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27 March 1970; revised 17 June 1970

Oil Spills: Method for Measuring Their Extent on the Sea Surface

Abstract. *It is difficult to estimate the area affected by an oil spill at sea, the degree of coverage by oil pollutants within the affected area, and the quantity of pollutants involved. Estimates of volumes and flow rates are based on estimated changes in areal extent of the spill. Uncertainties in measurement of area degrade the accuracy of estimating other parameters. To resolve this problem, available stock components have now been assembled into a system that yields repeatable, economical measurement of the areal extent of oil spills at acceptable levels of accuracy. The system comprises overflights with a thermal infrared imaging system, densitometric color enhancement of the infrared images, and automatic digital planimetry of the areas of specified image densities.*

Recurrent spillages of petroleum and petroleum products are becoming ever more serious sources of pollution of the marine environment. It has been difficult to estimate the area affected by a given oil spill, the degree of concentration of pollutants within the affected area, and the quantity of pollutants involved. Oil on the sea surface does not image well in the spectral bands recorded by conventional black-and-white or color photography. By use of a thermal infrared mapper and densitometric color enhancement of the resulting infrared image, in combination with automatic digital planimetry, it is now possible to map the areal extent of an oil spill at a given time and to obtain, automatically and economically, a repeatable and accurate measurement of the area of sea surface actually covered by oil pollutants. We have tested a fairly simple system that shows a good potential for breaking through the bottleneck of much uncertainty and considerable disagreement in the estimates of oil spill magnitudes.

The Santa Barbara oil spill is one of the events that stimulated our present, newfound awareness of the delicate environmental balance and its vulnerability to pollution. The Santa Barbara oil spill was touched off on 28 January 1969, when well No. 21 blew out of control on Union Oil Company's platform A (some 9 km south of Santa Barbara, on Federal Lease Parcel No. 402). Vast quantities of crude oil polluted the channel during the following $10\frac{1}{2}$ days, until the well was plugged. Some 4 days after the well was cemented, vigorous oil leaks began to flow from the fractured bedrock beneath the sea floor adjacent to platform A (*1*). This flow has gradually decreased to the point where only about 1000 gallons (3000 to 4000 liters) per day are still leaking out at present.

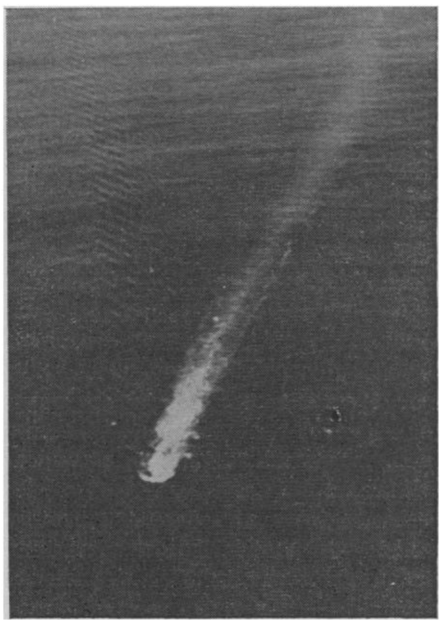
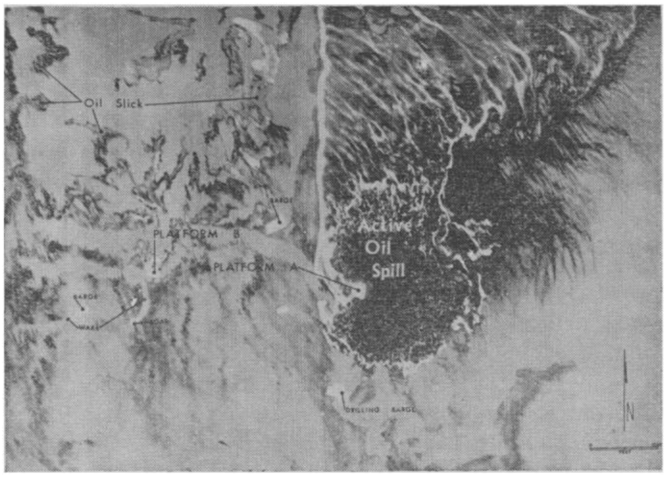


Fig. 1. Black-and-white rendition of a color photograph showing oil-covered sea surface except where underlying water is revealed in the boat's wake. Without the contrasting tone image of the boat's wake, this photograph and the color original from which it was made would be perceived as showing a normal sea surface.

Estimates of the amount of spillage vary: a low figure was proposed by Union Oil and the U.S. Geological Survey, and much higher estimates by independent researchers. Alan A. Allen of General Research Corporation computed that 2.2 million gallons ($8\frac{1}{3}$ million liters) of crude petroleum poured into the Santa Barbara Channel during the first 10 days and that spillage during the spill's first year was 3.3 million gallons ($12\frac{1}{2}$ million liters). Both Allen and the Union Oil Company now agree that present flow rates average about 30 barrels (5 m^3) per day. Allen's flow rate estimate of 220,000 gallons (830,000 liters) per day during the first 10 days is ten times that of the oil company's more reassuring figure of 500 barrels (80 m^3) daily for the same time period (*2*). On the assumption that an unbiased search for truth motivated all estimates, such a tenfold variability demonstrates the need for developing simple, standardized techniques that could be applied uniformly and that could materially increase the accuracy of estimating such basic parameters.

Floating oil on seawater does not photograph well on panchromatic emulsions. The contrast between an oil patch and the adjacent water is very low. High contrast occurs only where a favorable sun angle accentuates reflectance from the oil. Even then, such oil reflectance is difficult to distinguish from sun glitter on oil-free waters. Oil-free areas of upwellings, surface currents, and localized air flows show a streaked, alternately choppy and smooth sea surface, which is difficult to distinguish from patchy oil slicks. Color photography is similarly ineffective. The color contrast between the oil film and the adjacent water is again very low. Except for areas where thick ropy streamers of oil register as dark gray, the oil-polluted waters show a grayish-green color, which the eye readily accepts as a normal sea surface tone. It is, therefore, often impossible to tell whether a particular air photograph shows a completely oil-covered or completely oil-free sea surface. Figure 1, a black-and-white rendition of a color photograph, illustrates this condition; only the boat's wake revealing the oil-free water underneath shows that the surrounding sea surface is entirely covered by oil.



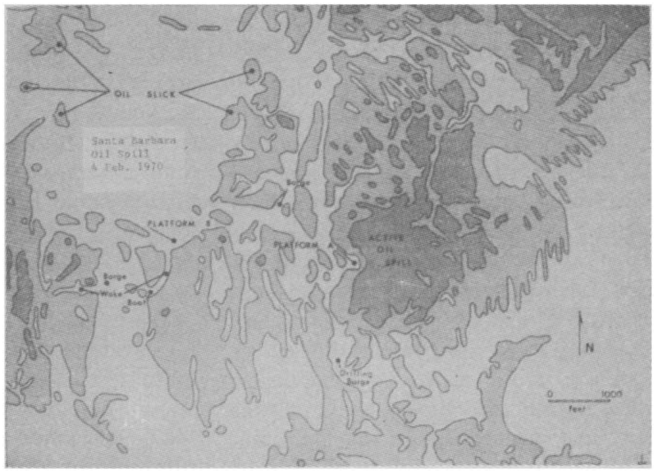


Fig. 2 (left). Thermal infrared image of the source area of the Santa Barbara oil spill, taken in early February 1969. The oil slicks contrast strongly with the background sea surface and can be readily delimited. [Courtesy of North American Rockwell] Fig. 3 (right). Cartographic rendition of a color-enhanced image displayed on the Datacolor screen. This is basically an isopleth map, showing nearly oil-free sea surface as the lightest area (green in the original), "lightly" oil-covered surface as the medium-dark area (yellow in the original), and "thickly" oil-covered surface as the darkest area (red in the original). Surface sampling concurrent with the imagery could have provided actual average thickness values to be assigned to these categories.

This problem of object-to-background contrast does not affect thermal infrared imagery. The oil-covered areas show up clearly and distinctly in Fig. 2, a thermal infrared image of the area immediately surrounding platform A in the Santa Barbara Channel, taken early in February 1969. The oil shows a mottled and streaked pattern, both lighter and darker than the background sea surface.

There are conflicting explanations for the apparent thermal anomalies that can be seen on images of oil patches in thermal infrared. Because it is darker than the ambient seawater, oil should have a higher emissivity and should show a lighter tone on a thermal infrared image scan (*3*). On the other hand, reflectivity of oil films and their interference with heat exchange at the air/sea interface substantiates expectations that oil patches should register as darker (cooler) tones on a thermal infrared image (*4*). Both types of tonal signatures are shown in Fig. 2. We assume the lighter areas, of higher infrared emissivity, to be areas where the oil has pooled into thick streamers. Patterns in which the oil-polluted surface is seen as darker than the background involve the areas of active upwelling at the actual blowout sites, where cooler fluids are displacing the warmer surface waters. Outside the main body of the blowout are diffuse patches, which are occasionally lighter but are generally darker than the background. These patches are areas of thinner oil films, whose iridescence makes them efficient reflectors and whose interposition at the air/sea interface reduces heat exchange and leads to a cool (darker) thermal infrared tonal image. The thin-film interpretation of the darker tone area is supported by the imaging of the boats' wakes, which obviously make clean sweeps through an oil-covered surface layer.

The precise nature of the emissivity characteristics of oil on water is a fascinating area of investigation in its own right, but our immediate concern at this stage is image detection. Here it is significant that a thermal infrared mapper shows distinctive responses for the oil-covered areas and allows them to be readily distinguished from the less polluted background. The particular sensing system with which Fig. 2 was obtained is North American Rockwell's modified Bendix 8-14 micrometer thermal mapper. Other thermal infrared imagers may yield comparable airborne performance. The choice of initial imagery acquisition for the remote sensing system is thus resolved; a thermal infrared imaging system can obtain imagery on which patches and slicks of oil pollutants can be readily discerned.

Densitometric color enhancement can aid in further discrimination of the tonal differences that distinguish oil slicks from the background water. Selected image density values are accentuated, while other density values are suppressed, to bring out a maximum contrast between selected image tones and the "background." In our test, a negative transparency of the thermal infrared image shown in Fig. 2 was processed through the Datacolor system. Figure 3 is a cartographic representation of the color-enhanced image produced on the Datacolor screen. The medium-dark and dark areas are stepped increments of density representing oil patches and slicks of varying thickness whose tonal image registered within one or another of these selected density ranges. The essentially unpolluted sea surface is shown as the lightest area.

The Datacolor film reader system, produced by Spatial Data Systems, Inc., of Santa Barbara, California, shares basic attributes and capabilities with a number of image-enhancing densitometers, some of which are propriatory custom-designed systems, others of which are commercially available. The Datacolor system can present the density values of a given photographic image as analog voltage levels of a video signal that can be displayed in color. An analog-to-digital converter operating at very high speeds (20 nanoseconds) continuously changes the analog voltage levels to discrete stepped values. Each single value is presented, in turn, to a number of digital-to-analog converters (three for each color), which produce the red, green, and blue voltage signals for the three electron guns of the color-monitoring display screen. The three colors can be mixed on the display screen to produce any desired hues, and the colors can be shifted to assign any hue to any selected density level. Quantitative density readings are obtained through a calibrated, photographic step wedge, which can be included as a reference. The density steps can be made to appear in different colors by adjustment of the color controls. The same colors will appear in all the areas of the image having the same density levels as the correspondingly rendered steps of the step wedge. The color enhancement of the image can automatically increase object-to-background contrast and can reduce a gradational variation to a limited number of discrete, incremental steps. This enhancement permits identification of any oil patches, slicks, and films that show even minor differences in density from the background water. Since a water body emits essentially as unity in thermal infrared, oil films that image as a density difference against this uniform background tone can be automatically enhanced and positively identified through this processing.

The Datacolor system also employs a digital planimeter. The planimeter provides a digital readout expressing the area of specific colored portions of the Datacolar display as percentage of the total image area. A push-button selector enables the operator of the system to measure quickly any one, or any combination, of the ten basic colors. A digital voltmeter then indicates what percentage of the total picture area is depicted in the selected color or colors.

The areas measured by the planimeter represent the proportion of the image that has a density range between the values of the two isodensity contours, as framed by the edges of the selected color. When the image being analyzed represents emitted thermal patterns, the planimeter directly reads the percentage of the scene that is emitting at selected values. Of the area imaged in Fig. 2, approximately 62 percent is within the density range interpreted as water. Barges, boats, and drilling platforms represent a further 0.5 percent of the area. Approximately 37.5 percent of the sea surface imaged here was covered by oil spill pollutants.

By allowing for linear distortion in the infrared scan, the authors have calculated the total area depicted in this image to be 2.51 square miles (6.5 km^2). Thus, an area of approximately 1.6 square miles (4.14 km^2) falls within the density range interpreted as water, and an area of about 0.9 square miles (2.33 km^2) falls within the density range interpreted as pollutants.

If we use a value of 0.01 inch (0.25 mm) as a representative average thickness of the oil layer in this part of the spill, some 155,000 gallons (590,000 liters) of oil are shown on this one image. The actual amount of oil present is a function of the estimate of thickness as applied to the measurement of the affected surface area. The total amount of oil spilled to create this coverage is further affected by allowances for evaporation and subsidence. The area measurement is basic to any such extrapolations.

We realize the limitations of assuming average thickness values without more research into this problem. Research here could be directed toward the investigation of appropriate sensor systems and the testing of their capability for automatic readout of oil slick thickness; there are a number of indications that this application is feasible. Another approach, which might be more readily implemented and initially more economical, would be the development of random sampling techniques to arrive at representative average thickness values for an entire oil slick or for specific image density values of an oil slick.

As shown above, the digital planimetry of a system like Datacolor can rapidly furnish a measure of the extent of pollution over a given area. From this areal measurement, a reasonable estimate of the volume of pollutants on the imaged area can be readily computed. To determine how much crude oil is actually involved, however, a number of other variables must be determined. The pollutants shown are not pure petroleum but are actually an emulsion of crude oil and seawater, which may vary in concentration over the spill area. The volume estimate would accordingly be reduced to reflect the accepted percentage value for water in the actual emulsion. On the other hand, oil can evaporate as much as one-fifth of its volume within an hour under properly turbulent conditions. The resulting volume value would thus have to be increased, in turn, to accommodate the complex corrections for evaporation. The question of *amounts* of polluting agent spilled, as distinct from areal extent of the pollution, may well become one of great legal and financial significance in the future. But even for determining the *amounts* of pollutants, accurate measurement of areal extent is a prerequisite. To our knowledge, areal extent has been determined up to now on the basis of educated guesswork and visual estimating. Digital planimetry, as we have utilized it, can now provide this basic information economically, automatically, repeatably, and accurately.

A functional remote sensor system would involve (i) sequential overflights of the oil spill area with a thermal infrared imaging system, at the highest altitudes commensurate with good imagery; (ii) densitometric color enhancement of the resulting imagery; and (iii) an automatic digital planimeter readout of the total areas under each of the selected image tones. This series of steps would provide a map, within acceptable accuracy limits, of the area affected by an oil spill; the map would show the distribution of oil patches and slicks at a given time and would provide a measure of the area actually covered by oil patches, slicks, and films. Sequential monitoring of the spill would add information on flow rates and behavior of the spill. The ambiguities that now affect oil spill estimates can thus be reduced to fairly small margins of error.

From such measures of areal extent, a number of extrapolations can be made regarding thickness of oil pollutants, volumes of pollutants involved, and thence flow rates. Volume estimates involve us in a number of variables that are difficult to measure by remote sensing and that are perhaps most economically measured on the surface. But, even here, knowledge of the areal extent to which these variables are to be applied is an a priori requisite—a requisite that would be supplied by the remote sensing system.

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1 May 1970