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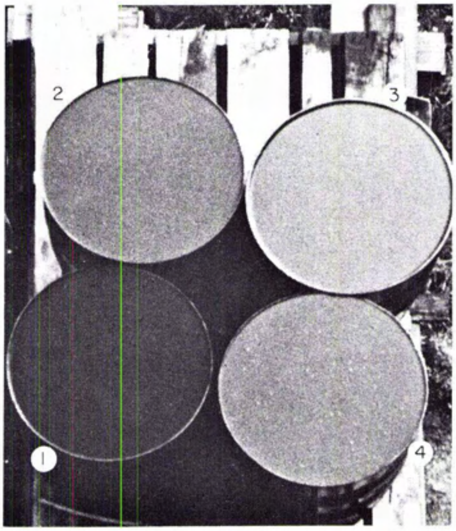


Frontispiece. Photograph of the water-filled, oil-covered barrels from the scaffold showing *(1)* river water, *(2)* Diesel fuel, *(3)* gasoline, and *(4)* spent lubricating oil.

Detecting and Monitoring Oil Slicks with Aerial Photos

Significant detection capability was found in the ultraviolet and blue regions of the spectrum, less in the near-infrared, and almost none in the green and red.

(Abstract on next page)

Introduction

The average world production of oil in recent years has been at the rate of about 2 × 10[15] gallons per year, according to a study by Horvath, *et al.*,[1] of the University of Michigan. Of this amount, the Environmental Protection Agency estimates that 1.5 billion gallons per year have found their way into the water bodies of the world. This oil is a significant source of pollution and is a major problem for the world ecosystems to contend with, even though it is only about 0.0001 percent of the total production. This quantity amounts to about 1.5 cubic feet of oil for every square mile of ocean surface on the earth. What really causes the high environmental impact is that 50 percent is spilled within 1 mile from ocean shorelines, and 80 percent within 10 miles. Virtually all shellfish and seabirds derive a living from these regions of the ocean; and some of man's best recreational areas are located there. All in all, the quantities of oil in ocean, lake, and river waters have become a major ecological concern[2] and have been labeled as a critical environmental problem by an MIT-sponsored study group.[3]

The chief sources of aquatic oil pollution are:

- Natural seepages such as those off the California coast near Santa Barbara.[4-7]
- Marine accidents, where vessels either collide with one another or with some natural obstruction.
- Offshore oil-drilling operations, where leakage is not adequately checked or where eruptions and fires get beyond control.
- Deliberate dumping of spent lubricating oils from private and industrial machinery such as automobiles, generators, etc.
- Willful and irresponsible dumping of tanker residual loads and bilge accumulations.

The effects of these oils on the aquatic ecology are not fully understood, but there is ample evidence to indicate that fish and waterfowl do suffer from it.[8] A news release by the National Oceanic and Atmospheric Administration in February, 1973, claimed that 700,000 square miles of the Atlantic Ocean were found to be significantly contaminated to various depths, suggesting that the persistence of the oil is appreciably greater than had been anticipated. It is obvious that beaches and seashores can be degraded for long periods of time.

In order to assess the extent to which oil spills occur and affect the environment, their initiation, location, and displacement need to be effectively detected and monitored on a regular basis. To perform this task, aerial photographic reconnaissance would be the most practical and economic method, provided it could furnish the desired information. Its chance of success is heightened by the facts that oil does not mix readily with water, but floats on the surface in slicks; and the optical and physical characteristics of oil are different from those of water. In addition, there is a considerable amount of aerial photographic equipment available, and the photographic record is both detailed and permanent.

For this work, tests were made with typical petroleum product slicks to answer the questions, (1) Is an aerial photographic detection system feasible? and (2) If so, what is the best photographic detection technique available? To this end, our quantitative data are presented here along with the statistical procedures and conclusions that could be drawn from them.

The bibliography includes more than just the articles referred to in the report; it is designed to lead interested readers to other sources on the broad topic of *oil on water* discrimination.

ABSTRACT: *The presence of large quantities of oil on ocean, lake, and river waters has become a major ecological concern. Agencies in charge of detecting and monitoring these oil slicks are looking for more efficient and reliable reconnaissance techniques. The spectral characteristics of oils and waters indicate that aerial photography could be a useful tool in oil-pollution detection. Photographs of Diesel fuel, gasoline, and spent lubricating oil slicks on barrels of Genesee River water in Rochester, New York, were used to define the brightness contrast between these oils and the water. The effects of types of oil, spectral region, and solar altitude on the photography were evaluated statistically. Significant detection capability was found in the ultraviolet and blue regions of the spectrum, less in the near-infrared, and almost none in the green and red. A method for detecting oil slicks by aerial photographic reconnaissance is presented utilizing standard black-and-white aerial film.*

CHARACTERISTICS OF OILS AND SLICKS

To understand the reason we might expect the images of oil surfaces to contrast with those of water surfaces when photographed simultaneously, consider the composition and some of the physical and optical characteristics of various oil products.[9] Petroleum is a dark-colored mixture of hydrocarbons, chiefly paraffins, with impurities such as muds mixed in. Different batches of oil vary in their chemical composition, which in turn depends on the location of the well from which they were derived. Some oils and gasolines also contain considerable amounts of aromatic and cycloparaffinic hydrocarbons (i.e., the naphthenes: cyclopentanes, cyclohexanes, and their homologs), which are known to fluoresce in the near-ultraviolet and blue regions of the spectrum.

Let us look at some of the distinguishing properties of oils relative to those of water. Of paramount importance for the photographic aspects of the problem are the differences in specific gravity, index of refraction, and the previously mentioned fluorescence, which are shown for both oils and sea water in Table 1.

Using the near-normal reflectance analysis of thin films by Vasicek,[10] Goolsby[11] was able to calculate an expected radiance intensity difference between water and oil surfaces. He showed (see Figure 1) that one can expect twice the radiance from an oil slick as from sea water, or in photographic terminology, a full-stop difference in exposure should occur. The quality of the illuminant—direct sunlight and skylight—as well as type and thickness of oil should have an influence on this difference owing to the dependence of the index of refraction on wavelength. Water purity is another variable that could affect brightness difference.

Besides the optical differences between oil and water, the physical characteristics are also of value in a photographic detection method. As was mentioned, oil floats because it is less dense than water. The lighter fractions are more volatile and water soluble; and thus, when the residue ultimately becomes denser than water, it will sink. One of the effects of the slick is the alteration of the water's surface, hence influencing the capil-

TABLE 1. PROPERTIES OF OILS AND SEA WATER

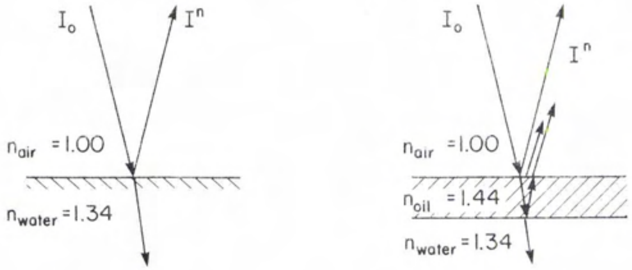
Property	Units	Range for Oils	Range for Typical Crude Oils	Average for Crude Oils	Sea Water
Specific gravity at 22°C	Ratio to water	0.7–1.007	0.79–0.93	0.857	1.024
Surface tension at 22°C	dynes/cm	20–37	24.4–31.8	28	73.02
Index of refraction (visible)	Ratio to air	1.40–1.58		1.44	1.34
Fluorescence	Compared to 1 ppm quinine sulfate	Crude Oils:	0 – 20 percent at 0.58 μ		None
		Gasolines:	over 100 percent in the UV		

lary wave structure (ripples) and resulting in a smoothing of the surface. This smoothing would affect the specular reflections from the surface, and hence could allow one to distinguish the slick area from the ocean water through differential specular reflectance. It must be noted, however, that a certain minimum slick thickness is required to control the ripples effectively, unlike the optical effects which persist for all oil-film thicknesses.

Considering the comparative advantages of photography, namely, maximum detail rendition, easy interpretability, and permanence of record, it is a very attractive method to detect oil slicks on water at just about all stages of the slick's existence.

PHOTOGRAPHIC INVESTIGATION

To gain insight into the problems of the use of photography for oil-pollution detection and monitoring, we devised a photographic test to determine the region of the spectrum that would yield greatest detectability for a specific pollutant. Three petroleum products were selected as being typical of much of what would normally be found as pollution. These were gasoline as a sample of a highly refined petroleum product, Diesel fuel as a sample of a product of medium refinement, and spent automotive lubricating oil as being typical of much of the waste oil that is being discarded. Slicks of these products on water from the Genesee River were then photographed in several spectral regions, at vari-



$$I^n = \left(\frac{n_w - n_a}{n_w + n_a}\right)^2 I_o \cong 0.02\, I_o$$

$$I^n = \left[\left(\frac{n_o - n_a}{n_o + n_a}\right)^2 + \left(\begin{matrix}\text{Secondary Refl.}\\ \text{+ Fluorescence+-}\end{matrix}\right)\right] I_o \cong (0.03 + 0.01)\, I_o = 0.04\, I_o$$

FIG. 1. Estimation of radiance intensity, I^r, from air/water and air/oil/water interfaces, as shown by Goolsby[11] where n is the index of refraction of the materials indicated and I_0 is the incident radiant intensity.

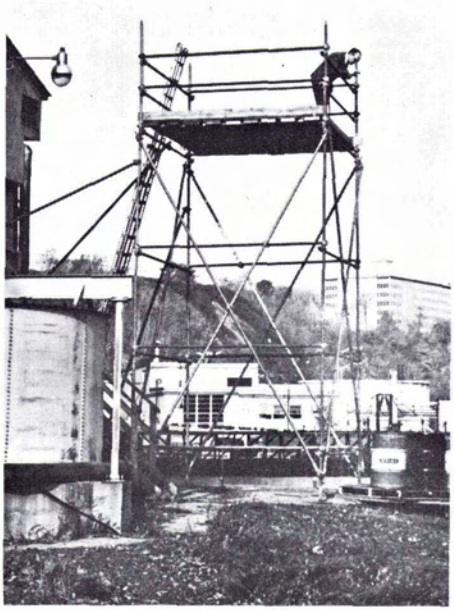


FIG. 2. Scaffolding and barrel placement for the tests.

ous solar altitudes and times of the year.

To simulate aerial photography, a scaffold was erected which would allow photography of the slicks from a near vertical position about 20 feet above the surfaces. The scaffolding had a gray matte finish, and was positioned so that as little reflectance from it as possible could affect the results. At the base of the scaffold, four 55-gallon steel drums were placed in a cluster so that each would be equally off axis from the camera axis. To have as little contribution as possible from the radiation reflected from within the drums, the insides of each were blackened with Kopper's black matte Bitumastic coating. As it turned out, the visibility through Genesee River water was on the order of only a few inches, so the bottom was never visible.

Every day that a test was run, the four drums were filled almost to capacity with river water. To three of the surfaces, the specific petroleum product was added in sufficient quantity to create a continuous slick over the surface. We encountered some problems in creating very thin slicks owing to a combination of cool weather and high wind which was prevalent at most of the times we made the tests. These conditions acted either to break up the slick surface or clump the oily products. The fourth drum, containing river water only, was used as the control. The color quality of river water was expected to vary, but it was believed that this sort of optical quality variation would also be typical of places where this detection method would be used. Thus, any detection capability must be significant enough to be able to override any of these ambient water differences. Figures 2 and 3 show the test site.

A schematic representation of the photographic variables of concern is given in Figure 4 for reference purposes. It can be seen that the illumination is partially specular due to direct sunlight, $E_{sun}(\lambda)$, and partially diffuse due to skylight, $E_{sky}(\lambda)$. This combination of light sources makes up the irradiance onto the oil and water surfaces and, as is described by Piech and Walker,[12] must be considered carefully by the photointerpreter. The brightness differences resulting from the reflectances from oil and water are then recorded by the photographic film. The selection of filters, camera lens, and films for the photography are made considering the difference in spectral radiance between the two surfaces. Figure 5 shows this spectral radiance as measured by Horvath[1] for a 26.1-A.P.I. crude oil and for sea water. The film sensitivity modified by the lens transmittance must be significant in the spectral regions where the oil and water radiances are most different. All other spectral regions can be excluded from the film through the use of special filters. As can be seen from Figure 5, the best results would be expected in the

FIG. 3. Barrel configuration at foot of scaffold: (1) water, (2) Diesel fuel, (3) gasoline, and (4) spent lubricating oil.

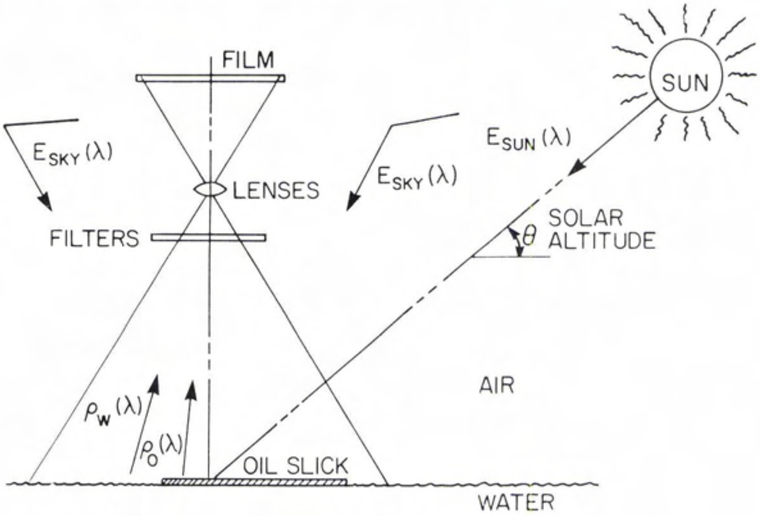


FIG. 4. Photographic system for oil-slick detection showing the direct sunlight $E_{sun}(\lambda)$ and skylight $E_{sky}(\lambda)$ incident on the oil and water surfaces, and the subsequent radiances $\rho_0(\lambda)$ from the oil and $\rho_w(\lambda)$ from the water responsible for the photographic record.

ultraviolet *(UV)*, blue, and infrared *(IR)* regions of the spectrum.

Three Leica M-3 cameras equipped with 50-mm Leitz Wetzlar Summicron lenses were used for the 35-mm photography of the slicks. These lenses were chosen because they transmit radiation from a low-wavelength limit of about 340 nm on into the *IR* region past where the films are sensitive. Many common lenses have a higher short-wavelength cutoff; for example, it is about 370 nm for the Zeiss Sonnar, Planar, and Distagon lenses used for 70-mm photography, and about 400 nm for the Wild RC-8 Universal Aviogon lenses used for 9.5-inch photography. If photography in the *UV* region is desired with these larger-format cameras, special lenses would have to be considered.

The films used in this test included:

★ KODAK PLUS-X AEROGRAPHIC Film 2402 (ESTAR Base). This is a panchromatic film with sensitivity to wavelengths from about 300 nm to about 700 nm.

★ KODAK Infrared AEROGRAPHIC Film 2424 (ESTAR Base). This film has extended sensitivity covering the spectral region from 300 to 920 nm with an insensitive green region between 480 nm and 560 nm.

★ KODAK High Speed EKTACHROME Film (Daylight). This color film has the standard red-, green-, and blue-sensitive layers, each capable of monitoring its own specific spectral band.

To isolate the various spectral regions of interest, a series of KODAK WRATTEN filters was used. These combinations are outlined in Table 2.

Figures 6 and 7 show the spectral sensitivities of both black-and-white films used and the spectral transmittances of KODAK WRATTEN Filters No. 18A and No. 39, which isolate the film's sensitivities to the spectral regions of primary interest.

The test site was photographed on seven days, the nine film–filter combinations listed in Table 2 being run twice each day. Each exposure was made at a known solar altitude,

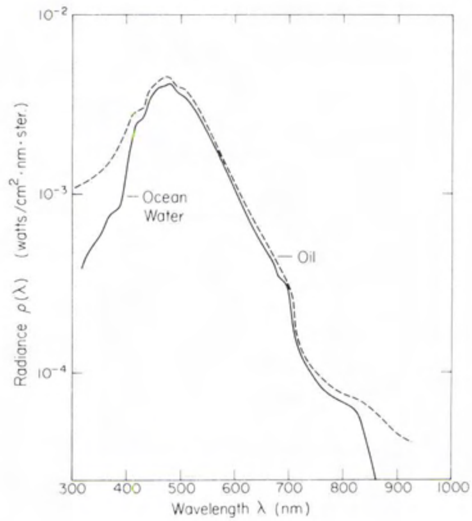


FIG. 5. Spectral radiance from a thin layer of 26.1 A.P.I. crude oil and moderately clear coastal water of infinite depth with 43° solar altitude (from R. Horvath, University of Michigan, WRL).

TABLE 2. SPECTRAL REGIONS RECORDED BY THE FILM/FILTER COMBINATIONS USED.

KODAK *Films*	KODAK WRATTEN *Filters*	*Spectral Coverages*
2402	18A	UV
2402	39	UV + blue
2402	none	UV + visible
2424	18A	UV + IR
2424	39	UV + blue + IR
2424	89B	IR
2424	none	UV + blue + red + IR
H. S. Ektachrome	2B	blue, green, red individually
H. S. Ektachrome	none	UV + blue, green, red individually

which ranged from 28° to 49° during the period from July 17 to September 28, 1972. During each session two seven-frame exposure series were made for each film–filter combination. The black-and-white films were processed in a KODAK VERSAMAT Film Processor, Model 11C, using KODAK VERSAMAT 641 chemicals at 85°F. The color film was proecessed in the standard KODAK Process E-4. This procedure resulted in 850 analyzable photographs to be evaluated, with from 5 to 10 frames available in each exposure series, for each specific brightness-difference determination.

RESULTS AND ANALYSIS

The density of each image of oil and water in each photograph was measured with an Eastman electronic densitometer, model 31A. A visual filter was used for the black-and-white photographs and filters that provide status A densitometry for the color. The integral color-density values obtained from the color measurements were then converted to equivalent neutral densities in order to obtain the response of the individual layers of the film. The basic theory of this conversion is treated by Evans, Hanson, and Brewer.[13] The density measurements were then converted to *log E* values using sensitometric curves to remove the photographic and processing variations from the data. An example is shown in Figure 8 for the case of gasoline relative to water. The *log E* differences between each type of oil and water in the same frame of the photographs then represent the logarithm of the brightness ratios between the oil and the water. The Frontispiece shows a photograph of the barrels to illustrate the type of images that were analyzed in the manner just described.

Because the photography was repeated many times for each comparison, it was justifiable to subject the resulting data to statistical analysis in order to test several interesting hypotheses. The first concern was whether or not the brightness-difference values, or contrast, between the oils and water for any film/filter combination were significantly different from zero. All the brightness-difference values calculated were grouped according to the film/filter combination used in the photography for each of the oils. For each group the average or mean value of the brightness differences and the standard deviation about that mean were found. The ratio of the group means to their standard deviation $(\bar{y}/s)$ was also calculated to serve as an indicator of the reliability of the respective mean value. Note that when this reliability index is *1 or less*, the variability at the 68-percent confidence limit $(\pm 1\sigma)$ is equal to or greater than the brightness difference obtainable from the photographs; hence, detection capability is not significant. These mean values, their standard deviations, and reliability indexes, presented in Table 3 for all trials, are listed according to film/filter combinations and type of petroleum product used.

There is no question as to the significance of the log brightness differences of nearly 0.30 found in many of the groups; this difference represents a factor of two for the oil's brightness relative to water and is more than enough to record and distinguish photographically. It is also interesting that the mean values obtained agree rather well with the estimate of a log brightness difference of 0.30 predicted on a theoretical basis by Goolsby.[11] As can be seen in Table 3, photography in the *UV*, blue, and *UV*-plus-blue regions of the spectrum all resulted in a log brightness difference nearly equal to 0.30 with the added support of a high reliability index. One can also see the relative lack of reliability of the color images as a detection tool.

The next question was to determine which film/filter combinations were most useful to

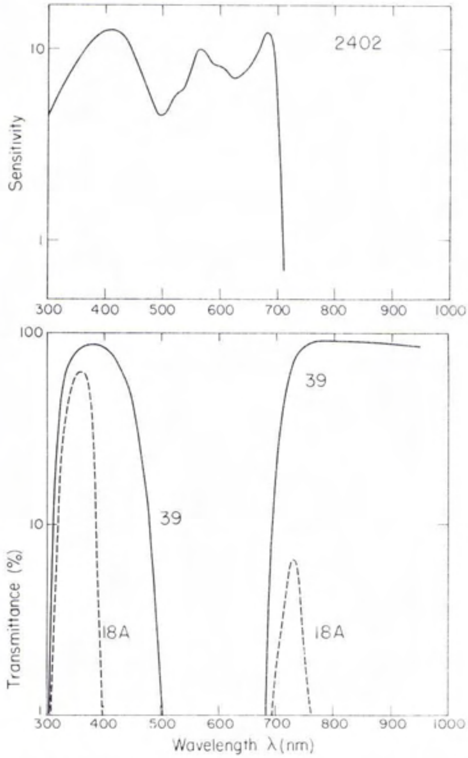


FIG. 6. Spectral sensitivity of KODAK PLUS-X AEROGRAPHIC Film 2402 with spectral transmittance of KODAK WRATTEN Filters No. 18A and No. 39.

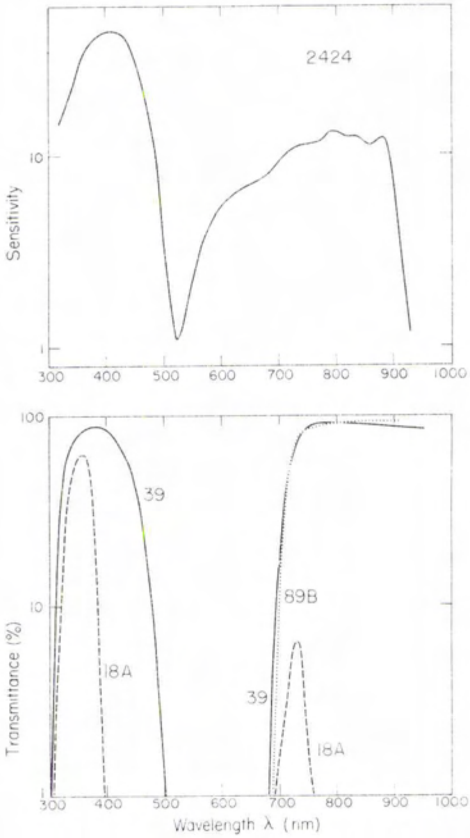


FIG. 7. Spectral sensitivity of KODAK Infrared AEROGRAPHIC Film 2424 with spectral transmittance of KODAK WRATTEN Filters No. 18A, 39, and 89B.

ensure detection. Ordering the log brightness difference averages was accomplished through the Duncan multiple range technique (DMRT), which helped organize the pooled mean brightness differences into a sequence of usefulness. The combinations in order of decreasing detectability or contrast, as derived by the DMRT, while also taking note of the reliability index, were 2424 with WRATTEN No. 18A, 2402 with WRATTEN No. 18A, 2424 with WRATTEN No. 39, and 2402 with WRATTEN No. 39. The differences in ability to distinguish between oil and water among these four film/filter combinations were small. The results obtained with the black-and-white films with no filter were excluded from further evaluation because the DMRT showed that under these conditions the results were less significant than those from the above four combinations.

In order to determine the effect of solar altitude on the brightness differences for the film/filter combinations judged most useful, the brightness differences were plotted versus the angular elevation of the sun at the time of the photography. Best linear and

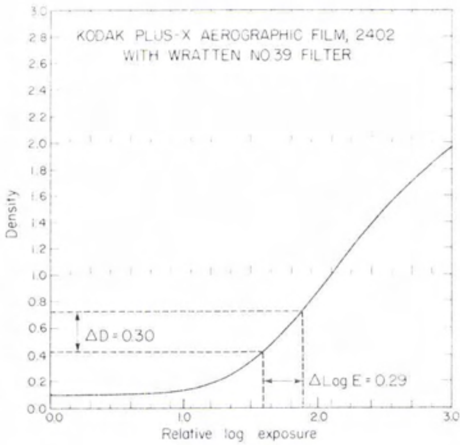


FIG. 8. Conversion of density values to log exposure values and the relationship between differences in each of these variables. Values shown are those of a gasoline slick.

TABLE 3. AVERAGE LOG BRIGHTNESS DIFFERENCES, THEIR STANDARD DEVIATIONS AND RELIABILITY INDEXES FOR THE OILS AND FILM/FILTER COMBINATIONS STUDIED. (DFL = DIESEL FUEL, GAS = GASOLINE, SLO = SPENT LUBRICATING OIL).

KODAK Film	KODAK WRATTEN Filter	Oil	Average Log E differ.	Std. Dev. S	Rel. Index $\bar{y}/s$
2402	18A	DFL	0.24	0.019	12.6
	(ultra-	GAS	0.29	0.047	6.2
	violet)	SLO	0.29	0.036	8.1
	39	DFL	0.24	0.027	8.8
	(UV and	GAS	0.27	0.042	6.4
	blue)	SLO	0.29	0.059	4.9
	none	DFL	0.22	0.039	5.7
		GAS	0.24	0.044	5.4
		SLO	0.29	0.112	2.6
2424	18A	DFL	0.23	0.039	5.9
		GAS	0.28	0.058	4.8
		SLO	0.28	0.041	6.9
	39	DFL	0.23	0.040	5.7
		GAS	0.26	0.038	6.9
		SLO	0.26	0.063	4.1
	89B	DFL	0.13	0.050	2.6
	(infra-	GAS	0.15	0.079	1.9
	red)	SLO	0.18	0.082	2.2
	none	DFL	0.21	0.032	6.6
		GAS	0.25	0.038	6.6
		SLO	0.27	0.069	3.9
H. S. Ektachrome Y	2B	DFL	0.23	0.092	2.5
		GAS	0.24	0.133	1.8
		SLO	0.26	0.153	1.7
M		DFL	0.16	0.073	2.2
		GAS	0.15	0.136	1.1
		SLO	0.19	0.158	1.2
C		DFL	0.15	0.079	1.9
		GAS	0.09	0.129	0.7
		SLO	0.18	0.180	1.0

quadratic functions relating these variables were obtained through multiple regression methods. Davies[14] has given the fundamental theory for all these analyses.

Figure 9 shows the data points and the regression analysis curves for the film/filter combinations with good detection capability. The variation in brightness difference due to solar altitude was statistically significant for some of the film/filter combinations and oils, although it is small compared to the brightness difference itself. The extent to which detectability is expected to change with solar altitude can be deduced from these curves. Only a percentage of the change in log brightness difference obtained from a regression curve can be categorically attributed to solar altitude. These percentages are the coefficients of determination obtainable from statistical analysis and are presented in Table 4 for the curves of Figure 9. It can be seen that the contrast increases with solar altitude for gasoline, it is relatively constant for Diesel fuel, and it decreases with increased solar altitude for spent lubricating oil. This result could be interpreted to indicate that

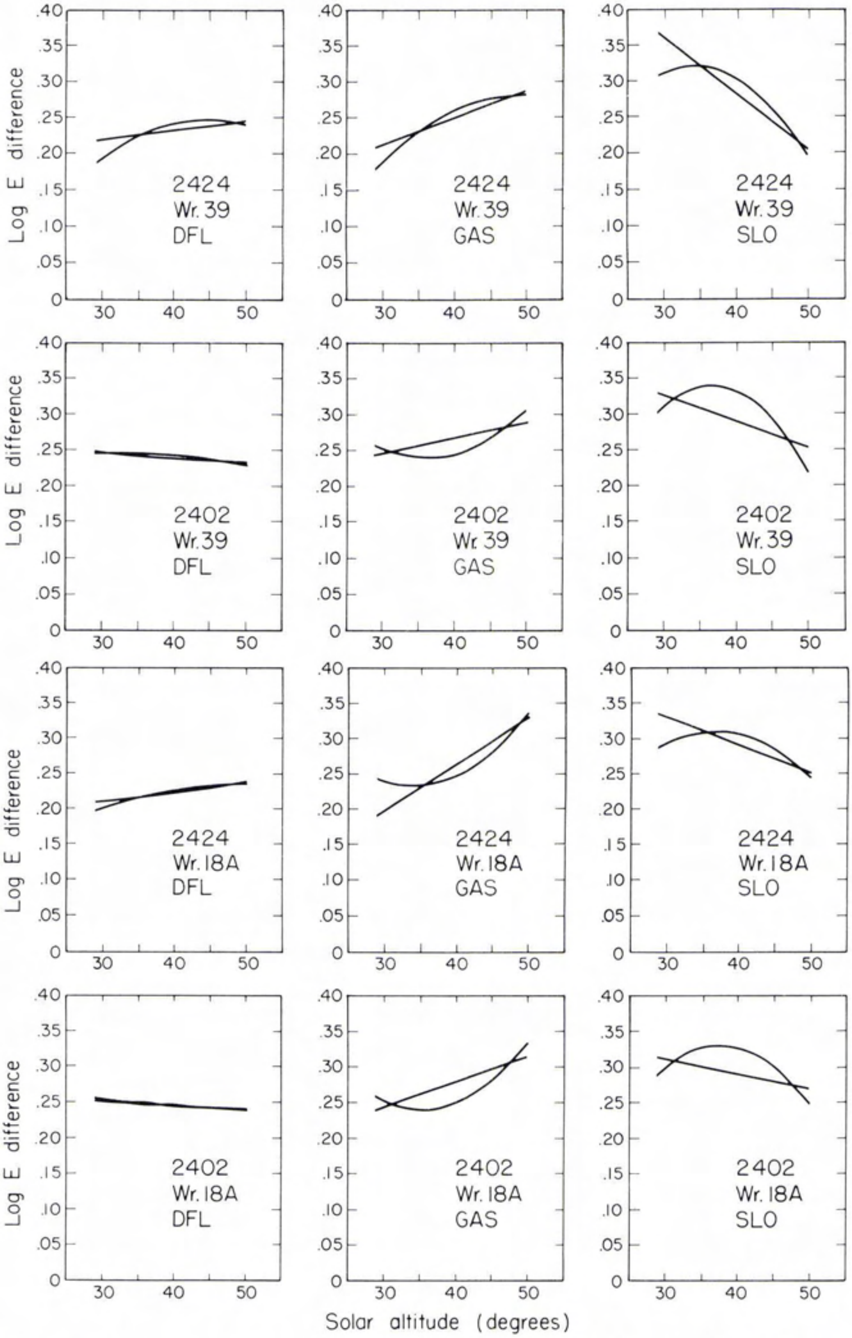


FIG. 9. Regression-analysis curves relating the log brightness difference dependence on solar altitude for the film/filter combinations found to have significant detection potential.

high solar altitude would be desirable if recording gasoline slicks, low solar altitudes for spent lubricating oil, and any time of day is good for Diesel fuel.

Where the interest is only in searching for slicks with aerial photography, one would normally not consider solar altitude. If the type of oil sought is known, and it is desired to identify it as such compared to other oils or pollutants, then solar altitude optimization

TABLE 4. COEFFICIENT OF DETERMINATION AND STANDARD DEVIATION OF BRIGHTNESS DIFFERENCE VALUE DEPENDENCES ON SOLAR ALTITUDE AS SHOWN IN FIGURE 10.

KODAK Film	KODAK WRATTEN Filter	Linear Model			Quadratic Model		
		DFL[a]	*GAS*[a]	*SLO*[a]	*DFL*[a]	*GAS*[a]	*SLO*[a]
2402	18A	9.1	40.0[b]	23.8	9.2	54.5[b]	63.7[b]
		0.02	0.04	0.03	0.02	0.03	0.02
	39	6.5	15.9	24.9[b]	6.9	27.9	50.3
		0.03	0.04	0.05	0.03	0.04	0.04
2424	18A	5.7	62.7	44.8	5.8	63.5	46.1
		0.04	0.04	0.03	0.04	0.04	0.03
	39	4.8	48.3	71.0	5.3	48.9	84.8
		0.04	0.03	0.04	0.04	0.03	0.04

[a] DFL = Diesel fuel, GAS = gasoline, and SLO = spent lubricating oil.
[b] Significant lack of fit is present.

may help. More data are needed to establish the effect of solar altitude for other petroleum product slicks.

As a practical test of the photographic method of detecting and monitoring oil slicks, we were able to locate the remnants of an accidental Diesel fuel spill in the Genesee River after the Coast Guard had declared the slick cleaned up and the residuals completely dispersed. Figures 10 and 11 depict the Diesel fuel plume as it enters Lake Ontario from the edge of the river-mouth pier. It was virtually invisible to the naked eye. Note in Figure 11 the wake of a boat that crossed the slick.

CONCLUSIONS

These tests have demonstrated that under closely controlled conditions it is feasible to detect slicks of the petroleum products we tested, with photography in the ultraviolet, blue, or ultraviolet-plus-blue regions of the

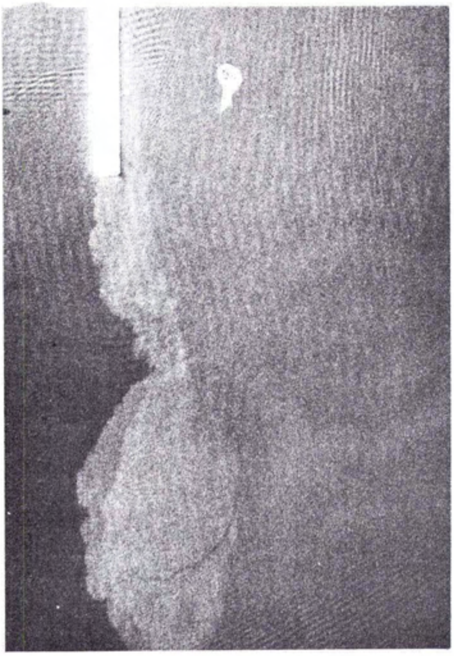


FIG. 10. Visually undetectable Diesel fuel plume flowing from the Genesee River into Lake Ontario. Spill occurred many hours before this photograph was taken.

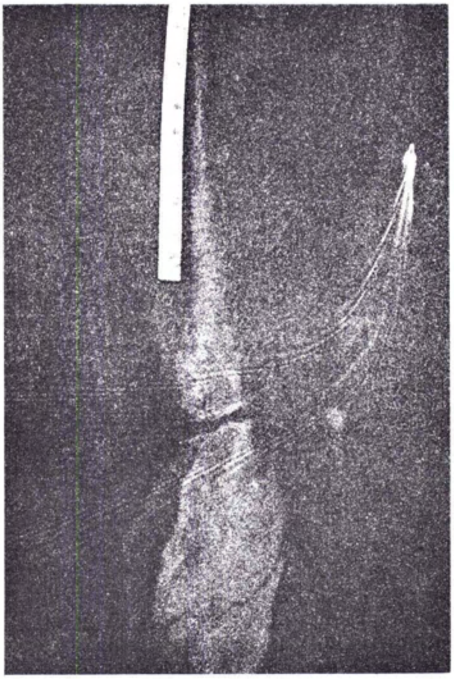


FIG. 11. Same spill as shown in Figure 10. Note the cut left in the slick by the traversal of a boat entering the river mouth.

spectrum. Some detectability also seems possible in the infrared region, but virtually none in the green and red regions. We realize these results cannot be unreservedly extrapolated to cover all cases of actual oil slick photography, because of area and wave consideration. However, in the one practical experiment, the procedures worked well, and we would expect these methods to be the best available under other conditions.

Although the combination of KODAK WRATTEN Filter No. 18A with either KODAK Infrared AEROGRAPHIC Film or KODAK PLUS-X AEROGRAPHIC Film provided the best detection capability, these combinations have the drawback of low sensitivity owing to the narrow pass band of the filter. The requirement of an exposure of about 1/125 sec with an *f*/4.0 aperture is not attractive for aerial photography because of possible image motion. With a KODAK WRATTEN Filter No. 39 and the same two films, excellent detectability is attained, along with a much more acceptable exposure requirement of about 1/500 sec at *f*/5.6.

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2. Ordinarily *two* copies of the manuscript and two sets of illustrations should be submitted where the second set of illustrations need not be prime quality; EXCEPT that *five* copies of papers on Remote Sensing and Photointerpretation are needed, all with prime quality illustrations to facilitate the review process.
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