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Oil Spills: Measurements of Their Distributions and Volumes by Multifrequency Microwave Radiometry

Abstract. *Aircraft-borne multifrequency passive microwave observations of eight marine oil spills revealed that, in all cases, over 90 percent of the oil was confined in a compact region comprising less than 10 percent of the area of the visible slick. These measurements show that microwave radiometry offers a means for measuring the distribution of oil in sea-surface slicks; for locating the thick regions; and for measuring their volumes on an all-weather, day or night, and real-time basis.*

Mounting concern is being voiced by the public and by officials affiliated with governmental agencies over the ever-increasing number of marine oil spills and the resulting pollution. Before appropriate corrective action can be taken, information on the nature, thickness, areal extent, direction, and rate of drift of the particular oil spill must be promptly obtained. The spreading of sea-surface oil spills is not uniform, nor is it without limit (*1*). Regions with thicknesses of a millimeter or more are formed which contain most of the oil, and these areas are surrounded by very much thinner and larger slicks. Reliable information on the thickness of the oil film is needed in order that the volume of the slick may 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 an assessment of the impact of the spill on marine life and environment. Perhaps most important, a knowledge of the distribution of the oil and the location of those regions containing the heaviest concentration of oil is necessary for effective confinement, control, and cleanup.

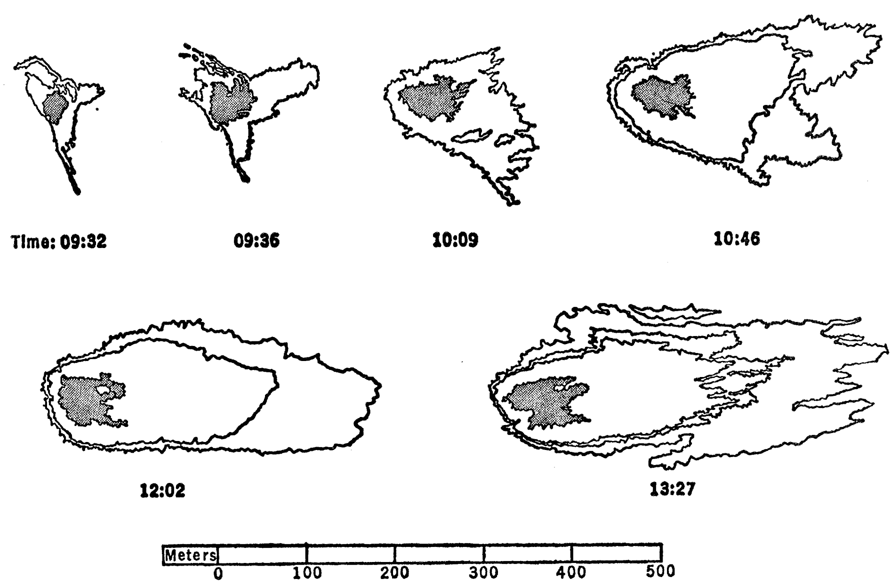

Fig. 1. The drawings are tracings of color photography of the oil slick resulting from a controlled oil spill of 2380 liters of No. 2 fuel oil. The oil had been dyed red in order to allow the thick regions of oil to be identified visibly. The outer line in each drawing represents the extreme edge of 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 thickest oil.

Microwave radiometry offers a unique potential for the determination of oil slick thicknesses greater than about 0.05 mm. The apparent microwave brightness temperature is greater in the region of an oil slick than in the adjacent unpolluted sea by an amount depending 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 (*2*). As the thickness of the oil film increases, 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 (*3*). 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 (*4*).

A series of eight controlled oil spills was conducted during the period from 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 to investigate the possibility of determining oil slick thickness with passive microwave radiometry. The spills, of from 760 to 2380 liters (200 to 630 gallons) of either No. 2 fuel oil or No. 4 or No. 6 crude oil, were conducted in accordance with the guidelines established by the Environmental Protection Agency for the discharge of oil for research purposes (*5*). All of the spills were conducted in relatively calm sea conditions with swell of less than 2 m and surface winds of less than 10 m/sec. The oil was transported to the ocean test site, about 10 miles (16 km) east of Chesapeake Light Tower off the east coast of Virginia, in 190-liter drums. The drums were unloaded, collected, and emptied from small rubber boats so as to obtain as nearly as possible an undisturbed point release.

Figure 1 shows a series of drawings traced from color photography of the 11 July 1972 oil spill. This spill consisted of 2380 liters of No. 2 fuel oil dyed with an oil-soluble red dye (*6*). The dye allowed the thick regions of oil to be easily identified visibly. The oil formed a well-defined thick region surrounded by a very much larger and thinner region. In situ thickness measurements (*7*) showed the oil to be

2.4 ± 0.3 mm thick at spots in the crosshatched region and typically 2 to 4 μm thick outside this region. The thick inner region spread at a much slower rate than the total slick. 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 Fay (*8*), which grows at a rate proportional to the square root of the time. It is somewhat slower than spreading rates reported by Guinard (*9*) or by Munday *et al.* (*10*). However, the spreading rate does vary widely because it depends upon many variables, such as (i) the volume, age, density, and viscosity of the oil; (ii) the surface-active materials present; (iii) the interfacial surface tension; (iv) the surface wind; (v) the sea state; and (vi) the surface current. 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. All of the spills conducted with each oil type exhibited this behavior. 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.

We used the NASA–Wallops Island DC-4 aircraft to make the microwave observations. 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. The measured antenna temperature T_a is the average of the brightness temperature over the antenna beam (*11*). The half-power antenna beam width at all three frequencies was 7.2°, which gave a beam spot on the surface of about 15 m for the aircraft altitude of about 122 m. We built up a two-dimensional T_a map of the oil slick by making repeated aircraft passes over the extent of the slick. It was necessary to make passes for approximately 15 to 30 minutes before and after the nominal time of the map in order to acquire sufficient scans for the creation of the map.

Contour maps of the increase in T_a above the unpolluted sea at 19.4 and 31.0 Ghz are shown in Fig. 2, B and C, superimposed on the outline of the visible slick for the spill of 11 July 1972 (Fig. 2A). These T_a distributions were used to derive the thickness contours shown in Fig. 2D. The T_a values and the derived thicknesses are weighted averages over the antenna beam. The half-power beam spot on the surface is represented by the small circle (right center). 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 ± 0.3 mm. Integration of the thickness contours derived from the microwave data gives a volume of 2460 ± 246 liters, which, taken with the volume of oil spilled of 2380 liters, indicates that nearly all of the oil is in the thick region. This is consistent with in situ measurements of film thicknesses of 2 to 4 μm outside the thick region since only 57 to 114 liters of oil would be needed to cover the entire area of the visible slick of 33×10^3 m^2 with a uniform film to those thicknesses. The ratio of the oil thickness in the thick region to that in the thin region (nearly 1000) also shows that nearly all of the oil is located in a small region of the slick.

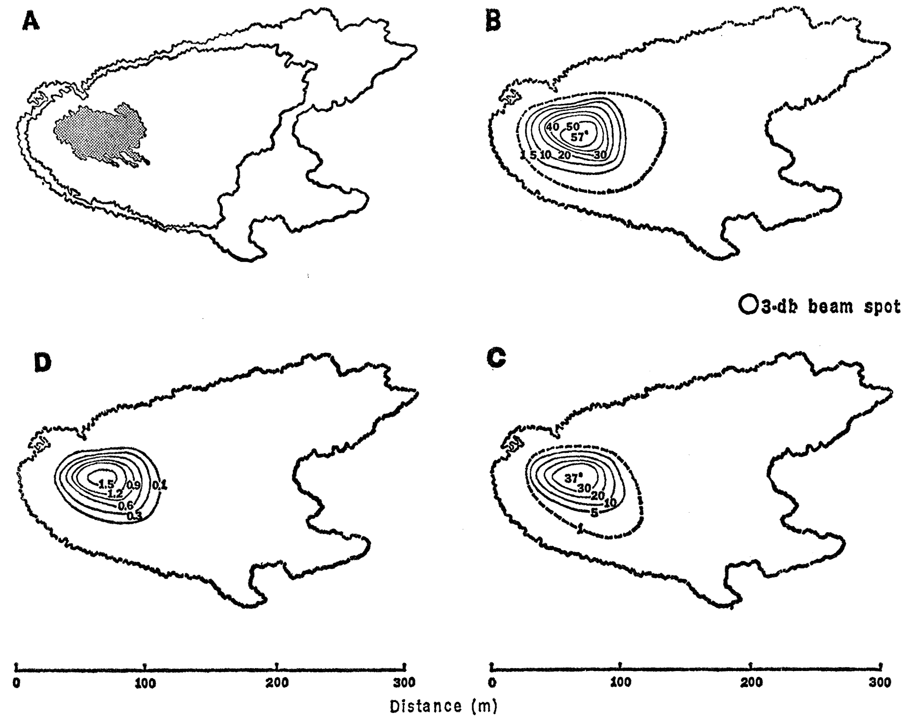

Fig. 2. (A) Tracing of the oil slick represented at 10:46 in Fig. 1. (B) The increase in T_a (in degrees Kelvin) measured at 31.0 Ghz superimposed on the outline of the visible slick. (C) The increase in T_a measured at 19.4 Ghz superimposed on the outline of the visible slick. (D) The thickness contours (in millimeters) derived from the microwave data.

The microwave measurements of all the oil spills of each oil type showed results very similar to those just described for the spill of 11 July 1972. All the slicks formed an identifiable region with film thicknesses of a millimeter or more and containing most of the oil, and this region 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. In every case it was possible to locate and delineate the thick region solely from the microwave observations, and the total volume of oil present derived from the microwave measurements was within about 25 percent of the volume of oil spilled. Thus multifrequency passive microwave radiometry offers the potential to measure the distribution of oil in sea-surface slicks, to locate the thick regions, and to measure their thickness and volume on an all-weather, day or night, and real-time basis. As such, it should prove a useful tool for the confinement, control, and cleanup of marine oil spills.

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12. We thank the staff at NASA-Wallops Island Station for their invaluable assistance and aircraft support, and the staff of the Virginia Institute of Marine Science for their aid in conducting the oil spills and carrying out surface measurements. This work was sponsored by the U.S. Coast Guard under contract Z-70099-2-21881.

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Oil and Ice in the Arctic Ocean: Possible Large-Scale Interactions

Abstract. *The diffusion and transport mechanisms generated by the pack ice dynamics of the Beaufort Sea, combined with the slow rate of biodegradation of oil under Arctic conditions, would combine to diffuse an oil spill over the sea and eventually deposit the oil on the ice surface, where it would lower the natural albedo over a large area.*

There has been considerable speculation concerning the biological effects of oil spills on both the Arctic tundra and in the Arctic Ocean. Because of the slow rate of biological degradation of oil at near-zero temperatures in temperate waters, biologists (*1, 2*) have suggested that, once oil has entered the Arctic Ocean, it might remain there for periods of the order of 50 years. We wish to discuss here some of the possible physical interactions between the highly mobile Arctic pack ice and an oil spill.

The Arctic pack ice covers an area of about 10^7 km^2 with an average thickness between 3 and 4 m. Many investigators (*3–5*) have shown that this thin veneer of ice is extremely important in determining the heat exchange between the ocean and atmosphere and have pointed out that, if the ice cover were removed from the Arctic, it might not reform. This sensitivity is attributable to the fact that during the months of June and July the Arctic above 70°N receives more radiation than any other comparable area on Earth. Because of the large amount of summer radiation to which it is exposed, the ice is very sensitive to small changes in albedo. On the basis of an examination of the present Arctic radiation and heat budget, Fletcher (*5, 6*) has argued that, if the ice pack were removed from the Arctic Ocean, the heat absorbed by the open ocean during the summer might be sufficient to prevent formation of ice during the winter. Because his argument is based on measurements over the present Arctic, it neither accounts for nor predicts the changes in both the planetary circulation and the cloud cover that might result, so that it is not known whether an open Arctic Ocean would remain open.

On the basis of a sophisticated one-dimensional thermodynamic model of sea ice, Maykut and Untersteiner (*3*) have shown quantitatively how changes in the albedo of sea ice affect its equilibrium thickness. Their model shows that a 10 percent reduction in the albedo of the ice during the period from 1 June to 30 August yields a 60 percent reduction in equilibrium thickness, and that a 20 percent reduction in the albedo causes the ice to disappear after 2 years. They also have demonstrated that elimination of the evaporative heat flux from the surface of the ice during the same period yields a 40 percent reduction in the equilibrium thickness. Maykut and Untersteiner have concluded that "modification of the snow or ice surface is the most effective means of large-scale ice removal. . . . The ideal material [for spreading on the surface] would be dark, nontoxic, lighter than water, slowly soluble in water, and have a low emissivity." A substance which satisfies a number of these requirements is oil.

Any consideration of the impact of oil on the Arctic Ocean must include the extremely dynamic character of the Arctic sea ice. The mobility of the pack ice on the open ocean would make oil cleanups within the ice immensely more difficult than on tundra or glacier ice. First, any oil spilled within the pack ice would be swept up in a continuously deforming matrix of ice floes and leads of varying sizes which may move at velocities as great as 40 km per day and in which velocities of 5 to 15 km per day are common. Second, leads and polynyas (large leads with areas as great as 500 km^2) move through the pack with even greater velocities than the pack velocity. Third, large shearing deformations occur within the pack. In general, sea ice is one of the fastest-varying large-scale features on the surface of the earth.

Numerous investigators have worked for years to create a predictive model for the dynamics of the Arctic pack ice (*7*). Although these models differ in fundamental ways, they all demonstrate the existence of certain large-scale features of the annual Arctic ice pack circulation, namely, the Beaufort Sea gyre and the transpolar drift stream, and show for the mean annual Arctic circulation that the Beaufort Sea should be a region of ice convergence.

Whether the Beaufort Sea ice pack is strongly convergent annually, as the steady-state theories suggest, or weakly divergent and convergent periodically with perhaps a zero-average annual convergence, as observations of the drift of ice stations suggest (Fig. 1), both theory and observations agree that the anticyclonic Beaufort Sea ice gyre is a real feature of the polar circulation. The existing theoretical models and observations suggest that, once an oil spill enters the ice pack of the Beaufort Sea, it would become part of the anticyclone system, circulate around the gyre, and diffuse into and around the gyre.