Using optical remote sensing model to estimate oil slick thickness based on satellite image

Y C Lu[1,2], W X Fu[3], Q J Tian[1,2], C G Lyu[1,2], and W C Han[4]
[1]Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Nanjing University, Nanjing, 210093
[2]International Institute for Earth System Science, Nanjing University, Nanjing, 210093
[3]Center for earth observation and digital earth, CAS, Haidian district, Beijing, 100094
[4]Petrochina Pipeline R&D Center, Langfang, 065000

E-mail: luyc.nju@gmail.com

Abstract. An optical remote sensing model has been established based on two-beam interference theory to estimate marine oil slick thickness. Extinction coefficient and normalized reflectance of oil are two important parts in this model. Extinction coefficient is an important inherent optical property and will not vary with the background reflectance changed. Normalized reflectance can be used to eliminate the background differences between in situ measured spectra and remotely sensing image. Therefore, marine oil slick thickness and area can be estimated and mapped based on optical remotely sensing image and extinction coefficient.

1. Introduction

Oil spills at sea can produce serious impacts on ecological environment and social economy than that on land for they can spread to more area in an oil slick with different thickness on the ocean surface [1], such as Deep-water Horizon oil spill accident in the Gulf of Mexico in 2010 [2,3,4]. Oil slick thickness should be an important parameter in marine oil spill remote sensing research.

Remote sensing technologies can be used to detect marine oil spill, such as multi/hyperspectral remote sensing [5, 6], thermal infrared [7], synthetic aperture radar (SAR) [2], laser fluorescence [8], and multi-angular remote sensing [9]. Oil slicks showed different optical characteristics and spectral reflectance within the visible spectrum bands [10, 11]. Therefore, optical remotely sensed images could be used to estimate oil slick thickness. Light interference theory can be used to describe the behaviour of the incident light onto oil slick layer. Oil slick thickness estimated models could be established with active or passive optical remote sensing [12-14]. Oil slick thickness can be determined by the appearance of characteristic interference patterns based on single-beam reflective laser optical interferometry [12]. In addition, two-beam interference theory has been used to interpret the behaviour of the refracted and reflected light when the incident sun light passed through the oil slick [13], an optical remote sensing model has been established in our previous work [14].

In this research, we collected the Hyperion image from EO-1 satellite which detected an oil spill in the Bohai Sea of China, seawater and oil from the same area. On the basis of the simulated data of laboratory experiment, the parameters of two-beam interference optical remote sensing model can be calculated by us [14]. Model analysis shows that the relationship of some parameters could be expressed in normalized reflectance to reduce the influence of background difference between satellite

imagery and simulated data, and then the oil slick thickness of oil spill accident on image data can be estimated based on this model and look up table of parameter.

2. Optical remote sensing model

The theoretical formula of two-beam interference is contains five parameters [13]. Based on the parameter analysis, a simple practical model has been deduced and has three parameters in our previous research [14]. The simple model can be written as Eq. (1).

$$R = a_0 + a_1 e^{-2a_2 d}. \tag{1}$$

Where

$$\begin{cases} a_0 = \left(R_{12}\right)^2 \\ a_1 = \left(T_{12} R_{23} T_{21}\right)^2 \\ a_2 = \dfrac{2a}{\cos\theta} \end{cases}. \tag{2}$$

R is the spectral reflectance of oil slick, d is the thickness of oil slick. They are the dependent variable and independent variable in this model. Respectively, the reflectivity of oil slick upper surface between oil slick and air is R_{12} and the transmissivity is T_{12}. The reflectivity of oil slick lower surface between oil slick and seawater is R_{23}. When the transmitted light from oil slick to air, the transmittance is T_{21}. a is the extinction coefficient and θ is the refraction angle of oil slick.

When the oil slick thickness approach to 0 or D value which is the maximum thickness that could be detected by optical remote sensing, the theoretical analysis showed that the model could be rewritten as Eq. (3)[14].

$$R_{oil} = R_{oil-\max} + \left(R_{water} - R_{oil-\max}\right) e^{-2a_2 d}. \tag{3}$$

Where $R_{oil-max}$ was the spectral reflectance of the oil slick which could be detected by optical remote sensing; R_{water} was the spectral reflectance of background water; R_{oil} was the spectral reflectance of oil slick, d was the oil slick thickness; a_2 was the extinction coefficient of oil in this case.

Eq. (3) can be rewritten as Eq. (4).

$$\frac{R_{oil} - R_{oil-\max}}{R_{water} - R_{oil-\max}} = e^{-2a_2 d}. \tag{4}$$

Equation (4) is important for optical remote sensing image processing, and $\dfrac{R_{oil} - R_{oil-\max}}{R_{water} - R_{oil-\max}}$ can be regarded as normalized reflectance (NR) of oil slick as Eq. (5).

$$NR = \frac{R_{oil} - R_{oil-\max}}{R_{water} - R_{oil-\max}} = e^{-2a_2 d}. \tag{5}$$
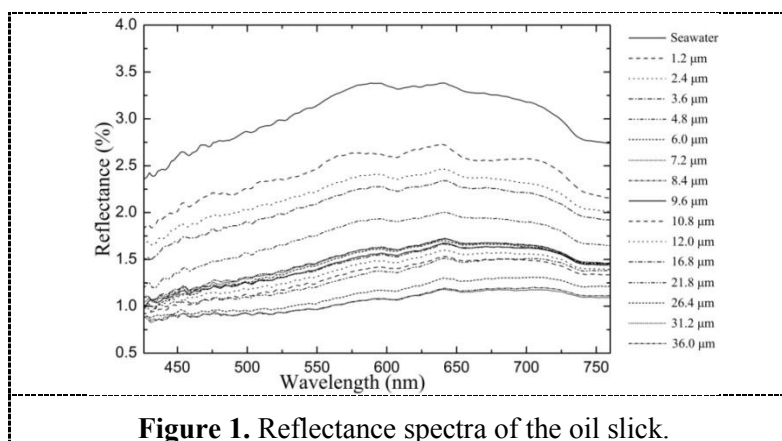
The normalization method has been used to reduce the influence of different background information between simulated data and satellite imagery. If we can obtain the extinction coefficient of oil (a_2) from simulated data, average spectral reflectance of background seawater (R_{water}) and spectral reflectance of the thickest oil slick from remote sensing image, and then we could used this model to estimate the oil slick thickness in satellite imagery.

3. Remotely sensed data

3.1. Simulation data

A laboratory experiment was designed to simulate the oil slick with different thicknesses floating on the water surface. The oil and seawater used in the laboratory measurements have been collected from the oil field in the research area. An oil spill accident has been detected by EO-1 satellite sensor in Bohai sea of China, 6th May 2007. Based on the laboratory experiment, the reflectance spectra of oil slicks with different thickness has been collected. As oil slick thickness increases, the simulated spectral reflectance

converges to the same value. The maximum oil slick thickness detected by optical remote sensing model is about 36 μm. Figure (1) showed that the reflectance spectra of seawater and oil slick which thickness change from 1.2 μm to 36.0 μm. The main detected bands were in visible wavelength from 380 nm to 760 nm.

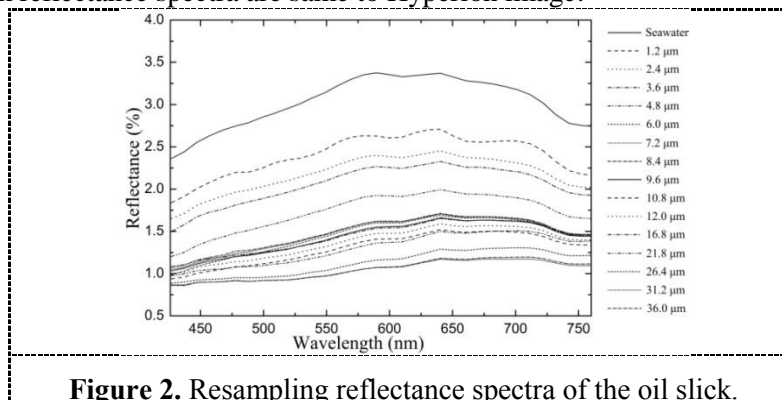**Figure 1.** Reflectance spectra of the oil slick.

3.2. Satellite data

The imaging spectrometers of Hyperion cover visible/near infrared and short-wave infrared wavelength from 356 nm to 2577 nm. The average spectral resolution is about 10 nm and the spatial resolution is 30 meter. The swath of Hyperion image is 7.5 Km [15]. The image used in this research is an L1T level image obtained at 10:27 AM (local time). Its Serial ID number is EO1H1200312007126110KZ, and the cloud cover less than 9%. The raw data can be change to a reflectance image through post-processing including the elimination of un-calibrated bands and bands seriously affected by water vapour, conversion of absolute radiation brightness value, and atmospheric correction. In this case, quantitative remotely sensed image (reflectance image) is an important basis for estimating oil slick thickness.

4. Results and discussion

4.1. Look-up table of optical remote sensing model parameter

As showed in eq. (3), if wanted to calculate the oil slick thickness based on a reflectance image, the parameter of a_2 must be known at least. This parameter is the inherent optical property of oil and can be calculated from laboratory experiment data. The oil slick reflectance spectra measured in laboratory experiment with spectral resolution of 1 nm should be resampled according to Hyperion image which spectral resolution is about 10 nm. On the basis of central wavelength and full width at half maximum (FWHM) of Hyperion image, we used Gaussian simulation method to resample reflectance spectra of experiment data. Figure (2) showed that the spectral resolution, central wavelength and FWHM of simulated oil slick reflectance spectra are same to Hyperion image.

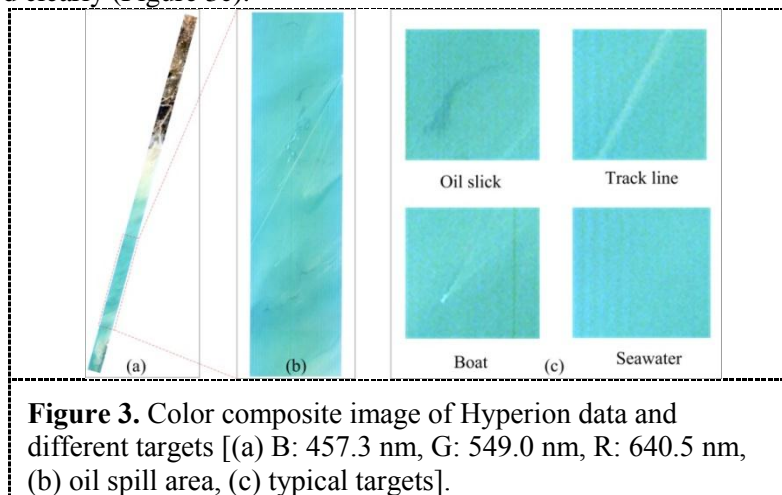**Figure 2.** Resampling reflectance spectra of the oil slick.

On the basis of these simulated data and eq. (1), the value of parameter (a_2) from 381 nm to 760 nm could be calculated. It is an inherent optical property parameter of oil slick as follow (table 1):

Table 1. Look-up table of paramater

Band (nm)	a_2	Band(nm)	a_2	Band(nm)	a_2	Band(nm)	a_2
426.8	0.185635	**518.4**	0.132395	**610.0**	0.120042	**701.5**	0.127811
437.0	0.17532	**528.6**	0.129194	**620.1**	0.120024	**711.7**	0.130157
447.2	0.166893	**538.8**	0.126703	**630.3**	0.119625	**721.9**	0.132295
457.3	0.160704	**548.9**	0.124698	**640.5**	0.119518	**732.1**	0.134156
467.5	0.15487	**559.1**	0.123493	**650.7**	0.120684	**742.4**	0.135876
477.7	0.148279	**569.3**	0.122452	**660.8**	0.120997	**752.4**	0.137698
487.9	0.143025	**579.4**	0.120968	**671.0**	0.121813	**762.6**	0.140141
498.0	0.13970	**589.6**	0.11981	**681.2**	0.123289		
508.2	0.135946	**599.8**	0.119761	**691.4**	0.125407		

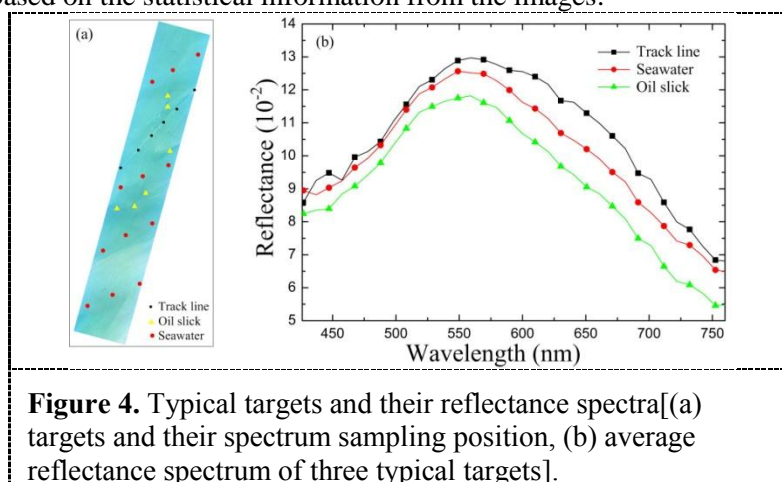*4.2. Spectral response analysis of Hyperion imagery*

The Hyperion image mainly covered the area near Liaodong Bay of the Bohai Sea which is China's continental sea (Figure 3a). The Liaodong Bay is an important area for producing oil in China [16]. The seawater in this area is the typical case 2 water which spectrum is influenced by chromophoric dissolved organic matter (CDOM or yellow substances), suspended particles, and phytoplankton. Therefore, the color of background seawater is blue-green in the true color composite Hyperion image for the highest spectra reflectance located in the wavelength range from visible blue band to green band (Figure 3b). Some typical targets included oil slick, track line, boat, and background seawater could be identified clearly (Figure 3c).

Figure 3. Color composite image of Hyperion data and different targets [(a) B: 457.3 nm, G: 549.0 nm, R: 640.5 nm, (b) oil spill area, (c) typical targets].
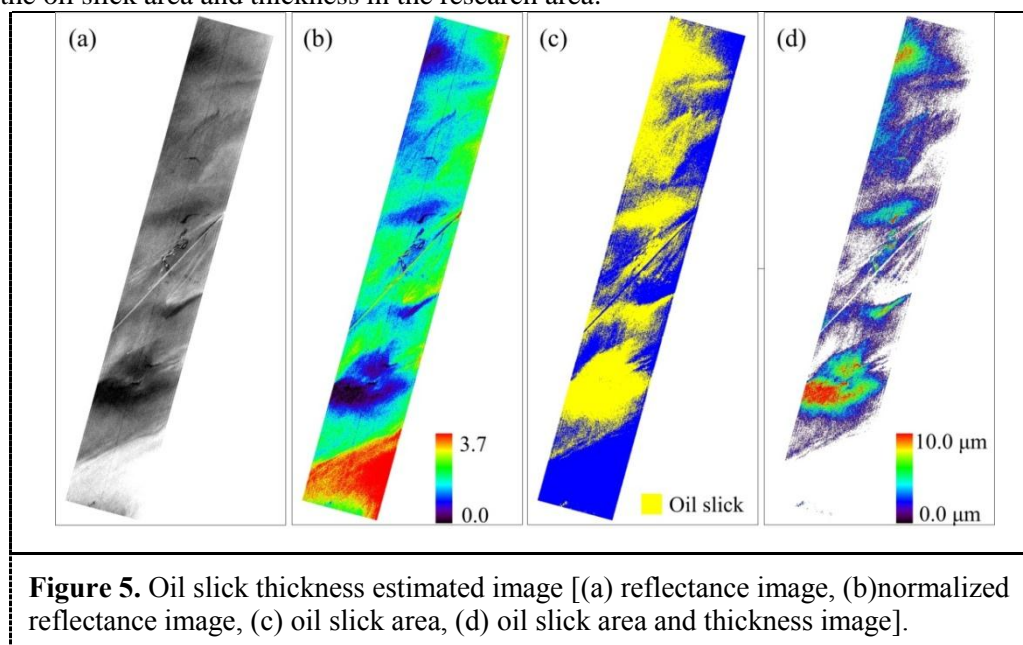
The average reflectance of background seawater and the reflectance of thickest marine oil slick are two important parameters for calculating normalized reflectance image from Hyperion data. We obtained the average reflectance of background seawater from image spectra sampling. Twelve spectra of back ground seawater without oil slicks, six typical spectra of the oil slick, and six spectra of seawater in the track line were collected and comparatively analyzed (Figure 4a). This average spectra are shown in Figure 4b. The reflectance spectrum of track line was greater than that of seawater and oil slick, because the water in track line included more suspended particle matter which increased more backscattering light to sensor. The reflectance of oil slick was obviously less than seawater and track line. The largest difference was located in the green and red bands, which are optimal bands for estimating oil slick thickness. The parameter R_{water} can be obtained from the average reflectance of

seawater in this figure. The parameter $R_{oil-max}$ is the reflectance of the thickest oil slick in this area and can be obtained based on the statistical information from the images.

Figure 4. Typical targets and their reflectance spectra[(a) targets and their spectrum sampling position, (b) average reflectance spectrum of three typical targets].

4.3. Oil slick thickness estimation from the Hyperion image

In our previous research [14], 580 nm is the optimal band for estimating oil slick thickness (Figure 5a). In this band, the reflectance of seawater is about 0.1228 and the thickest oil slick is about 0.1064. Based on these parameters and eq. (5), normalized image of band in 580 nm could be calculated and is shown in figure 5b. The value of normalized image is from 0 to 3.7. In the normalized reflectance image, the area with value greater than 1.0 should be due to turbidity, seawater in track line and boats, the area which value is less than 1.0 should be the oil spill area. Image mask were used to extract the oil spill area which showed yellow area in figure 5c. On the basis of normalized oil spill image, look-up table of parameter (a_2) and equation (5), oil slick thickness can be estimated and mapped. Figure 5d shows the oil slick area and thickness in the research area.

Figure 5. Oil slick thickness estimated image [(a) reflectance image, (b)normalized reflectance image, (c) oil slick area, (d) oil slick area and thickness image].

5. Conclusions

On the basis of the practical optical remote sensing model could be established to estimate oil slick thickness. Extinction coefficient is an important inherent optical property of oil and will not vary with the changed background seawater. Look-up table of it could be used to estimate the oil slick thickness

which has been formed from the same crude oil. In addition, normalized form of spectral reflectance in this model has the function of eliminating background seawater spectrum differences. Remotely sensed image normalization is another key basis of oil slick thickness estimation. The parameters of image normalization can be obtained based on the statistical information from the optical remotely sensed images. Therefore, if we knew the extinction coefficient, the oil slick thickness could be estimated based on optical remote sensing image using this model. Last but not the least, the stability of background seawater in image should be given more attention. Uniform stability reflectance of background seawater will be helpful in oil slick thickness estimation.

Acknowledgments

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