has been suggested.

Aerojet-General Corp. made measurements at frequencies of 1.5, 6, 13.4, and 37 GHz in September 1969 and in July 1970 at the Department of Agriculture Water Conservation Laboratory in Tempe, Ariz. The September 1969 data are inconclusive because of unseasonable rains in Tempe. The July 1970 data have not been completely reduced; preliminary analysis (Edgerton 1970) shows that the measurements have a low rms noise level and that a wide range of soil moisture values were obtained. These data show a brightness temperature change of about 100° K for a 20-percent change (5 to 25 percent) in soil moisture. From these and other data (Edgerton et al. 1968), it appears that typical sensitivities are 3° K to 5° K per percent change of H_2O (that is, a 1-percent change in soil moisture produces a change of 3° K to 5° K in the brightness temperature).

To exploit fully this temperature change information, one needs to know the soil type, vegetal cover, and soil temperature. The microwave energy emitted is a function of these variables as well as the soil moisture; it is not obvious that all of these variables can be taken into account in every set of measurements.

The determination of <u>frozen versus unfrozen ground</u> has not been systematically investigated; however, because there are significant differences in the dielectric properties of liquid water and ice, it should be possible to differentiate between a mixture of soil and liquid water and a mixture of soil and ice. The determination of the <u>depth</u> to which the soil is frozen would be more difficult. Further complications exist where snow is present over the soil.

The determination of <u>surface temperature</u> (land or water) by means of microwave radiometry presents a problem because of the wide range of emissivities of naturally occuring material. The emissivity of water varies with roughness, salinity, temperature, and frequency. Furthermore, because the emissivity of water, and hence its reflectivity, is about 0.5, a surface measurement contains considerable reflected sky

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[1] Private communication from D. Trexler, Aerojet-General Corp., 1969. Mr. Trexler's present affiliation is with Microwave Sensor Systems, Downey, Calif.

radiation (see the next section for a further discussion of water temperature measurements). Over land, the surface emissivity can vary as a function of soil moisture, vegetal cover, soil density, and composition. Over uniform areas, however, it has been demonstrated that near-surface brightness temperatures at 13.4 and 37.0 GHz correlate extremely well with thermometric soil temperatures at a depth of about 0.5 to 1 cm (Edgerton et al. 1968).

Other

The markedly lower emissivity of water in comparison with that of land makes surface water, including flood expanse, easy to map except perhaps where rain clouds are present. This has been demonstrated with aircraft measurements at 19.4 GHz (Catoe et al. 1967). Although resolutions better than 100 m would be highly desirable for this purpose, resolutions on the order of 500 m would still be quite useful; such resolutions appear feasible, with the largest antennas proposed for spacecraft use in the middle 1970's.

The areal extent of ice, in the absence of rain clouds, also would be easy to map because of the high emissivity of ice relative to that of the surrounding water (Catoe et al. 1967).

Determination of ice thickness would pose some difficulties. Interference phenomena have been calculated and observed at 13.4 and 37.0 GHz for ice (Edgerton et al. 1968). Basically, this phenomenon occurs as the ice thickness passes through multiples of the radiometer wavelength. It might be possible to use this phenomenon to obtain information about ice thickness by using a sweep frequency technique or perhaps by varying the look angle.

To obtain the location, size, and perhaps intensity of precipitation areas also appears feasible. Areas of precipitation have been delineated from a high-altitude aircraft carrying a 19.4-GHz radiometer (Catoe et al. 1967) and from a low-altitude (3 km) aircraft carrying a 15.8 GHz (1.9 cm) radiometer (Singer and Williams 1968). Precipitation rates have been correlated with multifrequency (8, 15, 19, and 35 GHz) ground measurements (Haroules and Brown 1969).

The problem of vertical temperature profiling in the water, land, snow, etc., like that of soil moisture profiling, is considerably more complicated than those discussed above. Infrared sensing is of little value here because of its lack of depth penetration. The microwave energy emitted is a function of several variables other than the temperature of the layer in question, so enough information must be obtained to permit separation of the competing effects.

3. APPLICATIONS OF MICROWAVE SENSING TO OCEANOGRAPHY

The most interesting oceanographic parameters from the standpoint of microwave measurements are sea state (ocean roughness), sea ice, and sea-surface temperatures. High-spatial resolution is not particularly critical for most oceanographic applications, thus even the typical unmanned satellites are capable of carrying antennas yielding areal resolution of 5 to 10 n.mi. at frequencies down to 10 GHz (see table 1).

Sea State

Ocean roughness, a function of near-surface wind speed, is one of the properties of the sea that appears amenable to measurement by microwave radiometry. Calculations by Stogryn (1967) for horizontally polarized radiation at 19.4 GHz indicate a fairly strong dependence of the brightness temperature (T_B) upon both wind speed and viewing angle (fig. 2). Measurements at 19.4 GHz from a CV-990 aircraft over the Salton Sea in California, the eastern North Pacific Ocean, and more recently over the North Atlantic and North Sea (Nordberg et al. 1969) have confirmed that T_B increases with wind speed. These results suggest, however, that the amount of increase is larger than that predicted by theory, and is just as large at near-nadir viewing angles as it is at larger angles. Further confirmation has come from 8.4- and 19.4-GHz measurements made by Hollinger (1970) at the Argus Island tower. Strogryn's model, unfortunately, does not take into account the influence of whitecaps and foam, and the measurements by Nordberg et al. (1969) and Edgerton (1968) show anomalously high T_B's (indicating greater emissivities) under the foaming conditions that occur with high winds. Much more research is needed to establish more quantitatively the influence of clouds, surface-temperature variability, foam and whitecaps, and possible saturation effects at high wind speeds on sea-state measurements from microwave radiometers operating at frequencies from 19.4 GHz to less than 10 GHz.

Active microwave systems, operating at frequencies of 0.5, 1.5, and 13.3 GHz, were tested on aircraft missions near Ireland early in 1969, but instrumental and data processing difficulties have delayed the presentation of conclusive results. A composite microwave radiometer-scatterometer (RADSCAT), operating at 9.9 GHz, has been proposed [2] for NIMBUS F and is now scheduled for inclusion on Skylab.

Sea Ice

The strong difference of emissivity between sea water and ice makes the mapping of ice features by microwave radiometry a promising possibility.

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[2] Proposal by W. J. Pierson, New York Univ., and R. K. Moore, Univ. of Kansas, to NASA, dated October 31, 1968.

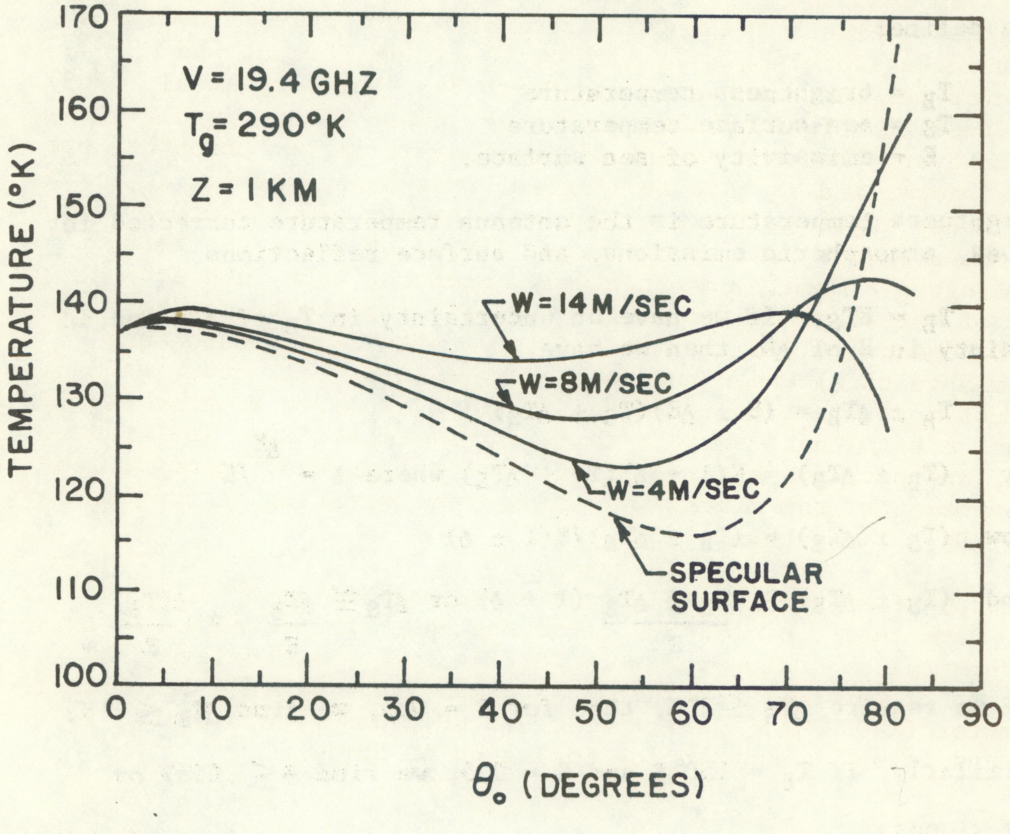

Figure 2.--Brightness temperature vs. viewing angle (θo) for various wind speeds (W in m/sec) (After Stogryn 1967)

Flight measurements of a 19.4-GHz radiometer gave changes of apparent brightness temperature from near 120°K for open water to near 240°K for solid pack ice (Catoe et al. 1967). Further studies of these data by the NESS (Strong and Fleming 1970) indicate that several categories of ice conditions may be defined within the large spread of temperature. An electrically scanning 19.4-GHz radiometer is scheduled for inclusion on NIMBUS E, and a 37-GHz radiometer has been proposed 3/ for inclusion on NIMBUS F.

Sea-Surface Temperature

It is more doubtful that measurements of sea-surface temperature can be obtained by microwave radiometry. The following simple calculation shows the accuracy required.

We define:

T_B = brightness temperature
T_S = sea-surface temperature
E = emissivity of sea surface.

The brightness temperature is the antenna temperature corrected for sidelobes, atmospheric emissions, and surface reflections.

$T_B = ET_S$. If we have an uncertainty in T_B of ΔT_B and an uncertainty in E of ΔE, then we have

$$T_B \pm \Delta T_B = (E \pm \Delta E)(T_S \pm \Delta T_S)$$

or $$(T_B \pm \Delta T_B) = E(1 \pm \delta)(T_S + \Delta T_S) \text{ where } \delta = {}^{\Delta E}/E$$

Now, $$(T_S \pm \Delta T_S) = (T_B \pm \Delta T_B)/E(1 \pm \delta)$$

and $$(T_S \pm \Delta T_S) \cong \frac{T_B \pm \Delta T_B}{E}(1 \mp \delta) \text{ or } \Delta T_S \cong \frac{\Delta T_B}{E} \pm \frac{\delta(T_B)}{E}.$$

If we require $\Delta T_S \leq 2°K$, then for $E = 0.5$, we find $\Delta T_B \leq 1°K$.

Similarly, if $T_B = 150°K$ and $E = 0.5$, we find $\delta \leq .0067$ or

$\Delta E \leq .0033$.

The emissivity itself is a complicated function of thermometric temperature, salinity, roughness, viewing angle, frequency, and polarization.

3/ Proposed by W. Nordberg, NASA Goddard Space Flight Center, as amended, July 13, 1969.

Thus, a change in emissivity of 0.003 can produce an apparent brightness temperature change of 1°K. With horizontal polarization, roughness variations alone can produce apparent brightness temperature fluctuations of more than 30°K. Measurements using vertical polarization and frequencies near 5 GHz tend to minimize roughness, emissivity, and salinity effects, and to enhance the detection of temperature variations (Paris 1969). North American Rockwell Corp. has recently begun flight tests of a 3-GHz radiometer over the Pacific Ocean near San Diego, Calif., to obtain additional measurements at this relatively low frequency 4/. McDonnell Douglas Corp. 5/ is developing a 10.6-GHz radiometer to make oceanographic measurements.

4. CONCLUSIONS

Although knowledge of microwave radiometry and the physics of emission properties of naturally occurring substances is not extensive, it is still possible to draw some conclusions about present microwave capabilities and limitations insofar as they apply to hydrology and oceanography. Because this report is concerned with the potential of microwave sensors carried aboard a satellite, atmospheric attenuation factors (see fig. 1) must also be considered.

As mentioned in the introduction, part of the attractiveness of sensing natural radiation from the earth's surface in the microwave region lies in the possibility of achieving essentially all-weather, day or night, observational capabilities and in the possibility of "seeing" at least a small distance below the earth's surface. Theory and limited field measurements suggest that these capabilities can best be realized at the longer wavelengths, that is, at frequencies of less than 10 GHz. For a given spatial resolution, however, the lower the frequency is, the larger is the antenna required. To obtain resolutions small enough to be useful to hydrologists, large antennas are required (at least for use with frequencies of less than 5 GHz); probably manned spacecraft will be able to carry them. Spatial resolution is not particularly critical for most oceanographic applications; unless quite low frequencies -- 5 GHz or less -- are required, relatively small unmanned satellites probably could be used successfully.

The number of actual field measurements bearing directly on hydrologic and oceanographic problems is rather limited. Near-surface measurements of hydrological interest are more plentiful than aircraft measurements. The near-surface experimental measurements are better controlled

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4/ Private communications from Stanley Roberts and Jack Rogers, Nov. 1969.

5/ McDonnell Douglas, Space Sciences Department, "Microwave Radiometer Systems," Feb. 1970.

and documented. More measurements of oceanographic interest were taken from aircraft than from sensors close to the sea surface, but the high-altitude data suffered from poorer "ground truth" and sometimes uncertain atmospheric attenuation. Although more experiments with good supporting data are needed before the feasibility and utility of certain microwave measurements from space can be ascertained with confidence, the results to date provide general guidelines to the most probable fruitful directions for work in the immediate future.

The hydrologic factors for which measurements from satellite microwave radiometry (excluding antenna considerations) appear most feasible are soil moisture, areal extent of snow or ice, and precipitation areas. Although the water content of the snowpack is as important as its areal coverage, and the areal extent of frozen ground is also significant, the determination of these factors using microwave sensing is very uncertain at this time. Snow cover and, to a considerably less satisfactory extent, precipitation areas can be delineated using satellite data in the visible and infrared region. But visual sensing of the areal extent of snow is limited by cloud cover and solar illumination; the mapping of precipitation areas requires a statistical technique for estimating the precipitation area and its intensity.

From an oceanographic standpoint, microwave techniques appear most likely to be successful for obtaining measurement of sea ice and sea-surface roughness. From the roughness data, it is hoped that the speeds of the near-surface winds can be derived. If a sufficiently dense grid of these winds can be derived, then the larger scale wind-driven waves can be mapped. Prospects for these measurements are hopeful, but details, such as, which is the optimum frequency and should the system be active, passive, or composite, are problems whose solutions require further research.

Detection of sea ice seems to pose no particular problems within the spatial limitations discussed previously because most clouds in polar regions are not characterized by a large water or ice content. Considering all the problems, sea-surface temperatures will probably be best measured from infrared radiometers despite the limitations imposed by clouds.

Clouds, and particularly precipitation, can significantly attenuate microwave energy transmission. Because total attenuation is a function of both the mass of liquid water and the frequency, the possibility exists for determining liquid water content by making simultaneous measurements at two or more microwave frequencies. The liquid water content, in turn, could be used for correcting the measurements of surface T_B.

A number of microwave sensors have been used rather extensively by various groups for measurements directly or indirectly related to hydrology and oceanography. The best known measurements perhaps are Aerojet-General Corporation's near-surface measurements of snow, soils, and snow-ice-water systems, made mostly with 13.4- and 37.0-GHz radiometers and 19.4-GHz scanning radiometer. Also, Pierson and Moore have made 13.3-GHz aircraft scatterometer measurements of radar sea return using NASA-Houston aircraft. Other microwave sensors, some recently installed, are also carried on various Houston airplanes; namely, 0.4- and 1.6-GHz scatterometers, 16.5-GHz side-looking radar, 13- to 17- and 19.3-GHz wave imagers, but to date virtually no reports have been published with analyses of data collected in conjunction with hydrology or oceanography experiments. No passive or active microwave system has been carried on a U.S. satellite, but a 19.4-GHz electrically scanning radiometer is to be carried on NIMBUS E; both a 10-GHz radiometer-scatterometer and a 37-GHz radiometer have been proposed for inclusion on NIMBUS F. A Soviet satellite has carried one recently (World Meteorological Organization 1969). It is anticipated that other spacecraft, both manned and unmanned, will be carrying microwave sensors by the middle 1970's.

The increasing tempo of theoretical and experimental studies in microwave radiation emission and attenuation, the general advances expected in microwave sensor and antenna technology, and the upcoming microwave experiments on NIMBUS E and NIMBUS F all point to the existence of a considerable potential for microwave measurements from earth satellites that could be useful to NOAA's hydrologic and oceanographic services.

The material in this Technical Memorandum is an outgrowth of a study by the four authors to assess the future of microwaves for NESS's mission. In addition to the works explicitly referenced, the authors found those cited in the bibliography of great value to their overall understanding of the problem.

REFERENCES

Born, M., and Wolf, E., *Principles of Optics*, Pergamon Press, New York, 1959, 803 pp.

Catoe, C., Nordberg, W., Thaddeus, P., and Ling., G., "Preliminary Results from Aircraft Flight Tests of an Electrically Scanning Microwave Radiometer, "*NASA Technical Report* X-622-67-352, 1967, 35 pp.

Edgerton, A. T., Mandl, R. M., Poe, G. A., Jenkins, J. E., Soltis, F., and Sakamoto, S., "Passive Microwave Measurements of Snow, Soils, and Snow-Ice-Water Systems," *Technical Report* No. 4, Contract No. NOnr 4767(00), NR 387-033, Aerojet-General Corp., El Monte, Calif., 1968, 344 pp.

Edgerton, A., *Progress Report for March 15, August 15*, Contract No. NOnr 4767(00), NR 387-023, Aerojet-General Corp., El Monte, Calif., 1968, 9 pp.

Edgerton, A., "Determination of Soil Moisture Content using Microwave Radiometry," *Monthly Progress Report* No. 1684M-1, Contract No. 0-35239, Aerojet-General Corp., El Monte, Calif., 1970, 4 pp.

General Dynamics, "Feasibility Study of Large Scale Erectable Antennas," *NASA Contract* NAS W 1438, Document N68-20267, Vol. II, 1967, 557 pp.

Haroules, G. G., and Brown, W. E., "Simultaneous Investigation of Attenuation and Emission by the Earth's Atmosphere of Wavelengths from 4 Centimeters to 8 Millimeters," *Journal of Geophysical Research*, Vol. 74, 1969, pp. 4453-4471.

Hollinger, J. P., "Passive Microwave Measurements of the Sea Surface," *Journal of Geophysical Research*, Vol. 75, 1970, pp. 5209-5213.

Nordberg, W., Conaway, J., and Thaddeus, P., "Microwave Observations of Sea State from Aircraft," *Quarterly Journal of Royal Meteorological Society*, Vol. 95, 1969, pp. 408-413.

Paris, J.F., *Microwave Radiometry and its Application to Marine Meteorology and Oceanography*, Reference No. 69-IT, Project 286-13, Office of Naval Research Contract No. NOnr 2-119(04), Texas A&M University, College Station, 1969, 210 pp.

Singer, S. F., and Williams, G. F., "Microwave Detection of Precipitation over the Surface of the Oceans," *Journal of Geophysical Research*, Vol. 73, 1968, pp. 3324-3327.

Stogryn, A., "Apparent Temperature of Sea at Microwave Frequencies," Transactions on Antennas & Propagation, AP-15, IEEE, 1967, pp. 278-286.

Strong, A., and Fleming, M., "Aircraft Microwave Measurements of the Arctic Ice Pack," ESSA Technical Memorandum NESCTM 25, Department of Commerce, Washington, D.C., 1970, 21 pp.

Strong, J., Concepts of Classical Optics, W.H. Freeman and Co., San Francisco, 1958, 692 pp.

World Meteorological Organization, "Scope of the 1972-1975 Plan with Particular Reference to the Meteorological Satellite Sub-System," World Weather Watch Planning Report No. 30, 1969, Appendix C.6.

BIBLIOGRAPHY

Edison, A., "Calculated Cloud Contributions to Sky Temperatures at Millimeter Wave Frequencies," NBS Report 9138, 1966, 26 pp.

Kreiss, W.T., "Meteorological Observations with Passive Microwave Systems," PhD.Dissertation, Univ. of Washington, Seattle, and Boeing Document D1-82-0692, 1968, 198 pp.

Porter, R.A., "An Analysis of Airborne Microwave Radiometric Data," Final Report, NASA Contract No. NAS 5-11685, Radiometric Technology, Inc., Cambridge, Mass., 1970, 116 pp.

Porter, R.A., and Florance, E.T., Feasibility Study of Microwave Radiometric Remote Sensing, Vol. 1, NASA/ERC Contract No. NAS 12-629, Ronald A. Porter, Professional Engineer, Cambridge, Mass., 1969, 348 pp., available from the NTIS.

Shifrin, K.S., Editor, "Transfer of Microwave Radiation in the Atmosphere," Transactions of the Main Geophysical Observatory, A. I. Voyeykov, No. 222, NASA Translation TT-F-590, July 1969, 185 pp., available from the NTIS.

(Continued from inside front cover)

NESCTM 11 Publications by Staff Members, National Environmental Satellite Center and Final Reports on Contracts and Grants Sponsored by the National Environmental Satellite Center 1968. January 1969. (PB-182 853)

NESCTM 12 Experimental Large-Scale Snow and Ice Mapping With Composite Minimum Brightness Charts. E. Paul McClain and Donald R. Baker, September 1969. (PB-186 362)

NESCTM 13 Deriving Upper Tropospheric Winds by Computer From Single Image, Digital Satellite Data. Charles S. Novak, June 1969. (PB-185 086)

NESCTM 14 Study of the Use of Aerial and Satellite Photogrammetry for Surveys in Hydrology. Everett H. Ramey, March 1970. (PB-191 735)

NESCTM 15 Some Aspects of the Vorticity Structure Associated With Extratropical Cloud Systems. Harold J. Brodrick, Jr., May 1969. (PB-184 178)

NESCTM 16 The Improvement of Clear Column Radiance Determination With a Supplementary 3.8μ Window Channel. William L. Smith, July 1969. (PB-185 065)

NESCTM 17 Vidicon Data Limitations. Arthur Schwalb and James Gross, June 1969. (PB-185 966)

NESCTM 18 On the Statistical Relation Between Geopotential Height and Temperature-Pressure Profiles. W. L. Smith and S. Fritz, November 1969. (PB-189 276)

NESCTM 19 Applications of Environmental Satellite Data to Oceanography and Hydrology. E. Paul McClain, January 1970. (PB-190 652)

NESCTM 20 Mapping of Geostationary Satellite Pictures - An Operational Experiment. R. C. Doolittle, C. L. Bristor and L. Lauritson, March 1970. (PB-191 189)

NESCTM 21 Reserved.

NESCTM 22 Publications and Final Reports on Contracts and Grants, 1969--NESC. Staff Members, January 1970. (PB-190 632)

NESCTM 23 Estimating Mean Relative Humidity from the Surface to 500 Millibars by use of Satellite Pictures. Frank J. Smigielski and Lee M. Mace, March 1970. (PB-191 741)

NESCTM 24 Operational Brightness Normalization of ATS-1 Cloud Pictures, V. Ray Taylor. August 1970. (PB-194 638)

NESCTM 25 Aircraft Microwave Measurements of the Arctic Ice Pack. Alan E. Strong and Michael H. Fleming, August 1970. (PB-194 588)