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Hyperspectral ultraviolet to shortwave infrared characteristics of marine-harvested, washed ashore and virgin plastics

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Abstract

Combating the imminent environmental problems associated with plastic litter requires a synergy of monitoring strategies, clean-up efforts, policymaking and interdisciplinary scientific research. Lately, remote sensing technologies have been evolving into a complementary environmental monitoring approach that might have future applications in the operational detection and tracking of plastic litter at repeated intervals covering wide geo-spatial areas. We therefore present a dataset of spectral reflectance measurements from the ultraviolet (350 nm) to shortwave infrared (2500 nm) of synthetic hydrocarbons (plastics). Spectral reflectance of wet and dry marine-harvested, washed ashore and virgin plastics was measured outdoors with a hyperspectral spectroradiometer. Samples were harvested from the major accumulation zones in the Atlantic and Pacific Ocean suggesting a near representation of plastic litter in global oceans. We determined a representative bulk average spectral reflectance for the dry marine-harvested microplastics and identified common absorption features at ~931, 1215, 1417 and 1732 nm, dataset available at https://doi.org/doi:10.21232/jyxq-1m66 (Garaba and Dierssen, 2019a). Similar absorption features were identified in the dry samples of washed ashore plastics, dataset available at https://doi.org/doi:10.21232/ex5j-0z25 (Garaba and Dierssen, 2019b) . The virgin pellets samples consisted of eleven polymer types typically found in floating aquatic plastic litter, dataset available at https://doi.org/doi:10.21232/C27H34 (Garaba and Dierssen, 2017). Magnitude and shape features of the spectral reflectance collected were also evaluated for two scenarios involving dry and wet marine-harvested microplastics, dataset available at https://doi.org/doi:10.21232/r7gg-yv83 (Garaba and Dierssen, 2019c). Reflectance of wet marine-harvested microplastics was noted to be lower in magnitude but had similar spectral shape to the one of dry marine-harvested microplastics. In addition, we include metrics for a subset of marine-harvested microplastic particle morphology including sphericity and roundness. These open-access datasets will be useful in radiative transfer analyses exploring the effect of plastics to ocean colour remote sensing and developing algorithms applicable to remote detection of floating plastic litter. The dataset is expected to improve and expand the scientific evidence-based knowledge on optical characteristics of common plastics found in aquatic litter.

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1 Introduction

The amount of plastic litter in the natural environment is growing exponentially, and this challenge has led to a huge demand for integrated and sustainable monitoring strategies (Lebreton et al., 2018;Maximenko et al., 2016;G20, 2017;Werner et al., 2016). One of these widely considered tools that can provide a complementary avenue of wide geo-spatial and spectral information about plastics in natural waters has been remote sensing (Maximenko et al., 2016). Current key requirements expected from remote sensing of floating plastics from an interdisciplinary perspective are 'detect, identify, quantify, track' capabilities. Feasibility studies centred on these four requirements have shown promising prospects in remote sensing of floating and submerged litter (Garaba et al., 2018;Aoyama, 2018;Kako et al., 2012;Topouzelis et al., 2019). Although current efforts are promising there is a need to advance remote sensing of plastics and adapt future sensors to generate plastic related end-product. In line with this, a new generation of satellite missions (e.g. PRISMA – Italian Space Agency, EnMap – German Aerospace Centre, PACE – National Aeronautics and Space Administration) is anticipated to improve remote sensing of the environment through hyperspectral observations from the ultraviolet (UV) to shortwave infrared spectrum (SWIR). Of course these future missions are not dedicated to plastic litter studies, they are likely to be an essential knowledge-base of high quality, hyperspectral, wide geo-spatial coverage information pertinent to plastics. Satellite missions are going to be complemented by observations from unmanned aerial systems, aircrafts and high altitude pseudo-satellites.

A limited number of high quality hyperspectral measurements of plastic types found in marine litter have been reported or are in open-access repositories. We therefore conducted measurements from the UV – SWIR with the goals to contribute towards (i) creating a high quality baseline hyperspectral reflectance dataset of weathered plastics being washed ashore or floating in the oceans (ii) identifying absorption features of naturally weathered plastics, (iii) demonstrating the high reflectivity of plastics compared to other optically active constituents of the oceans, (iv) creating an open-access spectral reference library for improved radiative transfer simulations and (v) proposing algorithms essential to 'detect, identify, quantify, track' plastics. We present the detailed steps that were completed to acquire these measurements of the virgin types and naturally weathered plastics found in marine and land-based litter.

2 Methods and Materials

2.1 Samples

We used a set of specimens consisting of macroplastics (diameter > 5 mm) and microplastics (diameter < 5 mm). The macroplastics were collected during clean-up activities along the west coastline of the United States of America (USA), now being used to create awareness under the theme 'Washed Ashore: Art to Save the Sea', a travelling art exhibition in USA. At

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the time of experiment around midday on 25 March 2015 the exhibit was at the Mystic Aquarium in Connecticut. We believe these objects (buoys, handles, bottle caps, containers, styrofoam, ropes, toys, diving fins and nets) had undergone natural weathering at sea and/or on land based on careful visual inspection with particular interest on shapes, type of original object and colour. The macroplastics had different colour shades ranging from blue, green, yellow, orange, peach, beige, ivory to white.

Marine-harvested microplastic samples were obtained from the west North Atlantic ocean using a Neuston net (mesh size = 335 µm) in the top 0.25 m seawater layer (Law et al., 2010). After collection by with the nets, the microplastics were left to dry followed by separation by hand before storage in glass scintillation vials at Sea Education Association archives. In order to explore the effect of particle size on the bulk spectral reflectance these microplastics were further grouped after successive filtration through metal sieves with mesh sizes ranging (i) 1.68 - 2.00 mm, (ii) 2.00 - 2.38 mm, (iii) 2.38 -2.83 mm, (iv) 2.83 - 3.36 and (v) 3.36 – 4.00 mm. A very small amount of samples was left after the sieving and was not used for any further analysis. Additional marine-harvested microplastic specimens used in this study were collected from Kamilo Point in Hawaii, USA by Bill Robberson and Anna-Marie Cook (Environmental Protection Agency, USA). The Kamilo Point was not sieved as the North Atlantic samples due to the quantity that was available, we therefore classified it as aggregated microplastics. Dry virgin pellets of varying opacity were chosen to represent the polymer source types that have been identified in specimens harvested from sediments and aquatic sampling (GESAMP, 2015;Hidalgo-Ruz et al., 2012). The polymer types considered were polyvinyl chloride (PVC), polyamide or nylon (PA 6.6 and PA 6), low-density polyethylene (LDPE), polyethylene terephthalate (PET), polypropylene (PP), polystyrene (PS), fluorinated ethylene propylene teflon (FEP), terpolymer lustran 752 (ABS), Merlon, polymethyl methacrylate (PMMA).

The variability in colour and shape of the marine-harvested microplastics and washed ashore macroplastics is a plausible representation of the plastic litter that is being found in the aquatic and terrestrial environment but may not necessarily represent all the plastic litter found globally.

2.2 Spectral reflectance measurements

The spectral reflectance (*R*) measurements of all specimens were conducted outdoors during daylight hours using an Analytical Spectral Devices (ASD) FieldSpec® 4 hyperspectral spectroradiometer (Malvern Panalytical, USA) between 350 and 2500 nm. An 8.5° foreoptic was used during the spectral measurements of the dry macroplastics at a 45° nadir angle 10 cm above target object. A 99 % Spectralon® diffuse plaque (Labsphere, USA) was used for white referencing and optimizing the integration time of the spectroradiometer. Spectra were recorded first over the plaque then from 5 different spots of each dry macroplastic object and then over the plaque. A single spectral measurement was derived as an average of 20 continuous automated scans. Microplastics were aggregated on a black rubber mat to create an optically dense target before each spectral measurement (**Figure 1**). This black rubber mat was used as background target because it had a negligible spectral reflectance

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over the spectrum range observed. At a 0° nadir angle, a 1° foreoptic was placed 8 cm above the aggregated microplastics on the black mat and reference measurements were made using a Spectralon® diffuse plaque (Labsphere, USA). Again here, a spectrum was first collected over the plaque followed by 10 measurements over the aggregated dry microplastics and then finally over the plaque. Before each measurement over the dry microplastics, we gently mixed the particles to rearrange the orientation and location of the particles in an effort to get a best representative bulk spectral signal. A similar approach was used to perform further spectral measurements of wet microplastics in filtered seawater with a salinity of 30 ppt. Our selected setup was determined to be optimum and minimized instrument and user shading. Natural outdoor lighting allowed us to measured spectral reflectance with good signal-to-noise from the UV to SWIR, with the exception of certain SWIR regions where the atmosphere is opaque. These regions of the spectrum are shown as gaps in the continuous spectrum, from 1350 nm to 1410 nm and 1800 nm to 1950 nm in the dataset. Average spectra was calculated for each set of repeated measurements. All data processing, statistics and plots were generated in MathWorks MATLAB. Similarity in spectral shapes was determined using the robust spectral contrast angle (Θ). Degree of spectral shape similarity was defined as very strong ($0° \leq \Theta \leq 5°$), strong ($5° < \Theta \leq 10°$), moderate ($10° < \Theta \leq 15°$), weak ($15° < \Theta \leq 20°$) and very weak ($20° < \Theta$) (Garaba and Dierssen, 2018). Absorption features noted by visual inspection were validated by derivative analysis of the measured *R*.

Figure 1 Experimental setup with the aggregated (A) dry and (B) wet marine harvested microplastics. A black neoprene rubber was used as a background in a dark spray painted container to mitigate background light during spectral reflectance measurements.

2.4 Microplastic Particle morphology

A Marathon electronic digital calliper was used to measure the size distribution of dry marine-harvested microplastic particles. Additional particle descriptors included sphericity, roundness, and a qualitative description of colour. Particle sphericity and roundness were determined according to a qualitative scale (Powers, 1953).

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3 Results

3.1 Macroplastics

Spectral reflectance of the different dry washed ashore macroplastics (Garaba and Dierssen, 2019b) had significant differences in the visible spectrum related to the intrinsic colour of each object (**Figure 2**). Blue objects peaked around 450 nm, green objects around 550 nm whilst the white objects had a flatter reflectance in visible wavelengths. Beige and ivory coloured object had rapidly increasing reflectance in the visible, an eightfold reflectance magnitude rise was note from 400 nm to 700 nm. Yellow, peach and orange object also had increasing reflectance in the visible but not as pronounced as in the beige and ivory objects, ranging from a three to fourfold increase in reflectance. Overall, the highest reflectance was noted on the beige object R = 0.88 around 850 nm. For all the objects, the reflectance peaked in the NIR followed by a general decrease in the SWIR with several absorption features resulting in localized dips and peaks. Despite the variations in the spectral magnitude and shape, absorption features common to all the macroplastics were observed at wavebands centred close to 931 nm, 1045 nm, 1215 nm, 1417 nm, 1537 nm, 1732 nm, 2046 nm and 2313 nm (**Figure 2**). The location of the absorption features was validated and confirmed by derivative analyses of each respective spectrum.

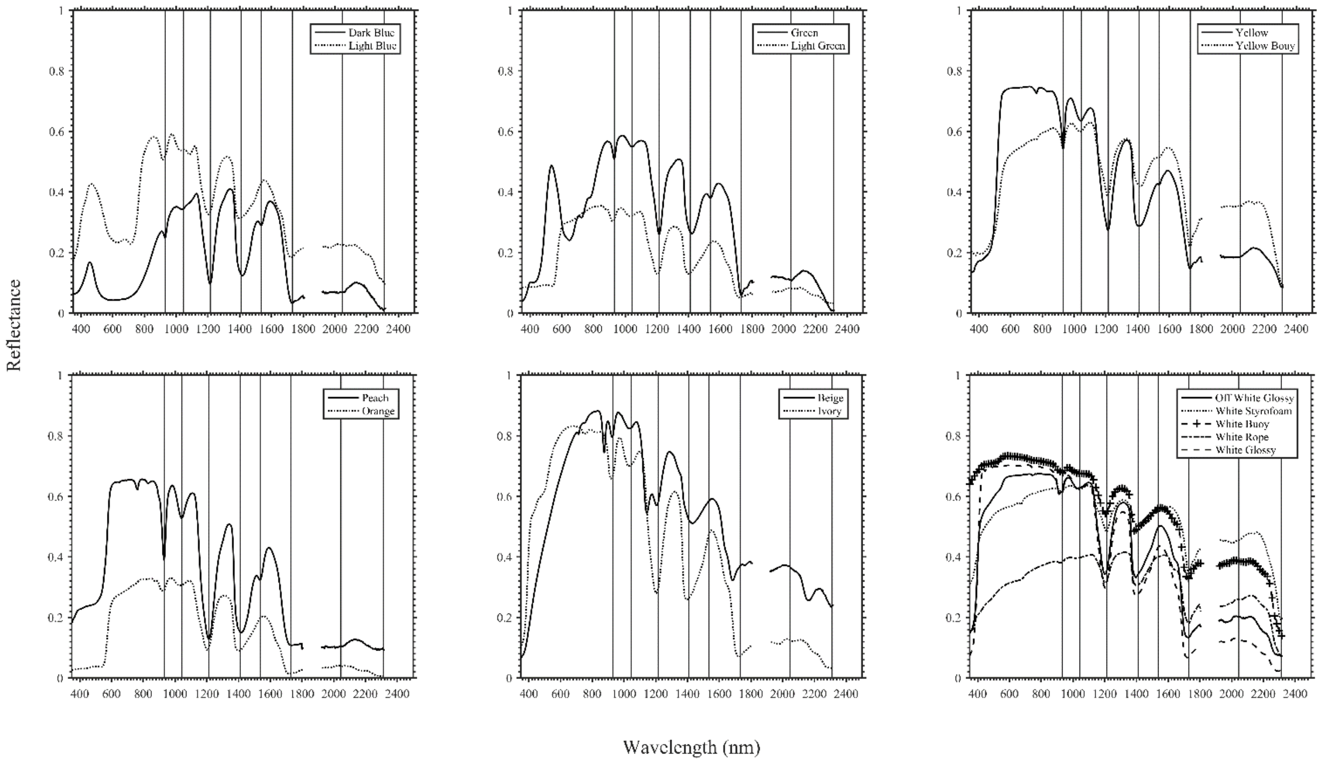

Figure 2. Spectral reflectance of dry washed ashore macroplastics harvested along the western coast of the USA. Absorption features noted in marine-harvested microplastics are highlighted by the vertical lines.

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3.2 Marine-harvested microplastics

Spectral reflectance of the dry marine-harvested microplastics (Garaba and Dierssen, 2019a) increased with wavelength reaching highest values in the NIR at 850 nm then decrease towards the SWIR wavebands. All spectra were close to uniform in both spectral shape (mean Θ < 5°) and magnitude (percentage ranges < 40 %) compared to the macroplastics. A non-parametric Kruskal-Wallis one-way analysis of variance was utilized to determine if any differences existed in the measured spectra of the dry marine-harvested microplastics. The statistical test suggested no significant differences ($p < 0.05$) in the spectral reflectance from 350 to 2500 nm. We therefore determined a representative dry marine-harvested microplastic spectral endmember (**Figure 3**). Absorption features identified in the dry washed ashore macroplastic specimens (**Figure 2**) were also found in the dry marine-harvested microplastics (**Figure 3**).

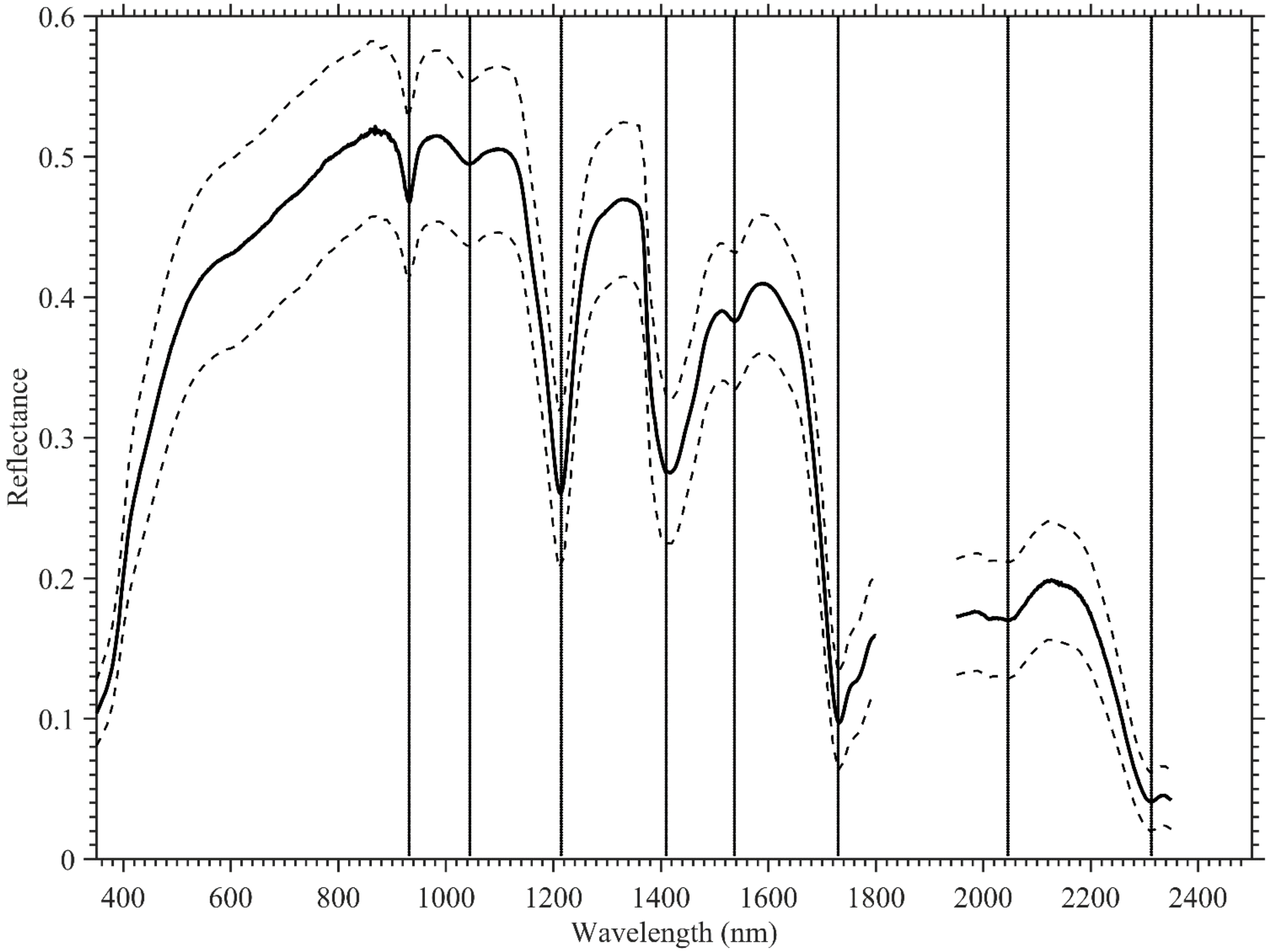

Figure 3. Endmember spectral reflectance with 1 standard deviation continuous error bars of the dry marine-harvested microplastics. Identified unique absorption features are highlighted by the vertical lines.

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Wet marine-harvested microplastics (Garaba and Dierssen, 2019c) had identical absorption features found in the dry marine-harvested specimens (**Figure 4**). However, the magnitude of *R* decreased by 12 % in the UV to 90 % in the SWIR due to the presence of water mixed with the samples. Average decrease in the measured R was 56 ± 23 %.

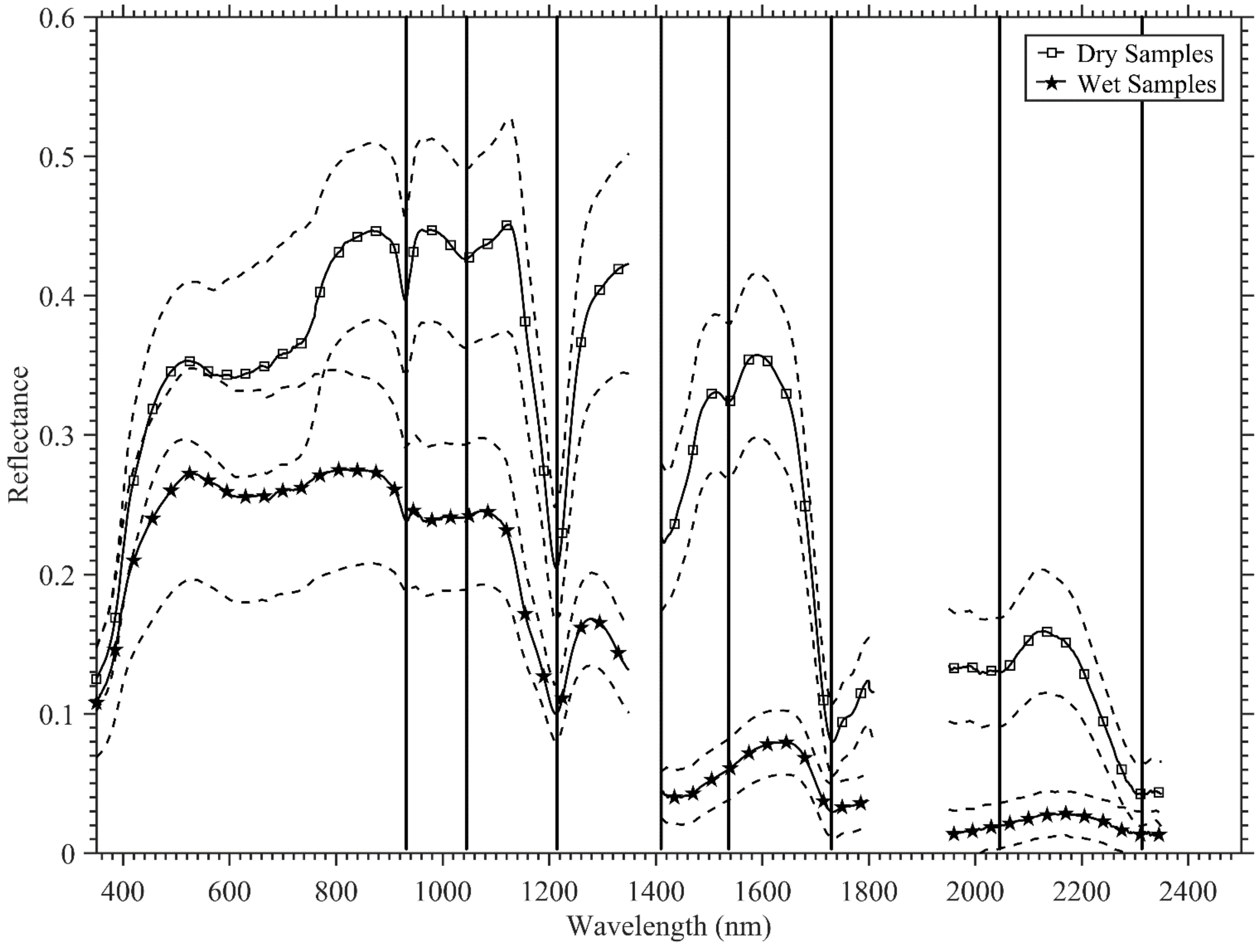

Figure 4. Mean bulk spectral reflectance of dry and wet marine-harvested microplastics with 1 standard deviation continuous dashed error bars. Absorption features noted in marine-harvested microplastics are highlighted by the vertical lines.

3.3 Virgin pellets

Spectral properties of the dry virgin pellets (Garaba and Dierssen, 2017) varied in magnitude and shape (**Figure 5**). However, two specimens of PA did show very strong similarities (Θ = 2.1°) although the apparent opacity of PA 6 was lower than that

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of PA 6.6. FEP was generally flat in the NIR to SWIR. Overall, the highest reflectance was observed in the specimens of ABS, PMMA and PVC whilst the lowest was observed in PET. Only FEP and PVC were noted to have a strong reflectance in the SWIR > 1900 nm with $R > 0.4$. The absorption features that were identified in the marine-harvested and washed were also found to be consistent with those in virgin pellets (**Figure 5**).

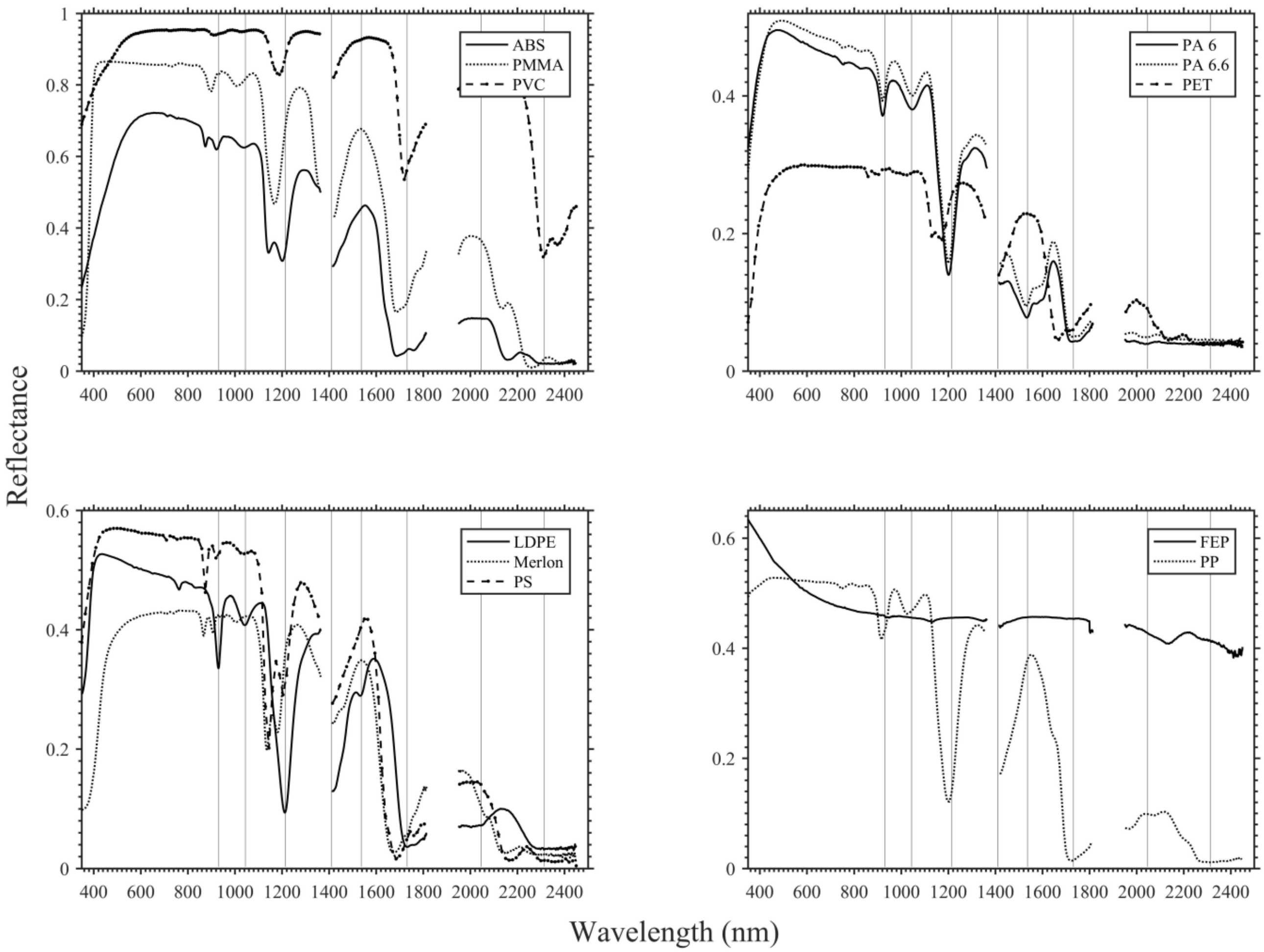

Figure 5. Spectral reflectance of dry virgin pellets and absorption features found in marine-harvested and washed ashore plastics highlighted by the vertical lines. Absorption features identified in marine-harvested microplastics are highlighted by the vertical lines.

3.4 Morphology of dry marine-harvested microplastics

Morphometric measurements were completed on a total of 47 microplastic particles from different size classes (**Table 1**). The particles were brittle and could fracture with handling. Sphericity of the observed particles ranged from low to high sphericity

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whilst the roundness was between sub-angular to very angular (**Table 1**). Dry virgin pellets common ocean plastic litter had varying opacity of the colour white.

Table 1. Microplastic particle side distribution and colour.

Length (mm)	Width (mm)	Height (mm)	Colour	Sphericity	Roundness
7.72	3.25	2.44	green	high	very angular
9.96	5.59	1.94	white	low	very angular
9.34	3.81	2.36	white	low	very angular
3.94	4.56	1.54	white	low	very angular
7.17	4.57	1.50	green	high	very angular
5.65	3.76	2.16	white	low	very angular
3.97	3.43	3.14	white	low	subangular
7.56	4.48	0.90	white	low	very angular
6.71	4.11	1.91	white	high	very angular
7.45	4.15	2.22	green	high	very angular
6.50	4.32	1.90	white	low	very angular
8.08	4.51	2.04	white	low	very angular
6.86	4.03	1.56	white	low	very angular
6.64	3.63	0.82	green	low	very angular
7.55	4.62	0.71	white	low	very angular
5.51	4.91	1.59	white	low	very angular
8.50	4.46	1.61	black	low	very angular
5.63	4.49	1.90	white	low	very angular
8.32	4.45	2.00	white	low	very angular
6.28	4.04	1.03	white	low	very angular
4.26	3.94	1.77	white	high	subangualr
5.55	4.94	1.40	white	high	very angular
5.04	3.79	0.90	white	high	very angular
5.89	4.43	0.91	white	high	very angular
6.47	4.57	1.75	white	low	very angular
13.07	3.82	0.42	white	low	very angular
4.50	4.29	1.35	white	low	sub angular
4.62	4.35	2.09	white	low	sub angular
6.57	4.69	1.37	white	low	very angular
17.21	4.58	0.36	white	low	very angular
7.77	5.32	0.60	white	low	very angular
5.19	4.28	1.26	white	high	very angular
3.85	2.71	2.62	white	high	very angular
6.14	4.41	0.85	white	high	very angular

10.54	3.66	0.35	white	low	very angular
5.59	4.25	1.62	white	high	very angular
8.29	4.66	1.01	white	low	very angular
10.16	4.15	0.89	white	low	very angular
15.08	4.38	0.25	white	low	very angular
7.33	4.34	0.68	white	high	very angular
6.30	4.00	0.61	white	high	very angular
8.52	5.77	0.42	white	high	very angular
7.17	5.64	1.23	white	high	very angular
4.93	4.28	1.09	white	high	subangular
6.35	5.34	0.77	white	low	very angular
6.68	3.67	0.62	white	low	very angular
7.64	4.46	0.65	white	high	very angular

4 Data availability

Quality control was performed according to the guidelines of SeaDataNet. All the datasets are in open-access via the online repository EcoSIS spectral library https://ecosis.org/. The dry marine-harvested microplastics spectral data are available at https://doi.org/doi:10.21232/jyxq-1m66 (Garaba and Dierssen, 2019a). Washed ashore plastics spectral data is available at https://doi.org/doi:10.21232/ex5j-0z25 (Garaba and Dierssen, 2019b). The virgin pellets spectral data is available at https://doi.org/doi:10.21232/C27H34 (Garaba and Dierssen, 2017). Dry and wet marine-harvested microplastics spectral dataset available at https://doi.org/doi:10.21232/r7gg-yv83 (Garaba and Dierssen, 2019c).

5 Conclusions

We have established an open-access dataset of hyperspectral reflectances of dry washed ashore macroplastics, dry marine-harvested microplastics, artificially wetted marine-harvested microplastics and virgin pellets. The dataset provides some of the first measurements that can be assimilated into radiative transfer modelling to improve scientific knowledge on the contribution of plastic litter to the bulk signal reaching remote sensing sensors. Furthermore, such knowledge about the hyperspectral characteristics of micro and macroplastics litter can be used to evaluate the capabilities and application of current multispectral sensors in remote sensing efforts. Using spectral response functions of current remote sensing tools (airborne, unmanned aerial systems, high altitude pseudo-satellites, satellites) it is also possible to simulate the spectral signature of our dataset, this information would be crucial in the design of future or planned remote sensing tools.

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Author contribution

SPG and HMD contributed equally to the experiment and manuscript preparation.

Competing interests

The authors declare that they have no conflict of interest.

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