Remote Sensing of Sea Conditions with Microwave Radiometer Systems

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Microwave radiometric techniques have been recently developed to provide continuous, all-weather monitoring of sea conditions from satellites. Data acquired with microwave radiometers from Earth orbiting satellites could provide meteorologists and fishermen alike with previously unattainable up-to-date information on sea state and sea temperature over the entire Earth. Since few well-calibrated radiometric measurements have previously been made, it is highly desirable, prior to committing to a satellite operation, that an experimental program be conducted in an environment with ground truth information readily available. The purpose of the program was to obtain data curves under carefully monitored conditions for initial pre-satellite data on sea state and sea temperature. In particular, the effects of white caps, foam, spray, and surface ripples were considered to show their contributions upon brightness temperature. This program is a continuing program, thus, up-to-date data will be presented upon fine detail effects as well as any other major sea state parameters influencing sea conditions.

Introduction

INFORMATION about the condition of the sea surface is of major importance to shipping, fishing, and naval operations. Likewise, other oceanographic activities and meteorological analyses and forecasts require sea surface data across the full expanse of the oceans. Two of the important parameters are sea state and sea surface temperature.

To date, determinations of sea state and sea surface temperature have been acquired as a result of local measurements and observations made either with in situ devices or visually from surface craft, shore observations, and where possible, observations from low-flying aircraft. Obviously, only limited coverage is possible through the use of these techniques, and significant data cannot always be made available on a timely basis. What is needed is an operational remote sensing system through which measurements of sea state and sea temperature can be made from a spacecraft on a world-wide basis and reported in a timely fashion. It is believed that such a capability is possible through the use of passive microwave radiometry.

Several microwave radiometric experimental programs were proposed early last year as a result of a number of studies made by Microwave Sensor Systems. The purpose of the experimental programs was to generate curves relating sea state and sea surface temperature to apparent radiometric temperatures, providing the basic data to be used with remote microwave radiometric measurements for determining sea state and sea surface temperature.

The experimental program consists of two types of measurements. The first experiments are a series of measurements on several closely controlled or monitored environments, such as water tanks and local piers. The results of the tank measurements may be used to establish the relationship between apparent (radiometric) and actual (thermometric) sea temperature as a function of frequency, viewing angle, and signal polarity. The results of the pier or tower measurements may be used to obtain qualitative relationships between radiometric measurements and sea state. Following these measurements, a series of aircraft measurements coincident with ground truth measurements will provide sea state data curves in an actual ocean environment. The results of the analysis for various aircraft altitudes can then be extrapolated to produce corresponding curves for satellite altitudes.

Following a discussion of the theory for determining sea state and sea temperature the data taken to date will be presented.

Application of Microwave Radiometry to Measurements of Sea State and Sea Temperature

The ability to determine sea state and sea temperature, regardless of weather, on a world-wide basis has many economic advantages (shipping routes, fishing grounds, etc.). Only very limited and infrequent coverage is presently provided, with considerable time elapsing before the observations are reported. The advantages of using a satellite to make these measurements remotely are immediately apparent. All information is centralized in a single time period.

The theory for sea state and sea temperature measurements may be briefly summarized as follows: The total radiation emitted from the sea surface is dependent upon the surface temperature and emissivity. The amount of radiation (energy) received by a microwave radiometer for a given frequency interval and field of view depends upon 1) radiation emitted from the surface being viewed, 2) angular relation between the radiometer field of view and the surface, 3) atmospheric effects upon this emitted radiation, and 4) amount of radiation contributed by the atmosphere to the radiometer.

A microwave radiometer is an ultra-sensitive receiver that measures the power impinging upon its antenna over a chosen frequency interval. The operating frequency of a microwave radiometric system, in general, is predicated on the use for which the system is intended. For Earth-looking applications, the frequency selected is generally within one of the so-called atmospheric "windows" wherein the signal is not significantly attenuated or masked by either the atmosphere or other meteorological effects. Since resolution is

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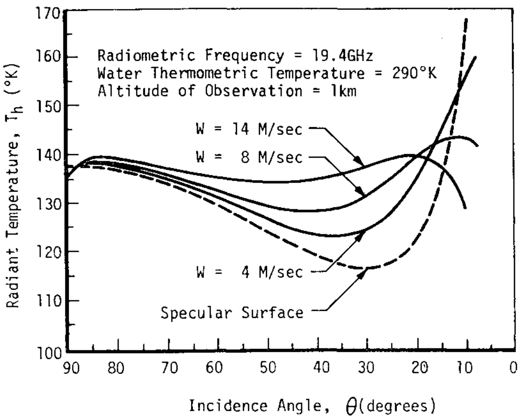

Fig. 1 Temperature of horizontally polarized radiation as a function of angle.

critical for most detection systems, operation within the highest possible window frequency is usually required.

The sensitivity of microwave radiometric systems has been considerably improved over the past several years. It is possible to fabricate highly reliable all solid-state systems (to operate at millimeter wavelengths) that are sensitive to extremely small changes in emissivity or reflectivity. The application of this technology to measuring sea state and sea surface temperature from either aircraft or spacecraft was investigated in detail in the course of studies performed for RCA by Microwave Sensor Systems (MSS). The results of these studies indicated that changes in sea state and sea temperature produce radiometric temperature values that are detectable with present-day microwave radiometric equipment. It was further shown that the effects of the atmosphere can be closely determined and removed from the sea state and sea temperature measurements.

Theoretical calculations by Stogryn[1] based on Kirchoff's approximations of a rough finitely conducting surface showed that significant apparent radiometric temperature changes can be observed in horizontally polarized signals§ for changes in sea state and incidence angle (Fig. 1). Stogryn's calculations further showed that for angles near 40° incidence to the water surface, vertically polarized radiometric temperatures are invariant with changes in sea state (Fig. 2). Furthermore, it has been shown[2] that the radiometric temperature is nearly insensitive to changes in the water thermometric temperature near the water absorption line (Fig. 3). A frequency of 30 GHz was selected since the radiometric temperature is still essentially invariant to water temperature and at a frequency within an atmospheric window. It has been determined that any deviation from radiometric temperature invariance can be corrected by means of interative computations.

In summary, the bases for performing sea state and sea temperature measurements using selected dual frequencies and orthogonal polarizations are 1) horizontally polarized microwave radiometric signals are significantly sensitive to changes in sea state and incidence angle (and in a lesser way to sea temperature); 2) vertically polarized microwave radiometric signals are invariant to sea state at or near an incidence angle of 40° to the surface; 3) microwave radiometric signals (of both polarizations) are nearly invariant to changes in the water thermometric temperature at frequencies at or near that of water absorption; and 4) the effects of nonpolarized loss mechanism like intervening atmosphere and, possibly, foam can be removed.

The purpose of the experimental program discussed herein is to obtain families of curves of apparent radiometric temperatures vs sea state and sea surface temperature using microwave radiometric systems at three frequencies within the microwave atmospheric windows—one at a frequency insensitive to thermometric temperature and the other two at frequencies sensitive to thermometric temperature. These curves will vary also with different contributions from the atmosphere and different losses of emitted and reflected radiation through the atmosphere. The application of Stogryn's theory to the generation of these curves during the experimental program and to the use of the curves to obtain sea state and sea surface temperature from satellite measurements has been previously described[2,3] and will not be repeated herein.

Experimental Program

The major goal of the microwave radiometer experiment described herein is to obtain airborne radiometric and ground-truth data as a basis for spacecraft sensing programs for sea state temperature. Specific tasks are to establish microwave radiometric temperature curves for various sea states and include the effects of sea surface ambient temperatures.

The measurement frequencies for all experiments were 10.2, 30, and 38 GHz. The measured data from the 30 GHz radiometer can be used in conjunction with that obtained from either the 10.2 or 38 GHz radiometers to determine sea temperature. Use of the 38 GHz radiometer is preferable because of the smaller antenna for eventual space use.

Both vertically and horizontally polarized radiometric measurements are made simultaneously. The vertical and horizontal measurements are made with the same receivers by time-sharing both the antenna and the receiver. This is accomplished with a Faraday rotator switch to select the desired output of a dual polarized horn antenna.

Measurements, both groundbased and airborne, in general, will be made at the invariant incidence angle; however, curves are made at other angles to verify the invariant angle and also to obtain sea state curves as a function of angle. These curves will determine the angle for maximizing the sea state signals if further experiments are conducted which do not require sea temperature information.

The microwave radiometric equipment used for all measurements were all solid-state, state-of-the-art instruments

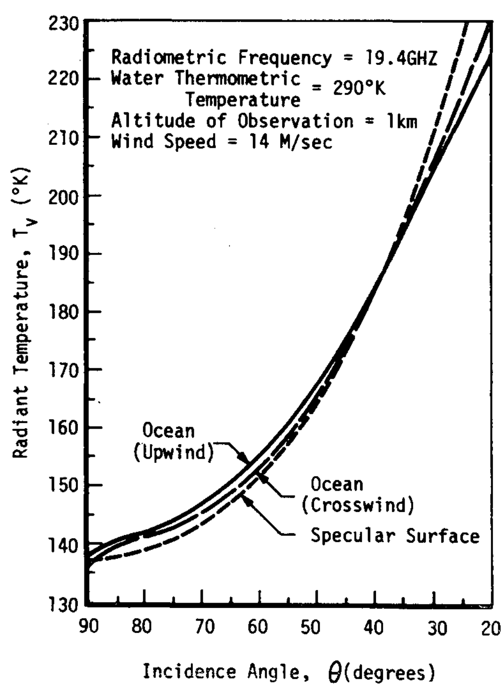

Fig. 2 Temperature of vertically polarized radiation as a function of angle.

§ The expressions, "horizontally" and "vertically" polarized signals, refer to the horizontal and vertical spatial components of the polarized signals received.

Table 1 Equipment parameters

Center frequency	10.2 GHz	30 GHz	38 GHz
Sys. sensitivity (=1 sec)			
Single polarization	0.10°K	0.18°K	0.20°K
Dual polarization	0.15°K	0.25°K	0.30°K
Prediction bandwidth (min)	400 MHz	400 MHz	400 MHz
Antenna bandwidth	4.5°	2.0°	2.0°
Power requirements (max)	20 w	12 w	10 w

easily adaptable to space operation. Major system parameters for these instruments are shown in Table 1. All instruments are dual polarized with internal calibration loads. With these instruments absolute measurement accuracy of better than ±0.5°K is possible.

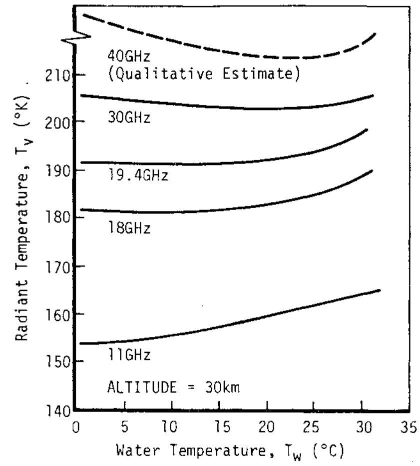

Fig. 3 Radiometric temperature vs ambient temperature.

Surface Based Measurement Program

Two sites were selected for pier type measurements in the Los Angeles area. The first site was along the San Gabriel River near the Alamitos Bay Southern California Edison Power Plant. The water in the river is tidal seawater exhausted from the Long Beach Harbor and seawater exhausted from the Cerritos Channel (on the other side of the power plant), used for cooling the generators. The exhaust water from the generators was reported to be nearly 10°C warmer than the sea water. It was hoped that the water exhausted from the power station would provide a source for measuring significant temperature changes by measuring up-stream or down-stream, with the changing tides. However, large temperature changes were not encountered as the volume of water from the power plant exhausts are so great that the water temperature changed less than 3°C on either side of the outlets, regardless of the tide's magnitude or direction. The quantity of water exhausted created considerable turbulence and large amounts of foam. While the site did not provide large temperature variations, data on foam and turbulence was readily available. A summary of the data is tabulated and compared with a no-foam/no-turbulence condition in Table 2.

Near the surface water temperatures for the values ranged from 25.1°C during the smooth conditions to 27.6°C. Sky temperatures were constant at 46°K and 59°K for 10.2 GHz and 38 GHz, respectively. The readings in the table have not been corrected for these small changes (0.8°K) in radiometric temperature due to thermometric water changes, as its effect is masked by the foam and not significant compared to the changes caused by turbulence and foam.

The beam intercepts for the 10.2 and 38 GHz systems were approximately 6 × 4 ft and 3 × 2 ft, respectively; thus, several small waves were viewed simultaneously except in the eddy current condition, which probably accounts for the colder reading for the 38 GHz horizontal beam intercept area.. The effects of foam on the water may account for the measured anomalies in Stogryn's analytical curves reported by Nordberg et al.,[3] as significant white caps were noted in the area.

A second site selected for collecting pier sea state data was in Long Beach off the Long Beach Marina Sea Wall. Large variations in sea state conditions do not exist, but within a 24-hr period the winds and weather consistently provide changes from sea states of 0 to 1 or 2 with little or no sea temperature changes. A summary of the data collected is listed in Table 3.

The results shown in Table 3 show that little or no change is noted in the average radiometric temperature with changes in wave height. This is probably due to the small beam intercept area of approximately 3 × 2 ft, and $1\frac{1}{2}$ × 1 ft at 10.2 and 38 GHz, respectively. Intercept area of this size, in general, can emit energy only from single waves; thus as shown in the data, increased wave height is shown only by an increase in the noise-like variations about an unchanging average. It is believed that these will appear as biasing parameters on larger samples. Foam, while not common at this site, did occasionally occur along with oil slicks, and has a marked effect on the radiometric signatures. Small quantities of foam were readily seen as an increase in temperature. Thin layers of oil reduced the noise-like wave readings as predicted by resultant lower sea states or reduction in ripple.[5]

Table 2 Radiometric temperatures with foam and turbulence at 50° nadir

% foam	Turbulence	Radiometric temperature H(°K)	Radiometric temperature V(°K)	Wave-action effect H(°K)	Wave-action effect V(°K)
		10.2 GHz			
0	1-in. ripples	107	177	...	...
5–10	2-3-in. waves	121	184	1	1
15	Eddy currents, some waves	123	197	20	15
80–90	Water boiling	213	243	40	15
		38 GHz			
0	1-in. ripples	157	237	...	...
5–10	2–3	163	238	2	2
Patches of 20	Eddy currents, some waves	158	241	15[a]	15[a]
80–90	Water boiling	230	275	35	15

[a] 3–4-in. waves with foam.

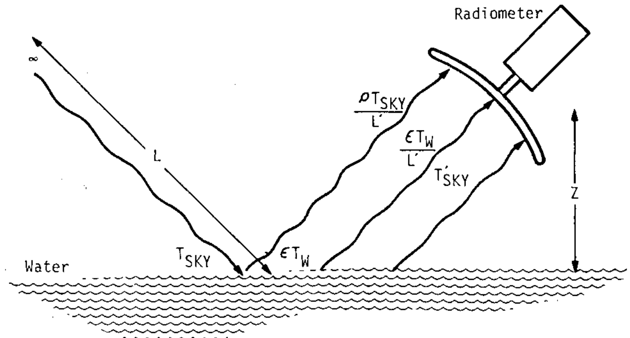

Fig. 4 Model of radiation components affecting sea state and sea temperature.

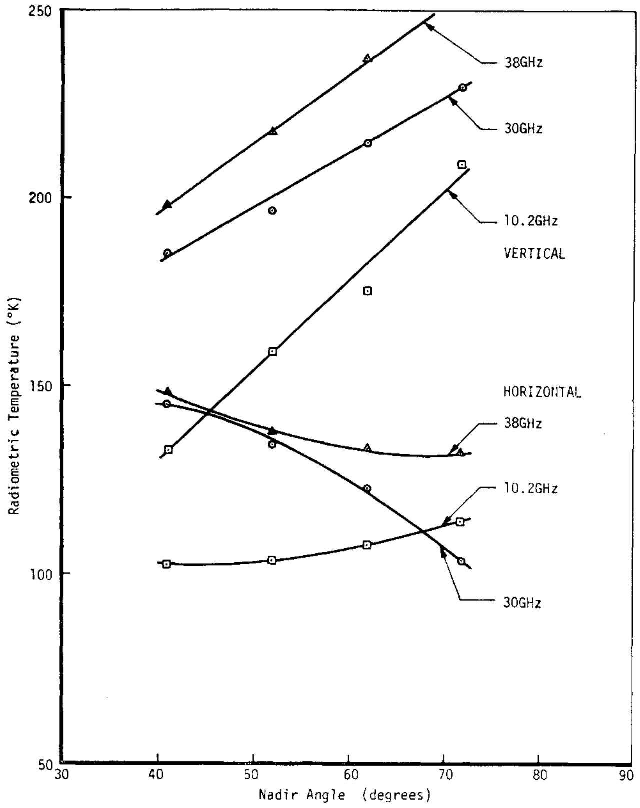

Fig. 5 Horizontal and vertical polarized measurement data.

Several measurements were made at various nadir angles and compared with those predicted by Stogryn. The results of these measurements are shown in Fig. 4. The curves are not corrected for antenna gain or sky temperature differences; however, the results shown have similar slopes as predicted and differ by predictable amounts for each frequency. Temperature effects have not been measured at this writing; however, tests are under way and will be presented as available.

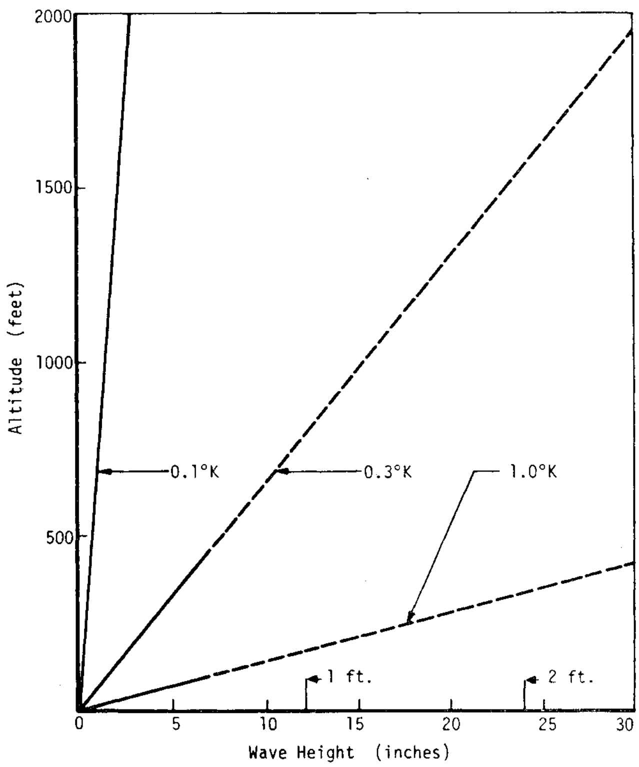

Fig. 6 Minimum measurement altitude requirements for various wave heights.

Airborne Measurements

Airborne measurements have not yet been initiated, but a result of the ground-based measurements point out the necessity of performing these airborne measurements. The airborne measurements are necessary to determine the effects of varying the slant range and to provide adequate slant range so that the resolution cell size does include several water surface wavelengths free from land effects. The beamwidths of the three antennas used for ground-based measurements were selected to obtain valid data for a spacecraft radiometer system. The principal consideration in beamwidth selection is that its intercept must be narrow enough to correspond to a specific incidence angle but still large enough to integrate over sufficient ocean surface area to pick up full wave trains and to average out local or transient phenomena.

Fine grain detail, described in Table 3, may be further examined to show the necessity of performing any additional measurements from an aircraft. Individual wave action produced 7°K variation at 38 GHz for 6- to 8-in. wave heights. These waves were a result of 15 to 20 knot winds with less than a mile of fetch. All of the measurements shown in Table 3 were sampled on a basis of approximately a 2-ft^2 spot size with a 38 GHz radiometer from 20-ft altitude. This spot size is not large enough to smooth statistically the 7° variations. To reduce the variations to 0.3°K uncertainties, the statistical sampling theorem indicates the number of samples (spot size) must be increased by a factor of 544. This number of samples implies that altitudes of nearly 500 ft are required to reduce the noise level to 0.3°K.

The increase in noise from individual waves continues to increase with wave height at a rate of nearly 1°K/in. of wave height. Measurements could not be continued for greater wave heights because fully developed seas were not available at this test site. However, extrapolations can be made relating required altitude of measurements to wave height (which may be related in turn to wind speed and sea state). Using the values of Table 3 and statistical sampling theory, the curves of Fig. 6 show the minimum altitude required to make measurements of certain wave heights at noise levels of 0.1, 0.3, and 1°K. Wave heights above 7 in. are shown as dashed values indicating extrapolated values.

The waves measured during this experiment are estimated to have wavelength to wave height ratio of nearly 10. In fully developed seas, ratios of 14 are typical. Values lower than 10 are not often encountered except in laboratory environments where ratios of 7 have been occasionally produced. The slope of the 0.3°K curve is nearly 775-ft altitude/ft of wave height. Extrapolating this curve shows that altitudes in excess of 15,000 ft will be required to measure 20-ft waves using a 2.4° antenna beamwidth. At that altitude, the beam intercept is approximately 1000 ft wide, which is

Table 3 Radiometric temperature with change in wave height at 50° nadir

Wave height	Radiometric temperature 10.2 GHz H(°K)	10.2 GHz V(°K)	38 GHz H(°K)	38 GHz V(°K)	Wave 10.2 GHz (°K)	Wave 38 GHz (°K)
Flat (ripple)	108	154	160	223	1	1
1–2 in.	107	151	161	215	1	1
3 in.	107	148	161	215	1	2
3–4 in.	107	148	162	215	2	3
4–5 in.	112	148	161	214	2	4
6 in.	116	153	161	212	3	6
6–8 in.	117	156	169	220	3	7

five times the wavelength expected for 20-ft waves. Altitudes of that range should be a minimum for looking at a fully developed sea. The curve of Fig. 6 shows that if the noise levels are to be reduced to 0.1°K, altitude requirements become too high for most measurement aircraft; however, altitudes to give 1° variations can be quite easily reached by conventional aircraft.

The aircraft data can be used to supplement or modify the previously derived curves which relate T_h, T_v, sea state, and T_w. It is expected that the results can be extrapolated to observation levels above the atmosphere for satellite applications. The aircraft measurements program will also provide additional information on sources of error in the microwave radiometric measurements, and ground truth measurements and airborne photographs should be used to aid in data analysis.

Summary

The ground based measurements indicate that foam and surface ripple must be considered in any system measuring sea state or sea temperature. The presence of foam significantly modifies the radiometric temperature by 20°–100°, depending upon the quantity of foam in the beam. The measurements further point out the need for airborne measurements to generate curves for sea state determination.

References

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