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Proof of concept for a model of light reflectance of plastics floating on natural waters

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ABSTRACT

Remote sensing of plastic littering natural waters is an emerging field of science with the potential to provide observations on local to global scales. We present the verification of a theoretical reflectance model of sunlight interacting with a water surface littered with buoyant plastic objects. We measured a few common litter items of different polymers as well as shapes, transparencies, and surface roughnesses. Spectral reflectance measurements in the field were backed up with measurements in the laboratory of coefficients of total and diffuse reflectance, transmittance and absorption. We evaluated a single-band algorithm for 850 nm wavelength and a dual-band algorithm using a second wavelength at a polymer absorption band between 1660 and 1730 nm. Both algorithms were plastic litter type specific. Our findings show that for interpreting spectral remote sensing of floating plastic, physical properties that control geometrical optics should complement information about the absorption spectra of the polymer.

1. Introduction

1.1. Background

Remote sensing (RS) of plastic pollution of natural waters is still in its early stages despite increasing concern about the environmental impacts and the lack of long-term, large scale monitoring. Each year an estimated 4.8 to 12.7 million metric tons (MT) of plastic enters the oceans from land and without waste management, plastic litter entering the ocean is predicted to increase by an order of magnitude by 2025 (Jambeck et al., 2015). Schmidt et al. (2017) estimate the global plastic debris inputs from rivers into the sea alone to range between 0.41 and 4 MT per year. Plastic persists in the environment for very long times (centuries); it can be lost from the sea by sinking to the bottom, beaching, degradation, and ingestion by animals. While ultraviolet light of the sun and chemicals dissolved in seawater degrade the plastic, breaking waves and collisions fragment macroplastics (>5 mm) into smaller and smaller pieces and finally into microplastics (<5 mm). Exactly what happens to marine plastic litter is uncertain as global budgeting exercises find significantly less material on the ocean surface than expected (Cózar et al., 2014; Eriksen et al., 2014; van Sebille et al., 2015). Some surveys of sea surface plastic debris have been undertaken in the global oceans (e.g., Law et al., 2010, 2014; Cózar et al., 2014, 2017; Eriksen et al., 2014; Lebreton et al., 2018) but there are still large data gaps. Three largely independent ocean circulation models have produced global microplastic distribution maps (Lebreton et al., 2012; Maximenko et al., 2012; van Sebille et al., 2012). The models agree reasonably well within the centres of the gyres where plastic debris accumulates and concentrations are high, but they strongly differ in the tropics, the high latitudes, and the Eastern Mediterranean (van Sebille et al., 2015). In the gyre centres, the weight density of plastic pollution is dominated by the largest size class (>200 mm) and estimated to be in the order of 10,000 g km^{-2} (Eriksen et al., 2014). Lebreton et al. (2018) recently reported exponentially increasing levels of ocean plastic pollution in the Great Pacific Garbage Patch (GPGP). Here they estimated at least 79 (45–129) thousand tonnes of ocean plastic floating inside an area of 1.6 million km^2 (three to eight times higher than 10,000 g km^{-2}) with over three-quarters of its mass consisting of debris larger than 5 cm. Lebreton et al. (2018) conducted aerial imagery using an aircraft mounted RGB camera to improve recordings of larger debris (>0.5 m) and increase the size of their survey area (311 km^2). The images were inspected by trained human observers and an experimental image processing algorithm capable of detecting potential debris applied to all their RGB imagery.

Remote sensing observations to verify the ocean circulation models of plastic particles have not yet been made. Maximenko et al. (2016) describe how remote sensing could answer basic questions about the dynamics of plastic debris that have so far remained unanswered. They

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propose different promising RS technologies (optical observations, imaging spectroscopy, Synthetic Aperture Radar (SAR), and Raman spectroscopy), not just for satellite sensors but also for airborne-, shipborne-, onshore-, and handheld sensors. We studied hyperspectral RS for buoyant macroplastics in the visible (VIS) to near infrared (NIR) to short wave infrared (SWIR) spectrum, comprising wavelengths from 350 to 1790 nm. In this paper we present the experimental results by validating our theoretical reflectance model of sunlight interacting with a water surface littered with macroplastics and evaluate RS algorithms based on this model (Goddijn-Murphy et al., 2018). We were particularly interested in how physical properties of the plastic items affected light reflectance and the performance of our model, and selected a few items accordingly. As this was a proof of concept experiment, we felt this to be acceptable. The theoretical model and RS algorithms are not exclusively applicable to the ocean but also to inland waters where plastic littering is a problem (e.g., Driedger et al., 2015; Hoffman and Hittinger, 2017).

Objects larger than a couple of radiance wavelengths (in the order of micrometres in the VIS-SWIR spectrum) can reflect this radiance (Hecht and Zajac, 1974), thus microplastics would in theory be included in our optical model. However, wind driven ocean mixing removes buoyant microplastics from the top of the ocean surface (Kukulka et al., 2012; Kooi et al., 2016). We therefore do not expect our method to be successful for the detection of microplastics, but by studying macroplastics we study a major and increasing source of microplastics (Filella, 2015). The optical signal of microplastics particles suspended in the water body would be better explained by their absorption (a) and backscattering (b_b) coefficients in analogy to those of suspended sediments and phytoplankton (Gordon et al., 1975; Morel and Prieur, 1977). However, well over 50% of marine microplastics are found below the top 15 cm of the ocean surface (Kooi et al., 2016) where most light in the NIR and SWIR is absorbed by water (Irvine and Pollack, 1968). Biofouling will reduce the buoyancy of plastic particles, so that they sink below the sea surface and the smaller their size, the sooner they sink due to the higher surface area to volume ratio (Ryan, 2015).

Although hyperspectral RS for the detection of marine litter has been suggested before (e.g., Veenstra and Churnside, 2012; Driedger et al., 2015; Maximenko et al., 2016), until recently few reflectance spectra of marine plastic litter were published. Goddijn-Murphy et al. (2018) used spectra of plastic bottles presented by Asner (2016) to support their theoretical concept model of hyperspectral reflectance. Since then, Garaba and Dierssen (2018) published daylight reflectance spectra of marine-harvested micro- and macroplastics and 'virgin' microplastic pellets for the 350–2500 nm wavelength range. The microplastics were aggregated into an optically dense target on a low reflectance black rubber mat and the reflectance of wet marine-harvested microplastics was also measured. We used the same spectroradiometer to measure daylight reflectance of buoyant macroplastics floating on top of water. Our approach was to evaluate how transparency, optical surface roughness, shape and size changed reflectance. We show that these optical properties of the plastic litter items should complement reflectance measurements of plastics in the form of aggregated pellets (Garaba and Dierssen, 2017, 2018) and of one layer of plastic in air (Fig. 4). The lighting environment during our outdoors measurements were far from optimal, but we could still use our results to help understand the interaction of sunlight with floating plastic items. In addition, we measured spectra of coefficients of total and diffuse reflectance, transmittance and absorption in the laboratory (Fig. 4), using the spectroradiometer as a desktop instrument with its own light source.

1.2. Concept model

Goddijn-Murphy et al. (2018) developed a model to explain light reflectance of buoyant plastic floating on waters, based on geometrical optics and the spectral signatures of plastic and water. They include all reflectance- and transmittance contributions of upwelling and downwelling light and then take out the smallest terms. Goddijn-Murphy et al. (2018) define reflectance R as L/E_d [sr^{-1}], with L [$\mathrm{Wm}^{-2}\,\mathrm{sr}^{-1}$] upwelling radiance in nadir view and E_d [Wm^{-2}] downwelling irradiance. In this current paper, we redefine R as dimensionless L/L_d with L_d the radiance reflected off a Lambertian reflectance panel (Lambertian reflected light is scattered equally in all directions so that $L_d = E_d/\pi$). This definition of reflectance compared more directly with our measurements which were made using the spectroradiometer in "white reference mode" and a Lambertian reference panel. In the present paper we consequently use definitions of total reflectance $R_t = L_t/L_d$ (with L_t total water and plastic leaving radiance), water reflectance in the absence of plastic $R_{w,0} = L_{w,0}/L_d$, and plastic reflectance $\rho_p = L_{pr}/L_d$ (with L_{pr} light reflected at plastic in air). Water leaving radiance, $L_{w,0}$, is the sum of light that is reflected directly at the air-water interface and light that is transmitted from below. For low subsurface water reflectance, subsurface upwelling light transmitted upwards through the plastic is neglected and reflectance at wavelength, λ, can be estimated using

$$R_t(\lambda) = \varepsilon(f,\lambda)R_{w,0}(\lambda) + f\,(\rho_p(\lambda) - \varepsilon(f,\lambda)R_{w,0}(\lambda)) \tag{1}$$

(Goddijn-Murphy et al., 2018). In Eq. (1), f is fraction of surface plastic and ε is defined as "shading factor", a factor to account for the reduction of underwater light due to plastic floating on top of it. This factor is expected to be close to one, especially for small f. If ρ_p is known and we can estimate $R_{w,0}$, we can calculate f as $(R_t - R_{w,0})/(\rho_p - R_{w,0})$ (Eq. (1)) for an area in nadir view, using ρ_p at a wavelength where reflectance is high. But if we do not know $R_{w,0}$ a priori, we could apply more than one wavelength to derive f. For example, if we can find a second wavelength, λ_2, for which $R_w(\lambda_1) \approx R_w(\lambda_2)$ while $\rho_p(\lambda_1) \neq \rho_p(\lambda_2)$ then,

$$f(\lambda_1,\lambda_2) = \frac{R_t(\lambda_1) - R_t(\lambda_2)}{\rho_p(\lambda_1) - \rho_p(\lambda_2)} = \frac{R_t(\lambda_1) - R_t(\lambda_2)}{\Delta\rho_p(\lambda_1,\lambda_2)} \tag{2}$$

(Goddijn-Murphy et al., 2018).

Natural downwelling light is a combination of direct light (the solar beam) and diffuse light (skylight). The ratio diffuse/total (F) depends on sky conditions (e.g., clouds and haziness) and increases with decreasing solar altitude and decreasing wavelength (Jerlov, 1968). Similarly, radiance reflectance at a surface can be specular (Fresnel reflection) and diffuse (in all directions), the former occurs at an optically smooth- and the latter at an optically rough surface. If we consider reflectance at an optically smooth surface, light received in nadir view consists of specular reflected skylight as the sun is generally not in zenith. At an optically rough surface, diffuse reflectance of the solar beam also contributes to nadir reflected light. Both the water surface and the plastic litter can have specular and diffuse reflecting properties. Goddijn-Murphy et al. (2018) apply their model to Fresnel reflectance of diffuse skylight. In this study, we found in the laboratory that the diffuse reflectance coefficient, r_{dif}, dominated the total reflectance coefficient, r, so that diffuse reflectance of all light (skylight + solar beam) should have been included in their model. An aim of this study was to find if we could use r_{dif} and r to predict ρ_p for plastic floating on water. RS of water quality is traditionally done at high solar angles and under clear skies. Under these conditions, direct reflectance at the water surface is minimized so that the proportion of water leaving light from below the surface, the light that contains information about the water body, is maximized. In our RS method for floating plastic litter we use the reflecting properties of the water and plastic surface and the more different those are, the more successful it should be. The lighting conditions may therefore be less critical and sufficient for testing the model.