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Title: Towards marine plastic debris detection from satellite remote sensing

ABSTRACT

Plastic debris (or solid synthetic polymers produced as a by-product of human activities) reaches every area of the ocean. Sustained observations and monitoring are required to determine the marine plastic debris mass balance and to provide monitoring tools for effective planning and management. However, observations remain scarce at the global scale. A remote satellite sensing system could make a substantial contribution to tackle this problem. Here, we make initial steps towards the potential design of such remote sensing system by: 1) identifying the properties of marine plastic debris amenable to remote sensing methods and 2) highlighting the oceanic processes relevant to scientific questions about marine plastic debris. We review remote sensing approaches and match them to the properties of marine debris and the relevant scales of observation to identify challenges and opportunities in this area of research. We discuss the necessary steps in developing marine debris detection by remote sensing.

1 Introduction

As a result of human activities, large amounts of solid waste are introduced into the environment each year (REF). Typically, synthetic polymers (i.e. plastic) are a major constituent of discarded solid waste

(Bergman et al., 2015). This is reflected in surveys of marine debris, which frequently identify plastic as the major component (REFS). Impacts to marine life depend on the concentration of plastic debris and on the vulnerability of the system (Clark et al., 2016; Law, 2017). A growing body of experimental evidence regarding encounters between organisms and marine plastic debris (de Sá et al., 2018); however, much uncertainty surrounds the spatio-temporal distribution of plastic and the global marine budget (REF). Marine plastic debris is linked to plastic production, which has grown exponentially over the last 70 years, from 1.7 million tonnes in 1950 to 322 million tonnes in 2015 (PlasticsEurope, 2016). It is estimated that between 4.8 and 12.7 million metric tonnes of plastic entered the ocean from terrestrial sources in 2010 alone (Jambeck et al., 2015), with rivers contributing to a large fraction of those inputs (Lebreton et al., 2017). Although roughly half of all marine plastic debris is positively buoyant at the time of entry to sea water, it is estimated that only 269 thousand metric tonnes float at or near the surface of the ocean (Eriksen et al., 2014). This mass-imbalance raises fundamental questions about the sources, pathways, sinks and processes that influence the spatiotemporal distribution of plastic in the marine environment (Ryan et al., 2009; Galgani, 2015; Law, 2017). At present, our ability to address these questions is hampered by the limited availability of in situ observations which in turn is being held up by the lack of standardised sampling and analysis methodologies (Galgani et al., 2013).

To help constrain uncertainties on marine plastic debris concentrations, distributions and variability, a solid evidence-baseis needed. Policy makers need such evidence to evaluate the effectiveness of policy interventions (Veiga et al., 2016This can be acquired through the introduction of a coordinated sampling effort: a global marine plastic debris observing system. (Maximenko et al., 2016; Maximenko et al., submitted). The main aim of this global observing system would be to monitor and assess the risk posed by marine plastic debris, by measuring concentrations and vulnerability of the marine system. Such an effort would include several Earth Observation (EO) components, including: citizen science based, in situ and a remote sensing from different platforms (satellites, aircrafts or drones). Because of its unique global capability to fill the gap in the spatial and temporal scarcity of marine debris data and its unifying power across different environments, a remote sensing system could play a critical role in a wider observing system. The aim of this paper is to explore the feasibility of a satellite remote sensing element for monitoring marine plastic debris. Specifically, the study relates to techniques for measuring marine plastic debris concentrations, as opposed to indirect inferences from oceanic currents or wind fields which have already been used or will be used in the future (a technique already in use for "indirect" methods REF required; Ardhuin et al., 2018).

The first step to design a system for detection of marine plastic debris from remote sensing, or indeed any other approach, is to define the requirements and expectations of users (IOCCG, 2012; Verstraete et al., 2015). The specifics of which material types need to be monitored, how often and with what spatial resolution (i.e. the observational needs) must be translated into concrete values that will ultimately translate into engineering specifications of the system. This paper is the first attempt to capture user expectations and translate them into threshold requirements (or the "minimum" values required for the success of the system) and goal requirements (or "limit" values which would be useful to advance the state of current knowledge, but could be lowered due to practical or cost considerations). To do so, we summarise the most relevant oceanographic processes controlling marine plastic debris in the ocean and their spatial and temporal characteristic scales.

Once observational requirements for remote sensing of marine plastic debris from satellite are defined, they need to be compared with current capabilities, to identify potential suitability and gaps. A mature satellite observing system exists (e.g. Copernicus and the Sentinel fleet), and it is necessary to examine its potential for monitoring marine plastic pollution before looking into new solutions.

We present an initial proposal for a set of observational requirements for the remote observation of marine plastic debris to the wider community. This first assessment is derived from an analysis of scientific and monitoring data needs. We review current and planned remote sensing technology matching these requirements, highlighting their potential and limitations. From this exercise, we draw recommendations for relevant scientific investigations as well as for science policy to support the inclusion of marine plastic debris requirements in new remote sensing programs.

2 Marine plastic debris and relevant scales of observation

To build a concept of a remote sensing system main objectiveof which is to monitor marine plastic debris, the characteristics of the method of observation (sensor) and the sampling strategy have to be defined (Verstraete et al., 2015). The sensor characteristics are defined by the property of the marine plastic debris that changes the signal in the electromagnetic radiation in a way that can be correlated with its presence or concentration. The sampling strategy in the spatial (i.e. coverage and spatial resolution) and temporal domains (i.e. duration or sampling frequency) is defined by the scales of the processes connected to the main uncertainties that the observation system needs to address.

2.1 An operational definition of marine plastic debris detection from remote sensing techniques

To develop a robust satellite remote sensing system, it is important to identify universal characteristics. Hartmann et al., (2019) have recommended a set of sequential criteria that define marine plastic debris. First is chemical composition: for an object to be classed as marine plastic debris it has to contain as an essential ingredient synthetic or heavily modified natural polymers. This definition excludes dyed natural fibres, but includes petroleum-based polymers such as polyethylene (PE), polypropylene (PP), polyurethane (PU), polyethylene terephthalate (PET), polystyrene (PS), and polyvinyl chloride (PVC). In addition to these, the proposition is to include biobased plastics synthesized from nonfossil feedstock and also those produced from inorganic monomers (e.g. silicone). Other criteria specify that the marine plastic debris should be solid (Hartman et al., (2019) Criterium II) and non-soluble in water (Criterium III, solubility in water <1mgl^{-1} at 20°C). Size, shape and structure, colour and origin are additional characteristics to the above qualifying criteria for marine plastic debris, but not essential qualifying properties. Of all the listed criteria, it is proposed here that the observable property for a remote sensing system should be primarily based on the electromagnetic radiation spectrum signature due to the unique chemical signature of the polymers that is affected by their presence and that is correlated with their concentration. Secondary identification can be obtained by the artificial shape and structure of the plastic debris item, but these are properties that may change with size. By targeting a particular type of chemical compound, the expectation is that a satellite remote sensing system should be able to separate the signature of plastics from all other kind of debris, man-made (e.g. glass, metal, wooden composites) or natural (e.g. natural wood).

2.2 Factors influencing marine plastic debris relevant to satellite remote sensing

In addition to the properties of the marine plastic debris, the open questions concerning their quantification in the marine system constrain the observation scales (Ryan et al., 2009; Galgani, 2015; Maximenko et al., 2016; Hardesty et al., 2017):

Question 1 (Q1): What are the magnitude, location and temporal variability of the sources and pathways into the marine environment of marine plastic debris?

Question 2 (Q2): What are the abundance, distribution and composition of marine plastic debris, and how do these attributes change over time?

Question 3 (Q3): Where does marine plastic debris tend to accumulate?

Question 4 (Q4): How is marine plastic debris transported and what are the dominant physical processes influencing its fate?

Question 5 (Q5): What role do biological, chemical and photochemical interactions play in controlling the movement and degradation of marine plastic debris?

All these questions are important to define the mass balance of marine plastic debris as well as to inform marine policy. However, the current review will focus on Q1 to Q3, which are potentially more tractable using satellite remote sensing. Also it is worth limiting the scope to the marine compartments with more urgent socio-economic importance and potential impacts: coastlines and upper ocean (sunlit ocean and air-sea interface) (Law, 2017; Hardesty et al., 2017). The way to structure the definition of observational requirements is through identifying the main processes that control marine plastic debris in those pools, as their temporal and spatial scales must be matched by the observations (Robinson, 2004; IOCCG, 2000).

Table 1 summarises the link between questions, processes, their spatial and temporal scales and the observational requirements and Figure 1 presents a graphical summary of the processes involved. Sources for input of marine plastic debris to the coastlines and upper ocean are land based (waste water discharges), maritime (fishing and aquaculture, shipping, ocean science and other ships and platforms) and common to both (lost pellets, catastrophic events and improperly managed waste) (Law, 2017). Modelling has identified that rivers are the most important pathway for input of plastics to the coastal ocean (Lebreton et al., 2017) and monitoring standards for marine plastic debris in rivers have been proposed recently (Gonzalez-Fernandez and Hanke, 2017). However, input from accidental spillage due to maritime transport activities is largely unknown, but expected to increase with increasing shipping volumes (Law, 2017). [relative importance of other sources?] Riverine inputs and accidental spillages (Figure 1) relate to Q1; and their time and spatial scales are detailed in Table 1.

On the shoreline, the dynamics of marine plastic debris relating to Q1 to Q3 above are controlled by different processes than in the upper ocean, and therefore associated with different scales of observation (Table 1). The accumulation of debris on the shoreline is the process with highest impact in this area. Anthropogenic factors such as coastal tourism and marine activities, proximity to urban areas and river mouths (Hoellein et al., 2014; Critchell and Lambrechts, 2016) as well as coastal currents, wind and wave action influence the accumulation of marine plastic debris on the shoreline

(Browne et al.,2010). Beach debris sampling is conducted in various sites around the world, through voluntary initiatives or beach monitoring programmes (e.g. OSPAR, 2010; Galgani et al., 2013). For temporal and spatial resolutions, standard protocols recommend that a beach should be monitored at least 4 times in a year. Yet it has been found that surveys at regular intervals of four weeks would make multi-year trend monitoring results more reliable than current monitoring frequencies, to avoid variations due to meteorological and tidal artefacts (Schulz et al., 2015). Quantification of marine debris should be carried out along 100 m of beach length (Galgani et al., 2013). However, they focus on a small stretch of coast and are done, at best, seasonally, which can result in limited trends of abundance and composition of debris. Changes with time in the amount of plastic debris on the shorelines would help also with providing information on fragmentation into smaller particles (Q4).

The dynamics of marine plastic debris in the upper ocean (Q2 and Q3) are studied at the global scale using models that describe the movement of small positively buoyant plastic particles (less than 5 mm; see Table 1 in Hardesty et al., 2017). Typically, these models have a horizontal spatial resolution of ~ $1/12^{o}$ (~10 km), with outputs saved daily or monthly, with the models resolving processes at spatial scales from ocean gyres down to mesoscale eddies. At present, such models disagree by up to a factor of 10 in their estimates of plastic abundance in the most frequently sampled areas with high concentrations of plastics like the Northern Pacific and Atlantic Gyres (van Sebille et al., 2015). Most of the disagreement among models was attributed to the lack of observations, even in the Gyres. At smaller spatial scales than those resolved by current models (~1 km), it has been hypothesised that physical structures, i.e. submesoscale frontal convergence areas (Taylor, 2018) will produce accumulation and patchiness of marine plastic debris. Detection and quantification targeting these accumulation zones would provide new information for models, to reduce their uncertainties.

Two points have been identified so far: first, the need to select operationally a property that can be distinctive for plastic debris. A recent proposition is based on the chemical composition of plastic, and already some studies have investigated the optical properties related to this (Section 3.1). Secondly, an initial proposal for the main scientific questions where remote sensing could have an impact has been presented, together with their associated oceanographic processes and their typical scales (Table 1). A salient characteristic of this analysis is that despite spatial resolution scales of observations being similar across all the processes considered, revisiting time frequency required for the coastal and oceanic processes (river discharge, spills and submesoscale convergence filaments) is greater than for shoreline accumulation processes, thus reflecting the dynamic nature of the marine environment. This separation in sampling frequency facilitates the analysis that follows, of available technologies and potential for new ones, which will require very different sampling characteristics.

3 Remote sensing methods with potential for marine plastic debris detection

Once the properties of interest and the most relevant processes and scales of observation have been identified, passive and active remote sensing methods with potential to detect marine plastic debris can be assessed, to uncover potential for application of current methods or to find out pointers towards research needed. A remote sensing method has detection potential if there is a direct relationship between the variable of interest and the feature of the electromagnetic spectra detected. Passive methods considered here measure the visible (400-700 nm) and near-infrared (NIR) to short-wave infrared (SWIR), i.e. 750- 2500 nm parts of the spectrum; whereas active methods measure in the visible (LIDAR) or in the microwave range (RADAR) (Robinson, 2004). It is relevant to discuss whether any of the remote sensing methods are able to uniquely attribute a relationship between the composition of plastic debris and a given radiometric property, under the proposed definition of marine plastic debris based on its chemical composition (rather than its shape, size or colour) as given by Hartman et al.(2019). Once the link to the property has been established, it is necessary to evaluate if any of the current or future missions can fulfil those measurements at the required observation scales to evaluate the gaps that need to be addressed.

3.1 Passive methods: radiometry and imaging spectrometry

Passive NIR to SWIR methods have recently demonstrated the potential to detect marine plastic debris specifically. Similar to hydrocarbon hyperspectral features (Hörig et al., 2001; Kühn et al., 2004) marine plastic debris reflectance features have been recorded at around 1215, 1732 and 2200 nm, despite different compositions, sizes and spectrum in the visible (Garaba and Dierssen, 2018). Figure 2 summarises the average spectrum of the plastic measured in those experiments, alongside the location of the features. Over clear oceanic waters, hyperspectral measurements from an aircraft and linear spectral mixing modelling confirmed that distinct spectral features appear at 1215 and 1732 nm (Garaba et al., 2018). Measurements on a controlled experiment with variable illumination conditions using a handheld hyperspectral radiometer have also confirmed a signal around 1732 nm (Goddijn-Murphy and Dufaur, 2018). SWIR features can be masked by a number of factors, the most important being water absorption. Garaba and Dierssen (2018) report a reduction of the median band depth index for wet versus dry plastics of 75%, 55% and 71% for 931, 1215 and 1732 nm respectively. The high pure water absorption coefficient values for those wavelengths (i.e. 12 , 124 and 644 m^{-1} respectively, Kou et al., 1993) not only affects the radiation through the atmosphere (i.e. clouds and water vapour effects are typically measured using nearby wavelengths), but also affects the signal coming back from the materials, thus constituting a separation between observation scenarios in dry and wet conditions.

Passive radiometers can be further classified according to the spectral resolution (i.e. capacity to resolve different wavelengths) of the instrument: pan-chromatic (high resolution optical imagers, capture the signal in the visible spectrum), multi-spectral (up to 20 spectral bands) or hyper-spectral (more than 20 spectral bands about 5-10 nm width).). Extensive reviews of current and planned radiometric-based multispectral and hyperspectral missions can be found elsewhere (Werdell et al.,2018 ;Transon et al., 2018). Here we focus on missions with wavelengths close to the proposed detection bands for marine plastic debris reported above. Table 2 summarises spatial, temporal and spectral resolution around the NIR and SWIR region relevant to marine plastic debris detection for current and some planned sensors. None of the current or planned sensors consider explicitly marine plastic detection, however it is useful to compare their sampling characteristics or requirements (if in planning phase) with the scales of the marine plastic debris problem in Table 1.

High spatial resolution instruments provide spatially detailed images of the Earth's surface. Their ground sampling distance (GSD, distance between the centres of pixels on the ground) is small in panchromatic mode (a single waveband), in the range of 25-30 cm (as in the so-called high resolution imaging camera). Spectrally, an increasing number of private sector-funded sensors with sub-metre resolution are quickly appearing with multispectral capabilities also in the visible, NIR and SWIR (e.g. e.g.: Worldview-3 is Multispectral Nadir: 1.24 m; SWIR Nadir: 3.70 m, but commercial delivery at 7.5m resolution). This increases the information content that may be derived from the imagery (including the ability for land cover classification) and allows corrections to be made, for example, for the effects of atmospheric water vapour on the measured surface parameters. Like all the passive radiometric techniques, they require clear sky and daylight to collect data. In addition to the spectral limitation of these sensors, the high spatial resolution global data may be of limited access due to their cost.

Ocean colour radiometers (e.g. OLCI in Sentinel-3) are now mature tools for global monitoring of optically active biogeochemical properties. Their original design requirements (spatial resolution, temporal frequency and spectral resolution) were mostly driven by ocean climate science. These requirements implicitly included the monitoring of marine ecosystems, coastal water quality, and dynamics of the upper ocean (Drinkwater and Rebhan, 2007). Accordingly, spatial and temporal observation scales match large-scale oceanic processes (seasonal and mesoscale processes), but not short-scale spatial and temporal variability related to the in-water scenarios in Table 1. Spectrally, near-infrared bands in OLCI are dedicated to water vapour absorption, vegetation and atmospheric correction, as the ocean is absorbing radiation at those wavelengths. In addition, the NIR-SWIR bands centres do not match with the proposed spectral bands for marine plastic debris, so it is expected that they will not be available for use in marine plastic debris detection. The planned NASA mission PACE has a matching band (1250 nm), but the instruments have not been specifically designed to detect the plastic signal.

At a finer spatial resolution than OLCI, the Multi-Spectral Imager (MSI) in Sentinel 2A and 2B, was mainly designed for land and inland water monitoring applications (ESA Sentinel-2 Team, 2010). Figure 1 shows the exact position of the Sentinel2B-MSI detection bands relative to the typical reflectance spectrum of marine plastics. Spatial and temporal observation scales match the shoreline monitoring requirement for plastic debris accumulations; however, band centred at 1610 was originally intended for snow/ice/cloud detection, or vegetation moisture stress assessment.

A number of hyperspectral imager spectroscopy missions are in different stages of development (Transon et al., 2018) with expected spectral resolution matching the wavelengths of potential features for marine plastic debris. The main applications for these sensors are vegetation, agriculture (Hank et al., 2018), soil, geology, disaster monitoring, land use change and water resources monitoring (Giardino et al., 2018). Spatial resolution is coarser and temporal revisiting frequencies are lower than MSI, but spectrally they may be suited to capture potential plastic features on the shoreline (dry plastics).

3.2 Active sensors: LIDAR and RADAR

LIght Detection And Ranging (LIDAR) systems are active sensors that have been deployed from ships and aircraft for characterizing ocean properties. Depending on the LIDAR technique used (based on elastic or inelastic processes), different types of data can be obtained, including bathymetry, inherent optical properties of water, oil pollutants, coloured dissolved organic matter, phytoplankton and zooplankton content (REF). LIDAR systems have distinct advantages over passive systems of ocean colour radiometry, in that they can be used day or night, at low solar angles, and can also provide depth-resolved information through the water column. LIDAR techniques based on inelastic processes such as fluorescence or Raman scattering, represent particularly promising remote sensing techniques for plastic identification (REF). Although some LIDAR systems are currently operating from satellites for atmospheric science applications, there are no LIDAR satellite systems specifically designed for ocean applications. For atmospheric science, the primary instrument on the CALIPSO satellite, launched in 2006, is the Cloud-Aerosol LIDAR with Orthogonal Polarization (CALIOP) sensor, and it has reliably collected global LIDAR measurements for the past 10 years. This sensor has a spatial footprint of ~100 m, and initial efforts to adapt it for marine micro-particles have shown promising results (Behrenfeld et al., 2013).

RAdio Detection And Ranging (RADAR) instruments can actively transmit at frequencies between 1 GHz and 35 GHz (operational and demonstrators) and measure the backscattered signal. Some state-of-the-art instruments and missions include airborne demonstrators, altimeters and scatterometters such as: L-Band (1.25 GHZ in ALOS PalSAR-2), C-Band (5.4 GHz in Sentinel-1), X-Band (9.65 GHz in TerraSAR-X/TanDEM-X/PAZ Cosmo SkyMED). This generates microwave images of the Earth's surface at high spatial resolutions (ranging from 1 meter in current payloads), with a swath width ranging from several kilometers up to 450 km (with reduced resolution of 50-100 m). There is a trade-off between swath width and spatial resolution: larger swath at the expense of a reduced resolution in azimuth, to keep the range ambiguities of such swaths under control. Future concepts such as high-resolution wide-swath allow simultaneously high resolution and wide swath. Synthetic aperture side-looking imaging radar systems fall into this category. This technique can be exploited for the direct and indirect detection of marine plastics.

Within radar technologies, Synthetic Aperture Radar (SAR) sensors are capable of detecting surfactants such as biogenic films, and targets such as derelict fishing gear and bigger items (DiGiacomo et al., 2004; Arii et al., 2014; Skrunes et al., 2014; Makhoul et al., 2015; Matthews et al., 2017) exploiting both intensity and polarimetric features of the backscattered signals; like SAR, altimetry has the potential also to detect marine debris as it distorts the measured sigma-0 or roughness. However, the particularities in composition and size of marine debris and their interaction with the background ocean, makes direct detection exploiting radar technologies very challenging. Though applicable to both the coastal and open oceans, mission configuration and optimization for sensor sensitivity and ambiguity control must be considered following experimental results.

On the other hand, these instruments, together with radar scatterometers, have demonstrated their capacity to indirectly track potential accumulation areas for plastics, by providing information on ocean currents and wind speeds (Romeiser et al., 2014; Li et al., 2014) and are capable of seeing through clouds, providing data on an all-weather conditions, day/night basis.

The conclusion is that currently there are no observational matches for marine plastic debris detection from space, which is especially critical in the marine (in and on water) context. This leads to the question of what are the main bottlenecks and where more effort should be devoted.

4 Challenges and opportunities for remote sensing detection of marine plastic debris

Gaps in research have emerged after evaluating the suitability of current remote sensing methods to the specific problem of marine plastic debris. These gaps are related to: 1) the fundamental relationship between the marine plastic composition and remote sensing reflectance and 2) to the proposed scales of observation. This discussion focuses on breaking down these two questions into tractable units (challenges) and proposing ways forward (opportunities).

There is initial evidence that the presence of plastic particles modifies remote sensing reflectance in the NIR-SWIR spectral region (Dierssen and Garaba, 2018). In addition to water, other materials with similar chemical composition to marine plastic debris can cause interference and their signal needs to be separated. Non photosynthetic vegetable matter, with high content in natural polymers such as lignin and cellulose, also has absorption spectral features in the proximity of the plastic absorption wavebands (Li and Guo, 2015). Also, the effect of bio-fouling on the spectral absorption around the wavelengths of interest is not yet known. Additional to contamination of the signal by different substances is the contamination by environmental sources. In the shoreline, plastic debris signal can be masked by the underlying matter, whereas in coastal and oceanic waters, bottom reflectance, sunglint, whitecaps, bubbles, high suspended sediment concentrations (Knaeps et al., 2012) can affect reflectance at wavelengths greater than 1000 nm. If progress in the definition of characteristics of a remote sensing system is to be made, fundamental investigations must be carried out to define the strength of plastic debris signal in the marine environment.

Challenge 1: to establish the signal-to-noise ratio (SNR) specific for detection of marine plastic debris for spectroradiometric techniques in realistic situations by linking chemical composition with optical measurements and to be able to separate the plastic debris signal from other sources

Opportunity 1: to sample marine plastic debris in the target scenarios (e.g. those in Table 1 and Figure 1) with simultaneous chemical and optical characterisation and/or perform controlled experiments with expected realistic situations.

As it has been shown, there is no unique remote sensing method valid for all observation scenarios considered here (Table 1), due to the disparity of time scales of the processes involved. The strong attenuation effect of water on the reflectance signal further marks this division separating the approaches for shoreline scenarios and in the surface waters. From this review, detection of marine plastic litter on the shoreline (above the tidal line) could at present be more feasible than in the water. Sentinel-2 MSI may have a capability to detect marine plastics on land that needs further investigation. Figure 3 shows deployment of a plastic target on a UK beach, as seen from Sentinel-2B MSI. Despite the lack of water interference, preliminary results from this experiment show that the brightness of the non plastic matter surrounding the targets over land, can affect significantly the retrieval if the size of the target is smaller than the ground sampling distance, as predicted by modelling studies on the effect of subpixel shapes on land detection indices for Sentinel-2 MSI (Radoux et al., 2016). It is very likely that with the advent of hyperspectral imaging spectroscopy from space (EnMap, PRISMA, SHALOM, HyspIRI or HYPXIM), the synergy between hyperspectral and multispectral images can be used to enrich collocated images. For instance, Acuña-Ruz et al., (2018), have demonstrated that a combination of in situ quantification, hyperspectrally resolved radiometric measurements with very high spatial resolution imagers (1 m), could be used for remote quantification of marine plastic debris on a beach. Guanter et al. (2018) have recently reviewed the techniques and potential for synergy between hyperspectral imagers, multispectral imagers, ocean colour radiometry and LIDAR techniques. Further studies on how these synergies can be exploited for land/shore accumulation of marine plastic debris should be addressed.

Challenge 2: to evaluate remote sensing methods on the shoreline.

Opportunity 2: to exploit synergy between high spectral resolution and high spatial resolution current and planned remote sensing methods.

Because of the highly dynamic nature of the processes in the marine environment controlling the fate of marine plastic debris (Table 1), there is no clear match of the current or planned radiometric missions to floating plastic monitoring. Ocean colour radiometry with higher sampling frequency and higher sensitivity is well adapted for the low levels of reflectance in the ocean. However, the spatial resolution (300 m) precludes its use for spills and submesoscale convergence filaments, but still could be useful to detect large fronts formed around river discharges. Synergy studies between ocean colour radiometry and high spectral resolution have detected harmful algal blooms in coastal areas, thanks to the specific pigment assemblage and its related radiometric signal in the visible part of the spectrum (Dierssen et al., 2015). Although common spectral features in the visible are not expected from marine plastic debris, changes in intensity of the reflected light could be exploited if in situ quantification and radiometry were available for validation (Hu et al., 2015; Wang et al., 2018). In addition to all these potential contamination issues, there is the problem to separate marine plastic debris from non-debris plastic matter in use. Similarly, continuous effort needs to be dedicated to algorithms for understanding and quantifying the contribution to the reflectance signal by non-marine plastic debris sources. A combination of methods, including ship positioning information (Kurekin et al., 2019) is in place for ship detection, and could be used for this task.

> Challenge 3: to develop remote sensing methods for specifically detecting floating marine plastic debris.

> Opportunity 3: indices to detect floating algae have been developed (Hu, 2009), and they could be used to separate photosynthetic floating matter from other floating objects.

Although it is worthwhile to exploit available methods and platforms to try to provide EO solutions for monitoring marine plastic debris in the short term, the ultimate goal is to be able to develop specifications for a system that can specifically target detection of marine plastic debris. Assuming that current and planned land observing systems could be adapted to detect marine plastic debris on the shore if properly calibrated and combined, one could focus on the limitations imposed by current and planned observation of water bound material. Recent work has been completed to define requirements for a mapping mission for aquatic ecosystem biogeochemistry (coastal and inland water bodies), not including marine plastic debris observations (CEOS, 2017). Spatial resolutions proposed are between 17 and 33 m ground sampling distance (GSD), which match river discharge, spills and submesoscale convergence filaments. Spectrally, CEOS (2017) defined requirements of spectral bands with 5 nm spacing between 360 and 1000 nm augmented by a shortwave infrared imaging spectrometer, which could also match marine plastic debris detection. However, there is no clear indication of the temporal observation scale in the CEOS recommendations. Requirements for satellite monitoring essential biodiversity variables in coastal ecosystems (Muller-Karger et al., 2018) were also similar to those listed in Table 1. Muller-Karger et al. (2018) proposed that an observation system should be set up with high spatial, high spectral, high temporal and high radiometric sampling specifications (i.e. a *H4* system). A spatial resolution of 30 m should be combined with a temporal frequency of sampling hours to days, which matches most of the processes included here. A 5 nm spectral resolution in the visible, 10 nm resolution between 900-2500 nm or at least two or more bands with centres at 1030 , 1240, 2125 and 2260 nm, were required mainly for atmospheric correction over turbid waters and wetland vegetation, but not explicitly including monitoring for marine plastic debris. In addition, a high radiometric quality is required (SNR above 800) based on signal levels typical of the open ocean, due to the wide range of reflectance in coastal areas, from very bright to very dark. Because these requirements are close to those for marine plastic debris detection, it is important that communication occurs with teams in charge of mission development at the early stage so that objectives on marine plastic debris detection can be included in the final mission specifications.

Challenge 4: to liaise with current mission planning to enhance the role of marine plastic debris detection in the requirements specifications.

Opportunity 4: to coordinate development of the remote sensing system for marine plastic debris at an international level, such that the specific requirements can be fed at the initial stage of development of future observation systems.

5 Conclusions, implications and recommendations

There are several steps required for the construction of an Earth Observation system (Verstraete et al., 2015) and there are several elements in it (Mouw et al., 2015). In this work we have identified the main processes relevant for marine plastic debris monitoring (Table 1) with a view to defining the observational requirements. Temporal and spatial scales of observation have been matched to current and planned observation techniques, to identify gaps and opportunities for development. Although active EO techniques have been reviewed, the main focus was around the passive radiometric methods and their spectral resolution and characteristics have been discussed, leaving aside radiometric quality, which stills needs to be addressed.

A clear separation between requirements for land/shoreline and in/on water has emerged from the review of the main processes controlling the fate of marine plastic debris. This separation is mainly due to a higher temporal requirement for observation in the floating or in water marine plastic debris. In addition to this, when considering the spectral properties that could be exploited, it has been shown that water content can attenuate significantly the signal for marine plastic debris in the NIR-SWIR. The implication of this result is that shoreline marine debris detection could be addressed by exploiting the NIR-SWIR spectral features through a synergy of hyperspectral imaging spectroscopy and multispectral imaging at high spatial resolution and that this approach is ongoing in the land EO community. Future experiments and in situ measurements needed to validate this approach will have to combine some quantitative measurement of plastics and its relationship to the spectral signal to be able to derive quantitative indices from EO, in a similar way that the link was made between ocean colour reflectance and chlorophyll concentration.

For the marine water bound environment, there is a greater challenge than for the shore (dry) detection. The extent of the signal available in the NIR-SWIR from current concentrations of marine plastic debris remains to be quantified. Experiments and in situ measurements of emerged and submerged marine plastic debris and associated radiometry should be conducted to explore the signal to noise ratio. River plumes frontal areas, opportunistic sampling of spills and sampling at filaments from submesoscale processes should be actively targeted as higher accumulation points.

Because of the novelty of this field of research, it was impossible to include observation requirements for marine plastic debris in previous descriptions for new missions. However, as has been shown here, there is an overlap in terms of temporal, spatial and likely, spectral requirements with both land and coastal missions being currently planned. This work should raise awareness of those missions to development teams, so that taking into account requirements for the monitoring of marine plastic debris at an early stage would help achieve a greater impact of new missions.

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FIGURES

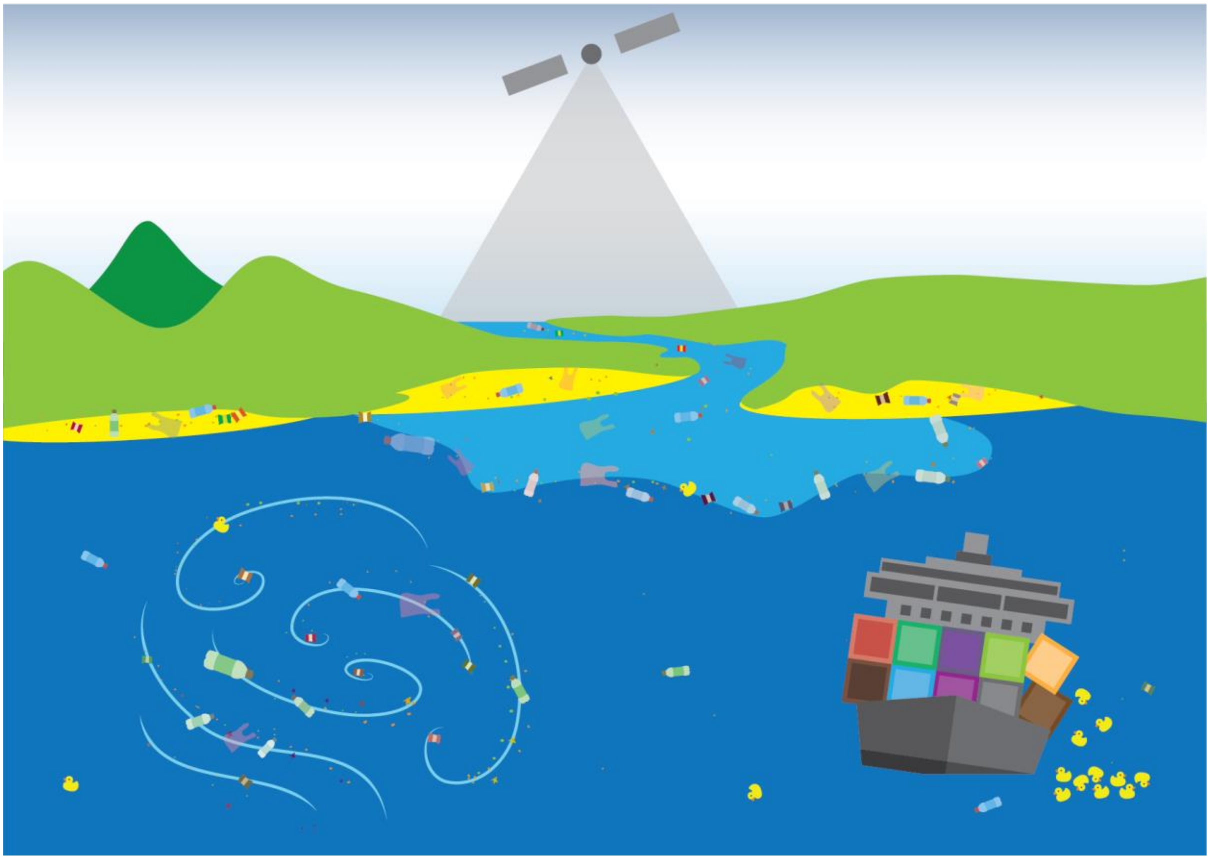

Figure 1: Diagram representing the four observational scenarios (not to scale) discussed in the text. (1) River discharge, (2) spills, (3) shoreline accumulation, (4) submesoscale convergence filaments.

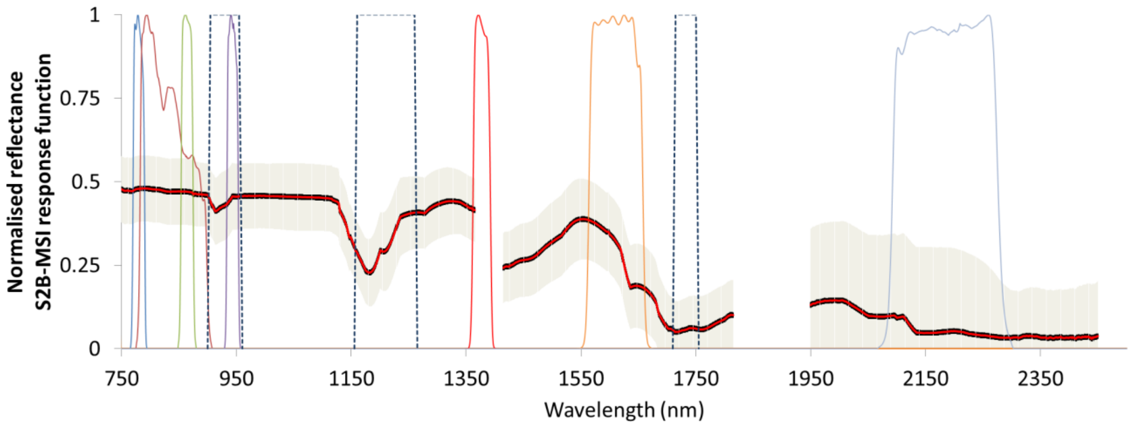

Figure 2: NIR-SWIR normalised reflectance spectrum, absorption feature location and satellite detection windows. Thick solid red line is median spectrum and shadowed area is Std.Dev./2 of all plastics measured (data from supplementary material in Garaba and Dierssen (2018)). Dotted lines highlight the regions of the spectrum with major absorption features according to Garaba and Dierssen (2018). Thin solid lines highlight the spectral windows from Sentinel 2B-MSI sensor.

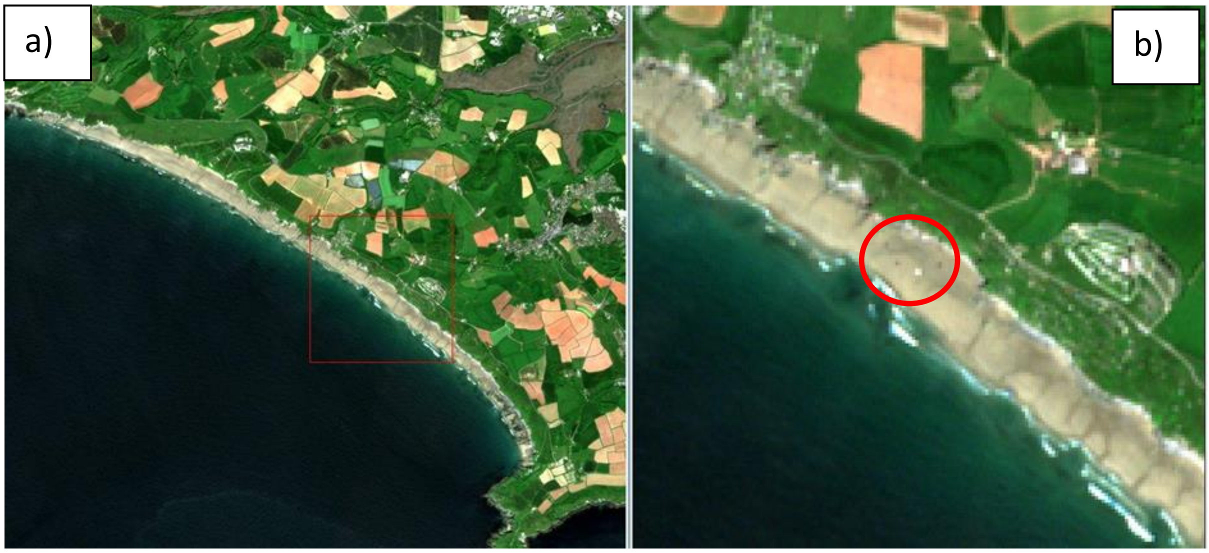

Figure 3: Example of an experimental setup for marine plastic debris detection. False true-colour image from MSI-S2B collected on the 15-May-2018 over Whitsands Bay, UK. a) Zoom out of the whole area with a red square marking zoom in shown in b) with the positions of the plastic targets (10 x 10 m) are clearly visible within red circle.

TABLES

Table 1: Major marine/oceanographic processes on the upper ocean and shore line that affect open questions with respect to marine plastic debris. Spatial extent and lifetime of the relevant processes are reported, alongside with spatial and temporal requirements needed to characterise them, in term of Goal (G) and Threshold (T) observational requirements, see text for definition.

Processes	Spatial		Temporal		Science Question Number
	Extent (max)	Resolution	Lifetime (max)	Revisiting time	
River discharge	100 km	30 m (G) 500 m (T)	1 month	3 h (T)	Q1
Spills	100 km	1 m (G) 50 m (T)	1 month	2 h (T)	Q1
Shoreline accumulation	1000 km	1 m (G) 5 m (T)	10 year	12 h (G) 5 d (T)	Q1,Q2,Q3
Submesoscale convergence filaments	10 km	30 m (G) 100 m (T)	1 month	1 d (T)	Q2,Q3

Table 2: Near-infrared (NIR) capabilities relevant to marine plastic debris detection from Earth Observation platforms, closer wavelengths to 1215, 1732 and 2200 nm (Garaba and Sosik, 2018). Spatial resolution described by the size on the ground (Ground sampling distance, GSD) of the minimum data unit and temporal frequency time between measurements over a given location.

Sensor	NIR bands close to plastic absorption features (nm)	Spatial resolution (GSD in m)	Revisit time (days)
OLCI (Sentinel-3)	900; 1020	300 (max)	1
PACE†	940; 1038; 1250; 1378; 1615; 2130; 2260	1000	2
MSI (Sentinel-2)	1373; 1613; 2202	10 (max)	5
PRISMA†	920 to 2500	30	7 to 14
ENMap†	SWIR I (950-1390)	30	4

	SWIR II (1480-1760)		
	SWIR III (1950-2450)		
SHALOM†	920 to 2500	10	4
HyspIRI†	1400 to 2510	30	16
HYPXIM†	1100 to 2500	8	3 to 5

‡NASA Landsat 8 mission (OLI sensor) measures at similar wavelengths

†Mission in different stages of planning, not launched yet.