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Concept for a hyperspectral remote sensing algorithm for floating marine macro plastics

Lonneke Goddijn-Murphy[a,*], Steef Peters[b], Erik van Sebille[c,d], Neil A. James[a], Stuart Gibb[a]

[a] Environmental Research Institute, UHI-NHC, Thurso, Scotland, United Kingdom
[b] Water Insight BV, Wageningen, The Netherlands
[c] Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, The Netherlands
[d] Grantham Institute, Imperial College London, London, United Kingdom

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ABSTRACT

There is growing global concern over the chemical, biological and ecological impact of plastics in the ocean. Remote sensing has the potential to provide long-term, global monitoring but for marine plastics it is still in its early stages. Some progress has been made in hyperspectral remote sensing of marine macroplastics in the visible (VIS) to short wave infrared (SWIR) spectrum. We present a reflectance model of sunlight interacting with a sea surface littered with macro plastics, based on geometrical optics and the spectral signatures of plastic and seawater. This is a first step towards the development of a remote sensing algorithm for marine plastic using light reflectance measurements in air. Our model takes the colour, transparency, reflectivity and shape of plastic litter into account. This concept model can aid the design of laboratory, field and Earth observation measurements in the VIS-SWIR spectrum and explain the results.

1. Background

Marine plastic litter is a global environmental problem that is of increasing concern (Rochman et al., 2016). Global plastic production increases annually (Andrady and Neal, 2009), with an estimated 4.8 to 12.7 million metric tons of plastic entering the oceans each year (Jambeck et al., 2015), posing a threat to seabirds (Wilcox et al., 2015), fish (Gregory, 2009), turtles (Mrosovsky et al., 2009) and marine mammals (Laist, 1997). However, there are still many questions about its sources, sinks, pathways, and trends in abundance of marine plastic litter, its harmful impacts on human and marine life, and the effectiveness of potential clean-up operations. Some surveys have been undertaken (e.g., Eriksen et al., 2014) but there is a lack of long-term, large scale monitoring. Remote sensing (RS) has the potential to provide long-term, global monitoring of floating marine plastics but is still in its infancy (Maximenko et al., 2016). In this paper, we describe a concept RS method for marine plastic litter floating on top of the sea surface, based on geometrical optics and the spectral signatures of plastic and seawater. The objective is to find a method that can derive the surface fraction of plastic floating on the sea surface from the measured reflectance of natural daylight in air. Asner (2016) has made some progress in the remote sensing of marine macroplastics in the visible (VIS) to short wave infrared (SWIR) spectrum and we base our modelling and experimental work on their reflectance spectra. VIS ranges from 400 to 780 nm, SWIR from 1.1 to 3 μm, and NIR (near infrared) represents the wavelengths in between.

Addressing questions around marine plastic litter is complicated because many different types of plastic exist in the marine environment. Plastic size can range from microplastics (smaller than 5 mm) to large plastic pieces such as “ghost nets” (lost or discarded fishing nets). The former can be toxic through adsorption of pollutants onto plastics and ingested by marine life and the latter can entangle animals and endanger mariners. Microplastics can originate from pellets or “nurdles” used in manufacturing, microbeads originate from certain cosmetic and personal care products, and textile fibres that enter the ocean in wastewater (primary microplastics) and from fragmentation of larger plastic pieces (secondary microplastics). According to Filella (2015) it is likely that this secondary source of microplastics dominates, or will dominate, the microplastics found in the marine environment. They base this expectation on the observation that the amount of macroplastic accumulating in the marine environment is increasing, while primary microplastics are predicted to decrease due to recent anti-pollution measurements. Therefore, by studying macroplastics in the ocean, one of the major and increasingly more important sources of microplastics are also studied. Unlike microplastics, larger plastics located using remote sensing could potentially be removed from the sea

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[*] Corresponding author at: Environmental Research Institute, CfEE Building, UHI-NHC, Ormlie Road, Thurso KW14 7EE, Scotland, United Kingdom.
E-mail address: Lonneke.Goddijn-Murphy@uhi.ac.uk (L. Goddijn-Murphy).

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and coastlines - contributing to the effort to “clean up” the ocean (Sherman and van Sebille, 2016). Plastic comes in many different chemical compositions, each with different properties and buoyancy. Common marine plastic polymers include polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), polystyrene (PS), and polyamide (nylons), while they may be in the form of pellets, beads, films, fragments, fibres/filaments, and foamed plastic. Marine plastic litter persists in the environment for varying, and mostly very long, times; it degrades under the influence of ultraviolet light of the sun and chemicals dissolved in seawater and fragments in breaking waves and collisions. The contribution of micro-organisms to the degradation of plastics in the marine environment by biological decomposition is negligible (Andrady, 2015). However, according to Eriksen et al. (2014), bacterial degradation becomes more important as plastic particles become smaller and facilitate their export from the sea surface in addition to the ingestion of smaller plastic particles by organisms. Plastic objects in the ocean attract marine life and all floating objects are biofouled. Biofouling will reduce the buoyancy of plastic particles, so that they sink below the sea surface. Small plastic items start sinking sooner than larger plastic items because buoyancy is related to item volume, whereas fouling is related to surface area, and small items have high surface area to volume ratios (Ryan, 2015). In summary, there is a wide range of sizes, types, shapes, and of chemical composition of plastic in the ocean. We will focus on floating macroplastics because buoyant microplastics do not stay on top of the ocean surface but are mostly in suspension and lost from the sea surface (Eriksen et al., 2014). Microplastics will therefore not be “seen” by our proposed method. Considering that marine plastic RS is still in its early stages, we think this is a reasonable starting point.

This paper is organized as in the following. First, we briefly describe the much-studied reflectance of sunlight of the open sea. Next, we investigate the consequences of introducing floating plastic to the sea surface in a theoretical approach and propose a mathematical reflectance model to calculate the changed reflectance. This model will necessarily be an approximation and in the consequent section, we discuss the neglected terms. Finally, we suggest measurements to verify the proposed model and give a short conclusion. The parameter definitions used in this paper are listed in Table 1 and illustrated in Figs. 1–2.

2. Reflectance model

2.1. Light reflectance of natural waters

As can be seen in Fig. 1a, downwelling sunlight hitting the water partly reflects directly at the water surface and partly penetrates the surface refracting downwards. In the water body, light photons are absorbed and scattered in all directions. Because of the repeated scattering, subsurface upwelling light in water is generally considered to be Lambertian, i.e., light is evenly distributed in all directions. If the water is optically deep (bottom is invisible), the fraction of light that scatters back upwards and passes through the water-air interface contains information about the optically active water constituents. The sub surface irradiance reflectance is generally found to be proportional to $b_b/(b_b + a)$ (Gordon et al., 1975) or b_b/a (Morel and Prieur, 1977; Kirk, 1994) with b_b total backscattering coefficient and a total absorption coefficient (b_b and a are dependent on the wavelength of light, λ). The main backscattering components are suspended sediments and phytoplankton (scattering by water molecules is negligible in comparison). Absorbing components are suspended sediments, phytoplankton, dissolved organic matter, and water itself. The optically active components determine the apparent colour of the water and their concentrations can be estimated from spectral reflectance measurements.

Downwelling sunlight consists of direct sunlight (the solar beam) and diffuse sky light (scattered in all directions); the composition of direct and diffuse light depends on the solar elevation angle and sky conditions (Jerlov, 1968). Direct and diffuse skylight interact differently with the water body.

Table 1

Definitions of the variables used in this paper; subscript “0” indicates in the absence of plastic.

Variable	Definition	Unit
A_p	Area covered by plastic, projected in nadir view	$[m^2]$
A_w	Total area projected in nadir view	$[m^2]$
ε	$L_{ds}/L_{ds,0}$	
f	Plastic area fraction A_p/A_t	
F	Fraction diffuse sky light $E_{d,dif}/E_d$	
E_d	Downwelling irradiance in air	$[wm^{-2}]$
E_{ws}	Upwelling irradiance in water	$[wm^{-2}]$
λ	Wavelength of light	[nm]
L_d	Downwelling radiance in air	$[wm^{-2}\,sr^{-1}]$
L_{ds}	Downwelling radiance in water	$[wm^{-2}\,sr^{-1}]$
L_p	Total plastic leaving radiance in air $(L_{pr} + L_{pt})$[a]	$[wm^{-2}\,sr^{-1}]$
L_{pr}	L_d reflected by plastic in air[a]	$[wm^{-2}\,sr^{-1}]$
L_{ps}	Total plastic leaving, downwelling radiance in water	$[wm^{-2}\,sr^{-1}]$
L_{pt}	L_{ws} transmitted upwards through plastic in air[a]	$[wm^{-2}\,sr^{-1}]$
L_w	Total water leaving radiance in air $(L_{wr} + L_{wt})$[a]	$[wm^{-2}\,sr^{-1}]$
L_{wr}	L_d reflected by air-water interface[a]	$[wm^{-2}\,sr^{-1}]$
L_{ws}	Sub surface upwelling radiance in water[a]	$[wm^{-2}\,sr^{-1}]$
L_{wt}	L_{ws} transmitted through water-air interface[a]	$[wm^{-2}\,sr^{-1}]$
L_t	Total upwelling radiance $(L_w + L_p)$[a]	$[wm^{-2}\,sr^{-1}]$
R	Ratio of upwelling radiance in nadir view and E_d in air	$[sr^{-1}]$
R_p	L_p/E_d	$[sr^{-1}]$
R_t	L_t/E_d	$[sr^{-1}]$
R_w	L_w/E_d	$[sr^{-1}]$
ρ_p	L_{pr}/L_d	
$\rho_{p,RS}$	L_{pr}/E_d	$[sr^{-1}]$
ρ_{pw}	Fraction of L_{ws} reflected by plastic	
ρ_w	L_{wr}/L_d	
$\rho_{w,RS}$	L_{wr}/E_d	$[sr^{-1}]$
r_{ws}	L_{ws}/L_{ds}	
τ_p	L_{pt}/L_{ws}	
τ_{pw}	Fraction of L_d transmitted through plastic	
τ_w	$L_{ds,0}/L_d$	

[a] In nadir view.

2.2. Light reflectance of water littered with floating plastic

Plastic objects floating on the water surface control surface leaving light in a number of ways, (1) downwelling light reflects differently off plastic than off water, (2) transmittance of downwelling light through plastic is different from transmittance through the air-water interface, changing the underwater light climate and hence the back scattered upwelling light, and (3) subsurface upwelling light transmits through plastic differently than through the water-air interface. The different pathways, illustrated in Fig. 1b, explain why measuring marine plastic is different from retrieving concentrations of optically active water components through their spectral scattering and absorption properties (Section 2.1). The mathematical model will have to include radiative transfer in water itself, as well as light interaction with plastics on the water surface with different optical properties (e.g., colour, transparency, and shape). We propose a mathematical model that can help select optimal wavelengths, design experiments, and develop a working algorithm for remote sensing marine plastic.

With A_t the total water surface area- and A_p the plastic covered area *projected in nadir view* (Fig. 2), the plastic area fraction, f, is defined by A_p/A_t. Both plastic- and open water leaving radiance, L_p and L_w $[Wm^{-2}\,sr^{-1}]$, contribute to total above surface upwelling radiance, L_t, leaving this area in nadir view. L_t received by the sensor in nadir view can be estimated with Eq. (1),

$$L_t(\lambda) = (1 - f)L_w(\lambda) + fL_p(\lambda) \tag{1}$$

For (semi-)transparent plastic, L_p does not only represent plastic reflected sunlight in air, as subsurface upwelling light that is