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A Multispectral Look at Oil Pollution Detection, Monitoring, and Law Enforcement

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C. E. Catoe and J. T. McLean

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Goddard Space Flight Center
Greenbelt, Maryland 20771

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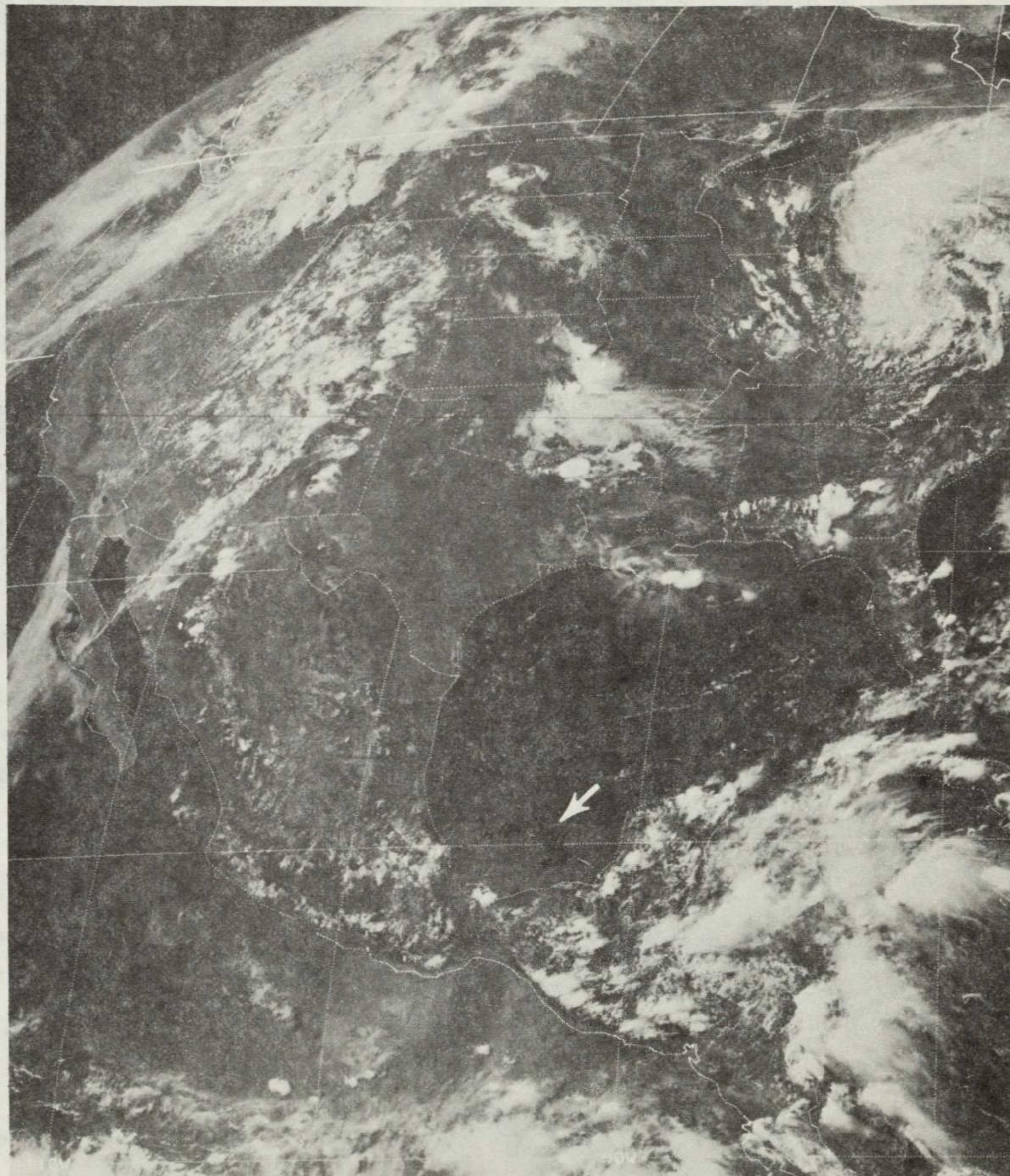


Picture of Mexican Gulf Well oil spill taken from NOAA's Geostationary Operational Environmental Satelite (GOES) on 30 June 1979.

A Multispectral Look At Oil Pollution, Detection, Monitoring, And Law Enforcement

By Clarence E. Catoe and James T. McLean

1. Introduction

Oil will continue to be for the present an important energy ingredient in the economies of most of the industrial nations of the world. Because of the huge quantities of crude oil and petroleum products that are transported in ships, the problem of oil pollution of both surface waters and benthic communities has increased considerably. Damages to the marine environment due to oil spills at sea are considered to be one of the main sources of pelagic pollution. It is currently estimated that more than six million tons of hydrocarbons enter the marine environment each year as a result of oil trafficking, and certain other coastal activities such as oil prospecting, sea mining, and natural oil seepage.[1]

In order to reduce the threat of oil pollution in the United States, the bulk of the private and government attention has been focused on developing regulations, methods, and procedures to reduce the probability of oil spillage. In any event, it is reasonable to assume that, in spite of the new regulations and preventive measures, there will still be oil spills, either due to human carelessness or calamities beyond human control, that will not be reported in a timely manner. What is needed to combat these unreported incidents are effective techniques for the remote detection and surveillance of oil slicks in sufficient time, so that adequate countermeasures can be utilized to minimize the pollution hazards to coastal and inland waters of the U.S. and to detect violations of U.S. and international laws concerning pollution of the sea by oil.

At the present time, it is known that oil does exhibit characteristic signatures. However, these signatures may vary with time and environmental conditions—a fact which may either help or hinder detection, depending on how well the phenomenon is understood.

There are a variety of devices for "seeing" oil on water—sensors that make use of both the spatial and spectral dimensions. All of the devices are limited to a greater or less degree, but all are also considerably more reliable than the naked human eye. It is obvious that no one sensor can do an effective job. What is required is a multispectral approach to resolve the problems of:

1. Detecting oil films on water
2. Mapping the areal extent of the slick
3. Measuring slick thickness
4. Identifying oil types

In this paper, a multispectral look at oil pollution, detection, monitoring, and law enforcement capabilities will be considered.

2. Signature Properties of Oil

In the generic sense, the signature property of oil refers to that particular characteristic of oil such as the energy emitted, reflected, or absorbed as a function of wavelength which enables one to differentiate it from its background. In Table 1, the relationship between the wavelength regions and the target detection mechanisms along with specific detection constraints are given for the ultraviolet, visible, infrared, and microwave regions.[2]

2.1 Ultraviolet Region—0.1 to 0.4 of a micrometer (μm)

The ultraviolet spectrum is commonly divided into three sections: far ultraviolet (0.1-0.2 μm), middle ultraviolet (0.2-0.3 μm), and near ultraviolet (0.3-0.4 μm). The use of ultraviolet in remote sensing has been severely hampered by the strong absorption band below 0.29 μm. However, the region from 0.3 to 0.4 μm appears to have some significance for the oil slick problem

When oil is exposed to broadband ultraviolet radiation from the sun, or some artificial source, it reflects and absorbs the incident radiation. In the case of oil slicks on the ocean, the reflectance contrast between oil and sea water is significant due to the fact that oil has a higher reflectance than sea water in the near ultraviolet region.

The characteristic yellow, brown, or brownish-black colors associated with most oils are related to their strong ultraviolet absorption, which extends into the visible region. Generally, these colors can be seen in oil slicks only with near-vertical viewing, where sky reflectance is weak.

In addition to the above, a portion of the ultraviolet absorbed by the oils is reemitted at longer wavelengths—0.4 to 0.7 μm. This phenomenon, known as fluorescence, may provide a means of remote detection of oil slicks. The fluorescence properties of oils result from the radiation of many groups of organic compounds, primarily the polyaromatic and heterocyclic hydrocarbons. Variations in the concentration and nature of these compounds will yield different fluorescence spectra and can be expected to aid in identifying oil. An analysis of the fluorescent intensities, emission spectra, and emission lifetimes of 29 different crude oils commonly transported in the marine environment tended to indicate that it may be possible to relate the fluorescence spectra of the oil to its API gravity.[3]

As indicated in Table 1, the mechanism for the detection of oil slicks is dependent upon the reflectance contrast between oil and water, and the fluorescence signature of oil. In this region oil presents 20 to 50% higher reflectance than water.[4] Light oils have a greater reflectance than heavy oils, as indicated in Figure 1. The reflectance also varies strongly with the thickness of the slick, as indicated in Figure 2; i.e., thin layers have a greater reflectance than thicker layers. This condition may be explained as follows: The radiance viewed by the observer consists of two components—a specular part related to the oil layer, and an upwelling diffuse portion from beneath. The specular radiance from the oil is essentially constant, whereas the diffuse radiance varies with oil layer thickness. The diffuse component is maximum for clean water and thin films, but approaches zero for very thick oil films. Repeatable positive response is obtainable from thin slicks on the order of 0.1 micron.

The fluorescence signature of oil can be considered from two points of view: artificial excitation and solar excitation.

In artificial excitation, the source is a narrow band, such as a mercury (Hg) lamp or a nitrogen (N_2) laser. The spectral character of the oil is strongly correlated to oil thickness and how closely the source wavelength corresponds to the excitation wavelengths of the particular oil, as indicated in Figure 3. Both the intensity and wavelength of fluorescent energy are strongly correlated to the oil type, i.e., API gravity, as shown in Table 2 and Figure 4. They are weakly correlated to temperature. The general decay characteristics of the oil are moderately to strongly correlated to oil type, but uncorrelated to oil thickness. All of the above characteristics are independent of ambient illumination conditions.

Table 1. Relationship between Wavelength Region and Target Detection Mechanism

WAVELENGTH REGION	DETECTABLE PARAMETER	SPECIFIC DETECTION CONSTRAINTS
ULTRAVIOLET (0.1 TO 0.4 MICROMETER)	• REFLECTANCE DIFFERENTIAL • FLUORESCENCE	• STRONG ATMOSPHERE ABSORPTION BAND BELOW 0.29 MICROMETER • ATMOSPHERIC SCATTERING
VISIBLE (0.4 TO 0.7 MICROMETER)	• REFLECTANCE DIFFERENTIAL	• ILLUMINATION REQUIRED • ATMOSPHERIC HAZE
INFRARED (.07 TO 1000 MICROMETERS) NEAR IR (0.6 TO 3 MICROMETERS) FAR IR (>3 MICROMETERS)	• REFLECTANCE DIFFERENTIAL • THERMAL EMISSION DIFFERENTIAL • THERMAL EMISSION DIFFERENTIAL	• UNDER ILLUMINATION CONDITIONS REFLECTANCE DIFFERENTIAL MASKS OUT THERMAL EFFECTS BELOW 3 μm • ATMOSPHERIC HAZE AND CLOUDS • NONHOMOPOLAR MOLECULAR ABSORPTION
MICROWAVE REGION (1 MILLIMETER TO 1 METER)	• EMISSIVE DIFFERENTIAL • REFLECTION/SCATTERING CROSS SECTION	• RAIN CLOUDS • NONHOMOPOLAR MOLECULAR ABSORPTION • POLARIZATION BIAS

When exposed to broadband solar radiation, the spectral character of oil is moderately to weakly correlated to oil type and thickness, whereas the intensity is strongly correlated to oil type, oil thickness, and ambient illumination conditions. The decay characteristics of oil under these circumstances are not detectable. Signal limitations associated with the fluorescence process prevent the detection of oil fluorescence except under strong solar illumination Atmospheric scattering appears to be the major deterrent to this technique through signal attenuation.

2.2 Visible Region—0.4 to 0.7 μm

The visible region refers to that portion of the electromagnetic spectrum to which the human eye is sensitive. In this region, the basic mechanism for oil detection is the reflectance differential between oil and water. As noted previously, the reflectance of an oil slick on water is made up of two components, specular and diffuse. The specular reflectance of an oil slick is always greater than that of water, whereas the diffuse component of reflectance usually will be less than that of water. Thus, the specular radiance component always produces a positive signature for oil slicks, while the diffuse radiance component always produces a negative signature.

The index of refraction of all petroleum oils and products observed to date exceeds that of either fresh or saline water at essentially all wavelengths which are usable for optical remote sensing in the earth's atmosphere.[5] Thus, the specular component of reflectance of any oil slick on water will exceed that of the water alone. The magnitude of this excess will depend upon oil type, wavelength, and slick thickness.

The maximum contrast between oil and water occurs in two different regions: below 0.4 μm and in the red above 0.6 μm. The minimum contrast between oil and water occurs between 0.45 and 0.50 μm.[6] In general, sky conditions are important in influencing the oil/water contrast. The best contrast is achieved under overcast sky conditions.

For longer wavelengths, the extinction coefficient of water becomes very large, and the diffuse reflectance becomes very small. Thus, only the specular component remains for which oil slicks universally exhibit higher radiances than water. No distinct absorption regions which would distinguish one oil from another have been observed.

The possibility of false alarms for active remote sensing of reflectance of oil slicks depends upon the chosen method of operation. If, for example, one intends to take advantage of the possibility of detection based upon the specular return by choice of an operating wavelength outside the region of water transparency, all false alarms resulting from subsurface effects (e.g., changing water quality and bottom reflectance) can be avoided. Then, only surface phenomena need be considered. For slightly rough waters, wind slicks could pose a false alarm problem. Also, the specular return from fish-oil slicks would look identical to that from many petroleum oil slicks because of the similarity of their respective refractive indexes.

The problems of false alarms relevant to passive remote sensing of reflectance of oil slicks are quite similar to those described for the active case. Operation at wavelengths less than 0.6 μm would allow the possibility of false alarms resulting from changes in water quality or bottom reflectance, either of which can produce both positive and negative anomalies. Fish-oil slicks would again be a problem at all wavelengths, since their optical properties are quite similar to those of many petroleum oils. In contrast to active remote sensing of reflectance, however, surface features such as wind slicks should not create a significant false alarm problem, since sea state is not a significant factor in passive reflectance remote sensing. However, an exception can be hypothesized for the case in which one is operating at a spectral wavelength where zero radiance contrast between an oil slick and water is prevalent, and the detection of the sea-smoothing effects of an oil slick is considered relevant.

2.3 Infrared Region—0.7 to 1000 μm

The infrared region is subdivided into near, intermediate, and far regions, depending upon how "far" removed the thermal radiation is from the visible spectrum.

In the near infrared region, which extends from 0.7 to 1.1 μm, the reflectance properties rather than thermal properties of the material are significant.[7] For this region the radiance from an oil slick is from 20 to 100% higher than that from the surrounding water. This condition is highly favorable for the daytime detection of oil slicks. At night, starlight and airglow provide sufficient diffuse illumination to cause about 50% greater radiance from the oil than from the water. During the daytime, the spectral region may also

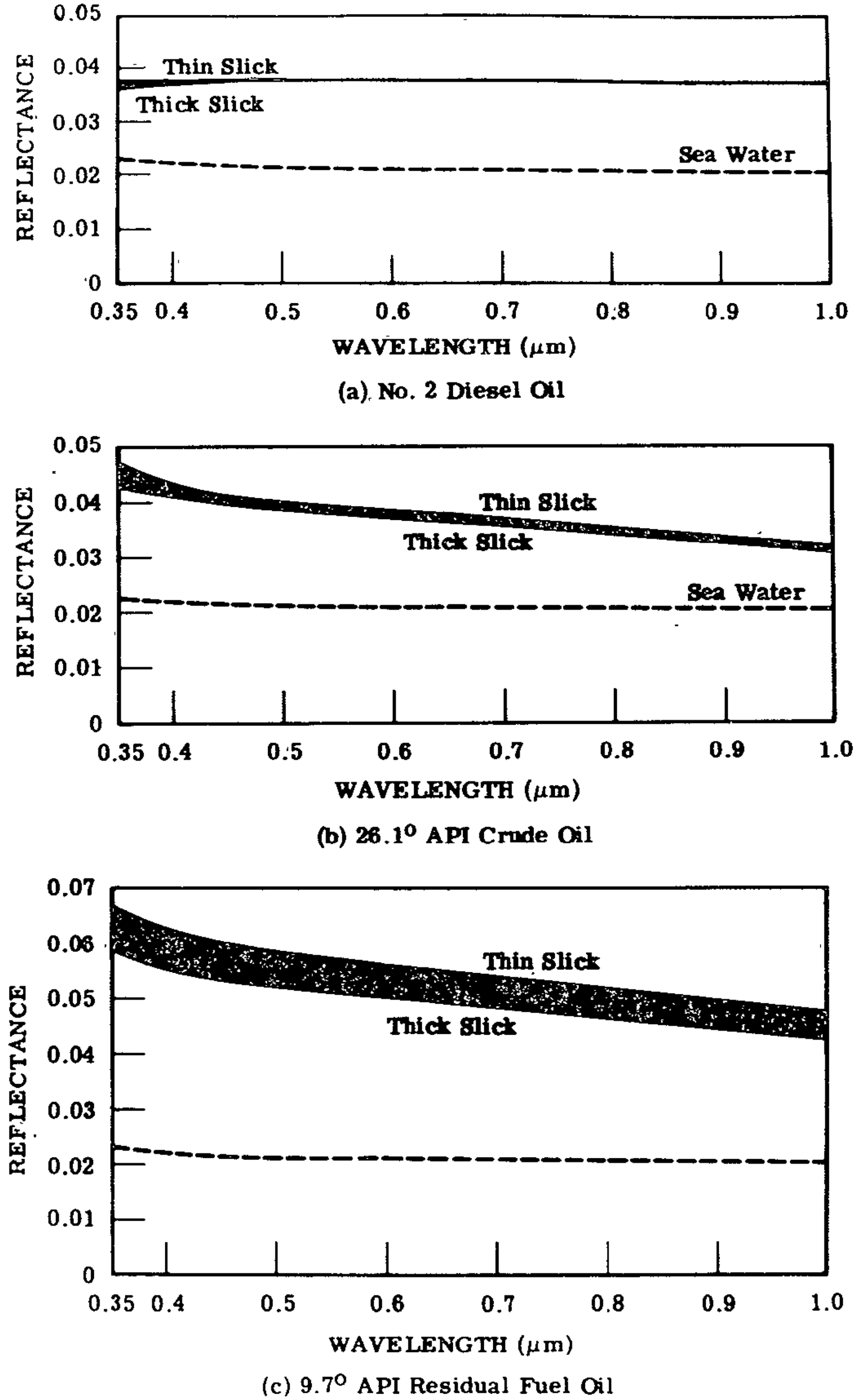


Figure 1. Spectral Variation of the Normal Specular Reflectance of Several Oil Slicks on Sea Water

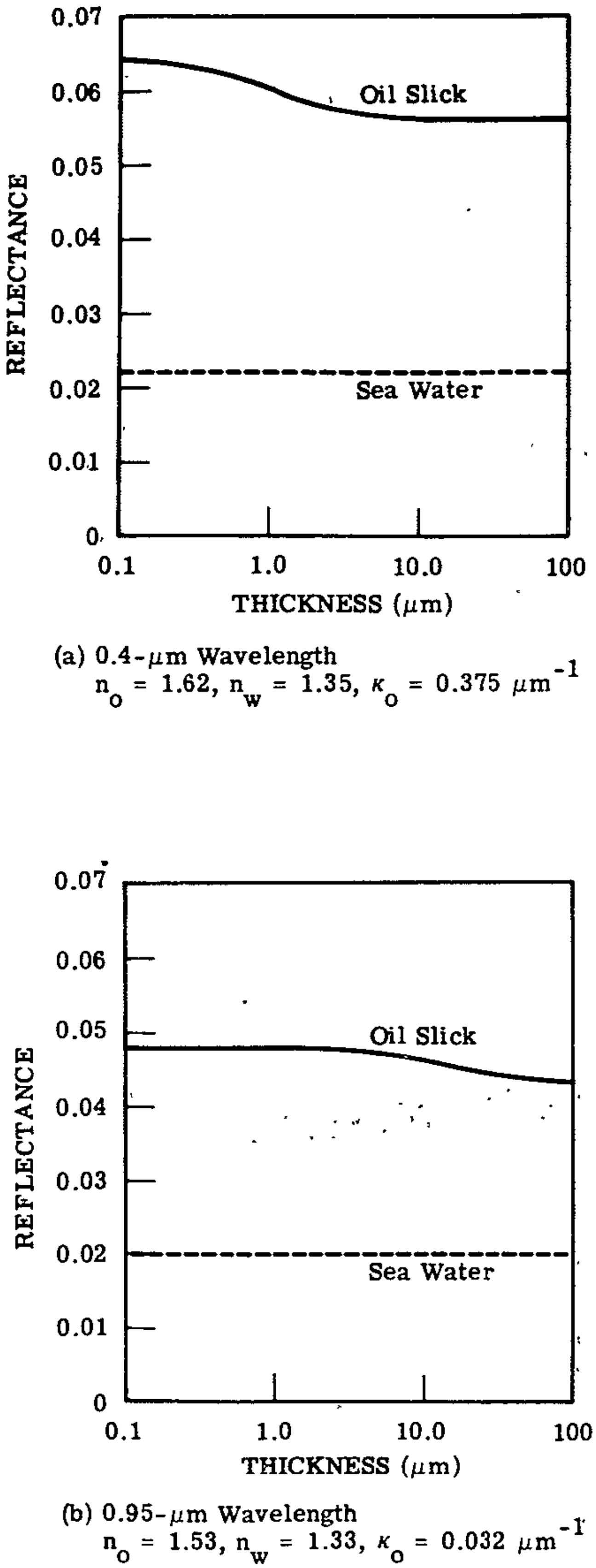


Figure 2. Specular Reflectance at Normal Incidence for a 9.7 °API Residual Fuel Oil Slick on Sea Water

be useful, although the ultraviolet region is preferred. Atmospheric attenuation is minimal except for that caused by heavy clouds.

The thermal-infrared region refers to that part of the spectrum greater than about 3 μm, because all materials at normal temperatures actively emit significant amounts of radiation as a result of temperature dependent atomic and molecular processes. This emission still exists at wavelengths less than 0.3 μm, but it is so small that its existence is normally ignored.

Remote sensing is usually accomplished passively within the thermal-infrared region by detecting primarily the self-emitted radiation. This emission is controlled by two factors: the temperature of the material and its emitting efficiency. Active remote sensing in the thermal-infrared region is also possible, but it involves the reflectance of the target, not its thermal emission.

Remote sensing at thermal-infrared wavelengths is usually confined to spectral regions called atmospheric windows, where the atmosphere is sufficiently transparent to allow radiation to travel over significant path lengths with little absorption. These windows exist principally in the 3.1- to 4.1-μm, 4.5- to 5.5-μm, and 8- to 14-μm regions. Strong absorption bands, resulting principally from atmospheric water vapor and carbon dioxide, effectively eliminate remote sensing outside these regions.

The emittance of petroleum oils and sea water is quite high in the atmospheric windows of the thermal-infrared region, because of the rather low values of reflectance involved. Since both water and petroleum oils have high absorption,[4] very low scattering, and smooth surfaces (at least microscopically), the directional reflectance is determined wholly by the specular Fresnel reflectance.

Normal emittance values for a number of oils and for sea water are presented in Table 3 as averages in the atmospheric windows. These values were obtained from the normal specular reflectances of the bulk, i.e, optically thick oil. Within each spectral region of Table 3, the emittances are generally larger for lighter oils.

The variation in emittance with slick thickness will only be significant when the bulk emittance of the oil differs significantly from that of water. Otherwise, reflectance at the oil/water interface will necessarily be negligible. Thus, the data in Table 3 indicate that thickness effects will be most significant in the 8- to 14-μm-region, where emittance differences are the greatest.

An oil film on a water surface will alter the thermal exchange with the atmosphere. Although the precise interrelationships involved are not fully understood, a number of reports which contribute to an understanding of the phenomena have appeared in the literature.

Bell et al. (1957), observed that the reflectivity of water increases at 10 μm when a thin oil film is introduced.[8] An increase in reflectivity means that the emissivity must decrease, thus causing a lower apparent temperature to be detected. Similar results to that above were obtained by Buettner and Kern[9] in their study of infrared emissivities of terrestrial surfaces. However, the situation is far more involved than can be explained simply in terms of reduced emissivity. It is also dependent on cloud signals reflected by the oil. For example, Buettner and Kern also pointed out that if a ship produces higher temperatures than the water, then an oil slick in its wake may appear radiometrically "warm" under overcast conditions and "cold" under a clear sky.

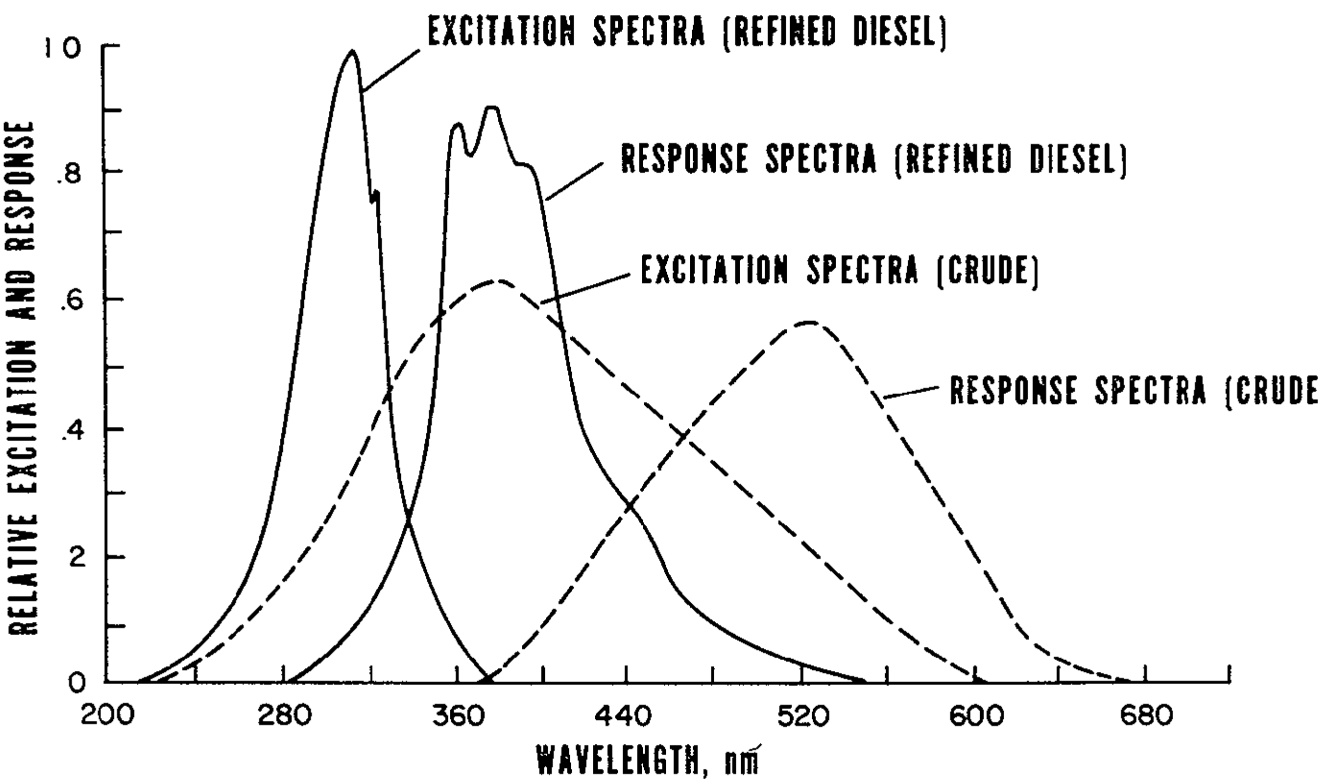


Figure 3. Relative Excitation and Response versus Wavelength

Table 2. Correlation Parameters

TSC Oil Sample	°API Gravity	Fluorescent Emission λM (nanometer)	Fluorescent Coefficient ϵ_0	Fluorescent Lifetime t (nanosec)	TSC Oil Sample	°API Gravity	Fluorescent Emission λM (nanometer)	Fluorescent Coefficient ϵ_0	Fluorescent Lifetime t (nanosec)
A3	-1.7	597	2.31×10^{-4}	10	C7	31.0	480	6.72×10^{-4}	12
D4	5.7	565	1.84×10^{-5}	9	C1	31.3	481	8.97×10^{-5}	10
A4	7.2	553	7.77×10^{-6}	9	B6	32.6	502	9.38×10^{-5}	10
A1	8.7	545	1.38×10^{-5}	9	C2	33.9	490	2.67×10^{-4}	10
B1	9.9	495	7.66×10^{-6}	9	C11	34.6	480	1.53×10^{-4}	10
A2	10.0	505	1.09×10^{-5}	9	C3	39.0	480	6.04×10^{-4}	13
D2	10.2	514	6.48×10^{-5}	10	C8	39.9	474	4.62×10^{-4}	12
B2	12.8	530	8.09×10^{-5}	10	C12	40.6	450	4.77×10^{-4}	17
B3	15.5	530	5.77×10^{-5}	10	C13	40.6	470	2.50×10^{-4}	11
B8	17.4	505	4.76×10^{-5}	9	C9	42.3	466	7.32×10^{-4}	15
D3	19.0	490	2.98×10^{-5}	10	C6	42.5	459	8.40×10^{-4}	13
B4	19.2	495	4.18×10^{-5}	9	C4	43.7	487	1.62×10^{-4}	11
B5	25.0	459	1.28×10^{-3}	19	D1	46.3	406	2.28×10^{-3}	21
C5	27.1	472	5.72×10^{-4}	11	C10	46.5	456	5.14×10^{-4}	12
B7	30.3	458	6.74×10^{-4}	16					

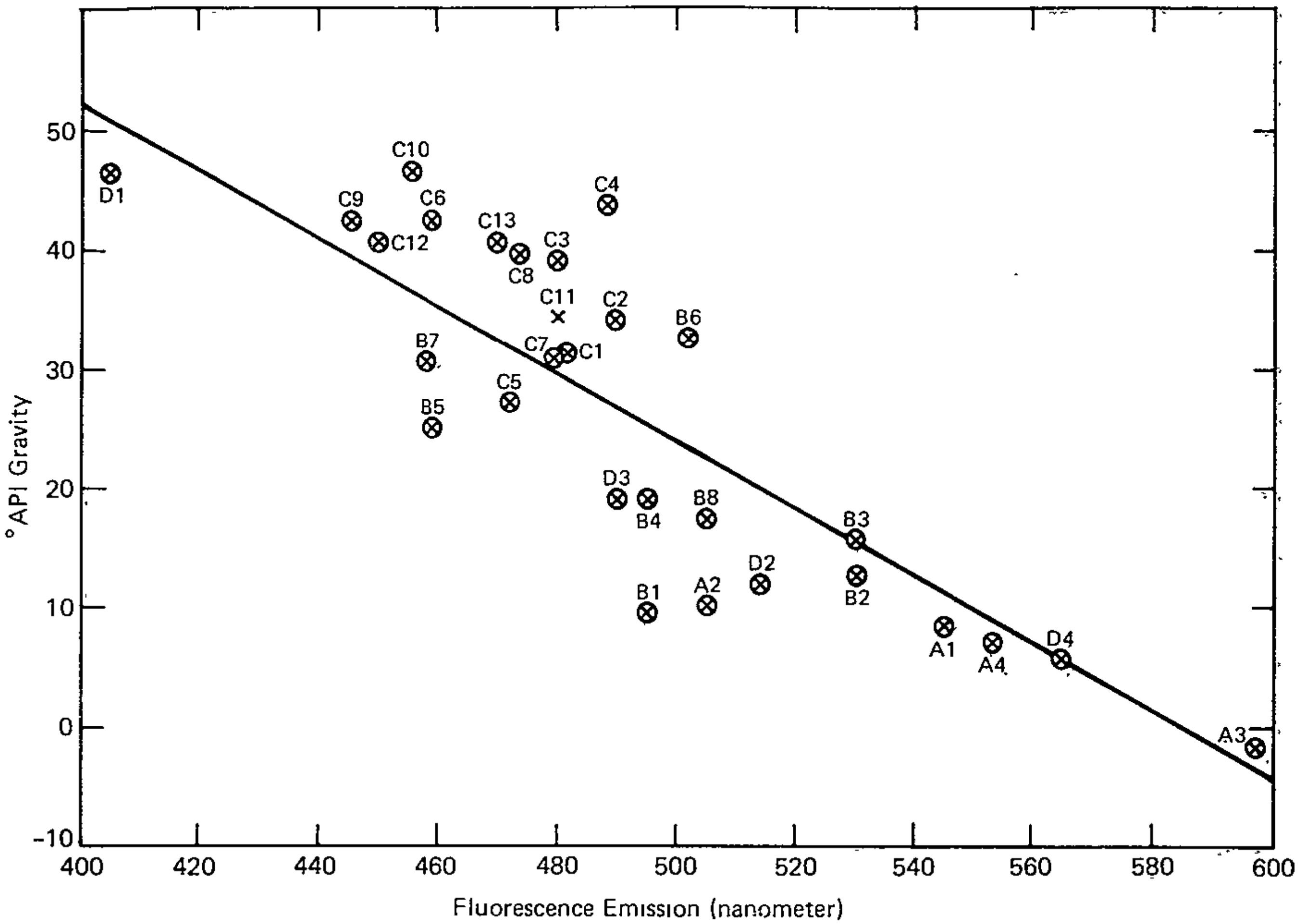


Figure 4. Peak Fluorescent Emission Wavelength versus ° API Gravity

In addition to the "apparent" radiometric temperature differences, some of the determining factors that might affect the actual temperature differences of the upper few millimeters of water are fundamental differences in thermal conductivities, solar heating, alteration of evaporation rates from the water surface, and evaporation of volatiles from oil pollutants (see Figure 5). It has been suggested by Horvath et al. that thickness variations have an effect on emitted radiation, in that as oil thickness increases, evaporation losses from volatiles present increase—thereby producing lowered temperatures in the slick. However, as the oil becomes thick enough to absorb significant solar energy, this cooling trend is overcome by solar heating, and as a consequence a "warm" slick results.[10] However, highly volatile and relatively transparent oil products apparently do not absorb sufficient solar energy to compensate for the reduction in temperature due to evaporation. Hence, these generally will appear colder than water.

Table 3 Normal Emittance of Oil and Water for Atmospheric Window Regions

Material	3 to 4 µm	4 5 to 5 5 µm	8 to 14 µm
100-Octane Fuel	0 98	0.979	0 973
Kerosine	0 968	0 968	0 968
Diesel Oil	0.968	0.969	0 972
SAE-30 Oil	0 965	0 965	0 970
8 6° API Residual Fuel Oil	0.958	0.958	0 964
44 7° API Crude Oil	0.973	0 972	0 973
31 3° API Crude Oil	0 969	0 970	0.967
19 5° API Crude Oil	0 969	0 970	0 972
Fish Oil	0 969	0 961	0 959
Sea Water	0 972	0.980	0 985

Chandler[11] states that the often observed "cold" response of oil and water is due to the large differences between their thermal conductivities, and further states that the thermal gradients within a slick are related to thickness.

Kennedy and Wermund[12] noted that oil trapped for several days against convergence lines, the brackish-marine waters interface, still appears cold relative to sea water. This tends to contradict the theory that cold signatures of oil are due to evaporation. A more acceptable explanation is that the contrast is due to an emissivity phenomenon. The primary reason is that the emissivity of oil is less than that of sea water. This is also compatible with the observation of small hot spots within the oil spill area. The hot spots seem to appear where there is emulsified foamy oil, which behaves like a diffraction grating. This results in high emissivity and resolves the interrelated observation to an emissivity function. Thicker oil causes an apparent emissivity decrease and appears colder, whereas thin oil allows some penetration of the underlying water radiation and thus becomes a function of an oil/water combination. The exact relationship between oil thickness and infrared

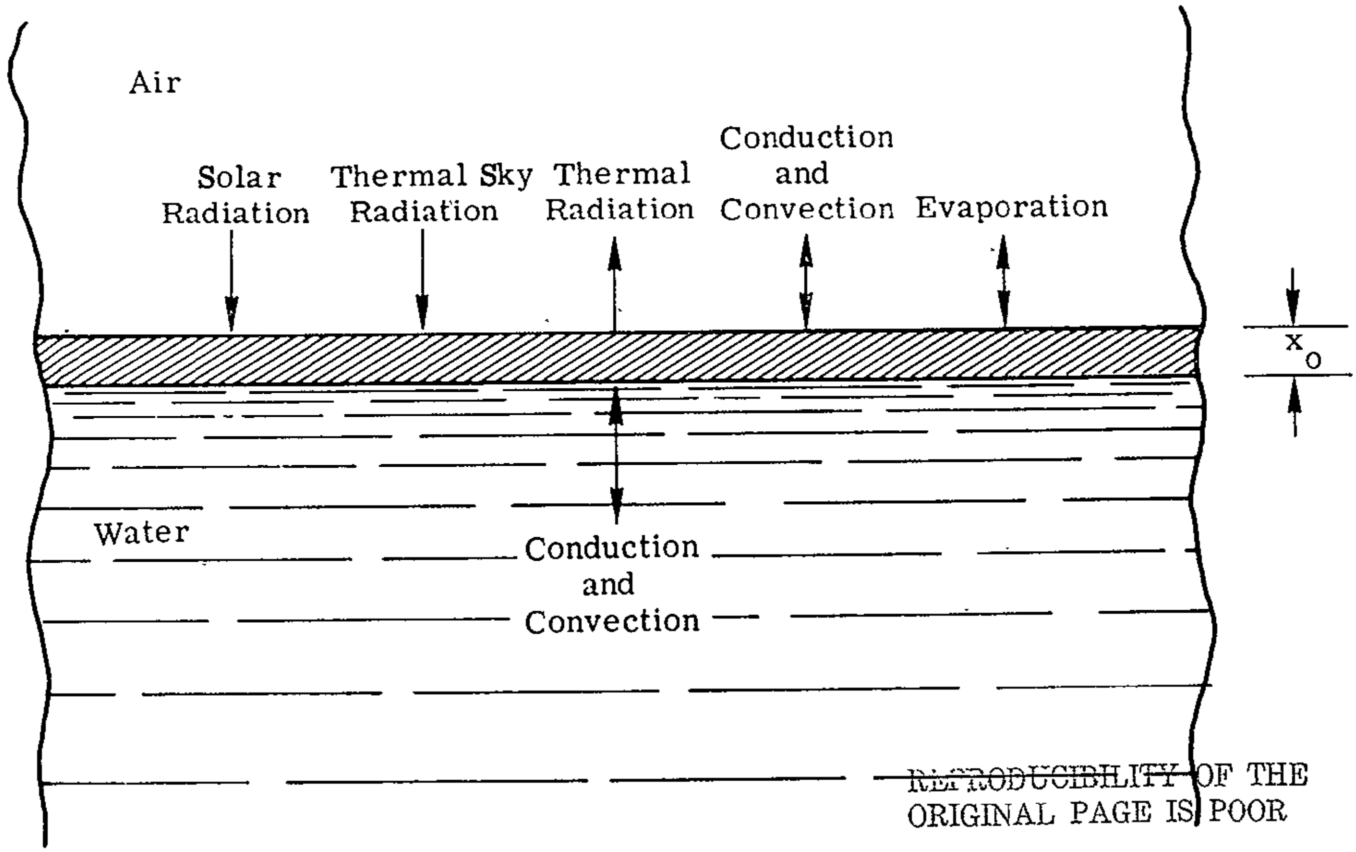


Figure 5. Thermodynamic Interactions for a Slab of Material on the Water Surface

temperature has not been quantified and indeed may be a function of oil type as indicated in Table 4.

It is clear from the preceding discussion that the complex interrelationships between oil and water, which affect radiometric temperature, are not fully understood. Nevertheless, the evidence found in the literature does indicate that measurements in the 8- to 14-μm region bear a relationship to oil thickness.

The problem of false alarms associated with thermal-infrared remote sensing of oil slicks can be significant. Natural waters can exhibit localized thermal responses from a variety of causes. River out falls, subsurface springs, and municipal or industrial discharges can all produce significant thermal anomalies in near shore areas, while upwellings from thermal structures and currents can result in significant thermal anomalies in off-shore areas. Many of these potential false alarms can, of course, be identified by spatial character or proximity to known sources. But, they can provide a confusing thermal background against which oil slick detection becomes more difficult.

A more important false alarm problem may be associated with vessel traffic. Because of the vertical stratification in water, the passage of a vessel often leaves a thermal anomaly in its wake from the upwelling subsurface water. Obviously, such a wake may exhibit the same kind of thermal signature as a continuous petroleum discharge from the vessel.

As was the case for reflective signatures, fish-oil slicks can be a false alarm for thermal remote sensing. Such slicks would probably exhibit signatures corresponding to petroleum of relatively low volatility and low solar absorption.

2.4 Microwave Region

Because microwave techniques have an adverse weather capability, a considerable amount of attention has been given to this approach. The signature mechanism to which a passive microwave receiver responds bears similarities to and subtle differences from those at the long and short optical wavelengths and radar. It will be necessary to detect the target slick against the natural, or background emission from the ocean.

The ocean surface is a dynamic, complex surface from which, as with all surfaces above absolute zero, microwave radiation is emitted. The basic equation[13] describing such emissions is given in terms of the radiometric brightness temperature of the ocean:

$$T_b = \epsilon T_w + RT_s = \epsilon T_w + (1 - \epsilon)T_s$$

where R is the reflectivity, ϵ is the emissivity of the ocean surface, T_w is the thermometric temperature of the water, and T_s is the temperature characterizing the sky radiance incident on the ocean surface. The quantities T_b, ϵ, and T_s depend upon the angle of observation, surface roughness, and whether the horizontal or vertical polarization is observed. In the above equation use has been made of the law of conservation of energy, and the assumption has been made that the surface is in equilibrium (the emitted and absorbed radiations are equal at the frequency of interest so that the absorptivity and the emissivity are interchangeable). It is known from theory as well as experimental observations that, for an uncontaminated sea, surface roughness increases the brightness temperature over that obtained for a smooth sea (Stogryn, 1967).[14] This is due to the fact that the emissivity of a rough surface is greater than that of a smooth surface of the same material at the same temperature.

Table 4. General Trend of Temperature Difference, $\Delta T_{o,w}$, between Oil Slick and Water for Various Conditions

			Environmental Conditions						
			Solar Irradiance	High	Low	High	Low	Low	Low
			Cloud Cover	None	None	None	None	Heavy	Heavy
Slick Characteristics			Water Evaporation	High	High	Low	Low	High	Low
Thermodynamic Character	Typical Products	Slick Thickness							
Volatile, Low Solar Absorption	Fuels, Very Light Crudes	Thin Thick		+ --	+ --	+ --	+ --	0 to + --	0 to - --
Volatile, High Solar Absorption	Most Crudes	Thin Medium Thick		+ - ++	+ - -	+ -- ++	+ -- --	0 to + - -	0 to - -- --
Nonvolatile, High Solar Absorption	Residuals, Very Heavy Crudes	Thin Thick		+ ++	+ +	+ ++	+ +	0 to + 0 to +	0 to - 0 to -
Nonvolatile, Low Solar Absorption	Light and Medium Lube Oils	All		+	+	+	+	0 to +	0 to -

Symbol		$\Delta T_{o,w}$ Trend
++	=	Strongly Positive
+	=	Slightly Positive
-	=	Slightly Negative
--	=	Strongly Negative

Oil slicks on the ocean surface affect the radiometric response in at least two important ways. First, the smoothing or damping effect of the oil reduces the sea surface roughness and emissivity, which results in a lower radiometric temperature. Second, the emissivity of oil is much greater than that of sea water. Oil films on flat or calm water surfaces tend to increase the emissivity of the surface and therefore the brightness temperature.

Laboratory measurements performed on petroleum pollutants indicate that:

1. The microwave signature of an oil film is inversely proportional to the sensor wavelength.
2. The horizontal polarized signature is twice the vertical polarized signature of an oil slick on a flat water surface.
3. All signatures are greater than calm water without oil.

In addition, the dielectric properties of the pollutants were measured at 0.8-cm wavelength using a precision ellipsometer (precision reflectometer). The real part of the dielectric constant for petroleum ranged from 1.85 to 2.41 as compared to 21 for sea water at 23° C. A slight increase in the real part of the dielectric constant and a large increase in the imaginary part were observed as the pollutants aged, as indicated in Figure 6. The ellipsometric measurements showed an almost linear increase in the dielectric constant for crude oils with decreasing API gravity.

Airborne measurements using dual polarized radiometers operating at 0.3- and 0.81-cm wavelengths at a depression angle of 45° tended to confirm laboratory measurements. Also, it was determined that: (1) time of day and age of oil

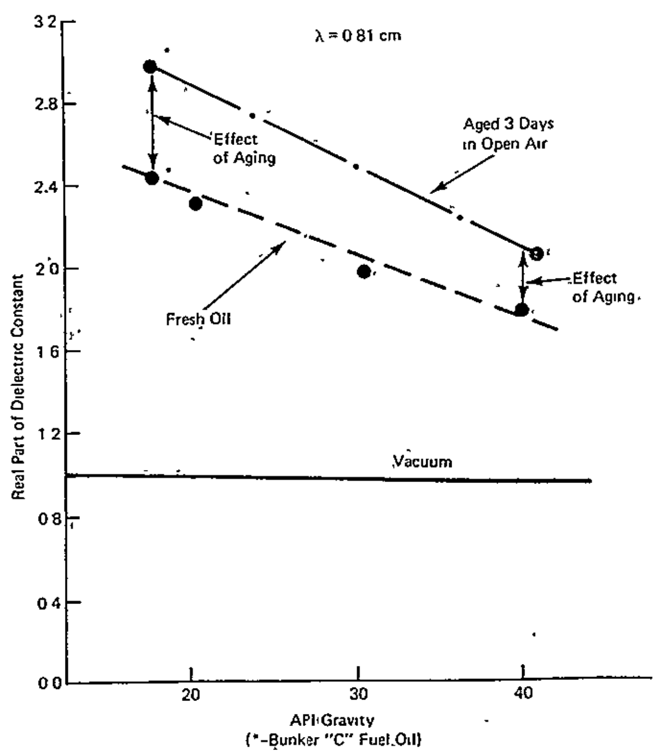
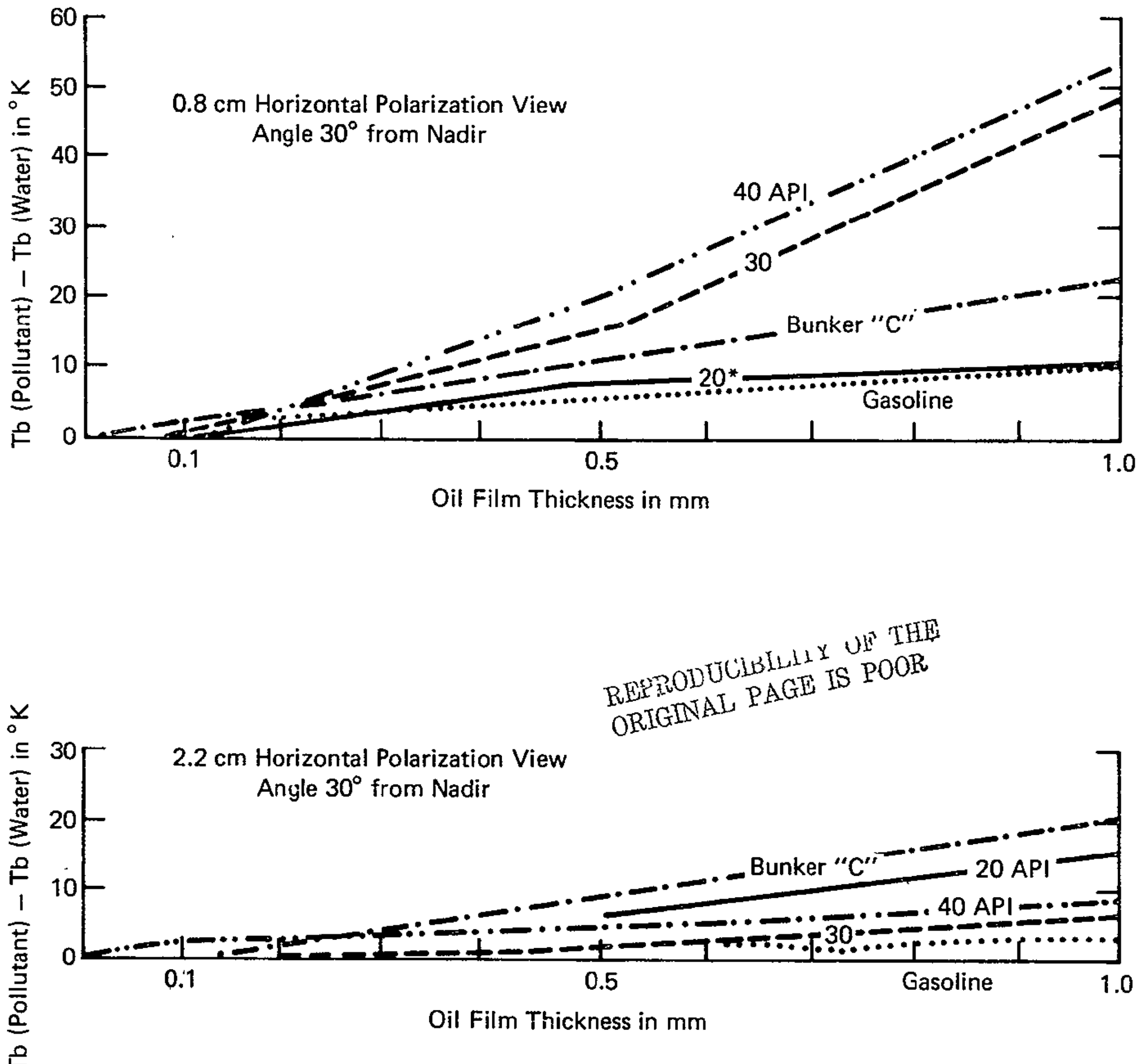


Figure 6. API Gravity versus Real Part of Dielectric Constant

have only small effects on the radiometric response; (2) detection improves with decreasing sensor wavelength; and (3) at high sea states, i.e., greater than sea state 3, it becomes increasingly difficult to detect oil against a sea background.[15,16]

Passive microwave remote sensing techniques are not only being used to detect oil slicks, but also to estimate slick thickness and areal extent, and hence, the volume of oil spilled. Currently, Hollinger[17] has conducted experiments using dual frequency microwave techniques to determine oil thickness (see Figure 7). This approach is based upon the fact that as the thickness of an oil slick is increased through successive integral multiples of a quarter wavelength, the brightness temperature passes through alternating maxima and minima. This behavior is shown in Figure 8, where the microwave brightness temperature of a slick, calculated for five selected frequencies, is plotted versus slick thickness. The first maximum occurs at progressively smaller thickness and the spacing of the maxima decreases as the frequency is increased. Because of the interference fringes, the same brightness temperature results from a series of oil slick thicknesses. By making observations at two or more frequencies, these ambiguities can be removed and a unique thickness determined as indicated in Figure 9. In addition to resolving ambiguities, multifrequency measurements will provide redundant information and greatly enhance the accuracy of the thickness determination. Further, for thicker slicks, the use at several frequencies may enable the dielectric constant of the slick to be estimated, and thus some information about the identity and nature of the slick material may be obtained.



*Low values may be due to non-uniform distribution of oil

Figure 7. Brightness Temperature of Oil for 0.8- and 2.2-cm Horizontal Polarization as a Function of Thickness

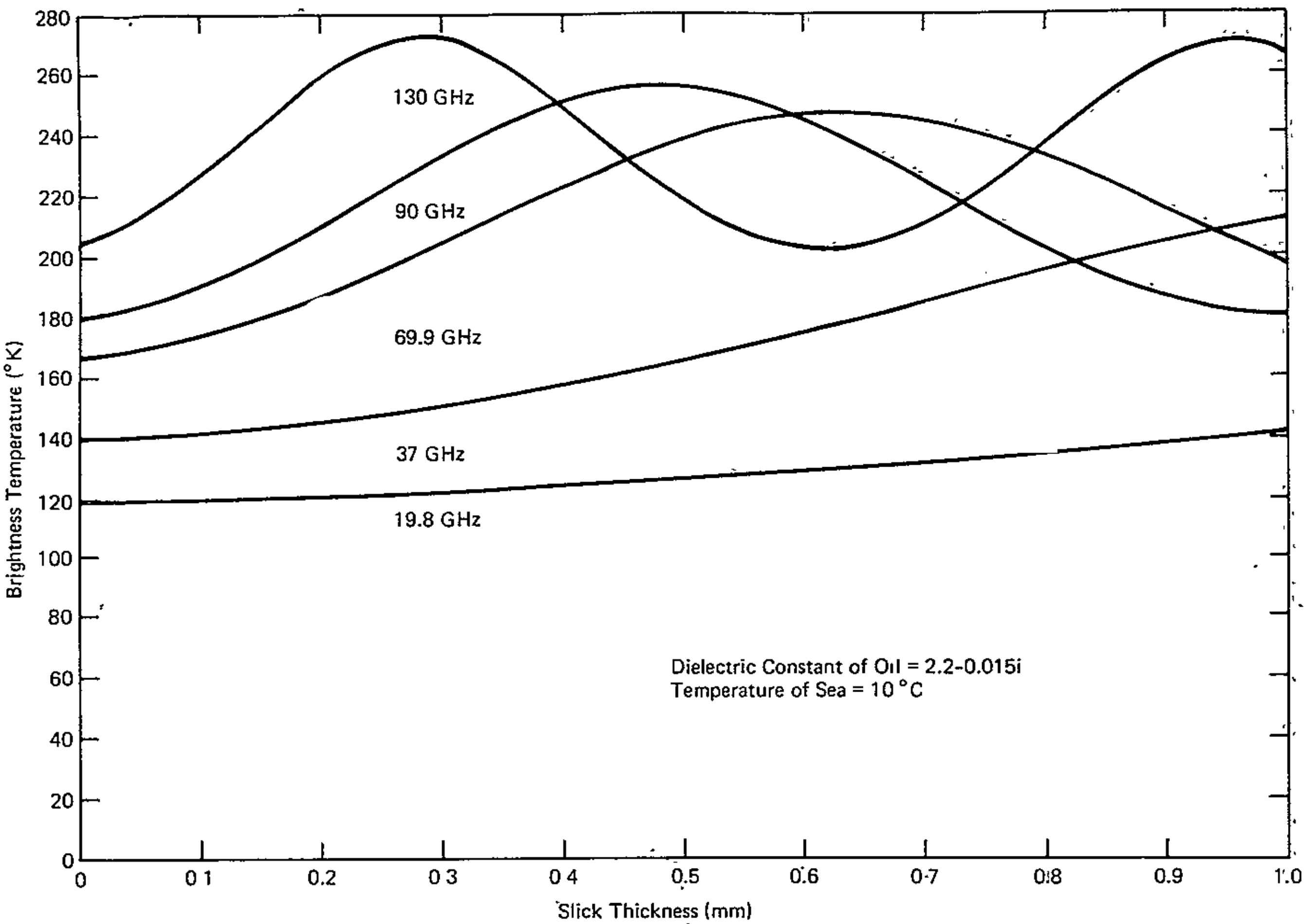


Figure 8 Microwave Brightness Temperature of Oil Slick Covered Sea Surface

In the microwave region the problem with false alarms is not as significant as it is in the ultraviolet, visible, and infrared portions of the electromagnetic spectrum. Microwave techniques have the capability of operating on a 24-hr basis; and hence, offer an important operating advantage in this regard. Additionally, microwave techniques are less affected by inclement weather than other techniques discussed thus far.

As indicated previously, oil signatures on water are greater than calm water without oil. However, this anomaly, which makes oil appear warmer than sea water, decreases substantially as the surface roughness increases. This is due to the fact that as the ocean roughness increases, its effective emissivity increases; thus, the apparent temperature contrast between oil and water decreases and becomes vanishingly small. For slicks whose thickness is less than 10 microns (films formed by many petroleum products are often less than 10 microns), it is questionable if one can detect them using sensors whose frequency response is less than 35 GHz. By going to 3 mm (94 GHz) this requirement for thin slick detection using a single frequency may be satisfied. However, atmospheric interference problems will substantially decrease its effectiveness as a detection tool. Clouds that are raining, or whose water droplet size approximates the observation wavelength, seriously hamper the effectiveness of this method for oil slick detection.

In the case of the multifrequency microwave techniques, sea surface roughness will affect the apparent temperature of the sea and of the oil slick in the manner indicated above. The oil slick will reduce the mean square slope of the surface by a factor of two, or so; and lower the apparent temperature in the region of the slick as compared to the unpolluted adjacent sea. Variations in slick thickness over the region of the slick will occur due to emulsification and puddling in the wave troughs. The effect will depend upon the range of thickness, sea roughness, age of the spill, and spatial extent of the puddling with respect to the spatial resolution of the radiometer. Corrections to an average measured thickness will have to be made. Puddling will tend to raise the average brightness temperature measured and allow slicks to be measured which might be undetectable in the absence of puddling.

2.4 Radar Region

The physical phenomenon that makes an oil slick visible on radar imagery maps is the damping effect that oil has on water waves. The short gravity-capillary waves that are superimposed on larger waves act as the predominant backscatterers. The oil's damping effect on these waves appreciably reduces the amount of energy being backscattered. In contrast to this, the surrounding oil-free areas continue to act as relatively good backscatterers. Consequently, the oil-covered areas appear dark since very little energy is being returned, while open areas appear as grainy grey-white sea return.

The Naval Research Laboratory[18] in 1970 conducted several experiments on detecting and mapping oil slicks, using the NRL four-frequency dual polarized radar system.

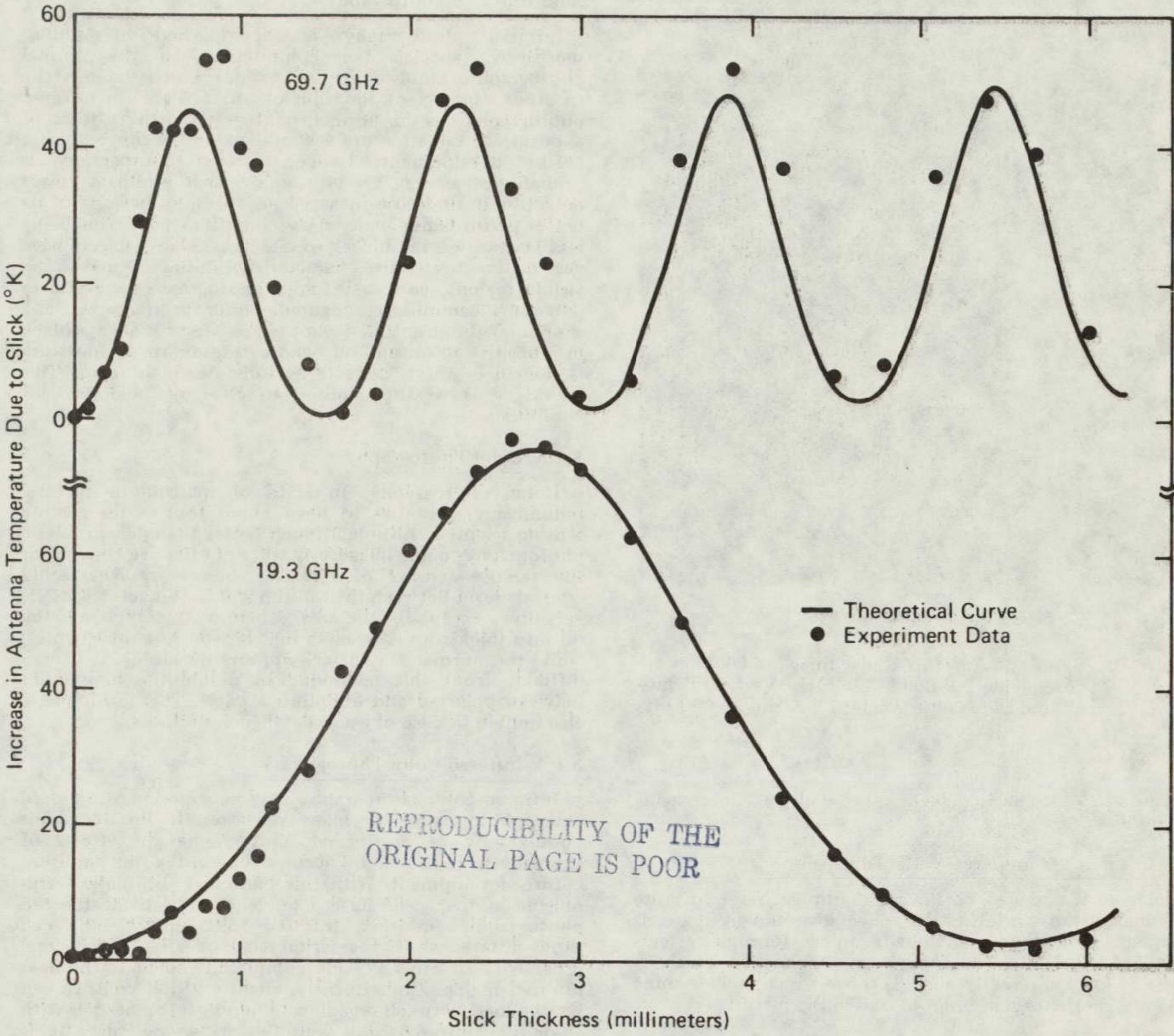


Figure 9. Results of Runway Laboratory Oil Tank Tests for No. 2 Fuel Oil

The four-frequency system is basically four different pulsed coherent radars transmitting at P-band/UHF (428 MHz), L-band (1228 MHz), C-band (4455 MHz), and X-band (8910 MHz) with approximately 25 kilowatts of peak power. Each of the four transmitters is designed to operate with two antennas, one polarized horizontally and one vertically, either separated or pulsed in rapid succession to provide a total of eight different frequency polarization combinations.

There are eight distinct transmissions from the four-frequency radar system, which result in 16 different frequency polarization combinations in the return. This is because the ocean roughness acts as a depolarizer and converts some of the incident vertically polarized energy return to horizontal and vice versa. Each of the signal returns has amplitude and phase information. For the production of a Synthetic Aperture Radar (SAR) image, however, only the phase of the return is required. The phase data are recorded on film from a cathode ray tube for later optical processing from which the SAR imagery is generated.

The tests performed with four-frequency radar indicated that it is possible to map the oil slicks in the vertical polarization, while the horizontal polarization is not responsive. In the vertical polarization (VV) the presence of oil on the synthetic aperture radar imagery is represented by a dark nonreflecting area, as shown in Figure 10. This can be attributed to the fact that within the oil areas, the capillary waves which are required for backscatter are being damped.[16] However, the horizontal polarization (HH) and the cross-polarized components give no indication of oil. This lack of apparent oil detection by the horizontal (HH) and the cross-polarized components (HV, VH) is not a characteristic of the oil slick as might be thought, but rather a characteristic of slightly rough surfaces viewed at shallow angles. Under such conditions, the horizontally polarized radar cross section (RCS) is much smaller (−20 db) than the vertically polarized RCS, and the cross-polarized RCS is even smaller.

3. Remote Sensing Techniques

The remote sensing techniques applicable to the oil pollution problem can be divided into two broad

Figure 10. Synthetic Aperture Radar Image of Oil Slick (Frequency: P-Band (428 MHz; Vertical Polarization; Depression Angle: 7° ; Altitude: 2000 ft)

categories: (1) imaging techniques and (2) nonimaging techniques.

3.1 Imaging Techniques (Spatial Dimension)

Imaging techniques, as the name implies, refer to those techniques whose information collected over a given area is displayed as a picture. Generally, image forming systems can be divided into two categories: (1) those in which an image is formed directly and (2) those which include some scanning mechanism in order to obtain the picture.

In the first category, photography is probably the most widely used technique. In this process light coming from an object focused upon a photosensitive surface causes a chemical reaction on the film. By developing the exposed film, the formed image can be recovered.

In the second category we have the scanners, or imagers. These devices are generally characterized by having the sensor electronically or mechanically scan one line at a time with a one-to-one correspondence existing between the resultant image and the scene viewed.

3.1.1 Panchromatic Photography

Panchromatic photography is a widely used technique because of its availability, relatively low cost, and high information content. The technique is well developed and it is widely used for mapping. However, standard panchromatic minus blue photography does not lend itself well to resolving the extent of an oil slick. The ability to resolve oil against a water background occurs only where a favorable sun angle accentuates the reflectance from the oil. Even where present, oil reflectance is difficult to distinguish from sun glitter on oil-free waters. This is especially true on alternately choppy and smooth sea surfaces. This technique is limited to fair weather daylight use.

3.1.2 Infrared Photography

Infrared photography is accomplished by adding sensitizers (special dye compounds) to the normal photographic emulsion (silver halide) which extends the spectral response of the film out to 1.2 μm. In infrared photography, as in normal photography, the effects of exposure to radiation are accumulated in the film emulsion before development. Hence, infrared photography is primarily an energy detector, rather than a radiant power detector. It finds use in aerial photography because of its better performance under hazy conditions, scattering being less because of the longer wavelengths. Many objects have very different reflective characteristics in the infrared to the visible regions, and so infrared photography is useful in detecting camouflage, mapping drainage features, and shorelines. In an infrared photograph water is always black in a positive print, and oil, whose radiometric temperature is less than water, appears as some shade of gray. This technique is weather limited to clear sky and daylight conditions.

3.1.3 Color Photography

Color photography, in spite of its built-in spectral redundancy, promises to be a major tool of the remote sensing scientist. Although much better than panchromatic photography, color imagery is still not effective enough for the remote sensing of oil. The object to background contrast level between the oil film and the adjacent water is very low, except for the areas where wave action rolls the oil into thick ropy streamers that register as a bluish color, while the normal sea surface appears dark blue. It is very difficult from this technique to define the boundaries between polluted and unpolluted water. This technique is also limited to clear sky and daylight conditions.

3.1.4 Infrared Color Photography

Infrared color photography may be superior to standard color photography for many purposes. In infrared color photography as in normal photography the effects of exposure to radiation are accumulated in the film emulsion before development. With this particular technique warm objects in the scene have a tendency to activate the red photographic emulsion. Infrared color photography can show differences in vegetation vigor clearly. The general reflectivity of most organic compounds occur in the near infrared region. Consequently, slightly higher contrast can be obtained between organic and nonorganic materials with color film. Infrared color is useful for "seeing" alien fluids in water. For example, oil on water would show up as a pink or red object against a blue background. This technique is limited to fair weather daylight conditions.

3.1.5 Multispectral Photography

Multispectral photography is commonly used with nine-lens cameras, or clusters of lesser numbers of small cameras. The spectral response of the camera cluster is defined by the spectral characteristics of the filter and film combination. Interpretation of multispectral photography requires information on the spectral signature of both the target and the background water features. Information needed to interpret multispectral photography has only been partially developed at this time. Data returns from some of the systems are voluminous and cannot be readily interpreted by conventional means. As with all photographic techniques, this approach is weather limited, i.e., operates effectively only during clear sky and daylight conditions.

3.1.6 Ultraviolet Imagery

Ultraviolet imagery techniques are based upon ultraviolet reflectance and fluorescence properties of objects. Reflectance contrasts among many natural objects are commonly greater in the ultraviolet than in the visible part of the spectrum. Oil on water may be detected, since oil reflects strongly when exposed to broadband ultraviolet irradiation, as shown in Figure 11a. In addition to reflecting the ultraviolet radiation, the part of the radiation that is absorbed and reemitted by the oil is said to fluoresce. The oil emits considerable blue light along with the ultraviolet, which can be detected by ultraviolet sensitive film (0.375 to 0.525 μm). This technique is limited to clear sky and daylight conditions.

3.1.7 Infrared Imagery

Infrared imagery has shown its value as a tool for measuring the apparent surface temperature difference. Because the emittance differences between oil and water are the greatest in the 8- to 14-μm region, a considerable amount of attention has been given to instruments that operate in this region. A number of 8- to 14-μm infrared scanners are currently available from commercial sources. Monitoring in the 8- to 14-μm region will normally define the area spread of the oil, as shown in Figure 11d (which is restricted to 9.3 to 11.7 μm), and provide radiometric temperature data which are related to oil thickness.

Infrared imaging techniques are weather limited, i.e., the slightest amount of water vapor or dust can attenuate the signals rapidly below the levels of detectability.

3.1.8 Multispectral, Optical-Mechanical Scanner Imagery

Multispectral, optical-mechanical scanners permit one to search for a spectral band or combination of bands wherein objects of interest exhibit the greatest contrast or differentiation. The spectral characteristics of each channel are determined by the filter transmission and detector response associated with the channel. (In general the multispectral scanner permits data to be acquired throughout a broader band of the spectrum (0.3 to 16 μm) than photographic systems.) Data can be acquired simultaneously on 10 or more channels. The resulting high data rates require the use of automatic data processing techniques. Such systems have been used to automatically survey distribution of water, to determine various pollutant distributions in water, agriculture crops, rock types, houses, and other cultural features. Automatically processed multispectral data hold high promise of aiding in water pollution detection and in land use surveys. This technique is weather limited and effective operation is hampered somewhat during the daylight due to solar reflection.

3.1.9 Radar

The use of radar for oil spill detection has been demonstrated by NRL.[16] Radar is a particularly good sensor because it is relatively unaffected by fog, haze, or moderate rainfalls. It can survey large areas in a relatively short time, and provide excellent contrast between the sea and the oil slick.

In general, there are two basic approaches for developing the specifications for radar systems that are optimally capable of monitoring oil slicks. The first is by utilizing Real Aperture Radar (RAR) operating in the forward or sidelooking scan mode. The second involves the use of Synthetic Aperture Radar (SAR) operating in the sidelooking mode. The trade-offs between these systems are basically as follows: antenna size, transmitter power, ease of processing, geometric fidelity, detection efficiency, coverage (swath width), and cost effectiveness. For RAR, the resolution along the track is dependent on antenna dimension, i.e., higher resolution requires larger antenna. The transmitter requires more power than SAR for a given signal-to-noise ratio (S/N). Real-time imagery is possible, and the resolution element size increases with increasing altitude. At altitudes up to 12,000 ft, the radar should be capable of detecting slicks, and the swath width of the radar should be greater than 30 miles. In general, RAR is more cost effective than SAR for short-range low coverage missions, such as those associated with policing limited coastal areas, such as shipping lanes, harbors, bays, etc.

For SAR, it needs less real aperture coverage for resolution. The transmitter normally requires less power than RAR. Real-time imagery is not presently possible, some optical process is required; however, recent advances in digital processing techniques, using charged coupled devices (CCD) show promise of providing near-real-time imagery.[19] For SAR, the resolution element is constant and independent of altitude. At an altitude approaching 35,000 ft this type of radar should be capable of detecting oil slicks over a 100- to 150-mile swath. SAR is more cost effective than RAR for long-range, high area coverage missions.

There is a strong functional relationship between the incident radar frequency, the sea state, and the thickness of the oil film. Although there are insufficient data to define the relationship, the observed trends indicate that thin films (~ 1 micron) are best detected in low sea states (10-knot winds and less) by low frequency transmission, while there is some indication that thick films may be best detected in high sea states by higher frequency transmission.

3.1.10 Passive Microwave Imagery

Passive microwave imagery records the energy emitted from the earth in the radio frequency region. The amount of energy emitted by an object depends on the temperature of the object and its emissivity. This technique is useful for mapping soil moisture distributions as well as oil slicks on the open ocean. In the microwave region oil slicks appear warmer than the surrounding ocean except at high sea states. Like radar, a microwave imager has the ability to penetrate fog and clouds, and monitor, on a 24-hr basis; and hence it offers an important operating advantage in this regard.

3.2 Nonimaging Techniques (Spectral Dimension)

Systems that make use of the spectral dimension are nonimaging in the conventional sense. They include spectrometers, radiometers, and interferometers which are designed to passively receive energy from relatively stationary objects for the purpose of making measurement of its spectral energy. Commonly, these systems are more easily calibrated than imaging systems and make useful adjuncts to images. Unlike the imagers, instead of generating a series of continuous scan lines perpendicular to the direction of flight of the remote platform which can be converted into an image, these devices are characterized by a fixed look angle which generates a line trace in the direction of motion of the platform. The following is a description of those nonimaging techniques under study.

3.2.1 Infrared Radiometry

Infrared radiometry is very useful for making sequential measurements of changes in land and water surface temperatures. Because it is a simple measurement technique, the data reduction process associated with this type of data is simpler than that for infrared imagery. Some of the infrared radiometer systems use multiwavelength arrays. Currently, radiometry is routinely used for periodic radiant temperature surveys of near oceanic areas. The thermal anomalies that exist between oil covered water and unpolluted water can be detected readily by this instrument. These data are commonly recorded on conventional strip charts.

3.2.2 Infrared Spectral Radiometry

Infrared spectral radiometry measurements are made with spectrometers, interferometers, and filter wheel

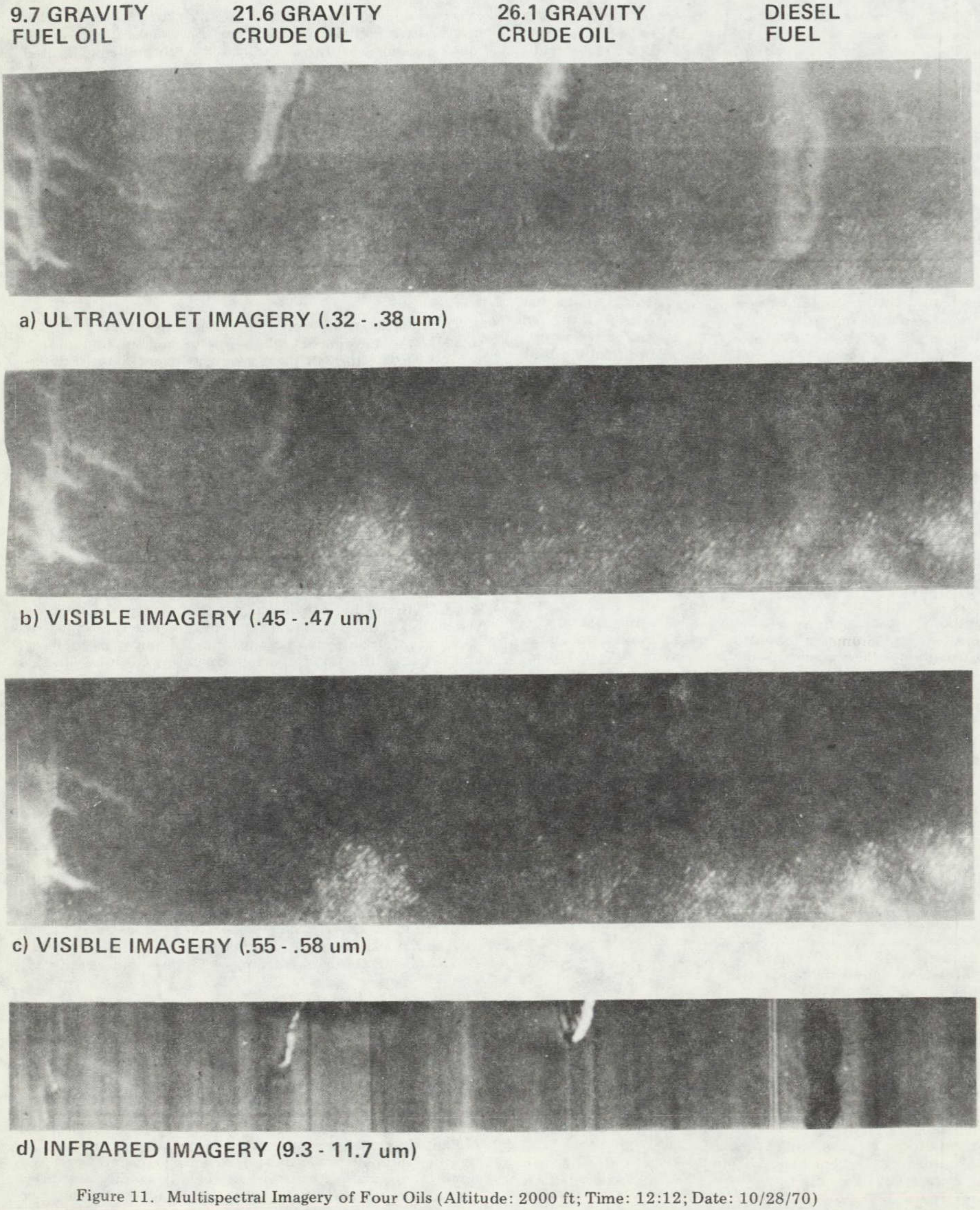


Figure 11. Multispectral Imagery of Four Oils (Altitude: 2000 ft; Time: 12:12; Date: 10/28/70)

radiometers. Observations have meaning with respect to plant, rock composition, apparent surface temperatures, and possible water pollution. Wavelengths observed using these techniques are from 1 to 16 μm. As indicated in Section 2, the signature properties of oil in the near infrared (0.6 to 1.1 μm) and in the far infrared (8 to 14 μm) are rather significant. Computer-stored libraries of "spectral signatures" are being compiled by such groups as Purdue University[20] and the University of Michigan.[21] Some of the representative systems in this area have a field of view of 1° or less, and an integration time of 1/16 of a second or less.

3.2.3 Passive Radiometry

The feasibility of using radiometry for the detection of oil pollution was investigated by the Geosciences Group, Microwave Division of Aerojet-General Corporation.

The investigation consisted of a series of laboratory and field measurements. The major conclusions resulting from this program were as follows:

1. The ability to detect oil film using microwave radiometry is inversely proportional to sensor wavelength.
2. Minimum detectable oil film thickness using a dual-polarized 0.81-cm radiometer appears to be in the range of 10 to 20 microns under sea conditions.
3. The roughness of the ocean surface affects the microwave signature.
4. Microwave radiometers for oil pollution detection must operate at wavelengths of 8 mm or less. Larger wavelength radiometers appear to be too insensitive to be useful for oil pollution monitoring.

The results of the above investigation demonstrate that microwave radiometry could be used for oil pollution monitoring. Microwave radiometers have the capability of operating on a 24-hr basis under adverse weather conditions.

3.2.4 Fraunhofer Line Discriminator (FLD)

The experimental Fraunhofer line discriminator, developed by the U.S. Geological Survey in collaboration with the Perkin-Elmer Corporation, appears to have the potential for detecting and monitoring a wide range of fluorescent pollutants, including oils.[22,23,24] The first FLD was designed to operate at the sodium D_2 line (5890 A) and has been used as an airborne fluorometer to monitor Rhodamine WT dye in aqueous solutions. The success of these experiments indicates that a fully developed FLD may have the potential for monitoring oil slicks.

The fluorescence peaks of the various oils range from approximately 0.4 to 0.7 μm. The fluorescence emission spectra of many crude oils, such as Santa Barbara crude and Wilmington crude, have fluorescence peaks at 0.5 μm.

The FLD is undoubtedly a very important instrument, which has great potential for detecting and measuring a variety of substances in an aquatic environment. However, examining the instrument concept from the standpoint of surveillance capability, the following characteristics are noted:

1. The techniques appear to be limited to operation on clear sunny days.
2. The record from the FLD is a line trace along the flight path.

Although the second of the above mentioned characteristics cannot be labelled as a serious limitation of the FLD, it does mean that the FLD cannot provide the two-dimensional view of an oil slick which is usually desired; and therefore, a large number of transects would normally be required to define the limits of an oil slick.

3.2.5 Barringer Correlation Spectrometer

The operation of the Barringer correlation spectrometer is based upon the concept of detecting and identifying substances through an analysis of its vapors, i.e., gases liberated by the substance. The substances are identified on the basis of their absorption or emission characteristics. Most liquids generally have a sufficiently high vapor pressure for appreciable quantities of vapor emitted in the immediate vicinity of the liquid. This is certainly true of fresh oil spills and other petroleum products.

The results of studies dealing with the optical characteristics of several fish oils, together with a diesel fuel oil and SAE 20 lube oil have been reported. Important spectral differences were noted in the 8- to 14-μm region between halibut liver- oil and diesel. Likewise, equally significant differences were noted in the same spectral region between sardine oil and SAE 20 motor oil.

Barringer indicated that the sensitivity for freshly formed slicks will be very much higher than those which have been exposed for a few hours.[25] The determination of the full potential of this technique for oil pollution monitoring will require additional field studies. The ability of this technique to monitor a variety of oils and petroleum products, under varying atmospheric and sea state conditions, is presently undefined.

3.2.6 Widerange Image Spectrophotometer (WISP)

The widerange image spectrophotometer is an airborne spectrophotometer which measures the spectral distribution of upwelling light from water. The spectral range of the instrument is from 0.4 to 0.7 μm. In order for this system to detect oil slicks on water it must operate in the red region of the spectrum to obtain maximum contrast, as indicated in Figure 12. In Figure 13 the spectral reflectivity curves from sea water and an oil layer are given.

An inspection of Figures 12 and 13 indicates that the optimum operating range for this instrument, when used for oil detection, appears to be in the area of 0.6 to 0.65

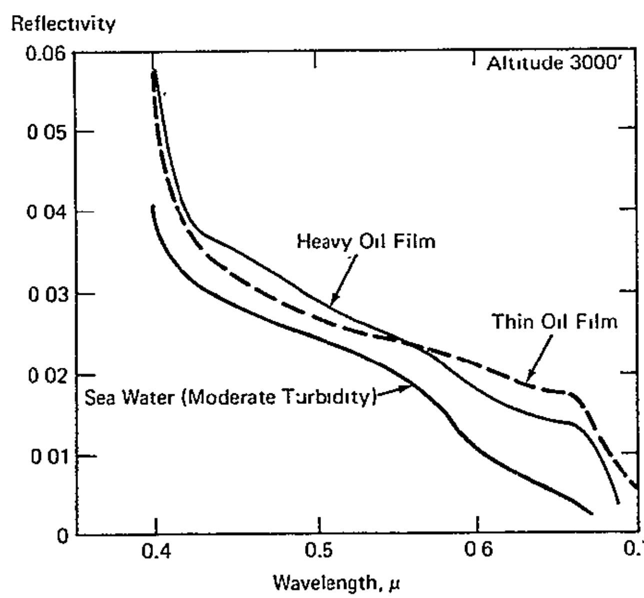


Figure 12. Spectral Reflectivity of Sea Water with and without an Oil Film

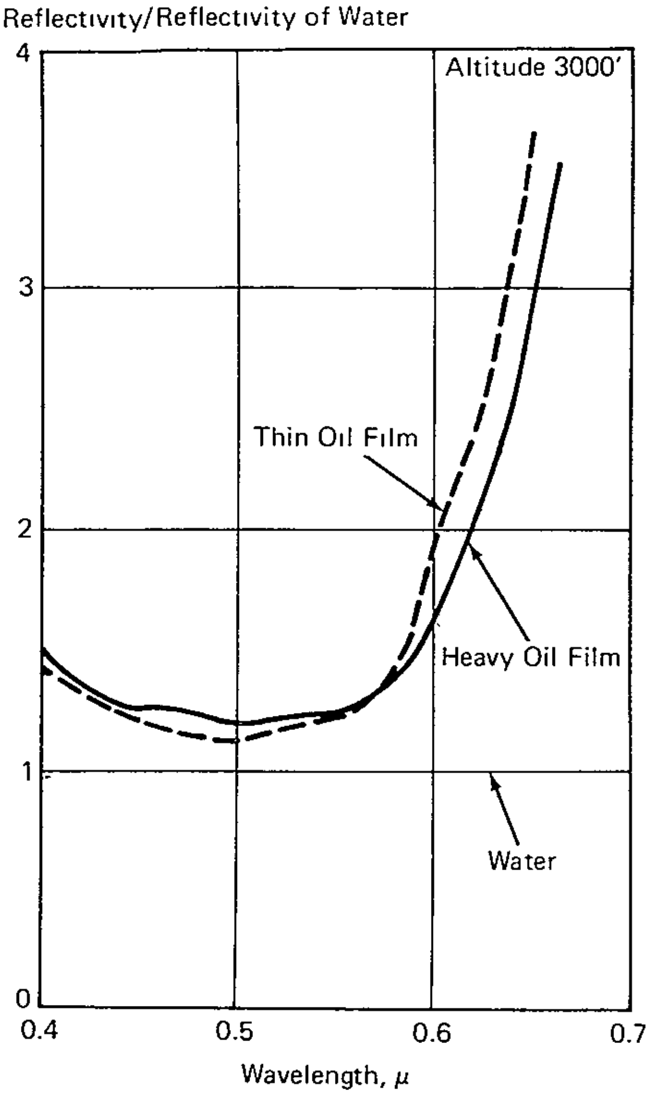


Figure 13. Reflectivity Ratio of Oil-Covered Sea Water to Normal Sea Water

μm. However, film thickness and oil type have an important bearing on the reflectivity; therefore, the relationships shown in Figures 12 and 13 must be regarded simply as the results observed for one set of conditions.

Efforts to detect thin oil films in the visible region of the spectrum have been less successful than techniques operating outside the visible spectrum. The results obtained to date with the WISP are impressive; however, serious doubts exist concerning the ability of any device which operates in the visible spectrum to detect the wide spectrum of soil pollutants, ranging from crude oil to refined petroleum products, under a variety of environmental conditions.

4. Oil Pollution System Considerations

Some of the factors that go into the development of the optimum system concept for oil detection, monitoring and law enforcement are given in Figure 14. The factors are the remote sensor characteristics, operational constraints, law enforcement requirements, and cost effectiveness.

4.1 Remote Sensor Characteristics

In Sections 2 and 3, the signature characteristics of oil slicks along with the general performance characteristics of remote sensing techniques useful for the mission of detecting and monitoring oil pollution are given. From the information supplied it is possible not only to specify the signature properties of oil in the ultraviolet, visible, infrared, and microwave portions of the electromagnetic spectrum, but also to detect and map the areal extent of the slick. All techniques show some variations with thickness; however, the exact relationships cannot be defined. Only the dual frequency microwave techniques show promise of alleviating this problem. Both microwave and radar techniques are capable of operating in adverse weather, whereas the other techniques considered are weather limited.

The fluorescence techniques show promise in identifying oil types. Also, the ultraviolet, visible, and infrared regions suffer from false alarm problems. This false alarm problem is substantially reduced in the microwave and radar regions. No one sensor can do the job; therefore, a multispectral system incorporating many of the operational techniques discussed in this report will be required to detect oil, map its distribution, estimate its film thickness. and characterize the oil type of the pollutant.

4.2 Operational Constraints and Law Enforcement Requirements

The Federal Water Pollution Control Act as amended by the Federal Water Pollution Control Act Amendments of 1972 (33 U.S.C. 1251 et. seq.) and Executive Order 11735 set forth the responsibility and enforcement authority for the protection of the marine environment from discharges of oil and other hazardous substances. Antipollution countermeasures and law enforcement can be improved significantly by developing an airborne oil surveillance system which will provide effective surveillance of large coastal areas independent of time of day and weather conditions.

Due to the nature of the Coast Guard problem, the following requirements exist:

Rapid Area Coverage: Effective utilization of personnel and equipment resources requires efficiency of operation. Costs for any program are directly related to the number of systems or people involved, and the time during which they operate. Thus, since the total surveillance area is usually fixed, rapid coverage implies fewer systems and fewer people to accomplish a given objective. In addition, much of the preventive impact of any law enforcement operation comes from the visibility of the enforcer, which in turn is proportional to mobility.

Reliable Detection, Identification, and False Target Rejection: Rapid area coverage leads to operational efficiency only if the probability of missed-detection is small. In addition, once an anomaly is detected, rapid identification as an oil slick or rejection as a false target must be accomplished so that unnecessary departures from the rapid coverage search profile are minimized.

Real-Time Display and Alarm: Due to the nonstationary nature of oil slicks, immediate determination of their presence is required. A time lapse of even a few hours can preclude relocation because of slick movement or dissipation. Of equal importance, the law enforcement aspect of the program rests strongly on tying a slick and its source together both spatially and temporally. Finally, direction of cleanup or damage prevention activities requires real-time coordination.

Oil Slick Size Determination: The size of an oil slick is important from a legal standpoint since, under some circumstances, limited discharges by vessels are allowable. Additionally, cleanup and damage prevention efforts must be coordinated to the areal extent of the slick in question. Finally, under some conditions such as congested harbors or sea lanes, an operational decision as to whether a

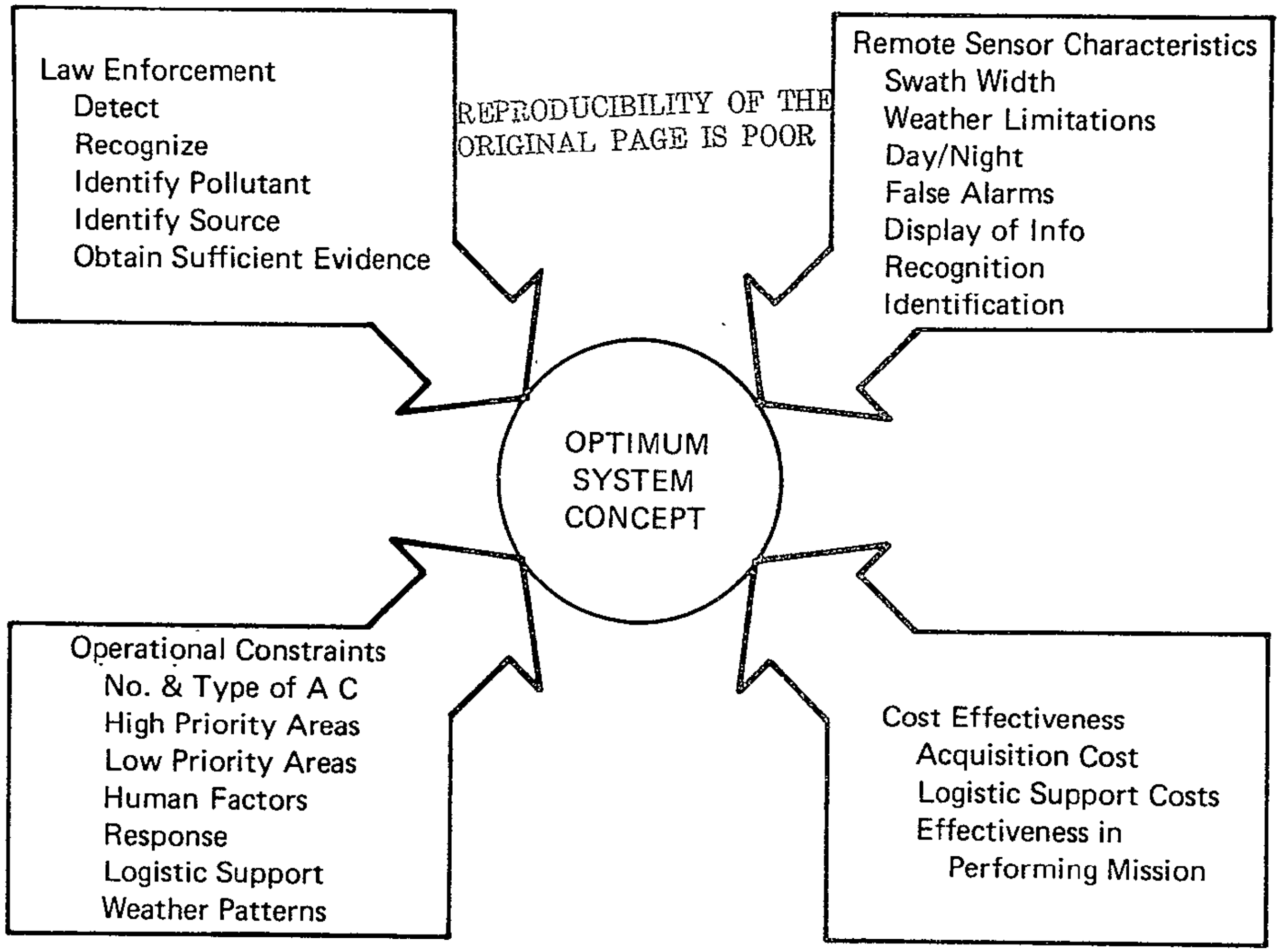


Figure 14. Optimum System Configuration Concept Strategy

particular slick is large enough to be worth attention may be required.

Permanent Record of Spill: The law enforcement aspect of the Coast Guard mission requires a permanent and reproducible record of the occurrence of the slick, its position, and the time of occurrence, and identification of the polluter.

In Table 5,[26] a comparison of the system requirements for law enforcement and pollution countermeasures missions are given. In general, the pollution countermeasures missions dictate real-time oil spill mapping capability over the widest possible range of weather and ocean surface conditions—the prime criterion being the ability of the system to assess spills whenever and wherever they occur.[27] The law enforcement mission requires a spill detection and identification capability with prime design being large swath, and the ability to detect small spills, to discriminate spills from false targets, and to identify the spiller. The system requirements dictated by the operational consideration are given in Table 6. This table summarizes the system implications and specific design constraints imposed by operational factors such as prevailing conditions, definitions of surveillance zones, patrol frequencies, etc.

4.3 Law Enforcement

With the passage of the Federal Water Pollution Control Act Amendments of 1972, the Department of Transportation through the U.S. Coast Guard, was assigned a major role with regard to the pollution of coastal and navigable inland waterways. The response actions to oil spills, or pollution incidents fell into five distinct areas, which are:

1. Discovery and Notification: Discovery may be through deliberate procedures such as aircraft searches and vessel patrols, or through random discoveries by pleasure boats, police, etc. Notification to Regional Response Center is required. (Failure of a polluter to notify is an infraction of the law.)
2. Containment and Countermeasures: Containment is accomplished by a variety of means, e.g., booms or barriers, etc.
3. Cleanup and Disposal: Actions to collect oil through use of sorbents, skimmers, and removal of beach sand.
4. Restoration: Action to restore to prespill conditions.
5. Recovery of Damages and Enforcement: A variety of activities are considered depending on the circumstances. One such activity includes the recovery of the costs for cleanup through the exercise of appropriate authority vested in numerous Federal, State, and local statutes and ordinances. The collection of scientific and technical information of value to the scientific community as a basis for research and development activities and for enhancement of our understanding of the environment is also considered here.

Table 5. Oil Pollution Surveillance Mission Analysis

MISSION	RELATIVE IMPORTANCE	PROBLEM ELEMENT	SYSTEM IMPLICATIONS	SPECIFIC DESIGN CONSTRAINTS
COUNTERMEASURES • Reaction to Major Oil Spills • Obtain Basic Data for Initiating Counter-measures (Clean-Up) Operations	Must Be Established Based on Analysis of Coast Guard Mission Requirements and Analysis of Surveillance System Expectations	SHIPS • Spills Generally Accidental (Collisions, Equipment Failures, Judgement Errors) • More Frequent in Adverse Weather • Random in Time • Random in Precise Location but Concentrated in Areas of High Ship Density OFFSHORE OIL ACTIVITIES • Stem From Equipment Failures, and Judgement Errors • Random in Time Location Known	• Rapid Reaction Critical To Minimize Damage to Property and Environment	• System Readiness Important. Must Be Exercised Extensively
			• Ability To React Anytime, Under any Weather or Ocean Surface Condition Important	• Adverse Weather Operation – Microwave Sensors Essential – Ku-Band (35 GHz) Radar Eliminated in Heavy Fog and Clouds – Passive Imagers Above 37 GHz Eliminated – X-Band (8-10 GHz) Radar Eliminated Under Low Wind (<10 Knots) Conditions Which Occur >40% of Time – C Band (4.5 GHz) Radar Best All Weather Choice
			• Spill Location Will Be Approximately Known (Assuming Spill Is Reported)	• Requirement for Wide Swath With High Spatial Resolution Relaxed. No Alarm Required • Real Aperture Radars and Passive Imagers Adequate
			• Area Mapping in Real or Near-Real Time	• Requires Real Time Position Referenced Display and Near-Real Time Hard Copy
			• Mission Place Infrequent but Intensive Demands on Aircraft System and Personnel	• High System Reliability Essential. Cost of Operation Not Critical Factor
LAW ENFORCEMENT • Reaction to International and Unreported (Minor) Accidental Spills		SHIPS • Pumping Bilges, Ballast Washing Tanks • More Frequent in Adverse Weather and Darkness • Generally Small! – Minimum Size ≳ 100 Ft X Several Hundred Ft. (Ship Underway) • Ship Density Greatest in and Near Harbors, Also Near Shipping Lanes OFFSHORE OIL ACTIVITIES • Minor Source of Intentional Pollution	• Routine Patrol Capability With Surveillance Concentrated in High Ship Density Areas	• Adverse Weather Requirements Relaxed Somewhat if Large Swath Can Be Achieved • Operating Cost a Significant Factor in System Design • Alarm System Important Design Consideration To Minimize Operator Fatigue
			• Desire Large Surveillance Swaths With Ability To Detect Small Targets	• Use of Radar Essential for Maximum Swaths • Synthetic Aperature Radar or High Frequency (35 GHz) Design for Maximum Swath With High Resolution
			• Must Minimize False Alarm Rate An Indicated Spill May Require Dispatching of Rotary Engine Aircraft or Surface Vessel to Spill for Confirmatory Sampling	• Radar Systems Cannot Distinguish Between Natural and Manmade Slicks • Multisensor Verification an Essential Part of System Design • Documentation of Spills Important

Table 6. Operational Considerations

OPERATIONAL CONSIDERATIONS		SYSTEM IMPLICATIONS	SPECIFIC DESIGN CONSTRAINTS
AVAILABLE AIRCRAFT	• Operational Ceiling, Range, Payload Capacity (Countermeasures Equipment), Operational Cost Per Mission • Availability for Immediate Deployment Against Major Oil Spills	• Operational Ceiling Determines Sensor Horizon (Max Theoretical)	• None
		• Aircraft Installation May Impose Serious System Design Constraints on Surveillance System	• Installation Must Be Considered Thoroughly in Pre-Design Phase
		• Uncertainties May Limit Mapping Accuracies	• Evaluate System Performance Requirements in Terms of Position Uncertainties
AREAL SURVEILLANCE AND PATROL FREQUENCY	• Must Periodically Patrol Harbor Rivers, Estuarine Areas, Harbor Approaches and Coastal Shipping Lanes • Desirable To Patrol Zone from Coastline Outward (~200 N Miles). Cannot Be Accomplished Without Excessive Aircraft Commitments	• System Must Be Responsive to Slicks Over a Wide Range of Conditions • System Should Provide Adequate Coastal Zone Surveillance With Minimum Number of Parallel Track Flights	• Low Angle Radars Impaired by Elevated Objects in Harbors, River Areas, Etc., Reliance on Passive Imager Is Necessary for Adverse Weather Performance Under These Conditions
FALSE ALARM RATE	• Must Be Minimized. Spill Verification and/or Antipollution Countermeasures Actions May Require Substantial Commitments of Resources and/or Manpower Similarly. Legal Actions Are Costly	• Redundant (Multisensor) Verification of Spills Important	• Design Specifically for Multisensor Redundancy and Discrimination of Natural (Fish Oil, Etc.) and Manmade Slicks
RELIABILITY MAINTAINABILITY AND HUMAN FACTORS	• System Must Eventually Be Deployed Among U S. Coast Guard Operating Districts	• System Must Be Designed and Controlled With Due Regard for Personnel Operating Capabilities and the Operating Environment	• Prototype Design Must Meet High Performance and Reliability Standards • Research Instrumentation Will Not Suffice
ENVIRONMENTAL CONDITIONS	U.S. Coastal Areas Experience the Following Weather Conditions • >50% Cloud Cover More Than Half the Year • Precipitation Occurs <10% of Year Except for Pacific NW and NE Coast Where Precipitation Occurs 10% of Time	• System Must Function in Presence of Clouds • System Dependence on Wind Speed Must Be Considered	• Must Use Microwave Sensors • X-Band Radar Not Useful in Low Wind Conditions

Table 7. Summary and Evaluation of the Impact of Variable Factors on Intrinsic Detection of Oil Slicks

Spectrum		Detection Mechanism	Weather Constraints	False Alarms	Day Ops	Night Ops	Sea State Limits	Oil Type	Slick Thickness	Slick Age	Observation Angle
OPTICAL	Near UV (.29-.4 um)	Reflectance Differential (Oil/Water Contrast)	Haze, Fog & Clouds Obscure Oil Slicks	Fish-Oil Slicks Suspended Solids Wind Slicks	Yes	No	None	Minor	Moderate	Minor	Minor
		Fluorescence			Yes	Yes *	None	Moderate	Major	Moderate	Minor
	Visible (.4-7 um)	Reflectance Differential (Oil/Water Contrast)	Clouds & Fog Obscure Oil Slicks	Fish-Oil Slicks Suspended Solids Shallow Water	Yes	No	Minor	Moderate	Major	Minor	Minor
	Near IR (.6-1.1 um)	Reflectance Differential (Oil/Water Contrast)	Clouds & Heavy Fog Obscure Oil Slicks	Fish-Oil Slicks Suspended Solids Upwellings	Yes	No	Minor	Minor	Minor	Minor	Minor
		Thermal Emission Differential				Yes					
Thermal (3-14 um)		Thermal Emission Differential	Heavy Clouds & Rain Obscure Oil Slicks	Fish-Oil Slicks Suspended Solids Upwellings	Yes	Yes	Minor	Moderate	Major	Moderate	Minor
MICROWAVES	Passive Techniques	Emmissive Differential (Oil/Water Contrast) Wave Structure Modification	Heavy Rain Obscures Oil Slicks	Suspended Solids Calm Seas	Yes	Yes	Major	Minor	Major	Moderate	Moderate
	Active Techniques	Wave Structure Modification Backscatter Cross-Section Differential	Heavy Rain Obscures Oil Slicks	Suspended Solids Calm Sea	Yes	Yes	Major	Minor	Moderate	Minor	Moderate

* Note: Requires artifical illumination to stimulate fluorescence.

An objective of the law enforcement mission is to obtain evidence of law violations which will stand up in court. In the case of an illegal discharge, it is necessary to have proof of the source. Any information which can be obtained is obviously of value. The remote sensing techniques considered in this paper can be of inexorable value in locating the spills, mapping the areal extent of the oil slick, determining the amount of oil spilled, and identifying the type of oil. In some cases this information may assist in tracking down the source of oil pollution.

The remote sensing surveillance patrols in order to gather evidence required for law enforcement can be thought of as embracing the functions listed above, namely:

Detection: The detection of any anomaly on the surface of the ocean which might be an oil spill.

Recognition: The determination that the anomaly is in fact oil.

Identification: Classification as to type of oil, source (directly if possible or if not—by inference), possible age, and amount of oil is important.

In terms of detection, it has been indicated that from the ultraviolet to the microwave region it is possible to detect oil slicks. Whether or not a particular anomaly can be positively identified as oil depends upon acquiring simultaneous multispectral data to reduce the problem of false targets. The oil polluter(s) may be identified using remote sensing in two possible ways:

1. By detecting the polluter(s) in the act of dumping oil.
2. By identifying the oil as being traceable to a given source.

In the first item above it is required that we have an image of the incident which contains time and location information for legal evidence, whereas in the second item above, it is required that we have some information which directly links the spectral nature of the oil to the source. In this particular instance, the evidence is basically circumstantial.

One cannot help but conclude that any remote sensing instrumentation technique which will assist in the detection, recognition, and identification of spills will be of value. Whether or not these techniques can be used to obtain convictions for oil pollutors is a complicated question which will have to await specific judicial tests.[28] Now that we hopefully have the tools that show promise of assisting in the law enforcement aspects of the pollution problem, the question that remains is, "What types of remote sensing data are acceptable as legal evidence in order to obtain a conviction of a potential polluter?" Undoubtedly, a considerable amount of work has to be done in the area of validating the "signature" of oil slicks so that they have the same weight as "fingerprints" in a court of law.

5. Conclusions and Recommendations

An analysis of the signature properties of oil from the ultraviolet to the radar region indicates that it is possible to detect oil films, oil slicks, and oil layers on water surfaces by remote sensing techniques. A summary of our findings is given in Table 7.

In the ultraviolet region, the reflective signature and the fluorescence signature are the basic mechanisms for oil detection. The fluorescence phenomenon associated with oil has great potential for the detection and identification of oil.

In the visible region, the reflective signature of oil is the primary mechanism for oil detection occurring near the ultraviolet and red part of the spectrum.

In the near infrared, the reflective signature of oil is used for detection, whereas in the far infrared, the thermal signature of oil is important.

The passive microwave signature properties of oil are dependent upon the emissivity of the oil and the resulting wave structure modification due to its presence on water; the active microwave (radar) signature properties of oil are dependent not only upon the wave structure modification but also upon the radar backscatter cross-section differences between oil and water.

Radar and passive microwave techniques appear very promising and show the best potential for providing adverse weather coverage of large areas on a 24-hr basis. Each of these techniques is affected by sea state. Low sea state conditions will prohibit the use of radar, whereas high sea state conditions will adversely affect microwave techniques.

Oil Detection and Identification

A multispectral system incorporating many of the operational techniques discussed in this report will be required to detect and identify oil.

Oil Thickness

Additional research is required to evaluate the problems of oil slick thickness and identification. The airborne fluorescence technique using laser technology appears to offer the most promise in resolving this problem; however, more data on the effects of oil aging on its fluorescence signatures are required.

The radiometric response in both the ultraviolet and the infrared regions appears to be linked very loosely to oil thickness. The dual or multifrequency microwave technique shows the most promise in resolving the thickness problem.

Law Enforcement

The question "Can remotely sensed data be used as legal evidence against an oil polluter?" is difficult to answer. Undoubtedly the techniques considered in this paper are a useful adjunct to the law enforcement mission. However, this gives us no insight on the kinds, or the form that this data must take in order to become a viable legal tool.

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16. Abstract

Oil is an important energy ingredient in the economies of most of the industrial nations of the world. The problem of oil pollution of both surface waters and benthic communities has increased considerably.

At the present time, it is known that oil does exhibit characteristics signatures. However, these signatures may vary with time and environmental conditions.

There are a variety of devices for "seeing" oil on water – sensors that make use of both the spatial and spectral dimensions. A multispectral approach can be used to resolve the problems of:

1. Detecting oil films on water
2. Mapping the areal extent of the slick
3. Measuring slick thickness
4. Identifying oil types

In this paper, a multispectral look at oil pollution, detection, monitoring, and law enforcement capabilities will be considered.

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