Advances in remote sensing of plastic waste

Published by

Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

Acknowledgements

GIZ thanks the IOCCG Task Force on Remote Sensing, Marine Litter and Debris; Nina Gnann (BfG), Dimitris Papageorgiou (University of the Aegean), Prof. Dr. Konstantinos Topouzelis (University of the Aegean), Bijeesh Kozhikkodan Veettil (Thu Dau Mot University, Vietnam), Dr. Jonas Franke (Remote Sensing Solutions), Jennifer Mathis (University of Georgia) and Dr. Stephan Ziegler (WWF Germany) for their expertise and contributions to this publication.

As a federally owned enterprise, GIZ supports the German Government in achieving its objectives in the field of international cooperation for sustainable development.

Published by:
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices:
Bonn and Eschborn, Germany

Dag-Hammarskjöld-Weg 1
565760 Eschborn, Germany
T +49 6196 79-0
F +49 6196 79-11 15

I https://www.giz.de/en/worldwide/93799.html

Programme:
Global sector project to support the BMUV in implementing the Marine Debris Framework – Regional hubs around the globe

Authors: (in alphabetic order of last names)
Steffen Blume (GIZ); Jonas Franke (Remote Sensing Solutions, Germany);
Shungu Garaba (University of Oldenburg); Phong Giang (GIZ);
Jennifer Mathis (University of Georgia, USA); Nadine Ortwig (GIZ);
Stephan Ziegler (WWF Germany)

Reviewers and Editors:
Phong Giang, Nadine Ortwig (GIZ)

Responsible:
Elisabeth Duerr
E elisabeth.duerr@giz.de

Design/layout:
kippconcept GmbH, Bonn, Germany

On behalf of
Federal Ministry for the Environment, Nature Conservation,
Nuclear Safety and Consumer Protection (BMUV)

Photo credits:
lavizzara/shutterstock (Title), Naeblys/shutterstock (p. 7),
AdobeStock (p. 16), M. Jurzyk/AdobeStock (p. 37), ink drop/AdobeStock (p. 40),
3dsculptor/AdobeStock (p. 52), Parilov/AdobeStock (p. 88)

Bonn 2023

Table of Contents

Acronyms

API	Application programming interface
ASEAN	Association of Southeast Asian Nations
BMUV	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and Consumer Protection
CYGNSS	Cyclone Global Navigation Satellite System
DOI	Digital object identifier
EO	earth observation
FML	Floating marine litter
GEO	Group on Earth Observation
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
GOCI	Geostationary Ocean Color Imager
GOOS	Global Ocean Observing System
GPML	Global Partnership on Marine Litter
IOCCG	International Ocean Colour Coordinating Group
IR	Infrared
LIDAR	Light Detection and Ranging
MWIR	Midwave Infrared
NASA	National Aeronautics and Space Administration
NIR	Near Infrared
NKUA	National and Kapodistrian University of Athens
NTUA	National Technical University of Athens
PO.DAAC	Physical Oceanography Distributed Active Archive Center
RGB	Red-Green-Blue
SWIR	Shortwave Infrared
TSM	Total suspended matter
UAV	Unmanned aerial vehicle

Table of Figures

Executive summary

Remote sensing technology is widely used in environmental monitoring for various purposes, such as assessing climate change impacts, monitoring forest fires, and tracking wildlife movement. In recent years, remote sensing has shown great potential for monitoring (marine) plastic litter, with promising results from the use of simple surveillance cameras, drones, and satellite imagery. The development of methods to support traditional monitoring concepts using satellite imagery has been in particularly driven by space agencies and national governments.

High-resolution satellites with multispectral wavebands and specific data models developed by multi-disciplinary teams have shown promise in detecting suspected plastic accumulation zones. However, standardized monitoring methods for plastics are not well established, and coordinated efforts for in-situ sampling matching satellite observation for validation and verification tasks are necessary for algorithm development. There are currently no market-ready applications available for (plastic) litter monitoring. Previous research has mainly focused on developing algorithms to improve the detection of plastic waste accumulation. The areas of quantifying the scale of pollution, identifying the type of plastic, and monitoring the pathways from source to sea are even less developed, and further research is necessary to develop a methodology that meets stakeholders' needs.

Preliminary scientific evidence-based studies have reported recommendations on possibilities to scale up from controlled experiments using artificial plastic targets and small area coverage studies. A prospective approach is the design and launching of a prototype satellite sensor aimed at bridging the gaps and improving the monitoring of plastic waste. A team of experts conducted a community user needs survey complemented by the current literature on remote sensing of plastic litter to define specifications, capabilities, and characteristics for such a prototype satellite. A prototype satellite could also be an opportunity for the community to define and set standardized methods for plastics assessments using well-defined baselines. Remote sensing experts believe that the invaluable scientific evidence-based knowledge derived from the proposed prototype satellite will allow for a more refined assessment of the capabilities of space-based monitoring of plastics.

A coordinated interdisciplinary, holistic approach is critical for a harmonized monitoring tool for plastics in the terrestrial and marine environment. One example is the International Ocean Colour Coordinating Group (IOCCG) Task Force on Remote Sensing of Marine Debris and Litter, composed of experts from academia, industry, civil service, non-profit organizations, governments, and space agencies. The Task Force coordinates and supports the advancement of the topic, especially through thematic workshops and networking events. One priority has been to engage stakeholders to better understand their user needs while also communicating the capabilities and limitations of remote sensing as a complementary monitoring tool for plastics in the aquatic environment. At present, efforts are currently underway, so this report provides a status on remote sensing of marine litter. The findings and scientific research gaps identified in recently completed projects will be bridged or supplemented by ongoing or future studies.

1 Introduction

Today, one of the most pressing global threats to the oceans is plastic pollution. Plastics and microplastics have become ubiquitous in landscapes as well as in marine and freshwater environments [1]. They disperse in and enter the sea through rivers, sink to the river and sea floor and accumulate in sediments and biota. While monitoring of marine litter and its impacts is still limited, research has already identified marine litter as a growing issue affecting various species of fish, cetaceans, reptiles and invertebrates [3]. Effects at population and ecosystem level still need to be better understood but could be significant [2]. A sound database derived from marine litter monitoring can help to demonstrate the dimension of the problem, to identify key sources of marine pollution, to initiate preventive measures and to show the effect of various planned or implemented measures [3]. Currently, there are different tools to assess and monitor the leakage of (plastic) waste into the environment, each of them with specific requirements of data collection and knowledge on data interpretation. However, for all tools the existing data collection systems are limited and thus unable to answer fundamental questions, e.g. regarding the concentration of plastic waste in the sea and its spatial and temporal dynamics. Efforts to fill the current gaps of marine litter monitoring have led to a growing interest in imaging or remote sensing technologies using boats, aircrafts or satellites to monitor physical characteristics of the earths environmental components [13] as it has the potential to complement existing monitoring approaches with high quality data in a cost-effective way.

The purpose of this report is to provide an overview of the emergence and current state of the art in remote sensing applications for plastic waste monitoring and as well as examples of current research projects.

The detailed objectives of this report are:

- To introduce remote sensing technologies and their modes of operation for environmental monitoring.
- To provide the reader with the context of application regarding marine litter detection and monitoring through remote sensing technologies.
- To present concrete examples of remote sensing projects in practice to combat marine plastic litter.
- To support policy makers in making informed decisions on marine litter monitoring strategies.

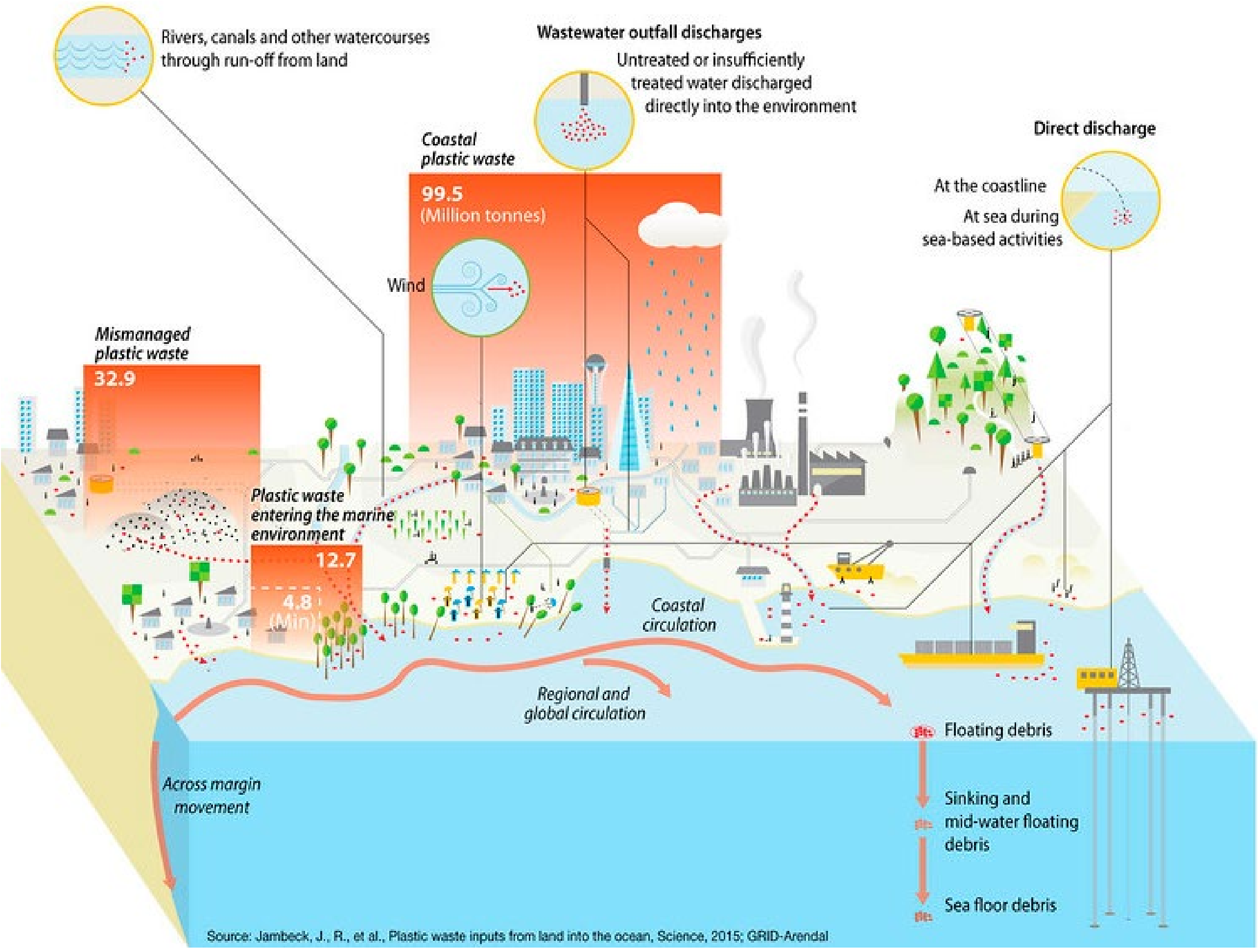
To this end, the report is structured as follows: Chapter one briefly summarizes the status quo of marine litter monitoring methods alongside their main challenges and introduces the emergence and foundations of remote sensing as a complementary technology for marine plastic litter detection and monitoring. The second chapter reviews in depth the existing advances of remote sensing in detecting, identifying, quantifying and tracking marine litter by illustrating existing use cases and presents web-based tools and stakeholder community initiatives in this context. Combining the insights from the two previous chapters, the report concludes with the (current) limitations of the applications and an outlook on the potential applications and development of remote sensing for marine litter monitoring. This study is part of the GIZ Global Marine Litter Project, which supports the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and Consumer Protection (BMUV) in the implementation of the funding program "Marine Debris Framework – regional hubs around the globe" (Marine: DeFRAG). The aim of the funding program is to support developing and emerging countries in improving their waste management system and to create incentives to prevent marine litter pollution.

1.1 Plastic leakage pathways and monitoring challenges

Marine plastic litter can originate from multiple sources, both land- and sea-based. A rather small fraction of it stems from sea-based sources, e.g. waste that ships discard directly at sea. Instead, most of the marine plastic litter comes from land-based sources, such as households, municipalities, (touristic) activities at the beach/coast or harbours/ports, agricultural activities and landfills.

Especially in low- and middle-income countries, due to a lack of centralised systems for separating and treating waste, plastics are often dumped in landfills and might end up in adjacent rivers, lakes and the sea[4]. The location and fluxes of plastic debris depend on various factors, such as pollution sources, local weather, site and water conditions (e.g. currents), as well as the type of plastic[5].

Figure 1: Pathways and fluxes of plastics into the oceans[6].



To identify the sources and assess the extent of plastic pollution, different monitoring approaches have been developed, which require in all cases a sound database derived from marine litter monitoring and waste management.

Figure 2: Process of monitoring marine litter (own delineation based on [5]).

Figure 2 describes the generic steps of a marine litter monitoring process. In advance of selecting an appropriate monitoring method, the monitoring objectives should be defined to enable the allocation of required resources. Potential monitoring objectives may be, for example, to generate comparable results based on which targeted preventive measures could be initiated and/or to raise public awareness on the issue of marine litter. After the determination of the goal, a monitoring approach typically starts with the selection and description of suitable sites prone to marine litter accumulation. Such sites are usually [7]:

- Areas near land-based sources of pollution (e.g. rivers, sewage);
- Coastal areas;
- Depressions on the seafloor;
- Sites with slow hydrodynamics (e.g. weak circulation, low currents) [7].

Based on the monitoring goal and the selected site, resources are being allocated, the selected location is divided into zones, the observation period is determined, and finally the data is collected, assessed and documented. Common methods for assessing plastic pollution in marine ecosystems, which can be grouped into sample gathering and visual observations, are:

Sample gathering:

1) *Beach litter monitoring* is a widely used method for measuring pollution in coastal environments. The method relies on area gridding, manual collection, counting and categorising litter by size, material and/or type of items. The method is simple, cost-effective and helps to understand the extent of littering, to raise awareness, and to facilitate preventive measures. It is less suitable for regularly cleaned beaches, poorly accessible shores, or extremely littered areas. Moreover, beach litter monitoring only provides a snapshot at a place at a given time, so magnifying the sample data and estimating the total amount of litter may not be accurate if not conducted regularly [5].

2) *Floating booms and nets* serving as floating litter barriers are typically used to measure floating litter on the surface of river basins and in the first metres of the rivers' water column enabling its collection, quantification, categorisation, and weighting. The method provides a snapshot of the litter in the part of the river that was monitored at a given time. Thus, high-quality data showing the variation of waste can only be derived if the method is applied frequently [5].

3) *Net trawling* to monitor benthic debris can cause serious environmental damage to the ecosystem and should therefore only be considered when existing regular bottom trawling programmes, for example in assessing fish stocks, are implemented. In addition to avoiding harmful consequences, monitoring costs can be reduced in this way. The main advantage of this method is its accuracy as it can provide extensive multi-parameter data for macro-waste [5].

4) *Scuba-diving* is used to monitor the nearshore environment for benthic pollution. If volunteers are not available, this method is highly cost intensive. Furthermore, the feasibility of scuba-diving depends on the accessibility of the diving sites and is prone to subjective perceptions of the divers [5].

Visual observations:

5) *Visual ship-based observations:* To reduce costs, surveillance from a vessel does not have to be a specific activity but can be conducted in parallel with other ongoing activities, such as fishing, research activities or tourist cruises [8].

6) *Visual off-shore observations* can be carried out either directly from observation platforms, aeroplanes, bridges, or indirectly through video

equipment. Visual off-shore observations can be performed both stationary and dynamically[9]. In stationary observations, an observer/device is stationed in a fixed spot, for example on a bridge over a river, while dynamic riverine observations, similarly to ship-based marine monitoring, rely on boats and use similar protocols[10]. This method is primarily suitable for macro-sized litter.

7) *Towed cameras:* Compared to monitoring with trawls and divers, monitoring benthic waste with the help of towed cameras is more accurate as it enables the avoidance of bias in sampling and assessment and allows for post-survey evaluation. The method is cost-effective and does not require a high level of expertise or expensive equipment. However, it is limited to areas with good water visibility and cannot be used in areas with dense vegetation or rough terrain[5].

Plastic items can be transported over long distances and accumulate over time in areas very far from their places of origin[12]. Existing data collection systems are limited and thus unable to answer fundamental questions, e.g. regarding the concentration of plastic waste in the sea and its spatial and temporal dynamics. This is partly due to the geographic scale of the problem[8], a lack of harmonized methodological approaches and non-comparable metrics[5, 11], and due to the diversity of the waste items themselves. Efforts to fill the current monitoring gaps of marine litter have led to a growing interest in imaging or remote sensing technologies using boats, aircrafts or satellites to monitor physical characteristics of the earths environmental components[13].

1.3 Remote sensing in the context of environmental monitoring

According to the U.S. Geological Survey, *"remote sensing is the process of detecting and monitoring the physical characteristics of an area by measuring its reflected and emitted radiation at a distance (typically from satellite or aircrafts)"*[13].

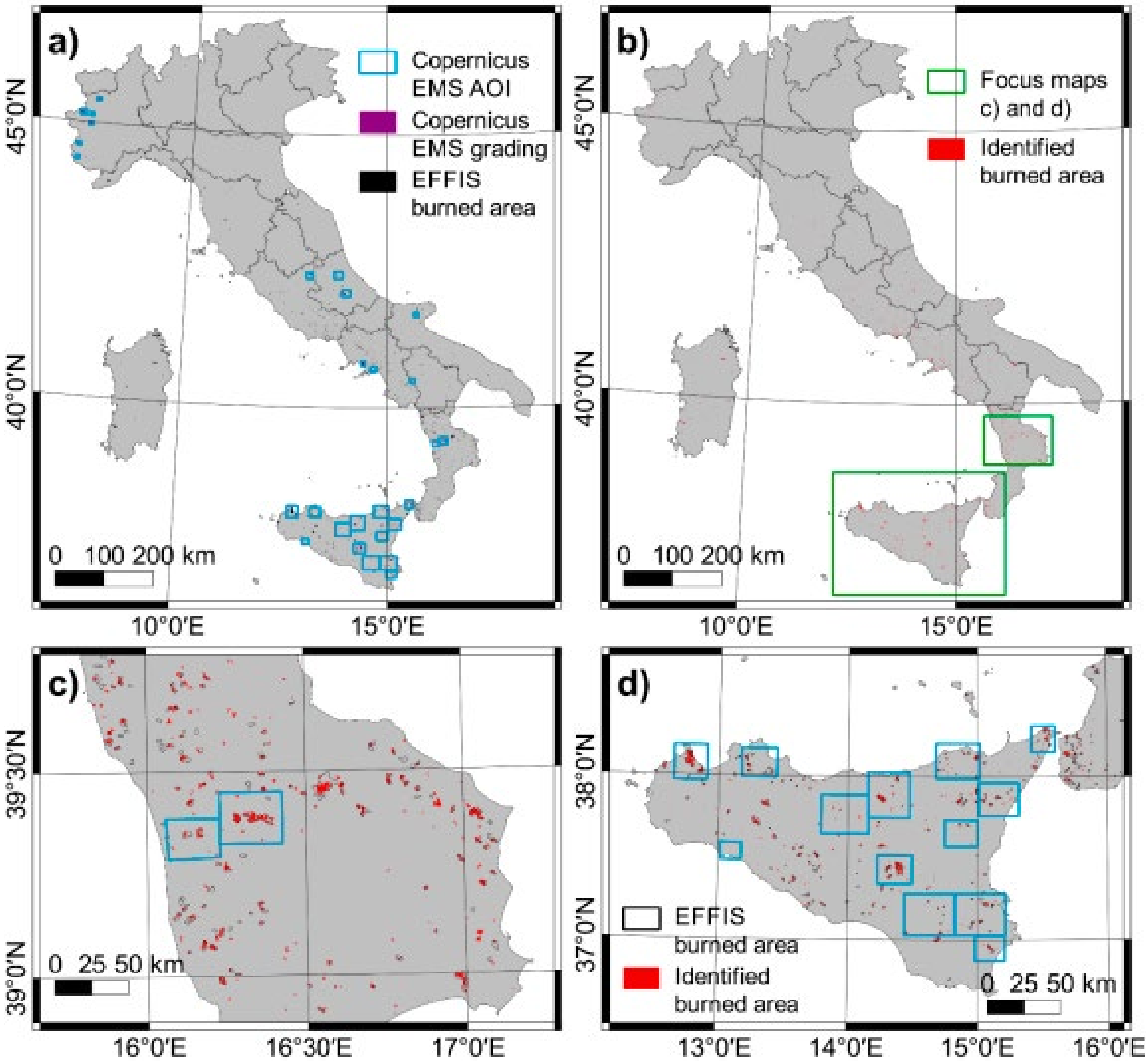
Examples for the application of remote sensing are[13]:

- Cameras on satellites and aircrafts taking images of large areas of the Earth's surface;
- Sonar systems on ships taking pictures of the ocean floor without having to sail or dive to the bottom of the ocean;
- Cameras on satellites can be used to take pictures of temperature changes in the oceans[13].

Specific uses of remotely sensed images of the Earth in the context of environmental monitoring include[13]:

- Mapping large forest fires;
- Tracking clouds for weather forecasting;
- Monitoring erupting volcanoes;
- Monitoring dust storms;
- Mapping changes in farmland or forests over several years or decades;
- Discovering and mapping the rugged topography of the ocean floor, e.g. huge mountain ranges, deep canyons;
- Monitoring animal populations and movements of the herds[13].

Figure 3: a) Spatial distribution of the "MODIS burned areas" reference products and Copernicus EMS rapid mapping activations (areas of interest are overlaid); (b) spatial distribution of the identified burned areas; (c) focus map of the identified burned areas over the Calabria Region; d) focus map of the identified burned areas over the Sicily region. (Derived from [14]).



1.4 History on Remote Sensing of Plastics

The early recorded remote sensing of anthropogenic waste was conducted from land or on boats through visual inspection combined with taking images or photographs [15-18]. Some of the early coordinated extensive activities were through the National Oceanic and Atmospheric Administration Marine Debris Program and the Japanese Government in the North Pacific Ocean as well as Alaskian waters revealing presence of plastic objects including styrofoam, ghostnets or derelict fishing gear [19]. With time, field surveys started using imaging sensors integrated on airborne and fixed platforms for wide aerial observations and direct measurements whilst satellites provided indirect data [20-23]. These manned airborne observations included trained human observers who counted visible floating and slightly submerged litter. Over time, the benefits of fixed, airborne and satellite sensors have been recognized by stakeholders as reflected by the significant resources being made available to the scientific and industry community to assess and propose remote sensing-based solutions for plastic waste monitoring.

Recently, satellite-based remote sensing technologies have been increasingly explored through with the support of space agencies interested in evaluating ways to best leverage remote sensing technologies for monitor plastics. The European environmental observation program Copernicus, coordinated by the European Commission, offers information services drawn from satellite Earth Observation (EO) and in-situ (non-space) data. Copernicus is served by a set of dedicated satellites (the Sentinels) and further commercial and public satellites as well as in-situ systems such as ground stations, which deliver data acquired by a multitude of sensors on the ground, at sea or in the air. The European Space Agency ESA is in charge of the space component, i.e. responsible for developing Sentinel satellites on behalf of the EU and data management services.

Table 1. Examples of space agency initiatives related to remote sensing of plastics.

Agency	Programme/Initiative	Goals
ESA	Atlantic Regional Initiative	Promote and explore the use of information about the environment (e.g., water quality, oil spills, leakage plastic litter) generated from remote sensing in the Atlantic region to support future operational monitoring and decision making.
	Blue Worlds Task Force	As a team of ESA Member States the task force has some focus on the use of remote sensing to support the sustainable and interdisciplinary monitoring of the maritime environment. The task force provides recommendations that contribute to priority issues for the ESA Council at Ministerial Level
	Discovery Campaign	Support innovative and disruptive scientific evidence-based research to assess the application of remote sensing technologies to monitor plastic marine litter.
	EO4Society	Support scientific evidence-based research to advance EOs, better understand the changes or state of the environment and make decisions based on gathered data.
	General Support Technology Programme	Evaluate and develop technologies for future space deployment (e.g., testing remote sensing technologies suitable for remote sensing of floating plastic waste).
	Plastic-Less Society	Explore the feasibility of commercializing information and services utilizing remote sensing technologies to address marine plastic waste pollution (e.g., locating hotspot, pathways, sources, sinks).
NASA	Research Opportunities in Space and Earth Sciences Program Element A.3 Ocean Biology and Biogeochemistry	Explore and evaluate the advances in remote sensing of the green and blue planet (e.g., check the prospects of remote sensing with current or future satellite sensors).
	Earth Science Technology Office	Support the advancement of sensor technologies relevant to space based remote sensing of the Earth system (e.g., testing new sensors for remote sensing of plastics).
PSA	AI Moonshot Challenge	Assess the combines use of remote sensing technologies and artificial intelligence to sustainably monitor the environment (e.g., marine plastic litter).

ESA also funded two feasibility studies for the projects RESMALI and OPTIMAL on remote sensing of marine litter [25]. The extensive research findings of these ESA activities have been critical in establishing an initial roadmap based on capabilities and limitations of remote sensing technologies relevant for plastic waste monitoring [26].

National Aeronautics and Space Administration (NASA) initiatives include the "Research Opportunities in Space and Earth Sciences Program Element A.3 Ocean Biology and Biogeochemistry" and future investments planned with synergies across NASA. Both ESA and NASA supported several workshops that brought together interdisciplinary international experts on the topic.

Governments and environmental agencies have also been investing in remote sensing research whilst some already gathered relevant information from drones at a small scale. A list of scientific research projects that have been conducted or currently ongoing is presented in the annex (Annex A1. Scientific Research Projects).

Several of these experimental scientific evidence-based efforts to leverage current remote sensing technologies have revealed the importance for implementing imagery fusion to better explore the detection, identification, quantification or tracking goals when monitoring floating plastic litter because these sensors are not fully fit-for-purpose or mature enough [26-28]. These disruptive experimental studies have unfortunately been limited to specific sensors, scenarios, times and study areas a challenge resulting with available resources in a field that is still in the early stages of development.

1.5 Basics of Remote Sensing

Remote sensing is a way of getting information about an object-of-interest by looking at it from a distance. It therefore means no direct contact between the observing sensor and targeted object-of-interest to the observer. Information recorded can be sound or light measured at specific temporal, geo-spatial pixel and spectral resolutions that is transformed into an image to derive shape, distance, size or colour details of the target using algorithms. An algorithm is a set of commands or steps to be followed for handling data to generate an output that can be a qualitative or quantitative variable.

In ocean colour remote sensing, the derived parameters are used as proxies or indicators of optical active constituents of the aquatic environment. Light or electromagnetic waves from the sun possess energy at different parts of the radiation spectrum. The spectrum includes high energy cosmic rays, x-rays, ultraviolet, visible to the low energy shortwave, thermal infrared, microwaves and radio waves. Visible light is the part of ambient light in the wavelength range from 400 to 700 nm that corresponds to the colours that the human eye can perceive and distinguish. True colour images apparent to the human eye are mainly composites of variable shades and tones of Red-Green-Blue (RGB) colours. Infrared (IR) the part of the electromagnetic waves or ambient light beyond the visible spectrum > 700 nm whereby the human eye cannot easily distinguish light. Common regions include Near IR (NIR, 700 – 1000 nm), Shortwave IR (SWIR, 1000 – 2500 nm), Midwave IR (MWIR, 2500 – 6000 nm) and Thermal or Longwave IR (LWIR, 1000 – 14500 nm). For example, the human eye acts as a sensor that detects visible light that is transformed in the brain to infer qualitative details like shape, tone, true apparent colour, size, form, texture or patterns of target objects.

Using manmade sensors both qualitative and quantitative information can be derived from the signal obtained from targets of interest. Remote sensing technologies relevant for monitoring the natural environment are grouped into active or passive sensors. These two types of sensors measure light that is then transformed into numerical numbers relevant about environmental geological, biological and physical characteristics of object-of-interest. Active sensors (e.g., laser scanner, sonar, LIDAR, radar) have to generate an energy signal that is sent or directed towards an object-of-interest and then this produced pulse is measured after interacting with the target. Passive sensors (e.g., imaging spectrometer, digital camera, thermal scanner, microwave radiometer) do not generate own energy signal but only detect ambient sunlight. Active sensors can be operated in any environment because of their ability to generate energy sources whereas passive tools depend on signals from other items like the sun. As passive remote sensors relevant for environmental monitoring depend on energy generated by external sources they are prone to environmental conditions (e.g., clouds, dust, rainfall) especially when operating at high altitudes (e.g., aircrafts, satellites).

Remote sensing technologies have spectral, geo-spatial pixel and temporal resolution characteristics parameters that are relevant to the monitoring of the environment. Spectral resolution is the amount of spectral information a remote sensing instrument can resolve from a measured signal. The primary specifications are the number of spectral wavebands or channels, spectral response function and full-width at half-maximum of the instrument. A true colour composite image requires three wavebands Red, Green and Blue (RGB; R = 650 nm, G = 550 nm, B = 450 nm). Instruments can be designed as single, multispectral (< 20 channels) or hyperspectral (> 100 channels) sensors. Spatial or geo-spatial pixel resolution refers to the least qualitative ground sampling distance or pixel size that can be determined from an image. Remote sensing images can be reported as course (> 1000 m/pixel), moderate (< 500 m/pixel), high (< 30 m/pixel) and very high (< 5 m/pixel) geo-spatial resolution. Temporal resolution refers to the time interval data of interest is gathered. Time intervals can range from seconds, hours, days to weeks. When monitoring anything the time resolution of the sensor or observing interval can be determined by how fast or slow the target physical/chemical/biological descriptors are changing. Satellite orbits explain how the sensor platforms move at different altitude, speeds, pathways relative to our Earth surface. Sun synchronous or polar orbiting travel from North to South over the poles at an altitude range of 200 – 1000 km collecting images over a fixed area at a specific time during daylight. Sun synchronous satellites have extensive applications in meteorological, ocean and terrestrial remote sensing.

Geostationary satellites move at the same speed as the Earth is rotating making it possible to image the same location at all times and find application in real-time applications such as communication, weather monitoring and tracking. Low orbit satellites include the International Space Station and other sensors used for on-demand remote sensing application. Water quality monitoring is widely conducted by using optical remote sensing technologies that obtain light signal in the visible and IR spectrum [29, 30]. The concept is based on the detecting and measuring artificial or natural objects that possess a unique optical signature that can be observed from optical remote sensing technologies. Objects that have any apparent colour the human eye can determine can be considered as optically active in the visible spectrum (e.g., plastics, algae, suspended sediments, vegetation, water). The colour of water is controlled by four optically active components (e.g., water itself, algae, organic material, suspended solids, dissolved organic matter). The unique signature of these optically active materials can be visualized as the signal (e.g., radiance, reflectance) over the light spectrum measured. A simple way to distinguish the observed signal is to use the spectral reflectance shape and magnitude. The shape can be explained as the peaks representing local region of very high reflectance or valleys meaning lowest magnitude in a given portion of the measured signal. Valleys in the spectral reflectance are also known as absorption features.

Remote sensing algorithms are used to produce maps based on statistical correlation of the measured signal (e.g., reflectance, radiance) and any in-situ measured parameter with the matching optical signature (e.g., vegetation). A relationship equation is derived regressing diagnostic wavebands to the in-situ measurements. The equation will be used to compute the proxy or indicator of the environmental parameter (e.g., amount of suspended sediments in the water) because from remote sensing we only measure and infer the target material based on the signal. Correlation tests that have been widely used to derive an index or proxy include empirical linear regression, polynomial fits and semi-analytical methods.

Maturity and Advances in Remote Sensing of Plastics

2

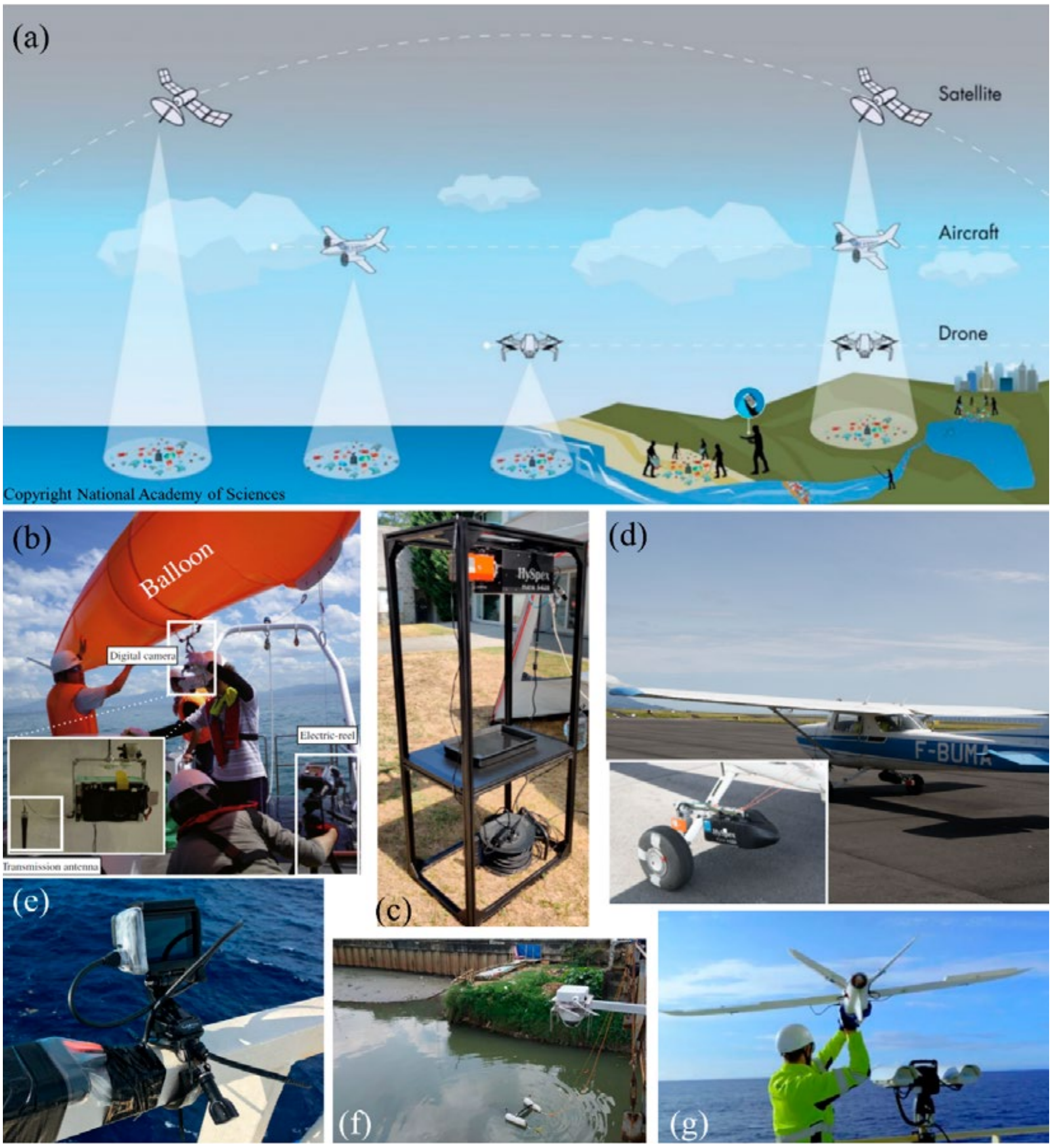
The field of remote sensing is still in the early stages and research is still ongoing with continued advances being reported. However, previous research has been revealing potential applications of direct remote sensing in the detection, distinguishing, quantify and tracking of aquatic plastic litter. These research efforts have been conducted in mostly controlled settings at various geographic location, examples provided in the following chapters as well as in Annex A2. Application of Remote Sensing of Plastic Waste.

An understanding of the physical properties of the plastics remote sensing technologies is ongoing and has been explored of wide range of relevant materials (Figure 4). The size classes that have been of interest include micro and macro plastics. Sampled materials were a combination of virgin and weathered plastics[31-34]. Microplastics were investigated after being manually aggregated to make a dense large target[35], the macro sized objects as either scattered individual items[31, 34], clustered to form large artificial targets[32, 36, 37] otherwise as a soup mixture of all size classes[38, 39].

Figure 4: Examples of plastic samples of varying sizes that have been observed in remote sensing experiments (a) ocean harvested microplastics[35], (b) soup of plastics in the Port of Antwerp[40], (c) mixture of litter in windrows imaged by Caroline Power, (d-f) 0.5 × 0.5 m aggregated plastic bottles and sheets[34], (g) 3 × 10 m target of floating plastic bottles[37] and (h-l) large floating and submerged plastic structures. (Images provided by Konstantinos Topouzelis).

Sensors were integrated on different platforms in space [36, 39, 41, 42], on aircrafts [20, 21, 43-46], unmanned aerial systems or drones [34, 47, 48], air balloons [23, 49], floating vessels [33, 50, 51], handheld [52], fixed frames outdoors and indoors [22, 31, 53]. Examples of the various platforms are presented below (Figure 5 and Table 2.1) and more detailed examples are showcased in (Annex A2.1 Platforms for Remote Sensing of Plastic Waste).

Figure 5: Overview of remote sensing platforms relevant for plastic waste [65], examples from (a) experiments over water using sensors (b) attached to balloons [49], (c-d) on moveable frames and aircrafts [46], (e) fixe to ships [33], (f) fixed on bridges and (g) on drones [33].



As widely showcased by the vast scientific evidence-based research projects, peer reviewed literature, workshops as well as conferences (more detailed examples in the Annex section), the potential application of remote sensing is limited to the surface layer of floating and slightly submerged plastics observed from nadir meaning the sensor will be looking straight downwards or perpendicular to the surface. Sensing from a viewing angle perpendicular to the target area has limitation in terms of abundance because only the surface area coverage can be revealed from imagery but no data about the depth or underlying objects in a three-dimensional form is revealed. The current steps and advances in the detection, identification, quantification and tracking of plastic waste from remote sensing technologies are summarized below (Figure 6);

Figure 6: (a) A simplified pipeline of the approach from image capture to deriving essential parameters from remote sensing imagery. (b) Example of the pipeline used in Coastal Marine Litter Observatory (CMLO, https://cmlo.aegean.gr/) and (c) CMLO maps of marine litter geolocations, types and densities. Courtesy and adapted from [66].

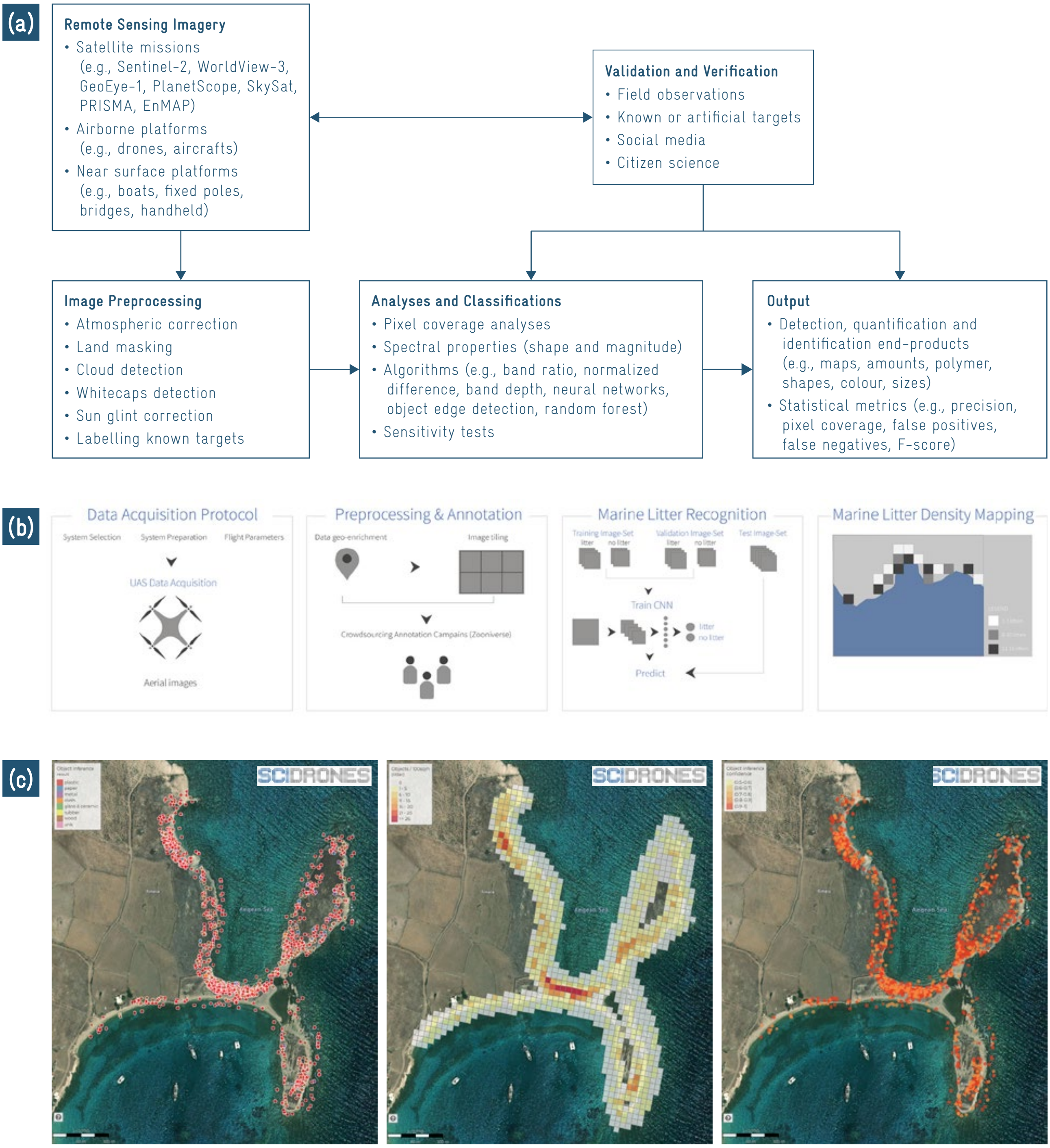


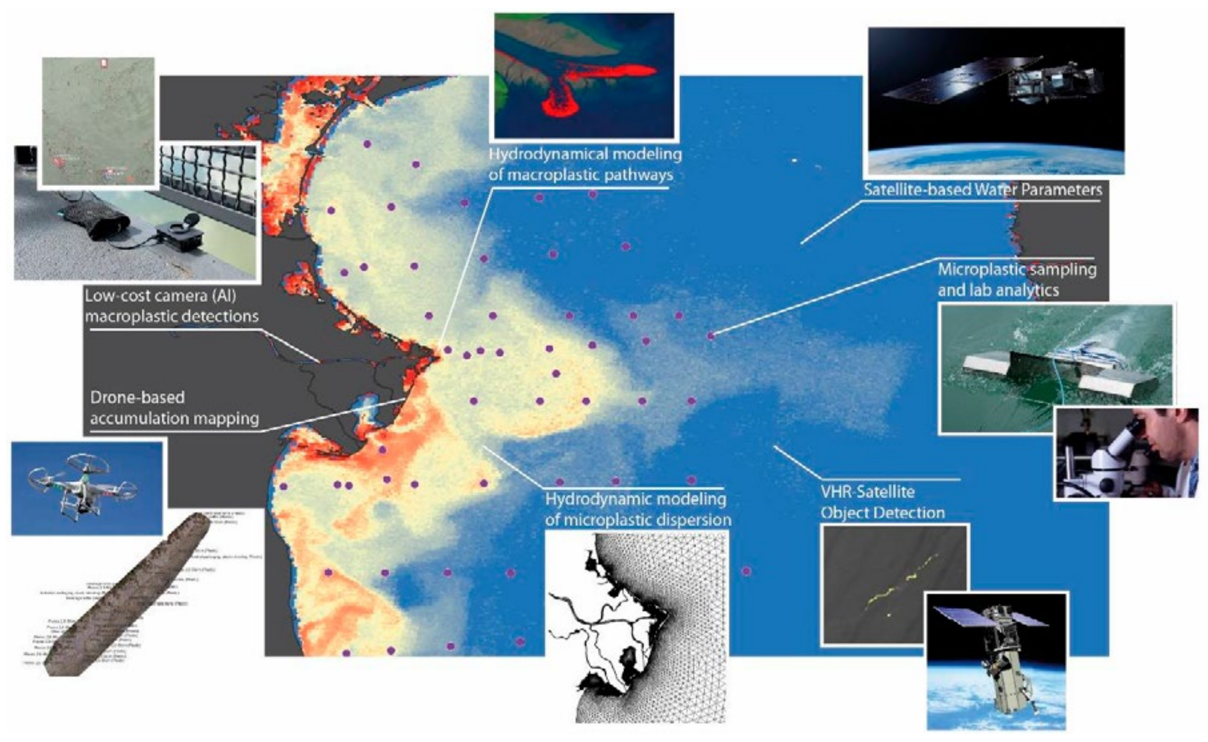
Table 2.1: Examples of remote sensing platforms used to study floating and beached litter.

Platform	Overview	Study
Fixed	A security camera was mounted to a customized frame with an extended arm on bridges in Indonesia to continuously monitor floating litter including plastics. The true colour RGB Dahua Easy4ip IPC-HDBW1435EP-W sensor was mounted perpendicular to observe directly downwards at the river surface. In this setup the water surface and any floating material were captured in the images.	Automated river plastic monitoring using deep learning and cameras [54]
	A webcam was placed on a pole attached to attached to a frame for the monitoring of a beach in Japan. True colour RGB images were collected at an angle using a Vivotek IP7361 sensor. Images captured the beach, water and part of the skyline.	A new technique for detecting colored macro plastic debris on beaches using webcam images and CIELUV [55]
Ship	Floating litter was observed continuously from a transporter vessel in the Great Pacific Garbage patch using a GoPro camera. The GoPro Hero 6 sensor was attached to the side of the vessel and viewed the ocean surface at an angle. Drones were also deployed to survey a wide area of the ocean surface. Mantra net trawling was also conducted to gather in-situ data.	Quantifying floating plastic debris at sea using vessel-based optical data and artificial intelligence [33]
	Trained human observers counted floating litter from a research vessel around Antarctica. The observers used binoculars to aid the survey from the bow or bridge of the vessel.	Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition [51]
Drone	The work investigated the presence of marine litter with a focus on the geomorphology and environmental characteristic of the areas it accumulated in Italy. The images used were captured using a DJI Phantom 4 Pro Obsidian DJI drone.	Understanding through drone image analysis the interactions between geomorphology, vegetation and marine debris along a sandy spit [56]
	A DJI Mavic 2 Pro quadcopter equipped with a video system was used to survey for floating litter in the Philippines. Floating litter was revealed to be a potential threat to nearby turtles.	Eye in the sky': Off-the-shelf unmanned aerial vehicle (UAV) highlights exposure of marine turtles to floating litter (FML) in nearshore waters of Mayo Bay, Philippines [57]
Aircraft	Hyperspectral sensors mounted on an aeroplane were used to observe an artificial set of plastic targets in Switzerland. The floating targets were built using Polyethylene terephthalate water bottles and information was collected from the visible to the SWIR spectrum (400 - 2500 nm).	Detection of sub-pixel plastic abundance on water surfaces using airborne imaging spectroscopy [44]
	Three artificial targets of common plastics were investigated from an aircraft with hyperspectral sensors (400 - 2500 nm). The targets were low density polyethylene orange with used oyster spat collectors, white plastic film and ropes.	Remote hyperspectral imaging acquisition and characterization for marine litter detection [46]
Satellite	Floating artificial targets were placed to investigate the feasibility of detecting litter using multispectral Sentinel-2 satellite data in Greece. The targets were composed of high-density polyethylene, wood and a mixture of plastic with wood. Additional remote sensing was achieved using a hyperspectral drone (400- 1000 nm).	Sentinel-2 detection of floating marine litter targets with partial spectral unmixing and spectral comparison with other floating materials [58]
	Floating litter from the Japan 2011 Tsunami was observed by several satellites. Sensors in space included PALSAR Synthetic Aperture Radar and WorldVew-2, RapidEye, AVNIR-2.	Dynamics and early post-tsunami evolution of floating marine debris near Fukushima Daiichi [59]

Single to multipixel optical imaging of floating or beach plastic litter has been achieved using single band [20, 34], RGB or digital camera systems [20, 22, 33, 34, 45, 50, 54], multispectral [36, 39, 42, 59], hyperspectral sensors [31, 43, 46, 52] covering the visible to thermal spectrum. The application of Light Detection and Ranging (LIDAR) [20, 60, 61] as well as radar [36, 62-64] technologies have been showing promise in monitoring plastic waste.

Tackling the plastic debris challenge at its source – Linking Earth Observation data with multi-source in-situ data for modelling debris pathways from source to sink

Figure 7: Linking Earth Observation data with multi-source in-situ data for modelling debris pathways from source to sink.

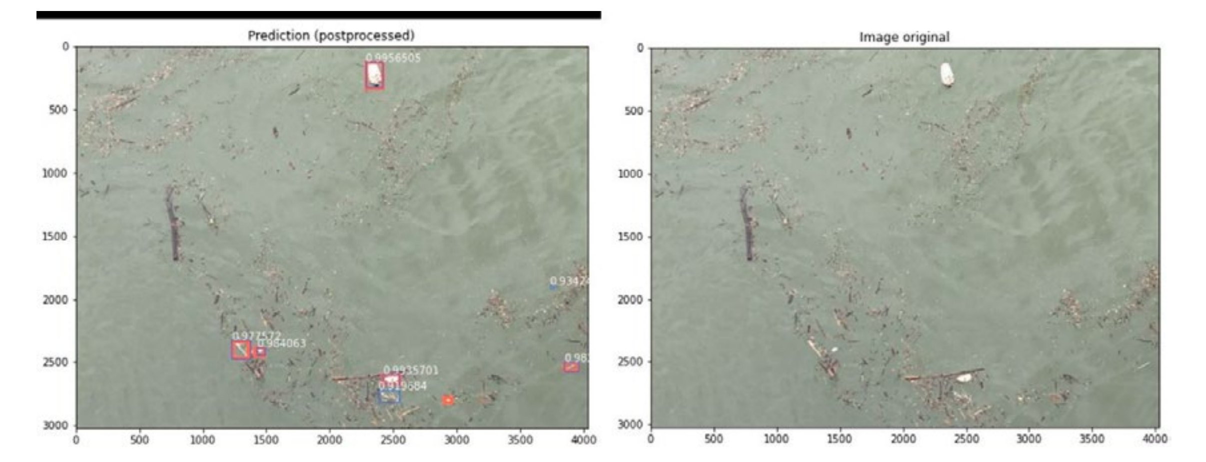


The project was funded by the European Space Agency's within its program "Basic Activities in the framework discovery campaign on Remote Sensing of Plastic Marine Litter" and implemented in 2020-2022. The objective of the project was to link earth observation data from different platforms with in-situ data for modelling debris pathways from source to sink. Knowledge about particle transportation is still limited as current practise of point measurements cannot provide a full view on complex source-sink relationships. Hence, upscaling in-situ point data of litter with EO and hydrodynamic models was the central concept of the project.

For the first time, a wide range of technologies were combined and tested, including satellite remote sensing, drone technology, near-range cameras, various in-situ plastic sampling techniques, lab analytics and hydrodynamic modelling. Each module was independently developed by the different partners, in order to test the readiness level of the various technologies. The modules were finally linked in order to demonstrate the inter-linkages and the benefits of the technologies as a whole.

Starting with low-cost camera systems operated from bridges above the Po River (Italy), to identify floating macroplastic particles in the images using artificial intelligence. The number of observed particles were used as input to seed a macroplastic transport model (HYDROMOD-Tracer) which provides transport pathways for the particles.

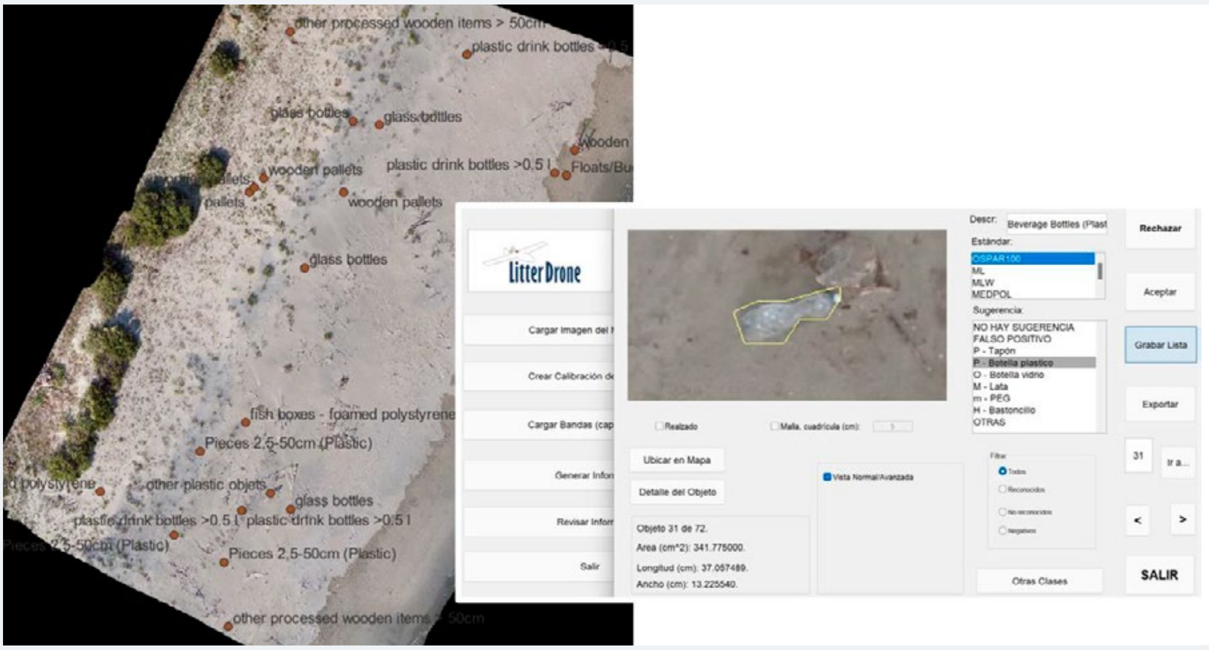
Figure 8: Camera-based macroplastic detection. Example of an original image (right) and the predicted detections of macroplastic particles (left). Particles with a blue and a red box indicate correct detections, areas with a blue or red box only indicate false positive or false negative detections, respectively.



In addition to the macroplastic, in-situ microplastic data collected in the river itself as well as in transects along the coastline, were used to calibrate and validate the hydrodynamic models (Regional Ocean Modelling System and the Lagrangian model) to simulate the dispersion pathways of microplastics. The collected in-situ microplastic samples were examined by laboratory analytics to quantify the abundance of microplastic and to qualify the plastic type. In addition, near-shore fronts with a high abundance of microplastic debris could be identified. The locations of these fronts have also been proved using satellite-based total suspended matter (TSM) information of Sentinel 3, in combination with a newly developed application for generating high-resolution (10m) TSM maps based on Sentinel-2 data and a machine learning approach.

Along the further transportation pathway, drones were used at potential hotspots along the coastline. By using the LitterDrone software which employs a machine learning algorithm, based on parameters such as the colour and shape of plastic objects and beach background, macroplastic particles (>2,5cm) could be identified in the very high-resolution images. With the acquired drone imagery, these particles were automatically classified to quantify the abundance of plastic litter.

Figure 9: Orthomosaic (composed of hundreds of single pictures) of Barricata beach with the detected and identified objects (left) by the LitterDrone software (right).



With additional research, development and test activities in the future, this monitoring concept can lead to an operational system that provides continuous spatial information crucial for entities and stakeholders involved in the mitigation and removal of plastics in the environment. Such monitoring system could then not only support prevention and counteraction activities, but also spatially target interventions and help to make them more efficient. Monitoring concepts such as demonstrated in this project can act as a significant contribution towards the creation of an urgently needed legal basis for avoiding water system impairment through plastic contamination, since threshold monitoring will require a functioning measurement system.

2.1 Detection

The human eye and synthetic sensor technologies are primary tools in the direct detecting of plastic litter using monochromatic, true RGB or false colour composite information. Detection is a simplified binary approach that can be exemplified by a zero suggesting absence and a one indicating presence of a target of interest. It can also be achieved by looking for anomalies in imagery. Anomalies can be used to directly or indirectly detect plastics by using prior knowledge about the environment and relevant descriptors of plastic waste. A trained observer can inspect true colour images manually to detect and derive Essential Plastic Litter Descriptors. Essential Plastic Litter Descriptors any qualitative and quantitative characteristic of plastic waste that can be used to distinguish it from other materials including shape, form, colour, size/ dimensions, polymer type, density or weight. However, applying machine learning algorithms after training the models has made it possible to automatically detect plastic waste, thus reducing the tedious effort by trained human experts. Therefore, the accuracy of the most automated detection methods depends on continuous training of machine learning models.

Further examples of how machine learning has been applied to the detection and quantification of remote sensing imagery is presented in Annex A3. Machine Learning Application in Remote Sensing of Plastic Waste. There are some benefits that have been reported with respects to using true colour images, is the capability for both manual as well as automated methods to extract details about shape, colour, size and form descriptors of suspected plastic waste [42, 45, 47, 48, 55, 67-70]. However, it is important to consider the fact that for the accurate verification of suspected plastic waste, polymeric identification or in-situ sampling needs to be added in any related monitoring protocol.

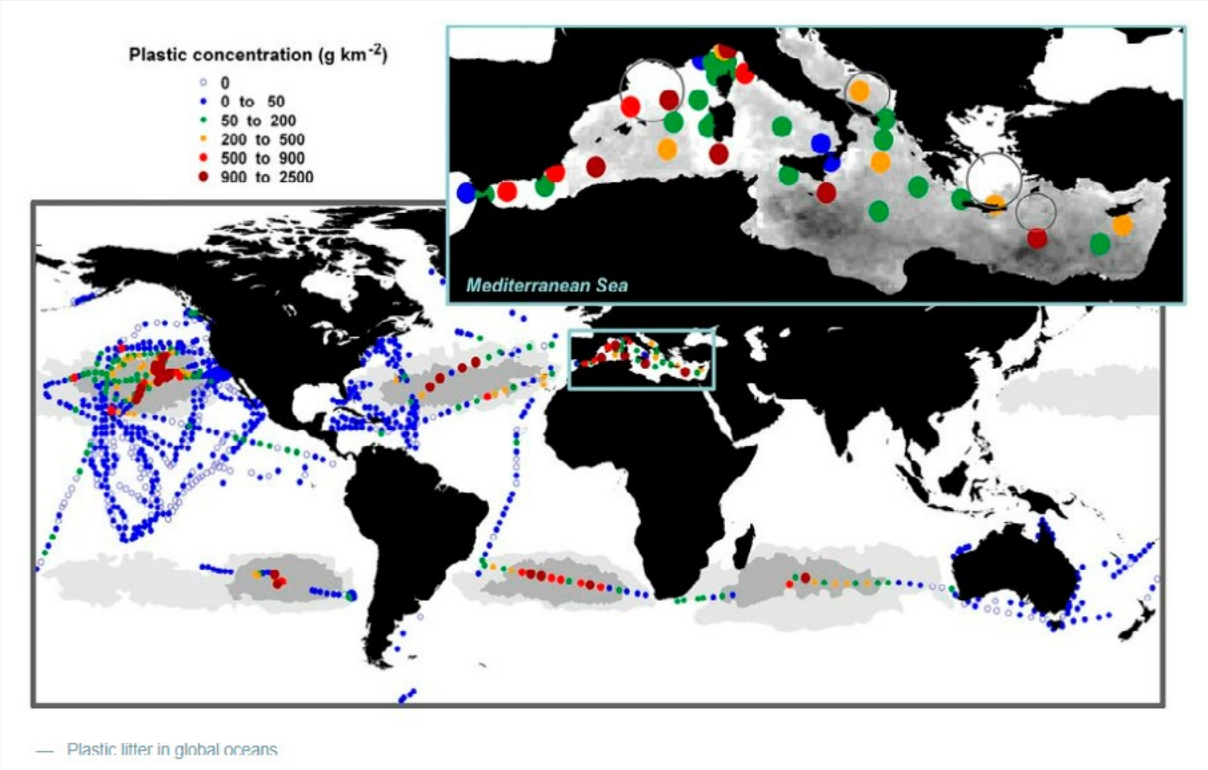
Size makes a difference when considering the detection capabilities of various sensors. Microplastics have been assumed to be detectable in relatively large, aggregated patches that might also consist of other size classes, whilst macroplastics can be observed as individual or aggregated items using high to very fine geo-spatial pixel resolution sensors (< 10 m/pixel). Depending on the geo-spatial capabilities of the sensors, further descriptors can also be derived from images to better classify the composition of the plastic waste.

Mapping of the surface distribution of plastics in various environments has been achieved through spectral based algorithms. These algorithms use spectral reflectance at specific wavebands as input to derive a numerical number or index that is used to infer presence or absence of plastic-based material. Deriving the index can be the ratio, difference or summation of the measured remote sensing wavebands in a linear or polynomial equation. Some examples include the Advanced Plastic Greenhouse Index [71], Floating Debris Index [72], Hydrocarbon Indexes [35, 73, 74], Normalized Difference Plastic Index [75], Plastic Greenhouse Index [76] and Relative Band Depth Index [77]. Uncertainties in derived distribution proxy maps from such algorithms have been associated with false positives. False positives can be resolved by adapting the thresholds through detailed in-situ validation exercises. Stakeholders tend to require the maps for various purposes, in some cases the degree of uncertainty is not a priority as the goal is to know the location or potential size of the plastic litter (e.g., when, where, how large). The alternative complementary detection can be achieved by indirect mapping of essential ocean variables. Essential ocean variables are the geophysical and biological properties of marine environment. Sea surface waves, currents, wind speed, direction and ocean colour end-products are some of the essential ocean variables that have demonstrated reasonable statistical correlations with waste accumulation dynamics and pathways [21, 78, 79].

Investigating detection of floating plastic litter from orbit

Researchers from the University of Michigan used satellite data from eight microsatellites that are part of NASA's Cyclone Global Navigation Satellite System (CYGNSS) mission to map the concentration of ocean microplastic [144]. CYGNSS satellites receive signals reflected from the sea from GPS satellites to measure the roughness of the sea surface. These roughness measurements are usually used to predict hurricanes. In the presences of plastic or debris in the sea, the waves are attenuated, resulting in lower roughness than expected, while in clean waters there is a high correspondence between sea roughness and wind speed. According to the researchers, the results showed that the deeper they moved towards the Great Pacific Garbage Patch, the greater was the discrepancy between wind speed measurements and surface roughness. Using this method in combination with plastic concentration data from the literature, the researchers mapped daily concentrations of microplastics throughout the ocean (fig. 4). This microplastic dataset was recently published in NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC).

Figure 10: NASA's CYGNSS mission maps the concentration of ocean microplastic with data from eight microsatellites



(Source: ESA investigating detection of floating plastic litter from orbit).

Satellite-based marine debris data set

Researchers from the Remote Sensing Laboratory of the National Technical University of Athens (NTUA) and the National and Kapodistrian University of Athens (NKUA) have recently developed a marine debris data set based on the multispectral data from the Copernicus program's Sentinel-2 mission. The research project is one of those ESA-funded projects working on remote sensing of marine litter based on Copernicus Sentinel-2 data. The study developed the MARIDA data set which allows the discrimination of marine debris from other co-existing features such as macroalgae, ships, waves and dissimilar water types. Based on the ground-truth events, the corresponding images were acquired from Copernicus Hub (https://scihub.copernicus.eu/) for the exact reported dates and locations using a mean time window of 10 days. Additionally, for the regions that are significantly affected by plastic pollution (such as river discharges), the seasonality and the periods of maximum plastic presence were examined. Complemented by literature review and intensive image interpretation, MARIDA provides 3399 marine debris pixels for various countries and different seasons, years and sea state conditions. The images are freely available (here) and could be used for evaluating existing detection methods and developing new techniques based on available Sentinel-2 data.

Further examples of applying remote sensing to detect and identify marine litter are listed in the following table.

Table 3.1: Examples demonstrating the detection, identification and quantification of litter from remote sensing.

Platform	Overview	Study
Fixed	Floating litter was imaged from a bridge using a handheld multispectral sensor in Italy. The sensor was the MAIA-WV2 that similar technical capabilities as the WorldView-2 satellite. Using machine learning it was possible to implement semantic segmentation of the floating plastics. Two classes were used that is plastic or non-plastic.	Random forest-based river plastic detection with a handheld multispectral camera [80]
	Camera systems mounted on a bridge railing and drone were used to study plastic waste in Belgium. Imaging was done using a MicaSense RedEdge-M multispectral camera. Classification into 11 groups of materials and quantification by area coverage was demonstrated using machine learning approach.	Targeting plastics: Machine learning applied to litter detection in aerial multispectral images [81]
Ship	Floating litter was observed continuously from a transporter vessel in the Great Pacific Garbage patch using a GoPro Hero 6 action camera. Machine learning supported the object detection and quantification of floating litter observed. Size distribution was derived from the images captured during the survey.	Quantifying floating plastic debris at sea using vessel-based optical data and artificial intelligence [33]
	Trained human observers counted floating litter from a research vessel around Antarctica. The observers used binoculars to aid the survey from the bow or bridge of the vessel. Floating objects were identified, classified and quantified. The main groups were different types of plastics and non-plastics. Properties of the litter recorded included colour, buoyancy, type of object, size and possible function it was used for.	Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition [51]

Platform	Overview	Study
Drone	Plastics waste surveys using DJI Phantom 3 Advanced (Adv) quadcopter were conducted in Saudi Arabia and the imagery captured was analysed using machine learning techniques validated by visual inspection. Quantification and classification of litter objects was achieved. Counts of plastic objects and abundance maps were generated	Use of unmanned aerial vehicles for efficient beach litter monitoring [48]
	DJI Phantom 4 RTK drone images captured in Portugal were analysed using machine learning methods to detect, group and quantify litter. The outputs were abundance maps, item counts of waste, plastic bottles, fishing ropes, octopus pots, fragments.	Detecting stranded macro-litter categories on drone orthophoto by a multi-class Neural Network [82]
Aircraft	Hyperspectral images gathered from an airborne survey in Portugal were analysed using machine learning classification approaches. The imagers were the Specim FX10e and HySpex Mjolnir S-620 measuring from 400 nm to 2500 nm). Known and unknown targets were water, orange target, white target, rope target, concrete pier, trees, and boats.	Hyperspectral imaging zero-shot learning for remote marine litter detection and classification [83]
	Human observers and imaging sensors aboard an aircraft observed floating plastic litter in the Great Pacific Garbage Patch. True colour RGB imagery were automatically analyses to quantify and classify the floating litter. Validation of the automated approach was completed by information gathered by the trained human observers. Dimension, shapes, colour and form of the floating litter was derived from the imagery analyses.	Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic [60]
Satellite	Marine beached litter was quantified and detected in Chile using WorldView-3 satellite imagery. The machine learning techniques were used to make maps of the Expanded polystyrene or mixed plastics groups and density in the study area.	Anthropogenic marine debris over beaches: Spectral characterization for remote sensing applications [84]
	A training dataset was created and a machine learning approach was evaluated on the potential classification of plastic waste areas in Sentinel 1 and 2 satellite imagery. The groups were known targets with various water, landcover classes including plastics with sub-categories like greenhouses, plastic, tyres and waste sites. Algorithms based on such a dataset might have the ability to detect pixels matching the proposed classes.	Application of Copernicus EO data [85]

2.2 Identification

Simple detection might not be sufficient to meet the needs of stakeholders interested in plastic waste hence there is a need to further identify or characterize the objects. The approach of validating what detection methods reveal as suspected or known plastic materials involves detailed analyses by humans in the laboratory or outdoors. Key ongoing research has been on scaling up identification of polymers from laboratory technologies to remote sensing tools in the natural environment using the prospective application of hyperspectral SWIR sensors on handheld or platforms [52, 86-88], aircrafts [43, 44, 46, 74] and satellite mission [41, 89] to sense plastics. Similar to the laboratory methods, a best prediction of polymer composition in plastic waste will be determined by matching the remote sensing signal of suspected plastics to an open-access or a commercial encyclopaedia of known materials. Efforts to further expand well curated open-access spectral libraries are ongoing but are still limited considering the diversity of virgin and weathered plastic bearing materials that continue to reach the natural environments as well as being produced by humans.

Detection of waste accumulation in Mumbai

The University of Georgia, in collaboration with the Indian Institute of Technology-Kharagpur, is carrying out a case study in Mumbai, India, to explore plastic pollution patterns across the urban landscape and the associated geographical and socioeconomic factors that often influence waste distribution. Mumbai has been chosen as a preliminary study area for its mosaicked urban landscape, socio-economic fragmentation, tropical monsoon climate, proximity to the ocean, and riverine environment. The work aims to create accurate, inexpensive, and scalable plastic waste detection methods for an urban feature space in India using satellite-based imagery and hyper-local socioeconomic data to elucidate waste accumulation patterns and to inform underlying challenges and successes of waste management efforts in the city, helping communities develop more targeted waste management strategies. Methods for a highly cognitive deep learning algorithm that fuses optical and RADAR modes of satellite data types (WV3, PlanetScope, Sentinel-2, and ICEYE) with community-level data were developed to detect waste accumulation sites comprised chiefly of plastic material.

Intensive testing has been conducted to date using PlanetScope's 8-band 3m spatial resolution optical satellite imagery. To address the spatial-spectral trade-off in PlanetScope data, instead of straightaway detecting waste, a heuristic method was devised to detect and remove all non-waste classes (e.g., buildings and vegetation) from the satellite image feature space. Remote sensing-based band ratios and indices that gave the highest separation between waste and non-waste classes were applied to the satellite image. This helped heuristically reduce the search space by 30% (95 million pixels to 66 million pixels). In this reduced search space, unsupervised k-means clustering, an algorithm that uses unlabelled data and clusters features based on shared similarities, was performed and then ranked based on how pure it was in terms of waste pixels. Validation sites were identified based on field sampling and interviews. Top-ranked clusters were selected as model-detected waste accumulation sites, correctly identifying 244 of the 247 ground-sampled waste sites. The preliminary results from the proof-of-concept image processing framework look promising in studying the spatiotemporal distribution of plastic waste in megacities with complex land use patterns. However, more false positives offset the high number of true positives. This requires further improvement of detection using multimodal data – optical, radar, lidar, and thermal. The resulting model will perform a long-term analysis to evaluate sources, pathways, and drivers of plastic waste at the urban land-water interface.

Figure 11: A cropped image (RGB) from Planet 3-m data for Mumbai showing the potential waste-positive localities after applying heuristic feature space reduction and clustering. Yellow pixels represent plastic waste locations obtained from the preliminary analysis.

2.3 Quantification

An additional descriptor about the plastic waste after detection would be the surface abundance as observed from a nadir viewing angle. Manual and automated methods have been used to provide estimates of plastics within a region of interest of a captured using monochromatic, false or true colour composite images. Machine learning has been applying supervised and unsupervised algorithms to quantify the suspected plastics from remote sensing images [47, 48, 67, 70, 84, 90, 91]. However, these related studies have limitations because the in-situ surveys do not cover the full extent of imaged regions or the targets are artificially placed to assess performance of the quantifying algorithms. In-situ datasets are important in developing remote sensing algorithms as they are used to statistically validate and verify the accuracy of the approach in estimating or indicating the abundance of observed target. Quantification techniques have been revealed to be challenging on water bodies compared to land surfaces. On water the plastic waste is constantly in motion yet fixed on land likely trapped in vegetation or lying on sand. The abundance efforts involved the task of detection, classification and quantification [48, 67, 82], derived counts or weight over a unit area observed [60, 84, 92], pixel percent coverage or heat map of suspected plastic waste [36, 91, 93].

Counts by trained observers combined with statistical techniques tend to be used as validation tools and findings can be regressed to extrapolate estimates of plastic waste in a selected region-of-interest. In a similar way, net trawl data can be statistically correlated or regressed to remote sensing products (e.g., signal in the form of spectral radiance or reflectance) better quantify better plastics in a wide geo-spatial area. Enumerating surface aggregated plastics can be biased and challenging especially for automated tools because they may rely on distinguishing edges of objects that tend to overlap as plastic waste litter of all sizes randomly aggregate in nature. Furthermore, a vertical profile of the plastics once they begin aggregating can be difficult to obtain from above surface imaging sensors. Without the side or vertical profile imaging matching above water remote sensing constraints the quantification details that can be derived about plastic waste especially at sea.

2.4 Tracking

The pathways from source (e.g., land, river, sea) to sink (e.g., land, river, sea) of the plastic waste can be obtained by continuous detection and quantification from a fixed point of reference. The images can be taken from fixed poles, bridges, drones, ships, aircrafts, satellites over the same target area at repeated intervals. These intervals are controlled by how fast the plastics as target of interest move on water or accumulate on land.

South Korean satellite Geostationary Ocean Color Imager (GOCI) has captured hourly images at 500 m/pixel of the Korean sea between 09:00 to 16:00 local time in the last decade. Despite the coarse geo-spatial resolution ongoing proof-of-concept have been exploring the detection and tracking of anomalies on the sea surface in GOCI data linked to the extreme weather events in 2011 namely East Japan tsunami and Japan earthquake. When anomalies are detected one problem is knowing the source or event generating such variations at the sea surface. During the tsunami extreme event these anomalies were more likely a result of the floating litter that was composed of natural and anthropogenic materials. Verification in-situ images were available from social media, environmental agencies and news outlets. However, during normal conditions in the region without the support of in-situ images, it is challenging to verify or confirm what would be causing anomalies if detected in satellite imagery. Therefore, it highlights the importance of in-situ datasets in remote sensing application.

Planet Labs PlanetScope offers very high geo-spatial pixel resolution of 3 m/pixel and SkySat 0.5 m/pixel. Imaging coverage is dependent on cloud cover and geographic location, some observations can be obtained at least twice a day over a region of interest. Such capabilities can be useful for the detection and tracking of plastic waste on land and over water bodies considering the flow rate of the waste is relatively similar to the daily observations.

Balloons, drones and low-cost fixed camera have also been explored as monitoring and tracking tools with promising results [22, 54, 94, 95]. Using a webcam fixed on a pole in Japan, beach litter dynamics were continuously tracked over several months. The method demonstrated the capability to investigate the types and amounts of litter that were reaching the beach whilst linking the observations to environmental conditions [22]. Litter passing under bridges in Indonesia was monitored using cameras mounted on bridges in Indonesia. The approach managed to detect, distinguish and quantify the plastics based on imagery captured by the camera system whilst validation of the findings was supported by visual inspection [54].

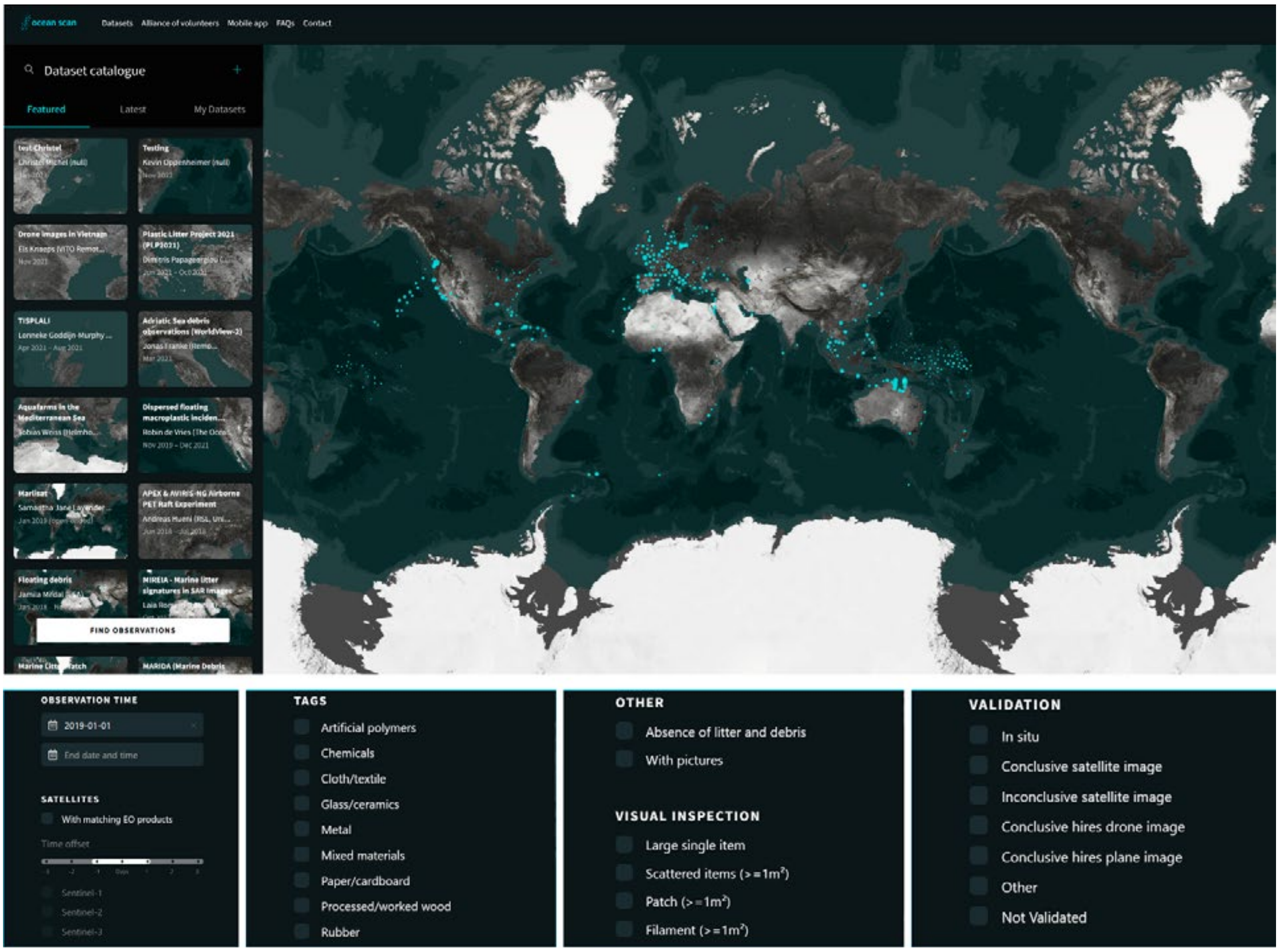
2.5 Online Platforms and Web-based Tools

Web-based tools related to plastic waste have gained a rising interest and usage in the last decade. The tools provide information about plastic litter characteristics that is either gathered from remote sensing or could support remote sensing application as sea-truth information. Examples of web-based tools that provide a wide geographic coverage with potential to support remote sensing application are presented below.

2.5.1 Ocean Scan

An advanced online data repository or database that is dedicated to remote sensing of plastic litter applications with the ability of automatically matchinguploaded field observations to available satellite data [96]. High-quality match-ups of relevant information enable the development of robust satellite algorithms that would have been validated using in-situ images with information about presence of plastic waste. Simple techniques to sophisticated artificial intelligence methods can be used to analyse such well curated imagery. Open-access to the interoperable datasets and uploads can be achieved via the user-friendly web interface (Figure 7), smartphone application or application programming interface (API). Datasets in the repository are assigned a permanent digital object identifier (DOI) through Zenodo online open-access repository allowing permanent citation and crediting of data source. A smartphone app 'Ocean Scan' is available for data capturing during field survey. Users can select in-situ datasets that have matching remote sensing imagery. The system thrives to automatically match any dataset to satellite observations over the same location and time of field uploaded information. Additional information required when uploading data into Ocean Scan is considered important for future users. Such information includes details about size of the patch observed during a survey, presence of plastics, time, geographic location and types of objects. The level of confidence in each dataset with regards to presence of plastics is provide by the validation options. Each dataset will carry a tag to indicate if there is in-situ information related to the dataset matching with remote sensing imagery reported in Ocean Scan.

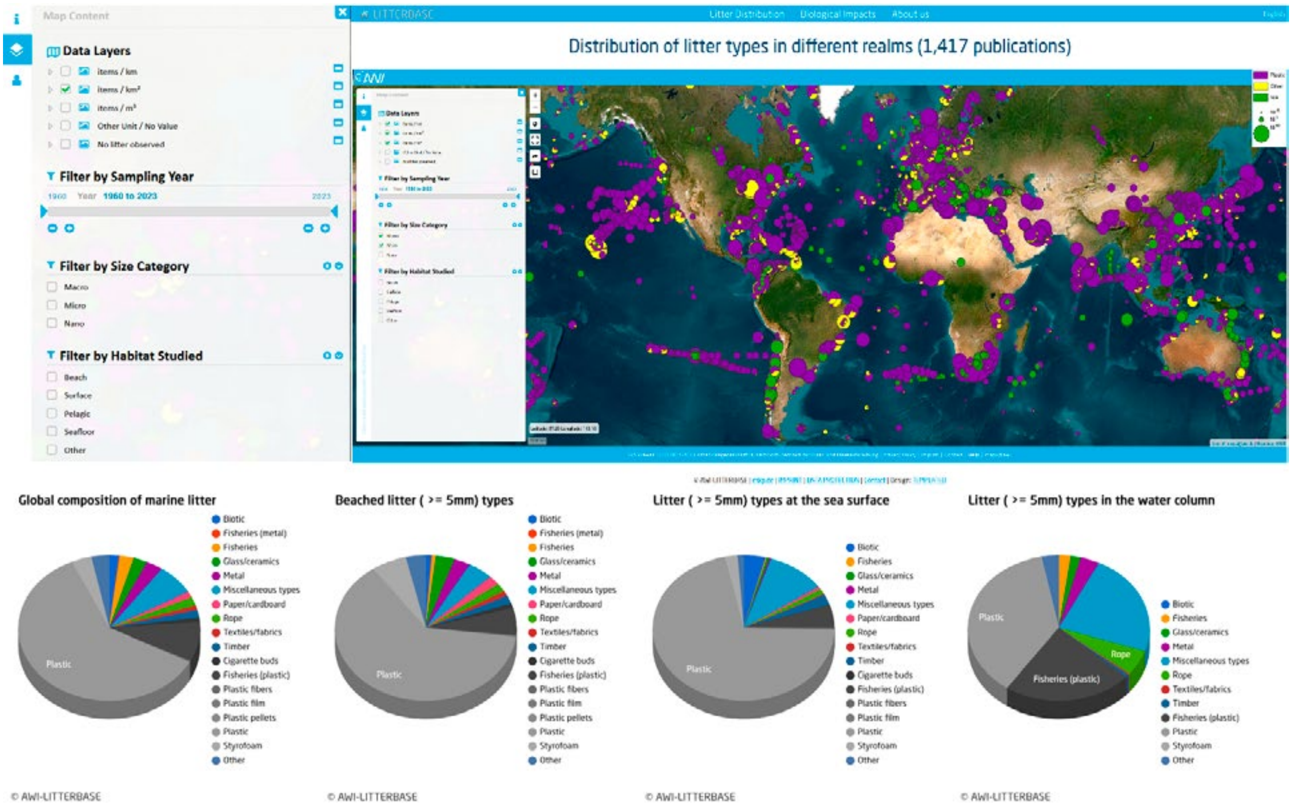
Figure 12: Ocean Scan graphic interface showing the dataset catalogue from various geographic locations and additional options related to matching satellite to in-situ data, observation platform for validation, time, type and size of litter.



2.5.2 Litterbase

The open-access PostgreSQL 9.5. tool provides a global visual map of peer-reviewed and citizen science studies related to plastic waste since 1960[97, 98]. Litterbase combines a living bibliography that allows a number of interdisciplinary analyses from the literature available in the database. The user-friendly platform allows the viewing of stored publication and related findings about plastic waste such as biome, geolocation, quantities, polymer type, environment[98]. Litterbase could be a prospective complementary resource for remote sensing validation effort for studies with information about geo-location, size and physical descriptors than can also be derived from imagery. Combining the satellite imagery information related to plastics statistical correlations can be explored by using matching in-situ observations in Litterbase. Litterbase graphic interface allows the user to group studies by the plastic size class, habitat of collection, time and location. The tool has relevance to the possible validation using in-situ data matching remote sensing imagery of the near surface, floating and beached litter that might have been captured by drones, aircraft or satellite.

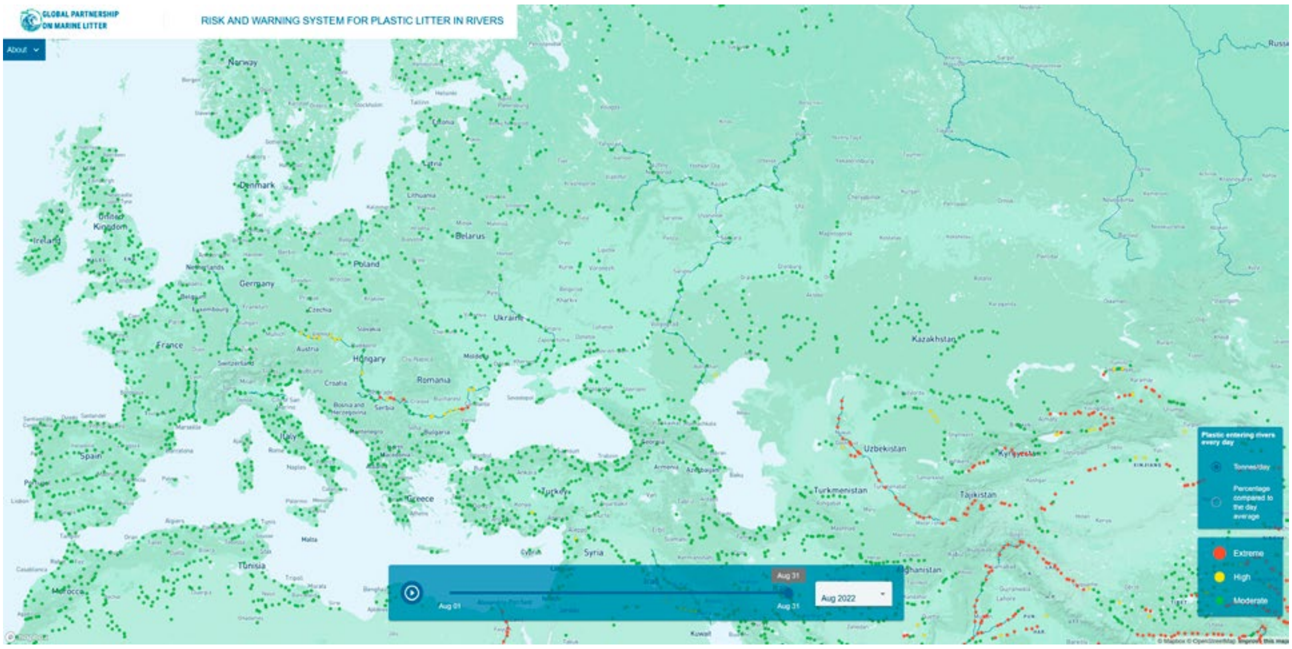
Figure 13: Examples of the features and products available in Litterbase graphic interface. Data layers allow user to select quantification units reported in literature, size classes, the habitat samples were harvested from and year of study.



2.5.2 Global Partnership on Marine Litter (GPML)

The GPML datahub tool provides a global map and analytical functions. The maps are statistical based distribution maps of estimated plastic waste in the natural environment whilst functionality ranges from modelling to data gathering applications. Key characteristics are prediction maps from numerical solutions or statistical models. Numerical solutions are derived from mathematical computations aimed at solving theoretical scenarios useful in hindcasting and forecasting applications. One of the test phase functionality or modules in the GPML is the Risk and Warning System for Macroplastic Litter (https://wrd-forecast-custom.azurewebsites.net/unep-plastics/). It can predict up to 9 months in advance the dynamics of waste in global rivers based on the advanced United Nations Environmental Programme Center on Water and Environment Global Hydrological Model and in-situ observations (Figure 9). Remote sensing data (e.g., precipitation, evapotranspiration, surface area of rivers) is also incorporated to infer plastic waste dynamics via the built-in module called Forecasted plastic litter in rivers of GPML as it tracks environmental changes. The tool includes a map viewer in the GMPL datahub that shows the relationship of different environmental parameters, such as transportation dynamics and plastic waste on the beach.

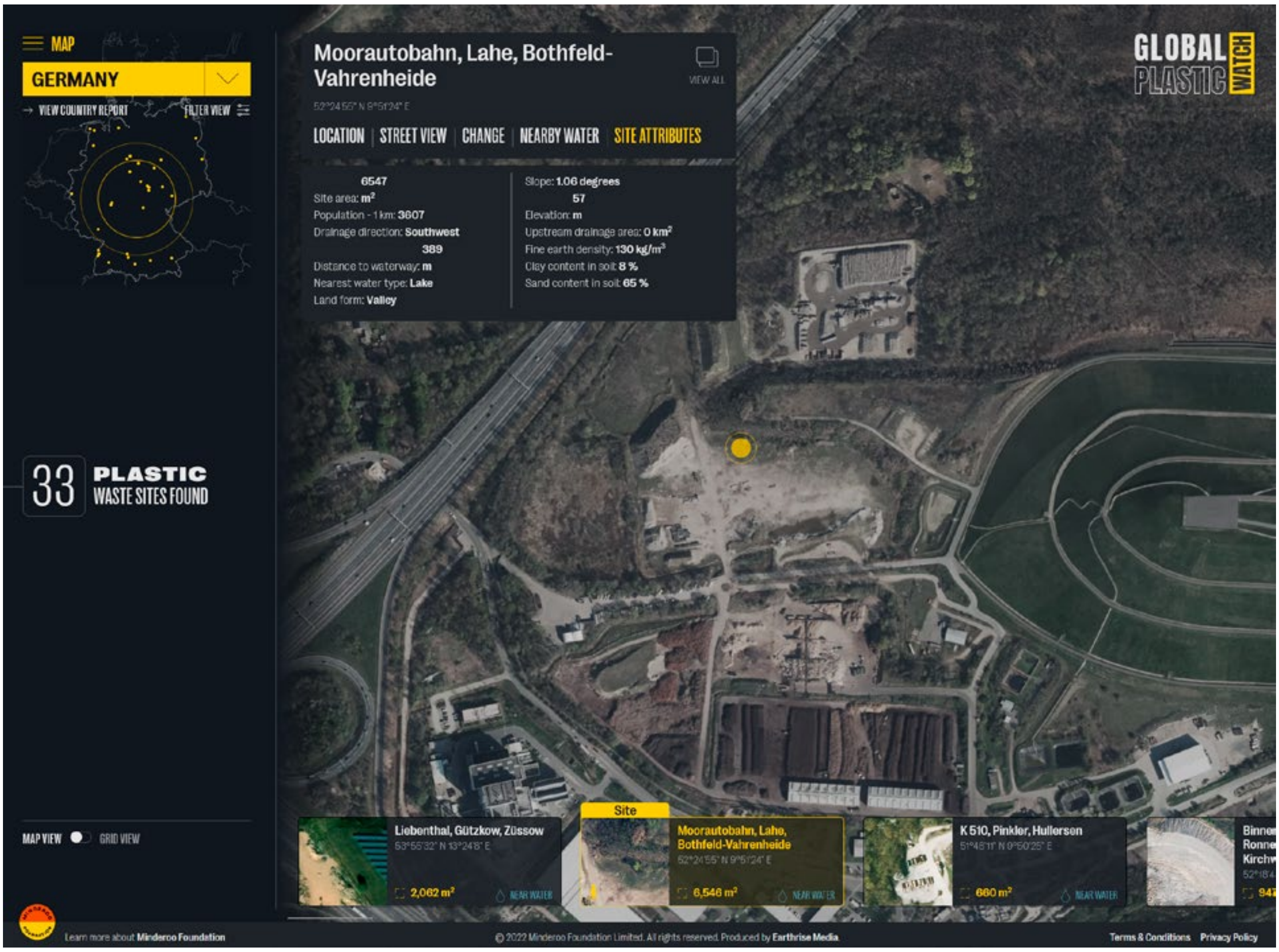
Figure 14: GPML Risk and Warning System for Macroplastic Litter user interface.



2.5.3 Global Plastic Watch

An online tool supported by artificial intelligence algorithms generates detection and abundance maps from the ESA Copernicus programme Sentinel-2 satellite mission at a resampled 10 m/pixel resolution [99]. Visualization in the web-based tool provides geo-location information and an estimated amount of suspected plastic litter as derived from satellite remote sensing (Figure 10). For each site additional information reported include distance to a water body, a time series of site area coverage and soil type content. The statistics in the user interface do not highlight uncertainties related to the detected litter abundance as well as dump site area coverage. Such data could be generated through ground-truthing or clean-up surveys in future advancement of the map outputs. Suspected plastic litter zones can also be verified to provide a probability metric for the detected regions. The platform provides a tool for the potential detection of plastics over land targets but as presented before the automated approaches require continuous datasets or validation to perform better. Similar ongoing efforts are being explored using Planet Labs PlanetScope images to detect floating litter at sea [100].

Figure 15: Example showing Global Plastic Watch web interface.



WWF Germany in cooperation with Earthrise Media has tested the feasibility to detect waste accumulation in Vietnam with Global Plastic Watch tool.

Vietnam has a pronounced relief and a dense network of rivers and water bodies. Thus, topography and proximity to the nearest water course influence the risk of plastic waste leaking from dumpsites and landfills into the marine environment. The system was tested in a high-sensitivity configuration to identify waste sites in Vietnam. The waste detection tool is composed of two convolutional neural networks that analyze and combine spectral, spatial, and temporal signals from data collected by the Sentinel-2 satellite. This data has 12 spectral bands, which capture visible and IR light. The resolution of the data is 10 meters per pixel. Following detection, relevant metadata about the geographic and physical setting is collected. The model was run across all of Vietnam between January 2019 and June 2022. The results are promising: 198 garbage dumps were discovered with accumulations of waste, 20 percent of which are within a sensitive 250 meters of the nearest body of water. With further improvement in detection, waste (distribution) could potentially be measured rather than modelled, and the development of waste sites could be monitored over time. The outputs of the tool can be seen at globalplasticwatch.org. This tool can help developing effective intervention strategies to better manage the major sources of plastic waste and understand which of these represent the greatest risk.

Figure 16: Potential illegal dumpsite close to a river. The site has changed significantly over time (Global Plastic Watch).

2.6 Stakeholder Community Initiatives

Monitoring and ocean observing initiatives are primary sources of the essential datasets needed by stakeholders about plastic litter pathways including Essential Plastic Litter descriptors. GPML and the Global Ocean Observing System (GOOS) have played major roles by establishing platforms to bring together stakeholders, resources and strategies. GOOS aims to support a suite of ocean observing platforms (e.g., in-water, above water, fixed, mobile, autonomous and manned) that could also contribute towards remote sensing of plastic waste. Harmonisation of the in-situ sampling and terminologies has been coordinated through the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) and G20/Ministry of Environment Government of Japan.

Member States of the Association of Southeast Asian Nations (ASEAN) with the support of the World Bank Group and PROBLUE initiative have Action Plans that emphasize the need for rigorous monitoring strategies for plastic waste [101]. Using imaging technologies on drones or bridges to observe water or land surface to perform analyses on the gathered high geo-spatial pixel resolution was showcased as an affordable monitoring strategy in Vietnam [102]. Artificial intelligence methods were used to quantify and classify plastics, but the challenge as reported is the limited number of datasets for training as well as validating the models. It therefore means such algorithms are region specific but can be transferred to other geographic regions after extensive model training and tuning for the new study location of interest.

European Union member states have been thriving to meet the proposed ideal scenarios outlined in the Marine Strategy Framework Directive 2008/56/EC. To this end, the monitoring strategies to determine changes in the aquatic environment that have been utilized include human visual observations, in-situ field sampling, airborne and satellites remote sensing. Visual observations have been commonly applied to detect and quantify floating litter objects, at least easy to see for the human eye from a distance, around European waters from research vessels e.g., [50, 103, 104]. Routine use of airborne platforms has also been gaining a rise in interest, the main aim has been to better locate hotspots for clean-up campaigns. A detailed overview of the current monitoring efforts by specific members states has been recently presented in literature [105].

The Blue Planet Marine Litter working group was also founded by the Group on Earth Observation (GEO) with the main goal to investigate the research gaps in technology and data needs of stakeholders though network platforms as well as workshops. The working group has held several workshops that have been developing a roadmap on best practices in observing and numerical modelling of aquatic plastics. Efforts are also underway to further develop and realize the proposed Integrated Marine Debris Observing System – IMDOS [27] that integrates the use of remote sensing as a data source.

More recently, the Task Force on Remote Sensing of Marine Debris and Litter was formed under the auspice of the International Ocean Colour Coordinating Group (IOCCG). The IOCCG Task Force provides a one-stop shop of resources related to remote sensing of plastics generated by four Core Topics dedicated to (i) technologies, (ii) algorithms and applications, (ii) datasets and (iv) interdisciplinary aspects. Living resources include a bibliography of peer-reviewed publications and datasets on the topic of remote sensing of marine litter. Related research projects (Annex A1. Scientific Research Projects) and events supported or coordinated (Annex A4. Conferences, Proceedings and Workshops) by the Task Force are also provided on the website. As remote sensing will be a component in IMDOS the Task Force also supports GOOS to address user needs, expectation and informing the community on capabilities of current technology as well as what could be improved in future sensors. The Task Force supported UN initiatives such as (i) Ocean Conference through the expertise of remote sensing Integrating Marine Litter Monitoring to Inform Action event on 29 June 2022 in Portugal and (ii) Ocean Decade Laboratory satellite activity by organising the Remote Sensing and Smart Tech for Marine Litter workshop.

Outlook

3

Remote sensing of plastic waste is an emerging approach that has been showing potential in meeting stakeholder needs to monitor the litter qualitatively and quantitatively in all environments. However, there is no market-ready application available yet, and current works are still in the early stages and aim to develop reliable algorithms to improve the detection and measurement of waste accumulation. Preliminary scientific evidence-based studies (e.g., Annex material) have been reporting recommendation on possibilities to scale up (e.g., handheld and drone based remote sensing) from controlled experiments using artificial plastic targets and small area coverage studies. A prospective approach is the design and launching of prototype satellite sensors aimed at bridging the gaps and improve the monitoring of plastic waste. Such a prototype satellite will possess characteristics that would have been identified from available extensive research on remote sensing of plastic waste using various imaging technologies. A prototype satellite could also be an opportunity for the community to define and set standardized methods that will allow monitoring of plastics assessments using well defined baselines.

3.1 Prototype Satellite

A team of experts at the Flemish Institute for Technological Research conducted a community user needs survey that was complemented by the current literature on remote sensing of plastic litter. The findings from the user needs survey were used to define specifications, capabilities and characteristics for a suitable satellite that could be launched to further assess the space based monitoring of marine litter [106]. The main regions of interest were identified as plastic waste hotspots such as landfills, beaches and coastal windrows. Technical specifications proposed included have ~26 wavebands covering the visible to short-waved infra-red (SWIR) spectrum with a very high geo-spatial pixel resolution (1 m in the visible, 3 m in SWIR). It is crucial to prioritize and dedicate resources for the proposed satellite as it could advance evidence-based knowledge about the application of remote sensing technologies to monitor plastic waste. Governments, space agencies and the industry have been recently reminded and encouraged to invest in the efforts as it will be a major step towards a more fit-for-purpose plastic waste satellite sensor [107]. Using the information that will likely be derived from the proposed concept satellite, remote sensing experts believe the invaluable scientific evidence-based knowledge will further allow a more refined assessment on the capabilities of space-based monitoring of plastics.

High geo-spatial pixel resolution (≤ 10 m) satellites with multispectral wavebands and specific data models developed by multidisciplinary teams have been showing promise in detection of suspected plastic by inferring the inherent accumulation zones of waste e.g., windrows, ocean gyres, fronts. Examples of such satellite include GeoEye, *Pléiades,* PlanetScope, RapidEye, Sentinel-2, Skysat. WorldView-2 and WorldView-3. The value of these satellite sensors could be advanced by including hyperspectral SWIR information as this might allow a better identification of plastics among other optically active materials in the natural environment or in the windrows.

Defining a sensor that is appropriate for remote sensing of plastics might seem simple yet complicated. The stakeholder needs based on detection, identification, quantification and tracking capabilities of remote sensing technologies are different considering the various parameters than can be resolved. For example, for a clean-up stakeholder just knowing where the litter is present and area coverage might be sufficient information meaning the colour, polymer types or shape details are not needed. Governments might want to detect, identify and track the litter to locate the source or sinks. To meet any of the above capabilities with a single sensor requires trade-offs or different imaging technologies because of the pixel size, spectral wavebands and temporal revisit resolution that must be integrated.

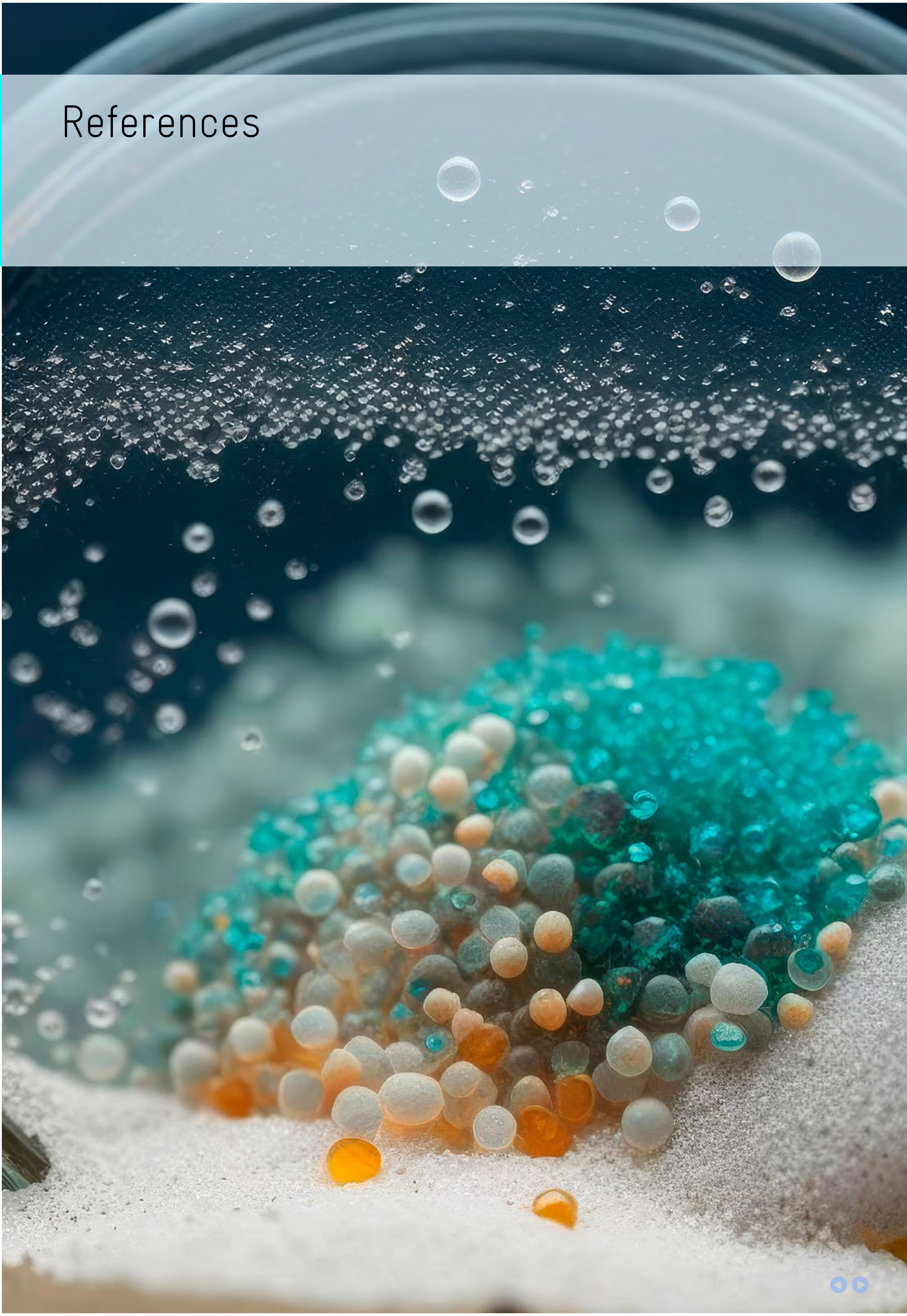
3.2 Baselines and Standardized Monitoring

Baselines can be established if standardized monitoring is continuous and regular times series exist. Unfortunately, standardized monitoring methods are still not well established in interdisciplinary research on plastics as various studies use different metrics to detect, classify and quantify waste [108]. Due to data gaps in satellite revisits of plastic sources and sinks, it is difficult to initiate clean-up campaigns solely based on remote sensing data. Ideally, a constellation and synergy of hyperspectral and very high-resolution imagery can be launched to support the detection, identification, quantification and tracking of plastics. Low-cost small satellite known as cubesats could be explored as supporting imaging tools in space. Additionally, it would be important to have coordinated efforts for in-situ sampling matching satellite observation for validation and verification tasks geared towards algorithm development as well as fine tuning.

3.3 Stakeholder Community Discussions

Similar to the efforts of proposing a prospective satellite sensor for marine litter monitoring a coordinated interdisciplinary holistic approach is critical for a harmonised observing tool for plastics. One example is the IOCCG Task Force on Remote Sensing of Marine Debris and Litter composed of experts from academia, industry, civil service, non-profit organisation, governments and space agencies. The Task Force thrives to coordinate and support the advancement in the topic especially through thematic workshops and networking events. One priority has been to engage stakeholders to better understand the user needs whilst also communicating the capabilities and limitations of remote sensing as a complementary monitoring tool for plastics in the aquatic environment. At present efforts are underway to provide status update on remote sensing of marine litter. The findings and scientific research gaps identified in the recently ended projects are to be assessed with the aim to bridge the gaps or addon the knowledge through ongoing or future studies.

References



1. UNEP *Marine plastic debris and microplastics – Global lessons and research to inspire action and guide policy change*; Nairobi, Kenya, 2016; p 274.

2. Harding, S. *Marine debris: understanding, preventing and mitigating the significant adverse impacts on marine and coastal biodiversity*; Secretariat of the Convention on Biological Diversity: Montreal, Quebec, Canada, 2016; p 78.

3. GIZ *Marine litter prevention. Reducing plastic waste leakage into waterways and oceans through circular economy and sustainable waste management*; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH: Eschborn, Germany, 2018; p 112.

4. Eremina, T.; Ershova, A.; Martin, G.; Shilin, M. In *Marine litter monitoring: review for the Gulf of Finland coast*, 2018 IEEE/OES Baltic International Symposium (BALTIC), Klaipeda, Lithuania, 12-15 June, 2018; Klaipeda, Lithuania, 2018; pp 1-8.

5. Miliute-Plepiene, J.; Fråne, A.; Haikonen, K.; Youhanan, L. *Overview of available methods to monitor marine plastic litter: Incl. method for riverine litter monitoring developed within BLASTIC*; IVL Swedish Environmental Research Institute: Stockholm, Sweden, 2018; p 47.

6. GRID/Arendal Pathways and fluxes of plastics into the oceans. https://www.grida.no/resources/6921 (Last 17 January 2023:
17 January 2023),

7. IMO *Review of the current state of knowledge regarding marine litter in wastes dumped at sea under the London Convention and Protocol. Final Report*; International Maritime Organization (IMO): London, United Kingdom, 2016; p 38.

8. Cheshire, A. C.; Adler, E.; Barbière, J.; Cohen, Y.; Evans, S.; Jarayabhand, S.; Jeftic, L.; Jung, R. T.; Kinsey, S.; Kusui, E. T.; Lavine, I.; Manyara, P.; Oosterbaan, L.; Pereira, M. A.; Sheavly, S.; Tkalin, A.; Varadarajan, S.; Wenneker, B.; Westphalen, G. *UNEP/IOC Guidelines on survey and monitoring of marine litter*; United Nations Environment Programme: Nairobi, Kenya, 2009; p xii+120.

9. USEPA *Marine debris in the north Pacific. A summary of existing information and identification of data gaps*; EPA-909-R-11-006; U.S. Environmental Protection Agency: San Francisco, USA, November 2011, 2011; p 23.

10. González, D.; Hanke, G.; Tweehuysen, G.; Bellert, B.; Holzhauer, M.; Palatinus, A.; Hohenblum, P.; Oosterbaan, L. *Riverine litter monitoring - Options and recommendations*; European Union: Luxembourg: Publications Office of the European Union, 2016; p 52.

11. Serra-Gonçalves, C.; Lavers, J. L.; Bond, A. L., Global review of beach debris monitoring and future recommendations. *Environmental Science & Technology* **2019**, 53, (21), 12158-12167, doi:10.1021/acs.est.9b01424

12. ESA-OSIP Remote sensing of plastic marine litter. Strategic Innovation Area: Discovery. https://ideas.esa.int/servlet/hype/IMT?documentTableId=45087640620544725&userAction=Browse&templateName=&documentId=ae460bb2ce3f682ea452f15f8bc3753f (Last 17 January 2023: 17 January 2023),

13. USGS What is remote sensing and what is it used for? https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used#:~:text=Remote%20sensing%20is%20the%20process,sense%22%20things%20about%20the%20Earth. (Last 17 January 2023: 17 January 2023),

14. Filipponi, F., Exploitation of Sentinel-2 time series to map burned areas at the national level: A case study on the 2017 Italy wildfires. *Remote Sensing* **2019**, *11*, (6), 622, doi:10.3390/rs11060622

15. Carpenter, E. J.; Smith, K. L., Plastics on the Sargasso Sea Surface. *Science* **1972**, *175*, (4027), 1240-1241, doi:10.1126/science.175.4027.1240

16. Horn, M. H.; Teal, J. M.; Backus, R. H., Petroleum lumps on the surface of the sea. *Science* **1970**, *168*, (3928), 245-246, doi:10.1126/science.168.3928.245

17. Carpenter, E. J.; Anderson, S. J.; Harvey, G. R.; Miklas, H. P.; Peck, B. B., Polystyrene Spherules in Coastal Waters. *Science* **1972**, *178*, (4062), 749-750, doi:10.1126/science.178.4062.749

18. Venrick, E. L.; Backman, T. W.; Bartram, W. C.; Platt, C. J.; Thornhill, M. S.; Yates, R. E., Man-made objects on the surface of the central North Pacific Ocean. *Nature* **1973**, *241*, (5387), 271-271, doi:10.1038/241271a0

19. Shomura, R. S.; Godfrey, M. L. In *Proceedings of the Second International Conference on Marine Debris*, 2-7 April 1989, Honolulu, Hawaii, USA, 1990; NOAA Tech. Mem. NMFS-SWFSC-154, U.S. Department of Commerce, Silver Spring: 2-7 April 1989, Honolulu, Hawaii, USA, 1990; p 1274.

20. Pichel, W. G.; Veenstra, T. S.; Churnside, J. H.; Arabini, E.; Friedman, K. S.; Foley, D. G.; Brainard, R. E.; Kiefer, D.; Ogle, S.; Clemente-Colón, P.; Li, X., GhostNet marine debris survey in the Gulf of Alaska – Satellite guidance and aircraft observations. *Marine Pollution Bulletin* **2012**, *65*, (1–3), 28-41, doi:10.1016/j.marpolbul.2011.10.009

21. Pichel, W. G.; Churnside, J. H.; Veenstra, T. S.; Foley, D. G.; Friedman, K. S.; Brainard, R. E.; Nicoll, J. B.; Zheng, Q.; Clemente-Colón, P., Marine debris collects within the North Pacific Subtropical Convergence Zone. *Marine Pollution Bulletin* **2007**, *54*, (8), 1207-1211, doi:10.1016/j.marpolbul.2007.04.010

22. Kako, S. i.; Isobe, A.; Magome, S., Sequential monitoring of beach litter using webcams. *Marine Pollution Bulletin* **2010**, *60*, (5), 775-779, doi:10.1016/j.marpolbul.2010.03.009

23. Nakashima, E.; Isobe, A.; Magome, S.; Kako, S. i.; Deki, N., Using aerial photography and in situ measurements to estimate the quantity of macro-litter on beaches. *Marine Pollution Bulletin* **2011**, *62*, (4), 762-769, doi:10.1016/j.marpolbul.2011.01.006

24. Maximenko, N.; Chao, Y.; Moller, D., Developing a remote sensing system to track marine debris. *Eos Science News by AGU* **2016**, *97*, doi:10.1029/2016EO061605

25. Martinez-Vicente, V.; Biermann, L.; Mata, A., Optical methods for marine litter detection (OPTIMAL) – Final Report. In Zenodo: Zenodo, 2020; p 54.doi:10.5281/zenodo.3748797

26. Martínez-Vicente, V.; Clark, J. R.; Corradi, P.; Aliani, S.; Arias, M.; Bochow, M.; Bonnery, G.; Cole, M.; Cózar, A.; Donnelly, R.; Echevarría, F.; Galgani, F.; Garaba, S. P.; Goddijn-Murphy, L.; Lebreton, L.; Leslie, H. A.; Lindeque, P. K.; Maximenko, N.; Martin-Lauzer, F.-R.; Moller, D.; Murphy, P.; Palombi, L.; Raimondi, V.; Reisser, J.; Romero, L.; Simis, S. G. H.; Sterckx, S.; Thompson, R. C.; Topouzelis, K. N.; van Sebille, E.; Veiga, J. M.; Vethaak, A. D., Measuring marine plastic debris from space: Initial assessment of observation requirements. *Remote Sensing* **2019**, *11*, (20), 2443, doi:10.3390/rs11202443

27. Maximenko, N.; Corradi, P.; Law, K. L.; Van Sebille, E.; Garaba, S. P.; Lampitt, R. S.; Galgani, F.; Martinez-Vicente, V.; Goddijn-Murphy, L.; Veiga, J. M.; Thompson, R. C.; Maes, C.; Moller, D.; Löscher, C. R.; Addamo, A. M.; Lamson, M. R.; Centurioni, L. R.; Posth, N. R.; Lumpkin, R.; Vinci, M.; Martins, A. M.; Pieper, C. D.; Isobe, A.; Hanke, G.; Edwards, M.; Chubarenko, I. P.; Rodriguez, E.; Aliani, S.; Arias, M.; Asner, G. P.; Brosich, A.; Carlton, J. T.; Chao, Y.; Cook, A.-M.; Cundy, A. B.; Galloway, T. S.; Giorgetti, A.; Goni, G. J.; Guichoux, Y.; Haram, L. E.; Hardesty, B. D.; Holdsworth, N.; Lebreton, L.; Leslie, H. A.; Macadam-Somer, I.; Mace, T.; Manuel, M.; Marsh, R.; Martinez, E.; Mayor, D. J.; Le Moigne, M.; Molina Jack, M. E.; Mowlem, M. C.; Obbard, R. W.; Pabortsava, K.; Robberson, B.; Rotaru, A.-E.; Ruiz, G. M.; Spedicato, M. T.; Thiel, M.; Turra, A.; Wilcox, C., Toward the Integrated Marine Debris Observing System. *Frontiers in Marine Science* **2019**, *6*, (447), doi:10.3389/fmars.2019.00447

28. Hu, C., Remote detection of marine debris using satellite observations in the visible and near infrared spectral range: Challenges and potentials. *Remote Sensing of Environment* **2021**, *259*, 112414, doi:10.1016/j.rse.2021.112414

29. IOCCG *Why ocean colour? The societal benefits of ocean-colour technology*; Reports of the International Ocean-Colour Coordinating Group, No. 7; Dartmouth, Canada, 2008; p 147.

30. CEOS *Feasibility study for an aquatic ecosystem earth observing system. Report 2.0*; Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia: Canberra, ACT, Australia., 2018; p 197.

31. Knaeps, E.; Sterckx, S.; Strackx, G.; Mijnendonckx, J.; Moshtaghi, M.; Garaba, S. P.; Meire, D., Hyperspectral-reflectance dataset of dry, wet and submerged marine litter. *Earth Syst. Sci. Data*, **2021**, *13*, (2), 713-730, doi:10.5194/essd-13-713-2021

32. Topouzelis, K.; Papageorgiou, D.; Karagaitanakis, A.; Papakonstantinou, A.; Arias Ballesteros, M., Remote sensing of sea surface artificial floating plastic targets with Sentinel-2 and unmanned aerial systems (Plastic Litter Project 2019). *Remote Sensing* **2020**, *12*, (12), 2013, doi:10.3390/rs12122013

33. de Vries, R.; Egger, M.; Mani, T.; Lebreton, L., Quantifying floating plastic debris at sea using vessel-based optical data and artificial intelligence. *Remote Sensing* **2021**, *13*, (17), 3401, doi:10.3390/rs13173401

34. Goddijn-Murphy, L.; Williamson, B. J.; McIlvenny, J.; Corradi, P., Using a UAV thermal infrared camera for monitoring floating marine plastic litter. *Remote Sensing* **2022**, *14*, (13), 3179, doi:10.3390/rs14133179

35. Garaba, S. P.; Dierssen, H. M., An airborne remote sensing case study of synthetic hydrocarbon detection using short wave infrared absorption features identified from marine-harvested macro- and microplastics. *Remote Sensing of Environment* **2018**, *205*, 224-235, doi:10.1016/j.rse.2017.11.023

36. Topouzelis, K.; Papakonstantinou, A.; Garaba, S. P., Detection of floating plastics from satellite and unmanned aerial systems (Plastic Litter Project 2018). *International Journal of Applied Earth Observation and Geoinformation* **2019**, *79*, 175-183, doi:10.1016/j.jag.2019.03.011

37. Themistocleous, K.; Papoutsa, C.; Michaelides, S.; Hadjimitsis, D., Investigating Detection of Floating Plastic Litter from Space Using Sentinel-2 Imagery. *Remote Sensing* **2020**, *12*, (16), 2648, doi:10.3390/rs12162648

38. Cózar, A.; Aliani, S.; Basurko, O. C.; Arias, M.; Isobe, A.; Topouzelis, K.; Rubio, A.; Morales-Caselles, C., Marine litter windrows: A strategic target to understand and manage the ocean plastic pollution. *Frontiers in Marine Science* **2021**, *8*, (98), doi:10.3389/fmars.2021.571796

39. Kikaki, A.; Karantzalos, K.; Power, C. A.; Raitsos, D. E., Remotely sensing the source and transport of marine plastic debris in Bay Islands of Honduras (Caribbean Sea). *Remote Sensing* **2020**, *12*, (11), 1727, doi:10.3390/rs12111727

40. Knaeps, E.; Strackx, G.; Meire, D.; Sterckx, S.; Mijnendonckx, J.; Moshtaghi, M., Hyperspectral reflectance of marine plastics in the VIS to SWIR. In *Data set. Available on-line*, 4TU.Centre for Research Data: 2020.doi:10.4121/12896312.v2

41. Kremezi, M.; Kristollari, V.; Karathanassi, V.; Topouzelis, K.; Kolokoussis, P.; Taggio, N.; Aiello, A.; Ceriola, G.; Barbone, E.; Corradi, P., Pansharpening PRISMA data for marine plastic litter detection using plastic indexes. *IEEE Access* **2021**, 1-1, doi:10.1109/ACCESS.2021.3073903

42. Park, Y.-J.; Garaba, S. P.; Sainte-Rose, B., Detecting the Great Pacific Garbage Patch floating plastic litter using WorldView-3 satellite imagery. *Optics Express* **2021**, 29, (22), 35288-35298, doi:10.1364/OE.440380

43. Garaba, S. P.; Aitken, J.; Slat, B.; Dierssen, H. M.; Lebreton, L.; Zielinski, O.; Reisser, J., Sensing ocean plastics with an airborne hyperspectral shortwave infrared imager. *Environmental Science & Technology* **2018**, *52*, (20), 11699-11707, doi:10.1021/acs.est.8b02855

44. Hueni, A.; Bertschi, S. In *Detection of sub-pixel plastic abundance on water surfaces using airborne imaging spectroscopy*, IGARSS 2020 – 2020 IEEE International Geoscience and Remote Sensing Symposium, 26 Sept.-2 Oct, Waikoloa, HI, USA, 2020; Waikoloa, HI, USA, 2020; pp 6325-6328.

45. Garcia-Garin, O.; Monleón-Getino, T.; López-Brosa, P.; Borrell, A.; Aguilar, A.; Borja-Robalino, R.; Cardona, L.; Vighi, M., Automatic detection and quantification of floating marine macro-litter in aerial images: Introducing a novel deep learning approach connected to a web application in R. *Environmental Pollution* **2021**, *273*, 116490(1-11), doi:10.1016/j.envpol.2021.116490

46. Freitas, S.; Silva, H.; Silva, E., Remote hyperspectral imaging acquisition and characterization for marine litter detection. *Remote Sensing* **2021**, *13*, (13), 2536, doi:10.3390/rs13132536

47. Gonçalves, G.; Andriolo, U.; Pinto, L.; Bessa, F., Mapping marine litter using UAS on a beach-dune system: a multidisciplinary approach. *Science of The Total Environment* **2020**, *706*, 135742, doi:10.1016/j.scitotenv.2019.135742

48. Martin, C.; Parkes, S.; Zhang, Q.; Zhang, X.; McCabe, M. F.; Duarte, C. M., Use of unmanned aerial vehicles for efficient beach litter monitoring. *Marine Pollution Bulletin* **2018**, *131*, 662-673, doi:10.1016/j.marpolbul.2018.04.045

49. Kako, S. i.; Isobe, A.; Magome, S., Low altitude remote-sensing method to monitor marine and beach litter of various colors using a balloon equipped with a digital camera. *Marine Pollution Bulletin* **2012**, *64*, (6), 1156-1162, doi:10.1016/j.marpolbul.2012.03.024

50. Hanke, G.; González-Fernández, D., Longterm deployment of the JRC Sealittercam on the Western Mediterranean Sea. In *Policy-oriented marine Environmental Research for the Southern European (PERSEUS) 2nd Scientific Workshop – Marrakesh 2014. Book of Abstracts*, Giannoudi, L.; Streftaris, N.; Papathanassiou, E., Eds. 2014; p 49.

51. Suaria, G.; Perold, V.; Lee, J. R.; Lebouard, F.; Aliani, S.; Ryan, P. G., Floating macro- and microplastics around the Southern Ocean: Results from the Antarctic Circumnavigation Expedition. *Environment International* **2020**, *136*, 105494, doi:10.1016/j.envint.2020.105494

52. Guffogg, J. A.; Soto-Berelov, M.; Jones, S. D.; Bellman, C. J.; Lavers, J. L.; Skidmore, A. K., Towards the spectral mapping of plastic debris on beaches. *Remote Sensing* **2021**, *13*, (9), 1850, doi:10.3390/rs13091850

53. Goddijn-Murphy, L.; Dufaur, J., Proof of concept for a model of light reflectance of plastics floating on natural waters. *Marine Pollution Bulletin* **2018**, *135*, 1145-1157, doi:10.1016/j.marpolbul.2018.08.044

54. van Lieshout, C.; van Oeveren, K.; van Emmerik, T.; Postma, E., Automated river plastic monitoring using deep learning and cameras. *Earth and Space Science* **2020**, *7*, (8), e2019EA000960(1-14), doi:10.1029/2019EA000960

55. Kataoka, T.; Hinata, H.; Kako, S. i., A new technique for detecting colored macro plastic debris on beaches using webcam images and CIELUV. *Marine Pollution Bulletin* **2012**, *64*, (9), 1829-1836, doi:10.1016/j.marpolbul.2012.06.006

56. Corbau, C.; Buoninsegni, J.; Olivo, E.; Vaccaro, C.; Nardin, W.; Simeoni, U., Understanding through drone image analysis the interactions between geomorphology, vegetation and marine debris along a sandy spit. *Marine Pollution Bulletin* **2023**, *187*, 114515, doi:10.1016/j.marpolbul.2022.114515

57. Abreo, N. A. S.; Aurelio, R. M.; Kobayashi, V. B.; Thompson, K. F., 'Eye in the sky': Off-the-shelf unmanned aerial vehicle (UAV) highlights exposure of marine turtles to floating litter (FML) in nearshore waters of Mayo Bay, Philippines. *Marine Pollution Bulletin* **2023**, *186*, 114489, doi:10.1016/j.marpolbul.2022.114489

58. Papageorgiou, D.; Topouzelis, K.; Suaria, G.; Aliani, S.; Corradi, P., Sentinel-2 detection of floating marine litter targets with partial spectral unmixing and spectral comparison with other floating materials (Plastic Litter Project 2021). *Remote Sensing* **2022**, *14*, (23), 5997, doi:10.3390/rs14235997

59. Matthews, J. P.; Ostrovsky, L.; Yoshikawa, Y.; Komori, S.; Tamura, H., Dynamics and early post-tsunami evolution of floating marine debris near Fukushima Daiichi. *Nature Geoscience* **2017**, *10*, 598, doi:10.1038/ngeo2975

60. Lebreton, L.; Slat, B.; Ferrari, F.; Sainte-Rose, B.; Aitken, J.; Marthouse, R.; Hajbane, S.; Cunsolo, S.; Schwarz, A.; Levivier, A.; Noble, K.; Debeljak, P.; Maral, H.; Schoeneich-Argent, R.; Brambini, R.; Reisser, J., Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Scientific Reports* **2018**, *8*, (1), 4666, doi:10.1038/s41598-018-22939-w

61. Ge, Z.; Shi, H.; Mei, X.; Dai, Z.; Li, D., Semi-automatic recognition of marine debris on beaches. *Scientific Reports* **2016**, *6*, 25759, doi:10.1038/srep25759

62. Simpson, M. D.; Marino, A.; de Maagt, P.; Gandini, E.; Hunter, P.; Spyrakos, E.; Tyler, A.; Telfer, T., Monitoring of plastic islands in river environment using Sentinel-1 SAR data. *Remote Sensing* **2022**, *14*, (18), 4473, doi:10.3390/rs14184473

63. Davaasuren, N.; Marino, A.; Boardman, C.; Alparone, M.; Nunziata, F.; Ackermann, N.; Hajnsek, I. In *Detecting microplastics pollution in world oceans using SAR remote sensing*, IGARSS 2018 – 2018 IEEE International Geoscience and Remote Sensing Symposium, 22-27 July, Valencia, Spain, 22-27 July 2018, 2018; Valencia, Spain, 2018; pp 938-941.

64. Evans, M. C.; Ruf, C. S., Toward the detection and imaging of ocean microplastics with a spaceborne radar. *IEEE Transactions on Geoscience and Remote Sensing* **2021**, 1-9, doi:10.1109/TGRS.2021.3081691

65. NASEM *Reckoning with the U.S. role in global ocean plastic waste*; The National Academies of Sciences, Engineering, and Medicine: Washington DC, USA, 2022; p 269.

66. Topouzelis, K.; Papageorgiou, D.; Suaria, G.; Aliani, S., Floating marine litter detection algorithms and techniques using optical remote sensing data: A review. *Marine Pollution Bulletin* **2021**, *170*, 112675, doi:10.1016/j.marpolbul.2021.112675

67. Wolf, M.; van den Berg, K.; Garaba, S. P.; Gnann, N.; Sattler, K.; Stahl, F.; Zielinski, O., Machine learning for aquatic plastic litter detection, classification and quantification (APLASTIC-Q). *Environmental Research Letters* **2020**, *15*, (11), 114042, doi:10.1088/1748-9326/abbd01

68. Kylili, K.; Kyriakides, I.; Artusi, A.; Hadjistassou, C., Identifying floating plastic marine debris using a deep learning approach. *Environmental Science and Pollution Research* **2019**, doi:10.1007/s11356-019-05148-4

69. Panwar, H.; Gupta, P. K.; Siddiqui, M. K.; Morales-Menendez, R.; Bhardwaj, P.; Sharma, S.; Sarker, I. H., AquaVision: Automating the detection of waste in water bodies using deep transfer learning. *Case Studies in Chemical and Environmental Engineering* **2020**, *2*, 100026(1-5), doi:10.1016/j.cscee.2020.100026

70. Martin, C.; Zhang, Q.; Zhai, D.; Zhang, X.; Duarte, C. M., Enabling a large-scale assessment of litter along Saudi Arabian red sea shores by combining drones and machine learning. *Environmental Pollution* **2021**, *277*, 116730(1-10), doi:10.1016/j.envpol.2021.116730

71. Zhang, P.; Du, P.; Guo, S.; Zhang, W.; Tang, P.; Chen, J.; Zheng, H., A novel index for robust and large-scale mapping of plastic greenhouse from Sentinel-2 images. *Remote Sensing of Environment* **2022**, *276*, 113042(1-24), doi:10.1016/j.rse.2022.113042

72. Biermann, L.; Clewley, D.; Martinez-Vicente, V.; Topouzelis, K., Finding plastic patches in coastal waters using optical satellite data. *Scientific Reports* **2020**, *10*, (1), 5364, doi:10.1038/s41598-020-62298-z

73. Kühn, F.; Oppermann, K.; Hörig, B., Hydrocarbon Index – an algorithm for hyperspectral detection of hydrocarbons. *International Journal of Remote Sensing* **2004**, *25*, (12), 2467-2473, doi:10.1080/01431160310001642287

74. Hörig, B.; Kühn, F.; Oschütz, F.; Lehmann, F., HyMap hyperspectral remote sensing to detect hydrocarbons. *International Journal of Remote Sensing* **2001**, *22*, (8), 1413-1422, doi:10.1080/01431160120909

75. Guo, X.; Li, P., Mapping plastic materials in an urban area: Development of the normalized difference plastic index using WorldView-3 superspectral data. *ISPRS Journal of Photogrammetry and Remote Sensing* **2020**, *169*, 214-226, doi:10.1016/j.isprsjprs.2020.09.009

76. Yang, D.; Chen, J.; Zhou, Y.; Chen, X.; Chen, X.; Cao, X., Mapping plastic greenhouse with medium spatial resolution satellite data: Development of a new spectral index. *ISPRS Journal of Photogrammetry and Remote Sensing* **2017**, *128*, 47-60, doi:10.1016/j.isprsjprs.2017.03.002

77. Asadzadeh, S.; de Souza Filho, C. R., Investigating the capability of WorldView-3 superspectral data for direct hydrocarbon detection. *Remote Sensing of Environment* **2016**, *173*, 162-173, doi:10.1016/j.rse.2015.11.030

78. Mace, T. H., At-sea detection of marine debris: Overview of technologies, processes, issues, and options. *Marine Pollution Bulletin* **2012**, *65*, (1–3), 23-27, doi:10.1016/j.marpolbul.2011.08.042

79. Maximenko, N.; Hafner, J. *SCUD: Surface currents from diagnostic model. IPRC Technical Note No. 5*; International Pacific Research Center,: Hawaii, USA, 2010; p 17.

80. Cortesi, I.; Masiero, A.; De Giglio, M.; Tucci, G.; Dubbini, M., Random forest-based river plastic detection with a handheld multispectral camera. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **2021**, *XLIII-B1-2021*, 9-14, 10.5194/isprs-archives-XLIII-B1-2021-9-2021

81. Iordache, M.-D.; De Keukelaere, L.; Moelans, R.; Landuyt, L.; Moshtaghi, M.; Corradi, P.; Knaeps, E., Targeting plastics: Machine learning applied to litter detection in aerial multispectral images. *Remote Sensing* **2022**, *14*, (22), 5820, doi:10.3390/rs14225820

82. Pinto, L.; Andriolo, U.; Gonçalves, G., Detecting stranded macro-litter categories on drone orthophoto by a multi-class Neural Network. *Marine Pollution Bulletin* **2021**, *169*, 112594(1-9), doi:10.1016/j.marpolbul.2021.112594

83. Freitas, S.; Silva, H.; Silva, E., Hyperspectral imaging zero-shot learning for remote marine litter detection and classification. *Remote Sensing* **2022**, *14*, (21), 5516, doi:10.3390/rs14215516

84. Acuña-Ruz, T.; Uribe, D.; Taylor, R.; Amézquita, L.; Guzmán, M. C.; Merrill, J.; Martínez, P.; Voisin, L.; Mattar B., C., Anthropogenic marine debris over beaches: Spectral characterization for remote sensing applications. *Remote Sensing of Environment* **2018**, *217*, 309-322, doi:10.1016/j.rse.2018.08.008

85. Lavender, S., Detection of waste plastics in the environment: Application of Copernicus earth observation data. *Remote Sensing* **2022**, *14*, (19), 4772, doi:10.3390/rs14194772

86. Balsi, M.; Esposito, S.; Moroni, M. In *Hyperspectral characterization of marine plastic litters*, 2018 IEEE International Workshop on Metrology for the Sea; Learning to Measure Sea Health Parameters (MetroSea), Bari, Italy, 8-10 October 2018, 2018; IEEE: Bari, Italy, 2018; pp 28-32.

87. Masoumi, H.; Safavi, S. M.; Khani, Z., Identification and classification of plastic resins using near infrared reflectance spectroscopy. *World Acad. Sci. Eng. Technol.* **2012**, *6*, (5), 141-148.

88. Moshtaghi, M.; Knaeps, E.; Sterckx, S.; Garaba, S.; Meire, D., Spectral reflectance of marine macroplastics in the VNIR and SWIR measured in a controlled environment. *Scientific Reports* **2021**, *11*, (1), 5436, doi:10.1038/s41598-021-84867-6

89. Taggio, N.; Aiello, A.; Ceriola, G.; Kremezi, M.; Kristollari, V.; Kolokoussis, P.; Karathanassi, V.; Barbone, E., A combination of machine learning algorithms for marine plastic litter detection exploiting hyperspectral PRISMA data. *Remote Sensing* **2022**, *14*, (15), 3606, doi:10.3390/rs14153606

90. Gnann, N.; Baschek, B.; Ternes, T. A., Close-range remote sensing-based detection and identification of macroplastics on water assisted by artificial intelligence: A review. *Water Research* **2022**, *222*, 118902(1-15), doi:10.1016/j.watres.2022.118902

91. Kataoka, T.; Murray, C. C.; Isobe, A., Quantification of marine macro-debris abundance around Vancouver Island, Canada, based on archived aerial photographs processed by projective transformation. *Marine Pollution Bulletin* **2018**, *132*, 44-51, doi:10.1016/j.marpolbul.2017.08.060

92. Gonçalves, G.; Andriolo, U.; Pinto, L.; Duarte, D., Mapping marine litter with Unmanned Aerial Systems: A showcase comparison among manual image screening and machine learning techniques. *Marine Pollution Bulletin* **2020**, *155*, 111158(1-11), doi:10.1016/j.marpolbul.2020.111158

93. Fallati, L.; Polidori, A.; Salvatore, C.; Saponari, L.; Savini, A.; Galli, P., Anthropogenic marine debris assessment with unmanned aerial vehicle imagery and deep learning: A case study along the beaches of the Republic of Maldives. *Science of The Total Environment* **2019**, *693*, 133581, doi:10.1016/j.scitotenv.2019.133581

94. Kako, S. i.; Isobe, A.; Kataoka, T.; Yufu, K.; Sugizono, S.; Plybon, C.; Murphy, T. A., Sequential webcam monitoring and modeling of marine debris abundance. *Marine Pollution Bulletin* **2018**, *132*, 33-43, doi:10.1016/j.marpolbul.2018.04.075

95. Merlino, S.; Paterni, M.; Berton, A.; Massetti, L., Unmanned aerial vehicles for debris survey in coastal areas: Long-term monitoring programme to study spatial and temporal accumulation of the dynamics of beached marine litter. *Remote Sensing* **2020**, *12*, (8), 1260 (1 - 23), doi:10.3390/rs12081260

96. OceanScan Ocean plastic from space. https://www.oceanscan.org/ (Last access: 23 September 2023).

97. Bergmann, M.; Tekman, M. B.; Gutow, L., Sea change for plastic pollution. *Nature* **2017**, *544*, (7650), 297-297, doi:10.1038/544297a

98. Tekman, M. B.; Gutow, L.; Peter, C.; Bergmann, M., LITTERBASE – Online Portal for Marine Litter & Microplastics and their Implications for Marine Life. In *6th International Marine Debris Conference*, San Diego, USA, 2018.

99. Kruse, C.; Boyda, E.; Chen, S.; Karra, K.; Bou-Nahra, T.; Hammer, D.; Mathis, J.; Maddalene, T.; Jambeck, J.; Laurier, F., Satellite monitoring of terrestrial plastic waste. *ArXiv e-prints* **2022**, 1-14, doi:10.48550/arXuc.2204.01485

100. Thomas, L.; Shah, A.; Ramasubramanian, M.; Priftis, G.; Maskey, M.; Ramachandran, R., Detecting floating marine debris from commercial small satellite imagery with deep learning. In *AGU Fall Meeting*, AGU: New Orleans, LA, USA. 13-17 December 2021, 2021; Vol. 2021, pp IN23A-04.

101. ASEAN Secretariat *ASEAN Regional Action Plan for Combating Marine Debris in the ASEAN Member States (2021-2025)*; Community Relations Division (CRD), The Association of Southeast Asian Nations (ASEAN): Jakarta, Indonesia, 2021; p 54.

102. WBG *Vietnam: Plastic pollution diagnostics*; Report No. 127695; World Bank Group: Washington D.C., USA, 2022; p 95.

103. Slabakova, V.; Zlateva, I.; Slavova, K., Initial assessment of composition, abundance, spatial distribution and hotspots identification of floating macro-litter in the Bulgarian Black Sea waters. *EnviroRISKs* **2020**, 537-547, doi:10.48365/envr-2020.1.49

104. Campanale, C.; Suaria, G.; Bagnuolo, G.; Baini, M.; Galli, M.; de Rysky, E.; Ballini, M.; Aliani, S.; Fossi, M. C.; Uricchio, V. F., Visual observations of floating macro litter around Italy (Mediterranean Sea). *Mediterranean Marine Science* **2019**, *20*, (2), 271-281, doi:10.12681/mms.19054

105. Vighi, M.; Ruiz-Orejón, L. F.; Hanke, G. *Monitoring of Floating Marine Macro Litter – State of the art and literature overview*; Publications Office of the European Union, Luxembourg, 2022; p 69.

106. Livens, S.; Knaeps, E.; Benhadj, I.; Bomans, B.; Dries, J., Feasibility assessment of a dedicated satellite mission for monitoring marine macroplastics. In *4S Symposium, 16-20 May*, Vilamoura, Portugal, 2022; pp 1-8.

107. Martinez-Vicente, V., The need for a dedicated marine plastic litter satellite mission. *Nature Reviews Earth & Environment* **2022**, *3*, (11), 728-729, doi:10.1038/s43017-022-00360-2

108. GESAMP *Guidelines or the monitoring and assessment of plastic litter and microplastics in the ocean. (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection).* International Maritime Organization – London, UK, 2019; p 130.

109. Veettil, B. K.; Hong Quan, N.; Hauser, L. T.; Doan Van, D.; Quang, N. X., Coastal and marine plastic litter monitoring using remote sensing: A review. *Estuarine, Coastal and Shelf Science* **2022**, *279*, 108160, doi:10.1016/j.ecss.2022.108160

110. Andriolo, U.; Garcia-Garin, O.; Vighi, M.; Borrell, A.; Gonçalves, G., Beached and floating litter surveys by unmanned aerial vehicles: operational analogies and differences. *Remote Sensing* **2022**, *14*, (6), 1336, doi:10.3390/rs14061336

111. Janssens, N.; Schreyers, L.; Biermann, L.; van der Ploeg, M.; Bui, T.-K. L.; van Emmerik, T., Rivers running green: water hyacinth invasion monitored from space. *Environmental Research Letters* **2022**, *17*, (4), 044069, doi:10.1088/1748-9326/ac52ca

112. Gonçalves, G.; Andriolo, U., Operational use of multispectral images for macro-litter mapping and categorization by unmanned aerial vehicle. *Marine Pollution Bulletin* **2022**, *176*, 113431(1-11), doi:10.1016/j.marpolbul.2022.113431

113. Kikaki, K.; Kakogeorgiou, I.; Mikeli, P.; Raitsos, D. E.; Karantzalos, K., MARIDA: A benchmark for Marine Debris detection from Sentinel-2 remote sensing data. *PLoS ONE* **2022**, *17*, (1), e0262247(1-20), doi:10.1371/journal.pone.0262247

114. Kremezi, M.; Kristollari, V.; Karathanassi, V.; Topouzelis, K.; Kolokoussis, P.; Taggio, N.; Aiello, A.; Ceriola, G.; Barbone, E.; Corradi, P., Increasing the Sentinel-2 potential for marine plastic litter monitoring through image fusion techniques. *Marine Pollution Bulletin* **2022**, *182*, 113974(1-20), doi:10.1016/j.marpolbul.2022.113974

115. Savastano, S.; Cester, I.; Perpinyà, M.; Romero, L. In *A first approach to the automatic detection of marine litter in SAR images using artificial intelligence*, 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, Brussels, Belgium, 11-16 July 2021, 2021; Brussels, Belgium, 2021; pp 8704-8707.

116. Andriolo, U.; Gonçalves, G.; Sobral, P.; Bessa, F., Spatial and size distribution of macro-litter on coastal dunes from drone images: A case study on the Atlantic coast. *Marine Pollution Bulletin* **2021**, *169*, 112490, doi:10.1016/j.marpolbul.2021.112490

117. Balsi, M.; Moroni, M.; Chiarabini, V.; Tanda, G., High-resolution aerial detection of marine plastic litter by hyperspectral sensing. *Remote Sensing* **2021**, *13*, (8), 1557, doi:10.3390/rs13081557

118. Basu, B.; Sannigrahi, S.; Sarkar Basu, A.; Pilla, F., Development of novel classification algorithms for detection of floating plastic debris in coastal waterbodies using multispectral Sentinel-2 remote sensing imagery. *Remote Sensing* **2021**, *13*, (8), 1598, doi:10.3390/rs13081598

119. Ciappa, A. C., Marine plastic litter detection offshore Hawai'i by Sentinel-2. *Marine Pollution Bulletin* **2021**, *168*, 112457, doi:10.1016/j.marpolbul.2021.112457

120. Merlino, S.; Paterni, M.; Locritani, M.; Andriolo, U.; Gonçalves, G.; Massetti, L., Citizen science for marine litter detection and classification on unmanned aerial vehicle images. *Water* **2021**, *13*, (23), 3349, doi:10.3390/w13233349

121. Andriolo, U.; Gonçalves, G.; Sobral, P.; Fontán-Bouzas, Á.; Bessa, F., Beach-dune morphodynamics and marine macro-litter abundance: An integrated approach with Unmanned Aerial System. *Science of The Total Environment* **2020**, *749*, 141474, doi:10.1016/j.scitotenv.2020.141474

122. Andriolo, U.; Gonçalves, G.; Bessa, F.; Sobral, P., Mapping marine litter on coastal dunes with unmanned aerial systems: A showcase on the Atlantic Coast. *Science of The Total Environment* **2020**, *736*, 139632, doi:10.1016/j.scitotenv.2020.139632

123. Garcia-Garin, O.; Aguilar, A.; Borrell, A.; Gozalbes, P.; Lobo, A.; Penadés-Suay, J.; Raga, J. A.; Revuelta, O.; Serrano, M.; Vighi, M., Who's better at spotting? A comparison between aerial photography and observer-based methods to monitor floating marine litter and marine mega-fauna. *Environmental Pollution* **2020**, *258*, 113680, doi:10.1016/j.envpol.2019.113680

124. Jakovljevic, G.; Govedarica, M.; Alvarez-Taboada, F., A deep learning model for automatic plastic mapping using unmanned aerial vehicle (UAV) data. *Remote Sensing* **2020**, *12*, (9), 1515, doi:10.3390/rs12091515

125. Kako, S. i.; Morita, S.; Taneda, T., Estimation of plastic marine debris volumes on beaches using unmanned aerial vehicles and image processing based on deep learning. *Marine Pollution Bulletin* **2020**, *155*, 111127, doi:10.1016/j.marpolbul.2020.111127

126. Papachristopoulou, I.; Filippides, A.; Fakiris, E.; Papatheodorou, G., Vessel-based photographic assessment of beach litter in remote coasts. A wide scale application in Saronikos Gulf, Greece. *Marine Pollution Bulletin* **2020**, 110684, doi>10.1016/j.marpolbul.2019.110684

127. Ryan, P. G., Using photographs to record plastic in seabird nests. *Marine Pollution Bulletin* **2020**, *156*, 111262, doi:10.1016/j.marpolbul.2020.111262

128. Goddijn-Murphy, L.; Williamson, B., On thermal infrared remote sensing of plastic pollution in natural waters. *Remote Sensing* **2019**, *11*, (18), 2159, doi:10.3390/rs11182159

129. Geraeds, M.; van Emmerik, T.; de Vries, R.; bin Ab Razak, M. S., Riverine plastic litter monitoring using unmanned aerial vehicles (UAVs). *Remote Sensing* **2019**, *11*, (17), 2045, doi:10.3390/rs11172045

130. Valdenegro-Toro, M., Deep neural networks for marine debris detection in sonar images. PhD Thesis Heirot-Watt University, Edinburgh, United Kingdom. *ArXiv e-prints – CoRR* **2019**, 1-241, doi:10.48550/arXiv.1905.05241

131. Watanabe, J.-I.; Shao, Y.; Miura, N., Underwater and airborne monitoring of marine ecosystems and debris. *Journal of Applied Remote Sensing* **2019**, *13*, (4), 044509, doi:10.1117/1.JRS.13.044509

132. Bao, Z.; Sha, J.; Li, X.; Hanchiso, T.; Shifaw, E., Monitoring of beach litter by automatic interpretation of unmanned aerial vehicle images using the segmentation threshold method. *Marine Pollution Bulletin* **2018**, *137*, 388-398, doi:10.1016/j.marpolbul.2018.08.009

133. Deidun, A.; Gauci, A.; Lagorio, S.; Galgani, F., Optimising beached litter monitoring protocols through aerial imagery. *Marine Pollution Bulletin* **2018**, *131*, 212-217, doi:10.1016/j.marpolbul.2018.04.033

134. Aoyama, T. In *Extraction of marine debris in the Sea of Japan using satellite images*, Proceedings of SPIE Volume: 10778, Remote sensing of the open and coastal ocean and inland waters, Honolulu, Hawaii, USA, 2018; Frouin, R. J.; Murakami, H., Eds. Honolulu, Hawaii, USA, 2018; pp 107780R-1--8.

135. Moy, K.; Neilson, B.; Chung, A.; Meadows, A.; Castrence, M.; Ambagis, S.; Davidson, K., Mapping coastal marine debris using aerial imagery and spatial analysis. *Marine Pollution Bulletin* **2018**, *132*, 52-59, doi:10.1016/j.marpolbul.2017.11.045

136. Serranti, S.; Palmieri, R.; Bonifazi, G.; Cózar, A., Characterization of microplastic litter from oceans by an innovative approach based on hyperspectral imaging. *Waste Management* **2018**, *76*, 117-125, doi:10.1016/j.wasman.2018.03.003

137. Hengstmann, E.; Gräwe, D.; Tamminga, M.; Fischer, E. K., Marine litter abundance and distribution on beaches on the Isle of Rügen considering the influence of exposition, morphology and recreational activities. *Marine Pollution Bulletin* **2017**, *115*, (1), 297-306, doi:10.1016/j.marpolbul.2016.12.026

138. Kako, S. i.; Isobe, A.; Kataoka, T.; Hinata, H., A decadal prediction of the quantity of plastic marine debris littered on beaches of the East Asian marginal seas. *Marine Pollution Bulletin* **2014**, *81*, (1), 174-184, doi:10.1016/j.marpolbul.2014.01.057

139. Garcia-Garin, O.; Borrell, A.; Aguilar, A.; Cardona, L.; Vighi, M., Floating marine macro-litter in the North Western Mediterranean Sea: Results from a combined monitoring approach. *Marine Pollution Bulletin* **2020**, *159*, 111467, doi:10.1016/j.marpolbul.2020.111467

140. Cortesi, I.; Masiero, A.; Tucci, G.; Topouzelis, K., UAV-based river plastic detection with a multispectral camera. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **2022**, *XLIII-B3-2022*, 855-861, doi:10.5194/isprs-archives-XLIII-B3-2022-855-2022

141. Cocking, J.; Narayanaswamy, B. E.; Waluda, C. M.; Williamson, B. J., Aerial detection of beached marine plastic using a novel, hyperspectral short-wave infrared (SWIR) camera. *ICES Journal of Marine Science* **2022**, 10.1093/icesjms/fsac006

142. Escobar-Sánchez, G.; Haseler, M.; Oppelt, N.; Schernewski, G., Efficiency of aerial drones for macrolitter monitoring on Baltic Sea beaches. *Frontiers in Environmental Science* **2021**, *8*, 560237(1-18), 10.3389/fenvs.2020.560237

143. Gonçalves, G.; Andriolo, U.; Gonçalves, L.; Sobral, P.; Bessa, F., Quantifying marine macro litter abundance on a sandy beach using unmanned aerial systems and object-oriented machine learning methods. *Remote Sensing* **2020,** *12*, (16), 2599, doi:10.3390/rs12162599

144. NASA EARTHDATA Open Access for Open Science: Tracking Ocean Plastics from Space. Accessed on 24th April 2023. https://www.earthdata.nasa.gov/learn/articles/ocean-plastic

Annex

A1. Scientific Research Projects

Information presented here has been sourced from Related Research Topics section of the IOCCG Task Force on Remote Sensing of Marine Litter and Debris (https://ioccg.org/rsmld-news-and-updates/). The living list is not exhaustive but provides an overview of ongoing and concluded scientific projects that have been supported by various funding entities.

Title: Advancing Remote Sensing of Microplastics on the Surface Ocean, SQOOP (March 2021 – March 2024)

Contact Person: Heidi Dierssen (heidi.dierssen@uconn.edu)

Funding Agency: NASA Ocean Biology and Biogeochemistry

Summary: Since the 1950's, positively buoyant plastic objects have been accumulating at the surface of the oceans, transported by currents, wind and waves. Small millimetre-sized pieces (<4.75 mm), known as microplastics, count in trillions at global scale and pose an increasing risk to marine biota. Floating microplastics concentrate along convergence zones in the five major ocean basins, but a comprehensive analysis of the spatial and temporal distributions is lacking, and the monitoring tools are not well developed to assess global distributions. Thus far, remote sensing methods have focused on larger macroplastics. Our specific objectives are to: 1) Evaluate geospatial and temporal trends in existing ocean colour products across hot spots that may be related to enhanced reflectance from plastics; 2) Propagate estimates of ocean surface hyperspectral reflectance using simple mixed pixel models to the Top of the Atmosphere (TOA) under different microplastic concentrations and atmospheric conditions; 3) Simulate spaceborne ocean colour remote sensing observations for different microplastic and atmospheric conditions using robust vector radiative transfer models for coupled ocean-atmosphere systems; 4) Assess microplastic remote sensing detectability using statistical information content assessment in terms of current and future instrument characteristics, microplastic quantity and nature, and external conditions, such as observation geometry and atmospheric state; and 5) Evaluate how results from the above analyses relate to our hypotheses and implications for the remote sensing of microplastic and provide recommendations for new algorithms and instrument design.

Title: Artificial Intelligence and drones supporting the detection and mapping of floating aquatic plastic litter, AIDMAP (September 2020 – March 2022)

Contact Person: Els Knaeps (els.knaeps@vito.be)

Website: https://remotesensing.vito.be/case/marine-plastic-litter

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: The AIDMAP project proposes an Artificial Intelligence (AI)-based approach for the detection of FML in accumulation zones. Vertical integration of small drone and satellite data will be evaluated for the detection of the marine litter at different spatial scales. These can be complemented by High Altitude Pseudo-Satellite (HAPS) in the longer term to come to a long-term sustainable solution. The AIDMAP project therefore responds to the quickly evolving EO landscape with an increasing emphasis on modern, affordable and sustainable technologies, such as Artificial Intelligence, and the launch of (constellations of) small satellites and non-orbiting platforms (such as HAPS) while also exploring the added value of the current Copernicus Sentinel program. Here, study areas in Vietnam are selected to demonstrate the proposed approach.

Title: Airborne & satellite observation strategies for marine litter monitoring, AIR-SOS (June 2020 – Sep 2021)

Collecting Multispectral data from floating debris using a seaplane over the Elbe river discharge area to validate current algorithms and methodologies.

Contact Person: Irina Rammos (i.rammos@skyflox.eu)

Website: https://skyflox.eu/, https://www.pml.ac.uk/, https://aufwind.aero/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Marine Litter is a global issue and can be found in all the seas from the equator to the poles, and in freshwater systems, such as rivers and lakes. Most of the marine litter is plastic and, as plastic production continues to increase, greater impacts are expected. Plastic marine litter dramatically affects marine life and ecosystems and has a great economic impact on coastal communities, tourism, and fisheries. It furthermore poses a concern for human health due to contamination of seafood with plastic particles and associated pollutants. Urgent questions around marine plastic pathways into the ocean, sinks, trends, and fate remain open, but cannot be answered satisfactorily using ground-based and model-based systems alone. The emerging field of remote sensing for plastic detection is promising for tackling unknowns around marine monitoring, but reliable *in situ* validation data are required to improve and optimise algorithms and approaches. The AIR-SOS (AIRborne & Satellite Observation Strategies for marine litter monitoring) study aims to do just that, by collecting high-quality and high-resolution data of floating objects in coastal waters near the mouth of the river Elbe. A seaplane will be used on clear and still (low wind) days to collect data coincident with Copernicus Sentinel-2 satellites overpass. In this way, the project will assess and demonstrate the value of the aircraft as a platform for validation of Sentinel-2 validation. The ability to fly sensors on General aviation Aircraft at lower cost, at lower altitudes (visual cross-checks) and the possibility to perform in situ measurements (sea-landings) makes this a multi-functional 'platform' suitable to for systematic validation of satellite remote sensing detection of marine litter.

Title: Assessment of the Effects of Marine Debris on Ocean Colour Signals (2021 – 2024)

Contact Person: Robert Foster (robert.foster@nrl.navy.mil)

Funding Agency: NASA Ocean Biology and Biogeochemistry

Summary: The objective of this research is to conduct an investigation into the effects of marine debris upon top of atmosphere (TOA) ocean colour signals. Since so little is currently known about the optics of both floating and suspended marine debris, primarily marine plastic, we will first conduct theoretical studies to examine how different types of debris affect changes in the TOA radiance. We will determine the limits of detectability of debris from orbit for current and planned satellite ocean colour sensors, followed by an analysis of current and historical remote sensing data from orbiting sensors such as the Hyperspectral Imager for the Coastal Ocean (HICO) and the DESIS Earth Sensing Imaging Spectrometer. This study will seek to address the following science questions: 1) In what ways does the presence of macro- and micro- marine debris affect the top-of atmosphere ocean color signal?; 2) What are the detectability limits for debris with current and planned satellite ocean colour missions?; 3) How do percent coverage, debris reflectance, and degree of submersion affect the detectability in the open ocean?; 4) Does marine debris, particularly plastics, alter the polarization of the upwelling radiance?; 5) Do existing remote sensing datasets support the conclusions?

Title: Brillouin – backscatter – fluorescence LIDAR research for Underwater Exploration of marine litter, BLUE (September 2020 – August 2022)

Contact Person: Valentina Raimondi, CNR-IFAC – Italy (v.raimondi@ifac.cnr.it)

Website: http://www.ifac.cnr.it/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Our idea is to investigate the potential of LIDAR – space, airborne and ground based – to address plastic marine litter. Recent studies have stressed how plastic litter at the sea surface represents only a small fraction of plastics entering the sea. Hence, the major contribution of our idea would be to investigate remote sensing methods with the potential to provide information on plastics distributed in the water column and its identification. Until now, the contribution of LIDAR to ocean plastic remote sensing has been almost unexplored, except for sporadic bathymetric data from airplane to detect large items. Meanwhile, spaceborne elastic LIDAR has already been used to detect algal blooms in oceanic waters, while fluorescence LIDAR has already been suggested for plastics characterisation in different contexts. The proposed approach is four-fold and aims at investigating the potential of: (1) elastic backscatter and Brillouin LIDAR from space to detect changes in the optical properties of the water column due to microplastics; (2) LIDAR bathymetric data from airplane to detect plastic items by processing airborne LIDAR data acquired over the Great Pacific Garbage Patch; (3) fluorescence LIDAR to identify plastic items from airborne, ship- or ground-based platform (e.g. at river outlets); (4) Raman spectroscopy to identify plastic items and microplastic as for the material type. For the first time, this study will provide an insight on the feasibility of using LIDAR for remote sensing of microplastics and for the characterisation of plastic items in terms of material type.

Title: Using Deep Learning Methods For Plastic Litter Detection From Satellite Remote Sensor, DL4PlasticLitter (June 2020 – April 2021)

Contact Person: Delphine Nobileau (delphine.nobileau@capgemini.com) – CAPGEMINI

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Artificial Intelligence (AI) could represent a powerful tool in support of the EO data processing for the detection of marine litter, provided the availability of a sufficiently large dataset of satellite images of marine litter accumulations. However, there are currently no such datasets publicly available yet. To address this issue, in the frame of the DL4PlasticLitter project, we first create realistic synthetic spectra of floating litter accumulations. We simulate combinations of reflectance spectra of seawater and macro-plastic for different observation geometries, different concentrations of chlorophyll and other substances present in the water, and we model the radiative transfer to the top of atmosphere and at sensor resolution. Then, we train AI models to learn to differentiate the spectra of modelled accumulations containing plastic. The last step consists in validating the developed AI models with real satellite images of marine litter accumulations.

Title: Detection of Ocean Litter Plastics with Hyper-to-multispectral Infrared Neural Networks, DOLPHINN (July 2020 – July 2021)

Contact Person: Yolanda Brown (Yolanda.Brown@mda.space)

Website: https://mda.space/en/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: This study seeks to determine the feasibility of using AI to better and more accurately detect and quantify ocean and beach plastics litter from space-borne multispectral data, particularly in the SWIR range. MDA is developing a novel spectral fusion approach that learns to associate multispectral data with full hyperspectral features so that single multispectral images can be used to detect plastics more reliably. Multispectral sensors already on orbit could then better contribute to marine litter detection. Once hyperspectral space assets such as CHIME become available, they could be used for continuous training of multispectral sensors to allow more coverage and revisit in ocean plastic detection and monitoring.

Title: Spectrometer for Marine Litter, ESAPlastics
(January 2020 – May 2021)

Contact Person: Hugo Silva (hugo.m.silva@inesctec.pt)

Website: https://www.aircentre.org/esaplastics/

Funding Agency: ESA, the European Space Agency (GSTP)

Summary: The objective of the project is to study, characterize, acquire, and process data from oceanic marine litter samples using heterogeneous sensors information. The project work is divided into three main parts: (i) the in-situ acquisition of marine litter samples from an oceanic marine litter hotspot in Faial Island Azores; (ii) the characterization and identification in laboratory environment of the individual components that are present in the collected marine litter samples i.e., type of material and other chemical elements contained, by using different sensors, e.g. Spectroscopy FTIR, Raman, and LIBS; (iii) performing extensive dataset campaigns using manned and unmanned aerial platforms, for acquiring remote hyperspectral imaging data of artificial marine litter concentrations, fostering the development of automatic methods based on supervised learning approaches for the detection using spatial/spectral information of marine litter concentrations from space.

Title: Tackling the plastic debris challenge at its source – Linking EO data with multi-source in-situ data for modelling debris pathways from source to sink, From Source to Sink
(August 2020 – July 2022)

Contact Person: Jonas Franke, Remote Sensing Solutions (franke@rssgmbh.de)

Website: http://www.remote-sensing-solutions.com/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Monitoring areas closer to plastic marine litter sources such as rivers and estuarine systems has the potential to improve mitigation strategies. Upscaling in-situ litter point data with earth observation (EO) and hydrodynamic models is our central concept. Multi-type in situ data will be collected at various points along the pollution pathway (in our demonstration site in the Po River delta in Italy): Imagery from installed cameras on bridges is analysed to detect floating plastic in rivers using deep-learning (in-situ type 1). Water samples from estuaries and coastal areas using manta trawls are used to quantify plastic litter abundances (in-situ type 2) Drone imagery along the shoreline is acquired for accumulation analyses (in-situ type 3) Beach samples through field surveys (in situ type 4) Sentinel-2 and -3, together with VHR data such as WorldView-3, are used to monitor discharging rivers and their estuaries (water constituents and river plume detection). Integration of these situ-data, multi-scale EO and hydrodynamic modelling serves as the development basis, allowing for the first time a monitoring of real-world debris transport pathways. Such source-to-sink monitoring systems can be used to identify environmental, economic, human health and safety-related impacts of plastic litter and would support targeted efforts of both off- and onshore-based clean-up projects.

Title: Global Monitoring of Microplastics using GNSS-Reflectometry, GLIMPS (November 2020 – December 2021)

Contact Person: Dr. Clarizia (maria-paola.clarizia@deimos-space.com)

Website: https://elecnor-deimos.com/project/glimps/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities)

Summary: The goal of GLIMPS is to produce global maps of the microplastics concentration in the oceans using GNSS-R data and algorithms based on machine learning. This will deliver information about the location and distribution of microplastics, which will be complementary to that provided by in situ measurements and ocean circulation models. The idea is built upon the assumption that microplastics and associated surfactants dampen the waves, reducing ocean surface roughness; and that this reduction in roughness can be sensed by satellite radar. GNSS-Reflectometry is a radar-based remote sensing technique which only requires cheap, lightweight and low-power receivers to be implemented, since it exploits existing GNSS transmitters of opportunity. The wealth of existing GNSS transmitters, and the nature of GNSS-R receivers, makes it easy to build a constellation, addressing the need for high space-time sampling that is crucial for monitoring microplastics from space efficiently.

Title: Hyperdrone: Development of spectroradiometric proxies of shoreline marine plastic debris for satellite validation using remotely piloted aircrafts, HyperDrone (June 2020 – December 2021)

Contact Person: Aser Mata (asm@pml.ac.uk)

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Developing instruments and algorithms for satellite remote sensing of ocean plastic needs standardised global in situ observations. This project plans to collect hyperspectral data from plastic targets to develop a standardised indicator for in situ radiometric detection of plastic debris on the shoreline, with a view to being deployed globally on different platforms. Field campaigns will be carried out that will include hand-held hyperspectral spectrometers (SVC) and state of the art hyperspectral imagers (BaySpec OCI-F and the Headwall Co-aligned VNIR+SWIR sensors) mounted on drone platforms flying at different altitudes. Spectra from different plastic targets will be collected on the shoreline in real conditions meeting traceability standards and with uncertainty estimates for each dataset (to be made freely available upon completion of the project). Taking advantage of the SWIR spectral features of plastic materials, HyperDrone aims to develop proxies for plastic detection on the shoreline and assess subpixel detection. Using an atmospheric radiative transfer model, we will simulate at-satellite sensor radiances to provide guidance on sensor requirements as well as model signal unmixing for retrieval of plastic pixel coverage.

Title: **Prediction of plastic hot-spots in coastal regions using satellite derived plastic detection, cleaning data and numerical simulations in a coupled system, LOCATE (June 2020 – May 2021)**

Contact Person: Dr José M. Alsina (jose.alsina@upc.edu); Dr Silvia Huber (shu@dhigroup.com)

Website: https://lim.upc.edu/en; https://www.dhi-gras.com/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: The LOCATE project concerns the identification of plastic hotspots in coastal waters and on the shore by using a coupled system integrating satellite derived information, regional coastal models, the computation of lagrangian plastic trajectories and information from cleaning campaigns. Satellite derived hydrodynamic information (Sentinel-1 SAR and Sentinel-3 altimeter) is being used to validate eulerian hydrodynamic simulations in coastal waters and will be also used to produce model inputs and data assimilation (bathymetry, hydrodynamic variables). Moreover, Sentinel-2 optical information is used to derive water quality (turbidity) which potentially can be correlated to plastic inputs, cleaning data and numerical simulations. Eulerian hydrodynamic simulations are produced using the numerical model COAWST and validated with Satellite hydrodynamic information (wave height, water surface elevation). Daily hydrodynamic forecasting outputs produced at the Catalan coast in Spain are stored in a dedicate web page at three different coastal grid domains (with grid sizes of 2500m, 350m and 70m). Simulations of plastic dispersion in the nested domains are obtained using the Parcels software. Plastic accumulation regions will be then identified and tracked in space and time and contrasted with cleaning data. The developed system will answer a high demand of a more efficient local to regional management of coastal plastic pollution by helping to identify hotspots of plastic accumulations in time and space. The developed system will answer a high demand of a more efficient local to regional management of coastal plastic pollution by helping to identify hotspots of plastic accumulations in time and space. The forecasting system will be made publicly available.

Title: **Marine Litter Aggregation Forecast (Sept 2020 – Dec 2021)**

Contact Person: Mario Castro de Lera (mario.castro.delera@deepblueglobe.eu)

Website: https://deepblueglobe.eu/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: The main goal of this project is to provide a new estimation of long-term marine litter accumulation areas at global scale taking advantage of numerical reanalysis databases of historical met-ocean conditions. Different machine learning techniques are applied to generate long-term climate-based series of those environmental variables that may affect the drift of marine litter over the sea surface such as currents, wind and wave-induced Stokes drift. The generated series will feed a state-of-the-art Lagrangian model in order to simulate the global long-term evolution of marine litter transport through the ocean surface. As marine debris sources coastal cities, river outputs and shipping routes are considered. Besides the main goal of the project, the proposed methodology has also the potential for interesting secondary achievements, such as providing the estimation of global scale marine litter distribution for specific past dates or predicting the expected future location and distribution of marine litter patches up to approximately six months ahead.

Title: Marine Macro Litter Drift Forecasting Service (May 2018 – December 2020)

Contact Person: Anne Vallette (avallette@argans.eu)

Website: https://argans.co.uk/proj-littertep.html

Funding Agency: Mercator Ocean (CMEMS)

Summary: The LITTER-TEP (Thematic Exploitation Platform) will provide a macro-litter beaching forecast service for local authorities, government agents, NGOs and environmental protection agencies. The fate of marine macro-litter can be forecast by modelling drift using Lagrangian models and bulk fluxes using Eulerian models. These will be parameterised using CMEMS products forecasting wave, wind and current data and supplemented with models of settlement, sinking and resuspension. Results of these simulations will be posted on a dedicated LITTER-TEP web portal along with a geo-browser to locate litter events associated with an area-of-interest (AOI), historical records and statistics. The expected results are maps of likely stretches of coastline that will be affected by marine-litter grounding subsequent to storm events. These will enable local agencies to forecast when and where clean-up operations will be needed.

Title: A full-range plastic marine litter monitoring service to support cleaning and littering reduction actions by mapping hotspots, pathways and littering sources, MARLISAT (June 2020 – December 2021)

Contact Person: Marc Lucas (mlucas@groupcls.com)

Website: https://www.cls-telemetry.com/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: A combined satellite-based solution is proposed to map plastic marine litter pathways and accumulation areas relying onto three innovative developments: 1) Utilising machine learning alongside an augmented land cover classification, accumulations of plastic litter across coastal and riparian zones will be mapped. 2) Based on the MAR-GE/T beacons with GPS positions relayed through the Argos satellite system, the proposed novel satellite tracker will be specifically designed to track plastic litter pathways, with better precision and realistic behavior. This miniaturized device will have a reduced environmental footprint. 3) Ocean surface currents and winds play a primary role in the transport and dispersal of plastic marine litters. A multi-year observations of ocean currents from space, in a synergetic use of satellite sensors (altimetry, scatterometers, …) and in-situ buoys, will be computed and used within a Lagrangian drift modelling tool to simulate the plastic litters pathways and map the hotspots. The combination of these three components will constitute a full-range monitoring system of plastic marine litter, from littering sources determination to hotspots and pathways identification, thus improving marine litter collection efforts.

Title: A Simulator for Marine Litter Observation from Space, ML-OPSI (June 2020 – September 2021)

Contact Person: Theodora Papadopoulou (tpapadopoulou@argans.co.uk)

Website: https://argans.co.uk/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: A breadboard for end-to-end (E2E) Marine Litter Optical Performance Simulations (ML-OPSI) is being designed in the frame of the ESA Discovery Campaign to support Earth Observation scientists with the design of computational experiments for Operations Research. The ML-OPSI breadboard will estimate Marine Litter signal at Top-Of-Atmosphere (TOA) from a set of Bottom-Of-Atmosphere (BOA) scenarios representing the various case studies by the community (e.g., windrows, frontal areas, river mouths, sub-tropical gyres), coming from synthetic data or from real observations. It is a modular, pluggable and extensible framework, promoting re-use and be adapted for different missions, sensors and scenarios.

The breadboard consists of the OPSI components for the simulation and the Marine Litter model components for the detection of marine litter. It shall consider the changes caused in the water reflectance and properties due to marine litter, exploiting gathered information of plastic polymers, different viewing geometries, and atmospheric conditions as naturally occurring.

Marine Litter scenarios of reference shall be built based on in-situ campaigns, to reflect the true littering conditions at each case, both in spatial distribution and composition. The breadboard shall be validated over artificial targets at sea in field campaigns as relevant.

Title: Multi-Functional Lidar Measurements to Identify and Characterize Marine Debris using Time-Resolved Fluorescence (2022 - 2023)

Contact Person: Madeline Cowell (madeline.cowell@ballaerospace.com)

Funding Agency: NASA ESTO Instrument Incubator Program (IIP) Instrument/Measurement Concept Demo (ICD)

Summary: Our goal is to characterize the laser induced fluorescence (LIF) return of marine debris both in the spectral and time domain. We will include measurements from naturally occurring targets, such as phytoplankton, to demonstrate sufficient differentiation in aquatic scenes between biogenic and anthropogenic material. Time-correlated single photon counting (TCSPC) will provide a measure of fluorescence lifetime of the various targets. After having success measuring fluorescence spectra and fluorescence lifetime independently, we propose to expand upon this research to feed into this study. The laboratory measurements will consist of a tunable pulsed laser as the excitation source, a photon-sensitive fast detector, and spectral filters tuned to the target's peak emission wavelength. To ensure high probability of classification, machine learning algorithms will be developed and tested. The results of this study will define the sensitivity of the fluorescence return for future performance modeling necessary for developing an effective space-based lidar system. Ultimately, this will inform a mission architecture to achieve global coverage for marine debris identification, characterization, and monitoring.

Title: Multi-Model synthetic S2-HS (hyperspectral) data for marine/plastic debris characterization, MUSS2 (December 2020 – June 2022)

Contact Person: Jonathan Cheung-Wai Chan (Jonathan.Chan@vub.be)

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: For effective identification and tracking of marine plastic, the sensor data we want is hyperspectral (HS) images including the wavebands at SWIR (1000-2500 nm) with a high spatial resolution around 0.5 m. These characteristics are non-existent in current EO missions. We propose to use novel spectral and spatial enhancement method to generate simulated EO HS SWIR from Sentinel 2 MSI using spectral response function modelling. For spatial enhancement, we apply spatial superresolution through a CNN (Convolutional Neural Network) based 2 branch feature extraction model for capturing detail feature in spatial and spectral domain for plastic debris identification.

Title: Characterization of light polarization properties of virgin and marine-harvested plastic litter toward remote-sensing mapping of ocean plastics, Ocean Plastics Polarization Properties OP³ (August 2020 – July 2022)

Contact Persons: Tristian Harmel (tristan.harmel@get.omp.eu); Shungu Garaba (shungu.garaba@uni-oldenburg.de)

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Measurements of polarization state of water-leaving light have been shown to be a significant tool to disentangle complex aquatic light signal to retrieve water constituents. On another hand, subsurface plastic marine litter (PML) might induce surfactants from “bio-fouling” production. In turn, those surfactants will smooth away capillary waves which can be detectable through polarimetric remote sensing. In the context of the future launch the satellite mission PACE (NASA) and 3MI-Sentinel-5 (ESA, EUMETSAT), embarking hyperspectral radiometers and polarimeters, we propose to fully characterize the polarization signature of PML in relation to other natural seawater constituents through: (i) laboratory experimentation, (ii) in-situ measurements, (iii) existing polarization data from older satellite missions (e.g., PARASOL). For this characterization up-to-date polarimetric sensors will be exploited as well as theoretical modeling of light propagation in PML contaminated waters (accumulation zones in the open ocean and estuarine systems) focusing on the water-leaving polarization and surface surfactants/roughness. This is foreseen as an important complementary effort along those of the Copernicus framework of operational satellite missions Sentinel 1 and 2 which have been shown to have potential monitoring application for PML.

Title: Ocean Scan: Marine litter database from Earth and space, Ocean Scan (July 2020 – October 2021)

Contact Person: Laia Romero (laia.romero@lobelia.earth)

Website: https://www.oceanscan.org/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Satellite remote sensing has demonstrated great potential to become a breakthrough in the mapping of marine litter. One limiting factor for its full development is the access to reliable, extensive, and consistent ground truth of plastic and litter occurrence in aquatic environments. During the past two decades, the amount of in-situ data and information about marine litter has greatly increased, especially during the last five years, however this information is sparsely located in different databases and often lacks the needed requirements or remote sensing technology research. Ocean Scan was designed to address this problem, by becoming the first inclusive global labelled database to integrate in-situ observations of marine plastic and litter with satellite data. In Ocean Scan, data will be presented on a global interactive map, where users can access information about marine litter in-situ observations and associated EO products. A web portal and a mobile application will provide user friendly access to the platform for data upload, consultation and download. Designed to maximise interoperability and scalability and to ensure a consistent data format and schema to fit the requirements of remote sensing technologies, the database will be free of charge and open to everybody, upon user registration. By ensuring data provenance and different levels of privacy for uploaded observations, Ocean Scan will provide a unified reference point for marine plastic and litter observations to support and promote international collaboration and research.

Title: Plastic waste and the Black Sea, monitoring litter at sea and on the land from Sentinel-2 data, Plastic Detection: Black Sea Test/PDBS (May 2020– May 2021)

Contact Person: Noelia ABASCAL-ZORRILLA (BSPlastics@argans.co.uk)

Website: https://argans.co.uk/proj-blackseaplastics.html

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: An EO processor for the detection of marine debris was originally developed and validated in different areas which were known for the presence of big patches of plastic. The current Argans Ltd. detector, based on the analysis of marine debris spectral reflectance for already well-known indices, was developed for fainter signals and proves to be a semi-robust litter and plastics detector. However, an assessment of the densities and volumes of plastics that could be detected in comparison to big patches, needed to be performed. The Black Sea, a semi-enclosed basin with numerous litter inflows by huge watershed rivers and with only a spillway at the Bosporus, is an ideal test area for the further development of the marine detector and the development of a land-litter detector. Therefore, the objective of the project is to be able to effectively use Sentinel-2 to identify both floating rafts of marine litter and sites of unconsolidated waste on land, providing information on both source and output areas. The detector is tuned to the probabilities of detection and false alarms, fixed by the operator. A Bayesian approach combined with an assessment of the diagnosis ability of the detector (represented by a ROC curve) allows an adjustment of the detector's thresholds according to the environmental, viewing conditions and the a-priori knowledge of plastics presence delivered by a litter drift model deployed in the Black Sea.

Title: Detecting riverine plastic conglomerations, fluxes and pathways in Indonesia, Plastic Monitor (April 2021 – March 2022)

Contact Person: Marieke Eleveld (marieke.eleveld@deltares.nl) – Deltares

Website: https://www.deltares.nl/nl/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: The general objective of Plastic Monitor is to assess detection of heavy plastic pollution loads in rivers by satellite imaging and demonstrate how it can enhance the quantification and monitoring of plastic input into the marine environment. Although none of the satellite mission concepts were specifically designed for the detection of plastic debris, there is potential for some sensors to be used in the detection of plastics. Therefore, our idea is centred around using a multi-sensor method, where satellite images from different sensors are analysed. This monitoring method is applied to rivers, to detect plastic litter before it reaches the oceans. This will be achieved together with a new plastic capture system, which first concentrates and then removes plastic floating in rivers and can, in this way, bring added value for monitoring of plastic fluxes. In the analysis we will develop advanced data science techniques to get information about the aquatic environment. The plastic detection capacity of existing sensors will lead to recommendations to inspire ESA's future mission design.

Title: Detecting water hyacinth patches as a proxy for riverine plastic transport, Plastic Plants (September 2020 – August 2023)

Contact Person: Louise Schreyers (louise.schreyers@wur.nl)

Website: https://plasticmonitoring.com/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: This project aims to develop and implement an algorithm to automatically detect floating macroplastic accumulation in rivers using remote sensing. It combines the detection of floating water hyacinths using mainly Sentinel-2 with in-situ estimates of macroplastic amounts carried by this invasive aquatic weed. Water hyacinths typically form large patches of several meters of width and length, and can thus be detected from space. Preliminary results show that they can aggregate as much as 80% of floating plastic debris in tropical rivers. The detection tool and field measurements will focus on the Saigon river, Vietnam, a river highly invaded by hyacinths. Our main scope is to quantify floating macroplastic transport and accumulation for the Saigon river over several years, using water hyacinths as a proxy. We will rely on robust in-situ data collected over one year, characterizing the share of macroplastic entangled in hyacinths and its spatiotemporal variability. The algorithms and spectral libraries may serve for future applications, notably for plastic monitoring in other tropical river systems. Given that tropical rivers invaded by hyacinths typically overlap with the highest plastic polluted waterways, this detection system could serve for global monitoring purposes.

Title: Can the microbial communities in the oceans help satellites to monitor micro-plastic pollution?, PLASTICSURF (October 2020 – October 2023)

Contact Person: Armando Marino (armando.marino@stir.ac.uk)

Website: https://www.stir.ac.uk/about/faculties/natural-sciences/our-research/research-groups/earth-and-planetary-observation-research-group/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: We propose to tackle the problem of monitoring plastic from another perspective. We aim at observing the effects of plastic on the microbial environment and, as a consequence, on ocean surface characteristics. This project brings together three pieces of research: a) Plastic in the ocean is heavily colonised by microbes; b) Microbes in water produce substances (surfactants) that dampen small waves; and c) Synthetic Aperture Radar (SAR) can identify surfactants as dark areas or stripes in images. We discovered that several ESA Sentinel-1 satellite images acquired over the garbage patches (Atlantic, Indian and Pacific oceans) present the same dark features we associate with surfactants. We observed that such features are not correlated with high chlorophyll-a and therefore microbes naturally occurring in the ocean (i.e. phytoplankton). Our hypothesis is that these dark patches are the signature of micro-plastics. Our experiments will show whether or not plastic-dwelling microbes can produce enough surfactants to be visible from space. We will use plastic submerged in fish cages in Scotland and also lab experiments. A ground radar and Sentinel-1 images will be used to check for surfactants around cages while the ground radar will be used with the lab tanks.

Title: Plastic Flux for Innovation and Business Opportunities in Flanders, PLUXIN (September 2020 – September 2023)

Contact Person: https://pluxin.be/nl/contact

Website: https://pluxin.be/

Funding Agency: https://www.blauwecluster.be/

Summary: PLUXIN focuses on plastic at the source prior to reaching the marine environment in rivers and canals by studying a critical knowledge gap about the whereabouts of plastics and about their flux towards the marine environment. This information is crucial to fast track cost-efficient plastic remediation measures. A central objective in this project is to develop a two-dimensional-horizontal (2DH) plastic dispersal model. The model will be calibrated and validated with experiments and field sampling data. In this context, plastics will be identified from remote sensing data through image recognition algorithms ('Deep Learning') captured from fixed cameras on the bridges and drone acquisitions, hence resulting in an automated plastic detection method. This information in combination with in situ sampling will validate the 2DH-model. Main object of the project is through remote sensing and in-situ observations in combination with numerical models contribute to our understanding of the sources, circulation patterns and fate of plastic in the aquatic environment.

Title: Crowdsourcing, Copernicus and Hyperspectral Satellite Data for Marine Plastic Litter Detection, Quantification and Tracking, REACT (June 2020 – June 2021)

Contact Person: Antonello Aiello (aiello@planetek.it)

Website: https://www.planetek.it/eng/react

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Earth Observation by satellite can contribute to marine plastic litter monitoring thanks to its global synoptic point of view. However, remote sensing of marine plastic litter is in its infancy, and it is a significant scientific and technological challenge. REACT is focused on presenting a Proof-of-Concept on remote sensing of marine plastic litter. The project aims to develop a methodology to detect plastic litter onshore or close to the shoreline and offshore. The methodology exploits data fusion of multispectral (i.e., Sentinel-2, WorldView) and hyperspectral satellite data (i.e., PRISMA), together with in situ data collection, and takes advantage of two different approaches. The first one based on spectral signature unmixing, and the second one on artificial intelligence methodologies. REACT aims at filling the gap related to: 1) The fundamental relationships between marine plastic and the reflectance captured in satellite remotely-sensed imagery, with current and future remote sensing instruments; 2) The sensitivity of existing sensors on marine plastic litters; 3) The identification of the satellite combination delivering the most useful fused-data; 4) The definition of spectral features and spatial scales recommended for future missions (CubeSat/small satellite missions) to be matched with major satellites as Sentinel-2.

Title: Remote Sensing of Marine Debris: Potentials and Limitations (June 2021 – May 2024)

Contact Person: Chuanmin Hu (huc@usf.edu)

Website: https://optics.marine.usf.edu

Funding Agency: NASA Ocean Biology and Biogeochemistry

Summary: Despite several pioneering studies showing potential in remote detection of marine debris using optical means, there are still technical challenges to be addressed. The project is to address these challenges with the following objectives: (1) To compile a spectral library of various types of marine debris as well as other floating matters. This will be through literature search, data mining, and laboratory and field experiments; (2) To determine the resolution requirements (spatial, spectral, radiometric) and optimal bands as well as potentials/limitations of current and future sensors in mapping and quantifying marine debris. This will be through radiative transfer simulations and sensitivity analysis using the endmember spectra and realistic measurement conditions; (3) To develop and evaluate practical approaches for several sensors to maximize their potentials in mapping marine debris; (4) To make recommendations on future satellite missions as well as on algorithms and approaches toward remote sensing of marine debris.

Title: **Development of a risk index for floating marine litter in coastal areas by combining optical and SAR techniques with numerical models, Satellite FRONTs for detection of Anthropogenic plastic Litter / FRONTAL (September 2020 – September 2022)**

Contact Person: Victor Martinez Vicente (vmv@pml.ac.uk)

Website: PML: https://www.pml.ac.uk/, https://www.isardsat.cat/ca/, https://www.isardsat.cat/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Fronts in coastal and oceanic regions are hot-spots for rich and diverse marine life, where floating marine debris also tends to accumulate. The goal of FRONTAL is to develop a prototype of a risk index for the accumulation of marine plastic debris at fronts. The approach is to combine state-of-the-art optical processing techniques of direct detection (from Copernicus Sentinel-2 MSI), validate the retrieval (using existing in situ datasets) and combine the results with front detection algorithms applied to thermal, optical and SAR satellite imagery. Opportunistically, we will take advantage of hyperspectral satellite data to explore the improvement of algorithms with collocated datasets.

In addition to mapping the risk areas for accumulation, their connectivity to the pathways into the ocean, through numerical dispersion models of coarse and high spatial resolution will be investigated. In doing so, we aim to provide a tool to local and regional policy makers to identify areas where intervention would be more effective.

As a case study, we are working in collaboration with local stakeholders in Da Nang (Vietnam).

Title: **diStributed AI systeM for mArine plastic debRis moniToring (SMART), SMART (May 2021 – May 2023)**

Contact Person(s): PI – Leonardo Azevedo (leonardo.azevedo@tecnico.ulisboa.pt);
CO-PIs João Tasso (jtasso@fe.up.pt) and Renato Mendes (renato.mendes@colabatlantic.com)

Website: SMART project (under construction);
AI Moonshot challenge (https://www.moonshotchallenge.ai);

Funding Agency: Portuguese Space Agency – Portugal Space (https://ptspace.pt) in partnership with FCT, ANI, ESA, Unbabel and the support of the Web Summit

Summary: SMART is an intelligent framework based on deep physics-informed learning, which combines automatic identification and classification of floating plastic debris from satellite images, spatiotemporal modelling of plastic accumulations with high-resolution numerical ocean modelling, physics-guided machine learning and a distributed system of sensors mounted on low-cost marine autonomous vehicles for long-term deployment and validation of the model results. This unique combination will allow to bypass the need of running full ocean numerical models at small-scale simulation grids, which brings numerical instabilities and are unable to assess uncertainty about the spatiotemporal predictions. Instead, the final outcome for the end-user will be a probability of plastic occurrence map at any time step required in the past and in the future. The probability of plastic occurrence map will allow authorities to devise strategies for ocean clean-up while making decisions under uncertainty. The project will be developed using two pilot sites in the North Atlantic and the results obtained will be validated in situ using low-cost marine autonomous vehicles, which will collect samples at key sensitive regions predicted by the model.

Title: Spectral Properties of Submerged and Biofouled Marine Plastic Litter, SPOTS
(September 2020 – December 2021)

Contact Person: Robin de Vries, The Ocean Cleanup (robin.devries@theoceancleanup.com)

Website: https://theoceancleanup.com/research/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: The SPOTS project will take a closer look at the influence of biofouling and water depth on the spectral reflectance of plastics. By varying the water depth and degree of biofouling in a systematic way and a controlled lab and outdoor environment, we will gather a more detailed dataset and predictive model about the influence of both these factors on the hyperspectral footprint of plastic litter. Besides debris from the marine environment, we will also investigate coastal and riverine plastic litter.

Title: Thermal Infrared Sensing of marine Plastic Litter, TISPLALI
(September 2021 – March 2022)

Contact Person: Lonneke Goddijn-Murphy (lonneke.goddijn-murphy@uhi.ac.uk)

Website: https://eri.ac.uk/research/major-projects/tisplali/

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: This project explores the potential of thermal infrared remote sensing for the detection of floating marine plastic litter and how it could complement other remote sensing methods such as those in the optical spectrum. For example, thermal infrared sensing does not depend on the presence of daylight and can look through light snow and rain. Some plastic materials that are transparent in the optical spectrum may appear opaque in the thermal spectrum. We focus on the consequences of the presence of sunlight and of different air and sea temperatures on the thermal infrared signal of plastic floating in water. The aim is to verify a thermal radiance model using imaging long-wave infrared (7.5 – 13.5 µm), near-infrared (850 nm), and visible colour (RGB) cameras, a drone, and plastic targets deployed at sea. This involves drone surveys during day- and night-time hours, and in summer as well as winter to cover a range of conditions. We support our findings with experiments in the laboratory where we can create a more controlled environment. One of these experiments is looking at plastic litter that has spent time in marine water, to study the effect of biofouling of the plastic surface on thermal infrared radiance leaving this surface.

Title: **TRACE: Detection and tracking of large marine litter based on high-resolution remote sensing time series, machine learning and ocean current modelling, TRACE (August 2020 – January 2022)**

Contact Person: Mathias Bochow (mathias.bochow@gfz-potsdam.de)

Website: https://www.gfz-potsdam.de/en/section/remote-sensing-and-geoinformatics/projects/trace

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: Using daily high-resolution optical (PlanetScope), SAR (Sentinel-1), and hyperspectral (PRISMA) satellite data, this project aims to obtain precise and reliable data on large pieces of floating litter, regarding their quantity, trajectories and accumulation zones, material properties, floating depth, and sources. To achieve this goal we will develop a scalable (current test area: Adriatic Sea) fully-automatic remote sensing based detection and tracking system of large marine litter and accumulation zones and couple it with oceanographic forecasting. After being operationally online the derived information will be published with a delay of 3-4 days on a web-map-server and may serve as a basis for the recovery of floating litter, for the elimination of its sources, and for preventing its dispersal.

Title: **Mapping Windrows as Proxy for marine litter monitoring from space, WASP (May 2020 – October 2021)**

Contact Person: Manuel Arias (marias@argans.co.uk)

Funding Agency: ESA, the European Space Agency (Discovery Element of the Basic Activities – Campaign on Remote Sensing of Plastic Marine Litter)

Summary: WASP is a data processor, developed in the frame of the ESA Discovery Campaign, exploiting Copernicus Sentinel-2 L1C images to detect and catalogue the presence of filaments of floating marine debris with high probability of containing man-made litter. WASP takes advantage of the prototype EO data processor developed in the frame of ESA project "Earth Observation (EO) Track for Marine Litter (ML) in the Mediterranean Sea" that successfully proved for first time that Copernicus Sentinel-2 data can detect the presence of marine litter accumulations as proxies of plastic litter content. The entire Sentinel-2 archive over the Mediterranean Sea will be processed and following an in-depth analysis, a database of the identified proxies will be created over the area. The final product will be a map of sub-mesoscale marine debris concentrations in the Mediterranean Sea based on Copernicus Sentinel-2. The product will consist on a census of these structures for each processed tile for the Mediterranean Sea, with potential for global scalability.

A2. Application of Remote Sensing in Monitoring Plastic Waste

Table A2. List of research studies on remote sensing of plastic waste since 2011 indicating sensor technologies, geographic location and key findings. Adapted from [109].

Geographic Areas	Methods and Material	Time	Type of Debris	Findings	Study
Multiple sites in Spain	Different drones (DJI). Manual and Machine learning algorithms.	2020	Beached and floating	Mapping marine plastic litter from UAV data can be improved by adding marine litter dynamics information.	110
Saigon, Vietnam	Sentinel-2 and WorldView-2 data. Spectral based methods and Naïve Bayes classifier.	2018 - 2020	Floating	Showcasing the benefits of satellite detection and quantification of hyacinths in a river.	111
Leirosa Beach, Portugal	Multispectral data from UAV (DJI Matrix 210 RTK V2). Spectral Angle Mapper classifier.	2021	Beached	Spectral information from 42 types of litter items used for characterizing litter types.	112
Global scale	Sentinel-2 (MARIDA) data. Machine learning algorithms.	2015 - present	Floating	A labeled dataset of satellite images with known or suspected litter targets useful for machine learning and detection algorithm development.	113
Lesvos Island, Greece	Sentinel-2 and WorldView 2/3 data. Image fusion algorithms.	2018 - 2021	Floating	Data fusion techniques applied to multispectral satellite data to improve plastic litter mapping accuracy.	114
Balearic Islands, Spain	SAR imagery and Sentinel-2 data. AI-based approaches and PCA analysis.	2020 - 2021	Floating	Floating marine plastic litter mapping using SAR data applying AI techniques.	115
Lesvos Island, Greece	PRISMA hyperspectral data. Machine Learning algorithms.	2020	Beached and floating	96% marine litter mapping accuracy achieved using hyperspectral data.	89
Quiaios Beach, Portugal	DJI Matrix 210 RTK V2, Multispectral Sentera AGX 710 12.3 MP imager. Multiresolution segmentation.	2019	Beached	Highlights evaluates the effects of coastal vegetation in mapping marine plastic litter using remote sensing. It quantified and classified beached litter.	116
Sardinia, Italy	DJI Matrice 600. Hyperspectral Bobcat 32 Xenics SWIR imager, data. Supervised classification.	2019 - 2020	Beached and floating	Hyperspectral data from UAV used for mapping both floating and beached marine plastic litter.	117
Limassol, Cyprus and Mytilene in Greece	Sentinel-2 data. Clustering, Support Vector Regression.	2018 - 2019	Floating	Detecting floating plastic debris from Sentinel-2 data.	118
Hawai'i Big Island, USA	Sentinel-2 imagery. Spectra indices.	2020	Floating	Floating marine plastic litter from Sentinel-2 data using spectral indices.	119
Delta de l'Ebre and Cap de Creus, Spain	Partenavia P- 68 aircraft, DJI Mavic Pro, Topografia and fixed-wing HP1 drones. Canon EOS REBEL SL1, FC220, Sony Alpha 7 R and Sony ILCE-6000 cameras. Deep learning algorithms.	2017 - 2019	Floating	Deep learning methods for automatic detection of floating marine macro-litter from aerial imagery. An R programming language application was developed MARLIT web-based tool.	45
Faial Island, Portugal	Cessna F150L and fixed frame. HySpex Mjolnir S-620 and Specim FX10e. Supervised machine learning methods.	2020	Floating	Hyperspectral characterization of plastic litter with accuracy between 70-80% and an evaluation of airborne detection of floating plastics.	46
Lesvos Island, Greece	PRISMA imagery. spectral indices.	2020	Floating	Spectral index-based marine plastic litter mapping using pansharpened PRISMA data.	41

Geographic Areas	Methods and Material	Time	Type of Debris	Findings	Study
Arno River estuary, Italy	UAV (DJI Phantom 4 Pro v2 quadcopter drone. CMOS 20 MP camera. Manual inspection.	2021	Beached	Assessment of drone captured RGB images of beached litter through citizen science classification.	120
Leirosa beach, Portugal	DJI Phantom 4 RTK (DJI-P4RTK) drone. 20MP camera. Manual inspection and Neural Networrk machine learning.	2020	Beached	Color-based approach can be used to improve the categorization of stranded litter on UAS orthophotos.	82
Leirosa Beach, Portugal	DJI Phantom 4 RTK (DJI-P4RTK). 20 MP camera. Manual inspection.	2019 - 2020	Beached	Beach dune erosion and marine litter density from UAV-based data.	121
Quiaios Beach, Portugal	DJI Matrix 210 RTK V2 drone. RGB DJI Zenmuse X5S 20.8 MP, Sentera AGX 710 12.3 MP Multi- Spectral imager. Manual inspection.	2019	Beached	Mapping marine litter along the Atlantic coast using UAVs.	122
Accra - Ghana, Da Nang - Vietnam, Gulf Islands - Canada, Scotland -UK	Sentinel-2 and visual observation in social media. Machine learning and spectral based algorithms.	2018 - 2019	Floating	Use of multispectral satellite data (Sentinel-2) for mapping floating plastic patches in coastal waters around the globe. Proposed the detection algorithm Floating Debris Index – FDI.	72
Mediterranean Sea, Spain	Partenavia P-68 high-wing aircraft. Visual and Canon EOS REBEL SL1 camera.	2019	Floating	Inter-comparison of trained human observer and automated camera monitoring approach for floating litter.	123
Cabedelo Beach, Portugal	DJI Phantom 4 Pro. 20 MP CMOS camera. Random Forest (RF) classifier.	2019	Beached	UAV data for mapping marine litter in Portugal using machine learning approaches. F-Test score 75% compared to manual mapping.	47
Cabedelo Beach, Portugal	DJI Phantom 4 Pro. 20 MP CMOS camera. Visual inspection and machine learning algorithms.	2019	Beached	Comparative analysis of manual and machine learning approaches for mapping marine plastic litter from imagery acquired using UAVs.	92
Lake Balkana and Crna Rijeka River, Bosnia and Herzegovina	DJI Mavic Pro. RGB camera. Convolutional Neural Network algorithm.	2019	Floating	A semantic segmentation algorithm revealed accurate mapping of floating litter based on drone imagery.	124
Fukiage and Sato Beach, Japan	DJI Phantom 4 drone. 4K RGB camera. Neural Network algorithms.	2018 - 2019	Beached	Estimation of beached marine plastic debris abundance using UAV imagery assessed by deep learning methods.	125
Bay Islands, Honduras	Landsat-8, Sentinel-2 and PlanetScope images. Spectral based and visual inspection.	2014 - 2019	Floating and beached.	Mapping source and transport of plastic litter from the sea to the beach using satellite remote sensing and spectral based evaluation of suspected or known litter material.	39
Northern Italian coast	DJI Phantom 4 PRO v2 with 20 MP digital camera. Visual interpretation.	2019 - 2020	Beached	Long-term monitoring of beached marine debris using UAV surveys.	95
Saronikos Gulf, Greece	Research Vessel. Nikon D80 10.2 MP Digital SLR camera. Regression analysis between *in situ* and camera data.	2017 - 2018	Beached	This study utilised regression analysis between in situ daya and vessel-based photographs for beached litter assessment. Image analyses were done to reveal classes and quantities of marine debris.	126
Ducie Atoll, southeast Pacific Ocean	Digital camera.	2019	Beached (seabird nest)	Detecting plastic litter in seabird nests using digital photographs.	127
Limassol, Cyprus	DJI Phantom 2 and Pro drone. Sentinel-2, Sony Exmor IMX206 multispectral imager, GoPro and 20 MP RGB camera, SVC HR-1024 spectroradiometer. Spectral based algorithms.	2018	Floating	Evaluated the detection of artificial floating plastic targets using the Sentinel-2 imagery and spectral based algorithms.	37

Geographic Areas	Methods and Material	Time	Type of Debris	Findings	Study
Tsamakia Beach, Greece	DJI Phantom 4. Sentinel-2 and 12.4 MP RGB camera. Spectral and object identification-based algorithms.	2019	Floating	Detection of artificial floating plastic targets using Sentinel-2 and drone data. The Plastic Litter Project (PLP2019) was also showcased.	32
Aegean Sea, Greece and global	ECMWF ERA5 data.	2018	Floating	Theoretical approaches are presented and prospect for thermal thermal IR remote sensing application in detecting floating plastics.	128
Alif Dhaalu and Faafu Atolls, Maldives	DJI Phantom 4 drone. 12.4 MP CMOS camera. Visual inspection and Convolutional Neural Network algorithm.	Not provided	Beached	Automated method proposed for the detection and quantification of beached marine plastic litter using aerial data from UAVs by applying convolutional neural networks.	93
Jalan Tengku Kalana bridge and Klang River, Malaysia	DJI Phantom 4 Advanced drone. 12 MP CMOS camera. Visual inspection.	2019	Floating (riverine)	Quantification of riverine floating plastics and its transport using UAV imagery supported by visual inspection.	129
Tsamakia Beach on Lesvos Island, Greece	S900 DJI Hexacopter drone. Sony A5100 24.3 MP camera, Slantrange 3P, Parrot Sequoia multispectral and FLIR Duo R camera, Sentinel-1, 2 data. Visual inspection and spectral analyses.	2018	Floating	Marine floating plastic litter detection using satellite and drone data. Spectral feature and atmospheric correction evaluation on top- and bottom-of-atmosphere data products.	36
Edinburg, Scotland	Nessie AUV. SoundMetrics ARIS Explorer 3000 acoustic camera. Deep Neural Network algorithms.		Floating and submerged	Submerged marine litter detection using sonar data with the support of dep neural network algorithms.	130
Hokkaido and Kanto, Japan	DJI Matrice 210 RTK. Go Pro Hero 6, Olympus Tough TG5, iPhone ZENMUSE X5S and ZENMUSE XT). Deep learning object detection algorithm.	2018 - 2019	Floating and submerged	Deep learning approaches were developed to detect and classify debris and other objects using images from underwater and airborne observations.	131
Atlantic Ocean, Pacific Ocean, Westcoast and Hawai'i, USA	PANalytical Boulder ASD FieldSpec 4 and AVIRIS data. Spectral indices, spectral mixing.	2015	Beached, ocean harvested and virgin	Shortwave infrared absorption features of synthetic hydrocarbons using airborne and spectroradiometer data.	35
Chiloé Archipelago, north-western Chilean Patagonia	Hyperspectral ASD, HyLogger-3 spectrometer and WorldView-3. SVM classification and Linear Discriminant Analysis (LDA)	2017	Beached	Spectral characterization of anthropogenic marine debris using spectrometer and WorldView-3 data analysis.	84
Fuzhou, China	DJI PHANTOM 4 PRO quadcopter drones. 20MP camera. Segmentation threshold method	2017	Beached	Automatic mapping of beached marine plastic litter using image segmentation by applying a threshold. Effective in quick monitoring in an area of interest.	132
North-East Marine Protected Area of the Maltese Islands (Malta, Comino, Gozo)	Aerial photographs from UAVs and GoogleEarth photographs. Generating point cloud and texture map.	2017	Beached	Marine plastic litter monitoring using aerial photographs taken from UAVs.	133
Pacific Ocean	SWIR (SASI) and RGB imagery. Lockheed C-130 Hercules aircraft.	2016	Floating	Airborne hyperspectral SWIR imagery for mapping ocean floating plastics based on spectral reflection properties.	43
Scotland, UK	FieldSpec hyperspectral data.	2018	Floating	Spectral properties of floating plastic litter using spectroradiometer (350-2500 nm).	53

Geographic Areas	Methods and Material	Time	Type of Debris	Findings	Study
Tsuruga Peninsula, Japan	WorldView-3. Spectral Angle Mapper.	2014		Spectral analyses of floating litter and plastic targets. Method proposed to distinguish marine litter from white-crested waves	134
Vancouver Island, Canada	Aerial photographs from airplane and GoogleEarth data	2014 - 2015	Beached	This study quantified marine macro debris around Vancouver Island in Canada using aerial photographs from airplane. Aerial photographs were processed by projective transformation and by extraction of debris pixels.	91
Saudi Arabian Red Sea Coast	DJI Phantom 4 mounted with 20MP camera. Machine learning algorithms.	2017	Beached	Mapping beached marine debris using photographs taken from UAV.	48
Hawaiian Islands, USA	High-resolution aerial photographs	2015	Beached	High-resolution aerial photographs for detecting coastal marine macro-debris (> 0.05m2).	135
Arctic, Mediterranean, South Atlantic and North Pacific	Hyperspectral data. PCA and Partial least squares-discriminant analysis.	2014 - 2017	Floating/submerged	Characterization of the polymeric composition of marine plastic litter using hyperspectral data (1000-2500 nm).	136
Fukushima Daiichi, Japan	ASTER, AVNIR-2, RapidEye, PALSAR, RADARSAT-2, WorldView-2, RGB camera	2011	Floating	Assessment of the litter dynamics after the tsunami event near Fukushima.	59
Isle of Rügen, Germany	Field survey and photographs from drones.	2015	Beached	Marine litter abundance and distribution on beaches using field data and photographs from UAV. The accuracy depends on vegetation.	137
Nanhui beach, Shanghai, China	RIEGL VZ-4000 terrestrial laser scanner LiDAR data. SVM classification.	2015	Beached	Semi-automatic detection of beached marine macroplastic debris using LiDAR data.	61
Coasts of East Asia	Sequential webcam photographs and particle tracking model.	2010 - 2011	Beached	This study estimated a 250-fold increase in beached plastic litters in East Asia in the next 10 years using sequential webcam photographs and particle tracking model.	138
Ookushi Beach and Ookushi Beach, Japan	Low-altitude aerial digital camera images from balloon.	-	Floating and beached	Monitoring marine and beach litters of assorted colours using photographs taken from balloon equipped with a digital camera.	49
Tobishima Island, Japan	Vivotek IP7361 Webcam camera. Colour references using a uniform colour space (CIELUV).	2010 - 2011	Beached	Mapping coloured beached macroplastic debris using webcam images	55
Ookushi Beach, Japan	Helium Sky Catcher Balloon. Digital camera and visual inspection. Threshold based on lightness value.	2009	Beached	Quantification by weight of beached plastic litter based on aerial photographs and *in situ* data.	23

A2.1 Platforms for Remote Sensing of Plastic Waste

Table A2.1 Detailed examples of platforms that have been utilized to investigate the potential applications of remote sensing in monitoring plastic litter. Adapted from [105].

Platform	Overview	Study
Ship	Quantification of macroplastics larger than 50 cm using of action cameras placed on vessels of opportunity. Macroplastic density is estimated through a twofold approach based on object detection and training object detection models. This study compared the distributions of macroplastics with concentrations of micro- and mesoplastics collected with manta trawl nets.	33
	The Convolutional Neural Network approach is able to train itself on images of plastic objects larger than a few centimetres and automatically predict the class of new images of macro plastic objects floating at sea. With the aid of a camera mounted on board a marine vessel, the system would scan the sea surface, and detect and recognise litter. The system was trained on three categories of plastic marine litter (bottles, buckets and straws) and the classifier was able to recognise these types of floating objects at a success rate of ~ 86 %.	68
Aircraft Drone	Floating plastics in aerial images were detected using deep learning models based on an algorithm that uses Convolutional Neural Networks capable of learning from unstructured data. This model was implemented in an application to detect and quantify marine litter in the images.	45
	Two combined methods to detect floating macro litter, visual observations and drone surveys, were compared. Both methods proved equally effective at detecting floating plastics. Two different commercial drones were used for drone surveys, equipped with a 12-megapixel camera. Flight height was set between 45 and 65 m to guarantee a ground sampling distance of 2 cm per pixel.	139
	RGB and hyperspectral short-wave infrared imagery were captured with equipment mounted on a C-130 aircraft surveying the great Pacific garbage patch at a height of 400 m and a speed of 140 knots. Position, size, colour and type (container, float, ghost net, rope and unknown) were recorded for every plastic piece identified in the RGB mosaics, and then the top 30 largest items within each plastic type category (0.6–6.8 m in length) were selected to investigate spectral information obtained with a SASI-600 imager (950–2450 nm). Analyses revealed unique spectral features common to plastics, with some variability probably influenced by differences in the objects' optical properties, water submersion and the atmosphere. Simulations confirmed that the plastics' absorption features have potential applications in detecting and quantifying ocean plastics from spectral information obtained from airborne images.	43
	Low-altitude remote sensing methods were used to monitor marine and beach litter with a remote-controlled digital camera suspended from a balloon filled with helium gas, suspended at 0–500 m above sea level. Photographs were taken at various angles, and images were processed to identify litter using colour differences between target objects and the background in the CIELUV colour space. With the balloon suspended at 150 m, a pixel represented an area of 100 cm^2.	49
Satellite	Novel supervised and unsupervised clustering algorithms were developed to identify floating plastics using in situ validated Sentinel-2 images with different size of deployed plastic targets (10 m × 10 m, 5 m × 5 m and 1 m × 10 m). Three different sets of bands and indices were employed to develop the attributes for the classification process. The best-performing method, Support Vector Regression based supervised classification, had an accuracy in the range of 96.9–98.4 %.	118
	This study explores for the first time the use of satellite hyperspectral PRISMA images to detect floating marine plastic litter. Thirteen pansharpening methods and denoising pre-processing techniques were employed (e.g., Bayesian, deep learning, component substitution) along with three novel indices to detect floating plastic targets with a low number of false positives.	41
	WorldView-3 imagery was used to detect known and suspected floating plastic materials in the North Pacific Garbage Patch. A simplified approach was proposed that utilizes the spectral anomalies by assuming the ocean surface signal as the baseline or background signature.	42
	Satellite technology was employed to investigate the feasibility of monitoring marine surface floating plastic litter in coastal areas.	72
	High-resolution multispectral satellite images from Landsat-8, Sentinel-2 and Planet satellite missions and in situ observations were employed to study the sources and trajectories of floating marine plastic litter in the Bay Islands of Honduras (Caribbean Sea). The determination and discrimination of floating litter was carried out manually by photo interpretation experts.	39
	A spectral signature for the polyethylene terephthalate targets was produced by modifying the US Geological Survey polyethylene terephthalate signature, using an inverse spectral unmixing calculation to perform matched filtering processing on the Sentinel-2 images. The results provide evidence that, under suitable conditions, pixels with a polyethylene terephthalate abundance fraction of at least as low as 25 % can be successfully detected.	32
	Sentinel-2 satellite images were combined with multispectral aerial images acquired from an UAV to determine if plastic litter on the sea surface can be detected using an artificial plastic target (3 m × 10 m). Images were processed using two newly developed indices, the plastic index and the Reversed Normalised Difference Vegetation Index.	37
	This study explored the application of unmanned aerial systems and open-access satellite imagery in remote detection of floating plastics in natural seawater, through a dedicated aquatic environment experiment using a set of three artificial floating plastic targets placed in the coastal zone.	36
	WorldView-3 images were combined with anthropogenic marine debris hyperspectral laboratory characterization to detect large and highly reflective plastic items on beaches. A spectral library for the implementation of a digital classification method applied to WorldView-3 satellite images was generated by collecting litter samples from the Chiloé Islands beaches (Chile) and assessing their spectral signature.	84

A3. Machine Learning Application in Remote Sensing of Plastic Waste

Table A3. List of example research studies that utilized machine learning algorithms to derive descriptors (e.g., presence, quantities, shapes, forms, colours) about plastic waste in imagery captured using remote sensing technologies. Adapted from [90].

Methods and Materials					
Image Source	**Algorithm**	**Annotations**	**Feature Space or Wavebands**	**Findings**	**Study**
Drone. Multispectral.	Segmentation and spectral angle mapping	Object-based	Blue, Green, Red, Red Edge, NIR	Density map, material counts of litter and plastics.	112
Drone. Multispectral.	Random Forest	Pixel-based	Violet, Blue, Green, Red, Red Edge 1, Red Edge 2, NIR 1, NIR 2, NIR3	Semantic segmentation of floating plastic.	140
Trolley. Hyperspectral.	Feature selection, spectral angle and correlation mapping	Pixel-based	8/36 wavebands in the range 1169-1233 nm and 1612-1677 nm	Semantic segmentation and detection of polyethylene and polypropylene plastics.	141
Drone. Hyperspectral.	Feature selection, Linear Discriminant Analysis	Pixel-based	10/320 bands in range 900 – 1700 nm – Feature Selection	Semantic segmentation and detection of polyethylene and polyethylene terephthalate plastics.	117
Handheld. Multispectral.	Support Vector Machine, Random Forest, spectral based indexes	Pixel-based	Violet, Blue, Green, Red, Red Edge 1, Red Edge 2, NIR 1, NIR 2, NIR3	Semantic segmentation of floating plastics.	80
Drone. RGB.	Support Vector Machine, Random Forest, Segmentation, Maximum Likelihood	Object-based	Red, Green, Blue	Object-based litter occurrence map litter.	142
Aircraft. Hyperspectral.	Support Vector Machine, Random Forest	Pixel-based	Wavebands from 400 – 2500 nm	Semantic segmentation and detection of 3 artificial marine litter targets.	46
Drone. RGB.	Shallow Feed-Forward Neural Network	Image samples	Red, Green, Blue and three colour spaces (HSV CIELab, YCbCr): 12 features	Density map, item counts of litter, plastic bottles, fishing ropes, octopus pots, fragments.	82
Drone. RGB.	Segmentation, K-Nearest Neighbour, Support Vector Machine, Random Forest	Object-based	Red, Green, Blue and three colour spaces (HSV CIELab, YCbCr): 12 features	Object-based litter occurrence map of beach litter.	143
Drone. RGB.	Random Forest	Image samples	Red, Green, Blue and three colour spaces (HSV CIELab, YCbCr): 12 features	Density map, item counts of beach litter.	47
Drone. RGB.	Random Forest, Convolutional Neural Network	Image samples	Red, Green, Blue and three colour spaces (HSV CIELab, YCbCr): 12 features	Density map, item counts of bottle, fishing string, plastic pieces, octopus pot, cap, boot/shoes, polystyrene, pieces	92
Satellite. Multispectral.	Support Vector Machine, Random Forest, Linear Discriminant Analysis	Pixel-based	8 wavebands in VNIR	Semantic segmentation, detection and quantification of beached litter including Styrofoam.	84
Drone. RGB.	Segmentation and Thresholding	Object-based	Blue, Green	Object-based litter occurrence map of beach litter.	132
Drone. RGB.	Random Forest	Image samples	Histogram of oriented gradients	Density map, item counts of beach Litter, drink containers, bottle caps, plastic bags.	48

A4. Conferences, Proceedings and Workshops

A4.1 Conference Proceedings 7th Marine Debris Conference, Busan, South Korea (7IMDC, 18 – 23 September 2022)

The IOCCG Task Force on Remote Sensing of Marine Litter and Debris and the NOAA Marine Debris Program supported and their representatives co-chaired the session TS-3.5 Satellite and Airborne Remote Sensing of Marine and Coastal Litter at the 7IMDC (https://7imdc.exordo.com/programme/session/110). Oral and poster presentations showcased advances and ongoing research on remote sensing of plastic waste.

Oral Presentations

Title: Towards a framework for modelling marine litter detection from space.

Author: Delaney et al., 2022

Link: https://7imdc.exordo.com/programme/presentation/407

Abstract: To optimise mission success, one needs the sensor characteristics to match domain requirements. The algorithms and processing need to be prototyped and tested rigorously before launch and during operation when introducing new features, and debugging are crucial to ensure longevity. Modelling and simulation enable engineers and scientists to understand how parts of a system interact and how the system behaves. Towards this end, the European Space Agency (ESA) Discovery Element funded the Marine Litter Operational Performance Simulator (ML-OPSI), a virtual breadboard to model the marine litter (ML) domain and simulate the acquisition of optical and IR signals at top-of-atmosphere (TOA) by user-defined EO sensors under varying environmental conditions. An aim is the assessment of the optimal characteristics required of a sensor to detect ML, thus informing future missions carrying the next generation of sensors. More generally, it supports EO scientists and engineers in designing and implementing computational experiments by acting as a 'virtual laboratory' capable of benchmarking, verifying and validating different algorithms. The objective is to enhance scientific evidence-based knowledge about how varying the quantities, composition and location of marine litter governs detectable water-leaving reflectance. As a proof-of-concept, a standalone demonstrator to estimate reflectance was developed, using the model of Goddijn et al., 2019 configured with laboratory measurements of ML spectral signatures. The aim is to model test scenarios in which aggregates of ML form, such as windrows, oceanic fronts and gyres, and river mouths, to provide a bottom-of-atmosphere (BOA) signal and, using the Free and Open-Source Software (FOSS) 6SV Radiative Transfer Model (RTM), propagate that signal to TOA and subsequent sensor detection. We designed ML-OPSI as a modular, pluggable and extensible framework that promotes re-use and adapting to different missions, sensors and scenarios. It is conceptually a component-based architecture composed of two packages, a Modeller and a Simulator, themselves modular in design and user-customisable to represent one or more EO domains, such as ML detection. The ML model comprises top-level modules responsible for scene generation, atmospheric correction, instrument detection and retrieval, and the definition of inputs, outputs, and parameters characterising the interface. The OPSI simulator comprises a GUI-based scenario/model builder and an orchestrator that manages simulation runs, configuration management, and performance assessment. We propose the sum of these parts is a framework for performing EO end-to-end simulations and, with appropriate configuration and real-time updates from an operational sensor, acting as a 'digital twin' to enable experiments and assessments to be performed on a simulated version of the physical asset. The authors call to action is to engage the ML community in discussion to converge towards a common goal considering the interface standards, models and data types available, implementation and deployment to advance ML-OPSI as a standardised EO modelling and simulation framework.

Demo-Version of ML-OPSI to get a proof of concept

Title: The development of a COTS-based multi-spectral imaging system for the airborne and space-based detection and imaging of plastics.

Author: Hibbitts and Bekker, 2022

Link: https://7imdc.exordo.com/programme/presentation/408

Abstract: The remote detection and mapping of plastics in the natural environments is challenging. While plastics have diagnostic spectral reflectance features in the shortwave infrared, those features also vary in strength and position with composition [e.g. 1]. However, spectral studies [e.g. 2] have shown that marine debris plastics tend to be dominated by a few plastic varieties, even if most/all types are present at some abundance. These most prevalent plastics consistently have spectral features near 1.2, 1.4, and 1.7 microns. Spectral obscuration by telluric absorptions occurs near 1.4 microns due to atmospheric water vapor, leaving the 1.2 and 1.7 micron absorption features for plastic detection. While hyperspectral instruments can discriminate between these plastics, detection only requires multispectral measurements. The modest spectral capability of a multispectral approach enables emphasizing high resolution imaging for acquiring high-quality compositional images. Because much of marine debris will remain subpixel in even the best aerial and especially space-based imaging, higher spatial resolution improves performance by increasing the fractional pixel area associated with plastics for a stronger signal, enabling even subpixel detection of plastics (such as by microplastics). Thus, spatial resolution is no longer driven by the impractical requirement to spatially resolve plastic objects but by the signal level associated with

the fractional area the plastic debris covers. Beaches containing plastic debris can be several meters wide. This resolution is easily achieved from an airborne instrument and is feasible from space. A spatial resolution of ~4 meters can be achieved with a 10-cm aperture at about 1.2 microns when observing from LEO such as from the ISS or a CubeSat. However, it is the ground sampling distance of over 7m achieved with even a relatively fast integration time of 1ms that will be the limiting factor. This resolution remains sufficiently fine to resolve many coastlines as well oceanic garbage patches and is superior to that achieved with spacebased hyperspectral imaging.We are developing a Distributed MultiSpectral Imaging System (DMSIS) using this approach for the detection and imaging of marine debris and other plastics in the natural environment. It is a reconfigurable multispectral imaging system consisting of four IR cameras with tailorable wavelengths. The 'imaging first' approach maximizes spatial resolution and the four modular cameras provide spectral information for detecting plastics. This modular approach leverages unmodified COTS SWIR imagers for a low barrier to entry intended to enable wide-scale adoption. A previous iteration using only two wavelengths has been demonstrated but the spectral sampling was insufficient for the reliable detection of plastics [3]. A third band is needed to better constrain illumination geometry effects and a fourth band is needed for discriminating plastics from spectral distractors. This approach of using separately filtered COTS cameras transfers the complexity and expense from hardware to software and is enabled by parallel camera data acquisition and software-based image registration.

References: [1] Garaba, S.P. and H. M. Dierssen, 2018, Remote Sens. Env., 205, 224-235; [2] Guffogg, J.A. et al., 2021, Remote Sens., 13, 4548; [3] Hibbitts, C.A. et al., 2019, Proc. SPIE 11012.

Title: Elucidating Patterns of Urban Plastic Pollution in Mumbai, India using Remote Sensing Technologies.

Author: Mathis et al., 2022

Link: https://7imdc.exordo.com/programme/presentation/414

Abstract: Because of the large scale over which plastic waste is managed or leaked into the environment, monitoring must also happen at a large scale to provide consistent and widespread assessments. However, reliable data on mismanaged waste remains scarce in the developing world, creating challenges for communities to design, implement and monitor policy and interventions to improve waste management practices. Large scale monitoring techniques like remote sensing can give communities the ability to analyze the spatiotemporal patterns of waste transformations in their locality, predict scenarios, and develop targeted solid waste management and intervention strategies. Further, fast, and accurate earth observation approaches that classify waste accumulation in the environment in satellite imagery paired with comprehensive local data can help to fill knowledge gaps, increase social connectivity, and detect zones with elevated risk. We chose Mumbai, India as a preliminary study area for its mosaicked urban landscape, socio-economic fragmentation, tropical monsoon climate, proximity to the ocean and its riverine environment. While the focus of this work uses optical satellite imagery to detect waste accumulation sites in Mumbai, it provides a baseline framework to develop accurate, inexpensive, and scalable methods that fuses satellite data types with hyperlocal data (e.g., socio-economic data that influences plastic patterns) that can help communities develop more targeted waste management strategies. ncept model was developed to detect waste accumulation sites in Mumbai, India using PlanetScope's 8-band 3m spatial resolution optical satellite imagery. To address the spatial-spectral trade-off in PlanetScope data, instead of straightaway detecting waste, a heuristic method was devised to detect and remove all non-waste classes (e.g., buildings and vegetation) from the satellite image feature space. Remote sensing-based band ratios and indices that gave the highest separation between waste and non-waste classes were applied to the satellite image. This helped heuristically reduce the search space by 30% (95M pixels to 66M pixels). In this reduced search space, unsupervised k-means clustering was performed and then

ranked based on how pure it was in terms of waste pixels. Top-ranked clusters were selected as model-detected waste accumulation sites, which ended up identifying 244 of the 247 ground sampled waste sites correctly. The preliminary results from the proof-of-concept image processing framework looks promising in studying the spatiotemporal distribution of plastic waste in megacities with complex land use patterns.

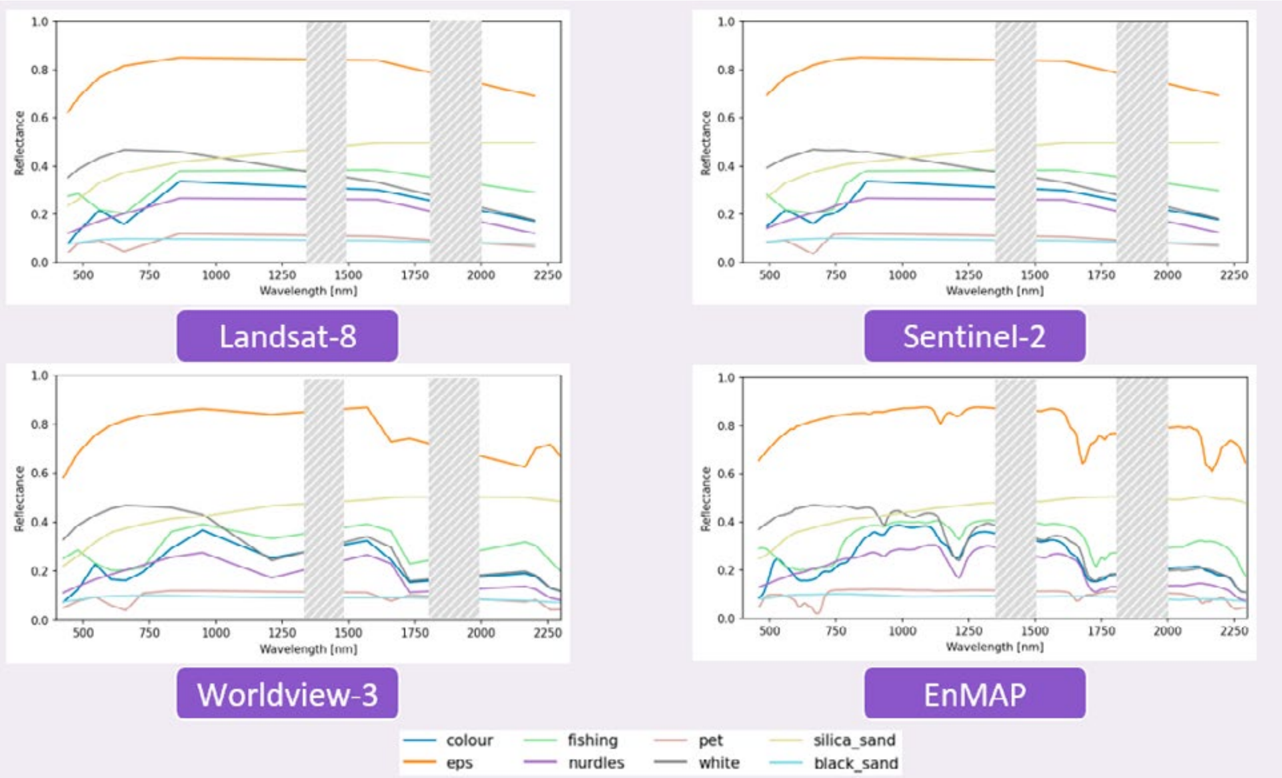
Title: Towards a spectral index for detecting marine plastics in beach environments.

Author: Guffogg et al., 2022

Link: https://7imdc.exordo.com/programme/presentation/409

Abstract: Plastic pollution in marine and coastal environments pose environmental and economic challenges. This marine plastic debris (MPD) often initiates from terrestrial sources and can move through, and accumulate in several environment sinks: open ocean surface waters, the water column, the benthic layer, coastal waters and beaches. While the bulk of MPD is in open oceans, movement of MPD between sinks is fluid, and a global MPD accounting system should consider each potential sink. Remote sensing is a cost effective and scalable solution that has gained traction over recent years for MPD detection. Spectral signatures of plastics found in the marine environment (polypropylene, high and low density polyethylene, and polystyrene) have been studied with the intent of using remote sensing platforms to locate and quantify MPD. However detecting MPD on beaches presents several challenges; MPD may co-occur with organic debris which is subject to similar forces of accretion, and underlying sediments can vary significantly in colour, mineral composition and grain size. We evaluate spectral reflection and several indices derived from experimentally generated mixed pixels containing plastics and sands. Investigating these indices contributes to the development of a novel method for detecting beached plastics using spectral absorption features in the VIS-SWIR (350-2500 nm) spectrum. We test these indices along with previously developed plastic debris specific indices (FDI, PI) to determine their usefulness for detecting beached MPD. Spectral libraries were developed from MPD collected from the Cocos (Keeling) Islands in the Indian Ocean. Linearly mixed synthetic pixels were created from endmembers of feldspar-silica, carbonate and basaltic sands, five types of MPD and three types of virgin plastics. The mixed pixels were then resampled to the spectral resolution of several candidate satellites: Sentinel-2, Landsat-8, Worldview-3 and EnMAP. Previously developed indices(PI, FDI) and general index formula (Ratio index, difference index, normalised difference index and soil-adjusted normalised difference index) were then generated for all possible 2-band combinations from the resampled pixels. Simple linear regression was used to determine the strength of the relationship between these indices and changes in MPD surface cover in the resampled pixels. Of the satellite sensors evaluated, Landsat-8 performed most poorly across all tested indices (r^2 0.04-0.42) and EnMAP performed the best (r^2 0.74-0.91). The improved spectral resolution of the Worldview-3 sensor compared to Sentinel-2 and Landsat-8 also showed promise for the development of new indices. However, the sand substrate influenced these results; For the ratio index, r^2 values ranged from weak (r^2=0.44) to strong (r^2=0.81) when all values were consistent except for the type of sand and for the soil-adjusted index, r^2 varied from 0.39 to 0.91. It was also found that the optimum value for the constant L in the soil-adjusted index differed depending on sand. Several indices have been proposed detecting floating plastics; however they have not been tested in beach environments. Our results progress the state of the art for detecting plastic debris in beach and coastal environments. This contributes to a better understanding of the total MPD across marine sinks.

Spectral reflectance of various material as observed by selected satellite missions.



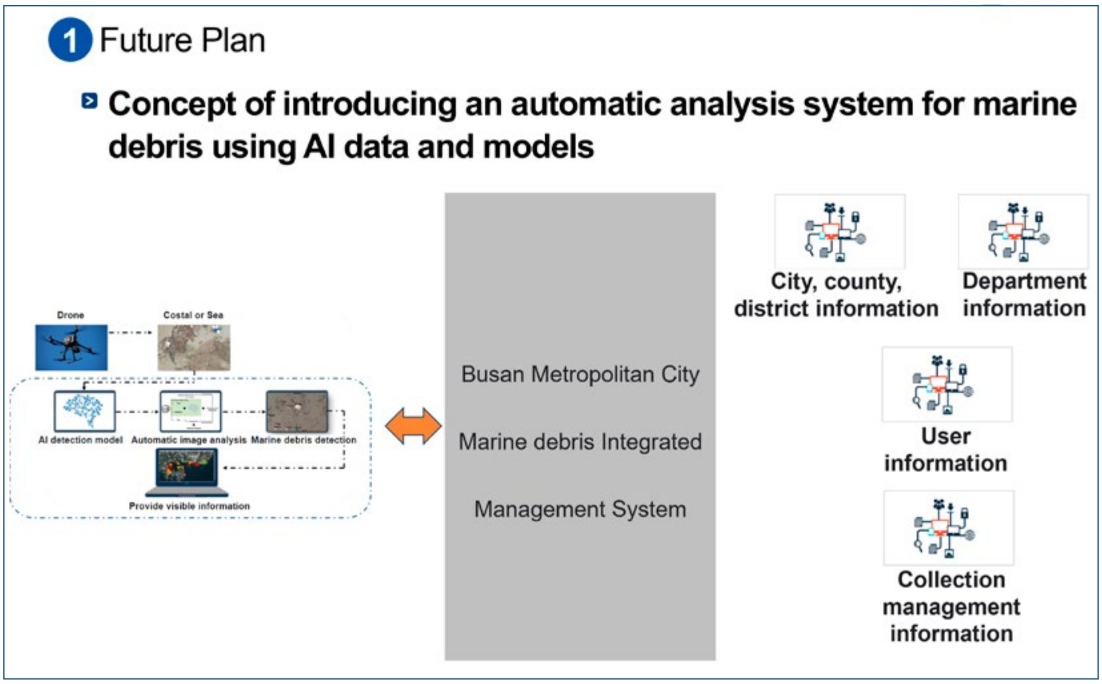
Title: Monitoring technology combining drones and artificial intelligence for efficient management of marine debris.

Author: Bak et al., 2022

Link: https://7imdc.exordo.com/programme/presentation/411

Abstract: In order to strengthen the ability to collect and manage marine debris, it is important to accurately understand the actual situation based on field survey information. Through the rapid collection of on-site information using drones and the analysis technology based on artificial intelligence, it is possible to support objective decision-making required for the rapid collection and management of marine debris. As of 2018, the annual inflow (generation) of marine debris in Korea is estimated to be 145,258 tons, and it is estimated that about 148,721 tons of garbage are present in the domestic ocean. Monitoring, which is currently being conducted for marine debris management in Korea, is conducted through visual inspection by ships and manpower, resulting in loss of time and manpower. In addition, it is difficult to grasp the exact condition of occurrence because it is difficult for manpower to access or there is a limit to investigating a wide range of space. In order to solve this problem, it was attempted to collect more than 420,000 pieces of data for each type of marine debris pollutant and pollutant, which are required to strengthen ICT-based marine debris collection and management capabilities, through drones, etc. In addition, it was attempted to objectively quantify the amount of marine debris by developing an AI detection algorithm using the collected AI learning data. In this study, the marine debris detection model was implemented into two types: an object detection model using data labeled in the form of a bounding box and a semantic segmentation model using data labeled in the form of polygon segmentation. As a result, in the case of the object detection method model, there is a difference in AP (Average Precicion) depending on the properties of marine debris, but in the IoU (Intesection over Union: 0.5 standard) detection performance evaluation, the mAP (mean average precision) of the entire

class is higher than 0.85. In the case of the semantic segmentation model using polygon segmentation labeling data, it showed a high level of accuracy such as 0.76 for beach litters and 0.85 for floating debris based on mIoU. In the future, it is expected that this study will support rapid marine debris collection and objective decision-making through a data-based scientific approach to the generation and distribution of marine debris.



Title: Plastic Litter Project 2022: first results on the detection of artificial floating marine litter targets.

Author: Topouzelis and Papageorgiou, 2022

Link: https://7imdc.exordo.com/programme/presentation/410

Abstract: Accurate observations of the sources, composition and densities of FML in oceans are sparse and lacking. Remote sensing can play a significant role in detecting and monitoring marine debris, and to this extent, adequate *in situ* observations of calibration and validation data are essential. Since 2018 we have launched a series of experimental field campaigns, the Plastic Litter Projects, to enrich the scientific community's understanding of FMLs spectral properties and behaviour. By developing, constructing, and deploying artificial floating targets containing various types of FML, we aim to produce a comprehensive remote sensing image database that can be used to develop, calibrate, and validate FML detection algorithms. Throughout the years, we have used various types of marine litter items such as PET bottles and HDPE bags and natural floating materials such as reeds in the construction of artificial floating targets. During the first years of the PLPs, we formed small-scale re-deployable artificial floating targets and made specific time-limited experiments. In the latter years, we moved on to long-term target infrastructure. During the 2021 experiment, we constructed two large long-term deployment artificial floating targets, which were deployed for a four-month acquisition period. The first target consisted of a circular 28 m diameter HDPE pipe frame, with white HDPE mesh attached acting as a representative target material, creating an effective target area of about 600 m^2. The second target was made from more than 350 wooden planks representing natural floating marine debris, approximating the same effective target area. One of the main project outcome was the production of an image database containing Senti-

nel-2 and very high resolution RGB aerial images of artificial marine debris targets. The drone data allow for the estimation of the targets' position in Sentinel-2 images and the derivation of pixel abundance fractions. Partial unmixing is used for the detection and concentration estimation of the FML targets in Sentinel-2 images. The PLP 2022 experiment is twofold; firstly, we plan to move on to a more replicable scheme using floating plastic targets which are deployed for an extended period and secondly, to examine the theoretical minimum plastic coverage that can be detectable from satellites. Spectral classification methodologies such as partial unmixing algorithms are expected to successfully detect FML using the mean spectral signature acquired during the PLP2021 deployment period. The present work will showcase a satellite and drone imagery analysis to detect FML and discriminate from natural floating materials or lookalike phenomena. Further analysis of the correlation between environmental and detection-affecting parameters and the resultant signal of FML will be helpful in operational scenarios of FML detection and monitoring.

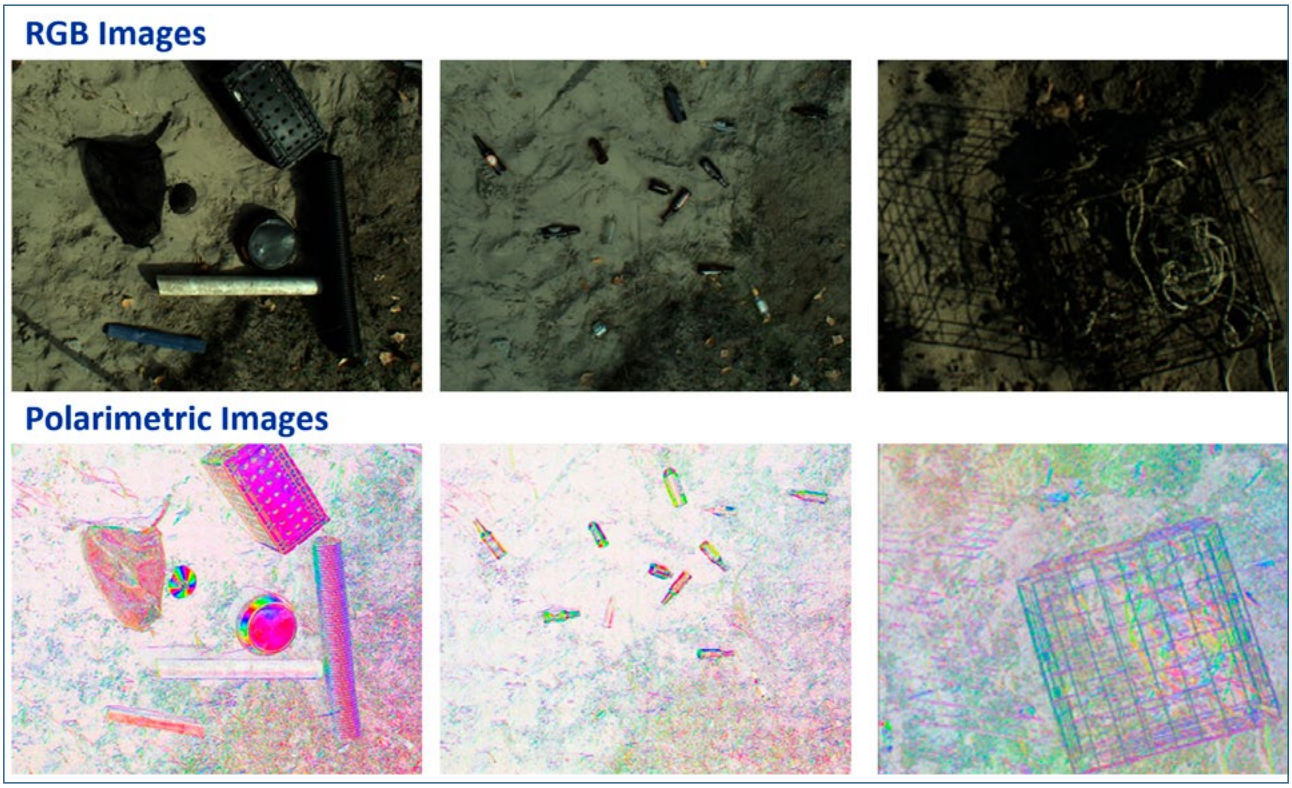
Title: Enhanced Detection and Characterization of Shoreline Marine Debris using Polarimetric Imagery.

Author: Uhrin et al., 2022

Link: https://7imdc.exordo.com/programme/presentation/412

Abstract: Polarimetric imaging is an emerging technology, which is proving useful in detection and characterization of objects within a scene. While traditional multispectral and hyperspectral cameras provide information about the reflectance of objects in different parts of the electromagnetic spectrum, polarimetric imaging cameras go beyond this by providing information regarding the polarization state of the received electromagnetic energy. This capability is valuable in obtaining information regarding objects' surface roughness and other characteristics. The combination of information acquired by spectral and polarimetric imaging often reveals independently distinctive features about human-made

objects, aiding in their detection and identification. This type of imaging is particularly valuable when discriminating weak target signatures from complicated surroundings under a range of illumination conditions. For these reasons, there are potential applications of this imaging technology to support marine debris detection on shorelines, where it is often intermixed with substrate, vegetation, or natural (woody) debris. In 2020, a team of NOAA scientists and Oregon State University remote sensing experts initiated a project to better understand the applicability polarimetric imaging to marine debris detection. The specific goal of this study was to investigate whether polarimetric imagery improves both visual and automated identification of debris objects on sand beaches compared to standard red-green-blue (RGB) imagery, and whether debris classification accuracy improves by including polarimetric bands. Using a FLIR Blackfly-S USB3 RGB polarimetric imaging camera, we created and evaluated three orthomosaic 8-band composite shoreline images comprised of three spectral (RGB) and five polarimetric bands. Images were collected from Neptune State Scenic Viewpoint in Oregon (staged debris) and two sand shoreline sites on San Jose Island, Texas (in situ field debris). Classifications were limited to seven debris material types including plastic, rubber, glass, processed wood, buoy, tope and aluminum. Correlation matrices revealed that bands representing the degree and angle of linear polarization were sufficiently different from the RGB bands such that their inclusion in the classification algorithm was beneficial. It was also shown quantitatively that the addition of the polarimetric image-derived bands improved the separability of debris classes. When polarimetric image-derived bands were included in a K-nearest neighbors machine learning algorithm, the overall accuracy of debris classification increased by 6.7 – 25.6 percentage points, depending on the site. Kappa statistics increased by 9.1 – 17.6 percentage points, again, site dependent. There was also marked improvement in both producer's and user's accuracy for most categories of debris when polarimetric image-derived bands were included. The ability to accurately detect and identify marine debris enables a comprehensive assessment for understanding its likely impacts while providing significant value in debris removal prioritization efforts. Our study provides strong indication that polarimetric imaging is a useful asset in detection and classification of marine debris found on sand shorelines when combined with RGB bands. Future work will focus on integration of polarimetric imaging cameras on uncrewed aircraft systems (UxS) for efficient marine debris detection and characterization.

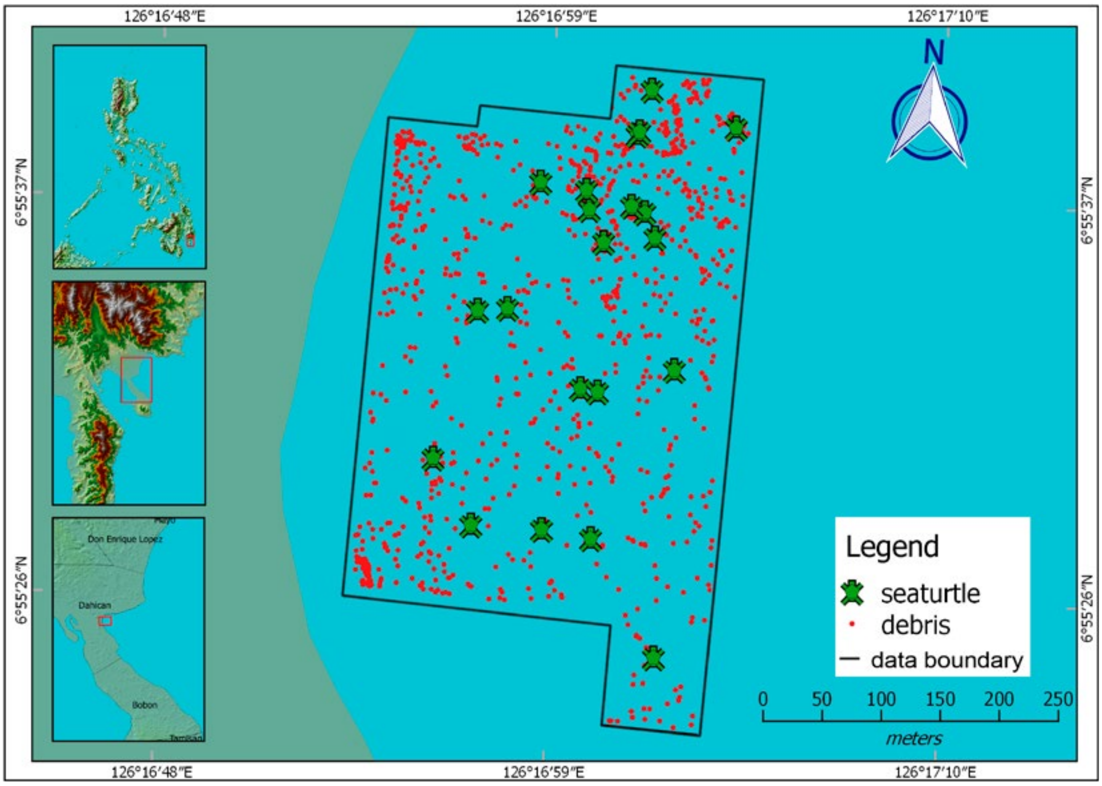


Title: Eye in the sky: Drone highlights exposure of marine turtles to floating litter in nearshore waters of Mayo Bay, Philippines.

Author: Abreo et al., 2022

Link: https://7imdc.exordo.com/programme/presentation/413

Abstract: Man-made litter is threatening the marine environment with detrimental effects on wildlife. However, limited marine litter data brought by funding and logistical challenges in developing countries, such as the Philippines, hampers the full understanding of the problem. Moreover, data from the Philippines are not comparable due to non-standardized methodologies used by different studies. Here, we employed commercially-available unmanned aerial vehicles (UAV) as a cost-effective tool to study risk exposure of marine turtles to floating litter in nearshore waters adjacent to a nesting beach in Mayo Bay, Davao Oriental, Philippines. A quadcopter drone was flown autonomously to a height of 30m at a speed of 8 m/s, with on-board camera pointed at nadir to collect videos. The videos were subjected to post-flight processing and still frames were extracted when either turtles or floating litter were detected. The extracted frames were georeferenced in QGIS software. Spatial statistical packages in QGIS and R programming language were used to analyse the relationships between the point patterns of floating litter and marine turtles. Results showed that within 50m radius, 68.2% of marine turtles were found in proximity to litter and 100% of turtles were in proximity to litter within a 150m radius. The mean number of floating litter surrounding turtles at 50m radius was 6.32 items; this increases to 79.27 items at 300m radius. The average minimum distance between turtle and litter was 40.06m (s.d. = 32.16), with the shortest distance observed at 0.36m. Also, Cross K function revealed that floating litter occurrence is clustered around marine turtle signifying spatial dependence between the two. A source of concern since the overlap in marine turtle and floating litter occurrences in nearshore coastal waters likely increases the risk of ingestion and entanglement, adding to the myriad of threats on the survival of these organisms and can deleteriously affect the marine turtle population. The study highlights the effectiveness of off-the-shelf UAVs in unraveling the relationships between litter and marine wildlife, especially in developing countries where it is costly and time consuming to collect data. Application of emerging technologies can provide the needed fine scale resolution data and empirical evidence to substantiate findings of marine litter modeling studies. Application of artificial intelligence and machine learning can further improve methodology presented here and could be an essential tool for standardization of data collection for comparability of marine litter studies. Finally, the cost-effectiveness of this methodology can allow for regular FML monitoring.



126°16′48″E
126°16′59″E
126°17′10″E
6°55′37″N
6°55′26″N
Don Enrique Lopez
Dahican
Bobon
N
Legend
seaturtle
debris
data boundary
0
50
100
150
200
250
meters

A4.2 ESA Living Planet Symposium, Bonn, Germany (25 - 26 May 2022)

The material presented here is adapted from the symposium report (https://ioccg.org/wp-content/uploads/2022/07/esa-lps-report-tf-rsmld_july2022.pdf) prepared by the IOCCG Task Force on Remote Sensing of Marine Litter and Debris. The coordinated activities by the Task Force included (i) scientific session and (ii) networking event. These activities were aimed to provide a status update to the stakeholders, provide a community two-way feedback and identify ways forward. The two scientific sessions were (a) A8.08.1 Advances and EO Applications in Remote Sensing of Marine Litter and Debris – 1, (b) A8.08.2 Advances and EO Applications in Remote Sensing of Marine Litter and Debris – 2 and a related poster session. A nettworking event The event was aimed at giving an overview of the Task Force to the ESA LPS attendees. Presentations about the proposed Simulator ML-OPSI, dedicated database Ocean Scan, WASP, Marine Litter mission concept MARLISE and RESMALI. An overview of the scientific session presentations and posters is provided below:

Oral Presentations

Time	Title
08:30	FRONTAL: Satellite FRONTs for detection of Anthropogenic plastic Litter V. Martinez-Vicente et al.
08:45	Observation of Marine Litter Windrows with Sentinel-2/MSI as a Strategic Target for Plastic Pollution M. Arias et al.
09:00	Satellite remote sensing of marine litter floating in open ocean and coastal waters Y.-J. Park et al.
09:15	Self-supervised learning for robust floating debris detection J. Mifdal et al.
09:30	Unraveling the spatial heterogeneity of floating macroplastics at the sea surface using Unmanned Aerial Vehicles (UAVs) R. de Vries et al.
09:45	Polarization signatures of nano- and micro-plastics suspended in the water column simulated at the water surface and top-of-atmosphere levels T. Harmel et al.
10:40	Plastic Litter Project (PLP) 2021 – calibration and validation data for Sentinel-2 floating marine litter remote detection D. Papageorgiou et al.
10:55	Exploring spectral signature unmixing techniques and machine learning algorithms on fused multi- and hyper-spectral data for plastic marine litter detection – the REACT project A. Aiello et al.
11:10	Spectral responses meet AI to detect Marine Litter M. Moshtaghi et al.
11:25	Presenter not available Marine litter detected by UAV over Patagonian Pristine beaches C. Mattar
11:40	Experimental tests for the detection and characterisation of Plastic Marine Litter by means of fluorescence LIDAR technique V. Raimondi et al.
11:55	Advancing Remote Sensing of Floating Marine Microplastics H. Dierssen et al.

Poster Presentations

Code	Title
62710	Eyes on Plastic – flying high, diving deep to fight aquatic plastic litter E. Haas et al.
62740	The Use of Spaceborne Radars to Image Ocean Microplastic Dynamics C. Ruf et al.
63621	Detecting and recognising surface accumulations in Sentinel-2 imagery T. Kutser et al.
63646	Monitoring of Large Plastic Accumulation Near Dams Using Sentinel-1 Polarimetric SAR Data M. Simpson et al.
63653	Ocean Global Watcher: Detection of marine anomalies using radar or optical satellite images A. Lagrange et al.
64067	Identifying macro plastics assisted by close-range hyperspectral remote sensing and deep learning N. Gnann et al.
64415	Coastal Marine Litter Observatory: drone imagery and AI for marine litter detection K. Topouzelis et al.
64611	Detection of Marine Plastic Source Locations using Machine Learning applied to Sentinel-1 & Sentinel-2 Data S. Lavender et al.
64613	River plastics from space: Combining Sentinel-1 and UAV imagery to monitor mixed debris patches L. Schreyers et al.
65419	Tackling the plastic debris challenge at its source – Linking EO data with multi-source in-situ data for modelling debris pathways from source to sink A. Brand et al.
65445	Using hyperspectral radiometry towards subpixel detection of plastic debris on rivers and shorelines. A. Mata et al.
65637	Feasibility of a satellite mission for monitoring marine macroplastics S. Livens et al.
66571	Assessment of Machine Learning for floating marine litter detection L. Fronkova et al.
66724	River plastic monitoring from space: Fact of fiction? T. van Emmerik et al.
66777	A review of the application of satellite mapping techniques for marine litter monitoring M. King et al.
66853	PLASTIC MONITOR: Detecting riverine plastic conglomerations, fluxes and pathways in Indonesia M. Eleveld et al.
66965	Using a drone-based thermal infrared camera to monitor floating plastic litter L. Goddijn-Murphy et al.
67309	Finding Floating Plastics in Plant Patches using Worldview-3 Satellite Imagery L. Biermann et al.
67385	Ocean Scan, a marine debris database from Earth and space L. Romero et al.
67469	Airborne backscatter LIDAR data over the Great Pacific Garbage Patch and their processing for the Detection of Marine Litter: pros and cons analysis L. Palombi et al.

Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH

Registered offices
Bonn and Eschborn

Friedrich-Ebert-Allee 32 + 36
53113 Bonn, Germany
T +49 228 44 60-0
F +49 228 44 60-17 66

Dag-Hammarskjöld-Weg 1 – 5
65760 Eschborn, Germany
T +49 61 96 79-0
F +49 61 96 79-11 15

E info@giz.de
I www.giz.de

On behalf of

Federal Ministry
for the Environment, Nature Conservation
Nuclear Safety and Consumer Protection