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Petroleum hydrocarbon inputs to the world's oceans are estimated to be about six million metric tons each year.[1] International interest in the study of spilled oil continues as evidenced by the technical papers originating during the past decade from the U.S.A.,[2-4] Canada,[5,6] The Netherlands,[7] Italy,[8] Japan,[9] and U.S.S.R.[10,11] An important aspect of oil film monitoring and control focuses on measurement of the total volume of spilled material. To this end the metric measurement of the film thickness is considered the most difficult dimension since the delineation of the horizontal spatial extent of a spill is possible using numerous techniques.

The remote airborne measurement of the oil film thickness using laser-induced water Raman backscatter was first theoretically proposed in 1976,[2] and feasibility of the practical field application was demonstrated in 1978.[3] The remote measurement of oil film thickness by means of laser-induced fluorescence extinction was actively proposed in a paper describing the laboratory investigation of the method by Visser.[7] He recognized that the fluorescence of naturally occurring dissolved organic matter (Gelbstoff) in the water can interfere with the oil fluorescence signal. However, based on long-wavelength (633-nm) laboratory investigations, the very important Gelbstoff contribution is unfortunately ignored in this ensuing derivation of the film thickness using oil fluorescence techniques. It is the purpose of this letter to point out (1) that the theoretical model of oil fluorescence by Horvath *et al.*[12] (and later inclusion of the water Raman spectral component by Kung and Itzkan[2]) contains the necessary constituents to provide for the natural background fluorescence that is also induced by the laser during the course of an oil thickness experiment; (2) how the various parameters of the model are obtained from typical airborne profile data; (3) that the water Raman backscatter (when available) may be used to assist further in the application of the data; and (4) the regions or water types over which the technique might be most useful or applicable.

In Fig. 1, curve (*a*) shows the background and oil fluorescence, the seawater Raman, and some of the quantities to be discussed for the situation where the airborne lidar is positioned over the oil slick. Curve (*b*) of Fig. 1 is an analogous situation for a lidar over seawater only. Figure 1 is essentially as presented in Ref. 3, but additional symbols have been added for discussion of the fluorescence depth technique for oil film thickness measurement. The notation used herein is primarily as found in Ref. 2. While the aircraft is over the slick the return signal K_i in the ith channel of the fluorosensor can be expressed as[2]

$$K_i = \eta_i P_0 \{1 - \exp[-(\kappa_e + \kappa_i)d]\} + \zeta_i P_0 \exp[-(\kappa_e + \kappa_i)d] + \delta_{ir}\psi P_0 \exp[-(\kappa_e + \kappa_i)d], \quad (1)$$

where the following notation is used:

η_i = fluorescence conversion efficiency in ith wavelength channel for an optically thick oil film;
P_0 = incident laser power;
κ_e, κ_i = extinction coefficient of the oil at the laser excitation wavelength and at any ith wavelength channel, respectively;
d = thickness of the oil;
ζ_i = fluorescent conversion efficiency of an optically thick seawater column exclusive of the water Raman;
ψ = Raman conversion efficiency of seawater;
δ_{ir} = delta function to select the Raman channel.

When the aircraft is outside or beyond the slick, $d = 0$, and the return signals are defined as J_i:

$$J_i = \zeta_i P_0 + \delta_{ir}\psi P_0. \quad (2)$$

Assume now that the water mass outside the slick is the same as present beneath the oil film. Evaluate Eqs. (1) and (2) at the same fluorescent wavelength $\lambda_i = \lambda_f \neq \lambda_r$ so that $i = f \neq r$. Combining the two resulting equations and solving for the thickness d yields

$$d = -\frac{1}{\kappa_e + \kappa_f} \ln\left(\frac{K_{f,\infty} - K_f}{K_{f,\infty} - J_f}\right), \quad (3)$$

where

$$K_{f,\infty} = \eta_f P_0. \quad (4)$$

Here $K_{f,\infty}$ is interpreted as the fluorescence signal intensity for an optically thick film at wavelength λ_f. The reason for this definition can be more clearly understood by evaluating

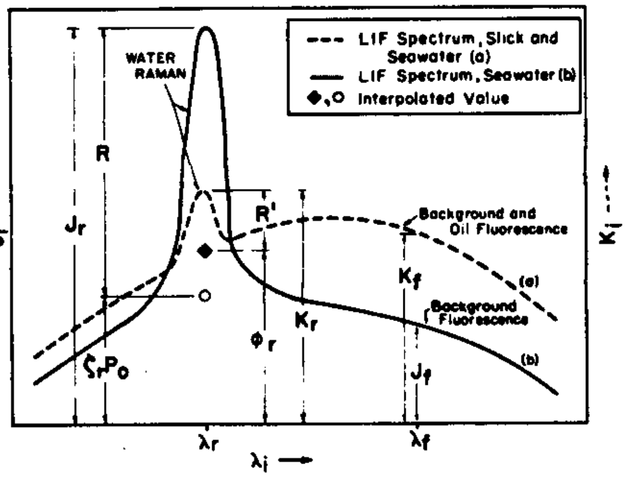

Fig. 1. Definition of several theoretical model parameters using the general shape of the laser-induced fluorescence spectrum from ocean water (a) having an optically thin floating oil film and (b) in the region surrounding the oil slick.

Eq. (1) at λ_f as d approaches large values. Thus to obtain the oil film thickness one must have (a) the extinction coefficients of the oil at the laser excitation and fluorescence wavelengths, (b) the fluorescence level from an optically thick portion of the oil, (c) the fluorescence level of the film portion whose thickness is to be measured, and finally (d) the background fluorescence. Equation (3) also shows how the background fluorescence of naturally occurring materials J_f must be treated. The background fluorescence must only be subtracted from the infinite thickness fluorescence level before normalizing the residual fluorescence $K_{f,\infty} - K_f$. Note that for the condition that the background signal vanishes ($J_f = 0$), the general result in (3) reduces to the special case considered by Visser.[7] The $J_f = 0$ is a physical condition which occurs in deep ocean areas where little organic material fluorescence is found.[3,13] In these types of water the fluorescence depth technique may offer little advantage over the water Raman suppression method.[3] The reason for this is that the water Raman backscatter is rather easily obtained since the attenuation of open ocean water is minimum. Ocean regions would, however, offer an excellent location to compare the Raman suppression and fluorescence depth thickness measurement techniques.

The $K_{f,\infty}$, K_f, and J_f components are illustrated in Fig. 2(a) for a hypothetical nonscanning flight line passage over a wind driven oil slick having an optically thick nontransparent head and a thinner tail. Using the implicit definitions in Fig. 2, Eq. (4) may be written

$$d = -\frac{1}{\kappa_e + \kappa_f} \ln \left(\frac{F'}{F}\right) . \qquad (5)$$

This illustrates more clearly that the thickness is related to the residual fluorescent component while over the slick F', normalized by the peak or background corrected saturated fluorescence component obtained from the optically thick portions of the slick F. Equation (5) may be used to calculate the oil film thickness of the spills by using the ratio of the fluorescence from the thinner regions F' to that in the optically thick area F. The extinction coefficients κ_e and κ_f for each oil must be separately measured in the laboratory using fresh oil samples.[7,14]

Figure 2(b) shows the seawater Raman signal variation expected in the lidar receiver channel centered at wavelength

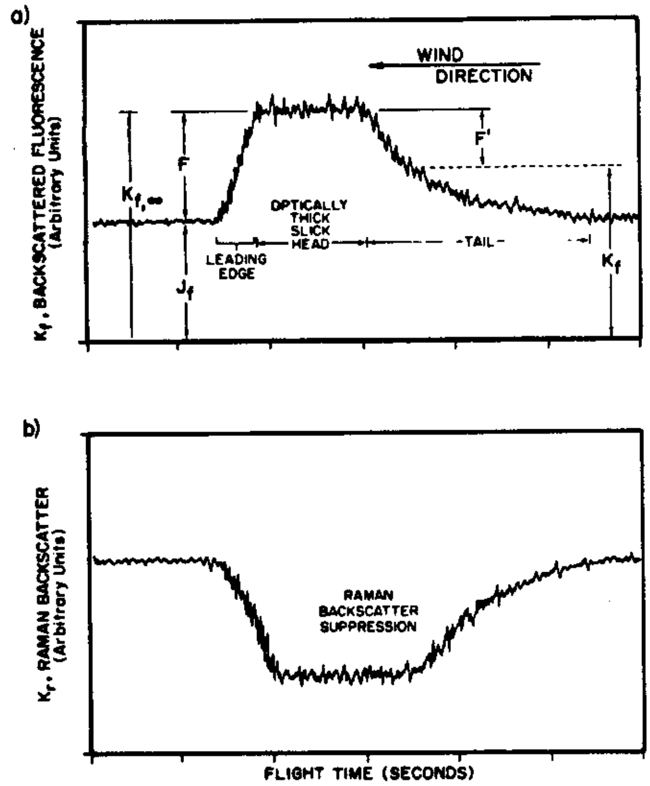

Fig. 2. (a) Fluorescence signature expected during a lidar overflight of an oil slick. (b) Typical Raman depression signature observed during lidar overflight.

λ_r during an overflight of an oil slick. This type of Raman signature has been reported previously[3] and is given here to illustrate the fact that one may use this signature to help define the optically thick regions of an oil slick for determination of F.

The fluorescence depth technique would actually be recommended for estuarine and riverine areas where the water is heavily laden with organics, $J_f \neq 0$. Here the absorption is so high that the laser beam penetration is severely reduced. (This is especially true for UV laser sources which are recommended for oil fluorescence work.[8]) Accordingly, little or no usable water Raman would be obtained for use with that thickness measurement method.

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