Assessing the Theoretical Suitability of Sentinel-2 and WorldView-3 Data for Hydrocarbon Mapping of Spill Events, Using HYSS

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Abstract—Identification of hydrocarbon oil in remote sensing images is often the first step in monitoring oil during spill events. Most remote sensing methods adopt techniques for hydrocarbon identification to achieve detection in order to model an appropriate cleanup program. Identification on optical sensors does not only allow for detection but also for characterization and quantification. Until recently, in optical remote sensing, quantification and characterization were only potentially possible using high-resolution laboratory and airborne imaging spectrometers (hyperspectral data). Unlike multispectral, hyperspectral data are not freely available, as this data category is mainly obtained via airborne survey at present. In this research, two operational high-resolution multispectral satellites (WorldView-3 and Sentinel-2) are theoretically assessed for their suitability for hydrocarbon characterization, using the Hydrocarbon Spectra Slope model (HYSS). This method utilized the two most persistent hydrocarbon diagnostic/absorption features at 1.73 µm and 2.30 µm for hydrocarbon mapping on multispectral data. In this research, spectra measurement of seven different hydrocarbon oils (crude and refined oil) taken on 10 different substrates with the use of laboratory ASD Fieldspec were convolved to Sentinel-2 and WorldView-3 resolution, using their full width half maximum (FWHM) parameter. The resulting hydrocarbon slope values obtained from the studied samples enable clear qualitative discrimination of most hydrocarbons, despite the presence of different background substrates, particularly on WorldView-3. Due to close conformity of central wavelengths and narrow bandwidths to key hydrocarbon bands used in HYSS, the statistical significance for qualitative analysis on WorldView-3 sensors for all studied hydrocarbon oil returned with 95% confidence level (P-value < 0.01), except for Diesel. Using multifactor analysis of variance (MANOVA), the discriminating power of HYSS is statistically significant for most hydrocarbon-substrate combinations on Sentinel-2 and WorldView-3 FWHM, revealing the potential of these two operational multispectral sensors as rapid response tools for hydrocarbon mapping. One notable exception is highly transmissive hydrocarbons on Sentinel-2 data due to the non-conformity of spectral bands with key hydrocarbon absorptions and the relatively coarse bandwidth (> 100 nm).

Keywords—Hydrocarbon, oil spill, remote sensing, hyperspectral, multispectral, hydrocarbon – substrate combination, Sentinel-2, WorldView-3.

I. Introduction

MONITORING of oil spills in terms of early detection and characterization is vital for protection and management of already fragile ecosystems [1]-[3]. Diverse remote sensing techniques have been developed to map hydrocarbon oil for the purpose of spill monitoring and management through detection of physical parameters relating to presence of oil, either on water, land or other earth surface features [4]-[8]. Among others, optical remote sensing offers direct detection via measuring light interaction with the chemistry of hydrocarbon oil. This light interaction, when measured with high resolution optical images such as laboratory and airborne imaging spectrometers, records absorption features that are diagnostic of hydrocarbon oil. These diagnostic absorption features result from overtone and combination bands used for detection, quantification, and characterization of hydrocarbon oil within near infrared and short wave infra-red region, particularly at 1.20 µm, 1.73 µm and 2.30 µm [9]-[13]. In order to check the performance of current operational high resolution multispectral satellite for hydrocarbon characterisation, Sentinel-2 and WorldView-3 were chosen to implement HYSS model. Since these absorption features are finer than the relatively broad spectral ranges in multispectral data, HYSS is a method that enables the of use multispectral data to achieve detection, quantification, and characterisation of hydrocarbon on water and some common background substrates.

With availability of data of limited or no cloud cover, this method holds the potential to be an inexpensive and fast approach for a remote spill assessment both on land and at sea, using free data from operational multispectral satellite [19]. Therefore, this research aimed to assess the theoretical suitability of Sentinel-2 and WorldView-3 multispectral data for HYSS method, in spill assessment and monitoring as required for after spill clean-up and remediation programs. Among other operational optical multispectral satellites, Sentinel-2 and WorldView-3 offer reflectance at short wave infrared channels at 20 meters or less, a resolution close to those achievable on airborne hyperspectral sensors such as AVIRIS.

Sentinel-2 is a high-resolution, wide-swath multi-spectral imaging satellite. It carries an optical instrument payload that samples 13 spectral bands at different spatial resolutions: four bands at 10 m, six bands at 20 m, and three bands at 60 m spatial resolution. The orbital swath width is 290 km, which potentially makes it suitable for monitoring of large spill events. This mission is based on a constellation of two identical satellites, Sentinel-2A and Sentinel-2B, launched separately. Similarly, WorldView-3 is a high-resolution multispectral satellite. Though its data are not free and have relatively small swath

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width (13 km), when compared to Sentinel-2 (290 km). However, it has finer spatial and spectral resolution, as well as a revisit time of 1 to 4.5 days which is useful for continuous monitoring of small and moderate spill sites.

These satellite systems are useful for present and future spill monitoring where cloud cover is limited as they are currently operational. Sentinel-2 has a 5-day revisit time and its data are freely available from Copernicus, an arm of the European Space Agency (ESA). Its coverage includes all continent lands and ocean water, making it a useful tool for continuous monitoring of marine, coastal and land future spill events. Sentinel-2 also provides both bottom and top of the atmosphere (BOA and TOA) reflectance coverage at short wave infrared (SWIR), which is useful for HYSS value for quantitative and qualitative estimation of hydrocarbon in spill events. Hydrocarbons have two persistent absorption features at 1.73 µm and 2.30 µm, both of which are vital for HYSS computation. Coincidentally, the two needed spectral channels at band 11 and band 12 on Sentinel-2A for HYSS have 20 m resolution, close to what is presumably obtainable on Advanced Visible and Infrared Spectrometer (AVIRIS) data (Table I). Though not centred at the precise wavelengths of the key hydrocarbon absorption features, these two central wavelengths are close enough to capture the HYSS but with a relatively broad bandwidth (91-185 nm). Similar to Sentinel-2, WorldView-3 has two spectral channels close to the key hydrocarbon absorption features in the short-wave Infrared. Band 4 corresponds to 1.71-1.75 µm while band 8 corresponds to 2.295-2.365 µm band width (Table II). Although with a relatively smaller swath width, narrow bandwidth, and high spatial/spectral resolution, WordView-3 can be adequate for monitoring small and medium sized spills. The two central wavelengths/bands used for HYSS application on these two satellites are shaded grey on Tables I and II. Remote sensing data from spill sites are not always available, since hydrocarbon oil disperses and evaporates within a relatively short timeframe. Also, while there are planned spaceborne hyperspectral satellites, very few are currently operational. Challenges for all EO satellites include cloud cover and coincidence of overpass times with the times of spill incidence. Multispectral sensors also have the problems stated in the latter, however, the data are often freely available. To characterize wide varieties of hydrocarbon oil, it is helpful and convenient to use data from a laboratory experiment. Therefore, in order to assess the theoretical suitability of Sentinel-2 and WorldView-3 data for hydrocarbon characterization using HYSS, hyperspectral datasets from laboratory spill experiments were used as a precursor by convolving these data to full width half maximum (FHWM) of both satellites. The resulting slope values obtained from this process are then analysed statistically using MANOVA for hydrocarbon characterization.

II. Dataset

The laboratory spill experimental data are comprised of seven different hydrocarbon oil (four crude oil and three refined petroleum oil) as contaminants over 10 different background substrates. These data were collected by [9] using ASD Field Spec™ Pro-FR2. The oil samples are heavy Crude oil (19.6 API), Intermediate Sour Crude oil (30.3 API, 1.8% sulphur), Intermediate Sweet Crude oil (32.2 API, 0.4% sulphur) and Light Crude oil (42.2 API) while the refined oils are diesel, gasoline, and motor oil. Spectra of these hydrocarbon oils are taken on a petri dish (with a Spectralon panel in the background) and also against 10 common additional backgrounds/substrates (i.e., asphalt, bentonite, a calcareous sand, calcite-dolomite crushed aggregate, concrete, gypsum, a soil with high (2.9%) organic content, Ottawa sand, a quartzitic beach sand, and senescent grass with accompanying leaf litter and underlying soil).

III. Method

In this research, we used HYSS to assess the Sentinel-2 and WorldView-3 data for hydrocarbon characterization. That is, different hydrocarbon oil types were discriminated using HYSS, despite having different substrates. The HYSS value is the ratio of the difference in reflectance at key hydrocarbon bands to the difference in their corresponding wavelength interval. This slope value is a reflection of light absorption by the oil, modified primarily by the dominant carbon chains in the oil. Ultimately, the depth of absorption features in the hydrocarbon oil determines the slope value. Therefore, the spectral slope value is a proxy for hydrocarbon characterization (i.e., the maximum depth of absorption features). Ideally, prominent hydrocarbon absorption maxima at 1.73 µm and 2.30 µm are used. However, spectral channels closer to these two wavelength positions have proved to yield comparable results [19]. In this research, band 11 and band 12 at a central wavelength of 1613 nm and 2202 nm were used to compute HYSS values for Sentinel-2 while band 4 and band 8 at 1.73 µm and 2.33µm were used for WorldView-3.

TABLE I
Spatial Resolution, Wavelengths, and Bandwidths of the Instruments on Sentinel-2 [14]

Spatial Resolution (m)	Band Number	S2A Central Wavelength (nm)	S2A Band width (nm)	S2B Central Wavelength (nm)	S2B Bandwidth (nm)
10	2	492.4	66	492.1	66
	3	559.8	36	559	36
	4	664.6	31	664.9	31
	8	832.8	106	832.9	106
20	5	704.1	15	703.8	16
	6	740.5	15	739.1	15
	7	782.8	20	779.7	20
	8a	864.7	21	864	22
	11	1613.7	91	1610.4	94
	12	2202.4	175	2185.7	185
60	1	442.7	21	442.2	21
	9	945.1	20	943.2	21
	10	1373.5	31	1376.9	30

In order to compute the HYSS, the laboratory spectra of oil types were convolved to the FWHM spectral resolution for Sentinel-2 and WoldView-3, respectively. Equation (1) depicts the mathematical expression for HYSS. These slope values were computed by extracting reflectance at band 11 and band

12 spectral channels that correspond to 1613 µm and 2202 µm centre wavelength positions for Sentinel -2 (see Table I) while band 4 and band 8 spectral channel corresponds to 1.73 and 2.33 µm central wavelengths for WorldView (see Table II).

TABLE II
SPATIAL RESOLUTIONS, WAVELENGTHS, AND BANDWIDTHS OF WORLDVIEW-3 [15]

	Band Number	Spectral Parameters: Central Wavelength (nm)	Bandwidth (nm)	Resolution Nadir/Off Nadir (m)
8 Multispectral regions	Coastal	425	400 - 450	1.24/1.38
	Blue	480	450 - 510	1.24/1.38
	Green	545	510 - 580	1.24/1.38
	Yellow	605	585 - 625	1.24/1.38
	Red	660	630 - 690	1.24/1.38
	Red edge	725	705 - 745	1.24/1.38
	Near IR 1	832.5	770 - 895	1.24/1.38
	Near IR 2	950	860 - 1040	1.24/1.38
8 SWIR Band	1	1210	1195 - 1225	1.24/1.38
	2	1570	1550 - 1590	3.7/4.10
	3	1660	1640 – 1680	3.7/4.10
	4	1730	1710 - 1750	3.7/4.10
	5	2165	2145 - 2185	3.7/4.10
	6	2205	2185 - 2225	3.7/4.10
	7	2260	2235 - 2285	3.7/4.10
	8	2330	2295 - 2365	3.7/4.10

$$S = \frac{a-b}{c-d} \quad (1)$$

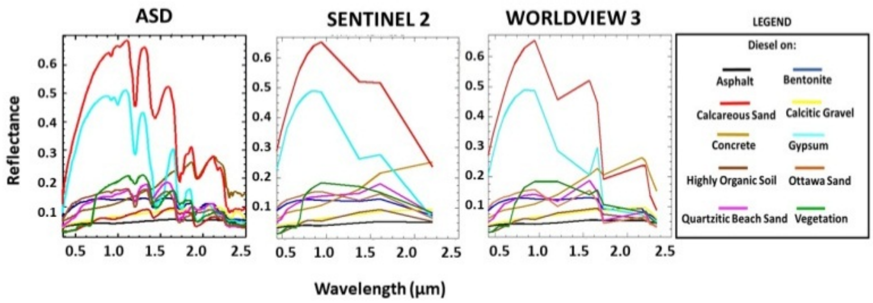
where a = Reflectance at wavelength position nearest to 2.30 µm; b = Reflectance at wavelength position nearest to 1.73 µm; c = Wavelength value of b (nearest to 2.30 µm); d = Wavelength value of a (nearest to 1.73 µm).

IV. RESULTS

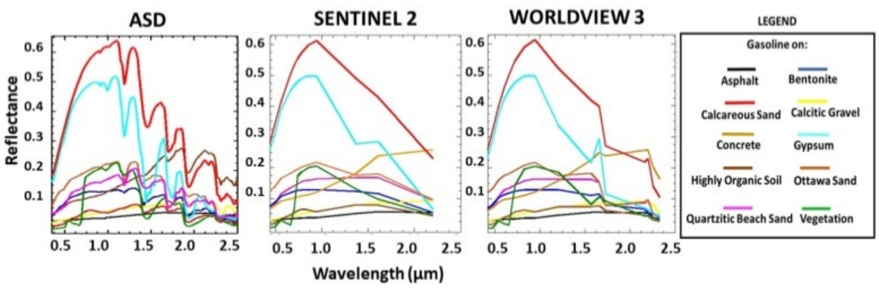
The slope values for all hydrocarbon-substrate combinations were computed for the library spectra (in ASD resolution (i.e., 1 nm), as well as the resampled spectra of Sentinel-2 and WorldView-3 FWHM. The response of these slope values to different oil type/substrate combinations, using the three sensors' FWHM are presented as spectra in Fig. 1. The bar charts in Fig. 2 are the HYSS results for all hydrocarbon oil/ substrate combinations obtained from the original ASD spectra and resampled spectra shown in Fig. 1. These slope values represent HYSS results from spectra of freshly applied oil on 10 different substrate backgrounds as discussed in Section II.

A. Discrimination of Oil Types

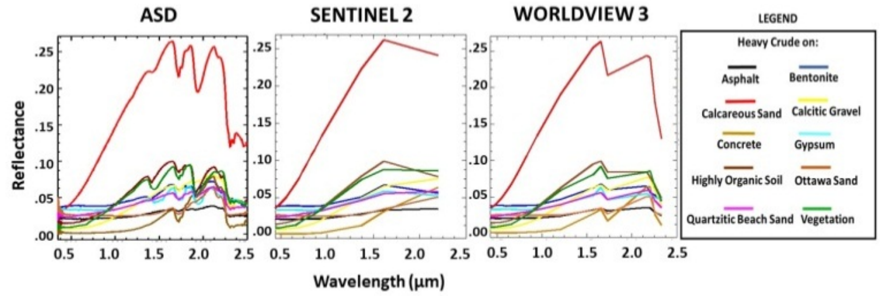
Representing magnitude of hydrocarbon slope values, Fig. 2 shows bar charts while Fig. 3 shows scatter plots for ASD data, and the resampled Sentinel-2, and WorldView-3 for all hydrocarbon-substrate combinations. In Fig. 2, each subplot is for one of the seven hydrocarbons, comprising four crude oils (heavy crude, light crude, intermediate sour crude, and intermediate sweet crude) and three refined products (e.g., gasoline, diesel fuel, and motor oil). Within each subplot, the HYSS value for each substrate is plotted, with one bar each for the original ASD measurement, in addition to the convolved values for Sentinel-2 and WorldView-3. Using HYSS, each hydrocarbon sample is distinguishable based on their slope values despite being on different substrates. HYSS variations are a function of not only the sensor, but also the hydrocarbons, many of which are partially (e.g., light crude) or highly (i.e., all three refined products) transparent in the SWIR, permitting substrate spectral features to influence results [9].



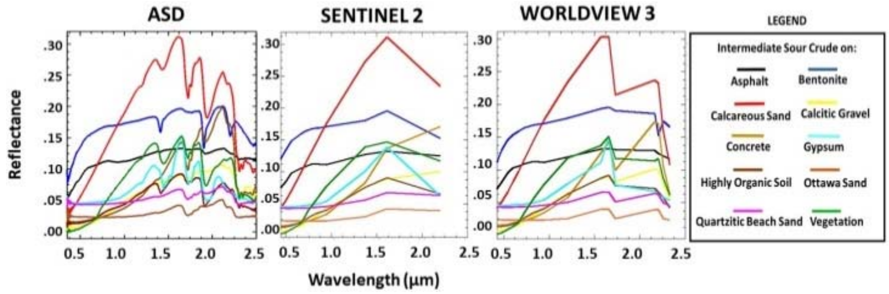
(a) Spectra of Diesel on Different Substrates



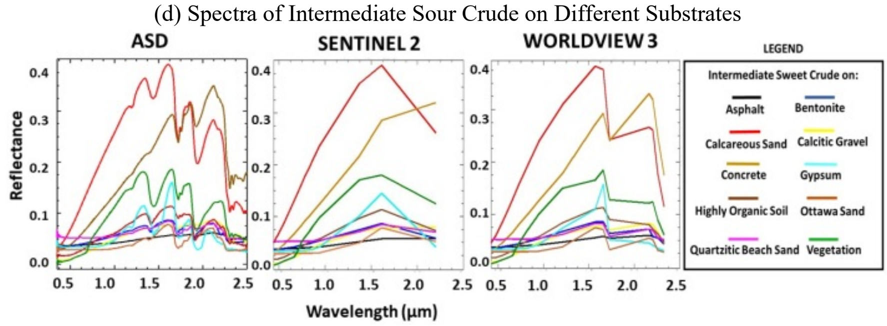
(b) Spectra of Gasoline on Different Substrates



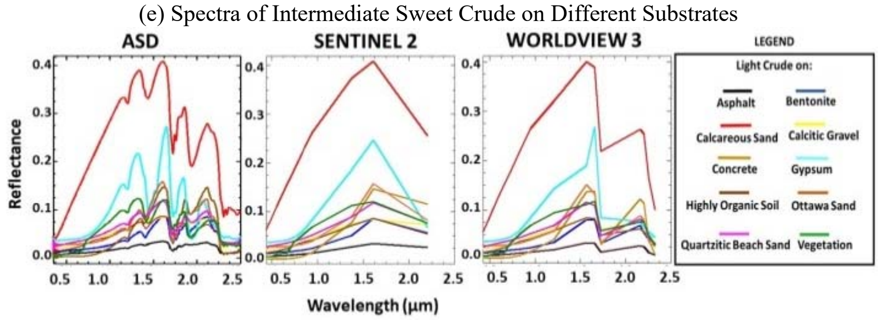
(c) Spectra of Heavy Crude on Different Substrates



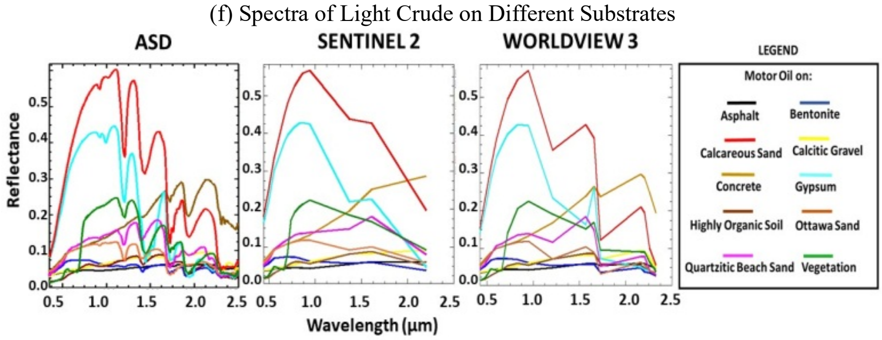
(d) Spectra of Intermediate Sour Crude on Different Substrates



(e) Spectra of Intermediate Sweet Crude on Different Substrates



(f) Spectra of Light Crude on Different Substrates



(g) Spectra of Motor Oil on Different Substrates

Fig. 1 Spectral profiles of seven different hydrocarbon oil–substrate combination from the original ASD measurements and resampled with Sentinel-2 and WorldView-3 spectral resolution (FWHM). Note that the y-axis is not the same in all plots

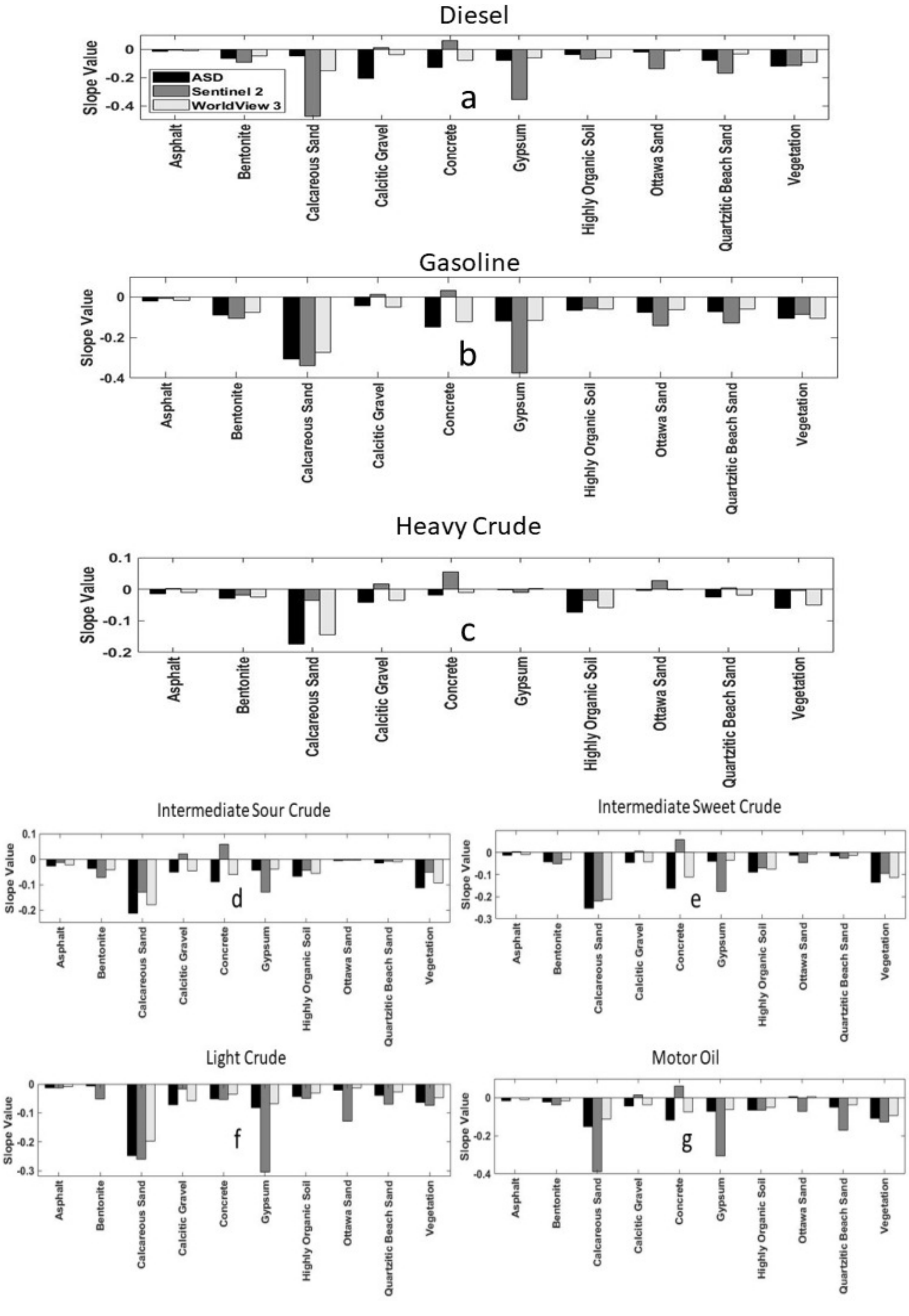


Fig. 2 Bar Charts of Slope values from ASD spectra and spectra from Sentinel-2 and WorldView-3 resolution (FWHM) for all hydrocarbon on 10 different substrates: (a) Diesel, (b) Gasoline, (c) Heavy Crude, (d) Intermediate Sour Crude, (e) Intermediate Sweet Crude, (f) Light Crude, and (g) Motor Oil

Fig. 3 is a combined correlation plot of HYSS values for hydrocarbon-substrates combinations from the ASD spectra measurements and other sensors presented in Fig. 2. Spectral mixing of these substrates (asphalt, bentonite, calcitic gravel, highly organic soil, concrete, gypsum, quartzitic sand, Ottawa sand, calcareous sand, and vegetation) affected the spectra slope value of each hydrocarbon oil differently. Most notably, calcareous sand, Ottawa sand, calcitic gravel, concrete, gypsum, quarzitic beach sand, and vegetation significantly influence HYSS values for the multispectral sensors (Black = Sentinel-2, grey = WorldView-3), causing them to deviate from linearity on the correlation plot (see black rings in Fig. 3). This behaviour is expected since the resampled data for the multispectral sensors (i.e., Sentinel-2 and WorldView-3) either do not intersect precisely with the hydrocarbon absorption maxima or have coarse spectral sampling with respect to the key hydrocarbon absorption bands used by HYSS. This is especially true for Sentinel-2 in instances where HYSS deviations produce slope values close to zero and positive values, mostly due to additional influence of concrete and calcitic gravel as background substrates (Figs. 2 (a)-(e), and (g)). Note that HYSS values for WorldView-3 (grey symbols) do not generally follow this trend, depicting a strong potential for hydrocarbon characterization on this sensor data using HYSS. This is expected since the spectral range of WorldView-3 short wave bands intersect well with the wavelength positions of key hydrocarbon diagnostic features, with only ~30 nm deviation at 2300 nm wavelength position. The calcareous sand and gypsum substrates are particularly ill behaved, largely due to a very large difference (~0.25) in reflectance between 1.73 µm and 2.30 µm, whereas all of the other substrates have values < 0.10 [9]. These substrate behaviours are particularly amplified on Sentinel-2 spectra due to incongruent bandpasses for both spectral channels used by HYSS. Similarly, both quartzic sands have very high transmission, especially the Ottawa sand, which results in stronger than expected hydrocarbon absorption features, and therefore, higher than expected HYSS values [16], [17]. This difference perseveres after liquid application due to some measure of transmission for all samples except for heavy crude and one intermediate crude at 1.73 µm and virtually no transmission by any liquid hydrocarbon at 2.30 µm. Notably, these liquids (asterisks and downward triangles, respectively) are usually outliers by producing lower than expected HYSS values, largely due to this lack of transmission and resulting near opacity at 1.73 µm. Liquids with much higher transmissions at 1.73 µm, such as diesel fuel (circles), motor oil (boxes), the light crude (diamonds), and intermediate sweet crude (sideways triangles) make up most of the HYSS values that are higher than expected. In order to sort through the complex mixtures of liquids and substrates, we used MANOVA to help determine how separable the hydrocarbon samples are from one other (see Subsection *B*).

Correlation of Spectra Slope Value from ASD against those from Sentinel-2 AND WorldView-3

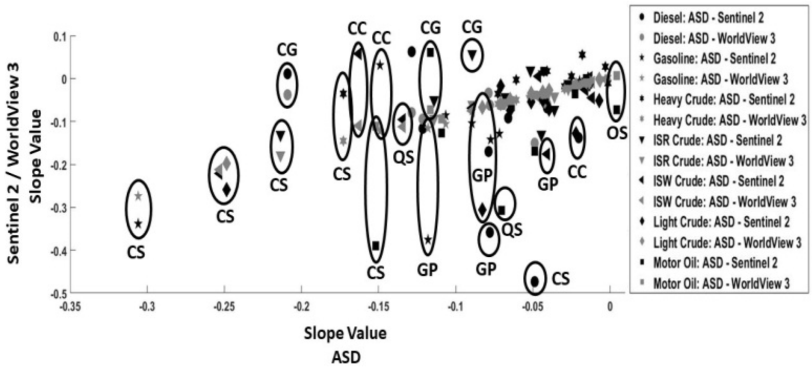


Fig. 3 Correlation of HYSS values for all oil types on substrates at resolution of ASD against that of Sentinel-2 and WorldView-3, showing the deviation of slope value from linearity between ASD measurements and convolved SNETINEL and WorldView-3 values due to the spectral response of substrates (Calcareous Sand -CS, Ottawa Sand -OS, Quartzitic Beach Sand -QS, Calcitic Gravel -CG, Concrete -CC and Gypsum - GP) and the effect of FWHM of the three sensors on HYSS

TABLE III
CORRELATION AND P - VALUES OF SLOPE VALUE OF DIFFERENT OIL TYPES FOR SENTINEL-2 AND WORLDVIEW-3

Oil types	Coefficient of Correlation (R) and P - Value	
Resolution	ASD – Sentinel-2	ASD – WorldView-3
Diesel	0.10 / 0.355 ↓	0.01 / 0.729↓
Gasoline	0.37 / 0.063 ↓	0.99 /<0.001
Heavy Crude	0.36 / 0.068 ↓	0.99 /<0.001
Intermediate Sour Crude	0.18 / 0.217 ↓	0.98 /<0.001
Intermediate Sweet Crude	0.18 / 0.226 ↓	0.98 /<0.001
Light Crude	0.43 / 0.040 ↓	0.99 /<0.001
Motor Oil	0.22 / 0.168 ↓	0.96 /<0.001

B. Statistical Analysis of the MANOVA Results

Table III presents the average correlation value and corresponding p value for each liquid hydrocarbon across all of the substrates for the Sentinel-2 and WorldView-3 sensors compared to the ASD lab spectra. Unlike the lab spectra, both multispectral sensors cannot measure the location of absorption maxima with ≤ 10 nm of precision and do not have the narrow bandpasses of a hyperspectral sensor that can isolate the spectral range of the hydrocarbon absorption features. This is especially true for Sentinel-2, which has both central wavelength for HYSS computation > 100 nm away from HYSS channels (1613.7 nm instead of 1730 nm and 2202.4 nm instead of 2300 nm). Conversely, WorldView-3 has bandpasses in the spectral range of hydrocarbon absorption features, with both central wavelengths < 50 nm from a HYSS channel (i.e., at exactly 1730 nm and 2330 nm instead of 2300 nm). For this reason, Sentinel-2 has poorer correlation coefficient (< 0.50) and high P values (> 0.05) across all studied hydrocarbon oils. These poor values are a reflection of the relatively broad spectral range of Sentinel-2 SWIR bands and the dynamic nature of both the hydrocarbon liquids and the some of the substrates over these large bandpasses (> 100 nm). For this reason, the slope value changes from negative to positive values on some substrates, as shown in Figs. 2 and 3. As a result, both the correlation coefficient and level of significance for these affected plots are much lower than they are for WorldView-3 (shown by downward arrow in Table III). Slope values for WorldView-3 are strongly correlated with those obtained from ASD lab spectra across all studied hydrocarbon oils (> 0.95) with high significance (< 0.001), except for diesel. The bandpass consistency for correlation strength is also depicted in

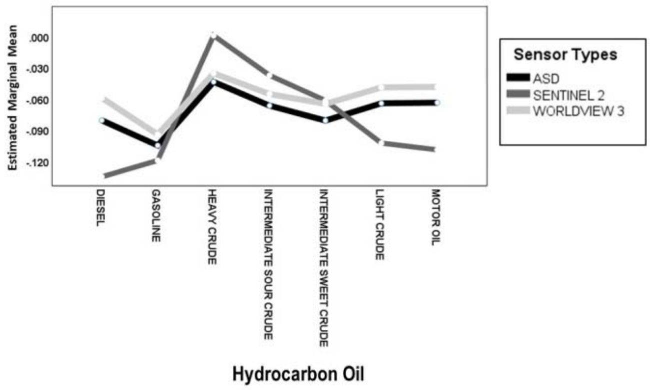
Fig. 4. Fig. 4 plots the estimate margin means of slope value obtained across the three sensors (ASD Fieldspec, Sentinel-2, and WorldView-3) and for background substrate. The corresponding dots on each oil type revealed how close marginal means for each oil types were modelled on each sensor types. For instance, slope value for heavy crude was best modelled by WorldView-3 compared to Sentinel-2 (while using ASD as standard). Slope values for other oil types are also closely model on WorldView-3 than on Sentinel-2. These plots demonstrate similar values between WorldView-3 and the ASD FieldSpec, unlike those from the Sentinel-2. Note for instance, the wide variation of estimated marginal mean slope value from Sentinel-2 compared to those from WorldView-3 for diesel, heavy crude, light crude and motor oil on this plot. This explained why relatively low significance was obtained for diesel and particularly for heavy crude, light crude and motor oil on the MANOVA results (Table IV) This implies the effect of incongruent bandspass of Sentinel-2 on the model result. That is, model with only WorldView-3 and ASD data will perform better. The incongruent bandpass of Sentinel-2 also exaggerates the effects of background substrates on the marginal means of slope value used by the model (Fig. 4).

TABLE IV
MULTIFACTOR ANOVA OF SPECTRA SLOPE VALUE FOR HYDROCARBONS OILS AGAINST SPECTRAL RESOLUTION AND SUBSTRATES

Hydrocarbon on Substrates	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Diesel on Substrate	0.105	9	0.012	1.052	0.437
Resolution	0.030	2	0.015	1.391	0.266
Gasoline on Substrates	0.203	9	0.023	5.993	0.000
Resolution	0.003	2	0.002	0.153	0.859
Heavy Crude on Substrates	0.035	9	0.004	3.295	0.013
Resolution	0.011	2	0.006	3.179	0.058
Intermediate Sour Crude on Substrates	0.061	9	0.007	3.962	0.005
Resolution	0.004	2	0.002	0.646	0.532
Intermediate Sweet on Substrates	0.107	9	0.012	4.424	0.003
Resolution	0.002	2	0.001	0.180	0.836
Light Crude on Substrates	0.272	9	0.030	6.103	0.000
Resolution	0.015	2	0.008	1.259	0.300
Motor Oil on Substrates	0.121	9	0.013	2.226	0.065
Resolution	0.020	2	0.010	1.205	0.315

In order to assess the qualitative discrimination of hydrocarbon oil-substrates combination, a MANOVA was used to test the significant difference of HYSS slope values as a basis for discrimination. The results show significance at a 95% confidence level (see Table IV). Discrimination of hydrocarbon-substrate combinations by slope values are highly significant with p value < 0.05 at resolution for ASD, Sentinel-2, and WorldView-3 for most hydrocarbon oils, except for some highly transmissive oils such as diesel and motor oil. This implies that both sensors are relatively successful in discriminating different hydrocarbon oils, despite the presence of different background substrates. In other words, at the resolution of the two sensors, spectral slope values are not significantly different with 95% confidence level (p value $<$ 0.05) for the qualitative analysis, except on highly transmissive hydrocarbon oils. Spectral slope values for most hydrocarbon-substrates are significantly distinguishable at the spectral resolutions of Sentinel-2 and WorldView-3, despite the broad spectral bandpasses of both sensors (particularly for Sentinel-2), as revealed on the correlation plots (Fig. 3). However, the poor performance of HYSS results on these transmissive oils (especially diesel and motor oil) and heavy crude oil are mainly a function of poorly resolved HYSS value from Sentinel-2 due to a broad spectral bandpass as shown Fig. 4. On both sensors, the effect of background substrates on HYSS values also caused a relative deviation from the original ASD spectra measurements as shown in Fig. 5.

Estimated Margin Mean of Hydrocarbon Slope Values Across Different Sensors Types



Estimated Margin Mean of Hydrocarbon Slope Values Across Different Sensors Types (due to the effect of Substrates)

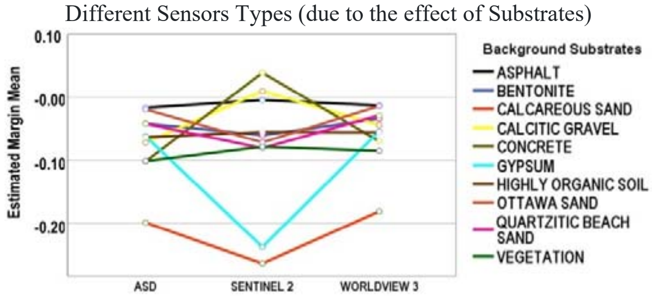


Fig. 4 estimated marginal different of slope value across ASD, Sentinel-2 and WorldView-3. Slope values from WorldView-3 are closely related to that of ASD while slope values from Sentinel-2 is largely different from that of ASD

V. DISCUSSION OF RESULT

Theoretical performance of Sentinel-2 and WorldView-3 for characterization of hydrocarbons on different substrates has been demonstrated using the HYSS method. Contrast within HYSS values obtained from both sensors and statistical analysis suggests a significant relative qualitative discrimination of different hydrocarbon oils on different substrates at 95% confidence level, particularly on WorldView-3. Comparing the corresponding slope value of ASD data to those from resampled spectra, bandpass location, combined with highly reflecting substrates, especially calcareous sand, gypsum, and quartzitic sands produce HYSS values that deviate from a well behaved linear spectral response. Nevertheless, slope values for hydrocarbon-substrates analysed in the research are statistically

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significant for discrimination at Sentinel-2 and WorldView-3 FHWM resolution. These results indicate that these two multispectral sensors are potential tools for qualitative characterization of hydrocarbons, even on a wide variety of substrates. The discriminative ability of HYSS for hydrocarbon-substrate can be explained as the model's ability to distinguish oils and refined products is a function primarily of differing transmission values for each sample, combined with the underlying substrate's reflectance. Other factors, such as absorption maxima at values different than 1.73 µm (e.g., gasoline) and differing asymmetric absorption feature shapes (e.g., triplets (gasoline) vs. doublets (all other samples)) are also likely contributors.

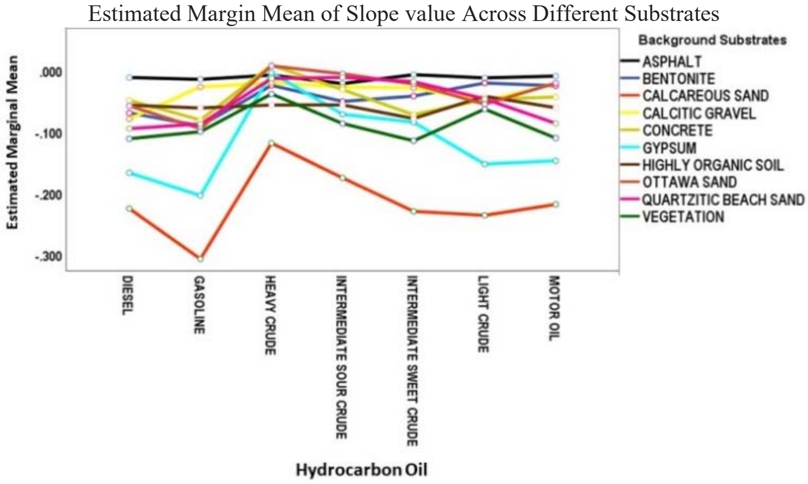

Fig. 5 Estimated effect of different substrates on the slope value across different Hydrocarbon Oil types. That is, a measure of effect of substrates on slope values from different hydrocarbon oil types (Diesel, Gasoline, Heavy Crude, Intermediate Sour Crude, Intermediate Sweet Crude, Light Crude and Motor Oil). Notably, Calcareous Sand, Gypsum, and Concrete (highly reflecting substrates) caused lower spectra slope than the average recorded slope value for all hydrocarbon oils

Beside the bandpass non-conformity of both sensors to HYSS band channels, particularly on Sentinel-2, the majority of observed deviations of the HYSS value (Figs. 3 and 4) are due to the effects of varying background substrates as shown in Fig. 5. These two factors seem to exacerbate the low discriminative effect of HYSS on highly transmissive hydrocarbon/substrates as seen in Fig. 4. In order words, these sensors' response is more promising for hydrocarbon mapping with a relatively homogenous background for spill assessment, by constraining the interference effect of the known background from spill site. This may proffer a solution to the common ambiguity of qualitative analysis of hydrocarbons on different substrates, particularly due to reflectance interference from key spectral bands of substrates [9], [18]. The complex interference of spectra of studied hydrocarbons shown in Figs. 2 and 3 influenced the resulting HYSS value but most crude and refined oils were significantly discriminated across all background substrates, particularly on WorldView-3 (see Table IV). Even on challenging substrates, result of HYSS from WorldView-3 provides significant discriminative power for all studied hydrocarbon oils on common substrates at 95% significance, as shown on Table III. That is, each hydrocarbon-substrate combination has significantly different slope value sufficient for discrimination.

VI. Conclusion

We have demonstrated the performance of Sentinel-2 and WorldView-3 data for HYSS hydrocarbon characterization. Discrimination of oil types achieved on all investigated hydrocarbon-substrate combinations are statistically significant for WorldView-3 but not for Sentinel-2. As expected, WorldView-3 performs especially well with the HYSS method since this sensor has a relatively narrow bandwidth for a multispectral sensor and spectral band channels that correspond well with key hydrocarbon spectral features. Unlike Sentinel-2, this sensor possesses sufficiently fine resolution for qualitative characterization as all results returned very high statistically significance with varying background substrates (95% confidence interval). The spectral responses of highly reflective and transmissive substrates limit the HYSS results, as these substrates produce results that deviate from the linear responses seen in the ASD data. WorldView-3 data seem to offer a relative measure of characterization that can be deployed for broad area search particularly for mapping land-based hydrocarbon spillage and seepage.

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