AD/A-001 302

THE DETERMINATION OF OIL SLICK THICKNESS BY MEANS OF MULTIFREQUENCY PASSIVE MICROWAVE TECHNIQUES

James P. Hollinger

Naval Research Laboratory

Prepared for:

Coast Guard

30 June 1974

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 2953	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD/A-001 302
4. TITLE (and Subtitle) THE DETERMINATION OF OIL THICKNESS BY MEANS OF MULTIFREQUENCY PASSIVE MICROWAVE TECHNIQUES		5. TYPE OF REPORT & PERIOD COVERED Final Report 6. PERFORMING ORG. REPORT NUMBER CG-D-31-75
7. AUTHOR(s) James P. Hollinger		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Prob. G01-08 USCG Z-70099-2-21881 DOT/USCG 2-21881
11. CONTROLLING OFFICE NAME AND ADDRESS Department of Transportation U. S. Coast Guard Washington, D.C. 20590		12. REPORT DATE June 30, 1974 13. NUMBER OF PAGES 143
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Water Pollution	Oil Slick Spreading
Oil Pollution	Oil Slick Detection
Oil Slick Thickness	Remote Sensing
Oil Slick Volume	Passive Microwave Radiometry

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A technique for the remote determination of the thickness and volume of sea surface oil spills using multifrequency microwave radiometry was investigated. Aircraft-borne measurements were made at 19.3 and at 31.0 or 69.8 GHz of a total of fifteen controlled marine oil spills. The spills consisted of from 200 to 630 gallons of either No. 2 fuel oil or No. 4 or No. 6 crude oil. The first eight spills were conducted under calm sea conditions with surface winds of less than 10 knots. A second

(Abstract continues)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. (Continued Abstract)

group of seven spills was subsequently carried out to investigate the effects of rougher seas and higher marine wind speeds. Measurements were obtained with seas of up to 5 feet, swell of up to 8 feet and winds of up to 24 knots during this group of spills.

The microwave measurements of the oil spills of each oil type showed very similar results. The slicks formed an identifiable region with film thicknesses of a millimeter or more and containing the majority of oil which was surrounded by a very much larger and thinner slick which contained very little of the oil. In general the thick region contained more than 90 percent of the oil in less than 10 percent of the area of the visible slick. It was always possible to locate and delineate the thick region solely from the microwave observations. The total volume of oil present derived from the microwave measurements was within about 25 percent of the volume of oil spilled. Multifrequency passive microwave radiometry offers the potential to measure the distribution of oil in sea surface oil slicks, locate the thick regions, and measure their thickness and volume on an all-weather, day or night, and real time basis. As such it should prove a useful tool in the confinement, control, and clean up of marine oil spills.

CONTENTS

THE DETERMINATION OF OIL SLICK THICKNESS BY MEANS OF MULTIFREQUENCY PASSIVE MICROWAVE TECHNIQUES

INTRODUCTION

Before appropriate corrective action can be taken to deal with marine oil spills a knowledge of the nature, thickness, areal extent, direction and rate of drift of the slick must be promptly established. Sea surface oil spills do not spread uniformly nor without limit (1, 2). Thick regions with thicknesses of a millimeter or more are formed which contain the majority of the oil and are surrounded by very much thinner and larger slicks. Reliable determination of oil film thickness is of major importance. It is the film thickness along with areal extent which allows the volume of the slick to be estimated. A knowledge of the volume of oil is essential for litigation and damage claims resulting from major oil spills as well as for assessing the impact of the spill on marine life and environment. Perhaps most important, a knowledge of the oil distribution and the location of those regions containing the heaviest concentration of oil would enable the most effective confinement, control, and clean up of the oil.

Multifrequency microwave radiometry offers a unique potential for the determination of oil slick thicknesses greater than about 0.05 mm. This promising technique arises because the apparent microwave brightness temperature is greater in the region of an oil slick than in the adjacent unpolluted sea by an amount which depends upon the slick thickness. In effect, the oil film acts as a matching layer between free space and the sea enhancing the brightness temperature of the sea. As the thickness of the oil film is increased, the apparent microwave brightness temperature at first increases and then passes through alternating maxima and minima due to the standing wave pattern set up by the sea surface. The maxima and minima occur at successive integral multiples of a quarter of the observational wavelength in the oil. By using two or more frequencies, thickness ambiguities introduced by the oscillations may be removed and the film thickness determined for a wide range of thicknesses. The film thickness along with the areal extent of the slick allows the volume of the oil spill to be found.

The objective of this study is to investigate the feasibility of remote determination of the thickness and areal extent of sea surface oil slicks using a multi-frequency, passive microwave technique. The investigations are divided into three main areas: theoretical studies, the laboratory measurements program, and the airborne measurements program.

The objective of the theoretical studies is to investigate the effects of the observational parameters of frequency, incidence angle and polarization, and the dielectric properties of oil on the increase in microwave brightness temperature of an oil slick as a function of slick thickness. In addition the effects of sea state and the effects of variations in the thickness of the oil film over the extent of the slick on the detection and measurement of oil slicks is investigated. The objective of the laboratory measurements program is to confirm the theoretical predictions of the increase in the microwave brightness temperature of an oil film covered water surface as a function of oil film thickness and oil type in a controlled laboratory environment. The objective of the airborne measurements program is to conduct aircraft borne multifrequency microwave observations of controlled ocean oil spills and to compare the film thicknesses and total volume of oil determined from the microwave measurements with in situ oil thickness measurements and the known volume of oil spilled. The approach is to conduct laboratory measurements to verify the theoretically expected variation of microwave brightness temperature with oil film thickness; these results in turn serve as a base for the interpretation of the airborne measurements which are used to test the multifrequency technique. The investigations in each of these three areas will be described and then the results and conclusions discussed.

THEORETICAL STUDIES

1. Parametric Study

The objective of the parametric study is to investigate the effects of the observational parameters of frequency, incidence angle, and polarization, and the dielectric constant and dielectric loss of the oil on the microwave brightness temperature of a smooth sea surface uniformly covered with an oil slick as a function of slick thickness. The oil slick is modeled as a uniform dielectric film covering a smooth semi-infinite sea. The effects of reflected atmospheric radiation and of surface roughness are not included in order to not unnecessarily complicate the parametric study. Their effects are considered separately in sections 2 and 3.

The appropriate equations for the emissivity of a smooth surface covered with a uniform film were developed following an outline of the solution of three layered media by Brekhovskikh (3). A computer program, TRIMEDIA, was written to perform numerical computations using these equations. The dielectric properties of the sea were obtained from a second order, two variable polynomial least square fitted to the data of Saxton and Lane (4).

All of the calculations were done for a uniform air-oilfilm-sea temperature of 20^{o}C and a sea salinity of 35 PPT. Calculations were made at the frequencies of 19.3, 31.0, and 69.8 GHz which were used in the laboratory and aircraft measurements programs. The dielectric properties of oil used were obtained from measurements by Edgerton and Trexler (5) and Howard, Thomas, and Licitra (6) and from "Dielectric Materials and Applications" by Von Hipple (7). These results indicate that the real part of the dielectric constant (E1) of the majority of oils is near 2.1 but ranges from about 1.8 to 2.6. The imaginary part of the dielectric constant (E2) of the oils measured is generally very small, usually less than 0.02, except for aged 40 gravity crude and Bunker C fuel oil where it may be as large as 0.3. The results of these calculations are given in Figures 1 through 11.

Figure 1 shows the increase in brightness temperature due to an oil slick at 0 degrees incidence angle versus slick thickness. Since the oil has a dielectric constant intermediate between air and water, the oil film behaves as a matching layer between free space and the sea. Reflection is minimized and emission is thus maximum when the film has a thickness equal to odd multiples of a quarter wavelength in the oil. Therefore the brightness temperature of an oil slick at first increases, reaches a maximum, and then oscillates with increasing slick thickness. The film thickness corresponding to the first maximum and the separation between maxima decreases with increasing frequency. The oil slick can increase the brightness temperature by 80^{o}K or more above the oil free sea surface. Note that the use of this group of three frequencies will allow oil film thicknesses between about 0.1 and 3.0 mm to be unambiguously determined.

Figure 2 shows the brightness temperature of both the vertical and horizontal linearly polarized components of the brightness temperature at 31.0 GHz versus incidence angle for an oil free sea and for oil films of 0.5, 1.0, and 1.5 mm thickness. Note, from Figure 1, that a thickness of 1.5 mm produces the maximum brightness temperature increase at 31.0 GHz. The largest increase due to the oil film occurs for the horizontal component with a somewhat larger increase in the region of 60 degrees than at 0 degrees. The initial large decrease in the vertical component near Brewster's angle at 80 degrees with increasing film

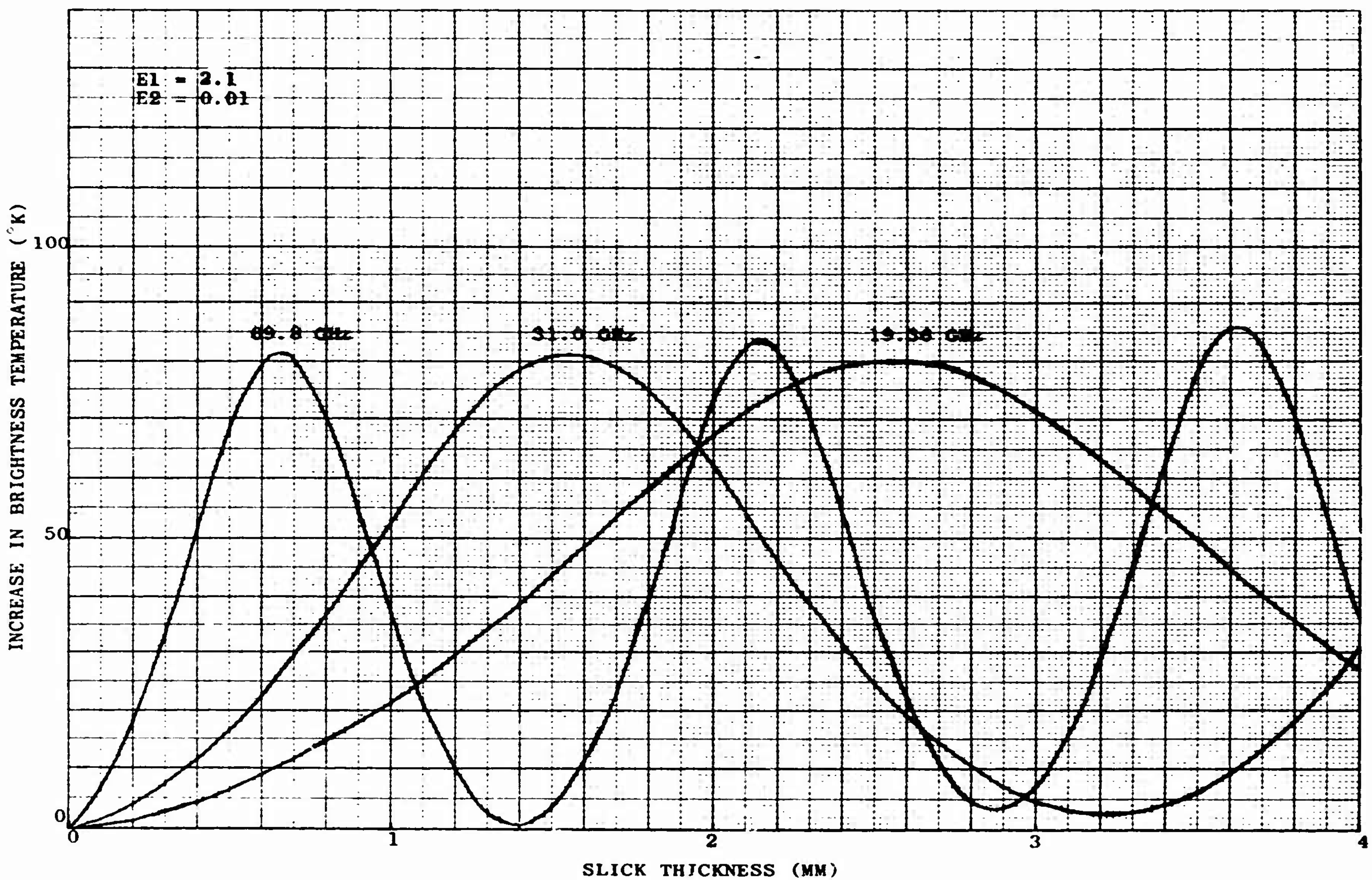
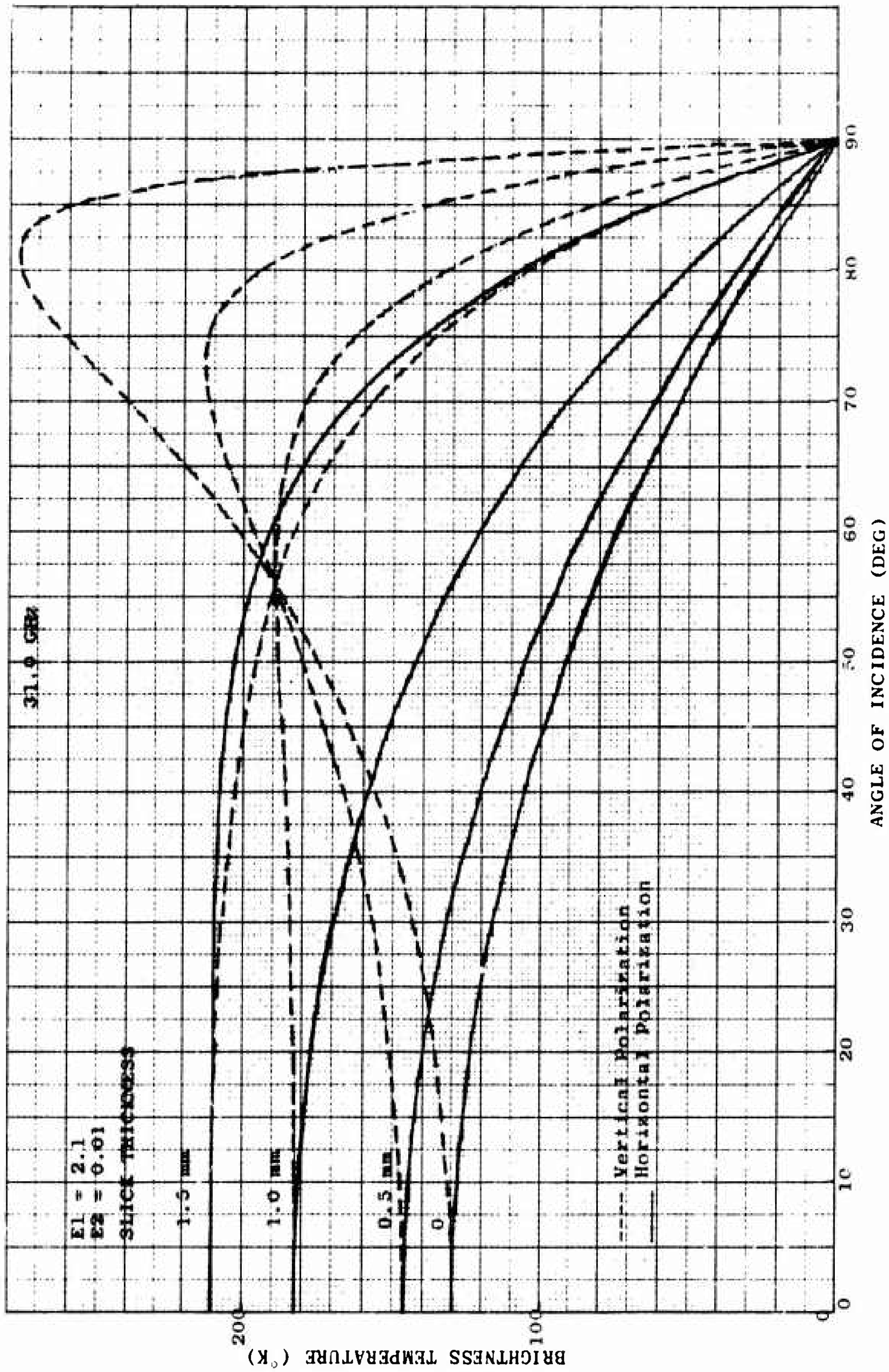
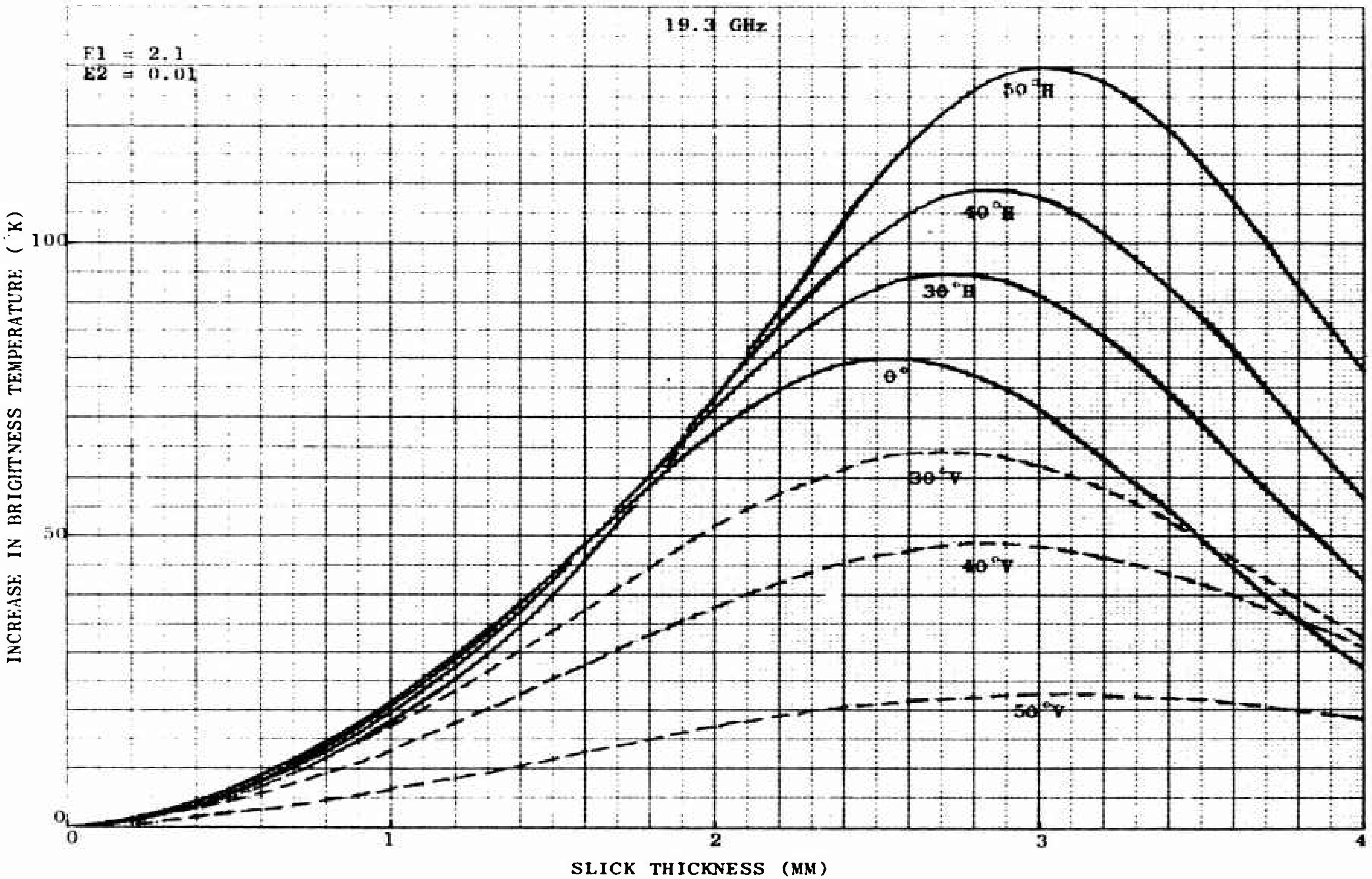

E1 = 2.1
E2 = 0.01
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
100
50
0
0
1
2
3
4
SLICK THICKNESS (MM)

Figure 1



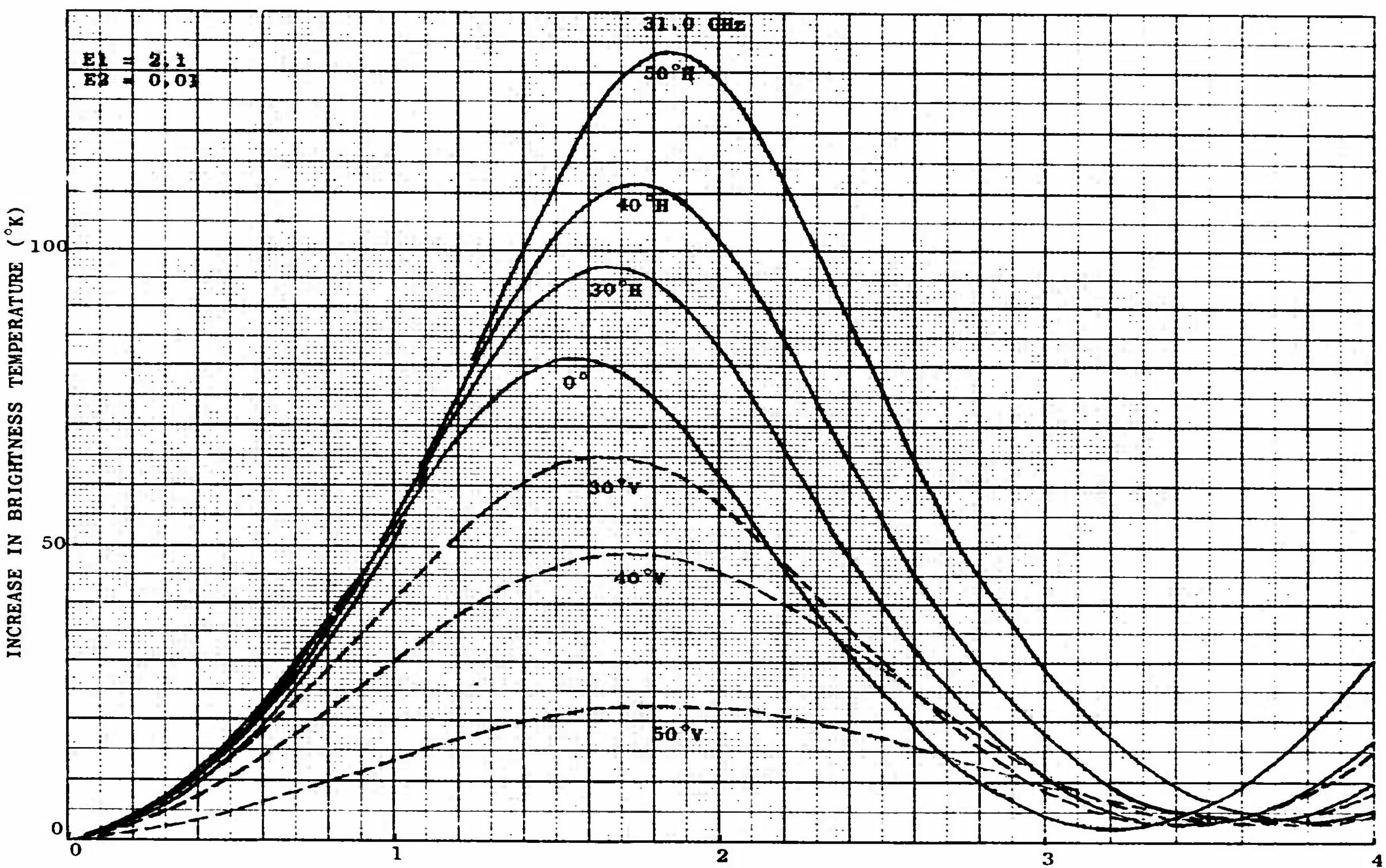
E1 = 2.1
E2 = 0.01
SLICK THICKNESS
1.5 mm
1.0 mm
0.5 mm
0
31.0 GHz
---- Vertical Polarization
—— Horizontal Polarization
ANGLE OF INCIDENCE (DEG)
BRIGHTNESS TEMPERATURE (°K)
0
10
20
30
40
50
60
70
80
90
100
200

Figure 2



19.3 GHz
E1 = 2.1
E2 = 0.01
50°H
40°H
30°H
0°
30°V
40°V
50°V
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
100
50
0
0
1
2
3
4
SLICK THICKNESS (MM)

Figure 3



SLICK THICKNESS (MM)

Figure 4

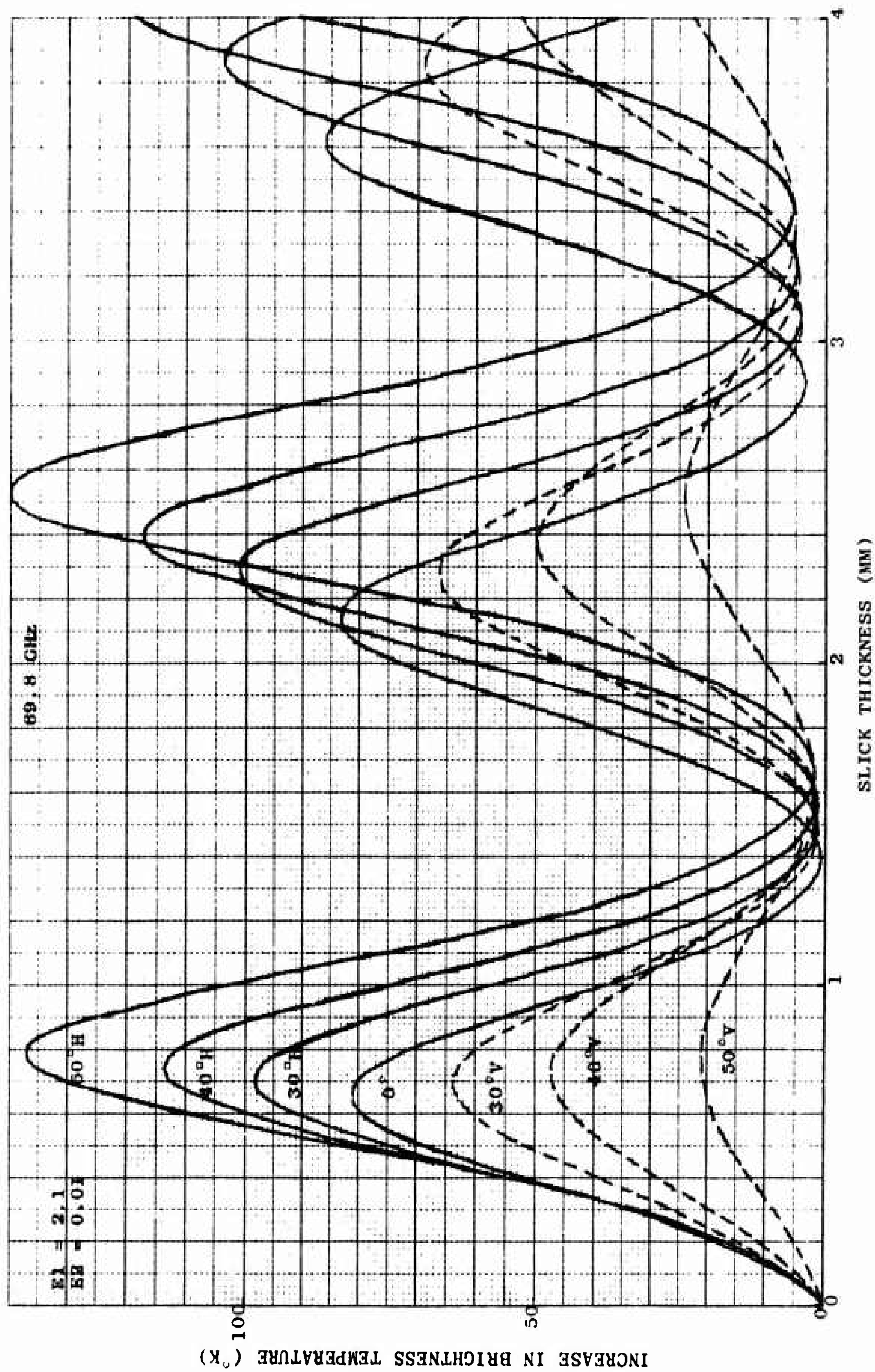

E1 = 2.1
EB = 0.01
69.8 GHz
50°H
40°H
30°H
0°
30°V
40°V
50°V
0
1
2
3
4
SLICK THICKNESS (MM)
0
50
100
INCREASE IN BRIGHTNESS TEMPERATURE (°K)

Figure 5

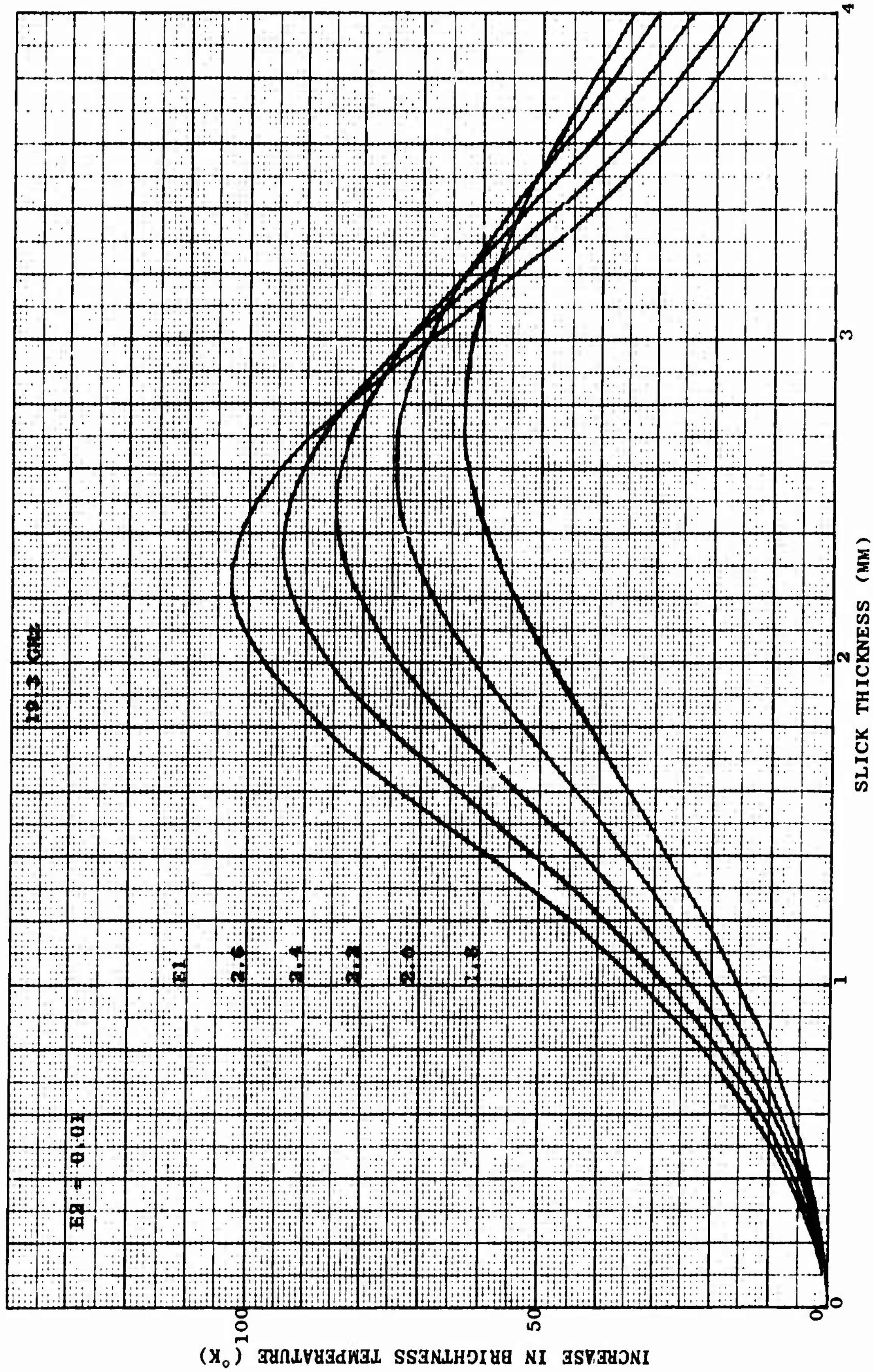

E2 = 0.02
19.3 GHz
E1
2.6
2.4
2.2
2.0
1.8
SLICK THICKNESS (MM)
0
1
2
3
4
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
0
50
100

Figure 6

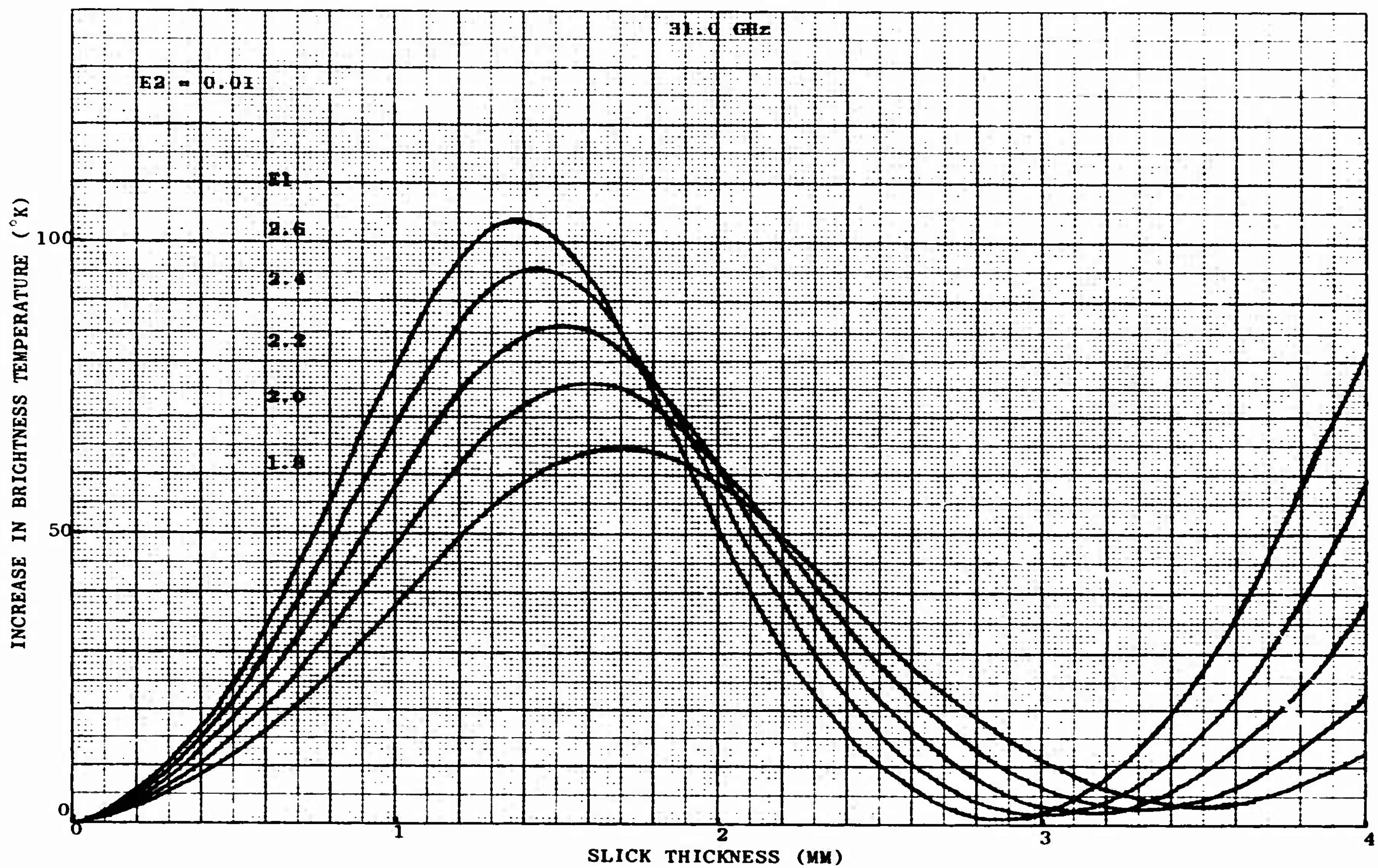

31.0 GHz
E2 = 0.01
E1
2.6
2.4
2.2
2.0
1.8
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
100
50
0
0
1
2
3
4
SLICK THICKNESS (MM)

Figure 7

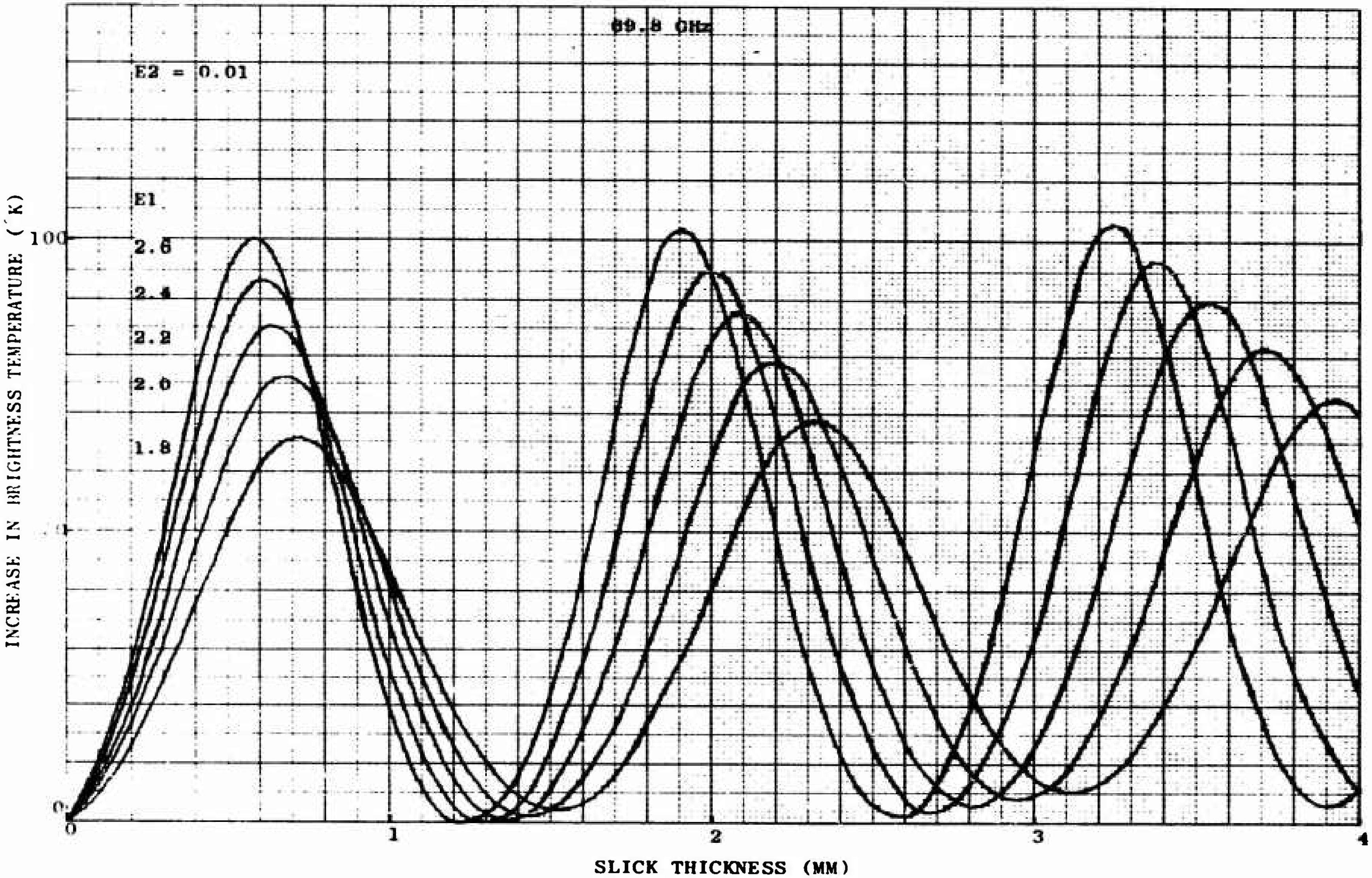

89.8 GHz
E2 = 0.01
E1
2.6
2.4
2.2
2.0
1.8
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
100
0
0
1
2
3
4
SLICK THICKNESS (MM)

Figure 8

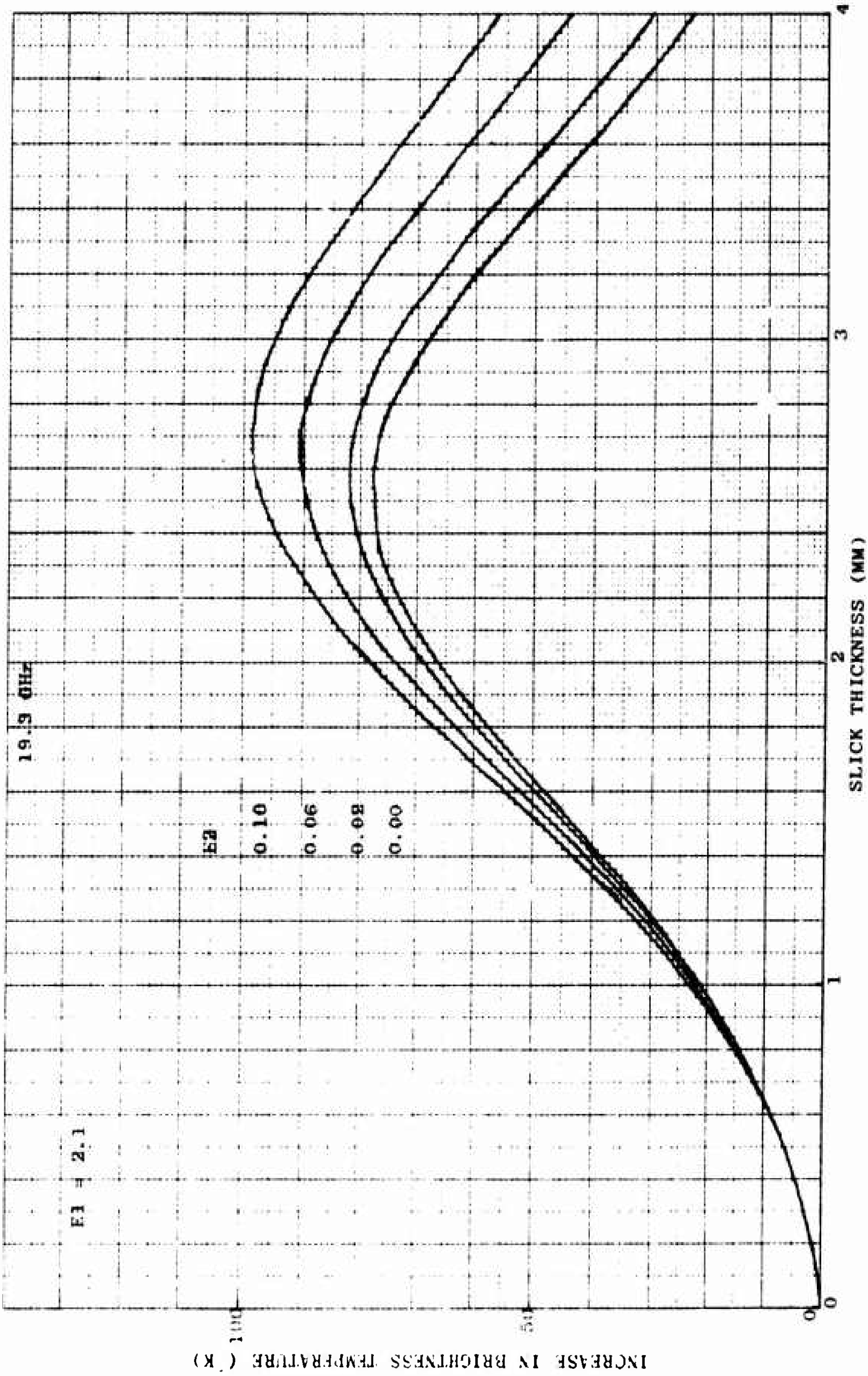
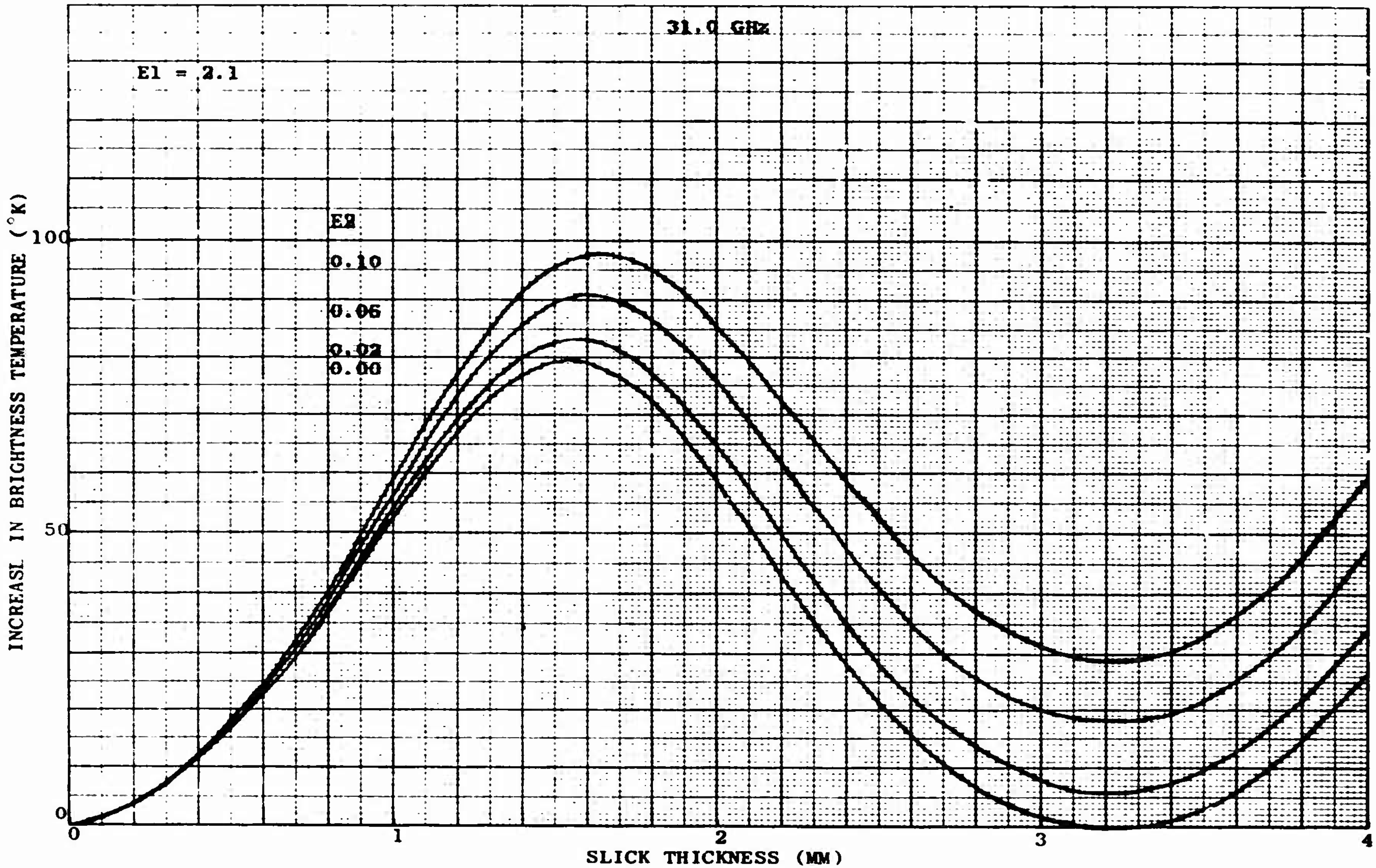

E1 = 2.1
19.3 GHz
E2
0.10
0.06
0.02
0.00
SLICK THICKNESS (MM)
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
0
1
2
3
4
50
100

Figure 9



31.0 GHz
E1 = 2.1
E2
0.10
0.06
0.02
0.00
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
100
50
0
0
1
2
3
4
SLICK THICKNESS (MM)

Figure 10

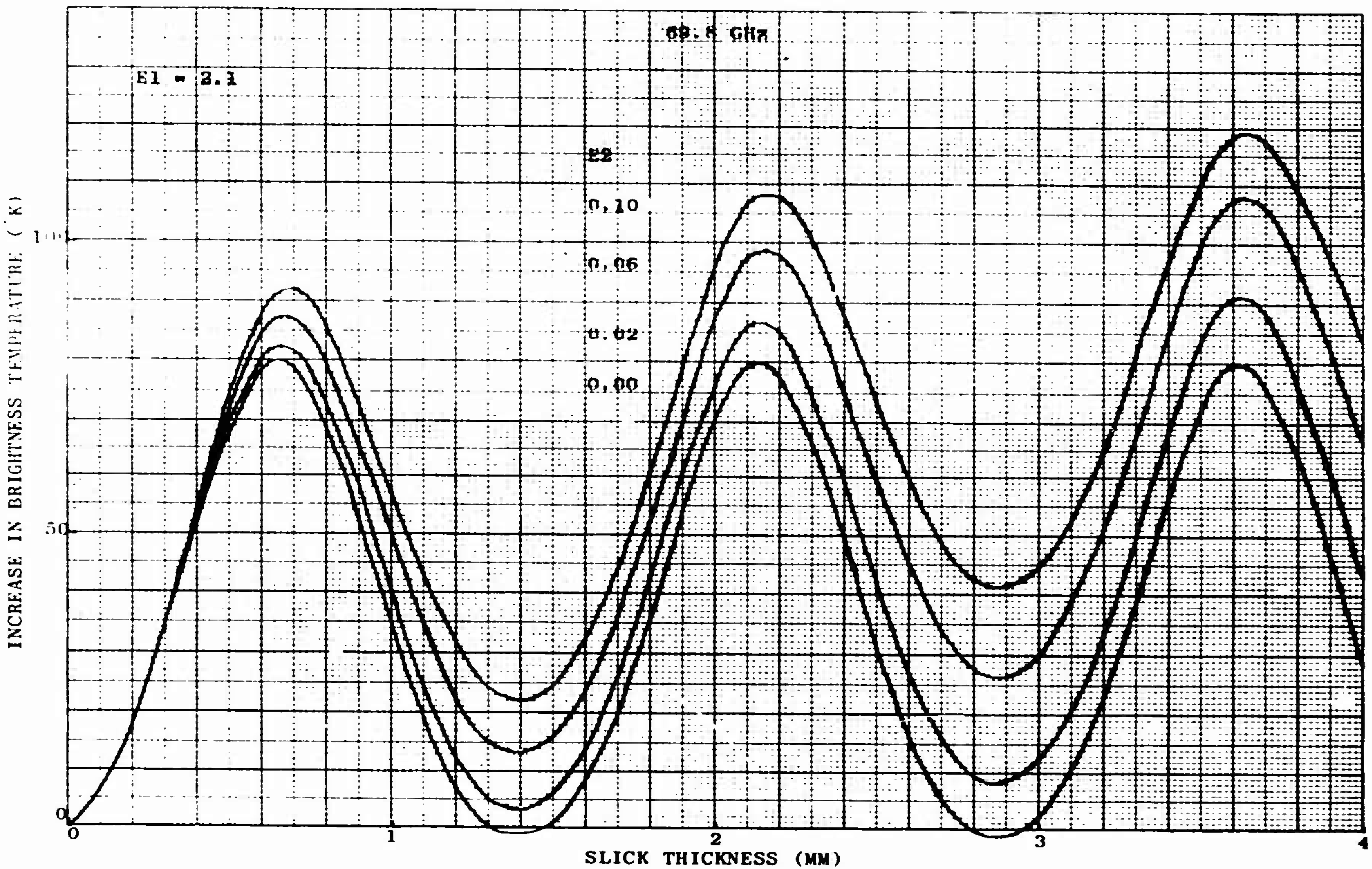

69.8 GHz
E1 = 2.1
E2
0.10
0.06
0.02
0.00
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
100
50
0
0
1
2
3
4
SLICK THICKNESS (MM)

Figure 11

thickness is not of practical significance since a slightly rough sea would greatly reduce the decrease and measurements would be very difficult at such a large incidence angle. The brightness temperature of the vertical component is independent of oil film thickness at about 55 degrees for thin films and low loss oil. As the loss in the oil is increased by forming very thick films, the brightness temperature will increase and approach the physical temperature of the oil.

Figures 3, 4, and 5 show the increase in brightness temperature at 0 degree and at 30, 40, and 50 degree incidence angles for both the vertical and horizontal linearly polarized components versus slick thickness at 19.3, 31.0, and 69.8 GHz respectively. Again it is clear that the largest increases in brightness temperature occur for the horizontal component at larger incidence angles. In addition the maxima and minima occur at increasing film thicknesses as the incidence angle is increased. The maximum value of the increase in brightness temperature also increases with incidence angle for the horizontal component and offsets the decrease, at small thicknesses, due to the shift of the maximum to greater thickness so that the sensitivity to very thin films is roughly independent of incidence angle.

Figures 6, 7, and 8 show the increase in brightness temperature at 0 degrees incidence angle for different values of the real part of the dielectric constant (E1) versus slick thickness at 19.3, 31.0, and 69.8 GHz, respectively. Increasing E1 raises the maximum brightness temperature increase and reduces the thickness at which the maxima and minima occur. The depth of the minima increases slightly and the separation of the maxima decreases markedly with increasing E1.

Figures 9, 10, and 11 show the increase in brightness temperature at 0 degrees incidence angle for different values of the imaginary part of the dielectric constant (E2) versus slick thickness at 19.3, 31.0, and 69.8 GHz, respectively. Increasing E2 raises the brightness temperature increase and greatly reduces the depth of successive minima. The spacing and separation of the maxima and minima are unaffected by changes in E2.

To summarize the above results, a uniform oil film on a smooth sea surface produces oscillations in the brightness temperature of the film as the thickness of the film is increased. The separation of the maxima decrease with increasing frequency. The brightness temperature increase is greater for the horizontal linearly polarized component than for the vertical component and is greatest near 60 degrees incidence angle. While increasing either E1 or E2 of the oil increases the brightness temperature of the film, the primary effect of increasing E1 is to decrease the separation of the maxima whereas the primary effect of increasing E2 is to increasingly raise the value of successive maxima and minima.

2. Effects of Sea State

The microwave brightness temperature dependence on sea state (wind speed) arises from two effects (8). The first effect results from the increasing roughness of the compact water surface and the second effect from the increasing coverage of white caps and sea foam with increasing wind speed. Although both are properly termed roughness effects, the first will be referred to as the surface roughness effect and the second as the sea foam effect.

The surface roughness effect is governed by the wave slope geometry and is primarily determined by surface waves with a wavelength comparable to the observational wavelength

(8). The presence of an oil film on the surface damps out the smaller wave structure and reduces the mean square slope of the surface. Cox and Munk calculated that an oil slick damped waves of 30 centimeter wavelength by a factor or 10 and that waves shorter than this were essentially eliminated (9). Further they found from measurements of sun glitter that an oil slick reduced the mean square slope with respect to a clean surface by a factor of two or three (10). This damping is essentially independent of oil film thickness (11). The effect of the damping of surface waves by an oil slick is to reduce the microwave brightness temperature in the region of the slick below its value from the adjacent unpolluted sea. This decrease is in addition to and counter to the increase in brightness temperature due to the increased emissivity of the oil slick over the clean water surface.

In order to calculate the decrease in brightness temperature due to wave damping by the oil slick, the differential scattering coefficients of both the clean and oil covered sea must be known (12). These coefficients were calculated using the geometric optics model developed by Stogryn (13). This model was chosen because it explicitly contains the wind speed dependence through the Cox and Munk sea surface slope distribution. The wave damping of the oil slick is then taken into account directly by using the sea surface slope distributions measured by Cox and Munk for both clean and for oil covered surfaces (10). In these calculations the complex Fresnel reflection coefficients for the sea surface must be evaluated at all angles appropriate to the surface slope distribution. In the case of the oil covered surface, the reflection coefficients for an air-oil-water surface were calculated.

The calculated depression of the antenna temperature increase resulting from an oil spill due to the effects of sea surface roughness at nadir look angle is given in Figure 12 for 19.3, 31.0, and 69.8 GHz as a function of wind speed. These calculations are based on Stogryn's geometric optics model, the damping of surface waves by the oil as measured by Cox and Munk and the use of Fresnel reflection coefficients for an oil covered water surface. The calculations were done for a uniform air-oil-sea temperature of 20^{o}C, a sea salinity of 35 PPT, dielectric properties of E1 = 2.1 and E2 = 0.01 for the oil, atmospheric opacities of 0.07 at 19.3 and 31.0 GHz and 0.55 at 69.8 GHz and for a nadir look angle. Computations were made for several selected oil film thicknesses ranging from 0.1 mm to 2.5 mm. The results are practically independent of oil thickness. A slight dependence on thickness, due to a reduction of the wind speed dependent component of the reflected sky radiation resulting from a reduced reflection coefficient at greater oil thicknesses, is present but is less than 20 percent of the total effect even at 69.8 GHz.

The sea foam effect is due to the relatively high brightness temperature of sea foam compared to the average sea surface and to the increasing surface coverage of sea foam with wind speed. An oil film will inhibit the production of white caps and hence the sea foam effect will result in a decrease in the brightness temperature in the region of the slick. Although relatively little detail is known about the microwave properties of foam, a brightness temperature increase of 100^{o}K due to foam is a reasonable estimate at the frequencies of interest here (14). In addition to incomplete knowledge about the microwave characteristics of foam, the determination of the brightness temperature dependence on wind speed due to sea foam is further

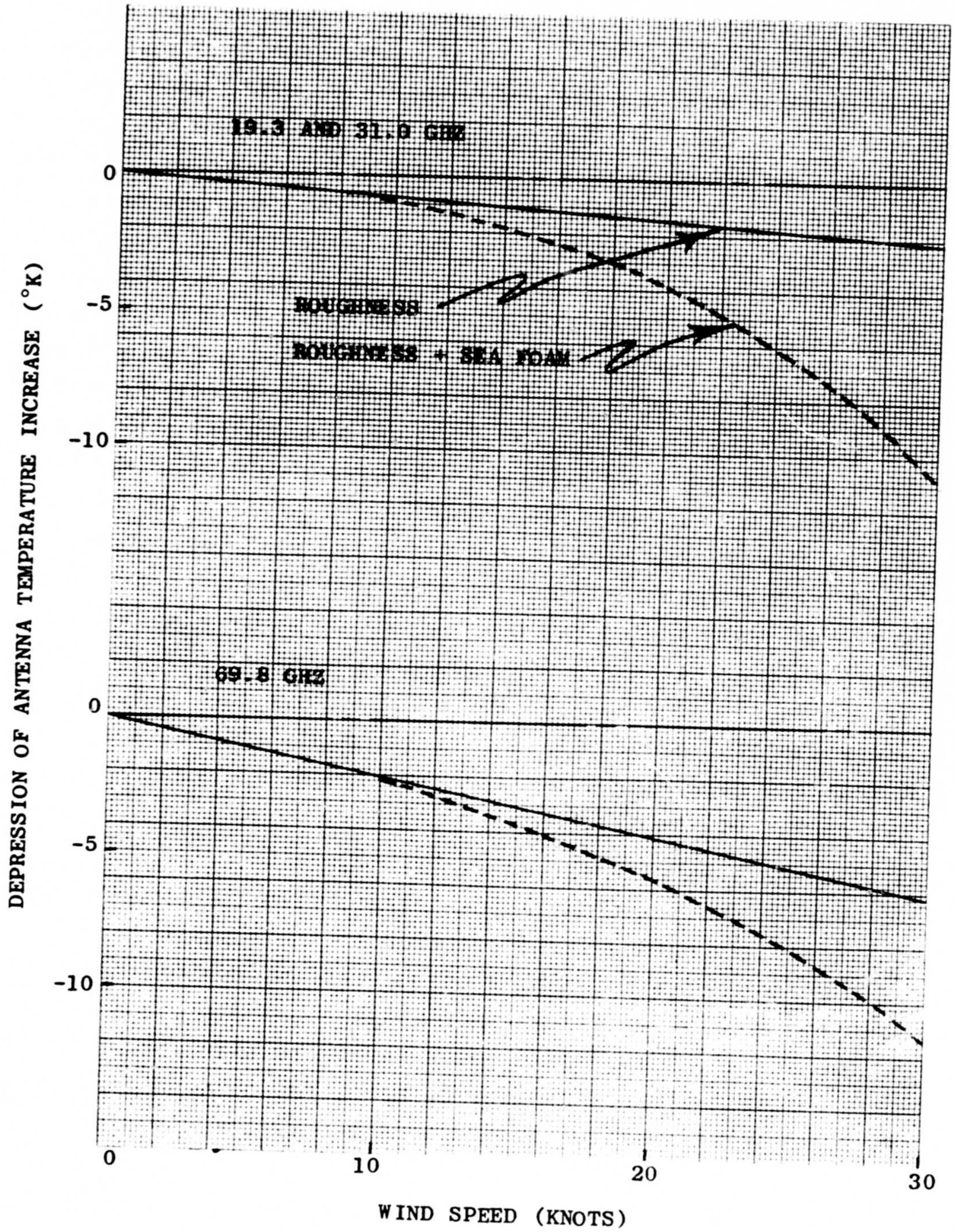

19.3 AND 31.0 GHZ
ROUGHNESS
ROUGHNESS + SEA FOAM
69.8 GHZ
DEPRESSION OF ANTENNA TEMPERATURE INCREASE (°K)
0
-5
-10
0
-5
-10
0
10
20
30
WIND SPEED (KNOTS)

Figure 12

complicated because the foam coverage of the sea surface does not depend only on the local wind. The foam coverage also depends upon the air-sea temperature difference, the duration and fetch of the wind, as well as on the history of the wave spectrum of the sea area being observed. A relation for the maximum oceanic white cap coverage as a function of wind speed is given by Monahan (15). The maximum depression of the antenna temperature increase due to the sea foam effect was calculated using this relation, $100^{\circ}K$ for the brightness temperature increase due to white caps, and by assuming that the oil film completely prevents the production of white caps (further ensuring an upper limit to the sea foam effect). This maximum effect due to sea foam plus the previous roughness effect is given by the dotted line in Figure 12. The total sea state effect at nadir is remarkably similar at all three frequencies. It may reasonably be ignored below about 20 knots without serious error but above 20 knots a correction will become increasingly important. Note that for very thin oil films, where the increase in emissivity is small, the sea state effect can result in a decrease in brightness temperature in the region of the slick.

3. Non-Uniform Film Thickness

When significant variations of oil film thickness occur only over dimensions large compared to the surface resolution of the radiometer antenna, a unique antenna temperature is measured and the thickness is readily found for each position of the antenna beam. If however there are significant thickness variations over the antenna beam, the antenna temperature measured is an average value determined by the distribution of thicknesses present and weighted by the antenna response pattern. The surface resolution of an airborne microwave system depends upon the antenna size and aircraft altitude, but in general will be tens of feet or more. For example, the radiometers used in this investigation have a surface resolution, or beam-spot, of about 60 feet at an altitude of 500 feet. Thus, in general, thickness variations much smaller than the surface resolution may be anticipated. This case, where the oil forms many small puddles or thickness variations over the antenna beam-spot was investigated.

In general the antenna temperature is given by

$$T_A = \int_{4\pi} f \, T_B \, d\Omega \Big/ \int_{4\pi} f \, d\Omega \ , \tag{1}$$

where T_A is the measured antenna temperature, T_B is the total apparent brightness temperature of the surroundings, and f is the normalized antenna response pattern. The angular dependence of T_A, T_B, and f have not been indicated in order to obtain an economy of notation. The integral may be divided into two parts; one over the main beam of the antenna and the other over the rest of space.

$$T_A = \left[\int_{mb} f \, T_B \, d\Omega + \int_{4\pi - mb} f \, T_B \, d\Omega \right] \Big/ \int_{4\pi} f \, d\Omega \ . \tag{2}$$

The main beam of the antenna is generally defined as containing the primary response lobe of the antenna and extending out to and sometimes including the first order side lobes. Let

$$\eta_{mb} = \int_{mb} f d\Omega \Big/ \int_{4\pi} f d\Omega = \Omega_{mb} / \Omega_{total} \tag{3}$$

where η_{mb} is the main beam efficiency. In the case of high beam efficiency antennas, such as are used in our airborne program, η_{mb} increases rapidly as the integral is extended in angle out from the main beam axis reaching a value typically between 0.85 and 0.95. Thereafter η_{mb} increases very slowly with angle and is therefore not sensitive to the exact choice of the limits of the main beam integral.

Consider only changes in the antenna temperature, ΔT_A, due to brightness temperature changes, ΔT_B, caused by the oil slick as the antenna is scanned over the region of the slick. The second term in equation (2) changes very little with antenna position and we have,

$$\Delta T_A = \eta_{mb} \int_{mb} \Delta T_B \, f d\Omega / \int_{mb} f d\Omega. \qquad (4)$$

Define:

T_o = physical temperature of the oil and water

T_{Bw} = brightness temperature of the water,

T_{Bo} = brightness temperature of the oil covered water,

T_{sky} = downwelling sky radiation in the specular reflection direction.

Assuming a specular surface (i.e. neglecting sea state effects) and for low altitude measurements where the atmospheric loss between the antenna and surface may be neglected,

$$\Delta T_B = \left[T_{Bo} + \left(1 - T_{Bo}/T_o\right) T_{sky}\right] - \left[T_{Bw} + \left(1 - T_{Bw}/T_o\right) T_{sky}\right]$$

$$\Delta T_B = \left(T_{Bo} - T_{Bw}\right)\left(1 - T_{sky}/T_o\right) \quad . \qquad (5)$$

Note that the effect of the reflected sky radiation is to reduce the apparent brightness temperature change, ΔT_B, and the antenna temperature change, ΔT_A, as given by equation (4), by the factor $(1 - T_{sky}/T_o)$. This factor is typically about 0.9 at 19.3 and 31.0 GHz and about 0.6 at 69.8 GHz except for heavy rain, when it can be much smaller.

Consider first the simplest case of many small puddles of the same thickness randomly distributed over the main beam. Equation (4) becomes

$$\Delta T_A = \eta_{mb} \Delta T_B \Omega_{oil}/\Omega_{mb} = \eta_{mb} \Delta T_B A_{oil}/A_{mb}. \qquad (6)$$

Therefore the antenna temperature increase is proportional to the fractional area of the antenna beam filled by the oil puddles. Since a single thickness is associated with each puddle, the antenna temperature increase is proportional to the volume of oil contained in the main beam. If the thickness of the puddles is known a priori, then the volume of the oil is uniquely determined from the measured antenna temperature increase over the region of the spill regardless of the size or spatial distribution of the puddles so long as the puddles are small compared to the antenna beam and randomly distributed over dimensions comparable to the beam-spot. Note that a fractionally smaller T_B over an area larger by the same fraction would result in the same T_A. However the volume would only be the same if T_B is linearly related to the thickness. An error in the assumed puddle thickness will result in an error in the volume estimated from ΔT_A. The magnitude of the error depends upon the actual and assumed thickness and is not unacceptable over certain thickness ranges.

Rather than pursuing the case of uniformly thick puddles consider the more general case where a distribution of oil thicknesses are present. For highly directive antennas, equation (4) becomes,

$$\Delta T_A = \left(\eta_{mb}/\Omega_{mb}\right) \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Delta T_B \, f \, d\xi \, d\eta \, . \tag{7}$$

Equation (7) is a statement of the basic antenna smoothing equation and represents a convolution of the brightness distribution ΔT_B and the antenna response f.

By the convolution theorem,

$$\overline{\Delta T_A} = \left(\eta_{mb}/\Omega_{mb}\right) \overline{\Delta T_B} \, \overline{f} \tag{8}$$

where the bar indicates the Fourier transform. Equation (8) is true for all spatial frequencies and in particular zero. But the value of a Fourier transform of a function at the origin is equal to the infinite integral of the function. In this case the infinite integral of f may be taken as Ω_{mb} and the infinite integrals of ΔT_A and ΔT_B may be replaced by integrals over the extent of the oil slick. Therefore,

$$\int_{oil} \Delta T_A \, dA = \eta_{mb} \int_{oil} \Delta T_B \, dA. \tag{9}$$

One approach is to assume that ΔT_B is proportional to oil thickness t. Let

$$\Delta T_B = C \left(T_o - T_{sky}\right) t \quad , \tag{10}$$

and using equation (5),

$$C = d \left[\left(T_{Bo} - T_{Bw}\right) / T_o\right] / d \left(t\right) . \tag{11}$$

The proportionality constant, C, is determined from equation (11) and the best linear representation of the theoretical dependence of $(T_{Bo} - T_{Bw})$ on thickness. Equation (9) becomes

$$\int_{oil} \Delta T_A \, dA = \eta_{mb} \, C \left(T_o - T_{sky}\right) \int_{oil} t \, dA . \tag{12}$$

But

$$\int_{oil} t \, dA = \text{volume of oil} = V. \tag{13}$$

Therefore

$$V = \int_{oil} \Delta T_A \, dA / \eta_{mb} \, C \left(T_o - T_{sky}\right) . \tag{14}$$

The volume of oil is proportional to the integral of the measured antenna temperature increase over the oil slick. This determination of volume is readily made and is independent of the detailed distribution of thickness present in the slick or the spatial scale of thickness variations over the slick. It requires only that ΔT_B may be approximated by a linear function of thickness. This approach has the attraction that it readily lends itself to a real-time, on-board estimation of oil slick volume using an imaging radiometer. It will be tested by applying it to the analysis of the aircraft-borne oil slick measurements.

Consider now the general case where the dependence of T_B on thickness at each point is according to the theoretical relationships described in the parametric study and where a distribution of oil thicknesses are present. Returning to equation (7), the basic problem is to restore T_B using the antenna temperature measurements. There are many methods for inverting equation (7); e.g. see reference 16. However there is no unique solution and some spatial detail will be lost. There will always be a certain degree of spatial averaging of ΔT_B depending upon the spatial variation of ΔT_B compared to the antenna beam-spot size. Let $\Delta T_B'$ represent the best possible restoration of ΔT_B from equation (7). Using equation (5) we find,

$$\left(T_{Bo} - T_{Bw}\right) = \Delta T_B'/\eta_{mb} \left(1 - T_{sky}/T_o\right) \quad . \tag{15}$$

From this estimate of $(T_{Bo} - T_{Bw})$ and the theoretical dependence of $(T_{Bo} - T_{Bw})$ on thickness the oil film thickness can be found at each resolution element over the slick. These derived thicknesses are then integrated over the areal extent of the slick to obtain the volume of oil present.

LABORATORY MEASUREMENTS PROGRAM

The objective of these measurements is to confirm the theoretical predictions of the increase in the microwave brightness temperature of an oil film covered water surface as a function of oil film thickness and oil type in a controlled laboratory environment. In addition it was possible to measure the dielectric properties of No. 2 fuel oil and Nos. 4 and 6 crude oils used in the controlled test oil spills of the airborne measurements program.

The measurements were made at NASA-Wallops Island Station, Virginia using radiometers at 19.3 and 69.8 GHz installed in the NASA-427 C-54 aircraft and the open runway area for the test site. Construction of the 31.0 GHz had not been completed at the time of these measurements. Figure 13 shows the measurement setup. Aluminum screen was placed over the runway to form a reflecting surface 100 feet long by 16 feet wide around the 4 foot by 4 foot test tank. This minimized the effects of that part of the antenna pattern not subtended by the test tank. The tank itself was made of wood, covered with aluminum, foil, and lined with a plastic sheet. The actual percentage of the antenna beam filled by the tank was determined by the technique described below and was found to be 85% and 90% for the 19.3 and 69.8 GHz radiometers, respectively. The tank was filled to a depth of 2-1/2 inches with fresh water and then a known volume of oil added to the surface. The incremental increase in the oil film thickness resulting from the addition of oil was calculated assuming uniform spreading of the oil over the surface area of the tank. The measurements made were of the horizontal linearly polarized component at 30 degrees incidence angle. This incidence angle was chosen to ensure that the effects of

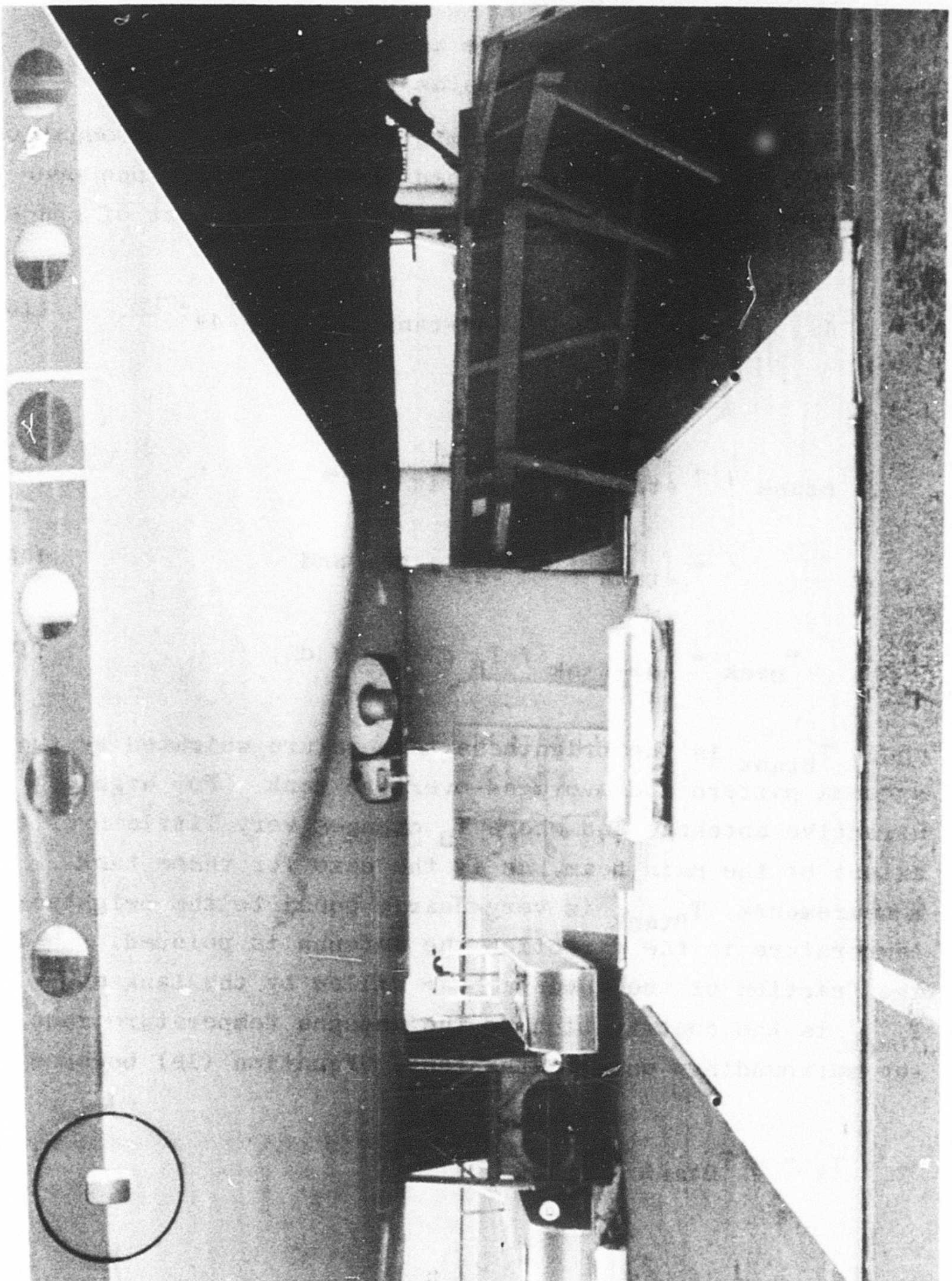


Figure 13

the overhanging structure of the aircraft, considerable at 0 degrees, were negligible.

The observation procedure and calibration techniques used for the measurements were as follows:

In general the antenna temperature is given by equation (1). The integral may be divided into two parts; one over the extent of the tank and the other over the rest of space.

$$T_A = \left[\int_{tank} f \; T_B d\Omega + \int_{4\pi - tank} f \; T_B d\Omega \right] / \int_{4\pi} f \; d\Omega. \qquad (16)$$

Let,

$$T_{Btank} \; \eta = \int_{tank} f \; T_B \; d\Omega / \int_{4\pi} f \; d\Omega, \qquad (17)$$

$$\eta = \int_{tank} f \; d\Omega / \int_{4\pi} f \; d\Omega, \text{ and} \qquad (18)$$

$$T_{back} = \int_{4\pi - tank} f \; T_B \; d\Omega / \int_{4\pi} f \; d\Omega, \qquad (19)$$

where T_{Btank} is the brightness temperature weighted by the antenna pattern and averaged over the tank. For highly directive antennas and where T_B changes very little over the extent of the main beam, as is the case for these tank measurements, T_{Btank} is very nearly equal to the brightness temperature in the direction the antenna is pointed. η is the fraction of the antenna beam filled by the tank and T_{back} is the contribution to the antenna temperature made by the surroundings outside the tank. Equation (16) becomes

$$T_A = \eta \; T_{Btank} + T_{back} \; . \qquad (20)$$

Define:

T_o — physical temperature of the oil and water,

T_{Bw} — brightness temperature of the water,

T_{Bo} — brightness temperature of the oil covered water,

T_{sky} — downwelling sky radiation in the specular reflection direction.

When the tank is covered with a perfectly reflecting screen, the antenna temperature measured is

$$T_{As} = T_{sky} + T_{back} , \tag{21}$$

for a clean water surface

$$T_{Aw} = \left[T_{Bw} + (1-T_{Bw}/T_o)\ T_{sky}\right] + T_{back} , \tag{22}$$

and when an oil film is present

$$T_{Ao} = \left[T_{Bo} + (1-T_{Bo}/T_o)\ T_{sky}\right] + T_{back} . \tag{23}$$

As long as T_{sky} and T_{back} do not change during the period of the measurements, we may obtain from equations (21), (22), and (23)

$$(T_{Bo} - T_{Bw}) = (T_{Ao} - T_{Aw}) \left[T_{Bw}/(T_{Aw} - T_{As})\right] . \tag{24}$$

T_{Bw} is readily calculated for a smooth water surface and T_{Ao}, T_{Aw}, and T_{As} are measured quantities. Therefore the increase in brightness temperature due to the oil film $(T_{Bo} - T_{Bw})$ is readily obtained from the measured increase in antenna temperature due to the film $(T_{Ao} - T_{Aw})$. The effects of spurious radiation entering the antenna from directions away from the tank and sky radiation reflected from the tank have been calibrated out by this technique. No detailed knowledge of the antenna pattern is required, nor is it necessary that the sky or background radiation be known, only that it remain constant during the measurement. The calibration measurements represented by equations (21) and (22) are made sufficiently often to ensure this condition.

It is not necessary to obtain the fraction of the beam filled by the tank to interpret the measurements but it may be found from equations (21) and (22),

$$\eta = \left[(T_{Aw} - T_{As})/T_{Bw}\right]/(1 - T_{sky}/T_o) \ . \tag{25}$$

In order to determine η, it is necessary to either calculate or measure T_{sky}.

Measurements were made using each of No. 2 fuel oil and Nos. 4 and 6 crude oils. No. 2 fuel oil is a thin pure distillate similar to API 30 gravity crude oil and commonly used as home heating oil. It spreads rapidly and apparently uniformly over the tank surface even for films as thin as 100 microns. Figure 14 shows the No. 2 oil film on the tank during the observations. No. 4 crude oil is a mixture of distillate and residual oils. It is heavy and viscous and formed splotches or lenses rather than spreading to form thin films as is shown in Figure 15. It was not until sufficient oil was added to cover the tank that additional oil did appear to spread relatively evenly and uniformly increase the film thickness by the calculated amount. This required a volume of oil equivalent to a film thickness of about 4 mm. Figure 16 shows the tank just after the addition of enough No. 4 oil to completely cover the tank.

Figure 14

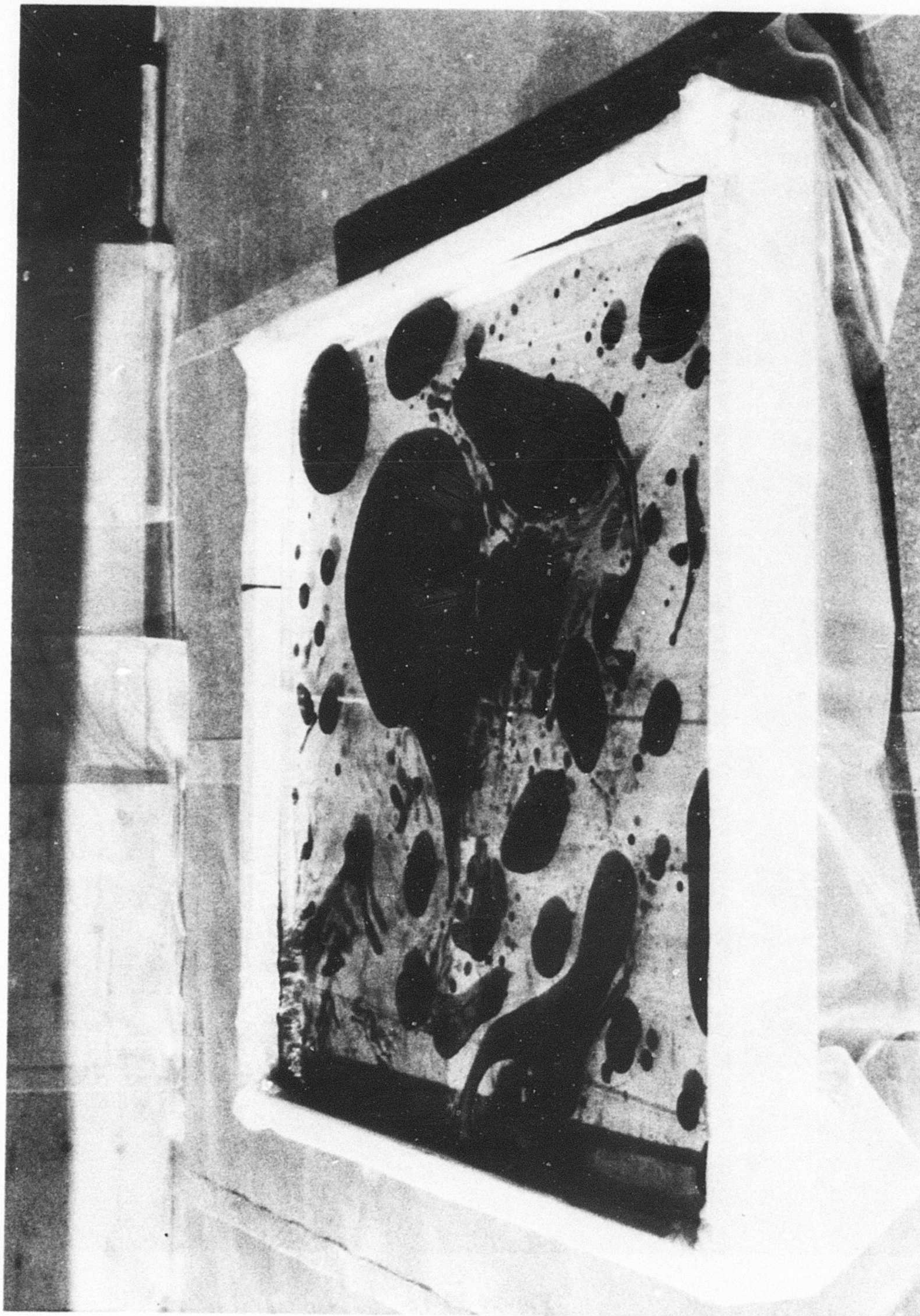


Figure 15

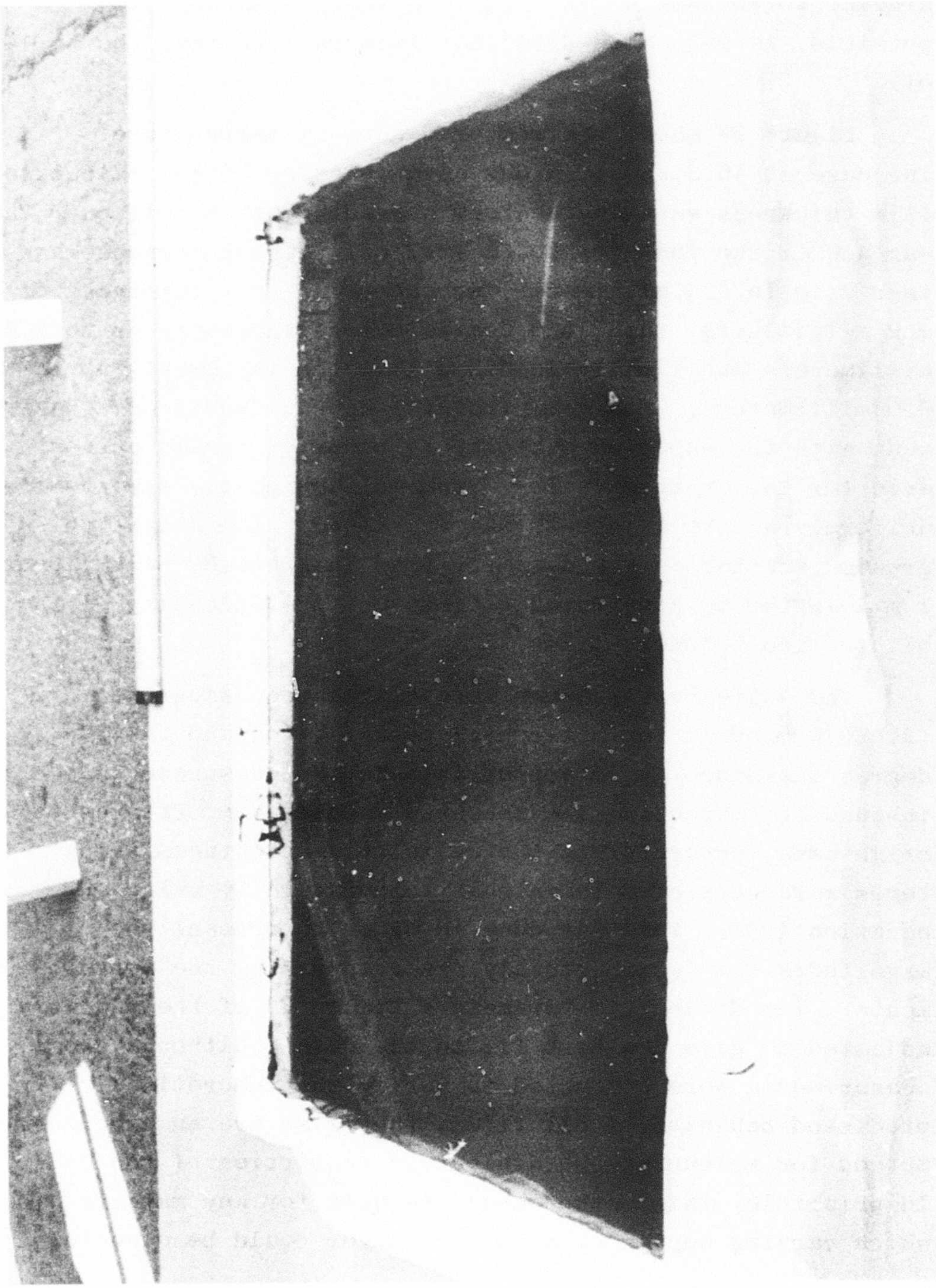
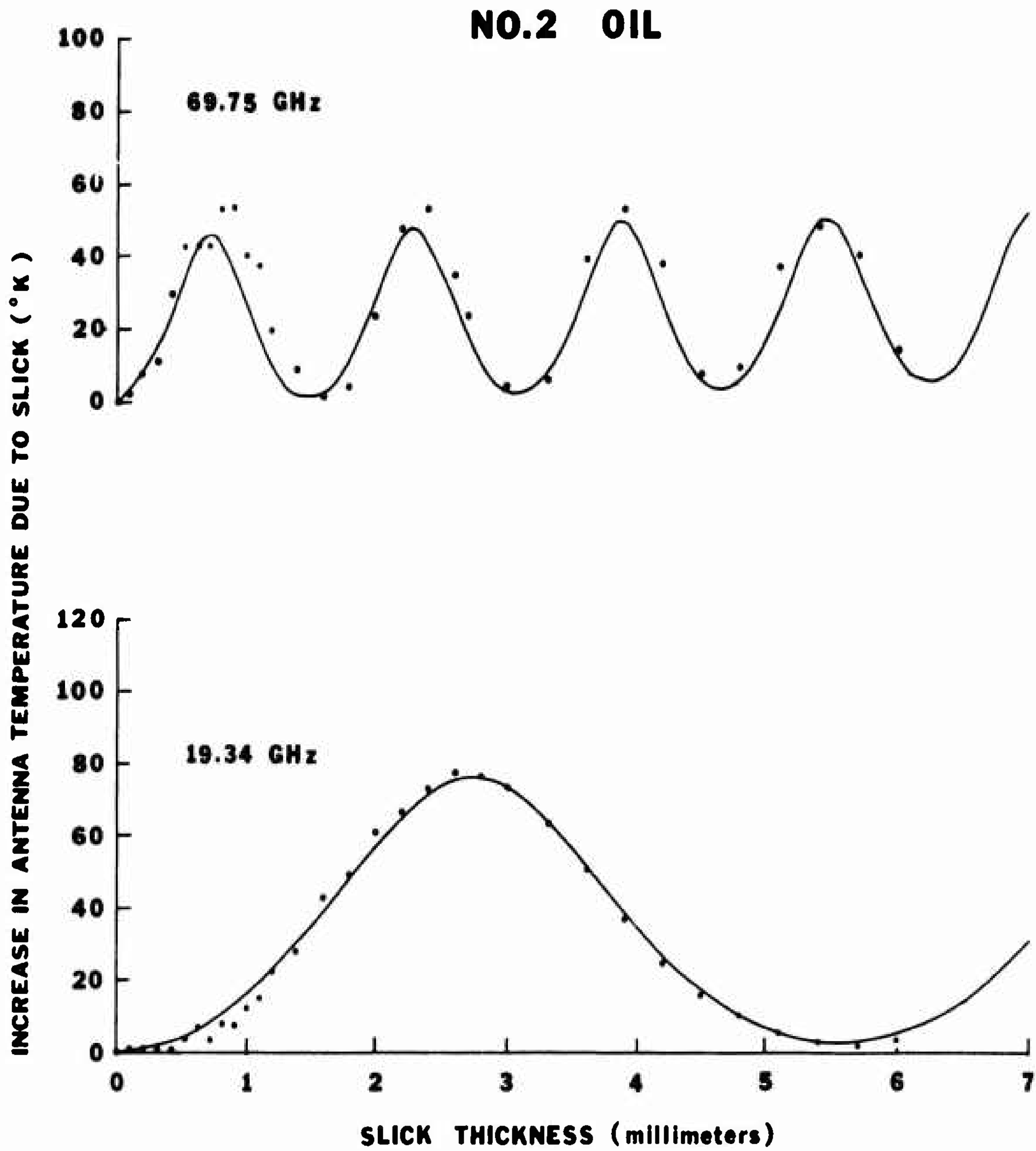


Figure 16

No. 6 oil is composed entirely of residual oils and acted similar to the No. 4 oil. It is a tarry mess and, if possible, is even more difficult to work with than the No. 4 oil.

Figure 17 shows the measured antenna temperature increase at 19.3 and 69.8 GHz as a function of the calculated film thickness assuming uniform spreading of the oil over the surface of the tank for No. 2 fuel oil. The thickness was increased in 0.1 millimeter increments up to a thickness of 1.2 millimeters, then in 0.2 millimeter increments up to 3.0 millimeters and finally in 0.3 millimeter increments up to 6.0 millimeters. The data (points) are in excellent agreement with the expected oscillatory behavior (solid curves) even for the thinnest films. The oil apparently spread more uniformly as the thickness was increased. The slightly greater scatter in the data for film thicknesses below about 1 millimeter is attributed to less uniform spreading of the oil for the thinnest films.

The solid curves shown were calculated using the TRIMEDIA program for horizontal polarization and the 30 degree incidence angle appropriate to the measurements. Instead of correcting the measured antenna temperatures to brightness temperatures, the calculated brightness temperatures were corrected to antenna temperature by using equation (24). This was done in order to present the magnitudes that were actually observed during the measurements. The dielectric parameters E1 and E2 of the oil were adjusted to give the best fit to the data. Although these measurements were conducted to verify the theoretically predicted behavior of oil films, they also are an excellent method for measuring the dielectric properties of the oil. In principle, this method could be used for any material for which varying depths of a uniform layer could be structured;



NO.2 OIL
69.75 GHz
19.34 GHz
INCREASE IN ANTENNA TEMPERATURE DUE TO SLICK (°K)
100
80
60
40
20
0
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
SLICK THICKNESS (millimeters)

Figure 17

such as ice, foam, or soil. The values of E1 and E2 determined for No. 2 oil are shown in Table 1. The errors are realistic but rough estimates as no detailed error analysis was performed. The values agree very well with those measured by Edgerton and Trexler (5) for 30 gravity crude oil, an oil very similar to No. 2 fuel oil, of E1 = 2.06 $\pm$ 0.05 and E2 < 0.015.

TABLE 1

MEASURED COMPLEX DIELECTRIC CONSTANT OF OIL

OIL TYPE	TEMPERATURE		19.3 GHz	69.8 GHz
No. 2 Fuel	$19^{\circ}C$	E1	2.10 $\pm$ 0.05	2.10 $\pm$ 0.05
		E2	$0.01 \begin{smallmatrix} +0.02 \\ -0.01 \end{smallmatrix}$	$0.01 \begin{smallmatrix} +0.02 \\ -0.01 \end{smallmatrix}$
No. 4 Crude	$26^{\circ}C$	E1	2.4 $\pm$ 0.1	2.2 $\pm$ 0.1
		E2	0.06 $\pm$ 0.04	0.07 $\pm$ 0.04
No. 6 Crude	$26^{\circ}C$	E1	2.6 $\pm$ 0.2	2.6 $\pm$ 0.2
		E2	0.05 $\pm$ 0.05	0.05 $\pm$ 0.05

The results of the measurements of No. 4 crude oil are shown in Figure 18. The data for thicknesses below 1 millimeter must be discounted as the oil did not spread uniformly but rather formed lenses many times thicker than that calculated assuming uniformity. In addition, a single lens drifting in or out of the antenna beam caused large unpredictable changes in antenna temperature making reliable measurements impossible. In any airborne measurement, the antenna beam will be much larger than a single lens and will contain many of them. In this case, statistically stable measurements will be possible and an average thickness can be determined. No data was taken between 1 and 4.6 millimeters. At 4.6 millimeters, the tank was completely covered

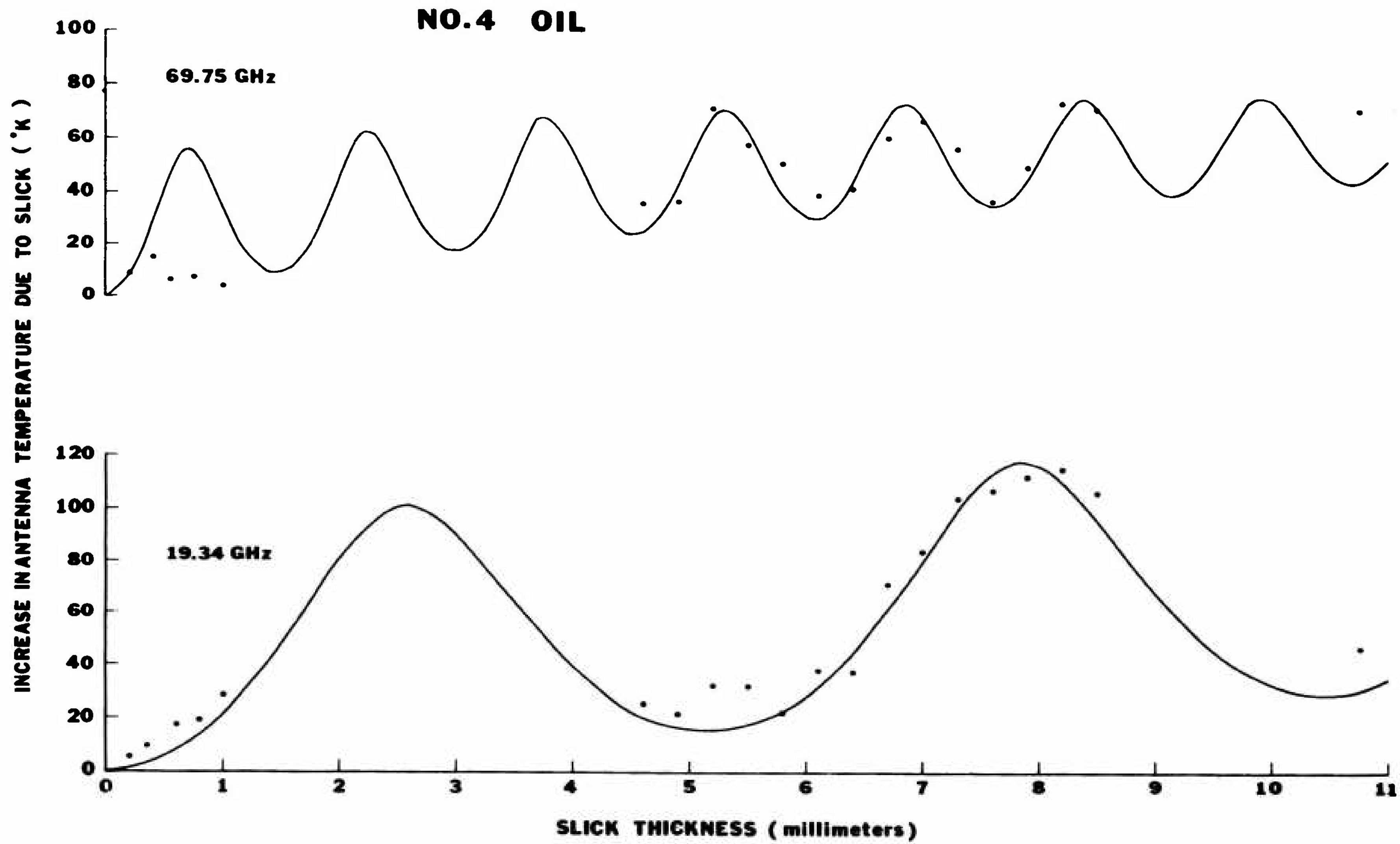

NO.4 OIL
69.75 GHz
19.34 GHz
100
80
60
40
20
0
120
100
80
60
40
20
0
INCREASE INANTENNA TEMPERATURE DUE TO SLICK (°K)
0
1
2
3
4
5
6
7
8
9
10
11
SLICK THICKNESS (millimeters)

Figure 18

and the thickness appears to increase uniformly from there on as the data are in good agreement with the theoretical expectations. The values of E1 and E2 determined from the measurements are shown in Table 1 and are in agreement with other measurements (5), (6), (7), of similar type oils. The difference between the measured values of E1 at 19.3 and 69.8 GHz is within the measurement error and is not significant.

The measurements of No. 6 crude oil are shown in Figure 19. This oil has no API rating and a Saybolt viscosity of 900 to 9000 seconds as compared to Saybolt viscosities of 32.6 to 37.9 seconds for No. 2 fuel oil and of 45 to 125 seconds for No. 4 crude oil. It is composed entirely of residuals from the distillation process and its composition varies over a wide range from heavy oil to a nearly solid material which must be heated to flow. Bunker C fuel oil is included in this category. The sample used in these measurements was very near the consistency of tar. It has to be worked with to be truly appreciated. The measurements were very difficult and far below the quality of those for No. 2 fuel oil and No. 4 crude oil. Considering the difficulty, the data agree relatively well with the theoretical predictions and the values of E1 and E2 given in Table 1 agree well with the values of $E1 = 2.41 \pm 0.05$ and $E2 < 0.0213$ measured by Edgerton and Trexler (5) for Bunker C oil.

In summary, the laboratory measurements of No. 2 fuel oil and Nos. 4 and 6 crude oils have verified the behavior of oil films predicted theoretically. The oscillation of brightness temperature with increasing thickness is confirmed. These measurements demonstrate the possibility of using multi-frequency passive microwave techniques to remove ambiguities resulting from the oscillations and to directly measure the thickness of oil slicks. In addition, they

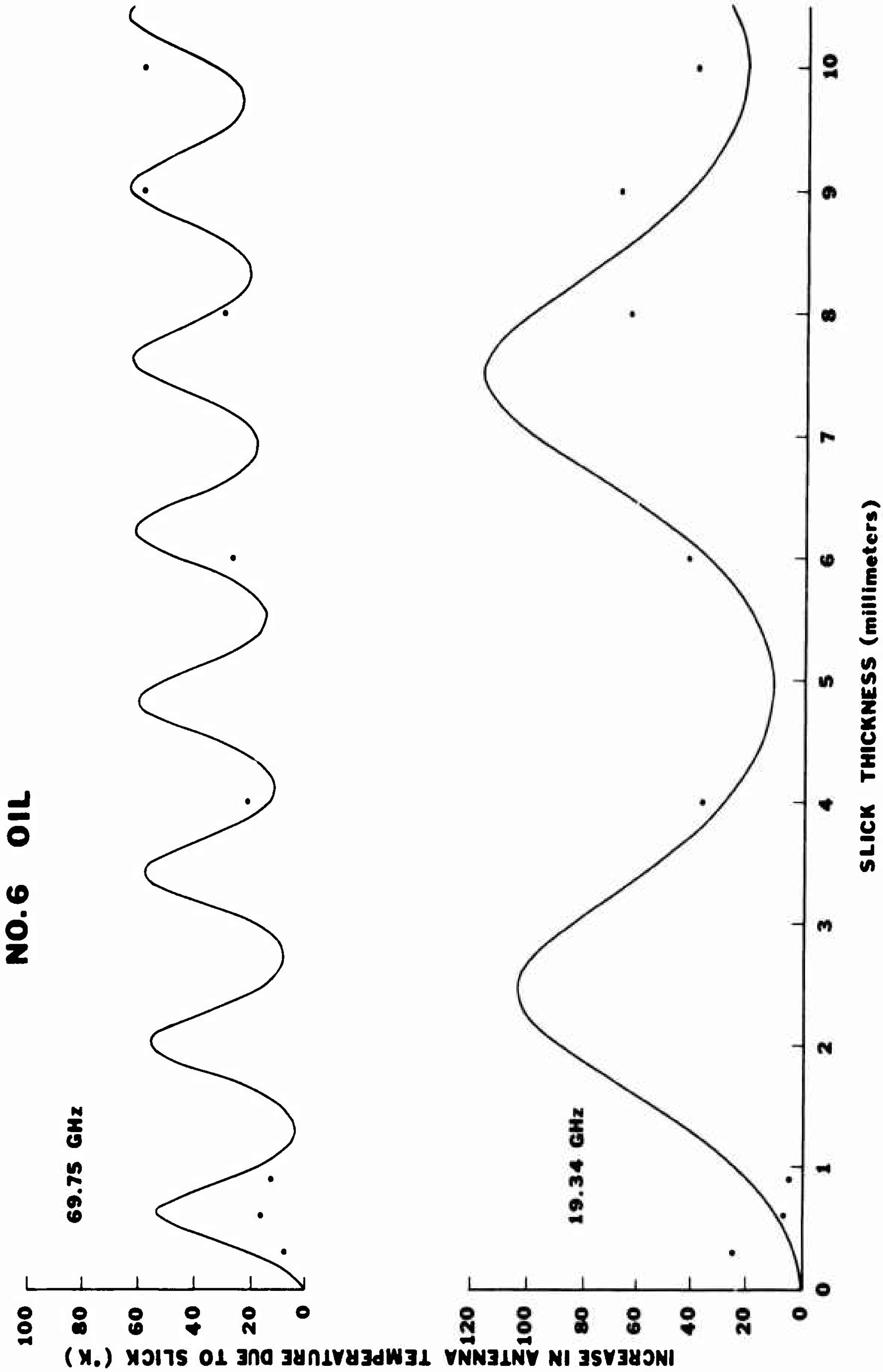

NO.6 OIL
69.75 GHz
19.34 GHz
100
80
60
40
20
0
120
100
80
60
40
20
0
INCREASE IN ANTENNA TEMPERATURE DUE TO SLICK (°K)
0
1
2
3
4
5
6
7
8
9
10
SLICK THICKNESS (millimeters)

Figure 19

have determined the dielectric properties of these oils and demonstrated a simple and useful technique for measuring the dielectric properties of any material which may be formed in uniform layers of variable depth.

AIRBORNE MEASUREMENTS PROGRAM

The objective of the airborne measurements program is to conduct multifrequency microwave measurements from an aircraft of controlled test ocean oil spills. Comparison of the oil film thickness and volume determined from the microwave measurements with values determined from in situ ground truth measurements constitutes an operational test of the multifrequency technique.

Aircraft-borne measurements were made at 19.3 and at 31.0 or 69.8 GHz of a total of fifteen controlled marine oil spills. These spills were divided into two groups. The first group consisted of eight spills which were conducted under calm sea conditions with surface wind speeds of less than 10 knots. They were performed as the initial tests to investigate and validate the overall multifrequency technique under ideal conditions. The benign conditions allowed maximum ease and control of the spill and acquisition of ground truth. A second group of seven spills was subsequently carried out to investigate the effects of rough seas and high wind speeds on the measurement technique. Measurements were obtained with seas of up to 5 feet, swell of up to 8 feet and winds of up to 24 knots. These two groups of spills and the results obtained from them will be discussed in turn.

1. Calm Sea Oil Spills

A series of eight controlled oil spills was conducted during the period August 1971 through August 1972 in cooperation with the NASA-Wallops Island Station, the Virginia Institute of Marine Science and the U. S. Coast Guard. Four other oil spills were scheduled but had to be cancelled because of Hurricane Ginger or rough seas. The eight oil spills conducted were: (1) 200 gallons of No. 4 crude oil on 3 August 1971, (2) 200 gallons of No. 2 fuel oil on 30 August 1971, (3) 200 gallons of No. 2 fuel oil and (4) 200 gallons of No. 6 crude oil both on 13 October 1971, (5) 616 gallons of No. 2 fuel oil on 17 May 1972, (6) 630 gallons of No. 2 fuel oil on 11 July 1972, and (7) 632 gallons of No. 2 fuel oil and (8) 350 gallons of No. 4 crude oil both on 15 August 1972. The spills were performed in accordance with the guidelines established by the Environmental Protection Agency for the discharge of oil for research purposes (17). All of the spills were conducted in calm sea conditions with swell of 2 feet or less and less than 10 knot surface winds. The oil was transported to the ocean test site, about 10 miles east of Chesapeake Light Tower off the east coast of Virginia, in 50 gallon drums. The drums were off-loaded, herded together and emptied from small rubber boats in a manner so as to obtain as nearly an undisturbed point release as possible.

The ground truth gathered included the type and volume of oil spilled, in situ oil slick thickness measurements, and airborne natural and color IR photography and thermal IR imagery as well as the environmental parameters of sea temperature, air temperature, relative humidity, wind speed and direction, sea state and general weather and cloud conditions. The oil in the two spills of 17 May and 11 July 1972 was dyed with an oil soluable red dye to aid in establishing the distribution of oil over the sea surface. The dye, nitro fast red B, allowed the thick regions of oil to be easily identified visibly.

The airborne measurements were made with Naval Research Laboratory radiometers installed in the NASA-427, a NASA-Wallops Island C-54 aircraft. Measurements were made at 19.4 and 69.8 GHz for the first five spills and at 19.4 and 31.0 GHz for the last three spills. The latter combination proved more effective for the oil thicknesses of up to several millimeters which were encountered. A horn-lens antenna is used at 19.3 GHz and a corrugated horn at both 31.0 and 69.8 GHz. All three antennas have half-power beam widths of 7.2 degrees and the antenna main-beam efficiency is 87% at 19.3 and 98% at 31.0 and 69.8 GHz. In each radiometer the antenna is followed by a conventional Dicke-type crystal mixer superheterodyne receiver. The receiver input is Dicke switched between the antenna and a matched reference load whose temperature is monitored and known to an accuracy of better than $1/2^{o}C$. The difference between the antenna temperature and the reference temperature is calibrated by an internal argon discharge noise standard. This standard is calibrated and referenced to the antenna input prior to each flight by using specially constructed blackbody enclosures at ambient and liquid nitrogen temperatures. Since no radome is used, no radome corrections are needed.

The rms noise output with a 1-second integration time constant is $1/4^{o}K$ at 19.3 and 31.0 GHz and $1\text{-}1/2^{o}K$ at 69.8 GHz. The radiometer output is passed through a low pass filter, sampled each 1/16 second, digitized and recorded on magnetic tape and on an analog strip chart recorder. The time, derived from a crystal controlled clock, is put on magnetic tape each second along with housekeeping data. This same time is put on a 35-mm camera, framed once a second and bore-sighted with the antennas. This photographic record is used to identify the surface position to be associated with the radiometer data.

After the flight the data are read from the magnetic tape into a computer and converted to antenna temperature. The data are then filtered with a sin X/X form filter to remove receiver and environmental noise corresponding to spatial frequencies to which the antenna cannot respond (e.g. see (16)). The computer program has the capability to further filter the data with Gaussian shaped filters to partially remove unwanted interference and improve the signal-to-noise ratio at the expense of resolution. The computer output is then available as tabouts or plots. An example of the plot output showing unfiltered data containing radar interference and after various filters is shown in Figure 20.

Oil Spill of 3 August 1971

This spill consisted of 200 gallons of No. 4 crude oil. It was the first spill attempted and the usual first time difficulties were experienced. Although some data were obtained, the data were of insufficient quantity and quality for detailed analysis.

Oil Spill of 30 August 1971

This spill consisted of 200 gallons of No. 2 fuel oil. Surface winds were less than 10 knots and conditions were clear and mild. The oil was spilled at 0930 EDT and airborne measurements were performed from 1030 EDT to 1110 EDT during which the slick was relatively stable. An Ektachrome color photograph taken at 1103 EDT is shown in Figure 21. Note that the oil coverage appears uniform and there is no indication of any thickness variations over the slick except near the edge. The visible slick covers an area of 101 x 10^3 sq. ft. The aircraft ground tracks which passed over the slick and the radiometer data for the passes which gave a non-zero response are shown in Figure 22. These data were then used to construct the maps of the increase in antenna temperature due to the slick above that of the adjacent unpolluted sea given in Figure 23. The contours are in ^oK.

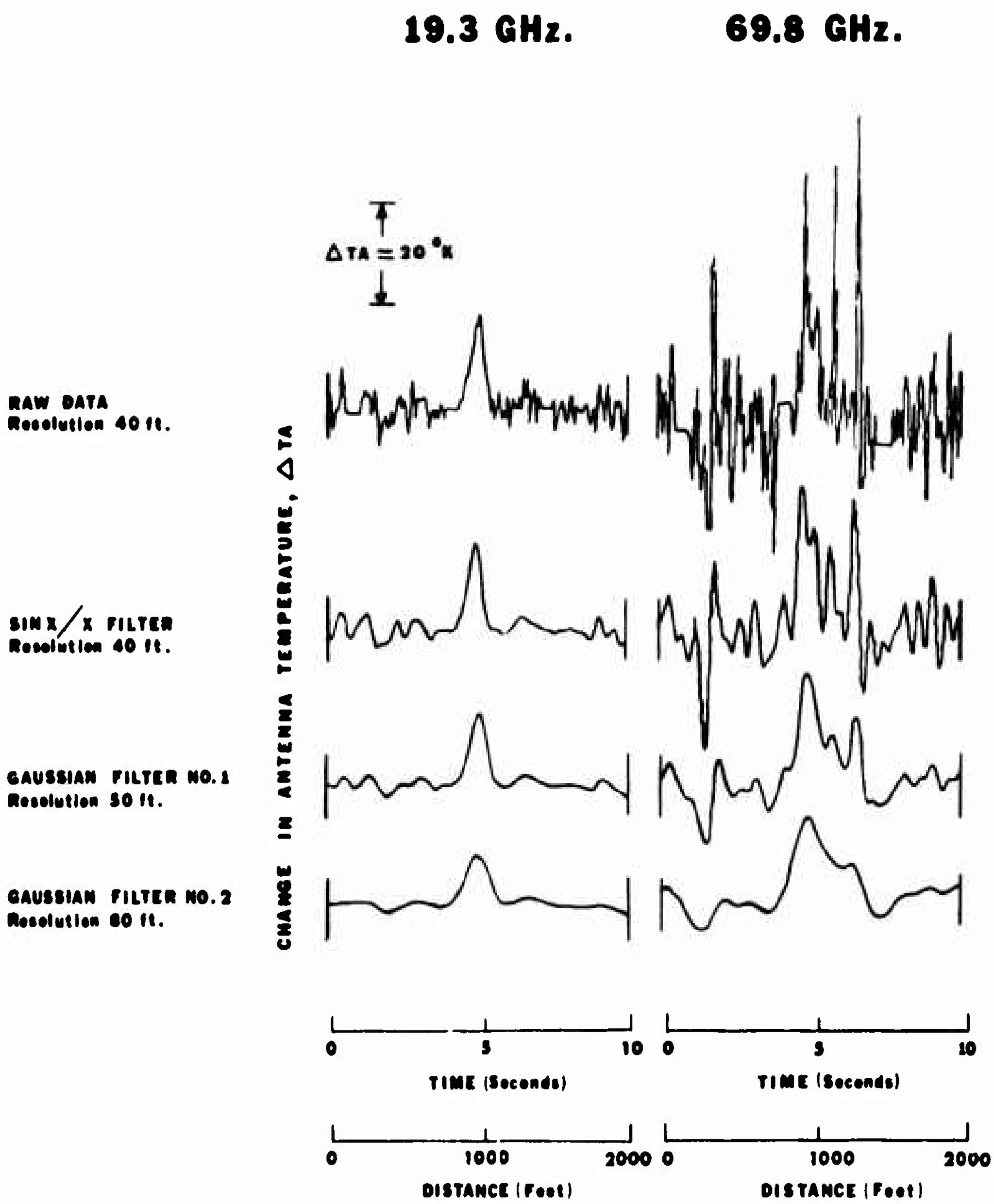

19.3 GHz.
69.8 GHz.
ΔTA = 20 °K
RAW DATA
Resolution 40 ft.
SIN X/X FILTER
Resolution 40 ft.
GAUSSIAN FILTER NO. 1
Resolution 50 ft.
GAUSSIAN FILTER NO. 2
Resolution 80 ft.
CHANGE IN ANTENNA TEMPERATURE, Δ TA
0
5
10
TIME (Seconds)
0
1000
2000
DISTANCE (Feet)

Figure 20

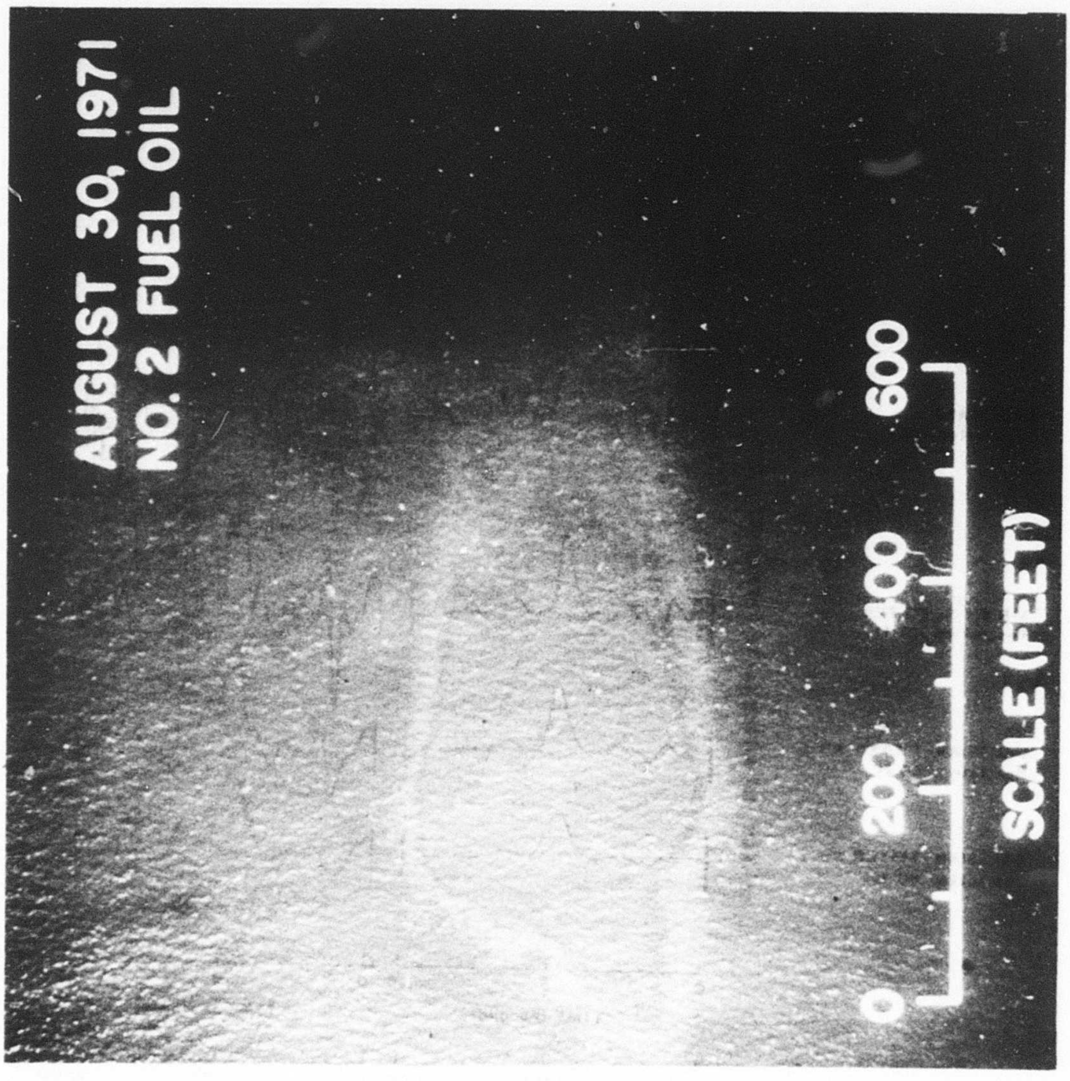
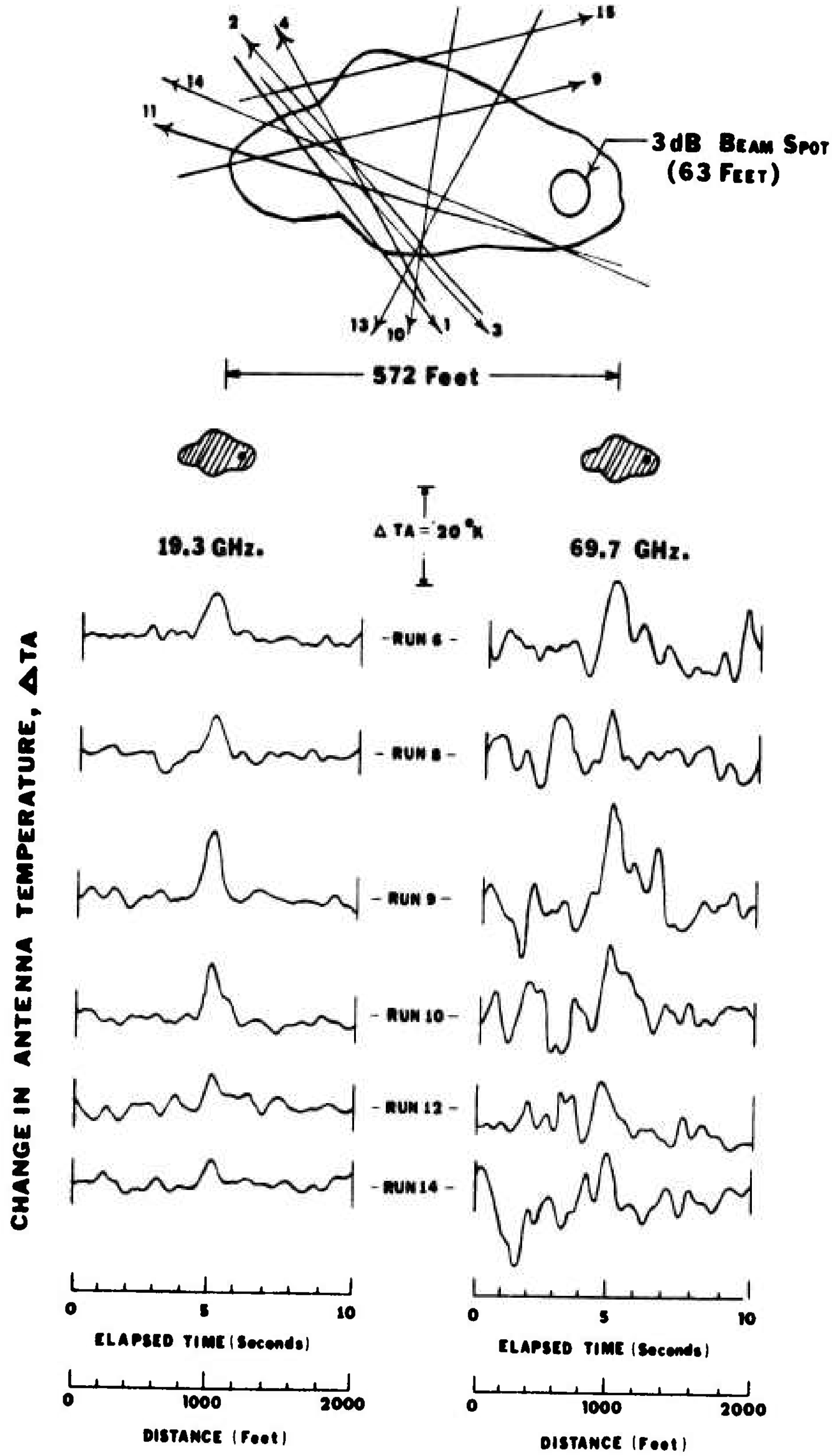


Figure 21



2
4
15
14
9
11
3dB Beam Spot
(63 Feet)
13
10
1
3
572 Feet
19.3 GHz.
Δ TA = 20 °K
69.7 GHz.
- RUN 6 -
- RUN 8 -
- RUN 9 -
- RUN 10 -
- RUN 12 -
- RUN 14 -
CHANGE IN ANTENNA TEMPERATURE, ΔTA
0
5
10
ELAPSED TIME (Seconds)
0
1000
2000
DISTANCE (Feet)

Figure 22

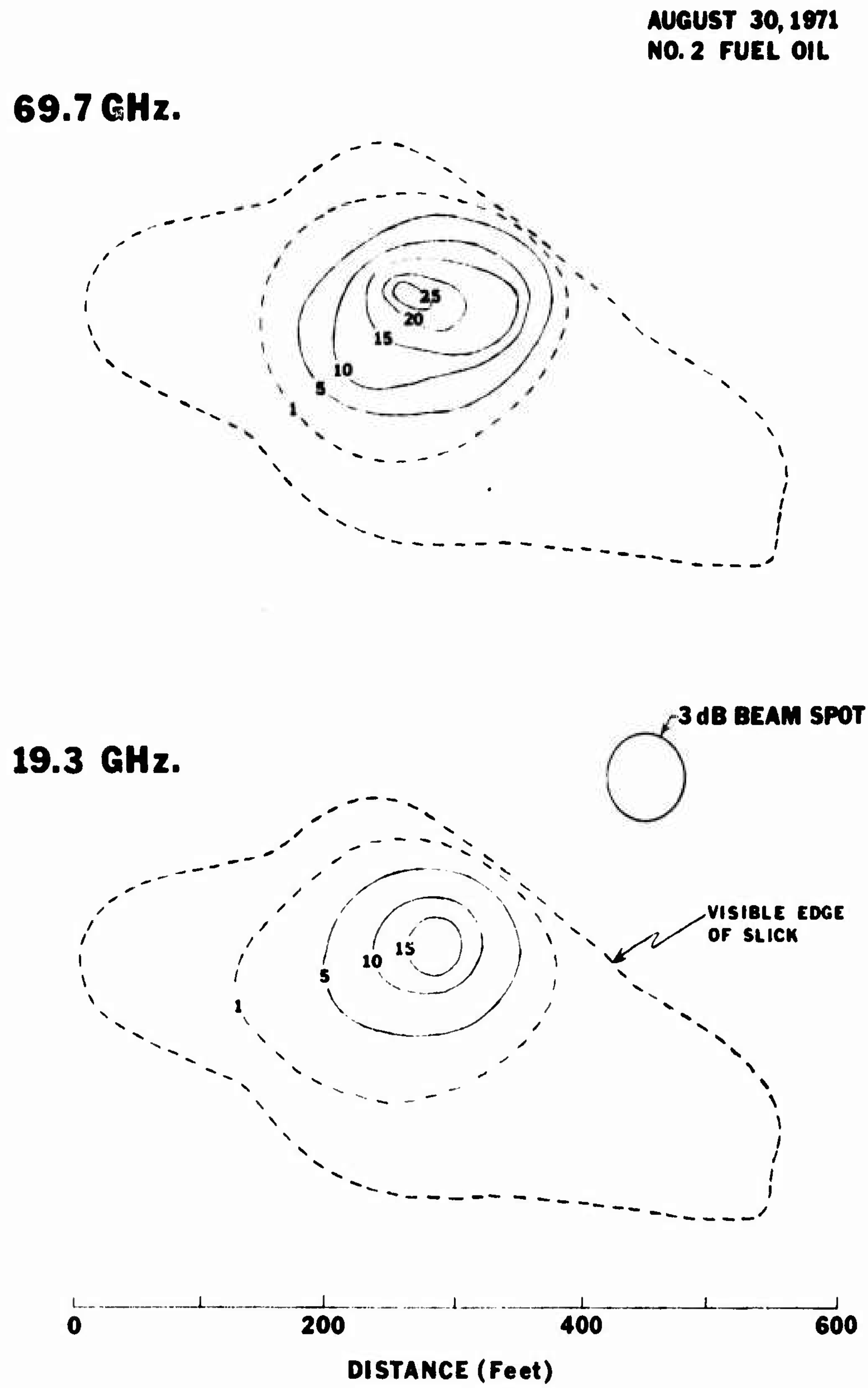
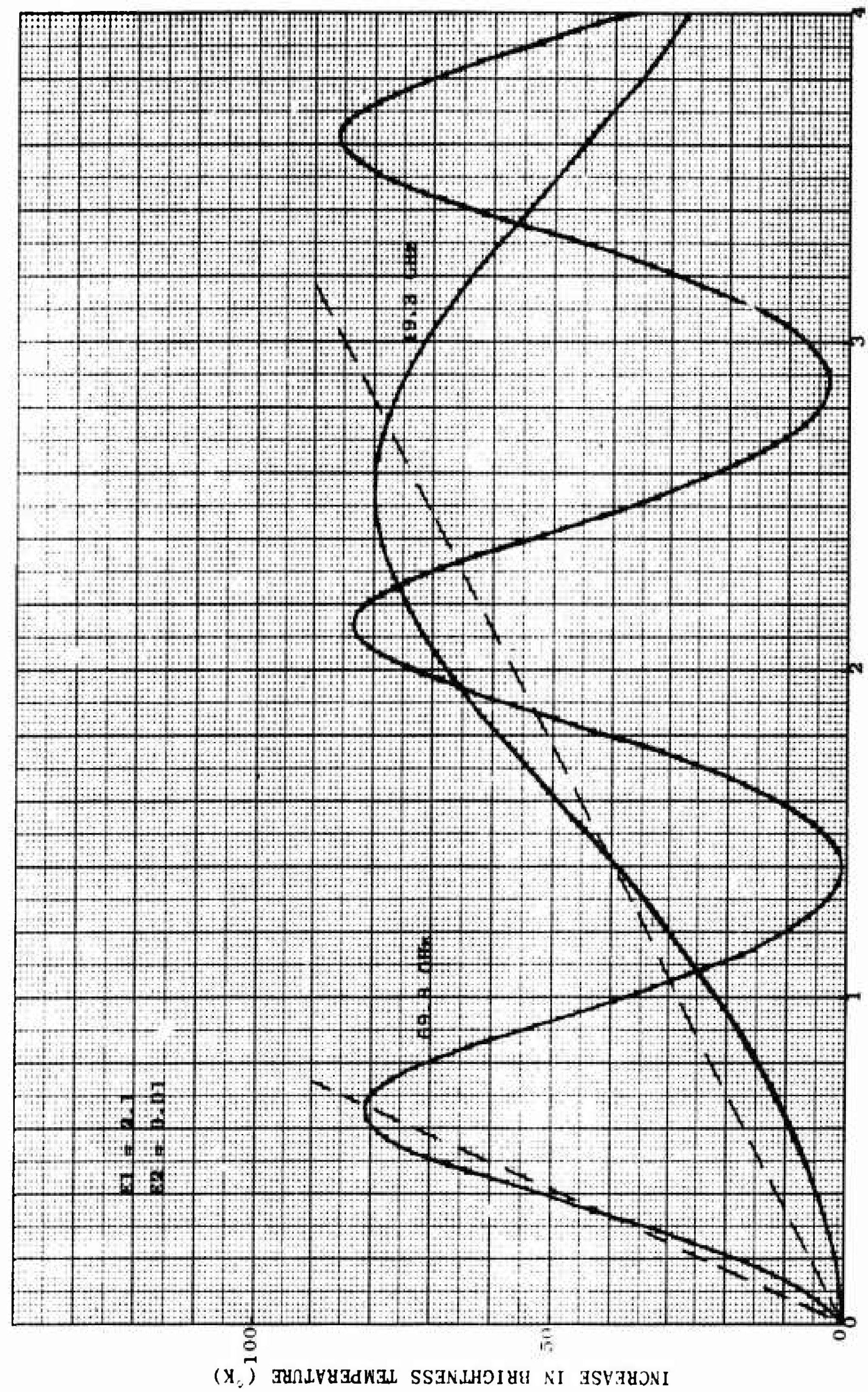

AUGUST 30, 1971
NO. 2 FUEL OIL
69.7 GHz.
25
20
15
10
5
1
3 dB BEAM SPOT
19.3 GHz.
VISIBLE EDGE
OF SLICK
15
10
5
1
0
200
400
600
DISTANCE (Feet)

Figure 23

The microwave data, contrary to the visible spectrum, indicate that the oil is not spread uniformly over the slick but rather that the majority of the oil is concentrated in a relatively small area of the slick. If the 200 gallons of oil spilled had spread uniformly over the 101 x 10^3 sq. ft. area of the visible slick, a film with an average thickness of 0.08 mm would have been formed. A film of 0.08 mm thickness would result in an antenna temperature increase of less than 3^oK at 69.8 GHz and at best it would be barely detectable. The peak antenna temperature increase actually observed of 27^oK indicates that much greater film thicknesses are present. The width of the antenna temperature response is consistent with the majority of the oil being concentrated in a region approximately 80 feet in diameter; an area of 5 x 10^3 sq. ft. or 5 percent of the visible slick. If the peak antenna temperatures of 19 and 27^oK are corrected for reflected sky radiation and main-beam efficiency following equations (4) and (5), main-beam brightness temperatures of 23^oK and 50^oK are obtained at 19.3 and 69.8 GHz respectively. These temperatures are consistent with an average thickness over the small thick region of about 1 mm as can be seen from Figure 24. A thickness of 1 mm over an area of 5 x 10^3 sq. ft. represents a volume of 123 gallons. This indicates that more than 60 percent of the oil is confined within 5 percent of the area of the slick.

It is clear that thickness variations exist over dimensions smaller than the surface resolution and a point by point thickness determination is not possible in this case. However it is possible to obtain the volume by integrating the antenna temperature map and using equation (14) as described previously. In order to apply this technique, the proportionality constant C must be determined. The dotted lines in Figure 24 are reasonably good linear approximations to the actual calculated dependence of ΔT_B on



SLICK THICKNESS (MM)

Figure 24

thickness out to the first maximum. If appreciable oil at thicknesses beyond the first maximum is present, serious errors will result. Since the microwave data indicate that oil thicknesses of 1 mm or greater are present, the volume determined from the 69.8 GHz map is not expected to be reliable since 1 mm is well beyond the first maximum at that frequency; however, the 19.3 GHz data should give a reliable volume measurement. The values for C of 0.096 $(mm)^{-1}$ and 0.40 $(mm)^{-1}$ were determined from the dotted lines in Figure 24 at 19.3 and 69.8 GHz, respectively. Integration of the antenna temperature contours results in a volume of 190 $\pm$ 50 gallons of 19.3 GHz. The error given is a realistic but rough estimate. A similar integration at 69.8 GHz indicates a volume of 110 gallons. This value is expected to be an underestimate and cannot be accepted because oil thicknesses beyond the first maximum are known to be present.

In summary, the microwave data of the 30 August oil spill indicates oil thickness of 1 mm or more were present and that more than 60 percent of the oil was concentrated in less than 5 percent of the area of the slick. The volume of the slick determined solely from the microwave data is 190 $\pm$ 50 gallons. This volume is in good agreement with the known volume of the spill of 200 gallons. Unfortunately it was not possible to obtain reliable in situ thickness measurements for this spill. However the microwave results are consistent with the general parameters and character of the slick determined from in situ observations and aircraft photography. The most surprising and important result is that the majority of the oil was present in a region comprising less than 5 percent of the total area of the slick. This was not expected since visibly the oil appeared to be more or less uniformly distributed.

Oil Spills of 13 October 1971

Two spills were conducted on this date: one of 200 gallons of No. 2 fuel oil and the other of 200 gallons of No. 6 crude oil. Both of these slicks spread rapidly. The resultant rapid changes in size and shape made it impossible to obtain sufficient aircraft passes to construct microwave maps before the slicks had significantly altered. Individual passes showed increased microwave emission only over very small portions of each slick indicating that the oil was concentrated in a small thick region(s). The microwave data from both slicks are consistent with the oil forming film thicknesses of 0.5 mm or more in a region(s) smaller than the antenna beam-spot of about 50 feet. This is in agreement with in situ observations which indicate that the oil in both slicks formed many small "lenses" or "blobs" in restricted portions of the slick. The No. 2 fuel oil "lenses" were a centimeter or so in diameter and very rough measurements indicated average thicknesses in these regions of 0.1 mm or so. The No. 6 crude oil formed larger thicker "blobs" with thicknesses visibly estimated to range from 0.5 to 5 mm.

At this point in the program it was clear that the oil formed small thick regions surrounded by a much larger and thinner slick. Unfortunately these thick regions in the test spills were smaller than the microwave beam-spot on the surface. In order to study the structure in greater detail, it was necessary to increase the surface resolution in terms of the size of the oil slick. The size of the thick region would be increased in future spills by tripling the volume of oil spilled, from 200 to 600 gallons, and the beam-spot would be reduced by flying at altitudes of about 300 feet instead of 500 feet. The "ground truth" of the oil distribution would be enhanced by dyeing the oil red with an oil soluble dye. This would have the further advantage of aiding pilot recognition of the slick and reducing the number of passes which miss the slick.

Oil Spill of 17 May 1972

This spill consisted of 616 gallons of No. 2 fuel oil dyed red. The seas were calm with 2 foot swell and winds less than 10 knots. It was warm and clear with only a slight haze on the horizon. The oil was spilled at 0922 EDT. Airborne measurements were begun immediately and continued to 1135 EDT at which time the slick was entered in small rubber boats to take oil thickness samples. This sampling was delayed until after sufficient microwave data had been obtained since entering the slick disrupts and distorts it to the extent that data taken before and after sampling are not comparable.

Measurements were made at 19.3 and 69.8 GHz. Antenna temperature maps were constructed to represent the slick at 1000 EDT and at 1100 EDT. Data within 15 minutes before and after these nominal times were used to construct the maps. A photograph of the slick at 1000 EDT is shown in Figure 25 and maps of the increase in antenna temperature at 19.3 and 69.8 GHz due to the slick, superimposed on an outline of the visible slick, are shown in Figure 26. A photograph of the slick at 1100 EDT is shown in Figure 27 and the corresponding microwave maps are given in Figure 28. A region of relatively very thick oil is sharply and clearly defined by the red dye. This is the dark region at the top of the photographs and is shown crosshatched in the drawings of the visible slick. In situ measurements indicated thicknesses in excess of 2 mm at spots in the thick region while a thickness sample of only 0.004 mm was observed outside of this region. Therefore a thickness ratio of as much as 500 exists between the thick region and the surrounding slick.

Figure 25

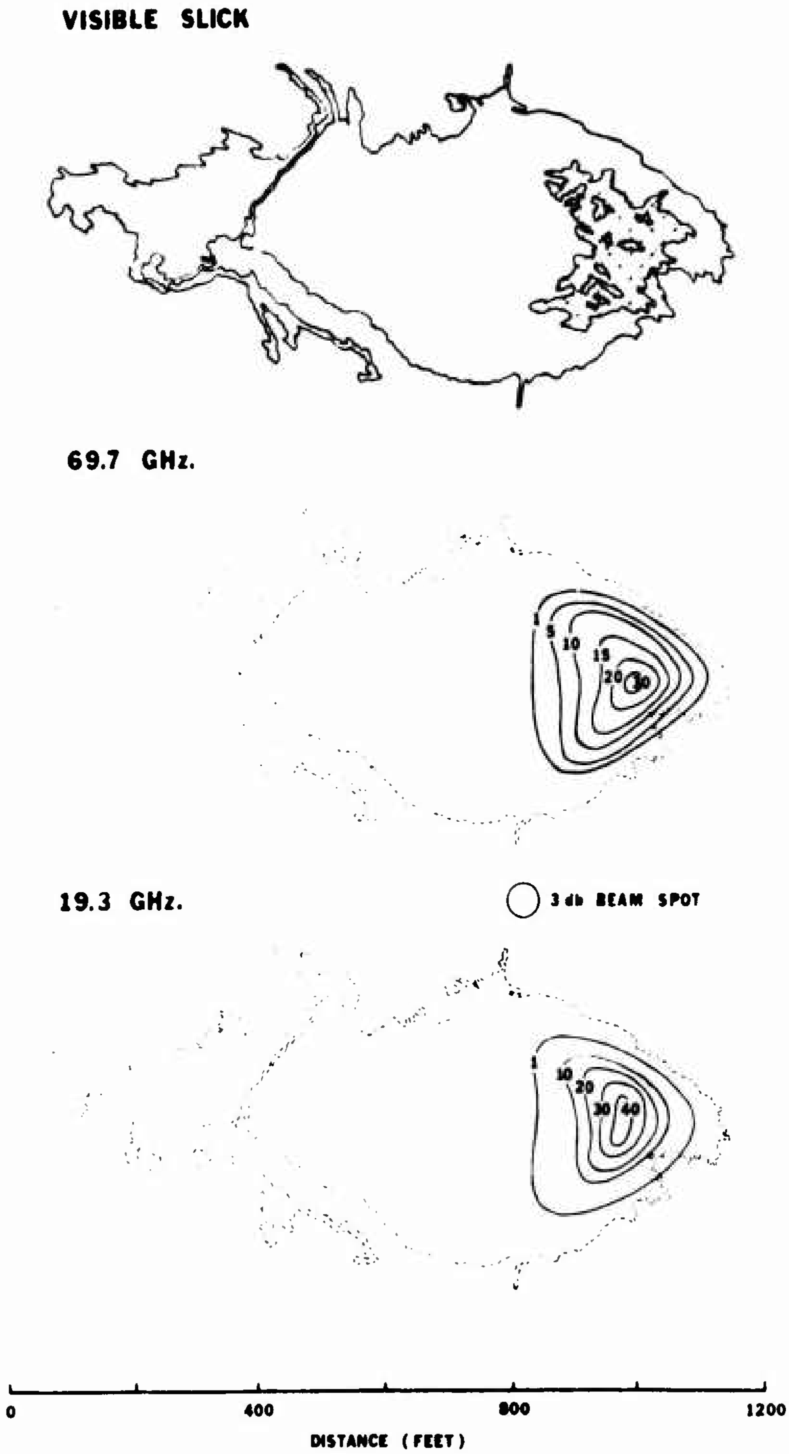

VISIBLE SLICK
69.7 GHz.
19.3 GHz.
3 db BEAM SPOT
0
400
800
1200
DISTANCE (FEET)

Figure 26

Figure 27

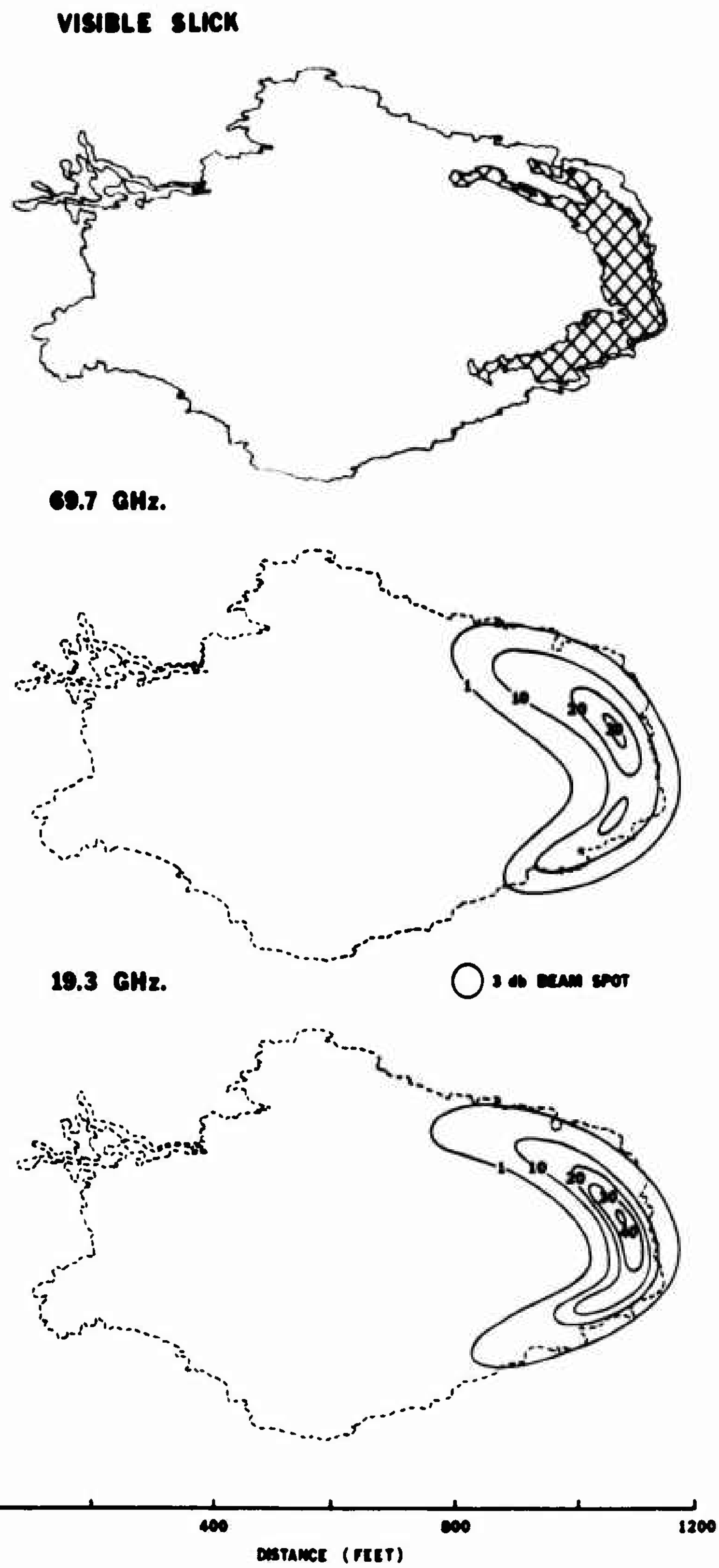

VISIBLE SLICK
69.7 GHz.
1
10
20
19.3 GHz.
3 db BEAM SPOT
1
10
20
0
400
800
1200
DISTANCE (FEET)

Figure 28

The thick region was located at the downwind end of the slick; eventually forming a crescent along the downwind edge as is shown in Figure 27. The region was sharply defined and was still intact and clearly visible when the aircraft left the test site at 1400 EDT. The area of the visible slick increased from 244×10^3 sq. ft. at 1000 EDT to 405×10^3 sq. ft. at 1100 EDT while the thick region spread much more slowly growing from 29×10^3 sq. ft. to only 33×10^3 sq. ft. in the same time.

The microwave signals coincide closely with the region of thick oil as shown in Figures 26 and 28. Peak antenna temperatures of 42 and 33^{o}K were observed at 19.3 and 69.8 GHz, respectively. Correcting for reflected sky radiation and main-beam efficiency following equations (4) and (5) results in peak main-beam brightness temperatures of 51 and 73^{o}K at 19.3 and 69.8 GHz, respectively. This indicates a thickness averaged over the main-beam of 1.8 mm which is well beyond the first maximum at 69.8 GHz. The volume of the slick determined by integration of the antenna temperature maps as given by equation (14) and using the same values for C as used for the 30 August spill is 678 and 754 gallons at 1000 and 1100 EDT from the 69.8 GHz data. The volume determined from the 19.3 GHz data is in good agreement with the known volume spilled of 616 gallons. Since film thicknesses well past the first maximum at 69.8 GHz are present, the volume determined from this data using the linear response with thickness approximation is expected to be too low. Note however that a larger volume was determined at 1100 EDT than at 1000 EDT. This is to be expected since the oil was spreading and thinning and there was less oil at thicknesses beyond the first maximum at 1100 EDT. Hence the linear approximation used to form the integral is more nearly satisfied and a more accurate value for the volume determined.

The results of this spill confirm those from previous spills. Considering the oil to have an average thickness of 0.004 mm outside the thick region as suggested by the in situ thickness measurement, only about 40 gallons of oil are outside the thick region. Considering nearly all of the oil in the thick region is consistent with the microwave measurements of volume. Further, since the 616 gallons spilled would cover the area of the thick region to an average thickness of 0.8 mm, it is also consistent with the peak thickness determined from the microwave data. Therefore we conclude that more than 90 percent of the oil is present in a sharply defined region with thicknesses of a millimeter or more and which comprises less than 10 percent of the area of the visible slick. Film thicknesses of a millimeter or more were not anticipated at the start of the program. The frequency of 69.8 GHz is not appropriate for such thick films. Therefore a new radiometer at 31.0 GHz was constructed to be used with the 19.3 GHz radiometer in future spills.

Oil Spill of 11 July 1972

This spill consisted of 630 gallons of No. 2 fuel oil dyed red. Conditions were very clear and sunny with winds of 3 to 6 knots and 2 ft. swell. The oil was spilled at 0930 EDT. Figure 29 shows a series of drawings traced from color photography taken periodically during the measurements. The outer line in each drawing represents the extreme edge of the visible slick, the next inner line is the region of color fringing when visible in the photograph and the crosshatched area is the region of thick oil. The oil formed a well defined thick region surrounded by a very much larger and thinner region. In situ thickness measurements showed the oil to be 2.4 $\pm$ 0.3 mm thick at spots in the crosshatched region and typically 0.002 to 0.004 mm thick outside this region.

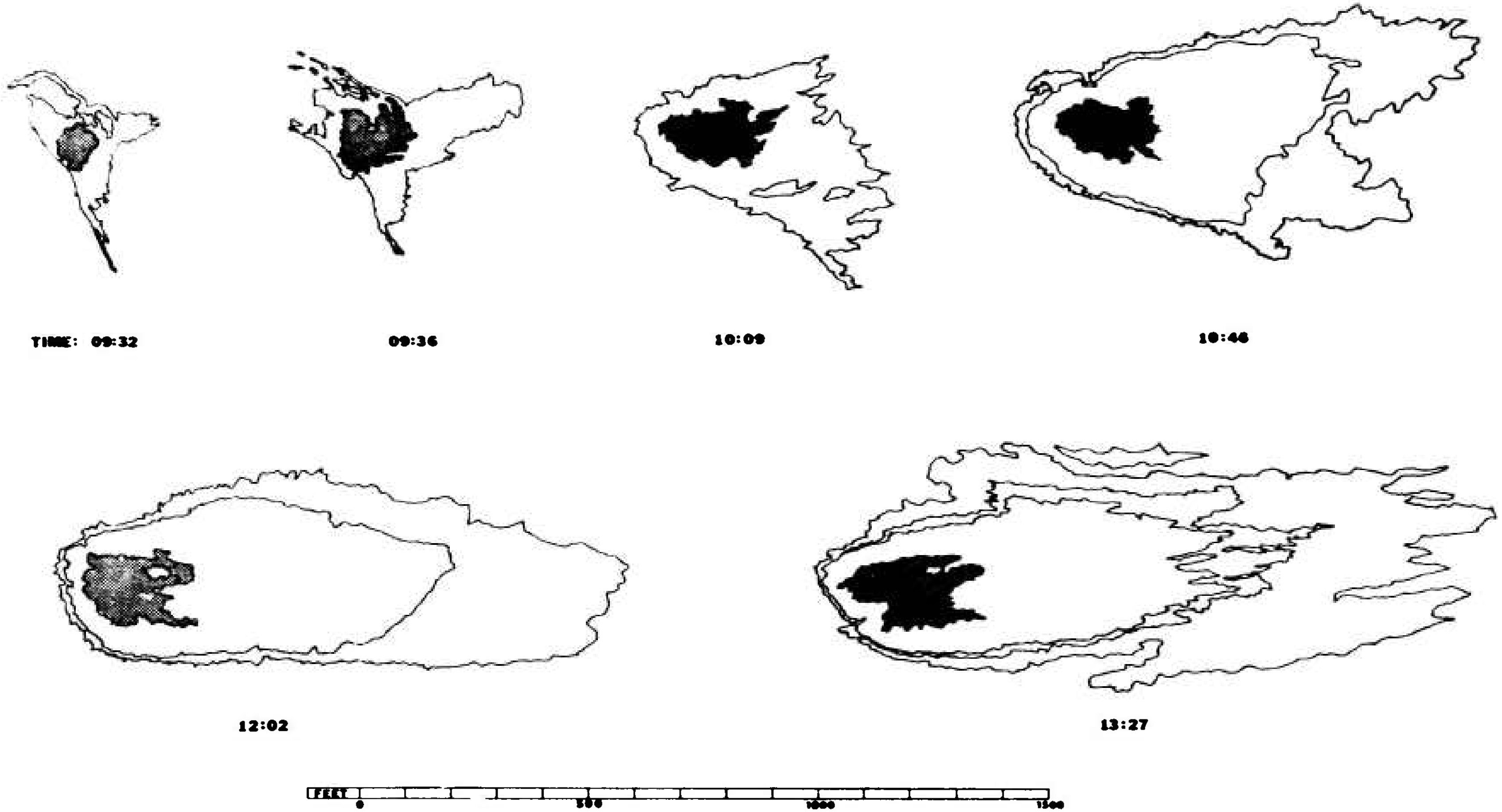


Figure 29

The thick inner region spread at a much slower rate than the total slick. This is shown in Figure 30 where the area of the inner region and the total area of the visible slick are given as a function of time on a log-log plot. If the dotted lines are taken to represent the measurements, the total area grew at a rate proportional to the time to the 0.6 power and the thick region only as the 0.2 power. The spreading rate of the total area most nearly matches the gravity-viscous spreading phase described theoretically by J. A. Fay (18) which grows at a rate proportional to the square root of the time. It is somewhat slower than spreading rates reported by Guinard (19) or by Munday et al. (20). However the spreading rate is dependent upon many variables such as initial volume, age, density and viscosity of the oil, the surface active materials present, and interfacial surface tension as well as the surface winds, sea state, and surface current present, and will vary widely. Most significant is the dichotomous behavior of the oil; dividing clearly into a thick, relatively compact region surrounded by a second much larger and thinner region. This is the same behavior as was exhibited by each of the previous spills. It may well be due to small quantities of surface active materials in the oil which spread more rapidly than the bulk of the oil, surrounding it, inhibiting its growth, and thus containing and controlling it (21).

Microwave observations were taken during the entire four hour period shown in Figure 29. Those data obtained within 30 minutes before and after the 1046 EDT photograph were used to construct microwave maps nominally at that time. The photograph of the slick at 1046 EDT is shown in Figure 31 and the contour maps of the increase in antenna temperature above the unpolluted sea at 19.3 and 31.0 GHz are shown at the right in Figure 32 superimposed on the outline of the visible slick. The antenna temperatures are

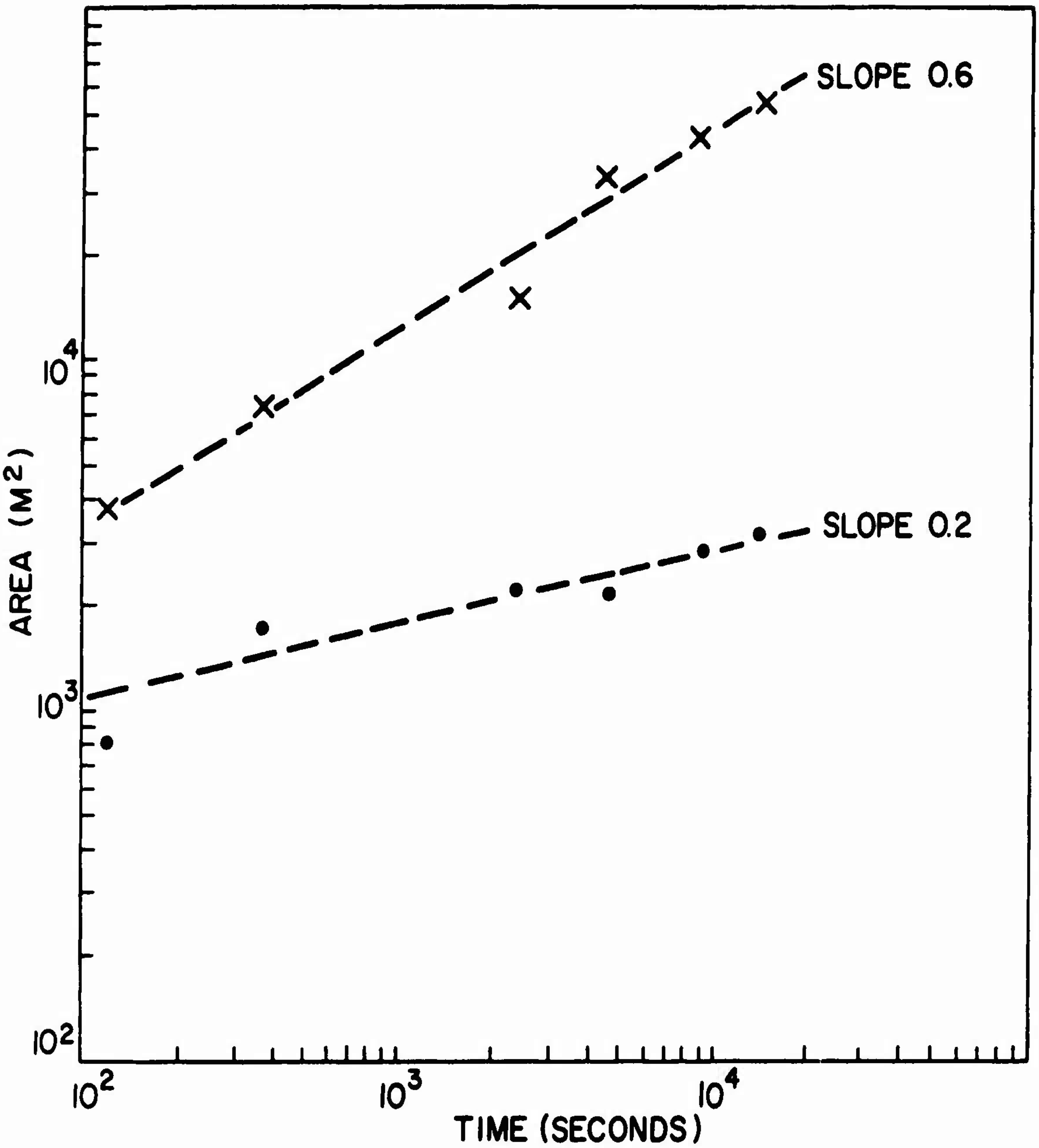
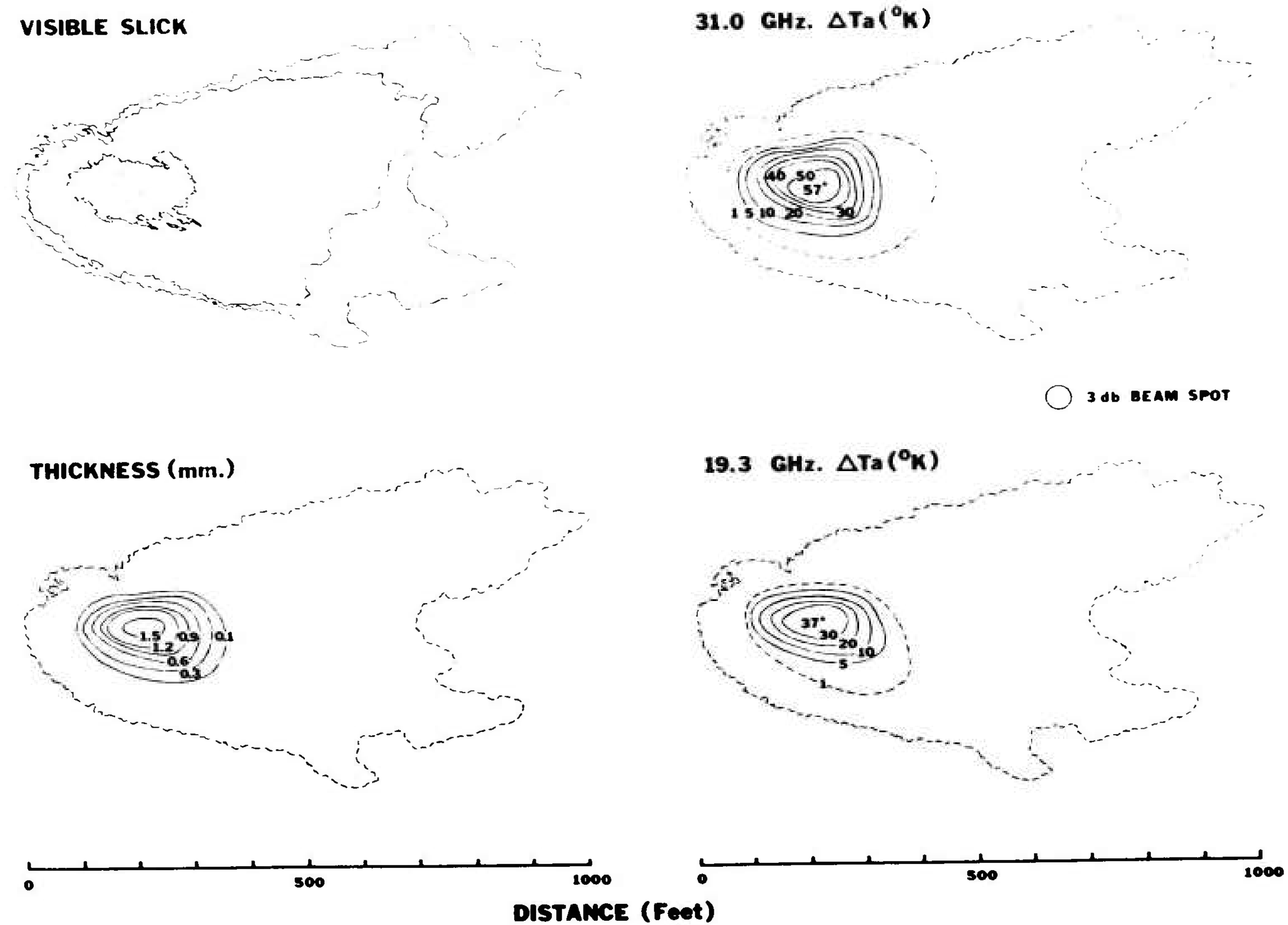


Figure 30

Figure 31



VISIBLE SLICK
31.0 GHz. ΔTa(°K)
1 5 10 20 30 40 50 57°
3 db BEAM SPOT
THICKNESS (mm.)
1.5 1.2 0.9 0.6 0.3 0.1
19.3 GHz. ΔTa(°K)
37° 30 20 10 5 1
0 500 1000
0 500 1000
DISTANCE (Feet)

Figure 32

weighted averages over the antenna beam as given by equation (7). The half-power beam spot on the surface is represented by the small circle. These antenna temperature distributions were used to derive the thickness contours shown at the bottom left of the figure using the method described previously and given by equation (15).

The microwave signals coincide closely with the region of thick oil and show that average thicknesses over the antenna beam of up to 1.5 mm are present in good agreement with in situ spot measurements in this area of 2.4 $\pm$ 0.3 mm. Integration of the thickness contours derived from the microwave data gives a volume of 650 $\pm$ 65 gallons which taken with the volume of oil spilled of 630 gallons indicates that nearly all of the oil is in the thick region. This is consistent with in situ measurements of film thicknesses of 0.002 to 0.004 mm outside the thick region since only 15 to 30 gallons of oil would be needed to cover the entire area of the visible slick of 350 x 10^3 sq. ft. with a uniform film to those thicknesses. If all of the 630 gallons of oil spilled were uniformly spread over the thick region, whose area of 23 x 10^3 sq. ft. is less than 10 percent of the area of the visible slick, a layer 1.1 mm thick would be formed which is consistent with the thicknesses derived from the microwave data. The ration of slick thickness in the two regions of nearly 1000 also shows that nearly all of the oil is located in a small region of the slick.

The volume of oil present was also found by integrating the antenna temperature contours and using equation (14) and the approximate method described previously. The values for C were 0.096 $(\text{mm})^{-1}$ at 19.3 GHz, as previously used for the spills of 30 August 1971 and 17 May 1972, and 0.16 $(\text{mm})^{-1}$ at 31.0 GHz. Volumes of 617 and 644 gallons were determined at 19.3 and 31.0 GHz, respectively. These values are in excellent agreement with the known volume spilled of 630 gallons and with the volume of 650 gallons obtained by integrating the thickness contours derived from the microwave data. The consistent result at 31.0 GHz indicates that there was not a significant amount of oil present with thicknesses in excess of 1.6 mm: the first maximum at that frequency.

Oil Spills of 15 August 1972

Two spills were conducted. The first consisted of 632 gallons of No. 2 fuel oil and the second of 350 gallons of No. 4 crude oil. The sea was calm with 1 to 2 ft. swell and winds of 6 to 8 knots. There was a heavy surface haze which limited visibility to about 4 miles.

A photograph of the No. 2 oil slick taken 1 hour and 40 minutes after the spill is shown in Figure 33. The oil was not dyed red as were the 17 May and 11 July, 1972 spills and there are no thickness variations over the slick apparent visibly. No thick regions were revealed either by photography using color SO-397 or color IR 2443 film or by RS-14 IR scanner images in the 3 to 5 and 8 to 14 micron bands. The RS-14 image in the 8 to 14 micron band is shown in Figure 34. It has not been corrected for aircraft motion and is foreshortened in the direction of flight. Contrary to these images, the microwave data shows a clearly defined small thick region. The increase in antenna temperature over the unpolluted sea at 19.3 and 31.0 GHz superimposed on the outline of the visible slick is shown in Figure 35. The data used to construct these contours were obtained within 30 minutes of the time that the photograph was taken. The upper portion of the contours are shown dotted because insufficient data were obtained in this region to reliably establish them. The volume determined by integration of the antenna temperature contours as given by equation (14) is

Figure 33

16-0040

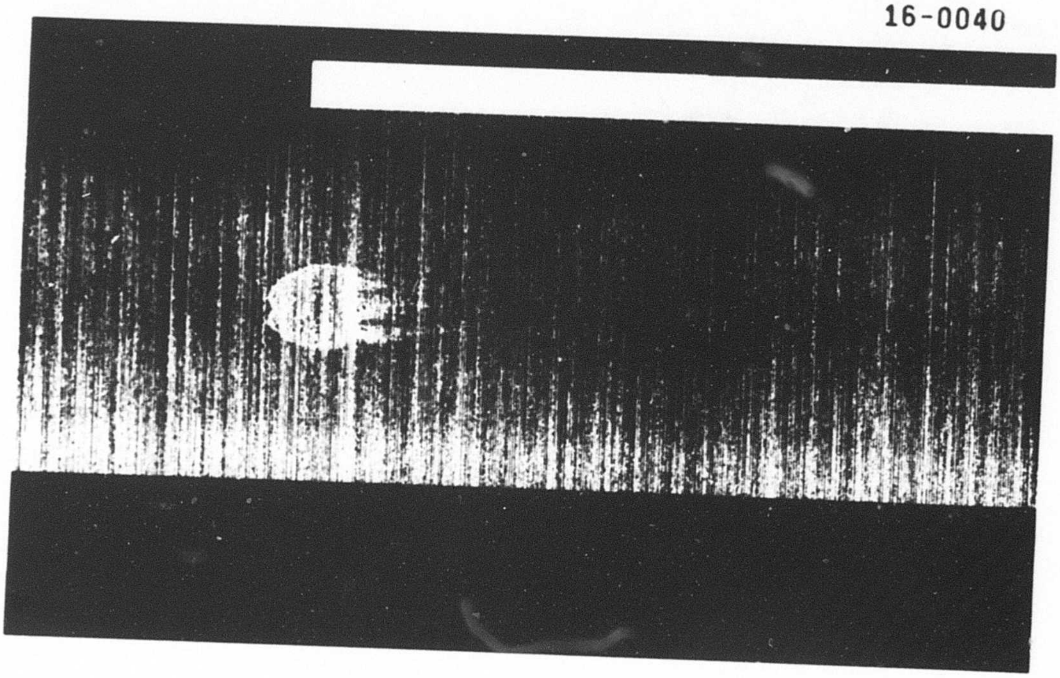


Figure 34

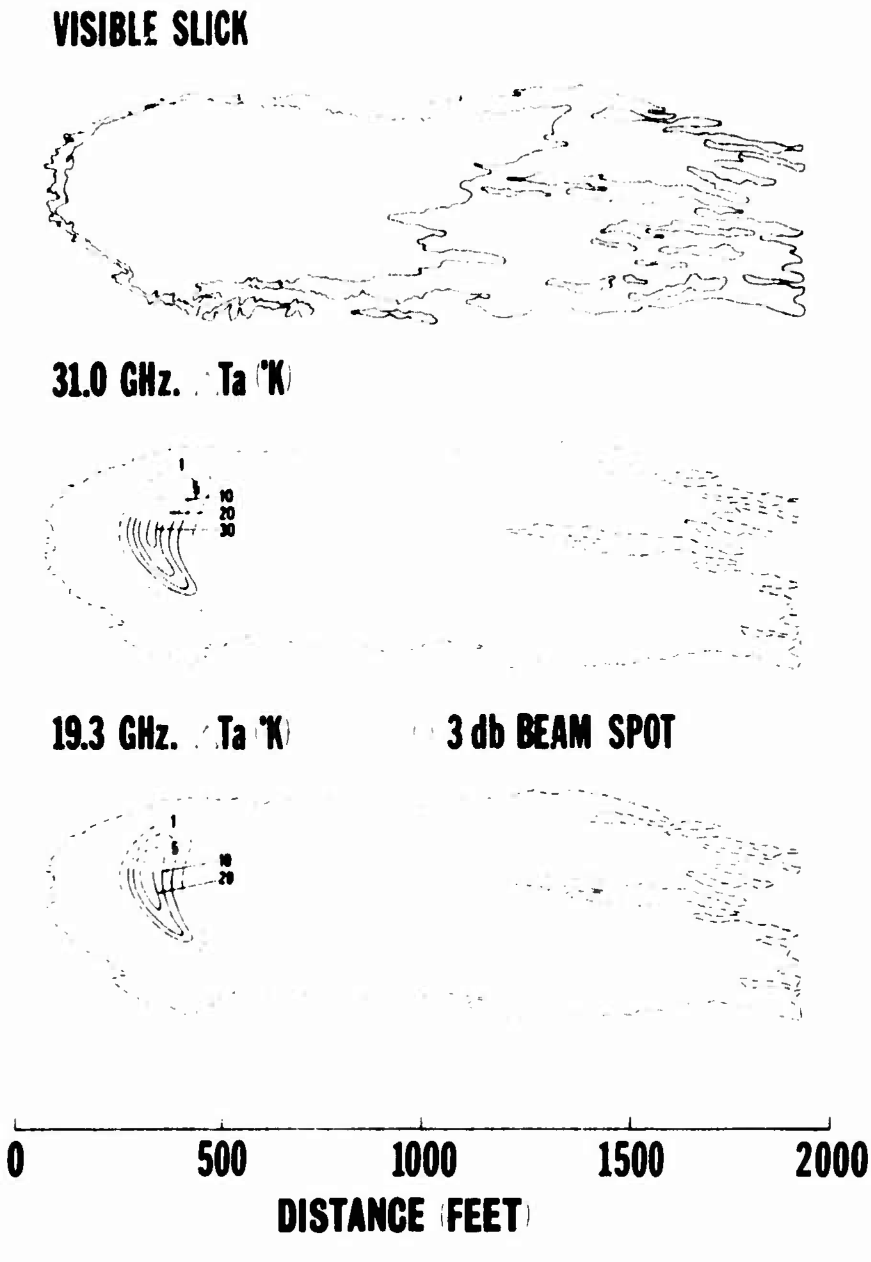

VISIBLE SLICK
31.0 GHz. Ta (°K)
1
10
20
30
19.3 GHz. Ta (°K)
3 db BEAM SPOT
1
5
10
20
0
500
1000
1500
2000
DISTANCE (FEET)

Figure 35

only a lower limit since the dotted portion was not included in the integration. The volumes so determined are 340 and 300 gallons from the 19.3 and 31.0 GHz data, respectively. The peak antenna temperatures indicate thicknesses averaged over the main-beam of up to 0.9 to 1.2 mm. These results are in agreement with those from the previous No. 2 fuel oil spills and are consistent with the oil forming a relatively small region with thicknesses of a millimeter or more and containing the vast majority of oil surrounded by a very much larger and thinner slick which contains very little of the oil. Perhaps most significant is the fact that, as in the 30 August and 13 October 1971 No. 2 fuel oil spills, the distribution of oil was shown only by the microwave data and was not apparent visibly or in the infrared spectrum.

A photograph of the No. 4 crude oil slick taken 40 minutes after the spill is given in Figure 36. Some indications of a thick region is evidenced by a slight darkening in the lower area of the slick in the photograph. This same region is just discernable on color IR photography. However it is quite apparent in the 8 to 14 micron band of the RS-14 IR scanner. That image, foreshortened due to aircraft motion, is shown in Figure 37. The microwave data at 19.3 and 31.0 GHz, which are presented in Figure 38, show very large signals from this same region. These data indicate peak thicknesses averaged over the main-beam of 1.8 to 2.0 mm. Unfortunately, due to cooperative efforts with the NASA P-3 aircraft, the extended period of 1 hour and 25 minutes after the photographic imagery was taken was required to obtain sufficient data to construct the microwave contour maps. During this time the slick grew and changed shape considerably and it is probable that blurring and enlargement of the microwave maps resulted. This would cause an over estimate of the amount of oil present. The volumes determined by integration of the antenna temperature contours of 490 gallons and 390

Figure 36

16-0034 NASA/MSC 210 AUG 72

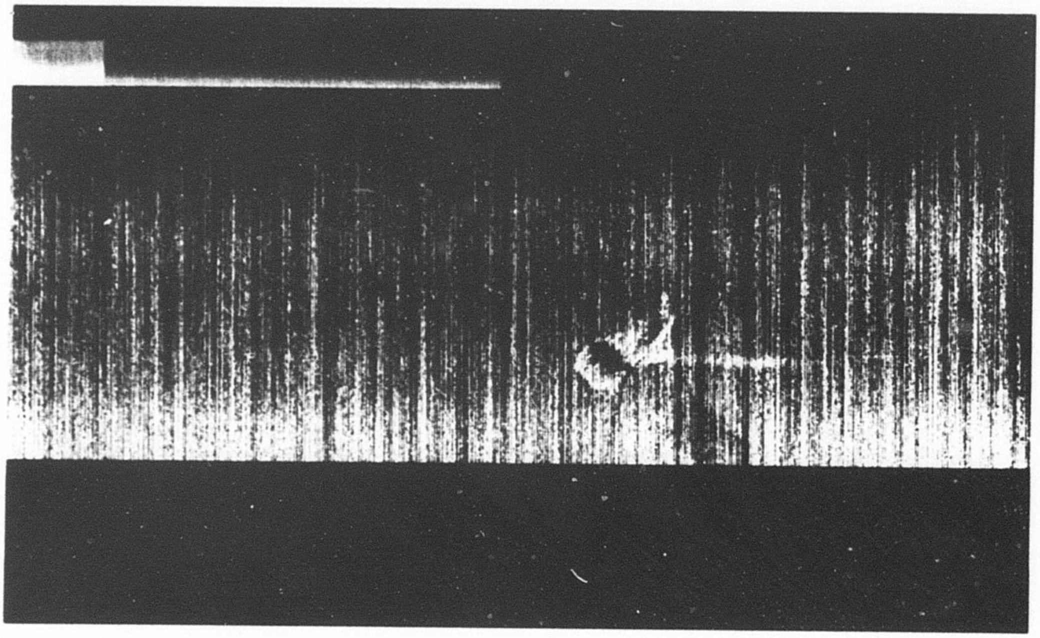


Figure 37

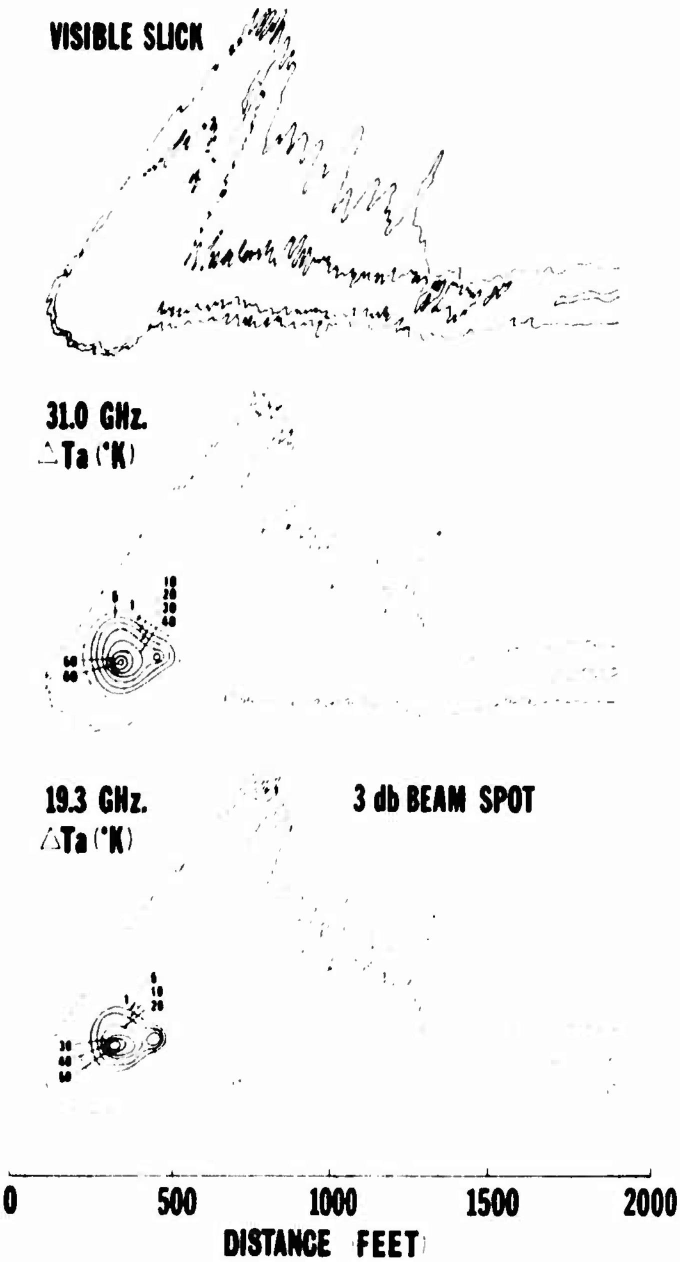

VISIBLE SLICK
31.0 GHz.
ΔTa (°K)
19.3 GHz.
ΔTa (°K)
3 db BEAM SPOT
0
500
1000
1500
2000
DISTANCE FEET

Figure 38

gallons at 19.3 and 31.0 GHz, respectively compared to the volume spilled of 350 gallons indicate that this may be the case. There is no doubt, however, that the majority of the oil was present in a small thick well defined region surrounded by a very much larger and thinner slick. The area of the visible slick was 688 x 10^3 sq. ft. and by far the majority of the oil must lie within the $1^{o}K$ contour at 31.0 GHz, an area of 53 x 10^3 sq. ft., or 8 percent of the visible slick.

The results for all of the calm sea oil spills of each of the oil types of No. 2 fuel oil and Nos. 4 and 6 crude oil are very similar. A clearly defined region with thicknesses of a millimeter or more and containing the majority of oil was always formed. This region was surrounded by a very much larger slick, hundreds times thinner, which contained very little of the oil. It was always possible to locate and delineate the thick region solely from the microwave observations. The thicknesses derived from the microwave data are consistent with in situ thickness measurements and the total volume of oil present determined from the microwave observations was within about 25 percent of the known volume of oil spilled. In general the microwave measurements determined that more than 90 percent of the oil was contained in less than 10 percent of the area of the visible slick. In summary the calm sea oil spill tests demonstrated that multifrequency microwave radiometry has the potential to measure the distribution of oil in sea surface oil slicks, locate the thick regions, and measure their thickness and volume.

2. Rough Sea Oil Spills

A series of seven oil spills was conducted during the period from March 1973 through February 1974 in cooperation with the NASA-Wallops Island Station and the U.S. Coast Guard. These spills were: (1) 550 gallons of No. 2 fuel oil on 28 March 1973, (2) 525 gallons of No. 4 crude oil on 29 March 1973, (3) 530 gallons of No. 4 crude oil on 8 May 1973, (4) 520 gallons of No. 2 fuel oil on 9 May 1973, (5) 520 gallons of No. 2 fuel oil on 16 October 1973, (6) 500 gallons of No. 4 crude oil on 4 February 1974 and (7) 500 gallons of No. 4 crude oil on 5 February 1974.

All phases of each controlled oil spill including ship operation, dispensing of the oil and the collection of ground truth were managed and conducted by the U. S. Coast Guard. The airborne measurements were made using the same radiometers and NASA-Wallops Island C-54 aircraft that were used for the calm sea spills. The measurement details, procedures and techniques were largely the same as those described for the earlier series of spills. However because of the anticipated rough seas a different method for dispensing the oil had to be employed. The oil was released via a tee fitting in the bottom of a 550 gallon tank, installed on the aft deck of the U. S. Coast Guard ship, via two 1 1/2 inch diameter hoses by gravity feed. While this arrangement enabled oil to be spilled even in very high seas a period of from 10 to 20 minutes or more, depending upon oil type and temperature, was required to complete the release of the entire 550 gallon capacity of the tank. During this interval the ship had to be maintained on station or the oil would trail out in a long thin ribbon from the hoses and be quickly segmented by wind and wave action. Even if the ship was kept stationary with respect to the spill the oil tended to envelop the ship. The slick would then be disrupted when the ship left the immediate vicinity of the spill. Both of these problems made it difficult to approximate the near point releases of oil obtained for the calm sea spills.

The spreading and shape changes caused by the higher seas and winds was too rapid to allow a sufficient number of aircraft passes to be made to obtain data over the entire slick before the slick had altered considerably. Therefore it was not possible to construct maps of the microwave brightness temperature over the slick by combining data from a sequence of aircraft passes as was done for the calm sea spills. Rather data from single passes were analyzed to provide thickness profiles along specific cuts through the slick. It should be noted that this restriction to obtaining data along the aircraft ground track is due only to the fact that scanning type radiometers were not available for these measurements and not to any inherent limitation in the microwave technique. In an operational system "imaging" radiometers in which a narrow antenna beam is rapidly scanned back and forth across the aircraft ground track as the aircraft passes over the slick would be used. This would make it possible to obtain a two dimensional image of the slick from each aircraft pass.

Oil Spill of 28 March 1973

This spill consisted of 550 gallons of No. 2 fuel oil dyed red. Unfortunately the slick was destroyed thirty minutes after release of the oil was completed by a submarine which passed directly through it before any microwave data had been taken. The spill was conducted in swells of 6 feet with 20 gust surface winds. The surface conditions during the spill are given in Table 2 and photographs of the spill taken with SO 397 type film at 14:00, 14:07, 14:10 and 14:20 EST are shown in Figures 39, 40, 41 and 42. The effect of the higher seas and winds as well as the greater difficulty in approximating a point release of the oil under these

TABLE 2

28 March 1973

TIME	SKY	VISIBILITY	WIND		DRY TEMP	WET TEMP	HUMIDITY	PRESSURE	SEA TEMP	SWELL
1400	CLEAR	7+ mi	030	20KTS	45.0°F	44.0°F	93%	30.34	6.42°C	040/6 ft
1430	CLEAR	7+	030	18	44.0	43.0	93%	30.32	6.30	040/6
1550	CLEAR	7+	030	18	43.9	41.9	93%	30.32	6.30	040/6
1615	CLEAR	7+	030	18	43.9	41.9	93%	30.33	6.30	040/6

GENERAL COMMENTS

550 Gallons of #2 Fuel Oil 1400 Commenced Spill

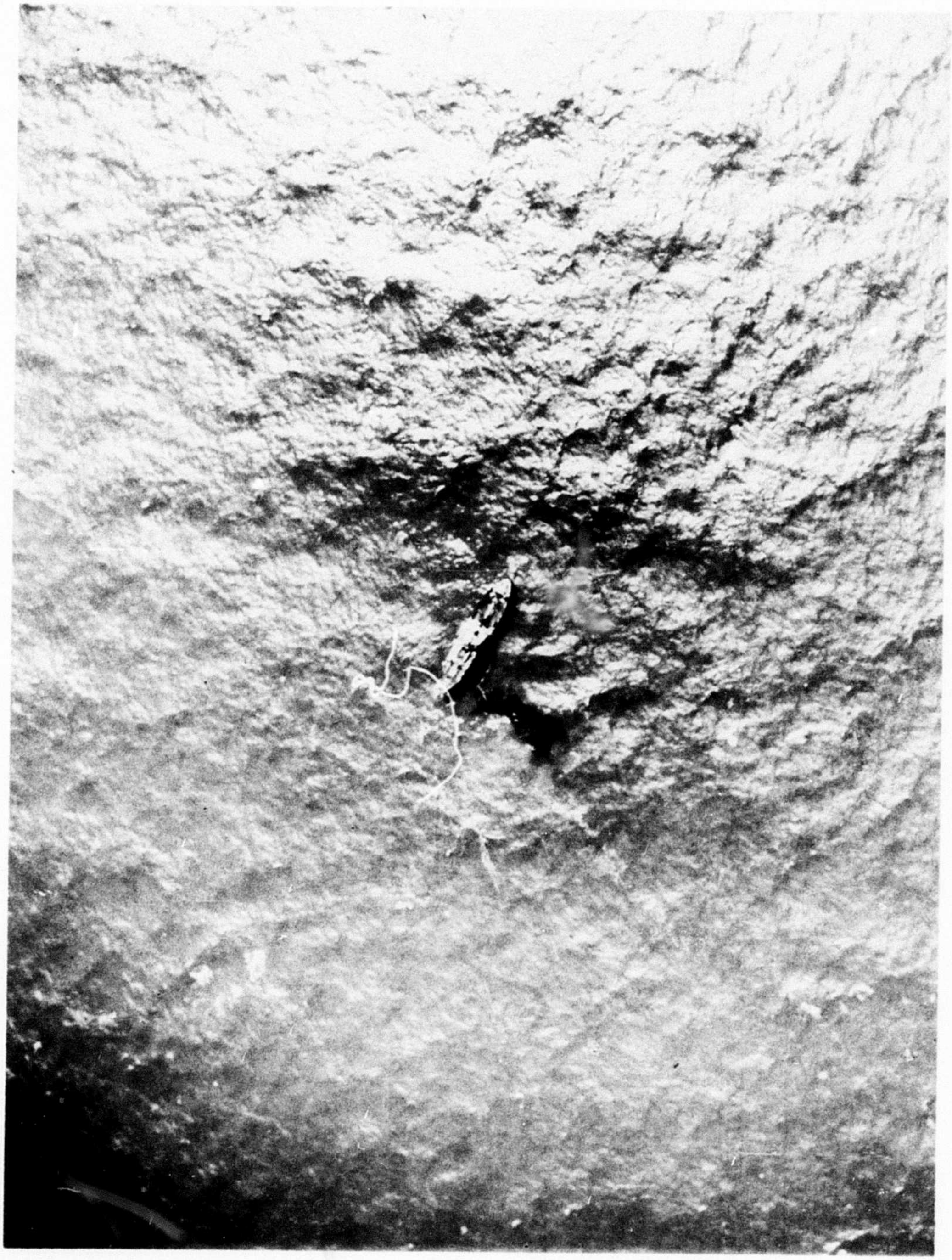


Figure 39

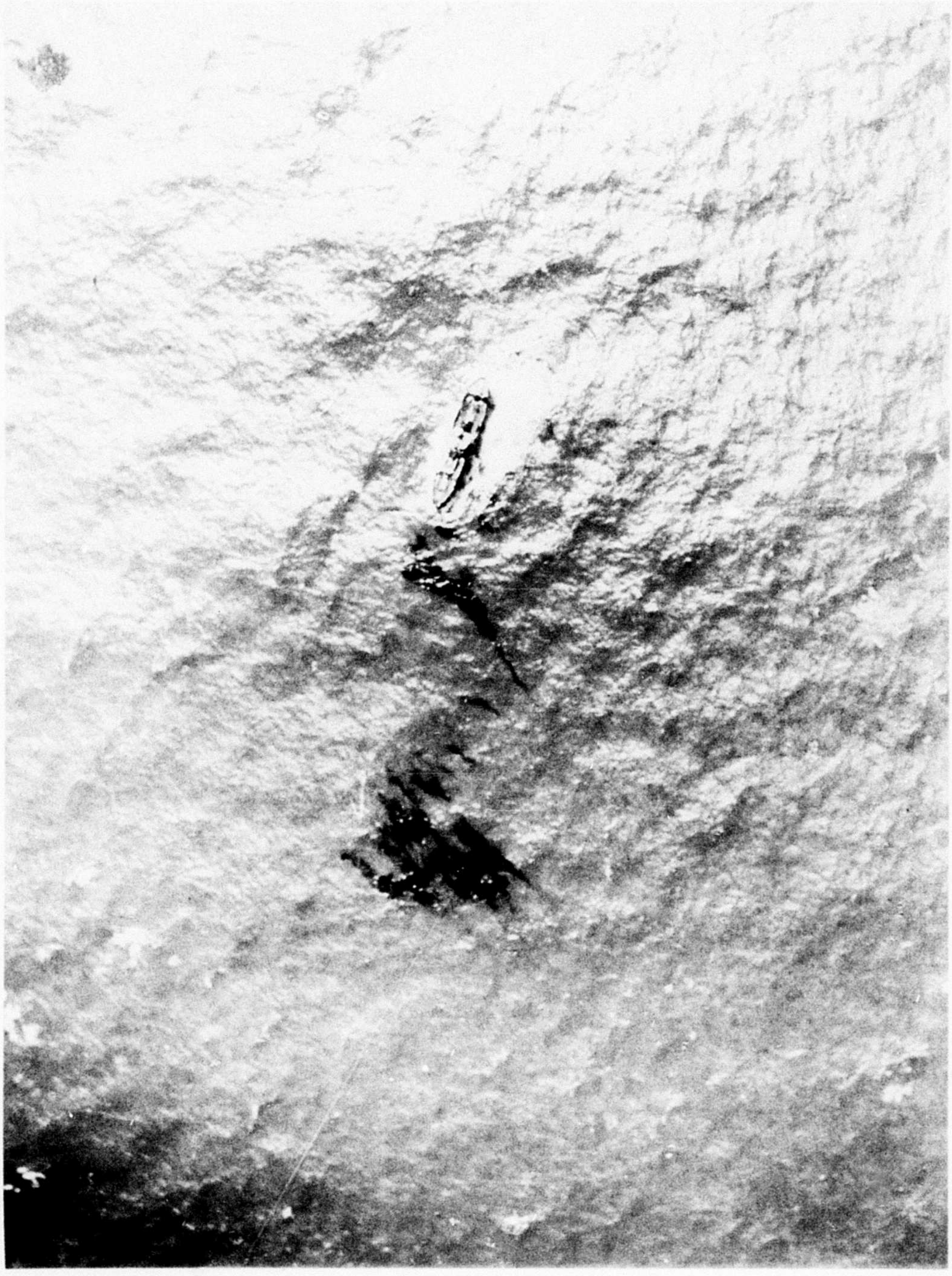


Figure 40

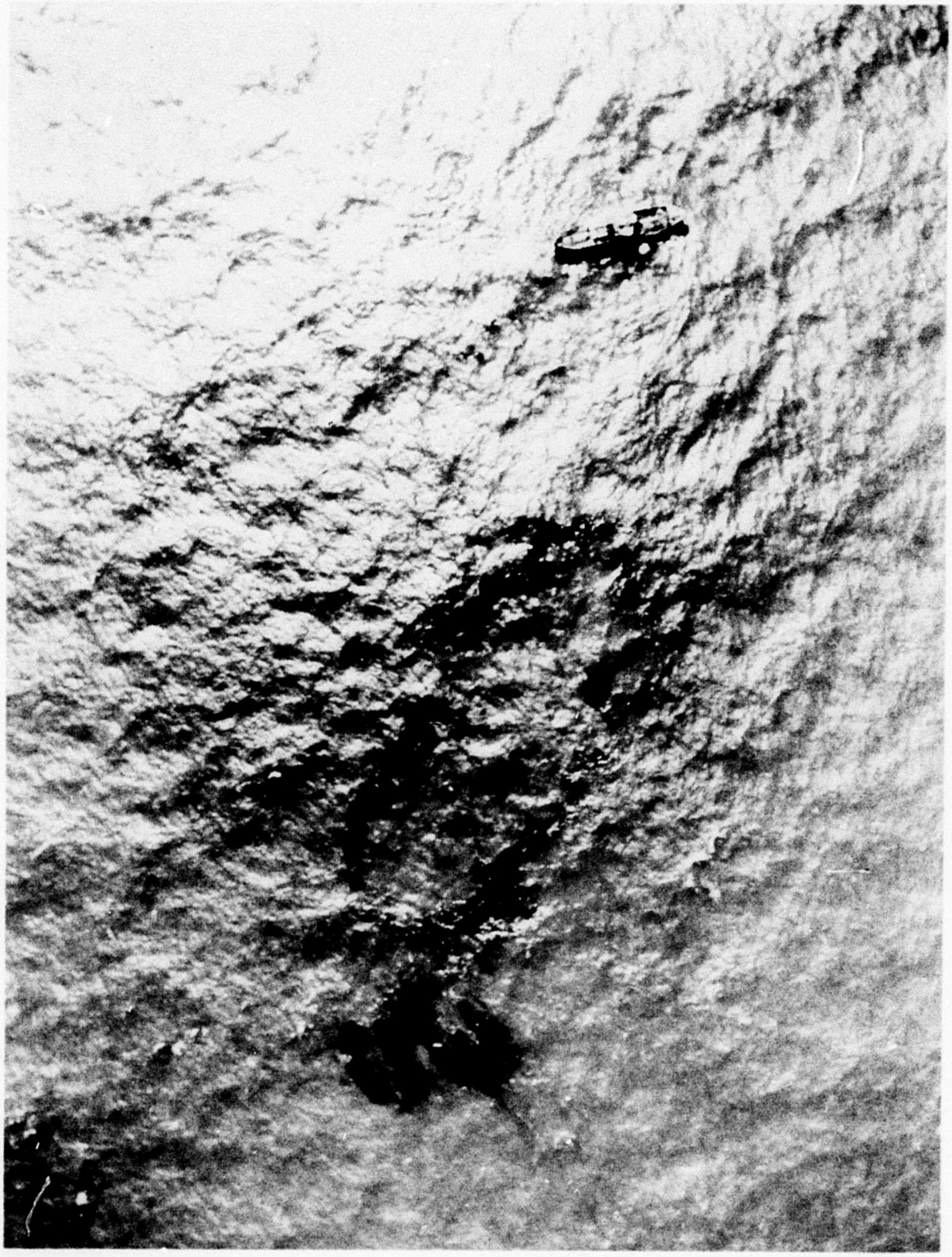


Figure 41

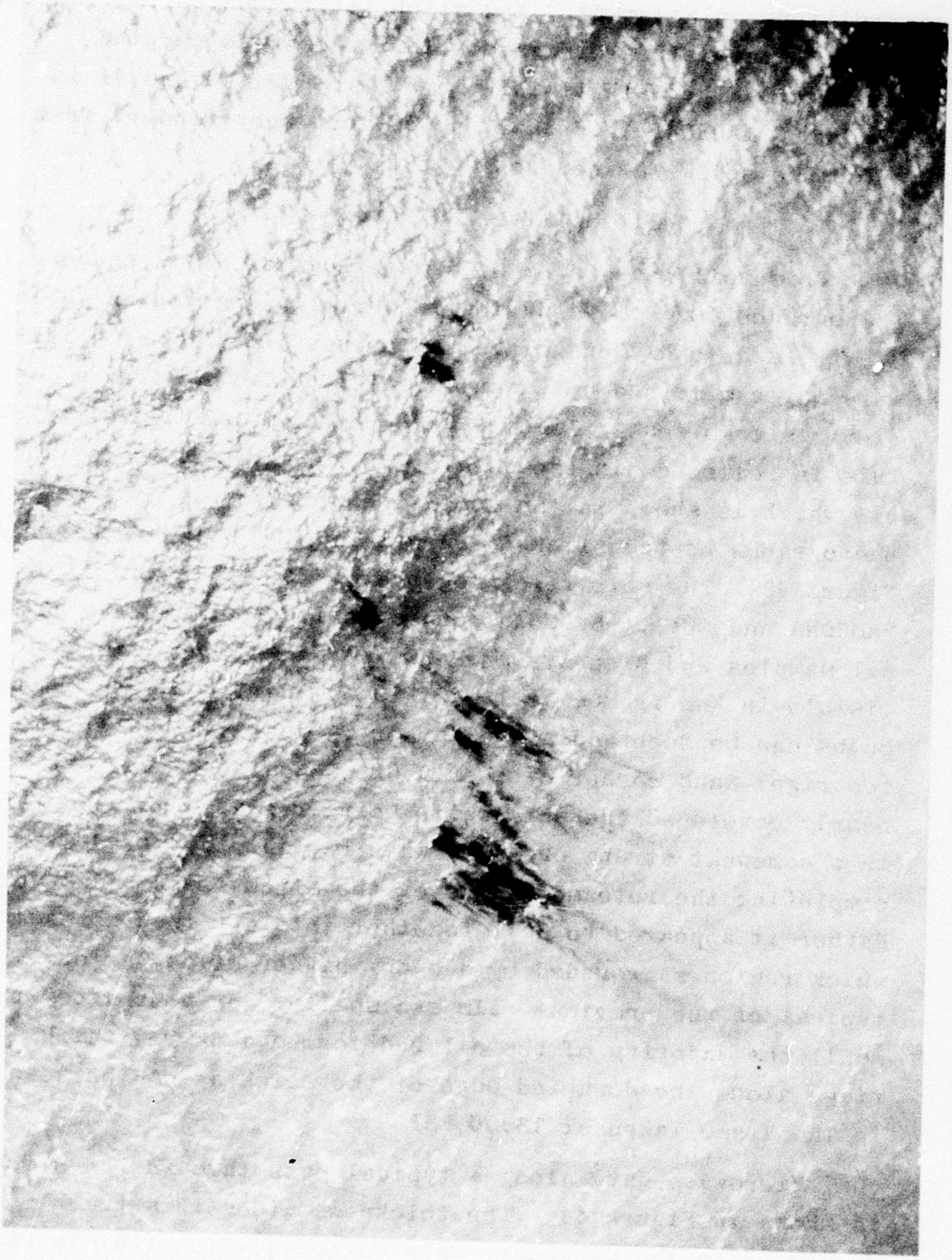


Figure 42

conditions is apparent. The slick is fragmented, spread out and with many streamers formed in the down to up wind direction. The ship visible in Figures 39, 40 and 41 is the USCGC MADRONA (WLB 302), a 180-foot buoy tender, from which the spill was conducted.

Oil Spill of 29 March 1973

This spill consisted of 525 gallons of No. 4 crude oil. The surface conditions during the spill are given in Table 3. The sea conditions of 10 knot winds and swell of 4 feet were quite mild and not significantly different from a previous calm sea spill of No. 4 crude oil on 15 August 1972. This is reflected in the relatively compact release of the oil which is shown in the composite of a series of six photographs of the slick taken with SO 397 film and given in Figure 43. The ship releasing the oil is again the USCGC MADRONA and the U. S. Coast Guard helicopter, used to gather oil samples and drop dye markers and smoke bombs, is also visible in the frames at 12:42, 12:49 and 12:52 EST. Smoke bombs can be seen and a dye marker is just visible in the top right hand corner of the 13:02 photograph. The oil nearly enveloped the ship while being released and was left in a somewhat strung out form when the ship departed after completing the release. However the slick was not disrupted. Rather it appeared to pull together into a rather compact thick region surrounded by a much thinner slick; a form typical of the previous calm sea spills. An hour after the spill the majority of the oil had formed a narrow thick ridge along the downwind edge of the slick as can be seen in the frame taken at 13:50 EST.

Microwave data along a typical pass through the slick is shown in Figure 44. The thickness along this track derived from the microwave data using equation (15) is also given. Notice the sharp clear boundary of the thick region.

TABLE 3

29 March 1973

TIME	SKY	VISIBILITY	WIND		DRY TEMP	WET TEMP	HUMIDITY	PRESSURE	SEA TEMP	SWELL
1235	10/10	7 mi	010	10KTS	46.0°F	45.0°F	93%	30.26	6.45°C	090/4 ft
1310	10/10	7	010	10	46.3	45.3	93%	30.26	6.75	090/4
1345										
1400	10/10	7	010	10	46.0	45.0	93%	30.25	6.55	090/4
1425	10/10	7	030	10	46.0	45.0	93%	30.24	6.52	090/4

GENERAL COMMENTS

525 gallons of #4 Fuel Oil

1235 Commenced Spill

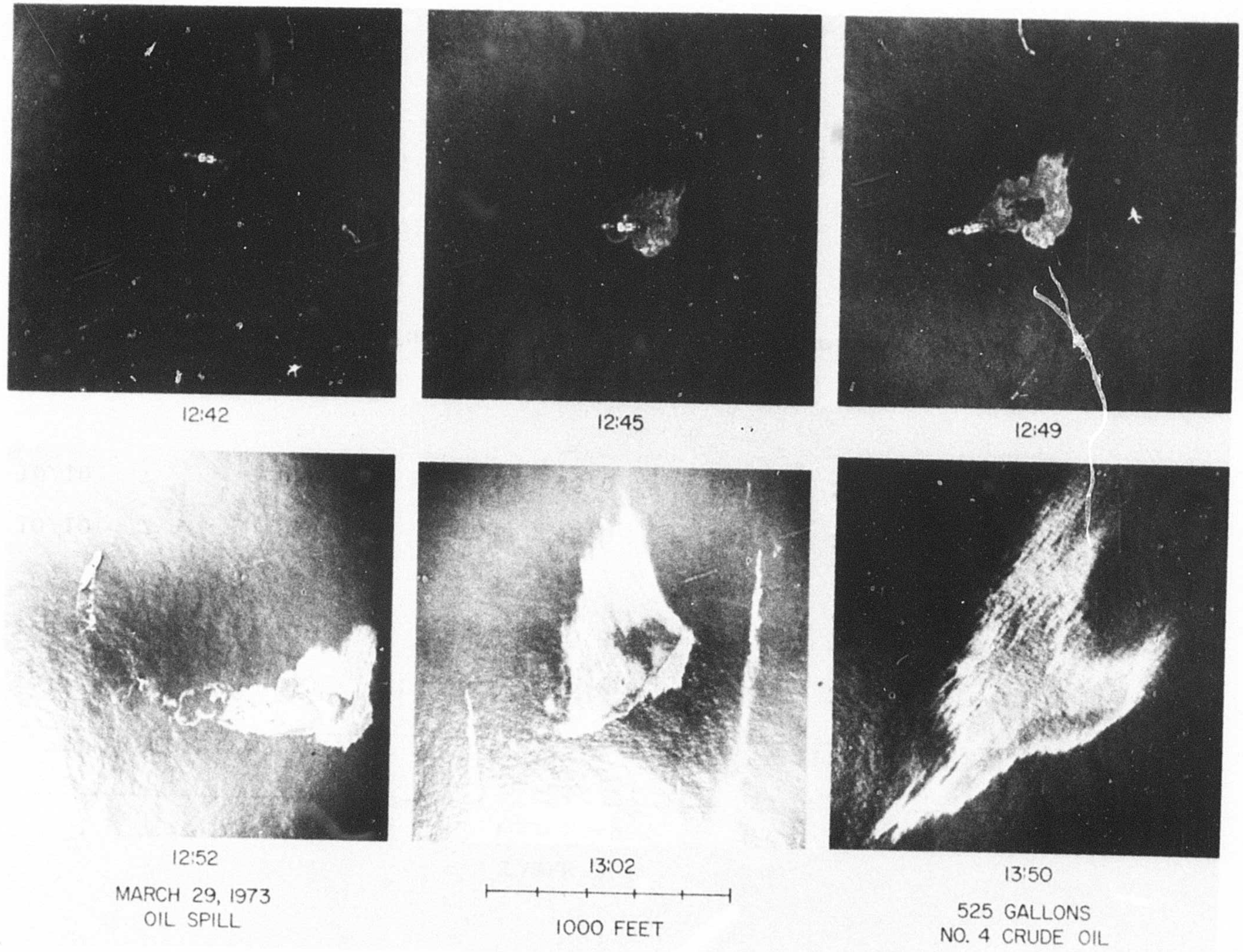

12:42
12:45
12:49
12:52
MARCH 29, 1973
OIL SPILL
13:02
1000 FEET
13:50
525 GALLONS
NO. 4 CRUDE OIL

Figure 43

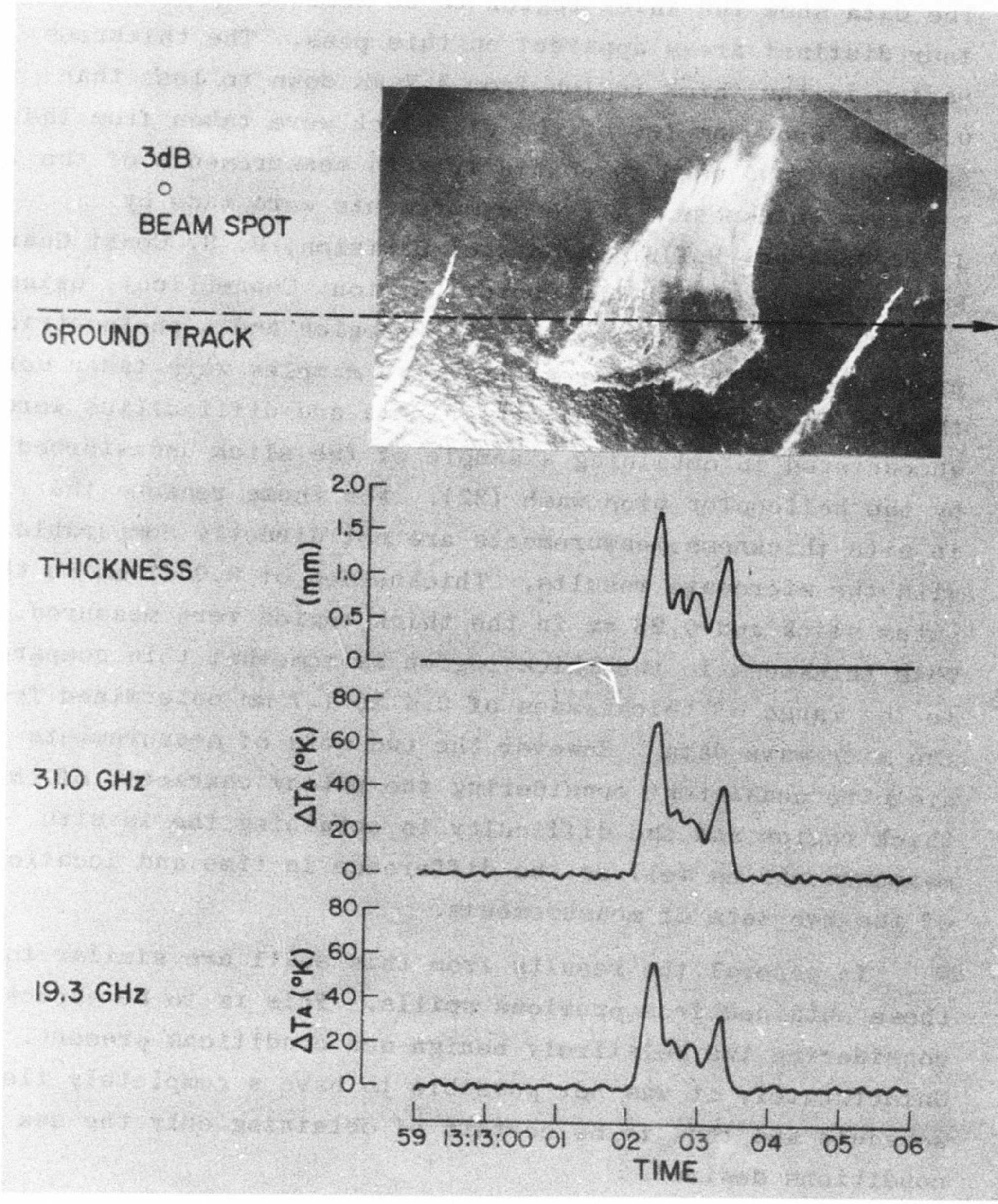

3dB
BEAM SPOT
GROUND TRACK
THICKNESS
2.0
1.5
1.0
0.5
0
(mm)
31.0 GHz
80
60
40
20
0
ΔTA (°K)
19.3 GHz
80
60
40
20
0
ΔTA (°K)
59 13:13:00 01 02 03 04 05 06
TIME

Figure 44

The thickness changes from below the level of detectability (less than 0.1 mm) to up to 1.7 mm in less than 60 feet. The data show the thick region to be somewhat patchy; with four distinct areas apparent on this pass. The thickness varies in the thick region from 1.7 mm down to less than 0.4 mm. Spot samples of the oil slick were taken from the helicopter and used to obtain in situ measurements of the oil film thickness. These measurements were made by J. R. Jadamec, Pollution Control Division, U. S. Coast Guard Research and Development Center, Groton, Connecticut, using a physical technique for the thick region and a photometric procedure for the thin regions. The samples were taken more than an hour after the microwave data and difficulties were encountered in obtaining a sample of the slick undisturbed by the helicopter prop wash (22). For these reasons the in situ thickness measurements are not directly comparable with the microwave results. Thicknesses of 0.0047 mm in the outer slick and 0.28 mm in the thick region were measured. This thickness in the thick region is somewhat thin compared to the range of thicknesses of 0.4 to 1.7 mm determined from the microwave data. However the two sets of measurements are quite consistent considering the patchy character of the thick region and the difficulty in obtaining the in situ measurements as well as the difference in time and location of the two sets of measurements.

In general the results from this spill are similar to those obtained from previous spills. This is to be expected considering the relatively benign sea conditions present. Unfortunately it was not possible to have a completely flexible schedule and thus to be certain of obtaining only the sea conditions desired.

Oil Spill of 8 May 1973

This spill consisted of 530 gallons of No. 4 crude oil. The surface conditions measured during the spill are given in Table 4. The wind speed increased from about 10 knots at the time of the spill to about 17 to 20 knots some two hours after the spill. Photographs of the spill taken at 12:27, 12:32, 12:38, 12:44, 12:56, 13:02, and 14:04 EDT are given in Figures 45 through 51. The photographs were taken with a six inch focal length T-11 aerial camera using SO 397 type film with a nine inch by nine inch image area. All the photographs were taken from an altitude of 1500 feet resulting in an image distance scale of 2250 feet by 2250 feet. The ship used to conduct the spill, the USCGC CHEROKEE (WMEC 165) a 205 foot ocean going tug, is visible in several of the photographs.

The development of the slick is similar to the 29 March spill and previous calm sea spills. This is to be expected considering the relatively calm conditions prevailing at the time of the spill. The growth of the slick is primarily in the downwind direction with the oil concentrated along the downwind edge. The wind direction is apparent from the smoke markers visible in Figures 48, 49, and 50. Dark patches of thick oil are very apparent, particularly on the original negatives. These patches are most visible in Figure 50.

The microwave data shown in Figure 52 was taken just prior to the photograph given in Figure 51. Unfortunately sun glitter in the photograph obscures all contrast over the slick and prevents the identification and location of thick oil patches. This prevents detailed correlation with the microwave data. However two thick patches are apparent from the microwave measurements shown in Figure 52 which

TABLE 4

8 May 1973

TIME	SKY	VISIBILITY	WIND	DRY TEMP	WET TEMP	HUMIDITY	PRESSURE	SEA TEMP	SEA/SWELL
1225	10/10	12 mi.	150 @ 10kts	63°F	60°F	84%	30.22	13.48°C	110/3 ft
1250	9/10	12	160 @ 10	64	61	84	30.21	14.60	110/3
1317	8/10	12		70	64	72		13.60	120/3
1330	8/10	12		69	61	63		13.70	120/3
1345	8/10	12		67	60	66		13.70	130/3
1400	8/10	12		66	60	71		13.80	130/3-4 ft
1409			160 @ 17				30.20		150/3-4 ft
1415	8/10	12		64	60	79		13.74	150/3-4 ft
1445	9/10	12	163 @ 20	64	59	74	30.19	13.80	150/3-4 ft
1508	9/10	12		64	60	79		13.60	150/3-4 ft
1513			150 @ 14				30.17		140/3-4 ft

GENERAL COMMENTS

530 gallons of #4 fuel oil

Test position: 37-05N, 75-24W

1225 Commenced spill

Figure 45

Figure 46

Figure 47

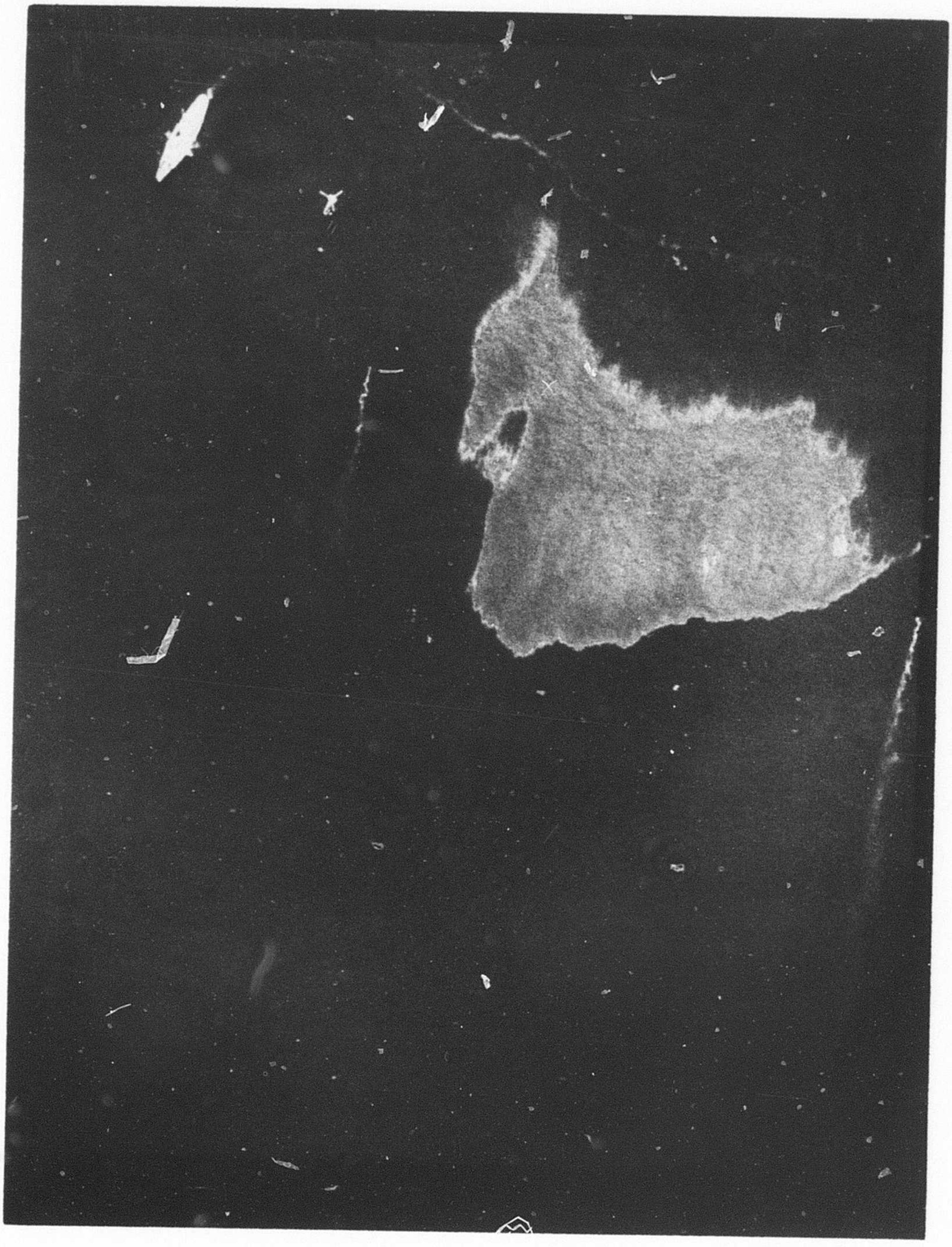


Figure 48

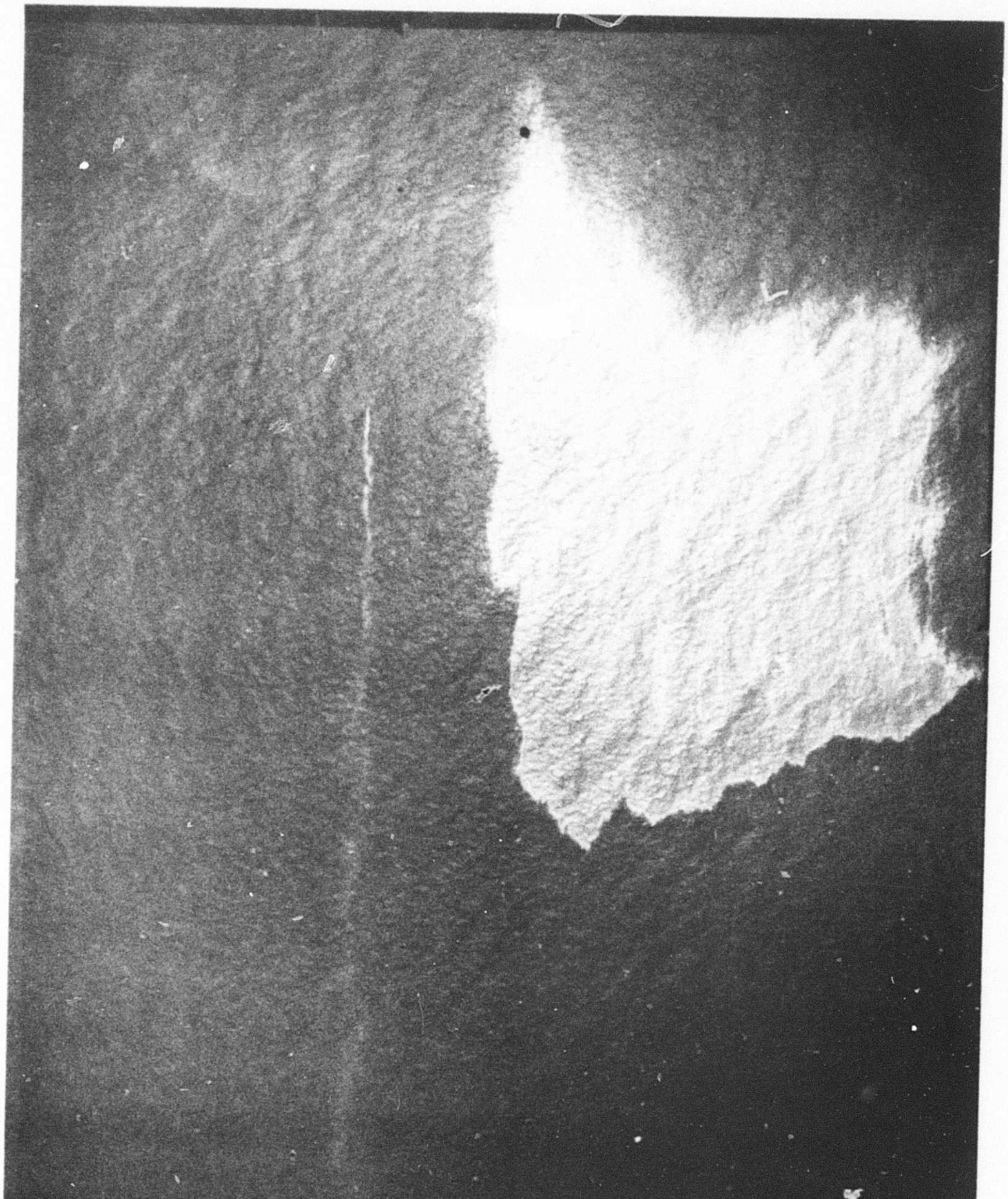


Figure 49

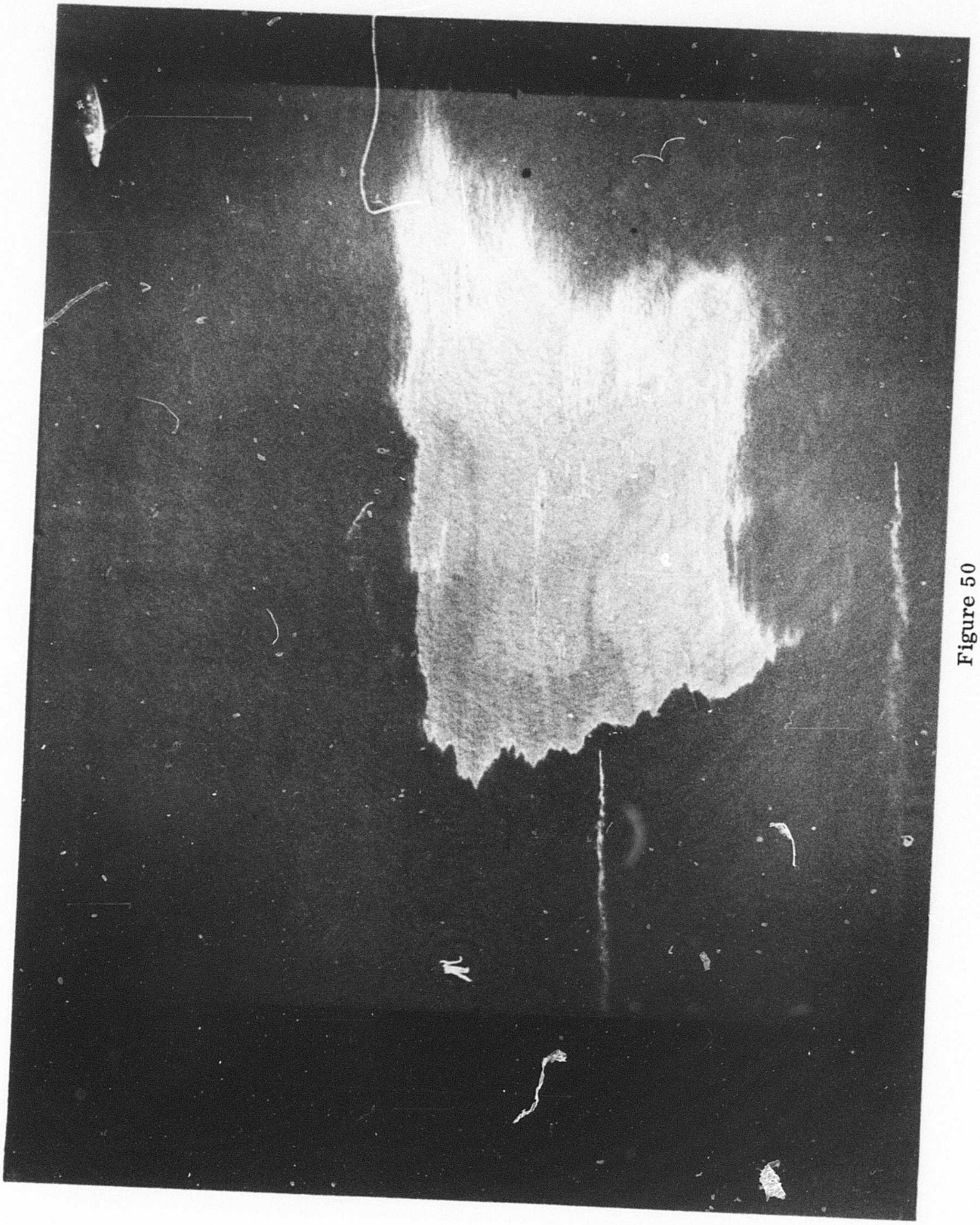


Figure 50

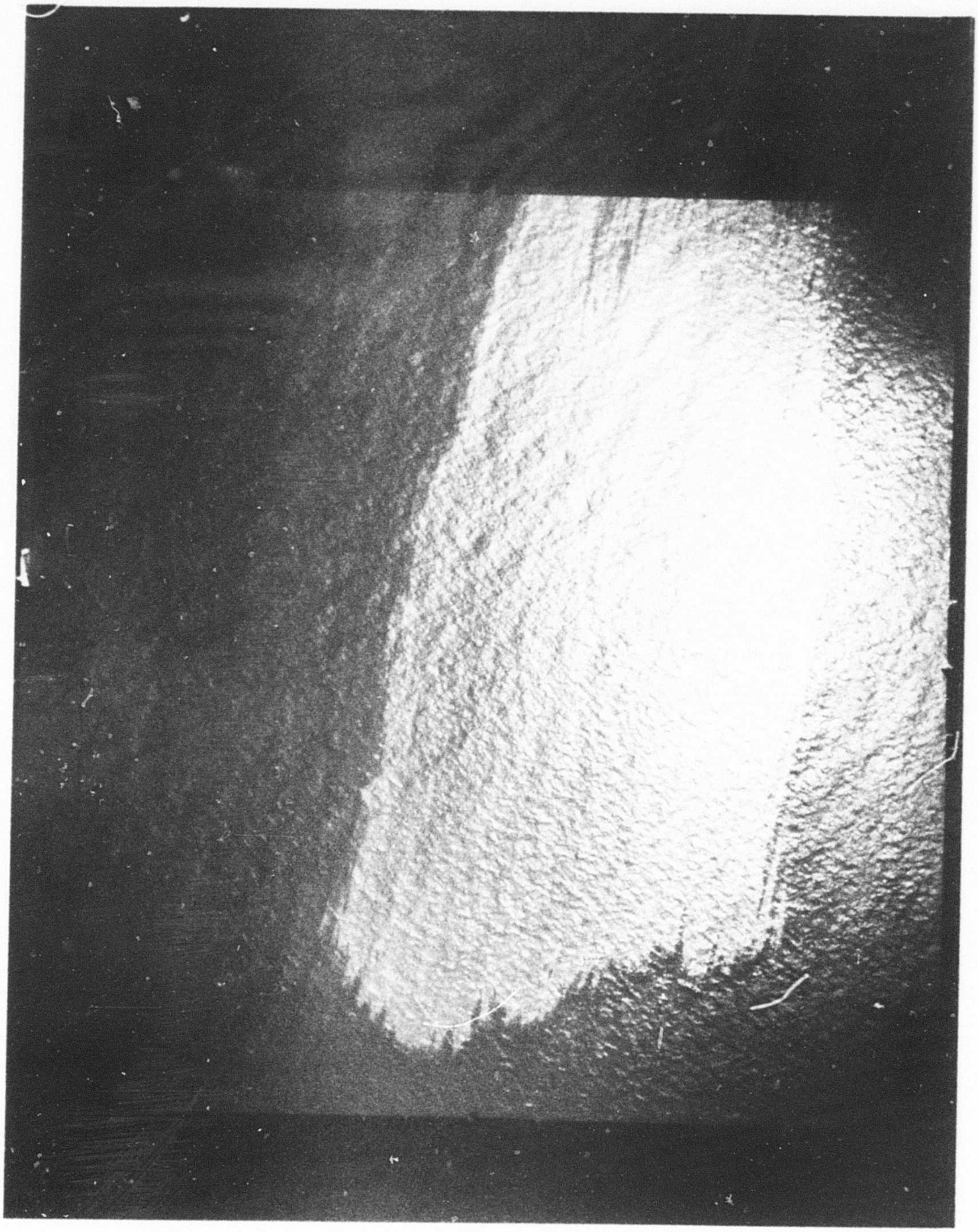
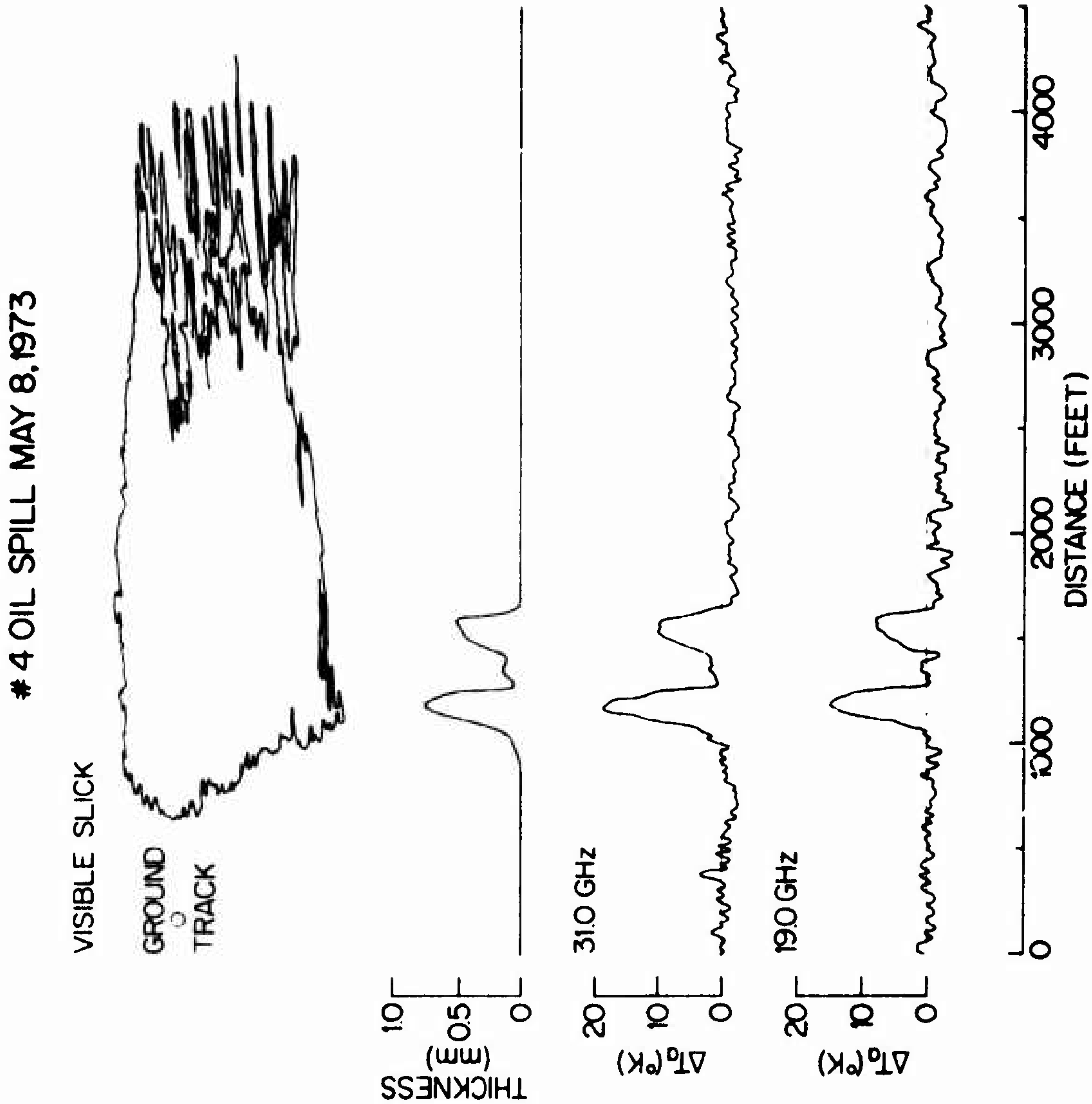


Figure 51



4 OIL SPILL MAY 8, 1973
VISIBLE SLICK
GROUND TRACK
THICKNESS (mm)
1.0
0.5
0
31.0 GHz
ΔTa (°K)
20
10
0
19.0 GHz
ΔTa (°K)
20
10
0
0
1000
2000
3000
4000
DISTANCE (FEET)

Figure 52

indicates peak thicknesses of 0.5 and 0.7 mm. Other aircraft passes over the slick showed similar thick patches present in the downwind portion of the slick. This is consistent with the earlier patchy appearance of the slick as shown in Figure 50. No in situ measurements were obtained in the thick patches of the slick. However a thickness measurement of 0.0002 mm was obtained in the area surrounding the thick patches visible in Figure 50 and a thickness of 0.00004 mm was obtained in the wispy portion of the slick at the extreme upwind edge of the slick. This indicates that much thicker regions were present since less than five gallons of oil would be required to cover the entire area of 9.3×10^5 sq. ft. of the slick at that time to a thickness of 0.0002 mm. If the remainder of the oil was in patches with an average thickness of 0.5 mm the patches would cover 4.3×10^4 sq. ft. or about 5% of the total slick area.

The surface winds of 17 to 20 knots were higher than for any previous spill. Superimposed on the increased signal from the thick oil patches there is a general depression of the signal of about 2^{O}K over the entire slick area relative to the adjacent sea. This depression is made clear by the dotted line in Figure 52 which represents the average signal level of the clean sea. This depression in signal is about what is to be expected due to the suppression of sea state effects as discussed on page 18 and shown in Figure 12. With the exception of this depression all other aspects of the spill, and in particular the presence of thick patches of oil containing the majority of the oil, are very similar to all previous spills.

Oil Spill of 9 May 1973

This spill consisted of 520 gallons of No. 2 fuel oil dyed red. The sea conditions measured during the spill are given in Table 5. Photographs of the spill taken on SO 397 type film with a T-11 aerial camera at 13:29, 13:37, 13:45, 14:07, 14:41 and 14:48 EDT are given in Figures 53 through 58. The first four photographs were taken from an altitude of 1500 feet resulting in an image distance scale of 2250 feet by 2250 feet. The last two photographs were taken from 2000 and 3000 feet respectively giving distance scales four thirds and twice as large. The USCGC CHEROKEE was again used to dispense the oil and can be seen in several of the photographs.

The wind speed of 18 knots is similar to the highest winds measured during the 8 May spill but on that day they were variable and gusty whereas the winds during this spill were steady. The sea was more developed than on the previous day and the waves were higher. The sea conditions were as rough as for any previous spill.

The slick developed in the usual manner; growing primarily in the upwind-downwind direction with thick patches of oil forming in the downwind portion. Although it is difficult to see them in the black and white reproductions given in Figures 53 through 58 distinct patches of thick oil are visible on the original negatives. In particular four distinct patches were present in the photograph shown in Figure 57. Spot in situ thickness measurements gave thicknesses of 0.78 mm and 1.1 mm in the thick patches and 0.0011 mm in the extended slick around the patches.

Passive microwave data taken about ten minutes prior to the in situ samples is given in Figure 59. The high signal at both frequencies near the edge of the slick is due to a thick oil patch. This was verified from the 35 mm pictures taken along the aircraft ground track with the 35 mm camera bore-sighted with the radiometers. The thickness of this patch derived from the microwave data is 0.8 mm in good agreement with the in situ measurements. Once again it is

TABLE 5

9 May 1973

TIME	SKY	VISIBILITY	WIND	DRY TEMP	WET TEMP	HUMIDITY	PRESSURE	SEA TEMP	SEA/SWELL
1330	8/10	8 mi	180 @ 18kts	63°F	61°F	89%	29.88	14.10°C	160/5 ft
1345	9/10	8		62	61	94		14.35	160/5
1400	9/10	8	175 @ 18	64	62	90	29.87	14.21	165/5
1415	8/10	8		64	62	90		14.30	165/5
1430	7/10	8		64	62	90		14.20	165/5
1440	7/10	8	185 @ 18	64	62	90	29.86	14.20	165/5
1445	7/10	8		64	62	90	29.86	14.20	165/5
1455	7/10	8	190 @ 18				29.86		160/5
1500	7/10	8		67	62	75		14.20	160/5

GENERAL COMMENTS

520 gallons of #2 fuel oil

Test position: 37-12N, 75-21W

1325 Commenced spill

Figure 53

Figure 54

Figure 55

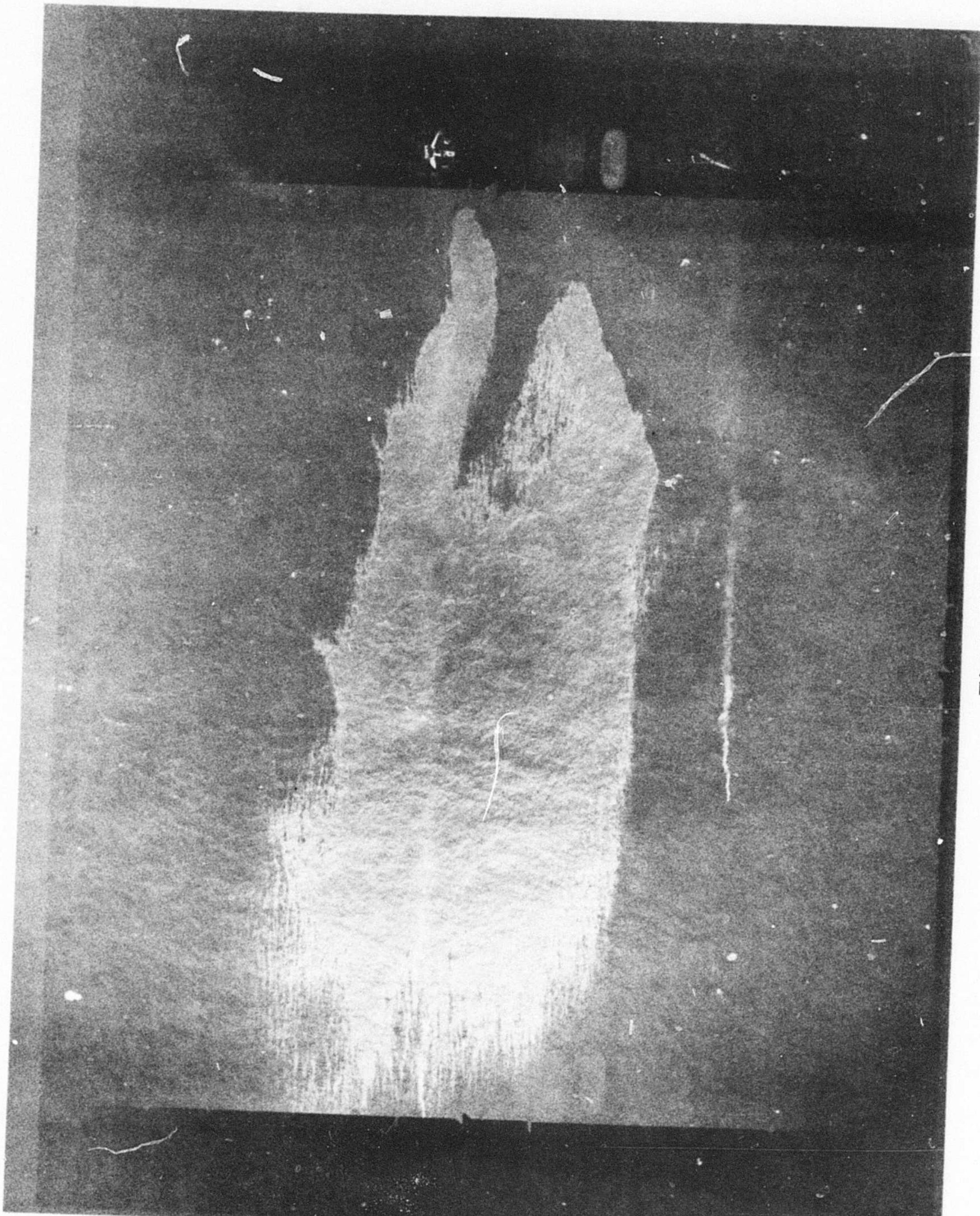


Figure 56

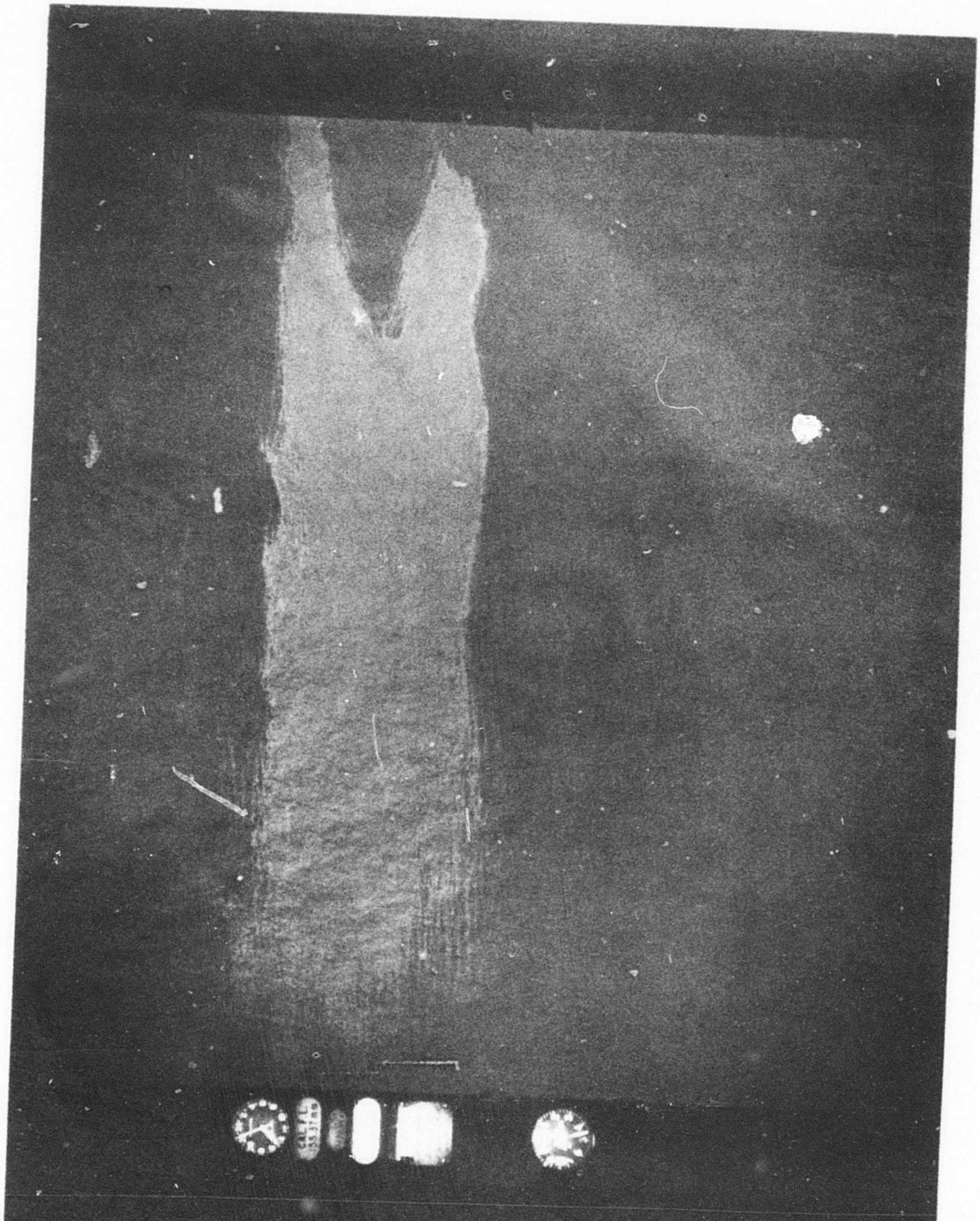


Figure 57

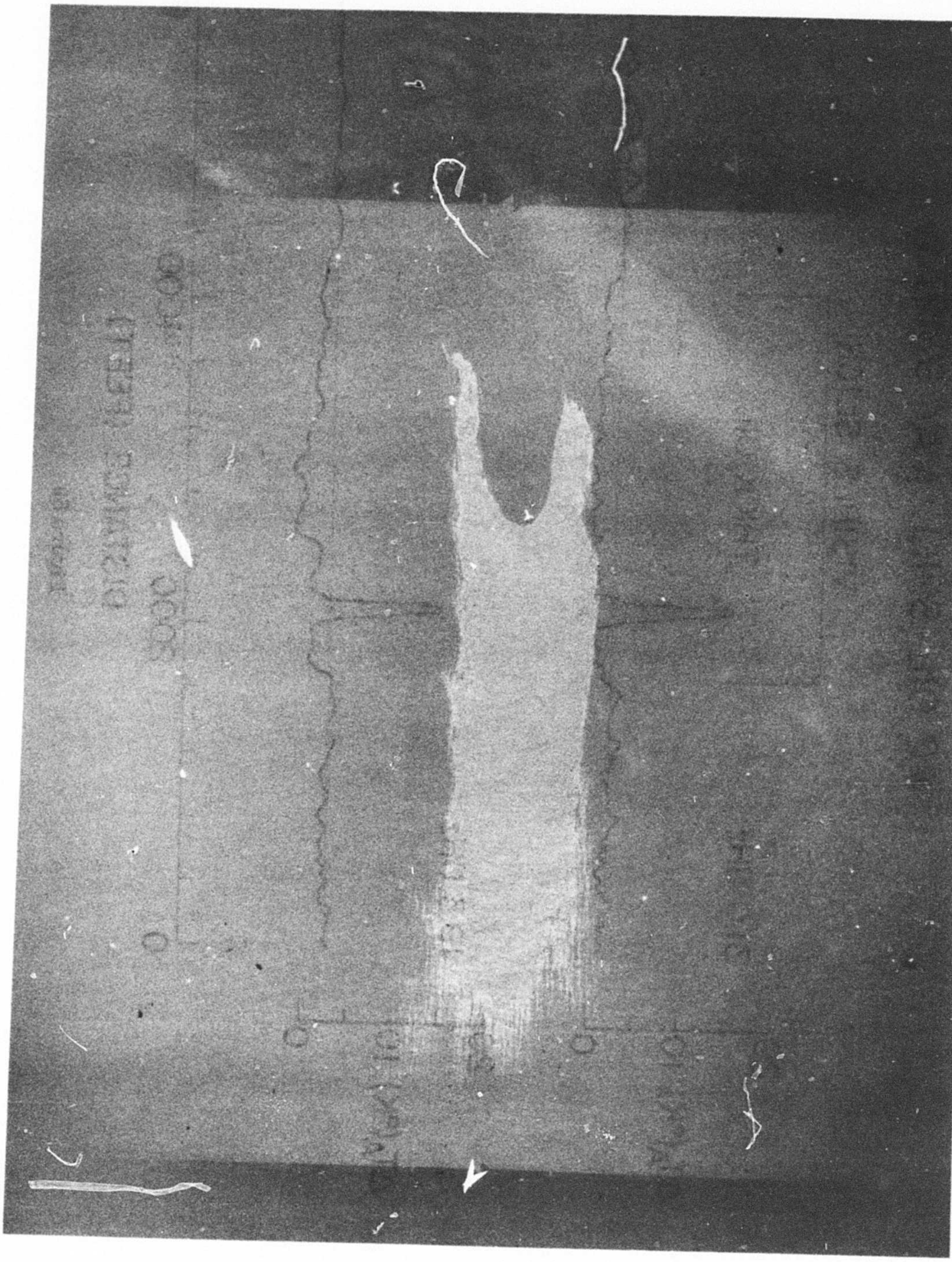


Figure 58

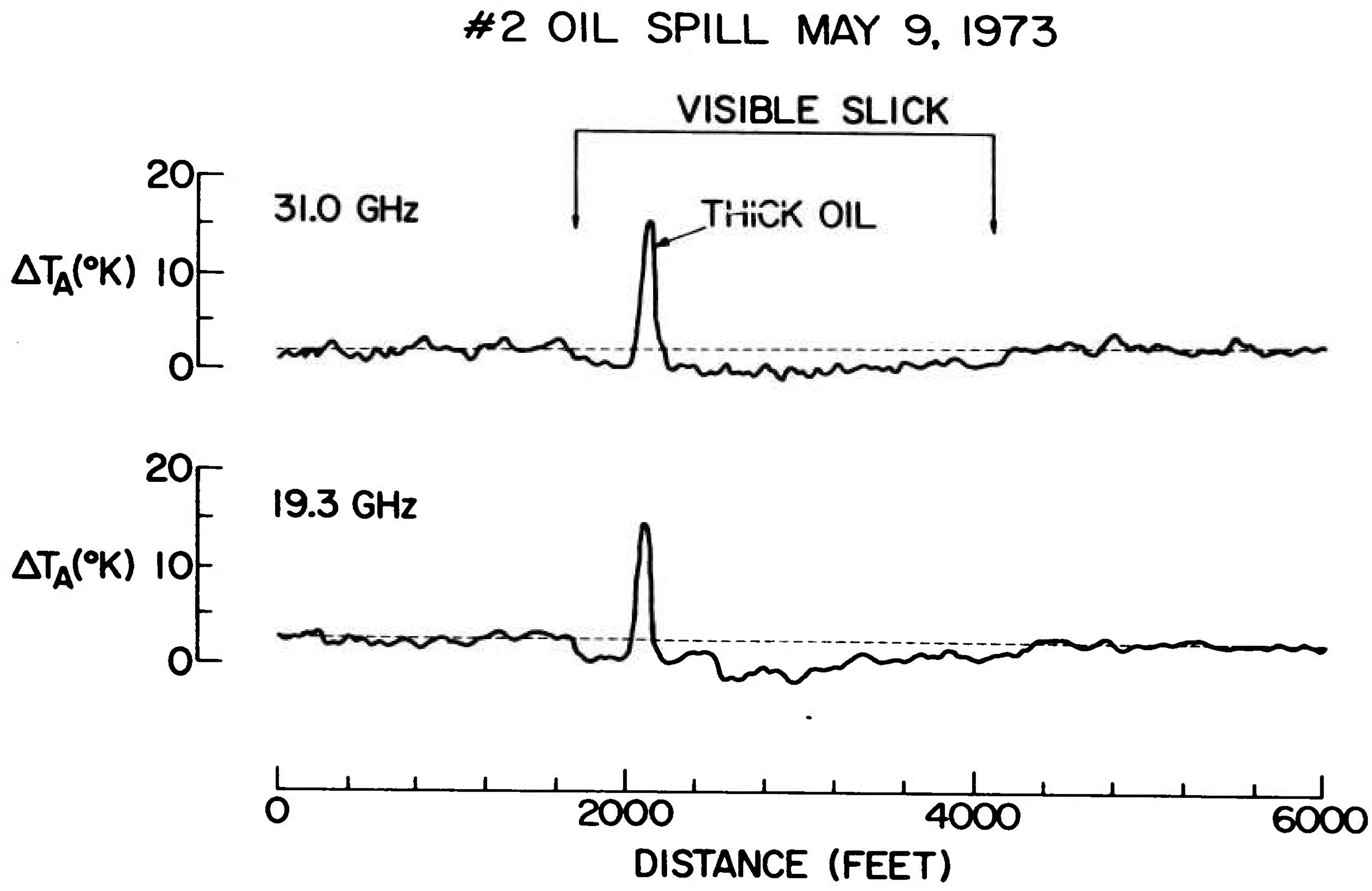

#2 OIL SPILL MAY 9, 1973
VISIBLE SLICK
THICK OIL
31.0 GHz
19.3 GHz
ΔT_A(°K)
ΔT_A(°K)
20
10
0
20
10
0
0
2000
4000
6000
DISTANCE (FEET)

Figure 59

clear that most of the oil was in the thick patches since only 73 gallons of oil would be required to cover the entire area of the visible slick of 2.7×10^6 sq. ft. to a thickness of 0.0011 mm. The increase in signal due to the thick patch of oil is superimposed upon a general depression of the signal over the entire slick. This depression of about $3^{\circ}K$ is about what is expected due to the suppression of sea state effects by the oil film and is similar to that observed in the 8 May spill. The behavior of the oil slick and the results for this spill of No. 2 fuel oil are generally the same as for the 8 May spill of No. 4 crude oil conducted under similar sea surface conditions.

Oil Spill of 16 October 1973

This spill consisted of 520 gallons of No. 2 fuel oil dyed red. The sea conditions measured during the spill are given in Table 6. The spill was conducted from the USCGC CHEROKEE. Unfortunately the photography taken with the T-11 camera on nine inch film was of poor quality due primarily to sun glitter. It was possible to get somewhat better contrast of the slick by selecting the best frame along the ground track taken with the 35 mm boresight camera. A composite of pictures of the slick taken from a series of aircraft passes is shown in Figure 60. The behavior of the slick is the same as found in previous calm sea spills as could be expected from the calm sea conditions of one to two foot waves with four to ten knot winds prevailing throughout the spill. Thick patches of oil are formed, driven to the downwind portion of the slick and grow very much more slowly than the overall slick.

Typical microwave data taken from an aircraft pass at 12:42 is given in Figure 61. A peak thickness of 1.0 mm was derived from the microwave data for the thick patch in line with previous findings. The measurements of this spill

TABLE 6

16 October 1973

TIME	SKY	VISIBILITY	WIND	DRY TEMP	WET TEMP	RELATIVE HUMIDITY	PRESSURE	SEA TEMP	SEA
1145	6/10	7+ mi.		70.0°F	64.8°F	76%	29.84	70.9°F	300/2 ft
1200	7/10	7+	010/10kts	71.1	64.7	71	29.84	70.2	300/2
1215	7/10	7+	015/10	69.1	64.5	78	29.84	70.0	305/2
1230	7/10	7+	015/9	68.3	63.6	77	29.84	69.9	300/2
1245	7/10	7+	015/9	69.0	63.8	77	29.84	70.0	300/2
1300	6/10	7+	015/10	68.6	63.7	77	29.84	70.0	300/2
1315	6/10	7+	015/6	68.1	63.2	76.5	29.82	69.9	300/1
1330	6/10	7+	015/6	68.2	63.3	76.5	29.82	70.0	300/1
1345	5/10	7+	015/6	71.1	64.7	71	29.81	70.1	300/1
1400	5/10	7+	015/6	69.0	63.9	76	29.81	70.1	300/1
1415	5/10	7+	015/7	68.9	63.7	76	29.81	70.1	300/1
1430	5/10	7+	020/4	69.0	63.8	75	29.80	70.0	300/1
1445	5/10	7+	020/4	68.9	63.5	75	29.80	70.0	300/1
1500	4/10	7+	020/4	69.2	63.6	74	29.79	70.1	290/1
1515	4/10	7+	020/6	69.0	63.5	74	29.79	70.0	290/1
1530	3/10	7+	020/6	68.3	62.7	73	29.78	70.0	290/1
1545	4/10	7+	020/6	68.9	62.8	72	29.79	70.1	290/1

GENERAL COMMENTS

520 gallons of #2 fuel oil

Test Position: 36-51.5N, 75-32.5W

1145 Commenced Spill

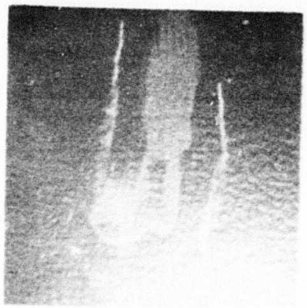
NUMBER 2 OIL SPILL OCT 16, 1973

11:55:33

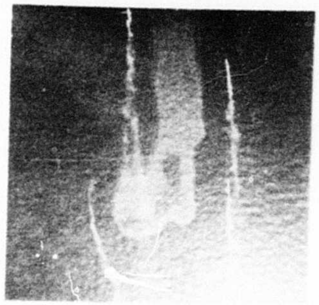
12:00:14

12:05:19

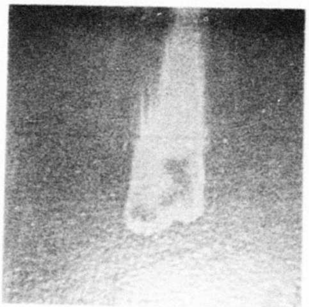
12:11:51



12:18:20

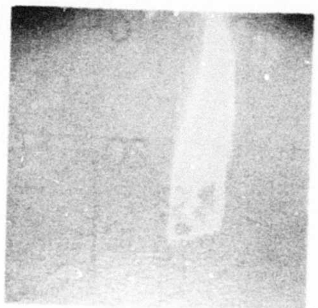


12:24:49



12:54:12

13:17:15



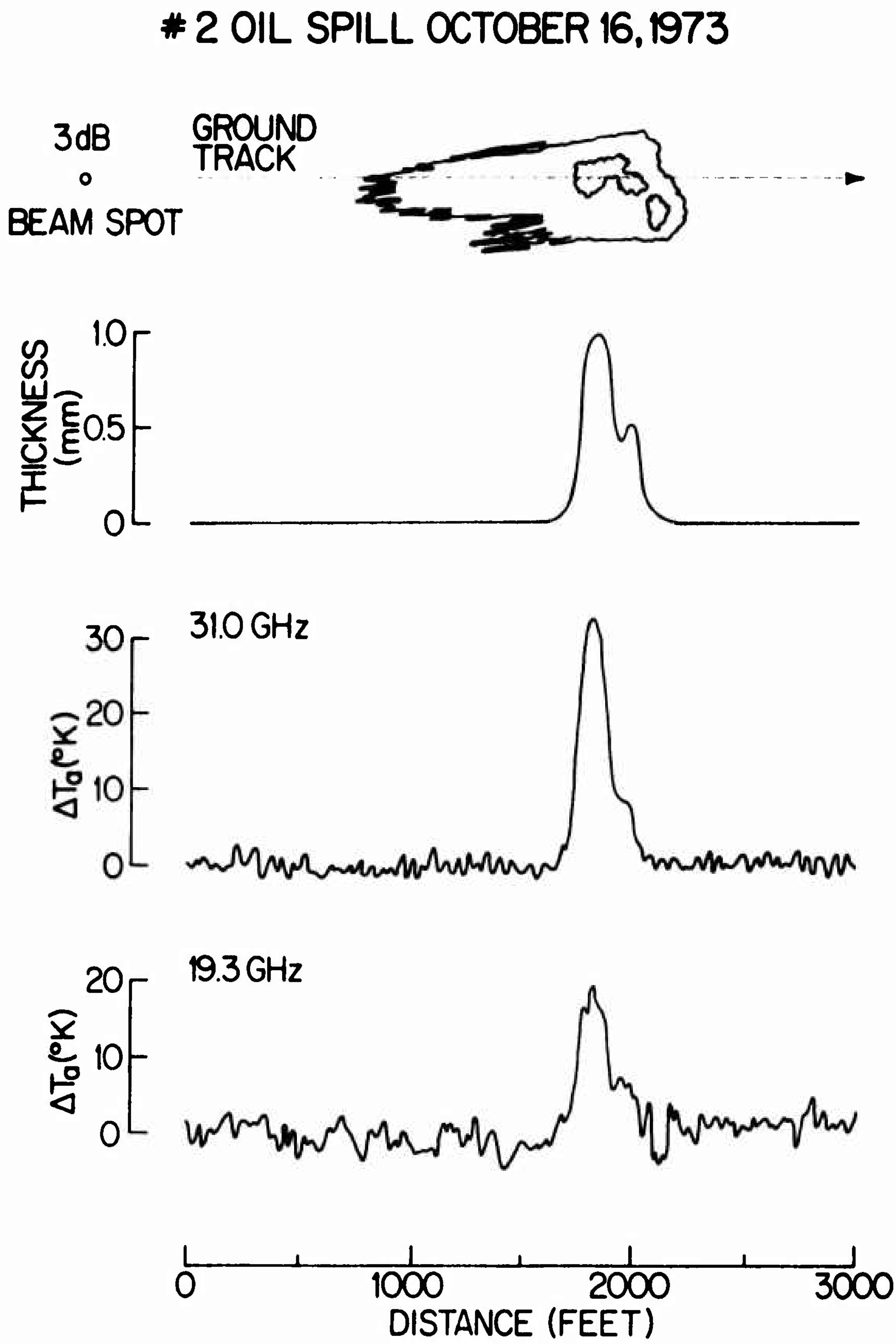
13:36:41

DISTANCE SCALE

2000 FT — 11:55:33 THROUGH 12:54:12

2000 FT — 13:17:15 THROUGH 13:36:41

Figure 60



2 OIL SPILL OCTOBER 16, 1973
3dB
BEAM SPOT
GROUND TRACK
THICKNESS (mm)
1.0
0.5
0
31.0 GHz
ΔT_a (°K)
30
20
10
0
19.3 GHz
ΔT_a (°K)
20
10
0
0
1000
2000
3000
DISTANCE (FEET)

Figure 61

serve primarily to confirm the results of earlier calm sea spills.

Oil Spill of 4 February 1974

This spill consisted of 500 gallons of No. 4 crude oil. The sea conditions measured during the spill are given in Table 7. The surface conditions with 20 to 24 knot winds, 5 foot seas and 8 foot swell were the roughest encountered during any of the oil spills conducted for this program. The atmosphere was clear with 30 to 40% cloud cover. The combination of sun glitter and dark cloud shadows on the sea surface made it very difficult to locate the slick visually and impossible to discern thick patches of oil. These conditions also make it nearly impossible to detect the oil spill at all from the photography: either from the T-11 camera or the 35 mm bore-sighted camera. In addition the surface conditions made the acquisition of ground truth very difficult. Therefore almost nothing can be determined about the details of the oil release, the subsequent development and growth of the slick or the presence and location of thick patches of oil.

Thirteen aircraft passes over the region of the slick were made. Typical data from one of these passes is given in Figure 62. The depression in signal due to the suppression of sea state effects by the oil film is very pronounced. The depression is $5^{o}K$ and is about what is to be expected (see Figure 12). The large signal just past the region of the slick is not due to oil but rather to a large patch of white caps which nearly fill the field of view of the radiometers. As the sea state increases and the size and coverage of white caps increases they will become an increasing source of noise and can constitute a false alarm and be taken for thick patches of oil. However since the oil film will

TABLE 7

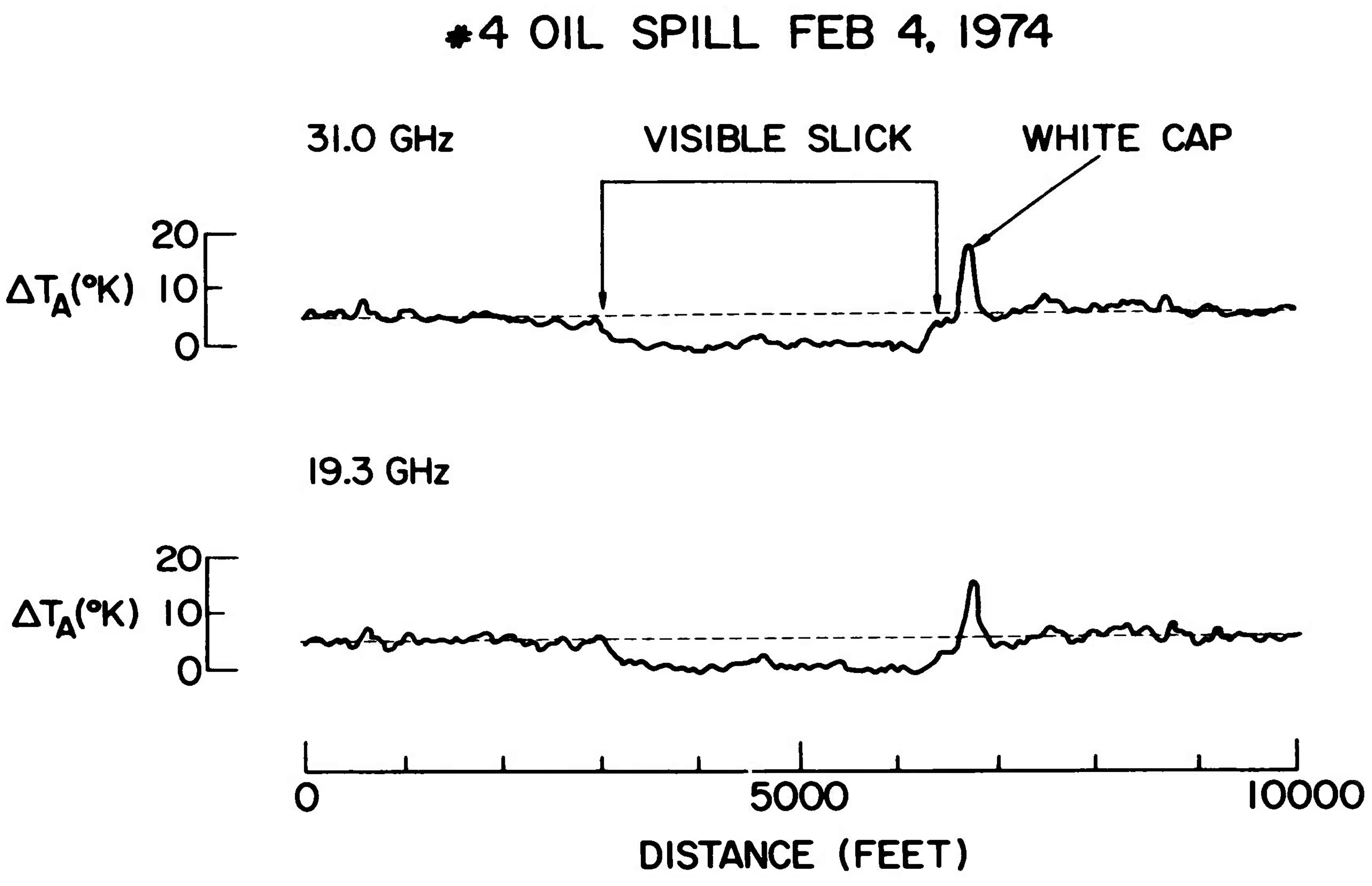
4 February 1974

TIME	SKY	VISIBILITY	WIND	DRY TEMP	WET TEMP	RELATIVE HUMIDITY	PRESSURE	SEA TEMP	SEA	SWELL
1430	4/10	10 mi.	330/20kts	40°F	36°F	68%	29.86	8.6°C	290/5ft	330/8ft
1445	3/10	10	330/22	40	36	68	29.85	8.6	290/5	330/8
1500	3/10	10	330/15	40	36	68	29.85	8.7	290/5	330/8
1515	3/10	10	330/24	39	35	67	29.86	8.8	290/5	320/8
1530	3/10	10	330/20	39	35	67	29.88	8.8	290/5	320/8
1545	3/10	10	350/22	39	35	67	29.87	8.7	290/5	320/8
1600	3/10	10	330/22				29.87		320/5	350/7
1615	3/10	10	330/20	39	35	67	29.88	8.7	320/3	350/7
1630	4/10	10	330/22	39.5	35	64	29.88	8.6	320/3	350/7
1645	4/10	10	330/22	39	35	67	29.88	8.6	320/3	350/6

GENERAL COMMENTS

500 gallons of #4 fuel oil   Test Position: 36-43.5N, 75-28.6W   1430 Commenced Spill

Langmuir streaks formed rapidly making ground truthing very difficult.



#4 OIL SPILL FEB 4, 1974
31.0 GHz
VISIBLE SLICK
WHITE CAP
20
ΔT_A(°K) 10
0
19.3 GHz
20
ΔT_A(°K) 10
0
0
5000
10000
DISTANCE (FEET)

Figure 62

inhibit the production of white caps within the slick there will be less chance of them being confused with regions of thick oil since the boundary of the slick will be apparent from the microwave data whenever sea conditions are severe enough to produce white caps.

Despite repeated passes over the slick no thick patches of oil were found. It is not possible to determine if this is because the aircraft ground track missed all thick patches on all thirteen passes or if no thick patches large enough to fill a significant fraction of the radiometer field of view were present. Certainly it was difficult to locate the slick visually and align the aircraft to pass over it. However a region of depressed microwave signal was obtained on each of the thirteen passes indicating that some portion of the slick was overflown. The ground track may not have been through the downwind portion where the thick patches would be most likely to occur since it was impossible to discern such patches visually during the pass or subsequently from the photography. It seems unlikely that all passes missed the thick patches if they were present. As described earlier it is difficult to achieve a point spill in high sea state conditions. If the ship is driven along the oil tends to be released in a long ribbon. Then it may be readily segmented into short small strips by the wind and wave action. It was noted from the USCGC CHEROKEE that Langmuir streaks were being formed rapidly during the spill. Thus it is more likely that no large thick oil patches were present due to the oil being dispensed over too great a path. There was a tendancy for this to occur in earlier spills on 8 and 9 May. In any event no thick oil was found either visually or with the microwave radiometers and there is no conclusive evidence as to why this is so.

Oil Spill of 5 February 1974

This spill consisted of 500 gallons of No. 4 crude oil. The sea conditions measured at the time of the spill are given in Table 8. The surface conditions for this spill were very similar to those prevailing during the 9 May spill except that the sea and air temperatures were considerably colder. Unfortunately sun glitter and cloud shadows on the sea surface made both visual and photographic recognition of the slick very difficult. The situation is very similar to that experienced for the spill of 4 February. It is very difficult to determine the details of the oil release and the subsequent development and growth of the slick. It appears from the photography that the oil was formed in a very elongated form with a striated or filamentary structure. The best photograph obtained is shown in Figure 63 taken 15 minutes after the release of oil began. The oil is strung out along a line running vertically down from the beam of the USCGC CHEROKEE to the bottom of the photograph and the striations run from the top left to the bottom right at an angle of about 30 degrees to the vertical. The striations are aligned with the wind direction. Unfortunately no details of the slick are discernible on subsequent photographs.

Passive microwave data was taken on 31 aircraft passes over the slick. Although a depression of the signal of about $3^{\circ}K$ was observed on 22 of the passes no increase in signal which could be attributed to thick oil was observed. The same remarks made in discussing the apparent absence of thick patches of oil in the 4 February slick apply equally well to this spill. It is difficult to understand why the behavior of this spill is apparently so much different from the spill of 9 May conducted under similar sea conditions unless, perhaps, the release of oil was much more compact in the earlier spill. If so, it would indicate that the oil

TABLE 8

5 February 1974

TIME	SKY	VISIBILITY	WIND	DRY TEMP	WET TEMP	RELATIVE HUMIDITY	PRESSURE	SEA TEMP	SEA	SWELL
1200	5/10	10 mi	340/18kts				30.33		320/4ft	340/5ft
1215	5/10	10	320/18	34°F	29°F	52%	30.32	7.9°C	320/4	340/5
1230	4/10	10	310.18	32	28	59	30.32	8.0	290/3	310/5
1245	5/10	10	310/16				30.32		310/3	330/5
1300	5/10	10	300/16	33	29	60	30.31	7.9	290/3	310/4
1315	4/10	10	300/16				30.33		290/3	310/4
1330	4/10	10	320/14	33	28	51	30.29	7.5	310/3	330/4
1345	4/10	10	320/16				30.29		320/3	330/4
1400	4/10	10	290/18	33	29	60	30.30	7.9	310/3	340/4
1415	4/10	10	310/16				30.30		320/3	340/4
1430	0	10	290/18	34	29	52	30.30	8.0	310/3	330/4
1445	0	10	310/16				30.29		310/3	330/4
1500	0	10	330/14	34	29	52	30.28	7.6	340/4	320/4
1515	0	10	330/12				30.28		310/4	300/4
1530				36	31	55		7.0		

GENERAL COMMENTS

500 gallons of #4 fuel oil   Test Position: 36-41N, 75-31W   1205 Commenced Spill

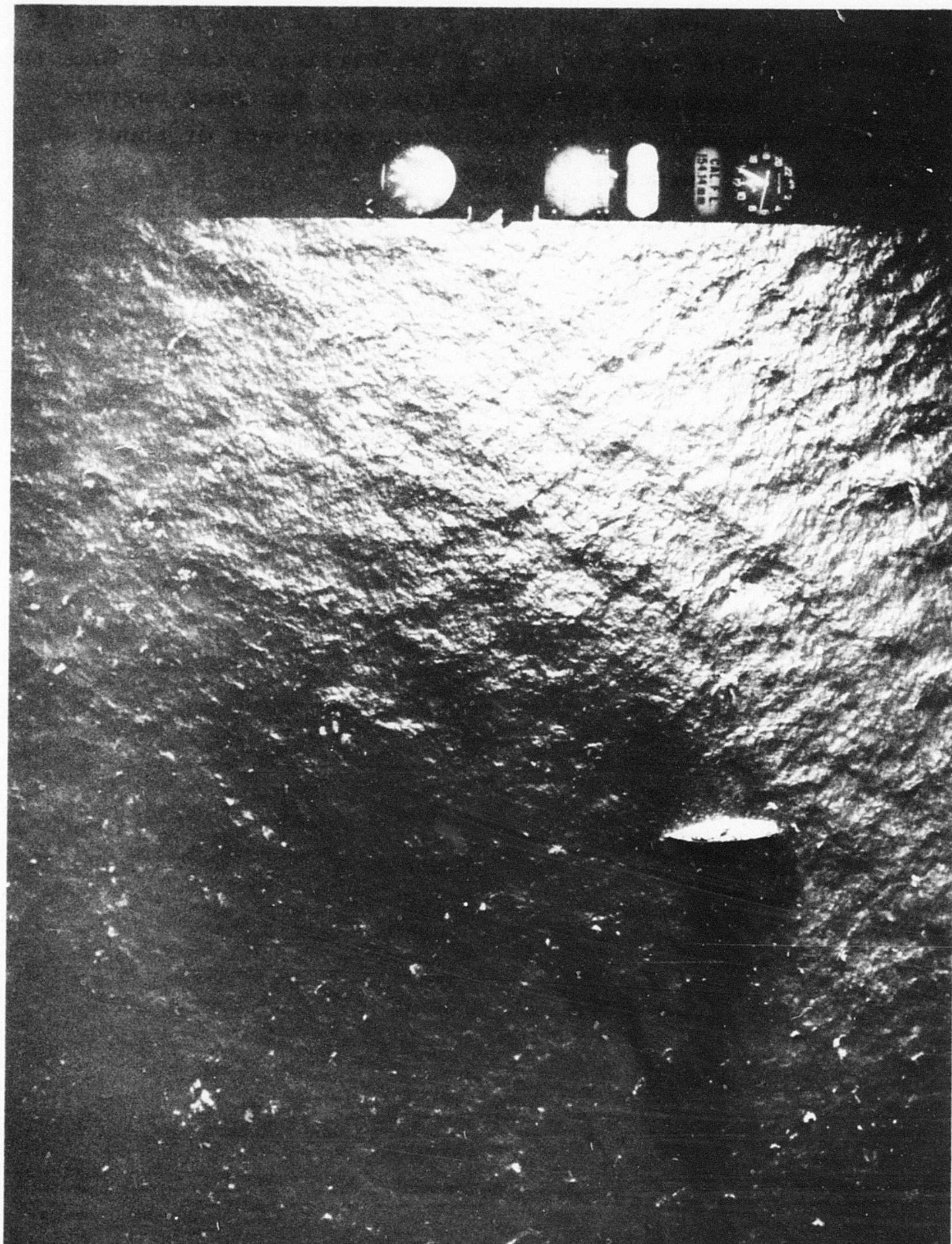


Figure 63

was released along a much longer trail for both the 4 and 5 February spills than for any of the earlier spills. Thus the oil was so dispersed during release that no thick regions of size comparable to the radiometer beam-spot of about 40 feet could be formed.

DISCUSSION AND CONCLUSIONS

The results of the rough sea oil spills are generally the same as those obtained from the calm sea spills with the exception of the spills on 4 and 5 February 1974. In the case of these latter spills no thick oil patches were detected. It is possible, but unlikely, that the thick regions were present but were undetected by the microwave radiometers because the aircraft ground track did not pass near enough to them, within about 20 feet, and were not found visually due to poor seeing conditions caused by sun glitter and cloud shadows and the difficulty experienced in obtaining ground truth. It is also possible that the oil was so dispersed over such a long trail during its release that no patches of any significant size relative to the radiometer beam-spot of about 40 feet could be formed. All of the previous 13 oil spills, three of which were conducted under sea conditions comparable to the February spills, contained thick patches of oil and exhibited a common behavior and structure. In each case the slick grew in the upwind-downwind direction with thick patches of oil with thicknesses of about a millimeter or so formed in the downwind portion. These thick patches contained the majority of oil, usually more than 90 percent, and were surrounded by a very much thinner and larger slick with thicknesses of about a micron or less. It was always possible to locate and quantify the thick regions from the microwave measurements alone. On the basis of these spills it appears that the anomalous behavior of the 4 and 5 February spills was due to the dispersal of oil during release. Thus the evidence from all the spills is that, at least for the range of sea states encountered during these tests, the majority of the oil from a point type spill will be present in thick patches constituting a small fraction of the area of the visible slick.

The lifetime of the thick patches and the slick itself is unknown. Thick patches of oil were observed in the slicks during the entire period of observation. The greatest duration of observations was about six hours in the case of the 630 gallon 11 July 1972 spill. Just how long the thick patches and slicks persisted after observations ceased is of course unknown but is probably less than 24 hours unless sea conditions were very calm. Certainly most slicks will eventually be broken up by wind and wave action and dissipated. If, as seems likely, the thick regions are formed and maintained by small quantities of surface active materials present in the oil itself (21) which spread more rapidly than the bulk of the oil, surround it, inhibit its growth and act as a control agent, the lifetime will increase with the volume of oil spilled (23). In addition very large spills would require a very long time to spread even in the absence of control agents simply because of the bulk of oil present to be distributed (18). These active materials will eventually be expended and the slick dispersed. However if the thick regions are contained long enough the oil may weather and form into a thick, viscous and relatively stable layer. Under some conditions certain crude and residual oils may form a stable emulsion described as "chocolate mousse" (24). Therefore the lifetime of the thick regions containing the vast majority of the oil will, in general, depend on the detailed conditions of each individual spill. Usually the lifetime will decrease with increasing sea state and increase with the volume of oil spilled.

Not unexpectedly oil slick growth was more rapid at higher wind speeds. This can be seen in Figure 64 where the area of the visible slick is given as a function of time on a log-log plot for seven different oil spills. The spills were conducted under average wind speeds of from 5 to 22

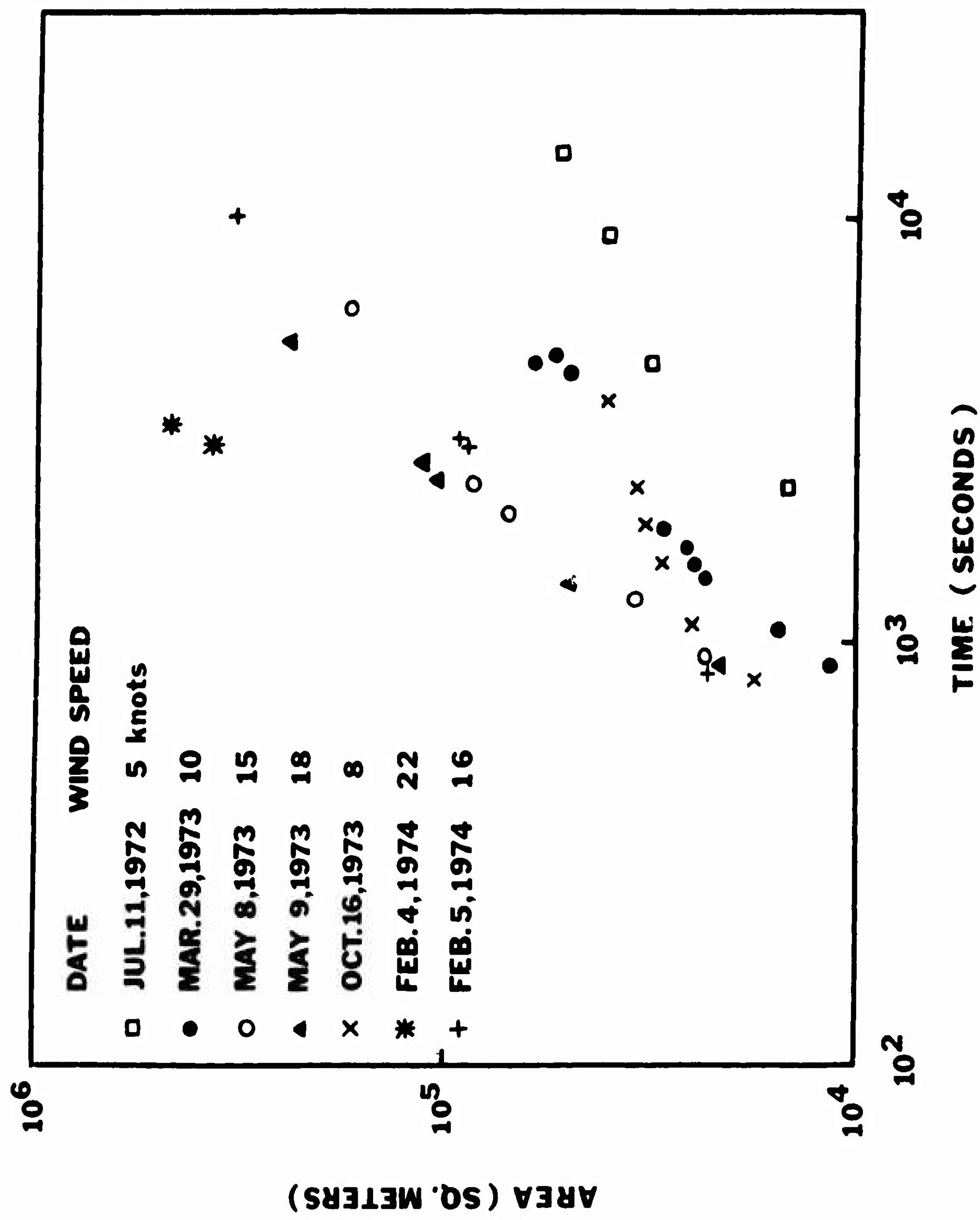

DATE WIND SPEED
□ JUL.11,1972 5 knots
● MAR.29,1973 10
○ MAY 8,1973 15
▲ MAY 9,1973 18
× OCT.16,1973 8
✱ FEB.4,1974 22
+ FEB.5,1974 16
AREA (SQ. METERS)
10^6
10^5
10^4
10^2
10^3
10^4
TIME (SECONDS)

Figure 64

knots. All the measurements were of the total visible slick as discernible on SO-397 film except for 4 and 5 February where microwave measurements of the depressed signal due to the slick were used to supplement the photographic data. As is apparent from Figure 64 the area of the slick grew with time in every case and the rate of growth increased with wind speed. Assume that the area at any time is proportional to the time to some power. The exponent of the time will be called the "spreading index." On the log-log plot of Figure 64 this assumption is that the data may be represented by a straight line whose slope is the spreading index. The spreading indices determined from straight lines fitted to the data of Figure 64 are given versus wind speed in Figure 65. As mentioned on page 63 there are many factors affecting the sea surface spreading of oil and the data presented here are from both No. 2 fuel oil and No. 4 crude oil and a range of air and sea temperatures and wave conditions but the increase in growth rate with wind speed is clear. In general the growth was primarily in the upwind-downwind direction; the slick taking on a characteristic roughly oblong shape with thick patches in the downwind end.

The measured depression of the microwave signal in the region of the oil slick with increasing wind speed due to the damping of small scale surface waves and the reduction of the amount of white caps and foam present by the oil film agrees quite well with the calculations given in Figure 12. This effect is relatively small but is significant since it permits the entire slick to be delineated by the microwave signal.

Two further possible roughness dependent effects will be considered; the increasing range of oil film thicknesses present with increasing roughness and the admixture of water with the oil by wind and wave action. As discussed previously

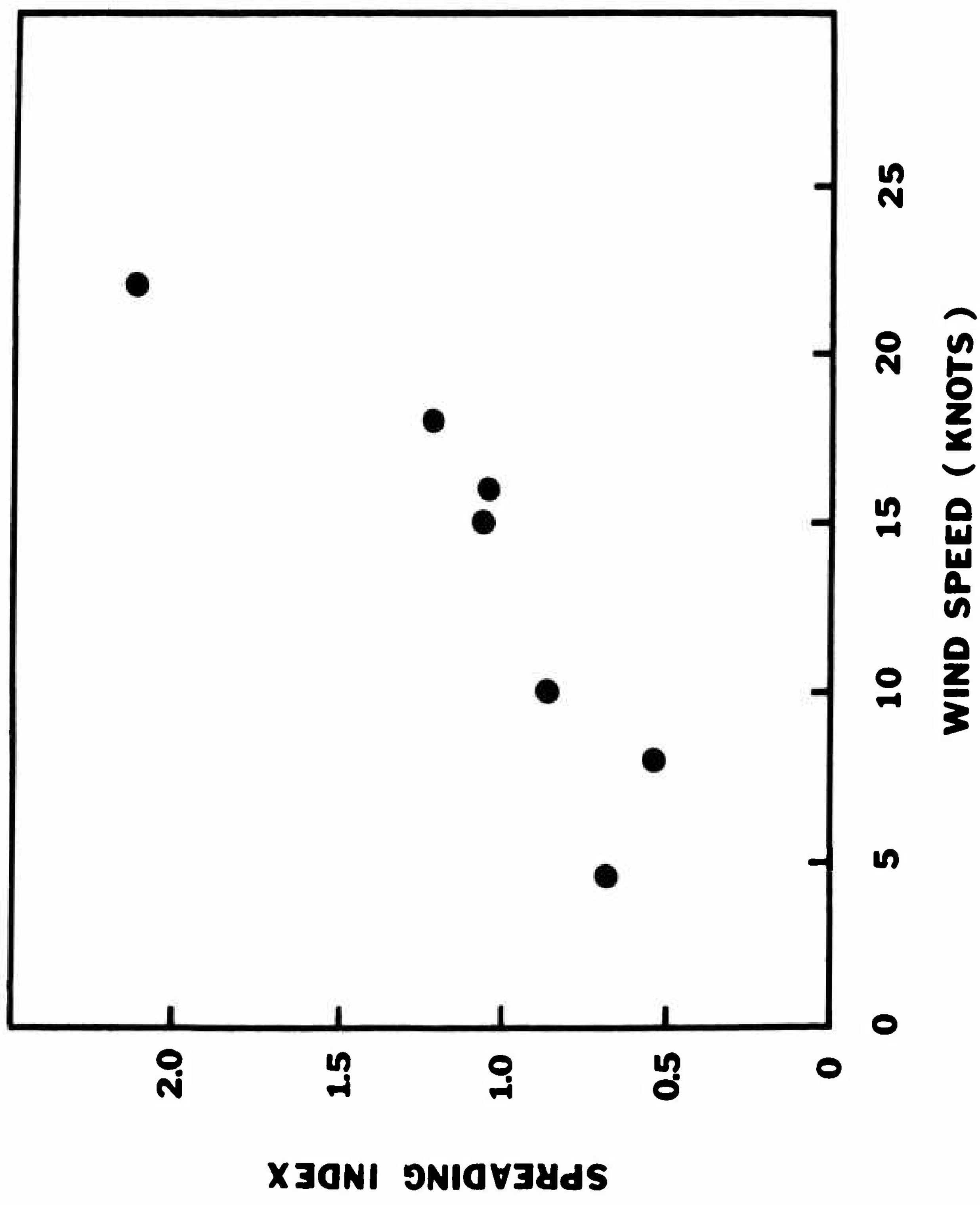


Figure 65

in the section on non-uniform film thickness on page 22 the antenna temperature measured is an average value determined by the distribution of oil thicknesses present weighted by the antenna response pattern. The derived thickness is then some average thickness which depends upon the thickness distribution. Following equation (4), page 24 we may write,

$$\Delta T_A = n_{mb} \int_{mb} \left\{ \int_t \Delta T_B(t) P(t) dt \right\} f d\Omega \Big/ \int_{mb} f d\Omega \tag{26}$$

where P(t) is the normalized thickness probability distribution function and

$$\int_0^\infty P(t) dt = 1.0 \ ; \quad \bar{t} = \int_0^\infty t P(t) dt \ . \tag{27}$$

The volume of oil present per unit area is given by $\bar{t}$. If the thickness variations occur over a scale that is small compared to the beam-spot size and if P(t) is stationary over this same scale equation (26) may be written as

$$\Delta T_A = n_{mb} \int_t \Delta T_B(t) P(t) dt. \tag{28}$$

In order to examine the effect of increasing the width of the thickness distribution calculations of equation (28) were made using a Gaussian form for P(t) for thicknesses up to two standard deviations above and below the mean thickness and P(t) = 0 outside this range. TRIMEDIA was used to calculate $\Delta T_B(t)$ and n_{mb} was set equal to unity. The results of these calculations are shown in Figure 66 for standard deviations of 0.2, 0.5 and 0.8 mm at 31.0 GHz for No. 2 fuel oil. The principal result is that the peak brightness temperatures are reduced and the minimum values increased relative to the brightness temperature to be expected from

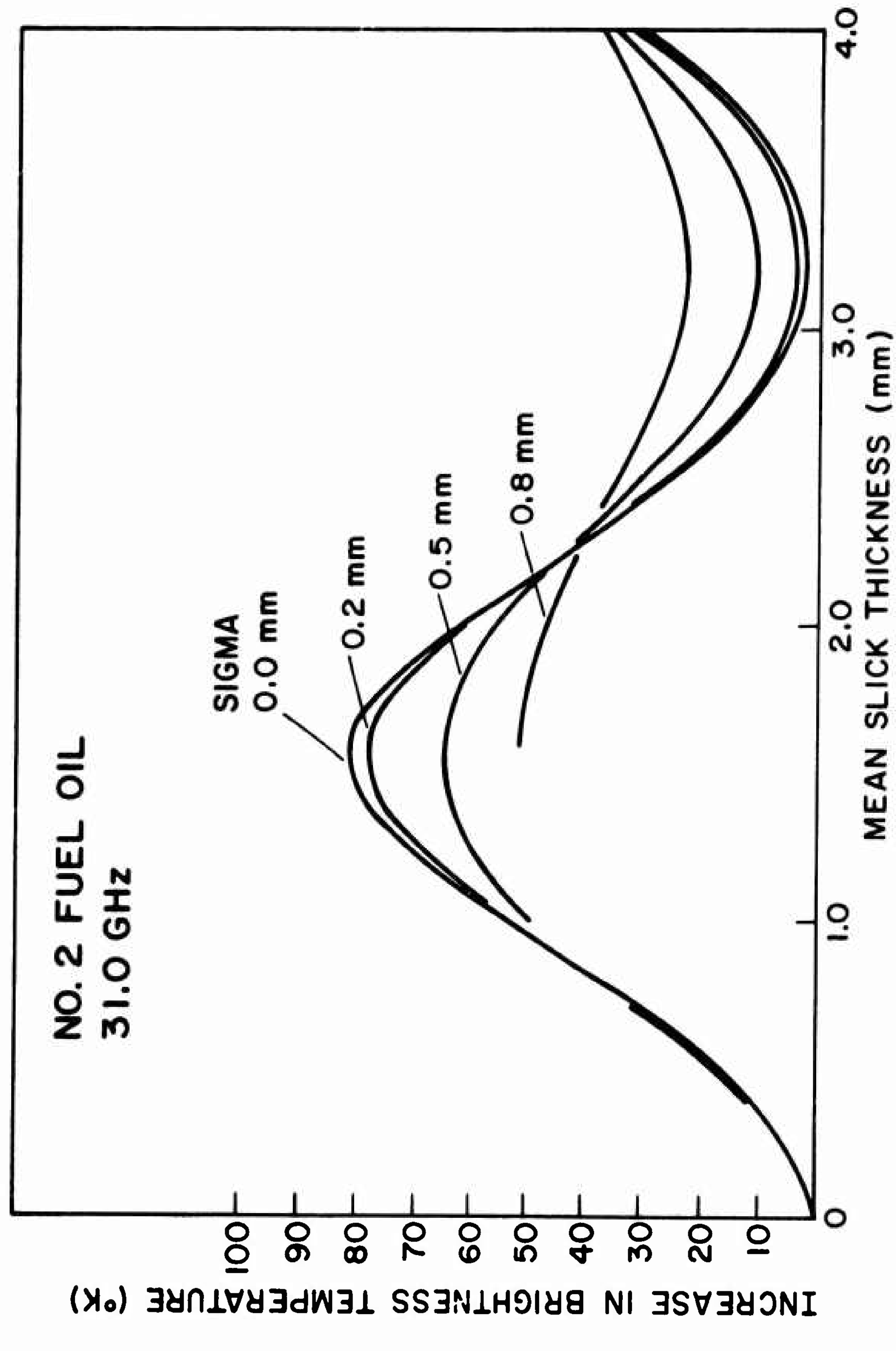

NO. 2 FUEL OIL
31.0 GHz
SIGMA
0.0 mm
0.2 mm
0.5 mm
0.8 mm
0
10
20
30
40
50
60
70
80
90
100
1.0
2.0
3.0
4.0
MEAN SLICK THICKNESS (mm)
INCREASE IN BRIGHTNESS TEMPERATURE (°K)

Figure 66

a uniform oil film. There is not a significant departure of the brightness temperature from that due to a uniform film for mean thicknesses up to somewhat less than the thickness of the first maximum and for standard deviations less than about a third of it. The exact effect of thickness variations will depend on the form of the thickness distribution function but will generally be to reduce the amplitude of the brightness temperature oscillations with thickness. While it is not possible to accurately estimate the effect of thickness variations under all conditions it appears that if the range of thicknesses present is reasonably less than the thickness of the first maximum distribution of thicknesses will not result in severe errors.

Increasing sea state results in increased mechanical mixing of oil and water by the wind and breaking waves. Under such conditions stable emulsions can be formed (24). Two types of emulsions must be considered, depending upon whether the water or oil is the continuous phase; either oil-in-water or water-in-oil. In the case of small oil droplets dispersed in the sea the oil is effectively lost (23). The oil is churned down into the water and may even end as sediment on the bottom if the water depth is not too great. More likely it will reappear on the surface some time later at a different location but with a greatly reduced concentration. The mixing breaks the oil into small droplets and drives them below the surface. Surface water flows over the oil droplets and effectively removes them from view. The oil is highly dispersed by this action and would be very difficult to recover. Thus oil-in-water emulsions are not of much practical concern because of the great dispersal and very low concentration of the oil and the near impossibility of detecting or recovering the oil.

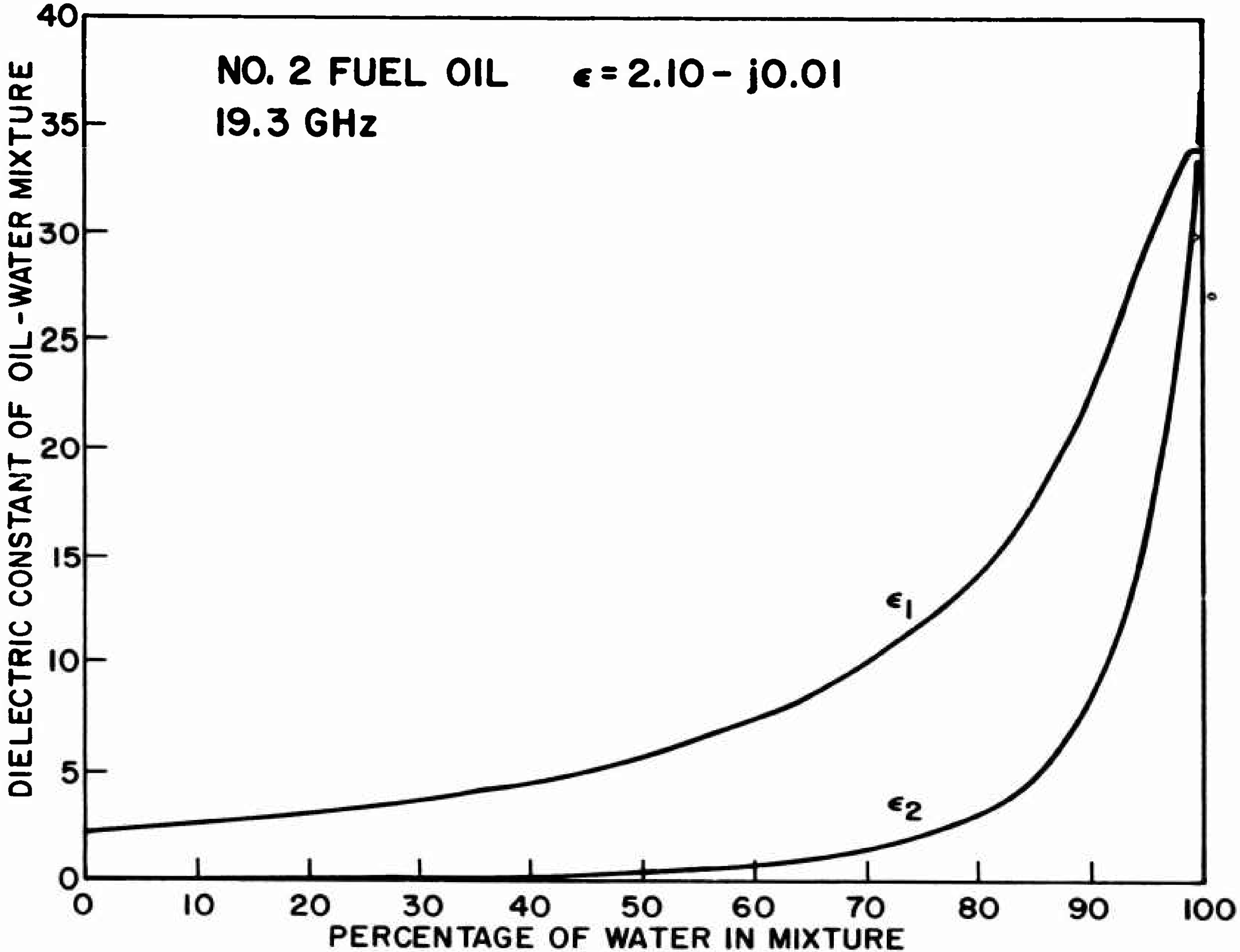
Normal petroleum stocks contain less than 10 percent water. However oil-in-water emulsions with water contents up to 80 percent can be found under wave and sea action. Emulsions with less than 50 percent water may be formed which appear to be neat oil and are free flowing oily fluids with the consistency of industrial fuel oils. Heavy lubricating oils such as paraffinic and naphthenic lube oils may form such stable fluid emulsions. Normal distillate products such as gasoline, kerosene and diesel oils do not form emulsions. Light lubricating oils may form initial emulsions but they are unstable and rapidly reform into oil and water layers after agitation ceases (24). Stable emulsions with a water content of between 50 and 80 percent can be formed from crude and residual oils. The stabilization of this type of emulsion, sometimes called "chocolate mousse," appears to be due to complex chemical components present in the non-volatile residues from crude, particularly asphaltenes, and possibly porphyrins, including vanadium complexes (24).

Water-in-oil emulsions would, in general, be expected to have a higher dielectric constant at microwave frequencies than the oil itself due to the higher dielectric constant of water. The dielectric constant of a matrix where one component serves as a continuous host material and the other component occurs as isolated particles within this matrix is given by

$$\frac{E - 1}{E + 2} = \frac{E_o - 1}{E_o + 2} P_o + \frac{E_w - 1}{E_w + 2} P_w \ , \qquad (29)$$

where E, E_o and E_w are the complex dielectric constants of the mixture, oil and water respectively and P_o and P_w are the volume fractions of oil and water (25). This equation has given good agreement between computed and measured values for a number of water-bearing rocks and should be a good representation of the dielectric constant of a water-in-oil emulsion. The dielectric constant of the emulsion as a function of water content was calculated using equation (29) for No. 2 fuel oil. Although the calculations are for No. 2 fuel the results would be very similar for any other oil since the dielectric constant varies very little with oil type (see page 4). The results are given in Figures 67 and 68 for 19.3 and 31.0 GHz respectively. E_1 and E_2 are the real and imaginary parts of the complex dielectric constant of the emulsion. The dielectric constant of the mixture does not increase linearly with the percentage of water in the mixture. Rather very little of the increase occurs before 50 percent water content is reached and the most marked increase occurs for water contents above about 70 percent. The effect of the increase of the dielectric constant of the emulsion on the increase in brightness temperature due to the oil slick was calculated using TRIMEDIA and the dielectric constant determined from equation (29). The results at 19.3 and 31.0 GHz for water contents of 0, 10, 25 and 50 percent are given in Figures 69 and 70. The major effect is that the maxima of the increase in in brightness temperature are increased and occur at smaller oil film thicknesses. In addition the minima are also increased. The net result of the water-in-oil emulsification would be to cause the oil film thickness to be over estimated. The effect should be negligible for distillate products since they do not generally form stable emulsions and it should only be appreciable for heavy lubricating oils and crude and residual oils and then only after a period of time, or perhaps days, which would be required for waves and weathering to form the emulsion.

Neither the effect of a distribution of thicknesses nor of the formation of emulsions was sufficiently appreciable to be apparent in the observations made for this study.


NO. 2 FUEL OIL $\epsilon = 2.10 - j0.01$
19.3 GHz
ϵ_1
ϵ_2
DIELECTRIC CONSTANT OF OIL-WATER MIXTURE
0
5
10
15
20
25
30
35
40
0
10
20
30
40
50
60
70
80
90
100
PERCENTAGE OF WATER IN MIXTURE
Figure 67

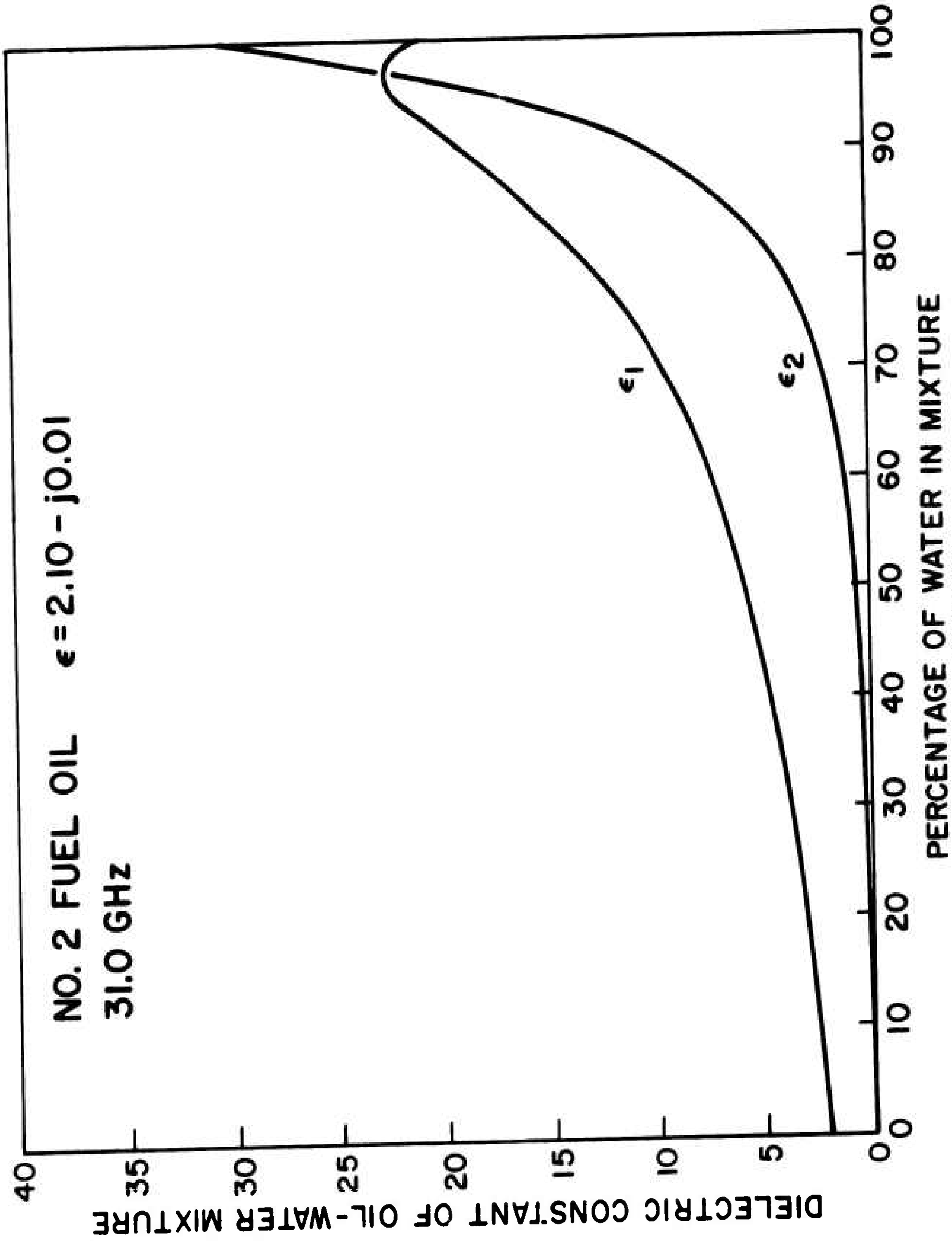

NO. 2 FUEL OIL
31.0 GHz
$\epsilon = 2.10 - j0.01$
ϵ_1
ϵ_2
DIELECTRIC CONSTANT OF OIL-WATER MIXTURE
0
5
10
15
20
25
30
35
40
PERCENTAGE OF WATER IN MIXTURE
0
10
20
30
40
50
60
70
80
90
100

Figure 68

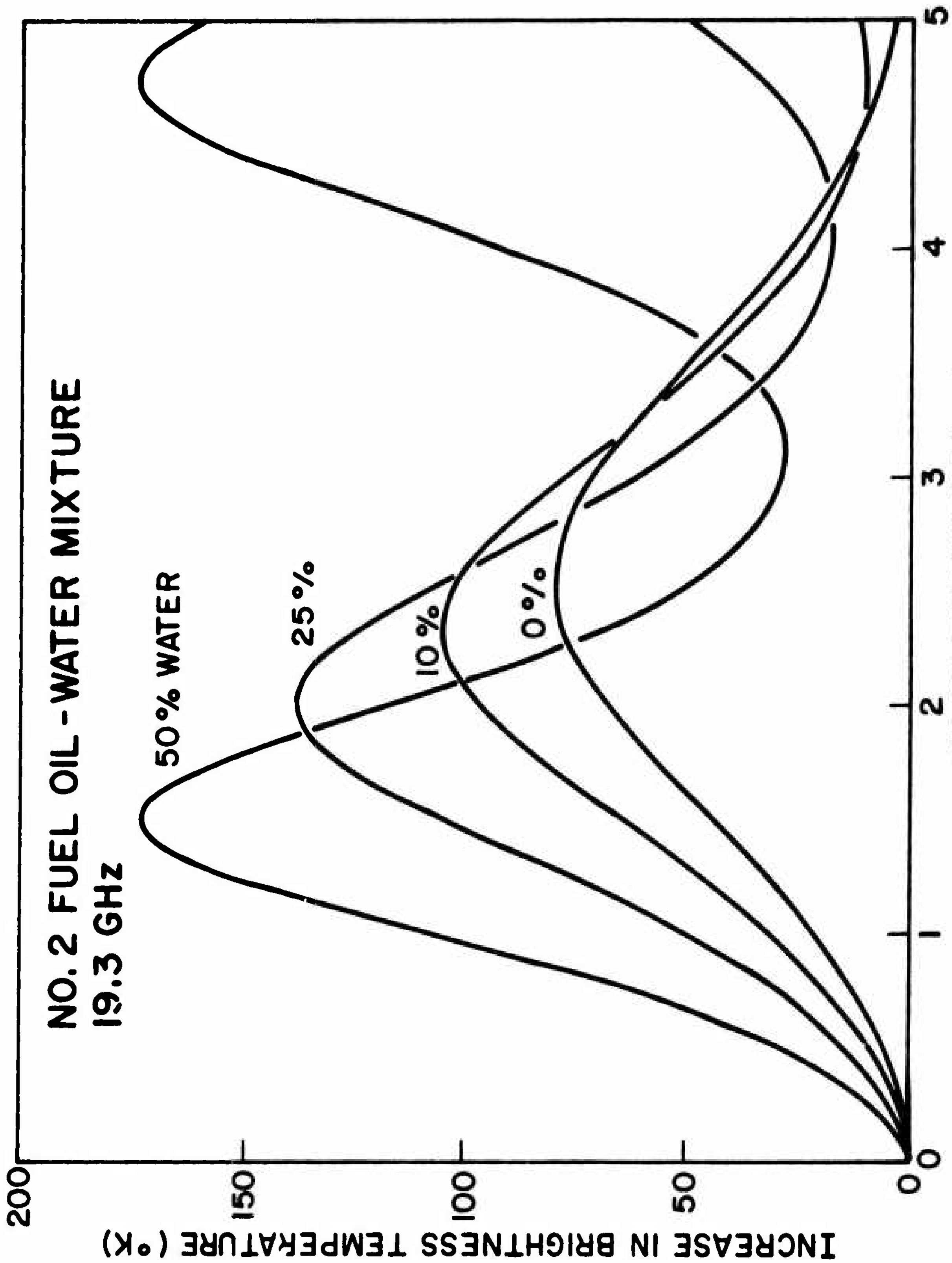

NO. 2 FUEL OIL-WATER MIXTURE
19.3 GHz
50% WATER
25%
10%
0%
SLICK THICKNESS (mm)
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
0
50
100
150
200
0
1
2
3
4
5

Figure 69

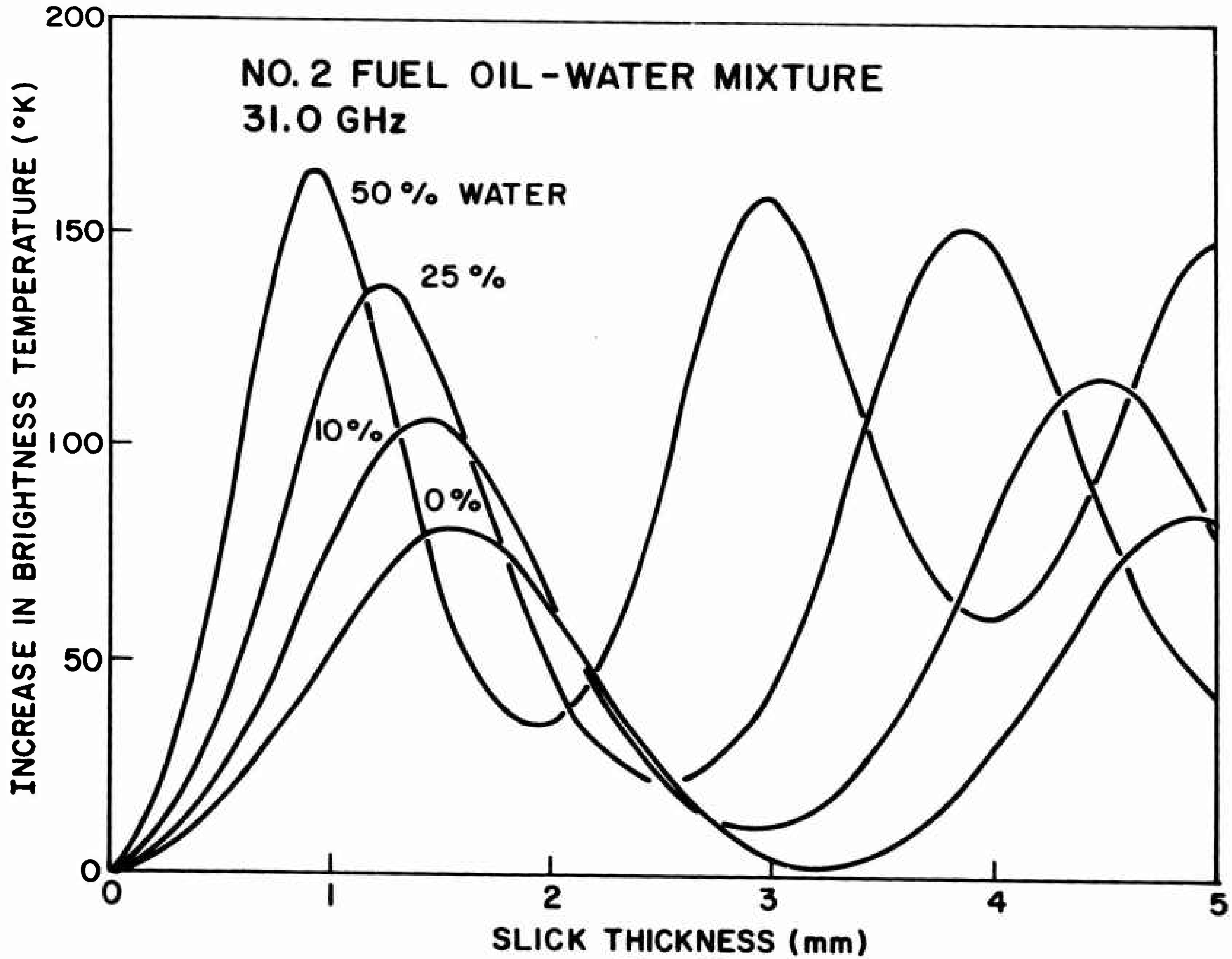

NO. 2 FUEL OIL-WATER MIXTURE
31.0 GHz
50 % WATER
25 %
10 %
0 %
INCREASE IN BRIGHTNESS TEMPERATURE (°K)
200
150
100
50
0
0
1
2
3
4
5
SLICK THICKNESS (mm)

Figure 70

In summary, for sea states with seas of up to 5 feet, swell up to 8 feet and winds of up to 24 knots, the results of the fifteen controlled oil spills conducted for this study showed very similar and consistent results. The slicks formed an identifiable region with film thicknesses of a millimeter or more and containing the majority of oil which was surrounded by a very much larger and thinner slick which contained very little of the oil. In general the thick region contained more than 90 percent of the oil in less than 10 percent of the area of the visible slick. It was always possible to locate and delineate the thick region solely from the microwave observations. The total volume of oil present derived from the microwave measurements was within about 25 percent of the volume of oil spilled. Multifrequency passive microwave radiometry offers the potential to measure the distribution of oil in sea surface oil slicks, locate the thick regions, and measure their thickness and volume on an all-weather, day or night, and real time basis. As such it should prove a useful tool in the confinement, control, and clean up of marine oil spills.

ACKNOWLEDGMENTS

The author acknowledges the invaluable assistance of R. A. Mennella in planning and conducting the airborne measurements, in organizing and supervising some of the oil spills and in reducing and analyzing some of the data. Thanks are due to S. R. MacLeod and J. A. Modolo for their fine work in the design, construction, calibration and installation of the radiometers and for their help in taking the measurements.

We wish to express our appreciation to the pilots, crew and staff at NASA-Wallops Island Station for their invaluable assistance and aircraft support and to the Virginia Institute of Marine Science for their aid in conducting some of the oil spills. We thank R. Matthews and the staff at NASA-Johnson Space Center for their aircraft participation and support in the 15 August 1972 oil spills. We are grateful to J. R. Jadamec of the U. S. Coast Guard for making in situ thickness measurements, to LT A. Maurer of the U. S. Coast Guard who organized and supervised the rough sea oil spills and was contract monitor and to CDR W. E. Lehr, CDR R. Ketchel, LCDR G. Woolever and C. Catoe of the U. S. Coast Guard who made this work possible.

REFERENCES

1. Stroop, D. V., "Report on Oil Pollution Experiments--Behavior of Fuel Oil on the Surface of the Sea" presented to the Committee on Rivers and Harbors, House of Representatives, Seventy-First Congress, Second Session, Hearings on H. R. 10625, p. 41, U. S. Government Printing Office, 1930.

2. Garrett, W. D., Naval Research Laboratory Report 7372, 1972.

3. Brekhovskikh, L. M., "Waves in Layered Media," Academic Press, page 44, 1960.

4. Saxton, J. A. and Lane, J. A., "Electrical Properties of Sea Water," Wireless Engineer, page 269, October 1952.

5. Edgerton, A. T. and Trexler, D. T., "Radiometric Detection of Oil Slicks," Report No. SD-1335-1, January 1970.

6. Howard, D. D., Thomas, N. A., and Licitra, M. C., "Microwave Monitoring of Sea Water Contamination of Navy Fuel Oils," NRL Report 6552, June 1967.

7. Von Hipple, A., "Dielectric Materials and Applications," John Wiley and Sons, 1954.

8. Hollinger, J. P., "Passive Microwave Measurements of Sea Surface Roughness," IEEE Trans. Geoscience Elect., Vol. GE-9, July 1971, pages 165-169.

9. Cox, C. and Munk, W., "Statistics of the Sea Surface Derived from Sun Glitter," J. Mar. Res., Vol. 13, 1954, pages 198-227.

10. Cox, C. and Munk, W., "Measurements of the Roughness of the Sea Surface from Photographs of the Sun's Glitter," J. Opt. Soc. Amer., Vol. 44, November 1954, pages 838-850.

11. Meeks, D. C., Williams, D. P., Wilcox, R. M. and Edgerton, A. T., "Microwave Radiometric Detection of Oil Slicks," Report No. 1335-2, Aerojet-General Corp., March 1971, page 6-2.

12. Peake, W. H., "Interaction of Electromagnetic Waves With Some Natural Surfaces," IRE Trans. Antennas Propag. (Special Suppl.), Vol. AP-7, December 1959, pages 5324-5329.

13. Stogryn, A., "The Apparent Temperature of the Sea at Microwave Frequencies," IEEE Trans. Antennas Propagation, Vol. AP-15, March 1967, pages 278-286.

14. Hollinger, J. P., "Remote Passive Microwave Sensing of the Ocean Surface," Proc. 7th International Symposium on Remote Sensing of Environment, Univ. of Michigan, Vol. 3, May 1971, pages 1807-1817.

15. Monahan, E. C., "Oceanic Whitecaps," J. Phys. Ocean., Vol. 1, April 1971, pages 139-144.

16. Bracewell, R. N., Handbuch Der Physik, Vol. 54, 1962, pages 43-129.

17. Federal Register Document 71-5369, 1971.

18. Fay, J. A., Oil on the Sea, Plenum Press, New York, 1969, page 53.

19. Guinard, N. W., "Remote Sensing of Oil Slicks," Proceedings of the Seventh International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, 1971, page 1005.

20. Munday, J. C., Jr., MacIntyre, W. G., Penney, M. E., and Obserholtzer, J. D., "Oil Slick Studies Using Photographic and Multispectral Scanner Data," Proceedings of the Seventh International Symposium on Remote

Sensing of Environment, Ann Arbor, Michigan, 1971, page 1027.

21. Garrett, W. D., Private Communication, 1973.

22. Jadamec, J. R., Private Communication, 1974.

23. Garrett, W. D., Private Communication, 1974.

24. Berridge, S. A., Thew, M. T., and Loriston-Clarke, A.G., "The Formation and Stability of Emulsions of Water in Crude Petroleum and Similar Stocks," J. Inst. Petroleum, Vol. 54, November 1968, pages 333-357.

25. Parkhomenko, E. I., Electrical Properties of Rocks, Plenum Press, New York, 1967, page 20.