Modeling of thickness dependent thermal contrast of native and crude oil covered water surfaces

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1. INTRODUCTION

Remote sensing of crude oil spills on sea surfaces has been of great interest in environmental protection and disaster management. An effective sensor needs to detect contrast signatures between native and thin oil film covered sea surfaces. Optical techniques have been widely employed in environmental monitoring because they can rapidly scan a wide region. Among various optical remote sensing techniques, thermal imaging using mid to far infrared wavelengths has been successfully commercialzed in recent years, in part, because of the cost of detector technology has decreased. Also since solar radiation peaks in the visible (~500nm), infrared measurements at mid-far infrared wavelengths range are much less sensitive to solar interference [1].

In several studies of crude oil spillage, the researchers observed that the apparent day time contrast of native and crude oil covered sea surfaces depends on the thickness of the oil film [1-3]. Because the refractive index of oil is usually larger than water, the bulk emissivity of water is higher than that of oil by the difference in specular reflectivity. Therefore, bulk water appears to be hotter than bulk oil if their temperatures are the same. On sunny days, however, differential heating causes oil to be raised to a higher temperature than the surrounding water because of its higher absorption of solar radiation and lower specific heat, giving rise to the commonly observed contrast of native and crude oil covered sea surfaces in day time remote sensing of oil spills. It has also been observed that a reversal occurs when the oil film is thinner than around 50-150µm. A plausible explanation to this is that since the oil film is thin, it is essentially in thermal equilibrium with the water underneath and thus the oil appears cooler because of its intrinsically lower bulk emissivity. Aside from the thermal equilibrium case, we believe that the contrast variations can arise from thin film interference effect, a well studied subject in many different contexts. In oil spill detection, the only film thickness dependent contrast model we have identified in the literature are in the visible wavelengths [4,5] where thermal emission is negligible, but not in the thermal infrared. The film thickness dependent contrast is of great importance for accurate delineation of the oil contaminated area, as well as estimate of the oil film thickness. However, there is relatively little theoretical consideration on this topic and the phenomenon has remained largely unexplained.

In this paper, we investigate the thickness dependent thermal contrast using thin film interference theory. We employ two different modeling techniques: indirect method based on Kirchhoff's Law and direct method by summing over volumetric radiators. We show that the optical interference effect plays an important role in the oil-water contrast. In addition, we demonstrate that thickness variation alone can indeed introduce the historically observed contrast reversal.

2. METHODS

Emissivity (ε) is defined as the fraction a gray body emits relative to a black body at the same temperature. From Kirchhoff's law [6], one can show that the emissivity in a given direction is identical to the absorptivity at the same wavelength if it were incident along the same direction. In addition, based on energy conservation, the reflected (R), transmitted (Tr), and absorbed (emitted, ε) portions of energy sum to one. Therefore, the emissivity can be calculated by $\varepsilon = 1 - R - Tr$. Since most crude oils and water are optically thick in the infrared spectral range of interest, *i.e.*, with very high absorption, the penetration depth of infrared light is usually limited. When little light is transmitted through, the emissivity of bulk oil and water is simply $\varepsilon = 1 - R$. This expression permits determination of emissivity based on reflectance and has been termed as the "indirect" method [7]. On the contrary, emissivity can also be calculated directly via radiative transfer theory without using the Kirchhoff's law. The major advantage of the direct approach is that the film and the underlying material can be assigned different temperatures when total thermal radiance is the quantity of interest.

3. RESULTS AND DISCUSSION

Infrared optical properties of key crude oil constituents have been published by the American Petroleum Institute in the 60's [8]. In general, these hydrocarbons have higher real refractive index than water, and show a slowly upward trend from 8 to 14 µm. The extinction coefficient, on the other hand, has multiple peaks corresponding to the absorption features in a particular constituent. Overall, the extinction coefficients of these constituents are smaller than that of water in the 8-14 µm range. Optical properties of water have been well documented [9] and the real refractive index varies from 1.29-1.11, and the extinction coefficient from 0.034-0.37 as wavelength increases. We selected four representative hydrocarbon constituents, including, iso-octane, n-heptane, n-decane, and o-xylene for our calculations and present the results from iso-octane here. In each case, we calculated the normalized contrast, defined as the ratio of the differential radiance (radiance of an oil-covered water surface minus that of a clean water surface) and the water radiance. The complex refractive index of iso-octane and water at 8 µm are 1.385+i*0.0063 and 1.291+i*0.0343, respectively.

In Figure 1, we observe the upward trend of contrast as thickness increases given sufficient temperature differences. In addition, since contrast reversal is defined as zero-crossing of the blue trace, multiple contrast reversals are identified, suggesting that contrast reversal can occur entirely because of thickness variations at a single wavelength. Further, the results here demonstrate that the contrast can be negative even when oil is hotter than water as long as the film is thinner than some transition values. When the oil film becomes thinner than the transition values, the probability of observing negative contrast increases significantly. The results here support the historically observed thickness dependent contrast reversal in oil covered sea surfaces. We note that the results do not preclude the possibility mentioned earlier that thin oil film can be in thermal equilibrium with the water.

Figure 2 shows the observation angle dependence of the contrast. Since the Fresnel coefficients are highly polarization dependent, we use different color to denote various polarization states. We observe that the contrast reversals shift rightward and further departing of the two polarization states as the observation angle deviates from nadir. To examine how the contrast varies spectrally, we selected 4 different wavelengths for iso-octane. Because the optical properties at these four wavelengths (listed in each plot) are different, quite different results are observed in Fig. 3. In particular, the rate of the rising trend is dictated by the extinction coefficient of the hydrocarbon. We have also investigated the combination of multiple wavelengths and constituents and found that because of phase mismatch in the interference patterns, the transition thickness falls in a much narrower range. Therefore, a single contrast reversal is more likely to be observed with a broad band detector.

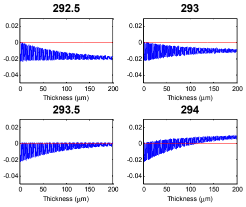

Figure 1. Contrast for different iso-octane temperatures. Water temperature was fixed at 293K and 8 µm wavelength was used in all calculations.

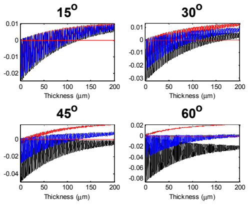

Figure 2. Contrast for different observation angles and polarizations: red, p-polarized; black, s-polarized; blue, unpolarized. Iso-octane at 8 µm wavelength is used as an example.

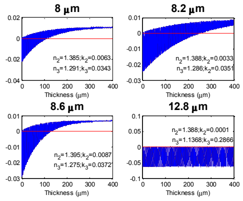

Figure 3. Contrast at different narrow wavelength bands for iso-octane at 294K: 8, 8.2, 8.6, and 12.8 µm.

4. REFERENCES

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