RESMALI
Remote Sensing for Marine Litter

Executive Summary

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- Company: **Argans Limited, 1 Davy Road, Plymouth Science Park, Derriford, Plymouth, Devon, PL6 8BX, United Kingdom**

Signatures

	Name	Company or Institute	Signature
Prepared by	Manuel Arias	ARGANS	
	Andres Cozar	UCA	
	Fidel Echevarria	UCA	
	Shungu Garaba	TOC	
Reviewed by	Julia Reisser	TOC	
	Laurent Lebreton	TOC	
	Guillaume Bonnery	AIRBUS	
Distribution list	Paolo Corradi, TEC-MMO	ESA/ESTEC	

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Acronyms

AAR	Application Analysis Report
AER	Atmospheric & Environmental Research Radiative Transfer Working Group
AD	Applicable Document
ADT	Absolute Dynamic Topography
AIL	Action Item List
AOI	Area of Interest
AOPs	Apparent Optical Properties
AOT	Aerosol Optical Thickness
APD	Absolute Percentage Difference
ASD	Analytical Spectral Device
ATBD	Algorithm Theoretical Basis Document
BGI	Blue Green Index
BIPR	Background Intellectual Property Right
BOA	Bottom of atmosphere
BRDF	Bidirectional Reflectance Density Function
CDOM	Coloured Dissolved Organic Matter
Chl-a	Chlorophyll-A
CMEMS	Copernicus Marine and Environment Monitoring Service
CO	Contracts Officer
CZCS	Coastal Zone Colour Scanner
CZMIL	Coastal Zone Mapping and Imaging LiDAR
DESIS	DLR Earth Sensing Imaging Spectrometer
DOC	Dissolved Organic Carbon
EMP	Experimental and Modelling Plan
EO	Earth Observation
ES	Executive Summary
ESA	European Space Agency
ESTEC	ESA Technical Centre
ETRAR	Experimental Test and Results Analysis Report
DP	Development Plan
FAI	Floating Algae Index
FMD	Floating Marine Debris
FOV	Field Of View
FR	Final Review/Report
FTIR	Fourier Transform Infra-Red
FWHM	Full Width at Half Maximum
(G)	Goal
GNDVI	Green Normalized Digital Vegetation Index
GPGP	Great Pacific Garbage Patch
GSD	Ground Sampling Distance
HAPS	High/Altitude Pseudo/Satellite
HDPE	High Density Polyethylene
HSRL	High Spectral Resolution LiDAR

IMDOS	Integrated Marine Debris Observation System
IOPs	Inherent Optical Properties
ISS	International Space Station
ITT	Invitation to Tender
KO	Kick-off
LDPE	Low-density polyethylene
LEO	Low Earth Orbit
LLPE	Linear low-density polyethylene
LTAN	Local Time of Ascending Node
LTDN	Local Time of Descending Node
LWIR	Long Wave InfraRed
MERIS	Medium Resolution Imaging Spectrometer
MCT	Mercury Cadmium Telluride
MD	Marine Debris
ML	Marine Litter
MODIS	MODerate Resolution Imaging Spectroradiometer
MoM	Minutes of the Meeting
MRD	Mission Requirements Document
MRs	Mission Requirements
MSI	Multi Spectral Imager
MWIR	Medium Wave InfraRed
MYSTIC	Montecarlo code for the physically correct tracing of photons in cloudy atmospheres
Nd:YAG	Neodymium-doped Yttrium Aluminium Garnet
NDVI	Normalized Digital Vegetation Index
NGO	Non-Governmental Organisation
NIR	Near InfraRed
Nm	Nautical mile
NP	North Pacific
OLCI	Ocean Land Colour Instrument
OSIP	Open Space Innovation Platform
PAN	Panchromatic
PM	Progress Meeting
PMDI	Plastic Marine Debris Index
PML	Plymouth Marine Laboratory
PRISMA	ASI PRecursore IperSpettrale della Missione Applicativa
R&D	Research and Development
RD	Reference Document
REPTRAN	Representative wavelengths absorption parameterization
RESMALI	Remote Sensing for Marine Litter
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SoW	Statement of Work
SNR	Signal to Noise Ratio
SNRr	Relative Signal to Noise
SR	Scientific Roadmap
SSA	Sea Surface Anomaly

SSGP	Space for Smart Government Programme
SWH	Significant Wave Height
SWIR	Short Wave InfraRed
(T)	Threshold
TTASR	Techniques and Technology Assessment Report
TC	Tendering Conditions
TO	Technical Officer
TOA	Top Of Atmosphere
TOC	The Ocean CleanUp
TRL	Technology Readiness Level
UCA	University of Cadiz
UKSA	United Kingdom Space Agency
UV	Velocity Field
VHR	Very High Resolution
VNIR	Visible and Near InfraRed
WP	Work Package
WPO	Wet peroxide Oxidation
WS	Wind Speed
WWF	World Wild Foundation

Applicable and reference documents

Id	Description	Reference
AD-1	SoW “Remote Sensing for Marine Litter”	ESA/AO/1-8758/16/NL/PS
AD-2	Technical, Management and Financial Proposal	ARG-003-035
AD-3	Application Analysis Report	SO-TN-ARG-003-035-002
AD-4	Mission Requirements Document	SO-TN-ARG-003-035-003
AD-5	Techniques and Technology Assessment Report	SO-TN-ARG-003-035-004
AD-6	Experimental Phase and Modelling Report	SO-TN-ARG-003-035-005
AD-7	Conceptual Design Specifications Performance Report	SO-TN-ARG-003-035-006
AD-8	Development Plan	SO-TN-ARG-003-035-007
AD-9	Final Report	SO-TN-ARG-003-035-008

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1 Introduction

1.1 Scope of the document

This document presents the Executive Summary Report (D7) corresponding to the project titled "RESMALI: Remote Sensing for Marine Litter", funded by the European Space Agency, under the programme "General Studies" (GSP), associated to ESTEC. The ESA Contract No. 4000121315/17/NL/PS was awarded to ARGANS Ltd (Plymouth, United Kingdom) who acts as Prime of this activity, after response and evaluation process of the Invitation to Tender (ITT) ESA/AO/1-8758/16/NL/PS published by the Agency on 6th September 2016.

The RESMALI project was kicked off on the 1st September 2017, after completing negotiations between the Agency and ARGANS Ltd. The project was completed on 3rd December 2019.

The contents of the following rport nurture from the documentation produced during the project, plus the additional activities related to it carried out by the consortium. These documents refer to the Statement of Work (SoW) [AD-01] provided by ESA, the Proposal [AD-02] submitted by ARGANS, the Application Analysis Report (D1) [AD-03], the Mission Requirements Document (D2) [AD-04], the Techniques and Technology Assessment Report (D3) [AD-05], the Experimental Phase and Modelling Report (D4 and D5) [AD-06], the Conceptual Design Specifications Performance Report (D6) [AD-07], the Development Plan (D9) [AD-08] and the Final Report (D7) [AD-09].

1.2 Structure of the document

The present report is composed of various chapters covering in a natural way the flow of the activities along the life of the project. The main information produced by the activity is hereinafter laid out, summarizing the principal outcomes and results. For that purpose, the document is structured as follows:

- Chapter 1 covers this introduction, giving the frame of the activity and the document structure.
- Chapter 2 describes the context and main objectives for the activity, the consortium and team involved in its execution, and the work structure and flow that was proposed and followed.
- Chapter 3 covers the results produced during the first phase of the project, involving a state-of-the-art of the issue of marine litter in the environment, an assessment of potential EO applications for Marine Litter (ML), plus an initial assessment of technologies suitable for them.
- Chapter 4 refers to the experimental plan, its results and the modelling exercise done by the team, in order to fill caveats and better assess the potential approach of an EO solution for ML.
- Chapter 5 includes the contribution of the team in defining a mission concept based on the results from the previous stages; in addition, the applications were revisited according to the proposed solution, and a development and scientific roadmap was laid out.
- Chapter 6 described the outreach and network activities also carried out by the team in the frame of this Contract.

2 RESMALI: From concept to reality

2.1 Background for the activity

The idea of Remote Sensing for Marine Litter was laid out by the Agency in the SoW, and details are provided below.

According to the United Nation Environment Program (2005), “Marine Litter” is defined as any item that has been made or used by people and deliberately or accidently discarded either directly into the sea or coast or transported from land into the marine environment.

Marine Litter (ML) is a global issue, affecting all the major bodies of water on the planet, from the surface to the sea-bottom. It can negatively impact wildlife, habitats, the economic health and burden of coastal communities and maritime activities, but also become an issue of public safety, considering the emerging concerns over ingestion of microplastics by marine particle feeders.

Among the conclusions of the G7 Ministers of Science Meeting in Berlin in October of 2015, ML, and in particular plastic litter and microplastics, was addressed as a threat to marine life and habitats and presenting health and safety concerns for humans (G7, 2015). The G7 committed in 2015 to an action plan to combat ML, in particular actions to combat land and sea-based plastic litter pollution, as well as removal actions and the need for education, research and outreach to other countries and stakeholders on this issue (G7, 2015b).

The joint report published in 2016 by the International Association for the Physical Sciences of the Oceans (IAPSO) of the International Union of Geodesy and Geophysics (IUGG) and the Scientific Committee on Oceanic Research (SCOR) of the International Council for Science (ICSU) summarized the conclusions of experts regarding the current scientific understanding of ML related issues, and reported recommendations for future action by G7 countries (Williamson et al, 2016). Among the conclusions of the section “Plastic pollution of the marine environment” (by Thompson, R., and N. Maximenko), it is reported that “research needs and G7 actions include appropriate sensors on satellites, autonomous aircraft and in-situ observing systems, capable of monitoring larger items of floating litter as well as concentrations of smaller items”.

Indeed, existing ground-based data collection systems are limited and are not able to answer fundamental questions (e.g. related to ML concentrations and spatial and temporal dynamics), due partly to the vastness of the problem, diversity of the types of ML and its general sparseness.

According to monitoring data, the majority of ML is plastics. It is estimated that several millions of tons of plastics enter the oceans every year (Jambeck et al, 2015). About 70% of the initially floating plastic waste sinks to the seafloor (due to biofouling), while the remaining 30% accumulates in the large ocean gyres or is washed up on coastlines and beaches. Plastics progressively fragments due to combined photodegradation of UV radiation and wave action. When these particles are smaller than 5 mm they are referred as “secondary microplastics”. Primary microplastics particles, e.g. included during the production in personal care products, are carried into the sea via wastewater. It takes centuries to plastic particles to completely disintegrate.

The ML topic is discussed in detail in, for example, (Bergmann et al, 2015). A synthesis of the ML issue and an introduction to some of the available remote sensing technologies are reported in (Maximenko et al, 2017).

2.2 The Integrated Marine Debris Observation System

A key activity that was carried out by the international scientific in this year (2019) was the elaboration of the specifications for an integrated marine debris observation system (IMDOS), in which its elaboration, the team for RESMALI actively worked. The activity crystalized in the publication of a white paper led by 62 authors, covering multiple disciplines with interest in marine debris. The work titled "Towards the integrated marine debris observing system" (Maximenko et al, 2019) has been published in the open journal "Frontiers in Marine Science".

The work was also presented and accepted for the OceanObs 2019 conference (Hawaii, USA, 2019), where the community supported the need for ad hoc observational systems able to support detection, measurement and monitoring of marine debris, and especially marine litter. Thus, the abstract of the publication condenses this need:

Plastics and other artificial materials pose new risks to the health of the ocean. Anthropogenic debris travels across large distances and is ubiquitous in the water and on shorelines, yet, observations of its sources, composition, pathways, and distributions in the ocean are very sparse and inaccurate. Total amounts of plastics and other man-made debris in the ocean and on the shore, temporal trends in these amounts under exponentially increasing production, as well as degradation processes, vertical fluxes, and time scales are largely unknown. Present ocean circulation models are not able to accurately simulate drift of debris because of its complex hydrodynamics. In this paper we discuss the structure of the future integrated marine debris observing system (IMDOS) that is required to provide long-term monitoring of the state of this anthropogenic pollution and support operational activities to mitigate impacts on the ecosystem and on the safety of maritime activity. The proposed observing system integrates remote sensing and in situ observations. Also, models are used to optimize the design of the system and, in turn, they will be gradually improved using the products of the system. Remote sensing technologies will provide spatially coherent coverage and consistent surveying time series at local to global scale. Optical sensors, including high-resolution imaging, multi- and hyperspectral, fluorescence, and Raman technologies, as well as SAR will be used to measure different types of debris. They will be implemented in a variety of platforms, from hand-held tools to ship-, buoy-, aircraft-, and satellite-based sensors. A network of in situ observations, including reports from volunteers, citizen scientists and ships of opportunity, will be developed to provide data for calibration/validation of remote sensors and to monitor the spread of plastic pollution and other marine debris. IMDOS will interact with other observing systems monitoring physical, chemical, and biological processes in the ocean and on shorelines as well as the state of the ecosystem, maritime activities and safety, drift of sea ice, etc. The synthesized data will support innovative multi-disciplinary research and serve a diverse community of users.

The activity clearly nurtures from the discussion already presented in a previous workshop happened in Hawaii (USA, 2016), which summary appears in Maximenko et al (2017).

In both documents, the use of remote sensing technologies to monitor marine litter is clearly stated, as the only tool really able to produce global coverage and provide synoptically view of the problem, in combination with in situ observations and models. Indeed, the publications states the following:

IMDOS builds on previous initiatives (e.g., MSFD, 2013; GESAMP, 2019) to include into consideration a broad variety of debris and its complete life cycle in the marine environment, and aims to stimulate the establishment of best practices as well as optimization and expansion of the existing observational networks. We review the properties and impacts of different types of marine debris, as well as observation techniques and technologies that are used or could potentially be used in the next decade and beyond, and we share our vision of how direct observation, remote sensing, and numerical modelling can be integrated to compose a global observing system.

Whilst the IMDOS concept was produced after kick-off of the RESMALI project, its relevance at this point is none the less significant, as it supposed a consolidation of the need of Earth Observation and remote sensing in general to support the study of marine debris and marine litter.

Answering to the question of whether Earth Observation can support this need is the main goal for RESMALI.

2.3 Consortium and team

ARGANS Ltd. identified a team of experts in the area of marine litter and Earth Observation. The requirements for the activity meant that a multidisciplinary team was the best solution to address the objectives and meet the goals of the activity. In particular, a good base knowledge about ML was needed, commonly offered by institutions and organisations working in the field. However, for the remote sensing elements, both expertise coming from ground-segment activities, applications and instruments was required.

Thus, the consortium which executed RESMALI had an important diversity, including oceanographers, remote sensing specialists, EO scientists and engineers.

2.3.1 Overall team composition and key personnel

The selection of the team members produced by ARGANS has been guided by the following criteria:

- The high level of expertise of the team;
- The adequacy of the team experience to the required skills to carry out the project activities;
- The current team cohesion allowing reactivity and flexibility indispensable to ensure everything goes as smoothly as planned, and a harmonious and efficient development of the project tasks.

Key personnel for this project were:

- Dr Manuel Arias (ARGANS Ltd, UK), who was Project Manager and Scientific Lead of the activity,

supported by the following task leaders:

- Dr Andres Cozar (University of Cadiz, Spain),
- Dr Laurent Lebreton (The Ocean CleanUp, Netherlands),
- Dr Guillaume Bonnery (AIRBUS DS, France).

In addition to these personnel, the consortium included additional staff members of these organisations:

- Dr Fidel Echevarria (University of Cadiz, Spain),
- Julia Reisser (The Ocean CleanUp, Netherlands)
- Dr Robin de Vries (The Ocean CleanUp, Netherlands)
- Dr Jennifer Aitken (Teledyne, USA, on behalf of The Ocean CleanUp)

- Dr Shungu Garaba (University of Oldenburg, Germany, on behalf of The Ocean CleanUp)
- Dr Guillaume Bourgeois (AIRBUS, France)
- Dr Jeremie Lochard (AIRBUS, France)

2.3.2 Expertise

The team included in this activity covers all the expertise identified as necessary for a successful outcome.

In particular, the understanding of the physical properties of ML, its spatial distribution and temporal variability were assessed by both the University of Cadiz and The Ocean CleanUp, being Dr Andres Cozar the leader for such tasks.

The definition of the potential applications and case studies was carried out as a joint effort from University of Cadiz, The Ocean CleanUp and ARGANS, being led again by Andres Cozar.

The initial definition of Mission Requirements was performed by ARGANS Ltd, which has a considerable experience in remote sensing applications.

The initial assessment of such requirements, along with the study of potential technologies to achieve them was produced by AIRBUS, with support from ARGANS, and under the lead of Dr Guillaume Bonnery.

The planning and execution of the field experiments was carried out by The Ocean CleanUp, with support from ARGANS and AIRBUS, being led by Laurent Lebreton.

The performance of the modelling activities and data simulation was carried out by ARGANS, with the support from AIRBUS, being this activity led by Dr Manuel Arias.

The design of the mission concept and of the development plan was produced by AIRBUS, with the support of ARGANS, and led by Dr Guillaume Bonnery.

Each of the task leaders was selected according to their background and experience in the tasks required. Cross-fertilization between the different areas was also granted, so to ensure that a full vision of the problem was provided and that the goals for the activity could be met. As indicated previously, the activity required a multidisciplinary team with capability to communicate in the technical aspects of the project and address the overarching requirements of RESMALI.

3 Initial assessment of Marine Litter

3.1 Understanding ML from the perspective of remote sensing

As per requirements in Task 1 and 2, it was necessary to address the Mission requirements that would, eventually, configure the characteristics of a potential EO mission, as well as to define the technologies that would be required for its achievement. The first requirement involved producing an understanding of the characteristics of ML that could be exploited by remote sensing techniques. In particular:

- Its spatial distribution and variability, including accumulation points and hotspots,
- Its temporal variability, including sources and pathways within the marine environment,
- Its physical properties that could be advantageously used to produce its observation.

These three points were key to explore the possible Mission Requirements and the technologies better suited for its observation.

To obtain this information, however, a state-of-the-art analysis had to be produced, with special emphasis on those three points. This was done thanks to the significant amounts of data and information already held by the consortium (specially coming from the University of Cadiz and The Ocean CleanUp) and reported in (D1). The high expertise of the team involved in this activity also helped to introduce as inputs for this phase the results of the international community. Dr Andres Cozar and Julia Reisser introduced RESMALI in various forums using their established (or new made) collaborations to produce it, as well as taking advantage of the networks already existing in their institutions.

The creation of this baseline was fulfilled, what allowed the team to produce the initial definition of possible applications and Mission Requirements. Both components were delivered to the Agency in (D2). It is important to mention at this point that this part of the activity significantly benefitted from a workshop organised by ESA and supported by PML in December 2017, gathering experts all around the world with specific interest in marine debris in general, and in marine litter in particular.

As result of the workshop, a community paper was produced and recently published in the Remote Sensing Journal, titled “Measuring Marine Plastic Debris from Space: Initial Assessment of Observation Requirements” (Martinez-Vicente et al, 2019), in which the RESMALI team actively participated.

The paper aimed to include the main conclusions of the workshop, which were closely related to the activity for RESMALI. From the abstract of the paper::

Sustained observations are required to determine the marine plastic debris mass balance and to support effective policy for planning remedial action. However, observations currently remain scarce at the global scale. A satellite remote sensing system could make a substantial contribution to tackling this problem. Here, we make initial steps towards the potential design of such a remote sensing system by: (1) identifying the properties of marine plastic debris amenable to remote sensing methods and (2) highlighting the oceanic processes relevant to scientific questions about marine plastic debris. Remote sensing approaches are reviewed and matched to the optical properties of marine plastic debris and the relevant spatio-temporal scales of observation to identify challenges and opportunities in the field. Finally, steps needed to develop marine plastic debris detection by remote sensing platforms are proposed in terms of fundamental science as well as linkages to ongoing planning for satellite systems with similar observation requirements.

It is worth mentioning, however, that whilst the paper contains a set of recommendations and possibilities, not all of them were tackled in the same way in RESMALI. In particular, the RESMALI team addressed the problem from a different angle and produced different conclusions than the ones yielded in this paper. The reasons for such decisions and divergence are showed in the subsequent sections of this chapter. Results for this activity are presented in section 3.3 of this document.

Using the results of the Applications Analysis and the definition of the initial Mission Requirements, AIRBUS performed also an initial assessment of the most suitable remote sensing technologies that could cover them. This initial assessment helped to identify the hypothesis that should be investigated during the experimental plan. Results for this activity are presented in section 3.4, below.

3.2 Monitoring Marine Litter

Surface-trawling plankton nets is, up to now, the sampling method that has provided the more extensive datasets on small ML (Cózar et al. 2014, Eriksen et al. 2014) as well as the longest historical series (Law et al. 2010, 2014). The number and spatial coverage of these measurements have demonstrated the global scale of plastic pollution and has allowed to achieve the first preliminary assessments of the floating plastic load in the world oceans (Cózar et al 2014, Eriksen et al. 2014, Sebille et al. 2015). However, after a preliminary compilation of the net tows carried out from 2006 to 2016 (3936 net tows) and using a typical area of trawling surface (0.0019 km^2; van Franeker and Law, 2015), we noted that this common method has hardly sampled 10 km^2 of the global ocean surface (362 million km^2), in spite of the international sampling effort developed over the past decade. Moreover, a large-scale assessment of the marine plastic pollution from other sampling techniques seems yet far more difficult to tackle (e.g. Browne et al. 2015). Our current capacity to analyse spatial and temporal dynamics of this global problem is extremely low, therefore the remote-sensed detection of a significant fraction of the marine plastic pollution would be undoubtedly revolutionary at both scientific and management levels.

3.2.1 Summary of physical properties and composition

3.2.1.1 Relevant size and weight distribution

The sizes of ML objects as found in the marine environment cover a wide range, from meters to microns, and potentially, even smaller. The reasoning behind this wide distribution is associated to the large variety of potential sources of ML, which extend from large pieces of ghost nets to microscopic particles used by the cosmetic industry, passing by daily use objects (bottles, containers, packing), personal hygiene products (ear batons, tampons) and/or industrial precursors (plastic pellets).

In addition to the origin of ML from its source, additional processes intervene in the definition of the sizes that can be found. ML objects at the sea suffer from mechanical degradation in coastal areas, as result of the collision with rocks and friction with sand and gravel. Plastic materials also breakdown into smaller pieces as result of the damages caused by UV radiation to the polymers composing them. In fact, if other phenomena are excluded, these two processes would eventually yield a large population of microplastics, smaller and smaller as the time goes.

However, size distribution does not follow this principle. By looking at the observational data, maximums of ML concentrations and relative abundances are found for the range between 0.5 to 5 mm. Outside this range, larger objects are less and less frequent as the size increases; on the other hand, smaller fractions are also less abundant, if well the mechanisms that explain this are not yet fully clear.

The biofouling changes the density of the pieces, reducing their buoyancy and causing their sinking as result of a ballasting process (Fazey & Ryan, 2016). The materials so affected precipitate to the bottom of the sea between 2 to 3 months, being the smaller fractions substantially faster affected by ballasting due to biofouling than larger items. However, rates associated to this removal effect are not well known and the exact areas in which this is happening is also unclear. Regardless, this process would be more related to areas with a high productivity (i.e. high rates of biomass production vs biomass consumption). Therefore, it is expected to have a major role in areas with higher concentrations of plankton, what links them to upwelling situations and seasonal variations of both temperatures and sun radiation. Other aspects unclear in this sense are the mechanisms of re-floatability of ML, as sunk pieces of ML due to biofouling could be released again to water column if the organic compounds are eaten or degraded, reducing the ballasting effect. However, the ballasting effect would be far more explained as result of carbonate-precipitating organisms (e.g. barnacles) that increase substantially the density, rather than soft organisms.

The ingestion of ML as a removal effect is an aspect that requires consideration. The feeding on ML is strongly dependent of their size, as there must be a compatibility between the size of the particle to be ingested and the size of the organism doing so. Because of the abundance of organisms is also inversely proportional to their size, feeding will have less and less effect on ML distribution as the pieces are larger. This involves that smaller size classes are the main target of feeders, and particularly, these fractions compatible with the size of zooplankton (e.g. copepods, fish and crustacean larvae, Desforges et al (2015)). By feeding into the smaller fractions, and considering their numbers and higher activity, these organisms contribute to the reduction of ML fraction at these scales. The ingestion means that they introduce ML within the trophic network of the ecosystems, and therefore, it imposes an effective way that explains the limited experimental results into the topic.

Nevertheless, even if this mechanism has been observed, its quantification and contraposition respect to the biofouling is unknown. As a matter of fact, biofouling has a higher probability to happen as a given particle is older. Indeed, there is a direct connection between age of a ML particle and the biofouling that appears on that. As the breakdown process also impacts more into older pieces, it means that both mechanisms are having more effect in the smaller fractions. It is, therefore, their combination what could explain the reduced presence of ML at the smaller size classes (from tens of micrometers down to nanometers, see section 2.2 from [AD-4] for further details).

One strong point for applications is that there are good indicators pointing towards a relationship between the varied ML fractions. For instance, similar distributions, in terms of size, has been found in both Mediterranean Sea and North Pacific Gyre, once data has been normalized accordingly. The result is very encouraging as it means that an observational solution for a fraction of ML could be used to model the entire distribution of ML and its quantification at the oceans.

One of the weaknesses of the existing data, however, is that is mainly focused into ML present at the sea surface and beaches, which are, of course, more accessible to the scientific community. The processes taking place at the sea bottom are poorly known, and no good estimations about the amounts of ML and their composition in these areas have been done. In fact, only indirect information is available. For instance, ML at the bottom of the sea can be studied as the difference between floating/stranded ML and total ML introduced in the system. In this sense, monitoring rivers as main input sources is important, as only mechanism to estimate ML at the bottom. Despite of that, size composition of ML at bottom of the sea can be considered as unknown at this stage.

In terms of weight, the observational data also yields interesting results. There is a clear inverse relationship between the abundance of a size class and the mass associated to it (Eriksen et al, 2014). The estimations done by models about floating ML identify that vast majority of the total mass of ML is found at the larger fractions, particularly over 200mm in first order, and between 20-200mm in second order.

Fractions below 20mm have significantly less and less mass. This is explained by the removal mechanisms indicated above, which are related to the residence time of the object. Larger objects are less prone to fractioning before bio-fouling mechanisms remove them from the surface, so their mass does not propagate fully towards smaller fractions. Composition is also one of the factors playing a role in the mass distribution as function of the size, as explained later in this document.

The main lesson here is that large objects are important to estimate the total mass of ML present at the oceans, particularly for the floating component of it. As per sizes, there are also indications that could be possible to do reasonably good estimations of total mass of ML by targeting one region of the size spectrum. Potential EO solutions covering a part of the ML could be enough to have a reasonably understanding of ML in our oceans.

3.2.1.2 Compositional aspects

ML has a large variety of compositions and types, as large as the variety of materials persistent into the environment humans can produce. This means that sizes, colours and compositions are wide and combined in multiple proportions depending on the human activity related to the areas in which ML is generated.

The statement above means that no simple/easy characterization of total ML can be done for an EO solution in those areas in which the diversity of shapes and materials is very high, and this aspect shall be considered when defining the MRs. Nevertheless, studies done by UCA show a clear relationship between plastic ML and non-plastic ML, which encourages again the approach of targeting a fraction of ML as detection goal and infer the rest of ML population based on that. Working in retrieval algorithms with these considerations will become an important activity in the future, for which additional datasets from in-situ campaigns shall be incorporated.

The findings of the RESMALI team about the characterization of ML in terms of composition and physical properties clearly points to the plastics as the main ML type at global scale, particularly in the ocean surface waters (> 90%). Also, plastic litter appears as indicative for total ML. The analyses of colours of the plastic litter showed wide diversity, with a predominance of white (31%), transparent, black, yellow, brown and blue colours. The compilation of data from polymeric analyses of worldwide microplastic samples confirmed the clear predominance of polyethylene (PE) and polypropylene (PP) especially in the surface water layers and offshore waters, which should make the spectral characterization of ML easier.

The “simplest” case is found at open oceans, where PP and PE can represent up to 100% of the plastic ML and even of the total amount of ML. The variety of observed compositions increase towards coastal areas and beaches. The most probable mechanism explaining this gradation as a function from the distance to the coast is aging and floatability, being the areas closer to the sources the ones showing a larger family of materials.

When studying ML at the surface of the ocean, another important aspect to consider is that composition is obviously biased towards light materials able to float. This is one of the factors that explains the large differences in composition of ML found in beaches respect to open ocean. Thus, materials denser than water will be mainly found at bottom of the sea and beaches, in which the storms and tidal currents can strand them or even drag them. However, at certain distance from the coast their presence will be far more reduced and limited to those objects with shapes that ensure buoyancy by means of a high volume/surface coefficient form.

There is also a variation of composition as a function of the floating ML size fraction under consideration. For instance, large objects are found to be composed by PE, PP, but also made from PET and PS. PET and

PS have larger densities, however, and usually their subsistence at surface level is explained by the volume/surface ration. Examples of those are buoys and any other object made to float. Because of that dependence associated to the buoyancy of the objects, PS and PET made objects disappear from the surface as soon as they degrade enough to allow water in or losing any part of their design that allows them to float, and therefore, sinking rapidly afterwards. This also helps to explain why microplastics (below 5 mm) are largely composed by PE and PP. These materials have their own floatability purely based into their density respect to water. Hence, they remain at the surface whatever degradation they suffer. Only other processes like stranding, ingestion and bio-fouling impact into their presence at the surface of the sea.

Given the heterogeneity and ubiquity of the ML together with the time/economic constrains of the project, we are obliged to delimit the observation target and define the study environment. First, the open ocean and particularly the highly plastic-polluted Subtropical Gyres typically show the world's clearest waters and likely the lowest interference for the on-site spectral characterization of the ML. As mentioned above, it is also evident that plastic material is the best target into the heterogeneous spectrum of ML. Moreover, buoyant litter and especially that floating on the offshore waters shows the most homogeneous features in relation to its nature (higher plastic percentages) or polymeric composition (mainly PE and PE), which should maximize the signal to noise ratio. Finally, we are aware that remote sensors might be only able to observe a fraction of the total floating stock. In this regard, the significant relationship found between the abundance of small and large plastics is encouraging for the development of algorithms to estimate total plastic litter from the remote sensing of just a fraction of the total plastic stock.

The preliminary information obtained in relation to the spectral characterization of ML (Garaba and Dierssen, 2018) suggests there is potential in using remote sensing technology to study plastic debris. It is therefore important to first obtain more hyperspectral and high-resolution information of plastics harvested from different aquatic environments and at different stages of degradation. The age of the plastics might be related to the spectral characteristics as measured by remote sensing tools. Furthermore, the presence of surfactants on the particles might influence the known inherent spectral features of the plastics. This spectral information collected can be useful both in a qualitative and quantitative manner, to detect and quantify ocean plastic pollution from available or future satellite or aerial platforms. Further steps will involve pixel analysis to quantify the plastics present within target regions. Particulate absorption properties must be measured via a filter pad inside an integrating sphere. A glass fibre filter pad is used hanging vertically or horizontally. In order to investigate the effects of biofouling the light measurements would be carried out on fresh ocean plastics before and after cleaning with Water Peroxide Oxidation (WPO) (Masura et al., 2015). The WPO method removes organic and other materials coating the plastics in natural environments. Measurements were conducted on ocean plastics within different type and size classes using TOC's protocol and sieving systems. The experiment measurements provided an inventory of the spectral behaviour of plastic as it exists in oceanic plastic pollution hotspots. The reflectance and absorption information per wavelength can be scaled and extrapolated to identify airborne and satellite instruments to remotely detect plastic in situ. Principal optical properties of floating ML

Spectral techniques could work for ML detection if a proper spectral signature is found into the water-leaving reflectance, as caused by ML. Such approaches could consider targeting PE and PP as main contributors to plastic ML, at least for these areas in which ML composition variety would have already been trimmed out by the specific characteristics of the domain and by the output mechanisms already described. PET and PS detection would be also desirable to track/identify large ML objects mainly in the size fraction over 200mm.

From existing studies, NIR and SWIR region of the spectrum contains a few promising bands for plastic detection. In these bands, the various materials considered above show characteristic signature in terms of absorption. As a result, it is to be expected that floating ML could be, in principle, detected by these means, as water has a far lower reflectance than plastics in this spectral region.

More specifically, the current set of potential bands are at NIR (890-970nm), and three at SWIR: 1160-1250nm, 1360-1440nm, and 1680-1760nm). Maximums for absorption are found at 931nm, 1215nm, 1417nm and 1732nm. There are other minor features that could be also considered but their magnitude is far less obvious and, therefore, less promising. Lab experiments with raw materials also show that wet plastic has considerably less reflectance at these bands, as expected by water absorption. Even so, floating or slightly submersed plastics are detectable, particularly at 1215nm and 1732nm, but also at 931nm (Garaba & Dierssen, 2018).

While the above features are general for the studied plastic polymers, (PP, PE, PS, PET, PVC, PA, PMMA), the maximum of absorption vary with the type, and specific features appear/disappear at different bands. This invites the possibility of estimating presence of different components over the observed pixels. However, further studies will be required to refine the current data available in this matter and to develop specific techniques to separate the spectral information observed in these bands in comparison with spectral libraries.

In terms of abundance, there is an obvious decrease of the reflectance as the percentage of the surface covered by plastics reduces. Very low concentrations could be challenging to detect based on the data, what means that large objects would be better detected with very high spatial resolutions, to ensure large coverage of the pixel by pastic, and the case of microplastics will require more detailed radiative transfer analysis and development of high signal to noise sensors.

Additional studies are also being carried out to understand better the signature of ML in other spectral regions, like in the area of microwaves (1mm to 1m of wavelength). While this detection method is unlikely to introduce information about composition, it could support into the finding of accumulation zones and hot spot, whenever the local concentrations are enough to introduce an effect into the local roughness. Indeed, it is expected that reflectivity of the materials will be differential from sea water surface, and patches of ML could be detected in this way, supporting other detection techniques. Currently, a variety of experiments are being run into this field, in order to better understand the potential of exploiting the reflectivity of plastics at microwave bands, which could have also a polarization effect associated to the shapes of ML.

3.2.2 Summary of time and spatial scales significant for ML observation

3.2.2.1 Principal spatial distribution characteristics

One of the main difficulties currently impacting the understanding of ML is, precisely, the poor spatial coverage of the existing studies, which joins to the sparse frequency in time. The total amount of the ocean surface that has been sampled by towing techniques is negligible. Similarly, coastal and beaches areas, which have been further studied, are also poorly sampled in most of the cases. In addition, many of these studies have been focused on predictable or known accumulation zones, what means that extrapolating their results would imply a probable bias in the determination of the spatial scales of ML.

Because of that, most of the information associated to spatial scales relevant to ML come from numerical models, in which the ingestion of ML estimations, based on different scenarios and/or with known in-situ data, allows for the analysis of a predicted field of ML based onto the hydrodynamic models under consideration. This approach has two advantages: a) It benefits of existing knowledge about ocean dynamics and predicts the behaviour of ML as a neutral oceanographic tracer; b) it allows to perform analysis about the behaviour of ML at different spatial scales. The last point is rather important, as it means that ML follows similar scales than the oceanographic phenomena, and therefore, any mission focused into ML shall address them directly, or indirectly. It also explains one of the main limitations of the towing methods or beaches, in which the spatial and time information is frequently lost as result of the integral method for data collection (e.g. accumulating ML by dragging a line of a few kilometres) that remove any signal at mesoscale and microscale.

Models and the existing sampled data show that ML is not homogeneously distributed around the surface of the oceans. The centres of the sub-tropical gyres have proven to be accumulation zones, with estimations of having 1000 times more ML than other "open ocean" conditions (e.g. Eriksen et al, 2014). Additionally, semi-enclosed seas and basins are also accumulation zones. In this sense, maximums have been detected in the North Pacific Gyre, and into the Sea of Japan, when goes to estimate the long-term large-scale concentrations. Once more, ocean dynamics is clearly the main driver associated to the spatial distribution of ML. Other factors to consider is the presence of main rivers and human population. Their role to understand ML spatial distribution is key, as they are the main point sources from which ML spreads around the seas. Being able to detect the input events and the sources is considered one of the main goals of any EO mission for ML monitoring, what naturally imposes some limits to the spatial resolution of the potential instruments. For the diffuse contamination, however, larger scales could be achieved, as they offer wider spatial patterns.

The main limiting factor for the remote detection of ML likely arises from the low percentages of surface covered by plastic on the ocean, and consequently the low spectral signal at the sensor. Studies performing wide-range analysis of the sea surface covered by floating plastic litter are very scarce. To our knowledge, only Goldstein et al. (2013) has reported this kind of information for the North Pacific Gyre, combining samplings with surface plankton nets and visual census. Taking advantage of the recent surveys carried out by TOC and UCA in the North Pacific and Mediterranean respectively, we are currently exploring the range of sea surface covered by plastic in two different accumulations regions.

Region	Size interval (cm)					Source	Macrodebris sampling
	0-2 cm	2-10 cm	10-30 cm	> 30 cm	Total		
North Pacifc (low range)	0.00000%	0.00000%	0.00000%	0.00002%	0.00002%	Goldstein et al. 2012	Visual census
Near-shore Med waters	0.00012%	0.00021%	0.00026%	0.00021%	0.00080%	MIDAS project (unpublished)	Mega-net
North Pacifc (high range)	0.00040%	0.00100%	0.00320%	0.01540%	0.02000%	Goldstein et al. 2012	Visual census

Table 1: Percentages of sea surface covered by plastic in relation to the size interval (0 - 2 cm, 2 – 10 cm, 10 – 30 cm and > 30 cm) for the North Pacific Gyre (including low and high range estimates) and the Mediterranean Sea accounting for large sampling areas (> 100 m). Methods to sample large debris are also shown.

Table 1 shows the available data, converging on (i) the high contribution of the large-sized debris to the total plastic surface, and (ii) the extremely low percentages of sea surface covered by the plastic litter. Even under the best-case scenario, the total surface covered by plastic on the ocean is quite lower than 0.1%. Nevertheless, we must consider that these estimations correspond to the average percentage over wide sampling areas (> 100 m), likely integrating high small-scale heterogeneity. Therefore, one of the best ways to increase the capacity for remote sensing of marine plastic litter is by increasing the spatial resolution of the spectral instruments. For considerably low observation areas (in the tens of cm), the percentages of sea surface covered by plastic might rise to 100% for large-sized debris. In this regard, the appearance of small-scale surface aggregations of ML could also trigger a spectral response observed by the sensors. However, the formation of these aggregations would make the detection capacity dependent, for instance, on the wind regime. Therefore, the best observation scenario would require wind regimes being comparable and ideally favouring the formation of small-scale aggregations to improve the detection capacity. In this framework, the knowledge of the conditions promoting structures of small-scale aggregation (e.g. steady and moderate winds) or the ML density into these aggregations appears as relevant objectives for the present EO mission. Based on the recent field surveys carried out by TOC and UCA, these gaps are expected to be filled in the upcoming months.

From the above it is possible to deduce that two main phenomena shall be targeted, and they are also linked to the spatial scales of ML. For instance, accumulation zones are important, in order to identify them and monitor them. However, monitoring shall consider the appearance of hot spots, as they act as an impulse of input ML into the system and because opens further applications, like detection of frontal areas, which are of relevance for the ecology of marine ecosystems, specially the pelagic ones. Hot spots are, frequently, short-lived accumulation zones, which can be correlated to specific events (e.g. land flooding, river watershed increments, tsunamis, container dropping at the sea, etc.). Temporary hot spots are expected to be of far smaller scales (clearly in the order of 1-5km or even below that), but accumulation zones like sub-tropical gyres of semi-enclosed seas could be monitored at larger scales. It is worth to mention here that all accumulation zones are hot spots, but not all the hot spots are accumulation zones.

Nevertheless, the situations in both cases are far more complicated than that. For instance, ML composition (both materials and sizes) of accumulation zones can substantially differ between them and from other types of hot spots. Sub-tropical gyres are characterized mainly by microplastics (0.5-5mm) and PE-PP materials are dominant. But hot spots at a river mouth will contain larger fractions in significant abundance and with a variety of materials covering from metal (e.g. cans), glass (e.g. bottles), PET (e.g. bottles, containers, packing), PS (e.g. boxes), etc. Beaches are also accumulation zones with their own dynamics, and variety of materials found there can be considerable, with a potential high contribution of organic components provided by near rivers during flooding events (e.g. drift woods, vegetation) or appearing naturally in the area (e.g. seaweeds).

In terms of common concentrations of ML, as per in situ campaigns, are set in the order of a few million pieces per km^2 in sub-tropical gyres, up to a few thousand particles per km^2 outside these areas. In practical terms, expected coverage at scale of kilometres is set between 2 to 20 ppm [AD-04]. It is to be proven that these averaged concentrations can yield spectral signature observable by instruments at large distances from the sea surface. It also means that accumulation zones or hot spots provide better chances for detection by means of the optical properties of ML rather than diffuse contamination present at the oceans (low concentrations of particles). Linked with this, it has been found that wind has a very important role into ML selection and accumulation. Windrows of ML have been commonly found in the continental shelf and coastal areas, particularly when wind conditions are steady and Langmuir circulation cells are established. These cells act as temporary convergence zones that accumulate ML in the form of lines a few hundred meters long and a few tens of metres wide. With enough spatial resolution these windrows can be resolved, and concentrations per area would also increase, what would favour detection.

By analogy, any general convergence zone at the sea will favour ML accumulation. Between others, these are: frontal zones including downwelling areas (e.g. ML accumulations found at the Artic), eddies at mesoscale (Figure 1), and the already mentioned large scale ocean circulation. The magnitude of the accumulation changes with the scale of the phenomena and the compositions will also vary accordingly to their time scales.

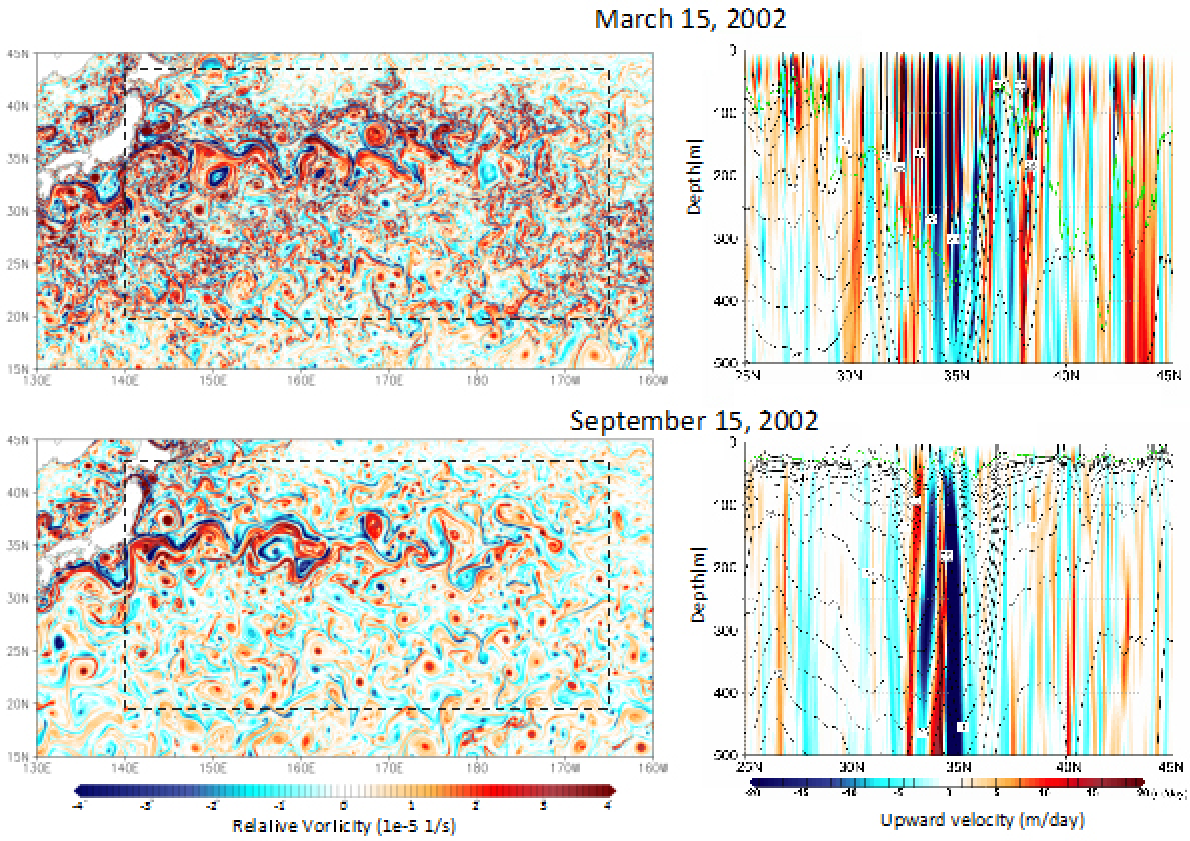

Figure 1: Surface relative velocity in the North-western Pacific in winter (March 15, 2002) and summer (September 15, 2002) (red colour indicates warm clockwise eddies, and blue indicates cold anticlockwise eddies.). Right: North-south cross sections of vertical velocity of 155˚E (colour) and density (contour). Around the Kuroshio Extension flowing eastward in the North-western Pacific from the South Coast of Japan, sub-mesoscale eddies (several km-50km) and filament structure are ubiquitous (top left), while mesoscale eddies (100km-300km) are dominant in summer (lower left). In winter, strong vertical motions with horizontal scale up to 50km are observed in the mixed layer with 200-300m thickness, where the density is about the same as at the surface (upper right), and vertical motions are weak in summer when the mixed layer depth is shallow (lower right). Credits: Jams Tec.

When considering the vertical axis of the ocean, distribution of ML seems to be rather uneven. Buoyancy of the items is the main factor driving this vertical distribution. When materials are naturally denser than seawater, they accumulate at the bottom of the sea, whatever domain they appear in. This is clearly the case in the shores and beaches, and probably in the areas acting as main inputs of ML. Some of the items can also float due to the relationship between volume they have and the surface. However, this floatability is temporal and, if enough time is provided, they end at the bottom once degradation and breakdown cause the loss of their geometric properties. Lighter materials usually remain at the surface, due to their high buoyancy. They do so despite of degradation and breakdown, and only ballasting caused by organisms attaching to the items allows them to appear at different depths. However, it is the case that objects reaching a neutral floatability obtain additional density by ballasting short after they reach this status, so their residence time in intermediate waters is short. These phenomena mean that the practical totality of ML appears whether at the bottom or the surface of the ocean.

Studies done in the water column have shown an exponential decrease of ML within the first 5 metres, with the largest fraction appearing at the very top. Only these elements which, by composition or ballasting, have a density closer to water appear below the first centimetres of the surface. The vertical profile, however, is affected by wind. Mix processes associated to vertical turbulence can force ML to appear at different degrees with the depth (Figure 2). The degree of mixing will be related to the wind speed (WS), the significant wave height (SWH) and the composition of the items. Once more, vertically there is a zoning associated to the composition of the materials. PP, PE and PS are less prone to mix at the water column due to the very low density they have, so only very extreme weather conditions will favour their appearance deeper in water. But again, biofouling can change these properties, so certain amount of ML could be also expected within the water column associated to the atmosphere-ocean interface.

It could be possible to build models that, by considering SWH and WS can estimate the concentrations within water column based on the information available at surface level. They can be very useful to correct ML estimations performed just by the content found at the surface weather. It is worth to mention here that conditions favouring mixing could involve difficulties for detection or estimation. Ideally, information of the water column would have an added value in any EO solution applied to ML.

In coastal areas, effect of vertical mixing is expected to be stronger as we approach to the shoreline. There waves breaking and strong dynamics associated to tides can favour it. Distribution of ML in coastal areas and beaches, however, will be strongly dependent of the local inputs, local hydrodynamics and the geomorphology of the area. These factors can produce, even in coastal areas close in distance, entirely different ML patterns, both in composition, size, mass and characteristics. Because of that, it is difficult to tailor global solutions, even if they are one of the main hot spots in terms of ML. Techniques that could work in these areas shall have into account the geological characteristics (e.g. nude rock vs sand banks, gravels of different sizes, presence of natural boulders, slopes, etc), which add up into a larger variety of materials and size classes, as coastal areas have less selective processes, and therefore, ML can be found in all the orders of magnitude in terms of size.

The above characteristics imply that, for beaches and near coastal areas, high spatial resolution could be a strong requirement for direct detection, or alternatively, enough spatial resolution to detect relative variations of relevant properties (e.g. roughness or radiometric variations).

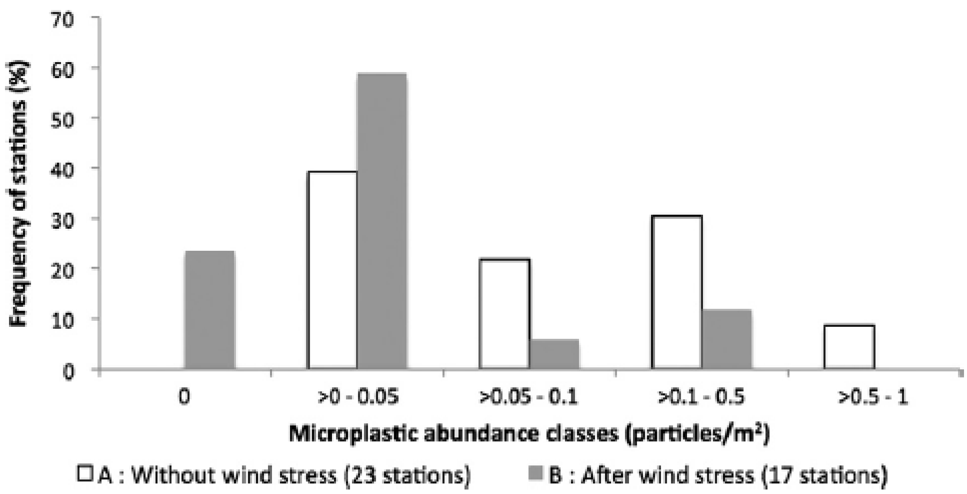

Figure 2: Frequency of the stations related to the classes of microplastic abundance (particles/m^2) for both parts of the survey (without wind stress and after wind stress). Sampling done over the first 10 cm of the column water. From Collignon et al, 2012.

The impact of wind is important in other aspects. For instance, effect of wind dragging will be different depending on the size class under consideration and their composition. Larger objects and items with high floatability will offer larger emerged fractions. Shape is also important, as flat or laminar shapes will offer far less surface to wind than spherical/tubular or parallelepiped shapes. Small object will be less prone to be dragged directly by wind. This means that wind stress over the surface of the ocean can produce fractioning of sizes and shapes, classifying materials. This dragging by wind is the only force opposing marine currents and ocean dynamics when goes to ML transport, and it could be very relevant to understand what part of ML generated at the coasts and/or introduced by river mouths can be displaced out of these domains.

In addition, the vertical mixing effect will also differ depending on the size of the particles. In general, smaller particles are more likely to suffer vertical mixing than larger objects. This has been well observed for particles below 5mm (Collignon et al, 2012).

The implication of these patterns is that vertical mixing shall be regarded as important depending on the goals of the specific application. These targeting large objects will not require so much attention to vertical distribution than those related to small particles (below 5mm).

3.2.2.2 Principal temporal distribution characteristics

Temporal distribution of ML suffers of entangled problems with spatial distribution: There is not much information about the ML variations on time and most of the available information is currently based into models. Therefore, temporal dynamics is, once again, driven by the natural time scales associated to the marine environment. There are, however, some exceptions into this rule. Seasonality of ML has been predicted by models associated to seasonality of ML production into the sources. Studies link this seasonality with rains cycles (Lebreton et al., 2017) through the rivers and any other continental watershed connected to precipitations. The connection is done because ML accumulates into the riverine areas during the dry seasons, and when the flooding seasons come, water drags these ML towards the oceans.

These observed seasonal behaviours are found in rivers, and subsequently, they also appear in the beaches and coastal areas. The pattern for coastal shelf and open ocean areas is, on the other hand, unclear. There is still lack of data and knowledge about ML explaining the mechanisms linking coastal areas and river mouths with ML concentrations appearing at the sub-tropical gyres and semi-enclosed seas, for example. The presence of rivers with significant amounts of ML seems to be well correlated with the maximums of concentrations found into the accumulation zones, but no seasonality is observed in these areas, and seasonal injection of ML is not well observed into these accumulation zones. One of the goals for an EO mission would be, precisely, to support the resolution of these processes, as eventually helps to understand where the ML introduced in the system goes.

There could be a few explanations for these variations of the time scales associated to each domain under consideration. One is practical, which is the fact that accumulation zones are poorly sampled on time. Multiple campaigns should be conducted every year in a given area and spamming throughout a few years in order to allow for identification of seasonal effects. However, in most of the areas in which a regular sampling has been provided, the frequency rarely gets over an annual campaign. On the other hand, rivers are far more monitored and easier to tackle, as much more options, and cheaper, are available to the scientist to control the presence of ML into them. Beaches have similar advantage, what could explain why seasonality is easily observable.

But despite of that sampling effect, which could be not enough to resolve seasonality in certain regions, no clear patterns of accumulation have been observed in the long term. The very few cases in which regular monitoring has been performed in accumulation zones (basically into the North Pacific sub-tropical gyre) show no trend in terms of ML present at each campaign. While production rates of plastic have increased constantly since the appearance of plastic production technologies, no special increase has been observed in terms of ML accumulation, which is surprising.

This characteristic means that additional mechanisms are taking place in that inter-phase between coastal areas and river mouths with the open oceans and continental shelves (Figure 3). One of the possible explanations could be the impact of local dynamics as natural barriers of ML. For instance, coastal counter-currents and contour currents happening in the coastal shelf can act as physical barriers preventing the transport of ML into further distances (Thiel et al., 2003). In this way, most of ML injected by river mouths would remain at short distances from the coast, and therefore more prone to get stranded at the shores or sinking there due to mechanical and photochemical degradation plus the increased productivity of these areas due to existing upwellings and better conditions favouring primary production. These conditions also mean a large presence of organisms that can further remove ML by means of ingestion of the pieces and transfer them to the trophic network. Under such consideration, coastal areas and areas in general with a high productivity will result in shorter residence time at surface or in water for ML items.

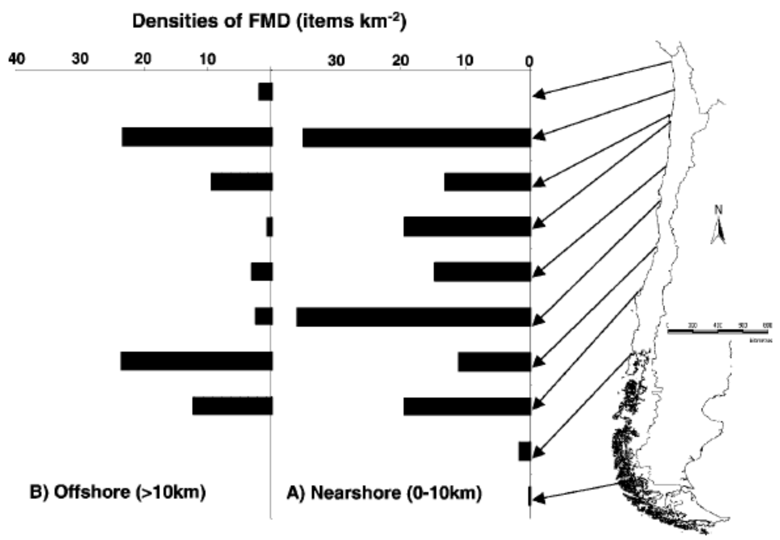

Figure 3: Densities of floating marine debris (FMD) in (A) nearshore, and (B) offshore waters of the SE-Pacific off the Chilean coast. From Thiel et al, 2003.

On the contrary, open ocean waters tend to have far lower productivity due to the lack of nutrients supporting primary production. They have less influence also in the mechanical breakdown of materials due to friction with gravels/rocks as it could happen at shores, plus the obvious lack of stranding possibility; so in general, at open ocean, the main processes involved into ML removal are the effect of UV radiation and ingestion by organisms, whenever the particles have the right size. Even this last one will be also of far less influence in open ocean accumulation zones, due to, precisely, the lower productivity, what makes populations of organisms substantially smaller than in areas with high productivity. These means that these areas are expected to have far longer residence times.

The previous paragraphs imply that ML appearing in open ocean could be mainly due to in-place inputs (i.e. fishing activity, ship wreckage, intentional dumping, container droppings, etc.) plus ML transported to these areas by extreme events (e.g. particularly intense flooding over some land areas, storms, tsunamis, strong winds, hurricanes, etc). These differences in terms of ML origin have been consistently reported as indicated in previous sections. The explanation is compatible with the above statements, as in any case, under normal circumstances, ML shed at water could take months or even years to reach certain areas at open ocean, and removal mechanisms will have more chances to act before they reach these parts of the ocean. Similarly, this duality between the domains help to understand the splitting of ML composition and why plastic ML variety at open ocean is far more limited: Only these items which properties makes them more resilient to removal mechanisms would survive time enough to reach these regions.

Most of the above has no proper information to be held but raises the importance or relevance in detecting ML inputs under these events, human or nature driven. A high temporal resolution could help into a better understanding of these processes and how ML is selected and transported to the middle of the ocean. This would also help detection of ML when it is still at high concentrations in the shedding areas and before items spread around due to ocean dynamics and wind dragging. Identifying and, potentially, quantifying them would be of high value to introduce data into models supporting the management and monitoring of ML at sea (Figure 4).

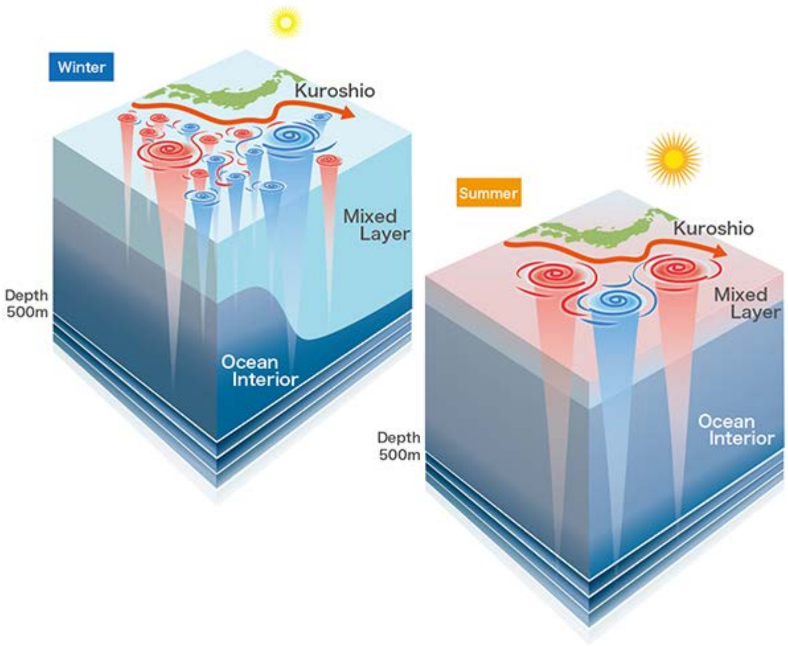

Figure 4: Seasonal changes in mixed layer depth and eddy activities. In winter, the mixed layer with consistent density at sea surface becomes thicker because of cooling of ocean surface with lower air temperature and strong surface wind due to active atmospheric cyclones (left). On the other hand, the mixed layer depth is shallow in summer due to calm wind and stronger solar radiation (right). Sub mesoscale structures (small scale eddies and filament structure) become active when mixed layer depth is large in winter (left), while becoming calm in summer when the mixed layer is shallow (right). As the season changes from winter to summer, a kinetic energy cascades from sub mesoscale to mesoscale structures, gradually growing the scale of active oceanic structures. Credits: JamsTec.

Additional time scales could be of interest in certain regions and/or domains. For instance, shorelines and beaches will be highly affected by tides. As a result of that, ML can substantially vary in these areas between tidal cycles, with stranding taking place from high to low tide, and recovering from low to high. As a rule, ML stranded at beach will only remain into it if it is allocated over the line of maximum tide, and therefore, following also the time patterns of tides. The materials in the inter-tidal zone are likely to be constantly stranded and recovered until energetic events (like storms) put them above that tidal line. Other mechanisms like wind or rain can also bring back materials, particularly if the density of materials is low and their size small. These processes are relevant as they determine the fraction of ML that can be found in these areas. Heavy and large items are likely to get stranded and remain at the high parts of the beach, accumulating there, while small fractions can “disappear” by transport back to the water or getting buried under sand accumulation (e.g. sand bar formations or dune dynamics). Of course, in touristic areas, local policies for ML management are also an ultimate factor for removal, if well many of these mechanisms will target ML over a certain threshold value of size, the other fractions remaining at the beach because of their size being similar to the granulometry of the sand/gravel.

As with the spatial scales, ML will also follow time scales corresponding to the general ocean dynamics, as per transport mechanisms of the floating debris. These ocean dynamics will also bring seasonality in some of the cases. Examples of that can be found by the association of ML to mesoscale circulation (e.g. Lebreton et al., 2012). These structures have their own seasonality and lifetime, which will determine the dynamics of ML and temporary accumulation zones.

In order to properly study beaches and shorelines, high temporal resolution would be required (sometimes even sub-day scales as per tidal cycles).

3.2.2.3 Concurrence of ML at different scales

It has been addressed in the previous sections the importance of the concentration of ML in order to define requirements. At this point, detection of presence of ML is a good enough target, even if aiming quantification and even composition is of high interest for the community. A binary detection (yes/no) per pixel or even a rough estimation of abundance (e.g. percentage of the surface covered, rough estimation of particles into the water column) would mean an important advance for ML experts. In fact, the possibility to couple hydrodynamic models with ML as particles transported by the velocity field allows to improve the understanding of ML dynamics. Accumulation zones can be predicted and the mechanisms connecting the sources with the accumulation zones could also be better understood. One of the advantages of that is that ML could be tracked at certain degree back to the source, critical point to drive environmental policies for its management and control. It also means that no complete information about ML is required even if desirable, to achieve a good degree of understanding and monitoring.

Quantification would be a great addition if technically possible, as it would allow to introduce diffusion equations (both turbulent and Brownian) into the models and predict behaviour of the detected sources. Diffusion mechanisms will impact differently to the particles depending of their size, due to the role of viscose friction as the particles become smaller. In general, solution of these equations implies knowing the concentration field or the mass of the shed, plus the velocity field. Due to that, any addition in this line to an EO solution would become a significant improvement.

One of the challenges here is to define a potential good target for an EO solution. The difficulty relies on the large variety of conditions, properties and phenomena associated with ML. When defining a target concentration, spatial resolution is important. For instance, a very high resolution could allow to detect individual objects if they are large enough but would likely limit to a "binary" monitoring for smaller items (i.e. presence or not of ML). Diffused contamination or presence of ML would require integration of data at larger scales. It is not necessary to identify microplastics one by one but knowing their concentration in a given area would be of large interest. In addition, large items accumulate most of the mass, but their abundance is also far inferior than to the smaller fractions (and particularly the range between 0.5 to 5mm). Hence, detection of large items and estimation of concentrations for the microplastics are desired objectives.

Alternatively, targeting accumulation zones and hot spots would be also a goal for the mission. The advantage of these is that ML is found in larger amounts and, hence, potentially easier to detect. In the case of events, ML would appear quickly in the medium and covering surface areas that could be observable. However, there are large differences between temporary accumulation zones and steady ones. This differentiation is important when defining the parameters for their observation. Temporary accumulation zones are quite often associated to "extreme" events as already indicated: floods, intentional dumping, storms, etc. They also appear in natural convergence zones, like the indicated windrows [AD-04]. Steady accumulations are usually happening associated to long time scale and large spatial scale phenomena (e.g. sub-tropical gyres).

The first ones have some advantages for detection. For instance, the concentrations are far higher than in the steady ones under normal conditions. They can also be expected by their connection to their original cause, in some of the cases. The downside is that their spatial scale is far smaller, generally, what implies needs for a higher spatial resolution. On the other hand, steady accumulation zones can cover vast parts of the ocean, and hence requiring less resolution, but they are also substantially less concentrated so detection techniques would probably have to improve in terms of sensitivity and SNR.

In this problem, understanding the patterns of size distribution for each domain can mean an important help. There are indications of ML sizes having an aggregational behaviour. For instance, there is a correlation between the sizes classes found in towing field campaigns in terms of abundance. This opens a window of opportunity for estimating the population of ML starting from just a part of it, by means of inferential techniques. The observed concurrences in terms of size classes are also found when targeting only plastic ML with respect to the non-plastic ML or total ML. These tools could be very helpful to cover predictable gaps into the data.

3.3 Preliminary Mission Requirements

The definition of Mission Requirements (MRs) for a potential EO mission devoted to ML detection and monitoring is a complex task. As deductible from the previous discussion, the nature of ML is wide and multiscale, both in time, space and size. This means that MRs are entirely defined by the potential applications and the characteristics of the domain to which they apply.

Because of that, the following approach has been derived, in order to produce the best solution as MRs in this document and, eventually, within the project. In a first order approach, general MRs are provided under the basis of the following three concepts:

- The general domain characteristics.
- The general ML characteristics per defined domain.
- The ML characteristics per size fraction under consideration.

Specific threshold and goal values are provided for each of the cases and listed parameters relevant for a mission of these characteristics are reported.

With this information, the specific MRs are found as the most restrictive combination of values obtained by crossing the relevant domain, ML general characteristics and ML fractional characteristics. Therefore, this methodology allows for the identification of different MRs for varied scenarios, depending on the application under consideration. Such applications are based on the scientific requirements imposed by the scientific and expert community, which has already identified some of them, in general terms.

In view of the Technologies and Techniques Assessment, the idea is to explore the provided MRs for each of the scenarios identified as per interaction with the community and during the performed Applications Analysis. This assessment allowed for the determination of the applications with a better likelihood of being technologically possible using current technologies or by affordable improvements in existing ones.

The result of the first assessment indicated also potential caveats in the knowledge base of ML applied to these applications, plus also narrow the range of initially good targets for an EO solution. During the second iteration, a refinement of MRs was done by further collecting data, via continuous bibliography assessment, the additional experimental data, plus discussions and interactions with the community.

The result of the second iteration was the identification of the best technology or technologies that shall be considered, based on their best technological possibilities and application coverage. The technology or technologies identified were then combined to produce the Mission Concept proposed for the RESMALI team.

The advantages of this approach are that allowed for a better definition of final MRs and technologies to meet them in a field of expertise that is very recent. At this point, remote sensing applied to ML is just in an exploratory phase, and full expertise linking both worlds is not yet developed. As a result, requirements are very varied and based onto limited studies and limited knowledge about ML, in many cases obtained by means of educational guessing done by the community and supported with models of limited capability up to date. This is one of the clear outputs of the 1st Workshop for Remote Sensing of Marine Litter held at ESTEC. Therefore, a tree approach in which the different branches are pruned until converging to a feasible solution seems a better way to obtain meaningful results from this activity.

3.3.1 Mission requirements per domain-induced variability and scales

As explained in the introduction of this section of the document, MRs for remote sensing of ML depend on both the characteristics of the domain and ML, and their final selection is entirely dependent on the targeted applications.

The analysis of the domain characteristics produces the following MRs (Table 2):

MR	Domain			
	Open Ocean	Continental Shelf	Coastal area	Shores & Beaches
Spatial Resolution	1-5km	20-250m	20-100m	1-20m
Time Resolution	2w – 2m	1-2w	3-7d	<1-7d
Coverage	Global	Global	Regional	Regional
Water penetration	Not essential	Added value	Desirable	N/A

Table 2: Summary of MRs per domain-induced variability and scales.

The choice of these parameters is based on the characteristic scales associated to the natural dynamics of the different domains and having into account enough resolution to resolve them with a good degree of accuracy. Note that the characteristics of ML in these domains (e.g. horizontal and vertical distribution, regional variability, etc) have been also taken into account, so the parameters are not entirely independent of ML. In this case, spatial resolution is required to be better than the scale representing the domain. In general terms, observational scales shall be better than the “objects” they want to resolve so to capture the features to characterise them. A second reason is that spatial variability of ML is expected to be larger than the variability itself of these domains, henceforth requiring higher spatial resolution to avoid representativity errors.

Characterization of ML into the water column is also difficult to assess in terms of requirement. ML can appear within the first 5m of the water column. However, most of it accumulates into the surface, and presence of ML below surface counts for a small fraction of the total. Wind and sea conditions are also very relevant to explain the amounts of ML within the water column. This means that in most of the cases, observation of ML within water column can be considered a goal rather than a threshold or condition for many applications, as models could be constructed to take into account for these other factors and infer ML in water column depending on the wind and sea conditions.

3.3.2 Mission requirements per fraction and characteristics

Similarly, as with the domain, MRs will also vary depending on the final set of applications and the targeted fractions of ML, which have distinguishable characteristics. Based on the available information, the following MRs are identified as a function of the ML fraction (Table 3):

MR	ML fraction			
	> 200mm	**200-5mm**	**5-1mm**	**<1mm**
Spatial Resolution	0.2-1m	20-250m	1-5km	1-5km
Time Resolution	<3d-4w	1-2w	2w – 2m	2w – 2m
Coverage	Global	Global	Global	Global
Water penetration	Not essential	Desirable	Added value	?

Table 3: Summary of MRs per ML fraction characteristics.

These MRs are based in the definition of the potential applications. For instance, large items (over 200mm) are not very frequent and they are likely to appear isolated in many cases. They, however, count for most of the total mass of ML at the oceans. Therefore, a proper census of them would be of relevance, and that would impose a high spatial resolution in order to be able to count them and, in some cases, to monitor them throughout the time. Smaller pieces are far more abundant, and if a way to determine their abundance in a given pixel would be of interest, individual identification is not required, so information integrated at larger scales is enough to characterise them at global scale.

In terms of temporal resolution, applications are the main drivers, and specific values shall be identified at each case. However, as we target coarser spatial resolutions, time becomes less important, and larger time windows are acceptable.

Water penetration, again, is not deemed as essential but of added value. Large items are usually detectable with information at surface, and due to their low occurrence, underwater detection cannot be considered a restriction. In the range between 5 and 200mm, however, particles have been observed in certain amounts within water column, specially under windy conditions. Obtaining information about them would be useful, if not essential. Below 5mm there is a clear selection in terms of materials so most of them are expected at surface level. However, their estimation within water column would be of great interest, as this size class has the largest abundance and is within the range more accessible to organisms (e.g. plankton). For the smallest fraction (below 1mm) not enough information is known about its vertical distribution to constrain any MR. In fact, MRs are basically the same of the size class of 1-5mm, assuming similar properties in terms of spatial distribution, time scales and extension.

Material composition of ML does not appear in this table as characteristic. The material composition information is correlated with the size class, i.e. smaller floating items have generally lower density, that means they tend to be composed generally of P and PP. Consequently, the material composition of ML becomes a dependent parameter in the MR definition (i.e. dependent from the size class).

3.3.3 Identified EO applications and their specific Mission Requirements

The RESMALI team has identified the following applications for remote sensing of ML, based on the information gathered up to this stage of the project, and from the 1st Workshop of Remote Sensing for Marine Litter at ESA/ESTEC. It is worth to mention that these applications are of different nature, corresponding also to the high variety of ML experts, who work at different domains and with different targets. Additional interactions with the community are required to further define these applications and obtain a better consensus about the goals a mission of remote sensing for ML should accomplish.

Within the spectrum of potential applications, five of them have emerged as of more interesting for the community:

1. Detection and identification of large ML items at the ocean.

2. Detection and quantification of concentrations of ML at global scale.

3. Detection and monitoring of hot spots and accumulation zones.

4. Monitoring of river mouths as main input flow for ML at the oceans.

5. Detection, monitoring and quantification of ML at shores and beaches.

Each of these applications imply rather different requirements. The following sections analyse each of them and determine the specific MRs for each one. As explained in the introduction, the MRs are determined by crossing the existing tables of MRs (Table 2 and Table 3) as a function of the domain and of the ML fraction being targeted. It is expected that the technologies assessment plus additional interactions with the community will imply refinement of the MRs and a narrowing into the list of best applications, which can also evolve throughout the project.

3.3.3.1 Detection and identification of large ML items at the ocean

There are many reasons why to monitor the large ML items appearing at the surface of the ocean.

To start with, they count for most of the total mass of ML, so any estimation of a global balance of total ML existing at the oceans shall have them into account. A global census of the large items would be of importance to establish the global status of the ML issue.

In addition, large items will concentrate around hot spots. Their detection can help to identify sources of ML into the ocean and potential accumulation zones. They can serve indirectly to improve maritime security and support search & rescue services around the world.

Other aspects why they are of interest are that they act as passive neutral oceanographic tracers. The possibility to monitor their displacement in time would help to improve the existing data and knowledge about surface marine currents. At the same time, due to the link with the currents, it will help to provide data to model ML behaviour and distribution around the world and better understand the formation of the accumulation zones.

Finally, tracking of large items could help to obtain further information about the aging and evolution of ML at the sea, one of the main gaps existing in the current data sets. Because of their size, they have more resilience to degradation and breakdown (at least far away from coastal border and shores), so they could be used as natural experiments to obtain further details about these aspects of ML.

This application naturally targets open ocean and continental shelf domains, areas in which global circulation and mesoscale phenomena take place.

The characteristics of this application are as follows (Table 4):

Scale	Global to regional
Domain(s)	Open ocean, continental shelf
ML fraction(s)	>200mm
Goals	Detection / Quantification / Monitoring / Identification / Characterization
Time scales	1-3 days

Table 4: Application characteristics for detection and identification of large ML items at the ocean.

Taking that into consideration, the resulting MRs would be (Table 5):

	Threshold	**Goal**
GSD	<1m	20cm
Revisiting time	3d	1d
Coverage	Regional	Global
AOIs	Ocean basin level	Coastal border
Objectives	Detection, Quantification, Monitoring	Detection, Quantification, Monitoring, Identification, Characterization

Table 5: Summary of MRs for detection and identification of large ML items at the ocean.

Examples of identifications would be buoys, ghost nets, large containers. Characterisation would involve classification of the plastic polymer, which could perhaps be achieved in these situations, if we consider that we get pure pixels of a single polymer.

3.3.3.2 Detection and quantification of concentrations of ML at global scale

Another application of interest for the community consists on the detection of the spatial distribution of ML at the surface of the oceans and the estimation of the concentrations. The application will allow for the identification and understanding of the global patterns of ML regardless their size class. Comparison of global maps within the time will serve also to understand the time evolution of ML and measure the impact of the human activity and policies on the ML presence at the oceans.

The application does not focus into individual identification of objects, it targets the integration of ML information and moderate spatial scales. The generation of ML anomalies (i.e. by subtracting of the “permanent” term) would allow for detection of ML dynamics (e.g. evolution of the steady accumulation zones, hot spot detection), becoming an application of great interest for the management of the ML problem and in view to drive environmental policies.

One derived application would also be the provision of assessment for other sectors of the economy (e.g. marine aquaculture, tourism) in order to prevent potential damage, plus also support the management of areas of interest, whatever for economic or environmental reasons, supporting their protection and conservation.

In this case, detection is considered already a good achievement (ML *vs.* no ML), and quantification as desirable if possible. Characterization would be also of interest (e.g. via spectral analysis of reflectance).

Construction of time series in this application is very relevant, as it supports the definition of ML anomalies plus also understanding better ML dynamics in the middle to long term. Time scales short enough to capture seasonality are wanted, ideally with capability for early detection of hot spots.

The characteristics of this application are as follows (Table 6):

Scale	Global
Domain(s)	Open ocean, continental shelf
ML fraction(s)	All
Goals	Detection / Quantification / Characterization
Time scales	2 weeks to 1 month

Table 6: Application characteristics for detection and quantification of concentrations of ML at global scale.

Taking that into consideration, the resulting MRs would be (Table 7):

	Threshold	**Goal**
GSD	5km	1km
Revisiting time	1 month	2 weeks
Coverage	Global	Global
AOIs	Ocean basin level	Coastal border
Objectives	Detection	Detection, Quantification, Characterization

Table 7: Summary of MRs for detection and quantification of concentrations of ML at global scale.

3.3.3.3 Detection and monitoring of hot spots and accumulation zones

With some similarities to the previous case, this application focuses on the surveying of hot spots and accumulation zones of high concentration. The goals are to detect the occurrence of events producing significant inputs of ML, its quantification and characterization. Hot spots are defined as concentrations of ML in areas of special relevance, whether they are temporary or steady places. Accumulation zones are understood as places in which ML significantly concentrates within time. They are considered acutely contaminated areas due to punctual or persistent events. The application does not aim at the detection of individual items.

The scales for this application are founded into the characteristics of these acute events. Of interest are the inputs generated by intentional/accidental dumping, and temporary accumulation zones associated to ocean dynamics (e.g. windrows associated to Langmuir cells). Also, because many of these events can be associated to human activities or as result of floods/storms over land areas, coastal border takes relevance here, with some spatial attention (but not limited) to river mouths.

In terms of time scales, and due to the focus on acute episodes that can disappear due to ocean dynamics in short periods, a good temporal resolution is also required (in the scale of days). With a good temporal resolution knowledge, it is possible to track how the mass of ML evolves from the date of appearance, giving very useful time information for models. These episodes will allow also to better understand their relevance into the total mass of ML at the oceans and support the development of policies to prevent them or mitigate them.

While detection is important, quantification provides the right added value for this application. Characterization of ML would be also of interest, but not as critical as the detection and quantification of these events.

Again, some derived applications could be provision of support to search & rescue services and early intervention to retain/remove punctual but intense spills of ML at the seas.

The characteristics of this application are as follows (Table 8):

Scale	Global
Domain(s)	Open ocean, continental shelf, coastal border
ML fraction(s)	All, but with high concentrations
Goals	Detection / Quantification / Characterization / Monitoring
Time scales	1 to 3 days

Table 8: Application characteristics for detection and monitoring of hot spots and accumulations.

Taking that into consideration, the resulting MRs would be (Table 9):

	Threshold	Goal
GSD	100m	20m
Revisiting time	3 days	1 day
Coverage	Regional	Global
AOIs	Coastal border	Global ocean
Objectives	Detection, Quantification	Detection, Quantification, Characterization

Table 9: Summary of MRs for detection and monitoring of hot spots and accumulation zones.

3.3.3.4 Monitoring of river mouths as main input flow for ML at the oceans

One aspect also of interest is the monitoring of the main known input sources, so to help to determine the ML flows in the marine environment. One of the gaps is, precisely, a proper estimation of these inputs and their later evolution within the system. Moreover, monitoring of river mouths will also serve to better identify the points of origin of ML, information very relevant to induce governmental policies for litter control and mitigation.

In this area, rivers are known to be one of the main input points of ML at the seas. Rainfall events at land, drag riverine litter towards the ocean, what also brings seasonality to ML presence at coastal areas, beaches, and potentially also to the continental shelf. No clear connection, however, is found with ML concentrations at the sub-tropical gyres.

Because of the target, specific constrains are imposed to the MRs driven by this application. Proper spatial resolution is required to detect and quantify these inputs so to have accurate values. In addition, proper time sampling is also required to have information enough to integrate the total volume/mass of ML being introduced at the sea by rivers.

For this application, determination of the composition of ML is also very relevant. Such information helps to better understand the main contributors to the total ML, which cannot be estimated only from open ocean information, due precisely to the removal mechanisms. Estimating such compositions supports the understanding of the selection mechanisms that explain ML at open oceans and also bring useful information to numerical models, which can use such data plus the hydrodynamics to map and predict the transport of ML from sources towards the rest of the areas of interest.

As ML inputs from rivers are directly connected to human presence in the riverine areas, regional studies are probably best option than a global scale monitoring. This can be more restrictive in terms of the technologies that can be applied, but it helps also to improve the opportunities to obtain the necessary information. In addition, the nature of these inputs has also a huge temporal variability, especially in magnitude, as rains and floods are explaining the largest inputs of ML. Hence, a high temporal resolution is required for these areas, so not to miss the acute events.

The characteristics of this application are in Table 10 and its MRs in Table 11.

Scale	Regional
Domain(s)	Coastal border
ML fraction(s)	All, but with high concentrations and potential ID of large objects
Goals	Detection / Quantification / Characterization / Monitoring
Time scales	From hours to 1 day

Table 10: Application characteristics for monitoring of river mouths as main input flow for ML at the oceans.

	Threshold	**Goal**
GSD	20m	<1m
Revisiting time	1 day	12 hours
Coverage	Regional	Regional
AOIs	Coastal border	River mouths
Objectives	Detection, Quantification, Monitoring	Detection, Quantification, Characterization, Monitoring

Table 11: Summary of MRs for monitoring of river mouths as main input flow for ML at the oceans.

3.3.3.5 Detection, monitoring and quantification of ML at shores and beaches

Beaches are one of the main accumulation zones for ML, due to direct deposit of litter from human activity or by stranding associated to the physical dynamics of these areas (storms, tides, winds…). They have also a huge impact into the local economy of the populations living near to them, and at larger scale, at nation level.

Because of that, and because they are the most visible manifestation of the ML issue, beaches have been the focus of many activities and studies in comparison with other domains. Management of ML in these areas is key.

Accumulation of ML at beaches is due to many factors, but among the others we can find the proximity to the sources (or input points like river mouths) and the possibility that the ML get stranded as response to the natural dynamics of the oceans/seas. Extreme events like storm, sudden sea level increases associated to low atmospheric pressure, or high tides force ML to get accumulated in the inter-tidal part of the shores and beaches, and in the high part of them. Inter-tidal ML is usually recovered by the tidal cycles, but the items reaching the dry sand will remain there for much longer periods. Wind also acts as an accumulation factor, and the specific geomorphology of the coastline with respect to it and dominant currents also has a significant role when defining ML accumulations on beaches.

All these characteristics impose a high spatial and temporal variability. There are additional restrictions in terms of requirements associated to the size of the domain. Most beaches around the world are very narrow (from a few metres to a 100m width) and their length is also very variable (a few tens of metres to a few kilometres). Their characteristics are also very heterogeneous in terms of geometry, colours, shapes, and nature.

Because of their economic impact, the agents interested in ML observation from a remote sensing perspective require commonly quantification of items and their characterization. The last point can be especially challenging, since ML on beaches is far more varied than in other domains. Because of the dynamics, floatability is not a requirement, and denser materials can be easily found (glass, metals, for example). Still, most of the ML is of plastic nature, so techniques able to detect plastic ML would still be valid for these areas, as far as their signature can be discriminated.

The high time variability also imposes high temporal resolution, with a minimum of 1-day revisiting time and ideally even less to consider tidal dynamics (i.e. 12 hours). The spatial scales of the domain also imply a requirement of high spatial resolution.

The characteristics of this application are as follows (Table 12):

Scale	Regional
Domain(s)	Shores & Beaches
ML fraction(s)	All
Goals	Detection / Quantification / Characterization / Monitoring
Time scales	From hours to 1 day

Table 12: Application characteristics for monitoring of river mouths as main input flow for ML at the oceans.

Taking that into consideration, the resulting MRs would be:

	Threshold	Goal
GSD	10m	20cm
Revisiting time	1 day	12 hours
Coverage	Regional	Global
AOIs	Local Shores & Beaches	Global Shores & Beaches
Objectives	Detection, Quantification, Monitoring	Detection, Quantification, Characterization, Monitoring

Table 13: Summary of MRs for monitoring of river mouths as main input flow for ML at the oceans.

3.4 Techniques and Technology Assessment

3.4.1 Candidate techniques for RESMALI

Under the primary goals of RESMALI, detection and characterization of debris can be achieved either by imagery or radiometry techniques. The following sub-sections cover the different options.

3.4.1.1 Visible imagery techniques

The size of the marine plastic debris ranges across several orders of magnitude, from nano- or micrometers to meters in the case of the so-called "ghost nets" (drifting fishing nets entangled with various floating materials, also including plastics). After aggregation (under the effect of the wind, tides, currents…) the patches of debris can reach hundreds of meters in length and tens of meters in width.

Figure 5: Example of large floating debris released by the March 2011 tsunami in Japan, and corresponding satellite image acquired by WorldView-2 (GSD in PAN ≈0.5m) the 14th of March 2011 (image presented at the American Geophysical Union Fall Meeting, 2012)

Figure 6: Example of windrow, one type of aggregate of debris (image taken by Caroline Power along the coastline of Roatan, near Guatemala).

The advantage of visible imagery techniques is that they resolve objects that cannot easily be detected by other means. For instance, passive radiometry techniques with coarser resolution integrate the signal associated to the water-leaving reflectance of the ocean's surface. This means that the relevant information is the integrated signal per unit area. However, these methods can easily ignore large and not very frequent objects, which are small compared with the footprint of the pixel and, therefore, do not trigger an anomaly. On the other hand, high concentrations of microplastics in a given area may have an overall impact on the reflected spectrum, which also triggers measurement opportunities.

As presented previously, the geographical distribution of the count density of debris is inverse to the density of mass, meaning that the debris smaller than 5 mm represent most of the occurrences, but at the same place in the ocean, the large debris account for the vast majority of the mass of plastic ML (cf. Figure 7 for an example of simulated result). While their low frequency makes of them a harder target for other techniques, they are good targets for visible imagery. Consequently, their identification and census could be a good proxy for the estimation of the floating stock at first order.

The tracking of large floating debris could also provide information on sea surface transport (as do drifting buoys). While visible imagery is not able to provide useful information about the plastic marine litter fraction corresponding to small size classes, it has a complementary role to other methods e.g. for correlation between large debris counts and other microdebris density.

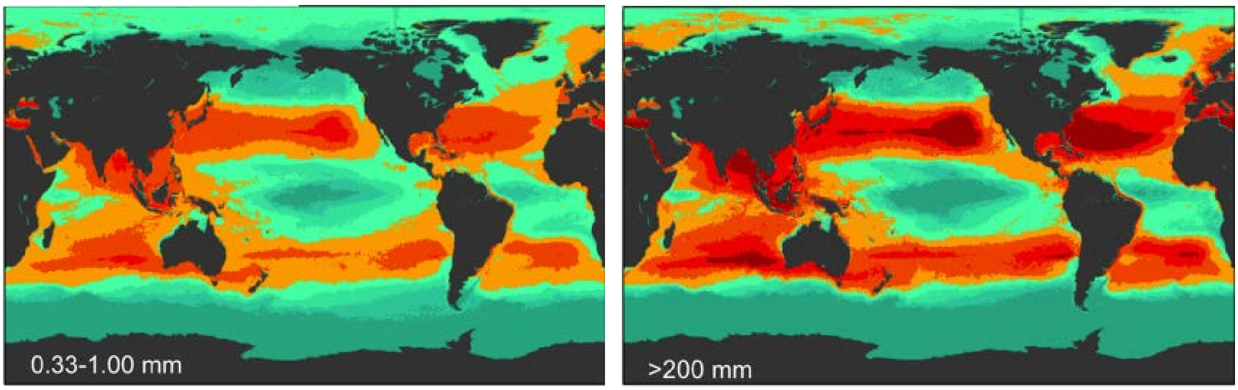

Figure 7: Modelled count density of microplastic in the class 0.33-1.00 mm [left] compared to the modelled density of mass for the class >200 mm [right] (extracted from Eriksen et al, 2014).

For the purpose of detecting floating debris by imaging techniques, the critical instrumental parameter is the spatial resolution. The best available performance for non-military missions being 25-30 cm in panchromatic (PAN) at the time of writing, the minimum apparent size for debris detection will be of the same order of magnitude. This limits the field of application to large debris, detected individually and possibly tracked over a given area of interest. With a swath limited to a few tenths of kilometres, a swarm of LEO satellites would be required to cover the global ocean every week or month. Or only a few areas of interest of a few tenths of km^2 could be covered by one satellite on the same temporal basis.

A variety of image processing techniques, starting from colour-aided contrast enhancement or spatial pattern recognition, can be used to detect the largest debris at sea, as they will contrast enough against the ocean background. With an enough revisit, these algorithms could even provide opportunities to track large items identified in different images by means of correlation functions. One major challenge of automatic single-look detection at sea will be the false alarms due to foam, white caps and floating organic objects (trees, algae, whales…), for which spectral data will be key in sorting the detection hits. The NOAA has made use of WorldView-2 multispectral images to investigate on a debris detection and characterization method using spectral properties (presented at American Geophysical Union Fall Meeting, 2012).

Classical visible imagery is a promising remote sensing technique for detection and characterisation of ML. It has the best chances to detect large objects, which are necessary to assess the total mass and to understand their concurrence with other size classes. The huge amounts of very high-resolution data will be a challenge for image processing (detection and filtering of false alarms).

Visible imagery is not further detailed here since its applicability to the remote sensing of ML seems well understood, and from the point of view of the sensor technology it does not represent a feasibility issue.

3.4.1.2 Proposition of most promising technique

At this early stage of the expression of the mission needs, many sensing techniques could contribute to the understanding, quantifying and modelling of the general ML issue. Due to the huge spectrum of temporal and spatial size scales, and the vertical distribution of the ML from the surface to a few meters underwater, ideally all of the techniques identified as relevant candidate could bring their stone to the edifice.

If a sorting by order of priority had to be done (and no doubt it has to at some point), we propose on the Figure 8 an example of sensor selection trade-off depending on the mission needs. It appears that very-high resolution imagery and LiDAR bring their own specific capabilities (detection and tracking of large objects and underwater measurements). The issues for the first are in the economic field (image cost) and in terms of amount of data to be processed. For the latter, beyond the cost of the system itself, the feasibility of the measurement from space of suspended ML using inelastic backscattering (bringing the most valuable information on the nature of the ML) remains to be demonstrated.

Hence the spectro-imaging techniques seem the most promising if the measurement of floating ML concentrations turns to be a significant step forward by the users and the scientific community. Note that the measurement of greenhouse gases has followed a similar path from global estimates of column-averaged concentrations to the recent attempts to retrieve the anthropogenic fluxes closer to the sources on ground.

But the feasibility of measurement of ML surface concentrations from space cannot be taken for granted. It was addressed in the second part of this study in complement to the work performed by (Garaba and Dierssen, 2018). In a first approach, a multispectral instrument with a few dedicated spectral bands for the detection of synthetic hydrocarbons could be a good candidate.

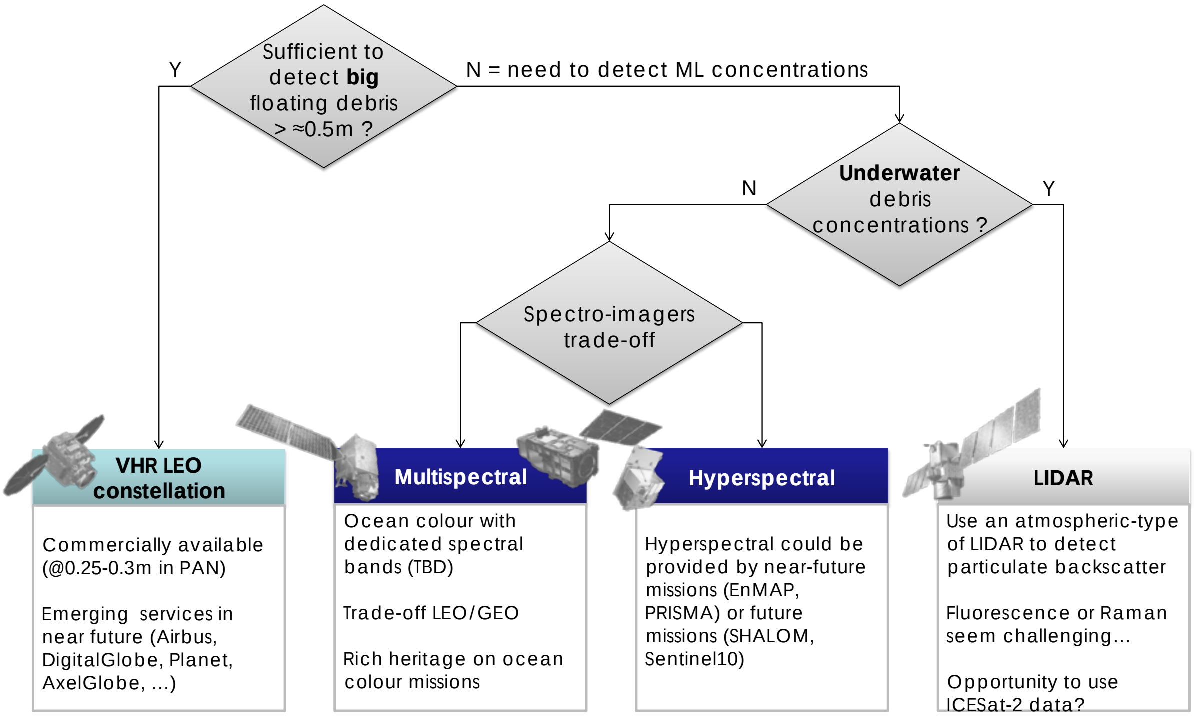

Figure 8: Trade-off on optical sensor type depending on mission needs (images of satellites for illustration only).

3.4.2 Existing capabilities: Sentinel-2

Besides the activities within the project RESMALI, the team has benefitted of additional effort that was actually born within the project. ARGANS Ltd. Has run side projects with a specific focus in the possible exploitation of existing satellite imagery for the study and monitoring of ML. Results of these side projects have been used in RESMALI, as well as this project has helped them. This occurred cross-fertilisation is showed in the next sections.

If well these activities were not originally included in RESMALI, it has been considered opportune to add them to this report, as they are key to understand some of the choices done by the team for the Mission Concept (see Chapter 5).

Two projects led by ARGANS Ltd were participant of this exchange of information:

- SSGP-201802-17 “GeoInt Service for Marine Litter” (UKSA, United Kingdom)
- ESA Contract 4000124861/18/I-NB “EO tracking of marine debris in the Mediterranean Sea”, in the frame of the EO Science for Society Open Call in the Directorate of EO Programmes.

Each of those yielded interesting results that helped to address the assessment of existing technologies for RESMALI.

3.4.2.1 GeoInt Service for Marine Litter

The project “GeoInt Service for Marine Litter” was a feasibility study funded by the Space for Smart Government Programme (SSGP) from the U.K. Space Agency (UKSA). It took place during February to August 2018, with the participation of the Environmental Agency and Cornwall Council as End-Users.

Whilst the SSGP project aimed to explore the possibility of extracting marine litter information from existing multispectral and VHR imagery, RESMALI aimed to identify how the optimal instrument should be. Of particular interest are the selection of the spectral bands that shall be used for such optimization, which are not necessarily present in current imagery. This is probably one of the main reasons of the current difficulties to detect marine litter in existing satellite data. It is clear, however, that complementarity of instruments will be required. In this sense, high resolution SAR could be a good candidate to support the observations. As proposed in the SSGP project but also analysed in RESMALI and other organizations specialized in SAR instruments (e.g. Remote Sensing Systems, and IsardSat), this technology has capability to detect floating debris appearing at the surface of the ocean, due to the change into the dielectric properties of the surface within the microwave region of the spectrum. Those active sensors could, henceforth, support optical and multispectral data to identify accumulation zones and clouds of debris, helping to discriminate the marine debris with respect other floating materials. Combination of both technologies becomes, therefore, a good candidate for a potential mission with this goal.

3.4.2.1.1 Application to the case of Marine Litter

The problematic of floating wastes detection might be similar to the *Sargassum* raft detection, all the more than wastes/debris rafts are mainly composed of vegetation (trunks, branches, bush, macro algae…) aggregated with plastics and other wastes, being the floating component mainly of organic nature or artificial polymers. Such waste rafts may have an optical sign that can be separate from the sea and then observed from space.

In the water, the floods of trashes which go out the river mouths further to huge precipitation and run-off are alike –for instance, images herein below (Figure 9).

Figure 9: Comparison between drafts of marine debris (left) and Sargassum (right).

So, the problematic of floating wastes detection might be similar to the Sargassum raft detection, all the more than wastes/debris rafts are mainly composed of vegetation (trunks, branches, bush, macro algae…) aggregated with plastics and other wastes. So, such waste rafts may have an optical sign that can be separate from the sea and then observed from space.

In addition, though marine litter does not contain chlorophyll, internal work has shown that, using non-vegetation indexes of the kind that work for *Sargassum* detection, it is possible to spot drifting marine litter (Figure 10). An example is shown herein below with Sentinel-2 and Sentinel-1: Honduras / Roatan Isle, 26 Oct 2016 following torrential rains in Guatemala on Oct 16 and an outflow of waste by the river Motuga. For Sentinel-2/MSI, the algorithm considers spectral properties of plastics (used on conveyor belts in recycling plants to distinguish plastics from glass, metal, vegetables, etc.).

If true, and we could track marine trash rafts further to the land wash and run-off by rivers, it may be a critical improvement for marine litter landing forecast.

Hu et al (2012) seems to make possible to distinguish trash from the ocean background as other EO marine specialists are able to spot and make a difference between different drifting seaweeds and oil slicks.

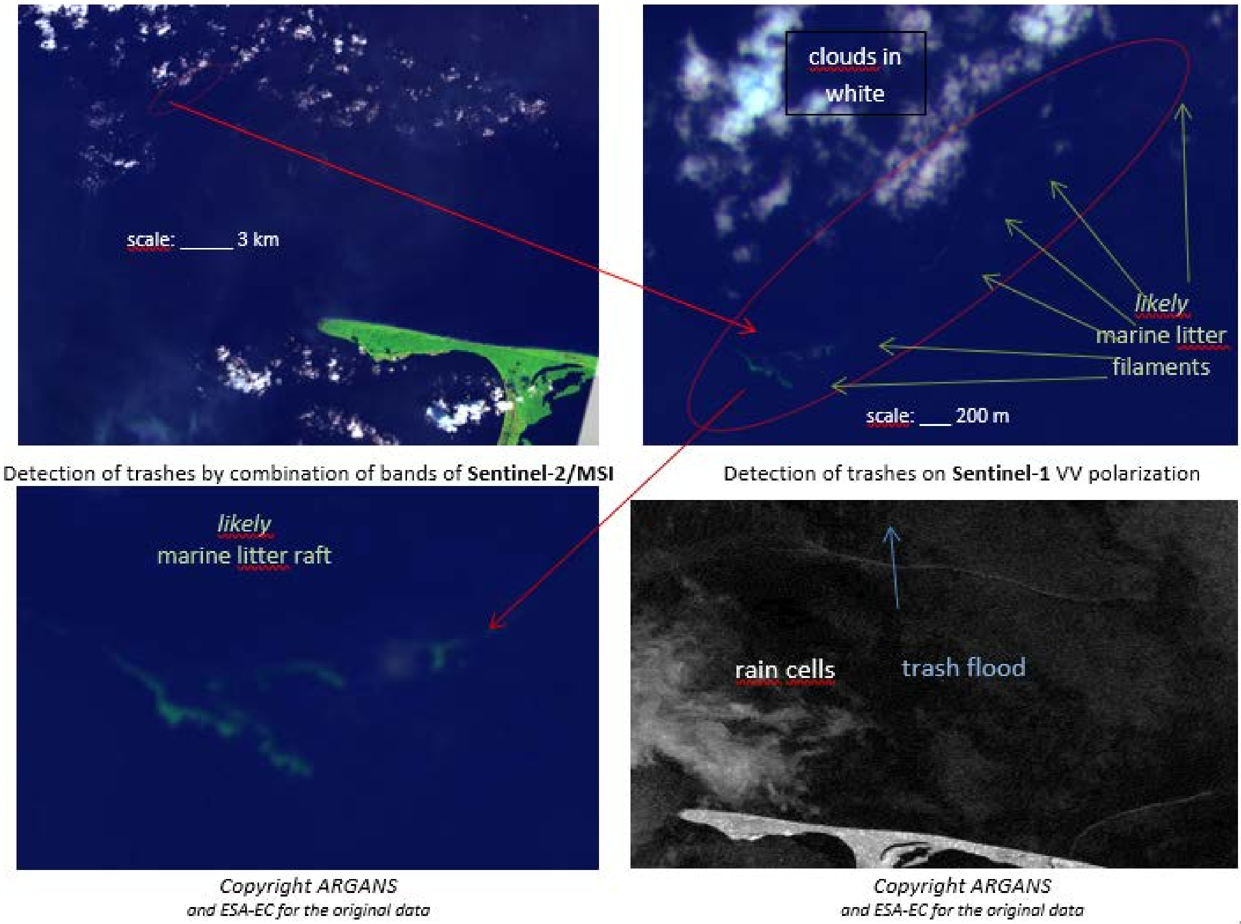

Figure 10: Sentinel-2 and Sentinel-1: Honduras / Roatan Isle, 26 Oct 2016 following torrential rains in Guatemala on Oct 16 and an outflow of waste by the river Motuga.

3.4.2.1.2 Case studies

This section describes the results produced from each of the case studies, using the methodology depicted above. Each case study is presented using a Sentinel-2 image of each area of interest (AOI) used to derive the spectral signature produced from each surface type. These are followed by plots (A) showing the multispectral profile of each AOI, taken as the average reflectance values across all Sentinel-2 Bands. These data are presented alongside the average reflectance values for the five bands of particular interest, highlighting the reflectance characteristics of each AOI in the visible (Band 2, 3 and 4), NIR (Band 8), and SWIR (Band 11) wavelengths. Following this, scatter plots (B) compare the reflectance values of all pixels across specific band combinations. The band combinations chosen for comparison are: Band 4 (Visible Red) / Band 8 (NIR), replicating the NDVI comparison ratio; and Band 8 (NIR) / Band 11 (SWIR). These band combinations were chosen as they appeared to show the greatest contrast between litter, vegetation and water pixels. These data show the range of reflectance values produced by each surface type. The final plot (C) summarises these results, with a single co-ordinate describing the average reflectance value in each of the compared bands, while showing the potential variability with one standard deviation error bars. Both plots B and C include the average vegetation index values produced by pixels within each surface type AOI.

3.4.2.1.2.1 Los Angeles River (USA)

Analysis of multiple Sentinel-2 images over an 18-month period (October 2016 – April 2018) reveals that the amount of debris in the boom, placed along the Los Angeles river, varies, with the largest amount observed in the period directly after a storm. The Californian winter of 2016/2017 was one of the wettest on record, with over 100 inches of precipitation over the Sierra Nevada Mountains (Climate.gov). During these months (Jan 2017 – Mar 2017), the garbage boom appeared to regularly fill up; the image produced on the 23/02/2017 shows the boom at its fullest (Figure 11, left). A more recent image from 05/03/2018 is used as a comparison, where the boom appears less full (Figure 11, right).

The multispectral reflectance data of the LA River garbage boom and surrounding surface types are described by a pair of Sentinel-2 (L2A) products:

SENTINEL-2A_MSIL2A_20170223T184421_N0204_R027_T11SLT_20170223T184421- 23/02/2018 (Figure 90)

SENTINEL-2B_MSIL2A_20180305T183229_N0206_R027_T11SLT_20180305T203124- 05/03/2018 (Figure 90)

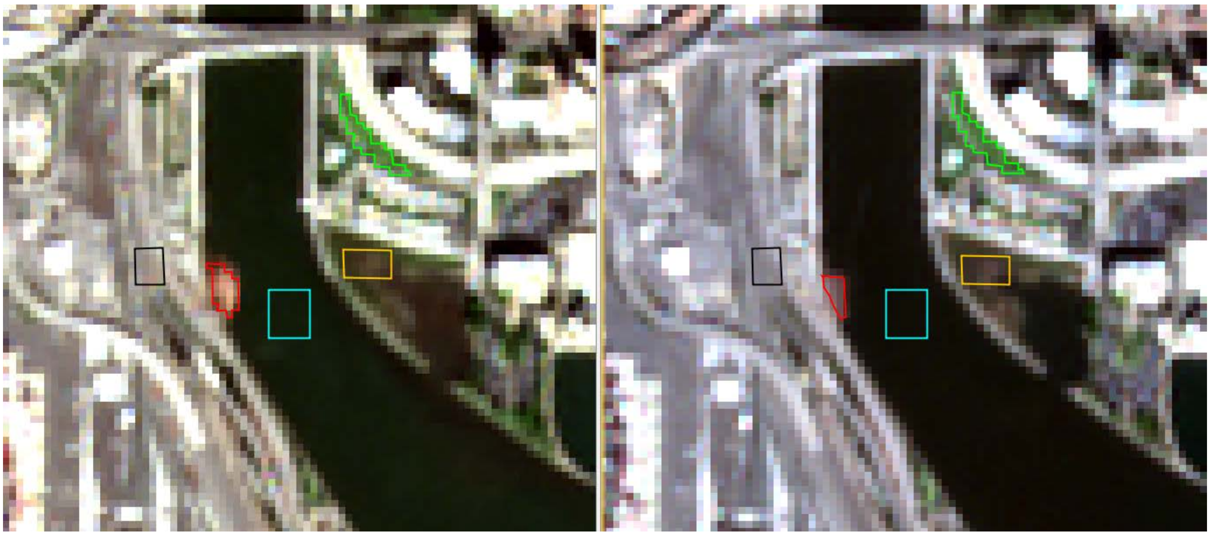

Figure 11: Natural colour Sentinel-2 (L2A) image of a Garbage Boom on the LA River on the 23/02/2017 (left) and 05/03/2018 (right). Natural colour RGB (Band 4 / 665 nm, Band 3 / 560 nm, Band 2 / 490 nm). Coloured polygons indicate pixels used to describe reflectance values of each surface type. Black = Urban, Red = Litter, Blue = Water, Green = Trees, Yellow = Grassy Lagoon. Source: Copernicus hub.

This part of the LA River provided multiple surface types to be compared including: Open Water within the river channel, built up Urban areas including buildings and roads, Vegetation in the form of trees, and Grass in an area surrounding a Lagoon (see Figure 11).

3.4.2.1.2.2 Lesbos Island (Greece)

The multispectral reflectance values of the three artificial plastic targets, placed in the Mediterranean Sea off the coast of the Greek island of Lesbos are described by the Sentinel-2 (L2A) product:

SENTINEL-2A_MSIL2A_20180607T085601_N0208_R007_T35SMD_20180607T114919 – 07/06/2018 (Figure 12).

In addition to the three targets, pixels describing the reflectance values of open Water in both shallow and offshore areas are extracted for comparison with the artificial targets.

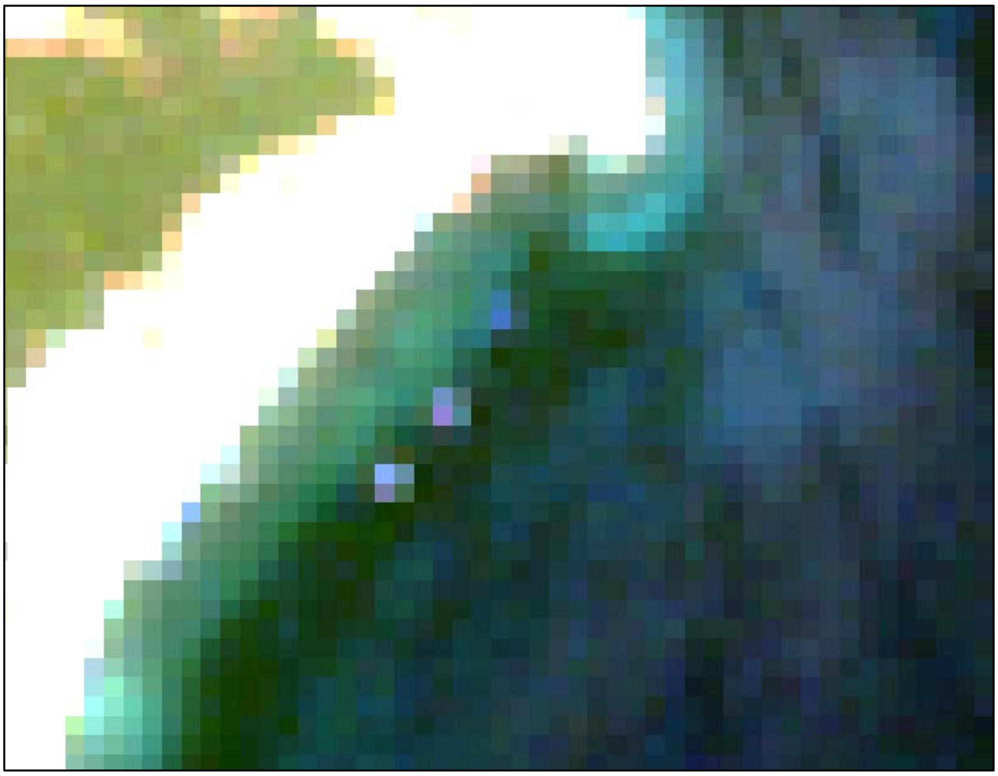

Figure 12: Natural colour Sentinel-2 (L2A) image of Lesbos Island, Greece on 07/06/2018. Natural colour RGB (Band 4 / 665 nm, Band 3 / 560 nm, Band 2 / 490 nm). Coloured polygons indicate pixels used to describe reflectance values of each surface type. Blue = Blue plastic sheet, Yellow = Fine Yellow Fishing Net, Red = Plastic Bottles, White = Open Water, Green = Shallow Shoreline. Source: Copernicus hub.

Figure 12 showed that it was possible to observe the 10x10 m targets in Sentinel-2 images. Despite using targets with dimensions equal to a single Sentinel-2 pixel resolution, the three plastic types appear to influence the reflected irradiance of four adjoining pixels (red, yellow and blue squares in Figure 12).

3.4.2.2 EO Track of Marine Litter in the Mediterranean Sea

Earth Observation (EO) Tracking of Marine Debris in the Mediterranean Sea from Public Satellites is a feasibility study funded by ESA in the frame of the EO Science for Society Open Call and focused on assessing the value of public satellites in tracking Marine Debris in the Mediterranean Sea. The project team successfully developed the EO Processor for Marine Debris (MD) Detection, a platform capable (in ideal conditions) of automatically detecting MD targets greater than 50 m^2 in Sentinel-2 images.

MD describes an aggregate of surface material, including floating vegetation and man-made plastic waste. Plastic litter in the Mediterranean Sea poses a significant ecological threat (Fossi et al., 2017; Poeta et al., 2016; Suaria et al., 2016), containing an estimated 24.7 x 10^{10} pieces of marine litter at any one time (Eriksen et al., 2014). Until recently, observation of MD relied on costly aerial observations and ship surveys. Typically, the first indication of MD issues occurs during beaching. Recent improvements in publicly accessible satellites, specifically Sentinel-2 have enabled regular observations at a spatial resolution with the potential of monitoring MD events offshore.

The successfully implementation of the EO processor provides critical information on MD locations, which could then be used to determine marine litter dispersion routes and potential beaching events, as well as a more accurate assessment of the Marine Litter problem faced across the globe.

The development of the EO processor was led by ARGANS, who specialise in EO satellite Ground Segment specification, development and operations, as well as data exploitation (real-time and re-processing), with a strong emphasis on data Quality Control, validation data processing chains and uncertainty assessments of outputs. ARGANS currently manages the Sentinel-2 Mission Performance Centre, under C-S. ARGANS maintains a lead position on the Litter-TEP (Thematic Exploration Platform) project, utilising wind and wave forecast data from ESA’s CMEMS project to model flows of Marine Litter in the North Atlantic. ARGANS has also worked with local UK based authorities, under the Space for Smarter Government Programme for the UK Space Agency, to deliver one of the first feasibility studies on detecting Marine Litter from EO data.The project boasts a strong team of partners, each providing significant expertise in the field of marine litter and remote sensing studies. These partners not only bring expertise, they also represent potential end users, and as such have significant insight into future development direction. This group includes: Stefano Alliani (SA), Head of the SCOR working group on Marine Litter; Konstantinos Topouzelis (KT) who has published on the validation of Sentinel data with drone data and conducted innovative experiments on the remote sensing of Marine Litter targets using Satellites and Drones; and Andrés Cózar (AC), an expert on Marine Litter developments who has published in National Geographic. Their inputs provided vital information on the state on marine litter in the Mediterranean Sea, providing in-situ validation information of MD targets identified in the field and completion of survey assessments on the performance of the EO processor, its value and potential as a service.

The EO processor has undergone verification and validation testing, in which plastic validation targets were successfully identified during ideal conditions. Testing showed that the EO processor worked best during cloud free conditions, with limited glint and low sea-bed reflectance (ideal conditions).

The EO processor has many advantages over traditional monitoring methods (ship/aerial survey and beach clean-up operations), key amongst these is the ability to deliver information at a far greater scale, and at a much lower cost (financial/time). The EO processor can automatically assess an entire Sentinel-2 image, monitoring a potential 10,000 km^2 area of open water, and identify rafts of MD. The processor has shown its ability to identify rafts as small as 50 m^2 (50% of one S-2 pixel), and is designed to report on location of windrows (elongated rafts of MD), which can vary in size from 10’s of meters to over a kilometre in length.

Importantly, the EO processor has been developed in just twelve months; in this short period, it has already demonstrated very promising capabilities. With further investment, this platform could be developed to its full potential. Accordingly, a service roadmap of future improvements has been clearly defined. In this 18-24-month plan, MD tracking capabilities will be enhanced, employing surface drift models such as the Litter TEP (Thematic Exploration Platform) currently being developed by ARGANS. This period will also allow time to adapt the EO processor to work with other satellite data, increasing both spatial and temporal frequency and increasing the probability of viewing MD during intermittent cloud conditions. Finally, this period will allow the team to increase the portfolio of verified MD case studies, providing a wealth of data from which to allow smarter Artificial Intelligence (AI), and improving the accuracy of MD detection. These investments and technical improvements will build on the successes of this project and ensure the EO processor is relevant, valuable, adopted and exploited by the user groups identified by the project team.

3.4.2.2.1 Summary of activities

The EO tracking of marine debris in the Mediterranean Sea project, was a twelve-month project, funded by the European Space Agency (ESA) under the EO Science for Society (EOEP-5, block 4) funding scheme. In partnership with academic and governmental partners from Mediterranean countries, ARGANS as prime led the project to determine the feasibility of monitoring MD from publicly available satellites. The project began in September 2018. The main objectives of this project included:

- Assess the scientific background for EO monitoring for MD, and development of an automated EO processor. (Task 1)
- Develop an algorithm and processor for routine ML detection from Sentinel-2 data. (Task 2)
- Validate results with in-situ case studies and field work campaign. (Task 2)
- Produce a roadmap for potential improvements in methodologies and capabilities of the service. (Task 3)

To achieve these objectives, work has taken place under the Project Management of ARGANS (Task 4). This work is described in the following sections.

3.4.2.2.2 Scientific Background and system specifications

The first task of the project focused in four key areas.

1. Determine the scientific background of EO monitoring of MD, as a baseline for algorithm design.
2. Determine the functional requirements of an EO processor.
3. Assessment of existing EO processors for automatic classification of optical data.
4. Develop a portfolio of MD cases studies for EO processor development and validation testing.

3.4.2.2.3 Results

Figure 13 demonstrates the classification scheme when applied to a MD target, most likely a Sargassum windrow off the coast of Cuba. In this example, most of the target has been classified as low to medium confidence, while a few pixels at the outer edge of the raft are highlighted as high confidence. Further analysis of observations made by the decision matrix are discussed in the Verification results section.

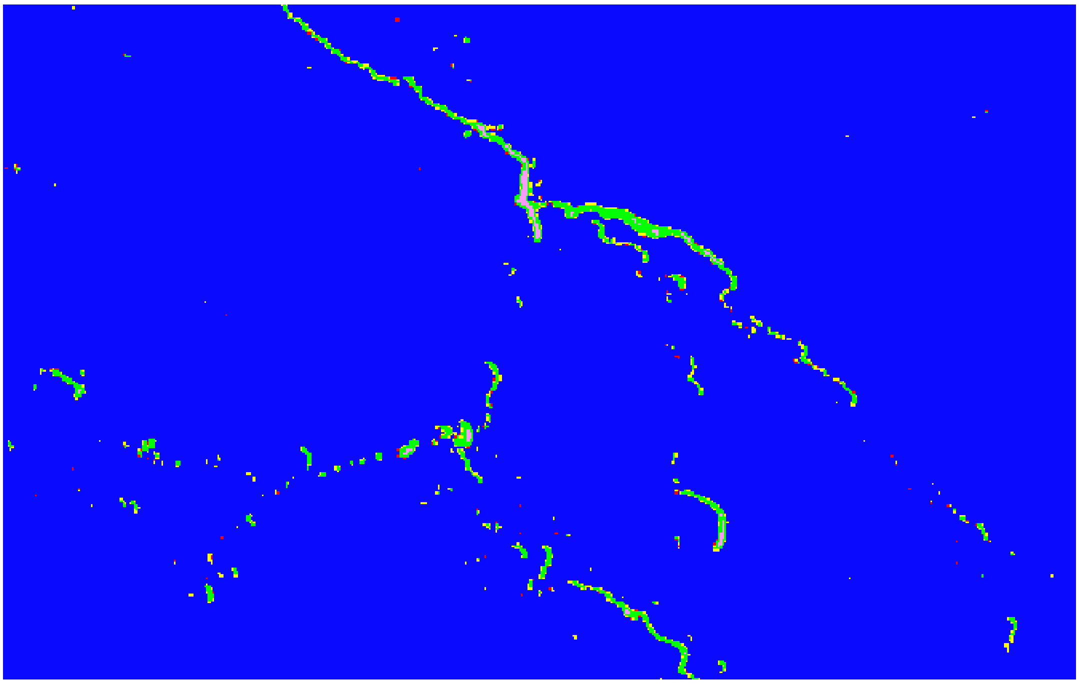

Figure 13: Sentinel-2 EO Processor for MD Detection classification output image from the Caribbean Sea, off the coast of Cuba (20.3°N, 78.1°W) on the 26th July 2018. Red = High Confidence Litter, Yellow = Medium Confidence Litter, Green = Low Confidence Litter, Pink = Not Classified, Blue = Open Water mask.

Low Probability targets (Verification fail rate = 76.2%)

Low Probability MD pixels received the lowest Verification test score of all metrics tested, scoring a 76.2% fail rate. The main cause of failure was the misclassification of targets over land, or in the proximity of cloud (Figure 14). According to the EO processor design, pixels in these areas should have been removed by mask. However, an issue with the mask protocol was discovered late into the development of the EO processor, preventing the land pixels from being removed. As a result, these areas are only classified as land, and subsequently reclassified as Low probability litter if their spectral signature meets the thresholds classification for MD. While this error was widespread within the verification case studies, this can be simply fixed by correction of the mask protocol.

The Low Probability classification pixels performed well in open water environments, clearly identifying organic substances where they appeared at the surface. Figure 15 shows and example of an algal bloom of the Pakistani region of the Makran Coast. In the RGB image, the brighter section of the bloom represents areas where the bloom appeared on the top of / just below the surface of the water surface. The darker green areas show less buoyant parts of the bloom, these submerged areas are not detected by the EO processor and are recognised as open water.

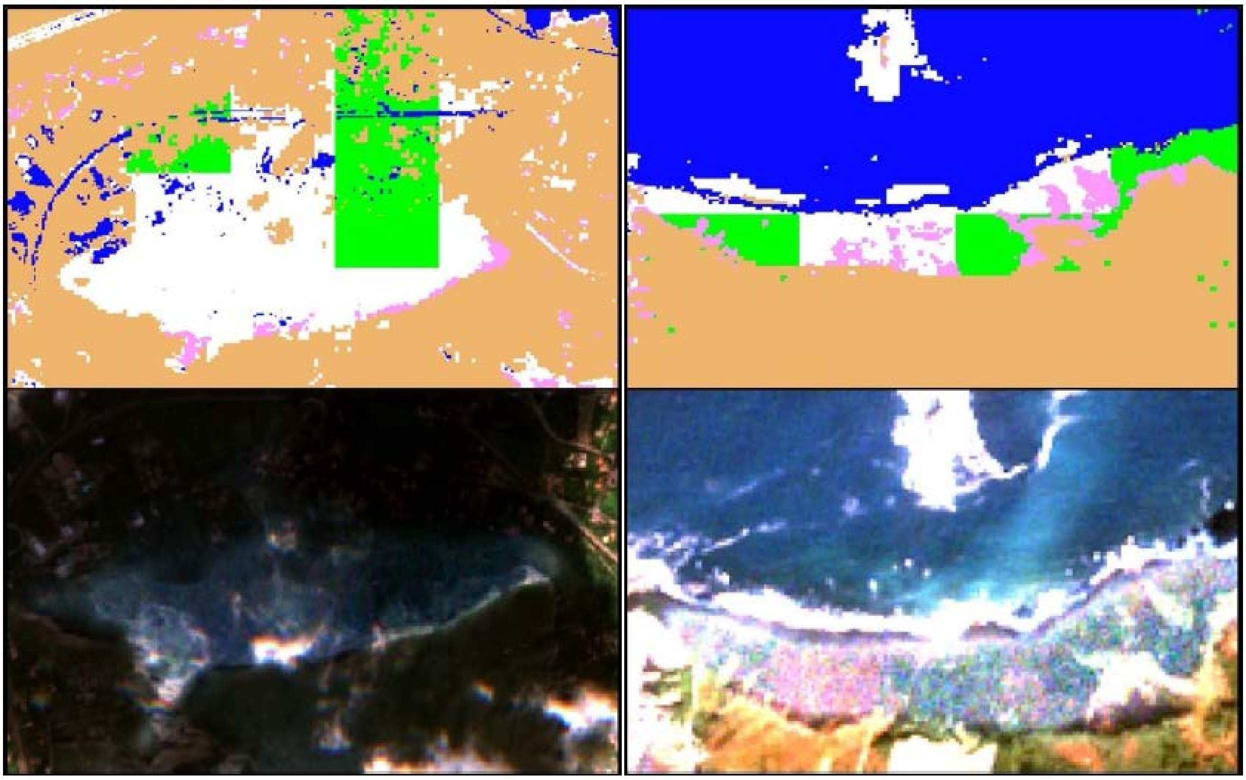

Figure 14: Low Probability Litter misclassifications in Sentinel-2 EO Processor of MD Detection output images. Left: Misclassified thin cloud overland, Sicily, Italy (38.1°N, 13.4°W) on the 4th November 2018: Right: Misclassified bright beach area in Bay of Biscay, Spain (43.4°N, -2.5°W) on the 24th October 2018. Blue = Open water, Orange = Land surface, White = Cloud / Brightness threshold, Green = Low probability, Pink = Unclassified. Bottom: True colour RGB composites.

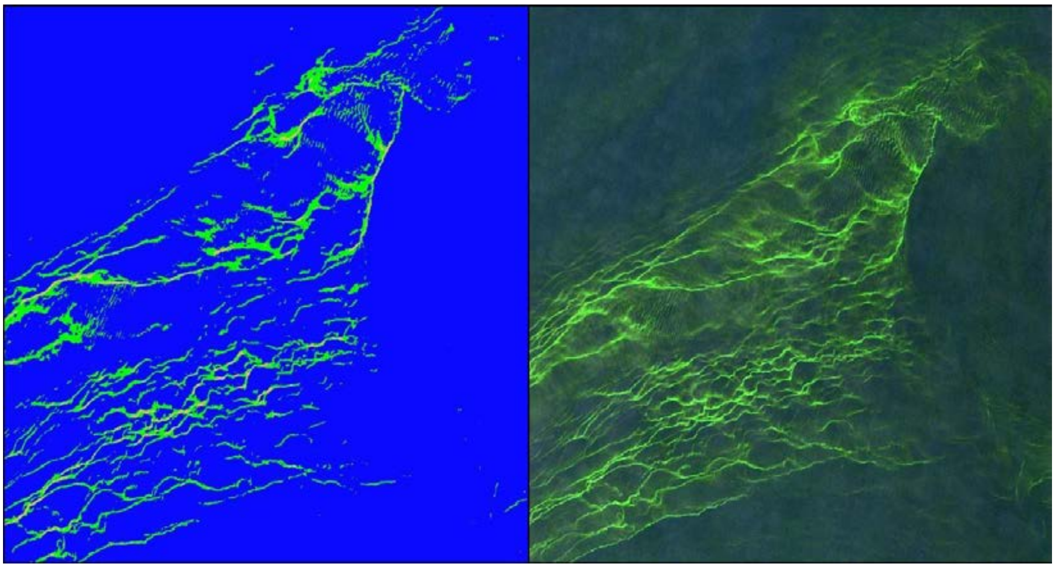

Figure 15: Left: Sentinel-2 EO Processor for MD Detection data of a chlorophyll bloom in the Arabian Sea, SE of Pakistan (25.0°N, 62.4°W) on the 6th March 2018. Blue = Open water, Green = Low probability Litter. Right: True colour RGB composite verifying the apparent presence of an algal bloom.

Medium and High probability targets (Verification fail rate = 46%)

Medium and High probability pixels include pixels that have passed the Litter index threshold only (high) or have passed the Litter index and either of the Vegetation or Algae index thresholds (Medium).

Verification fail was most frequently caused by cloud pixels being misclassified as MD (Figure 16) or weak wave glint pixels being misclassified as MD. These fails are more systematic of issues with the Cloud mask / Brightness threshold and the Land Mask. Accordingly, the verification fail rate described here does not fully represent the performance of the Medium and High probability classification.

Excluding issues with the mask protocol, the Medium and High Probability classifications have worked as designed. The algorithm has effectively identified multiple targets in many areas around the Mediterranean Sea (Figure 17, next page). These include areas near the Po River Delta and the Calabria coastline. Each location was highlighted by MLSC members CNR ISMAR, who recognised each of these sites for their increased frequency of floating litter following heavy rainfall on the Italian mainland. Following visual analysis, these targets have been identified as windrows of surface material, formed and transported by surface winds. Windrows are known to collate a large amount of surface litter and are likely to provide the most effective way of locating litter in open seas and oceans. Typically, these features cover a small area (several 100 m^2), relative to the scale of the Sentinel-2 tile (10,000 km^2). Accordingly, identifying them manually through an operator is very challenging. However, the methodology designed into the EO processor has provided an efficient means of highlighting these surfaces.

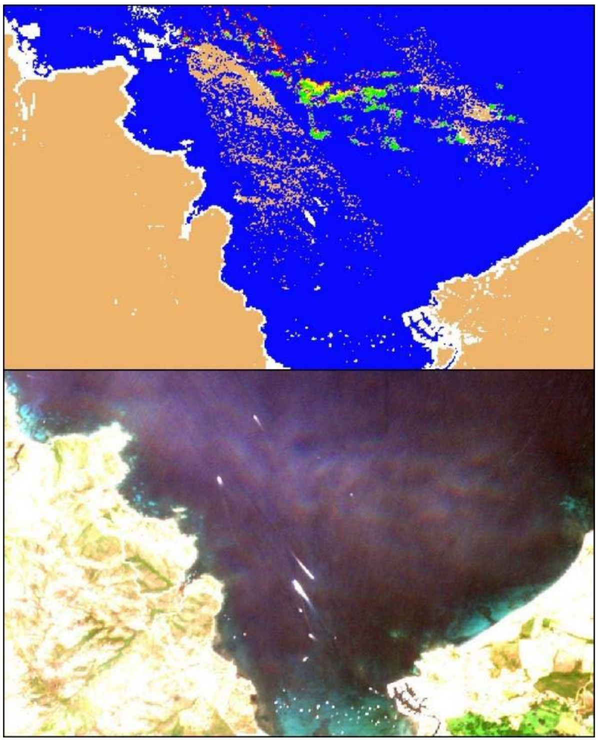

Figure 16: Top: Misclassification of cloud in Sentinel-2 EO Processor for MD detection output image of the north coast of Corsica, France (42.8°N, 9.3°W) on the 28th July 2018. Blue = Open water, Orange = Land surface, White = Cloud / brightness threshold, Green = Low probability, Yellow = Medium probability, Red = High probability. Bottom: True colour RGB composite indicting the presence of semi-transparent cloud.

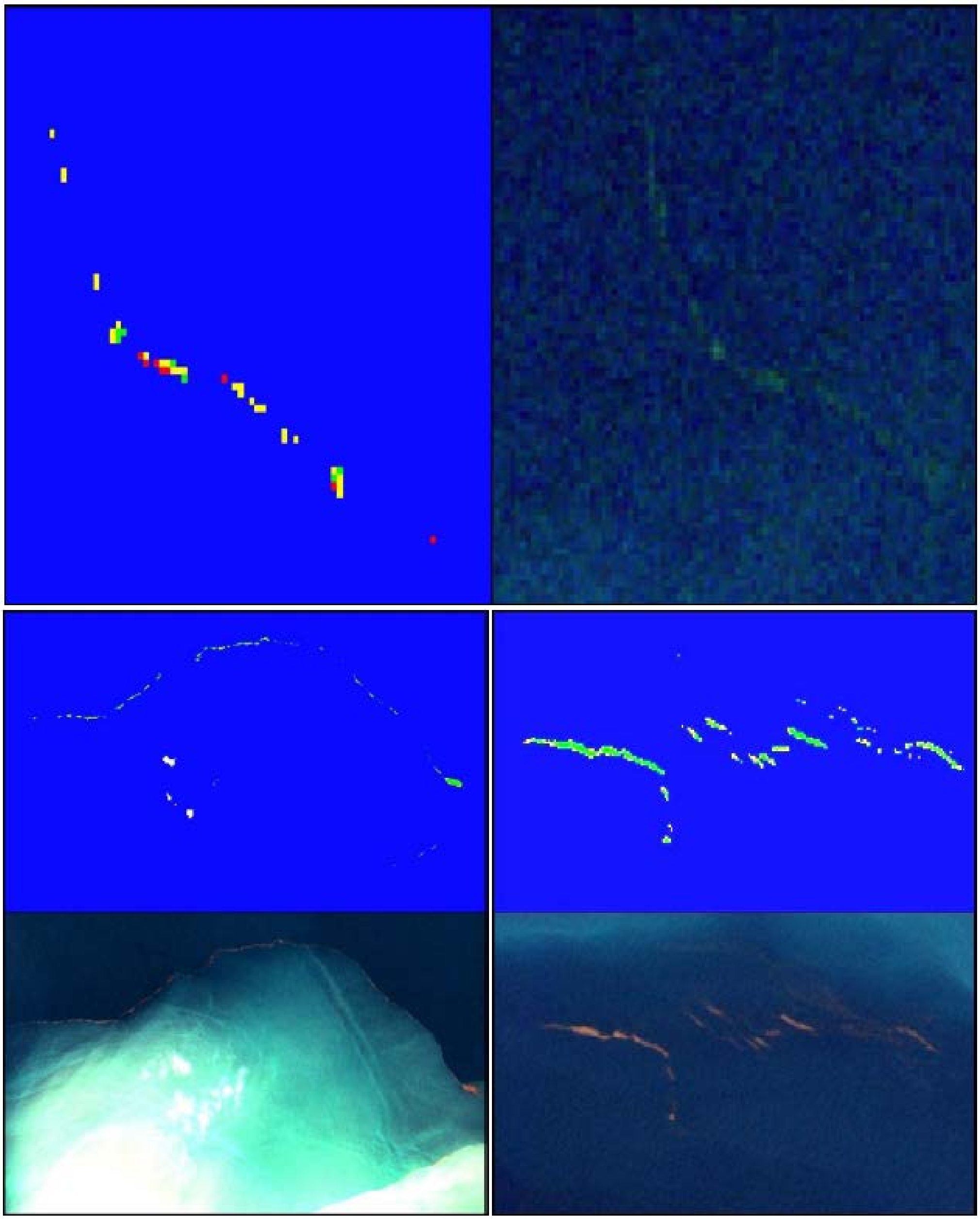

Figure 17: Selection of windrow identifications in the Mediterranean Sea from Sentinel-2 EO Processor for MD Detection output images. Top: An area east of the Po River Delta, Italy (45.0°N, 12.6°W) on the 29th August 2018. Bottom left: An area north of Crete, Greece (35.4°N, 24.3°W) on the 21st January 2019. Bottom right: An area south of Calabria, Italy (38°N, 15.8°W) on the 22nd October 2018.Blue = Open water, Green = Low probability, Yellow = Medium probability. Bottom Right: Opposite panels represent true colour RGB composite of each image.

3.4.2.2.3.1 Validation

Validation testing was completed by comparison of in-situ data of marine litter locations and EO processor output images. These data were acquired from field campaigns around the Mediterranean Sea and included observations of MD targets of varying size from survey vessels and deliberately positioned plastic targets (Figure 18).

The validation field campaign was designed by members of the MLSC, with the field work performed by the Marine Remote Sensing Group (MRSG) at the University of the Aegean, under the direction of Dr Konstantinos Topouzelis. The Plastic Litter Project 2019 (PLP2019) originated from PLP2018, a similar experiment carried out in 2018, where three 10 x 10 m targets of various plastic polymers, were positioned off Tsamakia Beach during a Sentinel-2 observation period.

The 2019 campaign was due to take place in two locations, firstly at Tsamakia Beach and secondly in the Gulf of Gera, however, weather conditions prevented the field campaign in the Gulf of Gera.

In summary, many of the validation targets were identified as MD by the EO processor, while none were clearly identified as purely litter. These results highlighted the importance of the size of the MD targets, and the issues caused by sub-pixel coverage. A minimum of 50% (50 m^2) coverage was required for MD detection. Where coverage fell below 50%, absorption of solar radiance by open water increased the probability that reflectance values would not exceed the water mask threshold, allowing these pixels to be removed from classification.

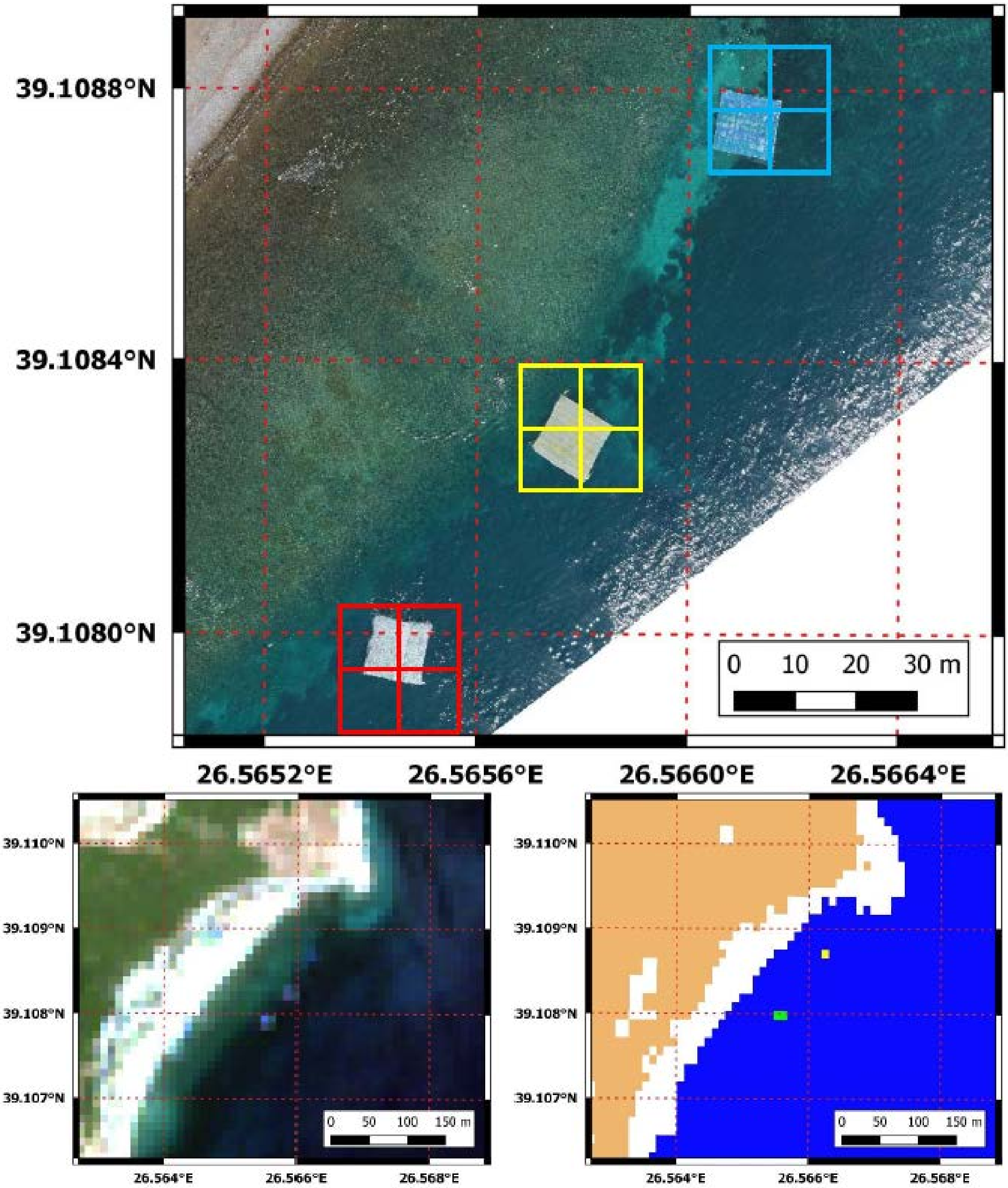

Figure 18: Results of PLP2018 validation experiment on 6th July 2018. Top: UAS true colour RGB image of three 10 x 10 m artificial plastic targets anchored off Tsamakia Beach, Lesvos Island. Grid indicates approximate position of

Sentinel-2 pixels. Targets South to North: plastic bottles, yellow fishing nets, blue plastic bags. Source MRSG. Bottom Left: Sentinel-2 True colour RGB composite. Right: EO Processor for MD Detection output image. Blue = Open water, Orange = Land surface, White = Cloud / Brightness Threshold, Green = Low probability, Yellow = Medium probability.

In contrast to the 2018 campaign, the 2019 experiment was composed of multiple artificial targets, with sizes 5x5 m and 2.5 x 2.5 m in size. The target frames were constructed from PVC (polyvinyl chloride) tubes of 50 cm diameter (ø), all joined by PVC welding material and fasteners. A mesh was installed within the frame, to act as a holding net for the plastics inside the frame.

The contents and the positioning of the targets varied between observation periods. The contents included two types of plastics, including plastic bottles made from PET-1 (Polyethylene terephthalate) and low-density Polyethylene (LDPE) plastic bags. Other targets were also made to contain organic reeds, to determine the signal from organic rafts. Furthermore, to represent the heterogeneous coverage of different plastics (as seen in typical marine debris floats), two of the targets will contain a mixture of the two plastic polymer types.

To mimic real-life distributions of plastic floats, the targets were positioned in different patterns, including parallel, single line and square. A GPS module was positioned at the centre of the targets, collecting data on the precise location of the targets. Data was collected by Sentinel-2 satellites and from an unmanned aerial system (UAS).

In total, there were thirteen planned experiments between 18th April and 27th June 2019.

In addition to the exercise for 6th July 2018 (PLP2018), additional results appear below.

18th April 2019 - PLP2019

During the first experiment of the PLP2019 campaign, four 5 x 5 m (25 m^2) targets were attached laterally, to produce a 5 x 20 m (100 m^2) target (Figure 19, next page). Positioned SW to NE the four targets include plastic bottles (SW) and plastic bags (NE). These targets are visible as four adjacent pixels in the Sentinel-2 true colour composite (Figure 19). Of the four pixels, all except the bottom left (BL) pixel have been removed by the open water mask. As with the 2018 validation campaign, these pixels have been removed due to the percentage coverage per pixel. Accordingly, the BL pixel contains the largest percentage of plastic and the highest Floating Algae Index (FAI) gradient. This pixel produced a medium probability MD classification, producing a reflectance characteristic very similar to the plastic bag target from the 2018 experiment (Figure 18).

7th June 2019 - PLP2019

The final successful Sentinel-2 observation occurred on the 7^{th} of June 2019. During this experiment, two 5 x 5 m (25 m^2) targets were created out of reeds and place side-by-side to create a 10 x 5 m (50 m^2) vegetation target. Further to the SE, four 5 x 5 m targets of mixed plastics were positioned in a square, making a 10 x 10 m (100 m^2) mixed target (Figure 20). To test the limit to which sentinel could observe a sub-pixel coverage, each of the four targets contained 50% plastic, with the rest of the frame empty.

In total, three MD pixels were identified by the EO processor (Reed = two, Mixed plastic = one). The reeds target was correctly classified as low probability plastic, while the mixed target failed to meet any of the classification thresholds and was therefore unclassified.

For the ‘Reeds’ target, the adjacent pixels produced distinctly different spectral signatures, with northern-most pixel (T) producing a distinctive peak in the NIR (0.09 digital number (Dn)) and exceeding the NIR reflectance value of any of the other observed validation targets. In contrast, the pixel with low percentage coverage (B) had far lower reflectance in the NIR, due increased absorption by the larger percentage of open water.

Despite covering a larger total area than the vegetation target, the mixed plastic target only produced a MD classification in one pixel. While this target exceeded the threshold for open water, the reflectance values failed to meet the requirements for any of the MD classification types and was therefore unclassified. However, examination of the spectral response of the unclassified pixel shows a similar pattern to the plastic bag targets observed in the previous experiments (i.e. peaking in visible blue and green (490 / 560 nm) before a second peak in the NIR). It is expected that the reduction in total coverage of plastic within each target caused a spectral dimming by the increased coverage of open water.

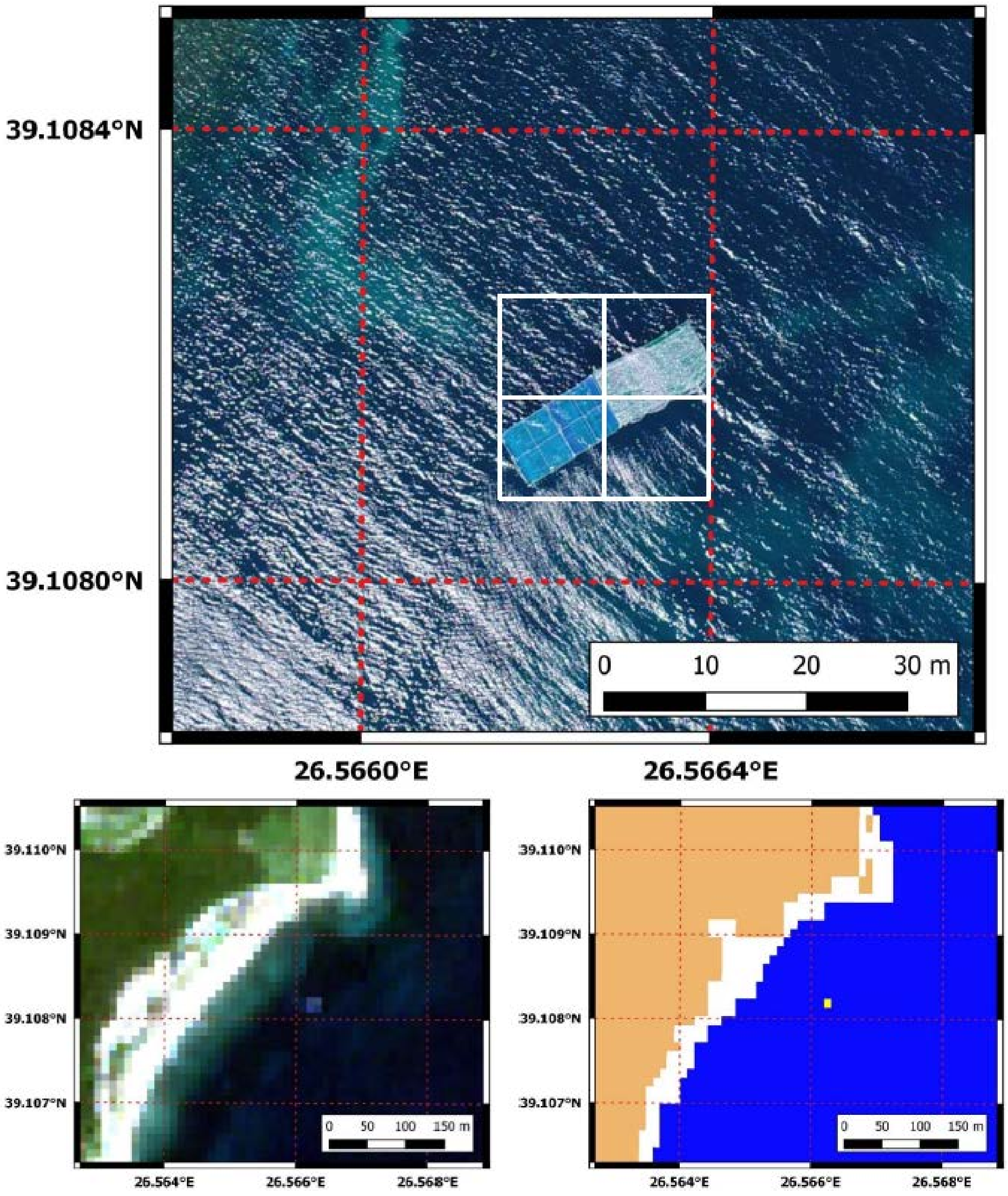

Figure 19: Results of PLP2019 validation experiment on 18th April 2019. Top: UAS true colour RGB image of the 20 x 5 m mixed plastic target (Blue Bags – SW, and Plastic Bottles – NE) anchored off Tsamakia Beach, Lesvos Island. Grid indicates approximate position of Sentinel-2 pixels. Source MRSG. Bottom Left: Sentinel-2 True colour RGB composite. Right: EO Processor for MD Detection output image. Blue = Open water, Orange = Land surface, White = Cloud / Brightness, Yellow = Medium probability Litter.

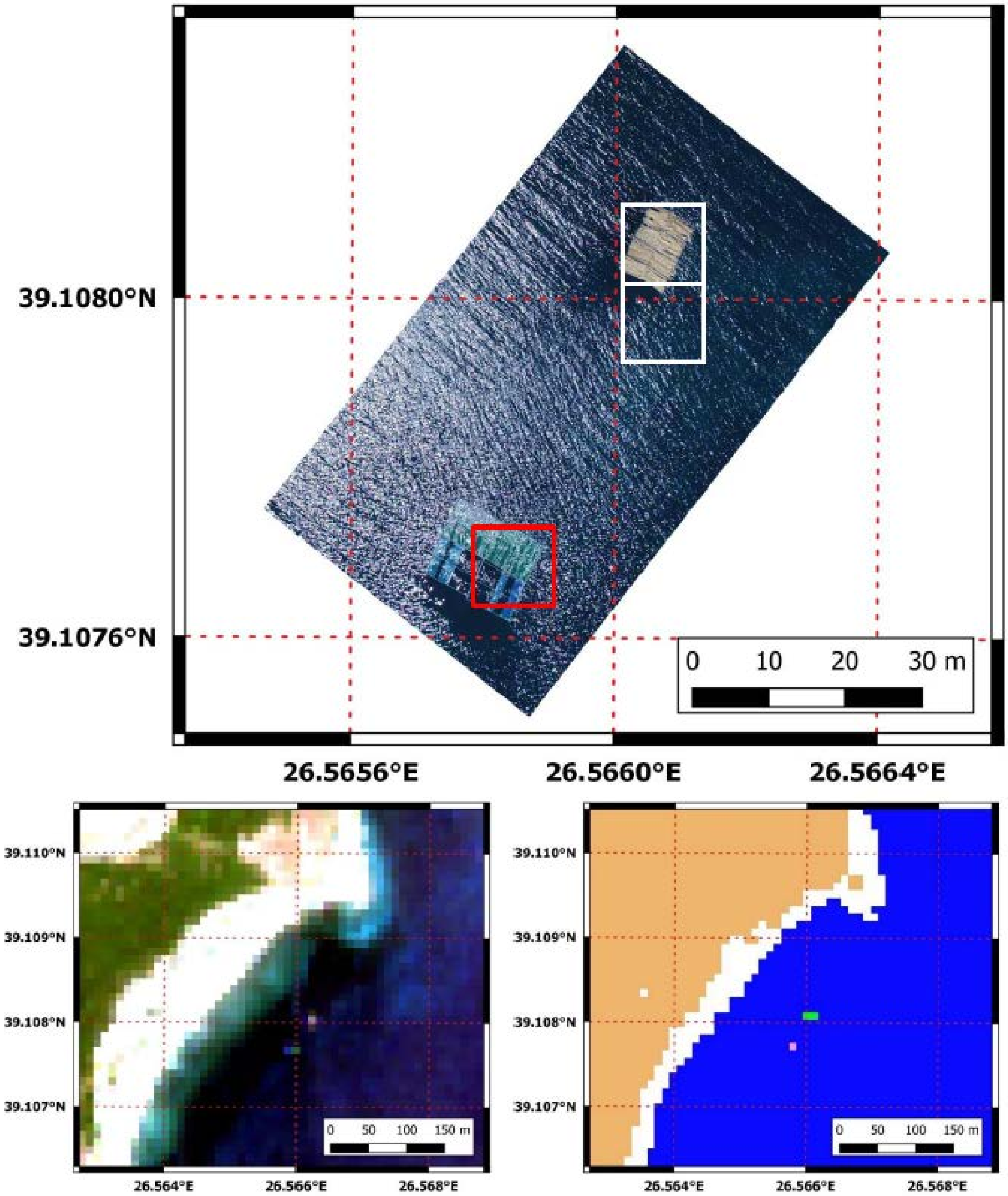

Figure 20: Results of PLP2019 validation experiment on 7th June 2019. Top: UAS true colour RGB image of the two targets, North: 5 x 10 m reeds (vegetation) target; South: 10 x 10 m Mixed plastic (25% bags, 25% bottles, 50% open water) target. Grid indicates approximate position of Sentinel-2 pixels. Source MRSG. Bottom Left: Sentinel-2 True colour RGB composite. Right: EO Processor for MD Detection output image. Blue = Open water, Orange = Land surface, White = Cloud / Brightness, Green = Low probability Litter, Pink = Unclassified.

3.4.2.2.3.2 Results in Marbella coast

From the 24th to 30th October 2017, the University of Cadiz commissioned multiple boat surveys along the southern coast of Spain. During this campaign, a total of thirty-two MD rafts were identified, and their positions logged along with their approximate size. Again, these data were checked to see where they aligned with the observation period of Sentinel-2. Given the short length of the campaign, only one cloud free image was available during this period. Figure 21 shows the location of all rafts spotted between 07:00 and 16:00 local time on the 26th October. Analysis of the Sentinel-2 data, acquired at 11:00 UTC (09:00 Local time) show several surface features to the south of the observations. As Figure 3.15 shows, these potential targets are located up to 10 km from the observations, however it is possible that some of the closer observations (blue box in Figure 21) could have travelled the shorter distance (2km) in the time between survey observation and satellite acquisition (up to 7 hours). Furthermore, the observations of the survey vessels may only indicate the presence of litter-containing-windrows in the area, while the coastline operation failed to spot the larger targets further offshore.

Figure 21: Map of marine litter raft observations off the coast of Marbella, Spain on the 26th October 2017 (36.4°N, 4.1°W). Insert: Sentinel-2 L1C true colour RGB composite image for the Marbella Coastline. Coloured squares highlight surface features visible in the image. Google Maps image showing the region the litter rafts were located.

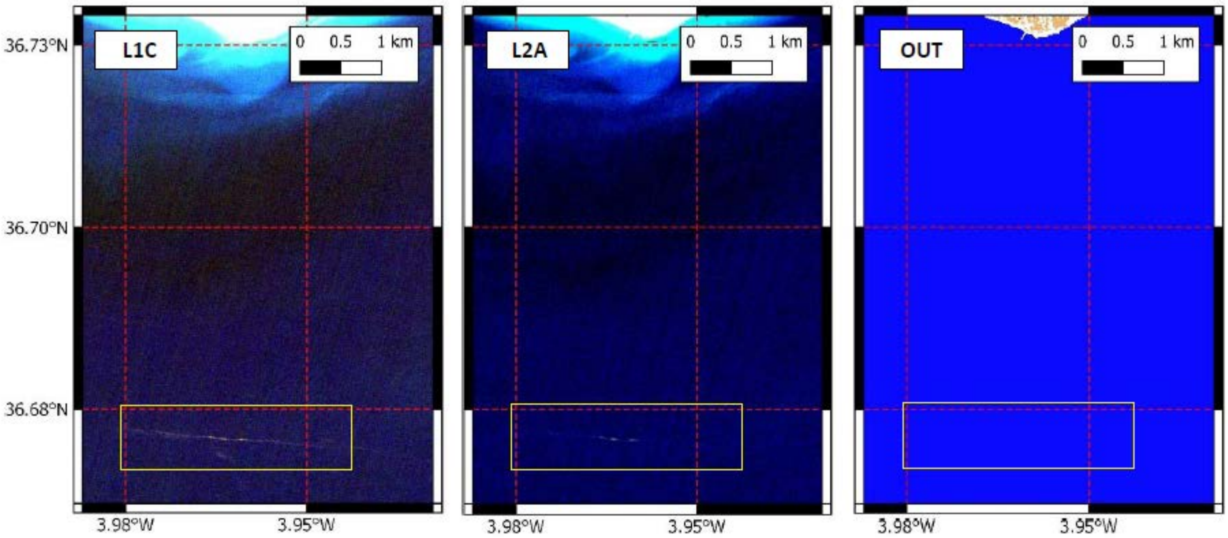

Figure 22: Marbella coastline validation results, comparison of Sentinel-2 L1C, L2A products with EO Processor for MD Detection output image (left to right respectively). Sentinel-2 acquisition on 26th October 2017.

One of these features can be prominently seen in the L1C product (yellow box in Figure 22). According to the EO processor design, the L1C product was transformed to a L2A product using the sen2cor programme. Despite being visible in the L1C product, the EO processor output image does not identify this feature as a MD target (Figure 22). Comparison with the L2A products shows that the target is less visible in the atmospherically corrected product. Two sections of the target were identified for further analysis, including an area of highest reflectance (across all bands) and a more diffuse section of the windrow to the west. Referred to as 'target' and 'tail', the spectral signature of these areas was compared in both L1C and L2A products. In both L1C and L2A products, neither area produce a maximum FAI value greater than the maximum threshold for open water (0.009 FAI). This is evident when examining the spectral curve of all areas, with no area producing a markedly positive gradient between 665 nm (V. Red) to 842 nm (NIR) average reflectance values. Accordingly, these areas are masked as open water in the Pre-Processing module of the EO processor.

Interestingly, in the BOA L2A product, both areas demonstrate a reduction in reflectance values across all Visible, NIR and SWIR bands. L2A product shows a reduction across the scene with no pixel exceeding 0.0022 Dn. Were any of the pixels able to pass the open water mask, none would meet the Litter classification threshold (>0.004 Dn) in either of the products, preventing a positive litter classification.

The reduction in the NIR reflectance between the TOA and BOA products ultimately did not prevent classification by the EO processor. However, it is important to examine the chances of potential targets being omitted by the processor due to this process. Future work will look to test alternative atmospheric models to determine the best option for open water environments. As this example has shown, targets which appear surrounded by water or slightly below the surface produce low reflectance values, particularly at longer wavelengths (NIR and SWIR). These values are outside of the current classification limits and highlight the need to acquire more verified windrow targets to produce a more-robust scheme.

4 The experimental phase

4.1 Field experiments and measurements

4.1.1 Goals

The main objective of this experiment was to obtain spectral reflectance from VIS to SWIR of different concentrations and compositions of marine-harvested plastics in sea water using an ASD spectrometer. Those were not available in publications to the scientific community. Thus, their acquisition is of relevance for the project and in order to assess the potential remote sensing requirements based on 'real' marine litter. With the spectral information gathered in this experiment, the RESMALI team aimed:

1. To identify unique and optimal wavebands for oceanic plastic remote sensing and estimate the minimal signal-to-noise ratio (SNR) for relevant optical sensors.

2. To better assess compatibility with existing airborne and satellite optical sensors to transpose airborne measurements into technical specifications for spaceborne systems.

3. Determine the minimum threshold of debris concentration for potential observation in spectral bands using the following composition:

    a. Raw new plastic, five different series of tests for HDPE, LDPE, PP, PS and a mix of PE-PP representative of plastic composition in the Great Pacific Garbage Patch (GPGP).

    b. Marine-harvested plastic, from the North Pacific, mostly made of PE and PP, four different series of tests for: type 'H' (hard fragment), type 'N' (nets, ropes, fibres), type 'P' (preproduction pellets or nurdles) and type 'F' (foam).

    c. Marine-harvested plastics with bio-fouled organisms, collected from the North Pacific and currently frozen.

4. For the proposed different scenarios of plastic composition, to build a spectral reflectance library for variable concentrations ranging from 0 to 100% of sensor field of view or surface pixel covered and for variable sensor geometry from 0° to 45° (to take into account potential apparent optical properties or AOPs) nadir angles using ambient light or solar lamps depending on weather conditions.

5. Based on the above, to identify the spectral variations of the plastic marine debris as result of aging effects for each type of polymer analysed in this study.

The laboratory-based and airborne spectral measurements coupled with radiative transfer modelling provided crucial mission requirement information for future spaceborne remote sensing of plastics. The temporal revisit interval, spectral and geo-spatial resolution was explored for different scientific questions related to detecting, tracking, quantifying and identifying the ocean floating plastics. During this experiment, we tested different configurations for ocean plastic concentrations, type of plastic debris and observation geometry. The results of this experiment allowed also for the prototyping of potential detection algorithms that could be made part of the mission concept provided within the project.

4.1.2 Outcomes

The reflectance spectra database from ASD spectrometer can then be explored to investigate:

1. differences in the spectral signature of raw plastic and ocean plastics of different composition;
2. effect of biofouling on spectral signatures;
3. effect of aging into the materials (coming from biofouling, weariness and UV degradation);
4. the influence of concentrations and angle of observation in the spectra signal and strength;
5. create a baseline for spectral signature from VIS to SWIR.

For science continuity, the results were compared with already-existing datasets (e.g. Garaba and Dierssen 2018) using similar techniques, materials and procedures. In this way, confirmation of outcomes was achieved and assurance of scientific quality of the measurements can be provided. Systematic errors appearing in the comparison allowed for applying correction to the data to harmonize the results with existing libraries (e.g. spectral libraries for polymers provided by U. of Connecticut).

4.1.3 Results

Marine-harvested samples included hard boards, foam, ropes and degraded pellets in artificial seawater (see Figure 23).

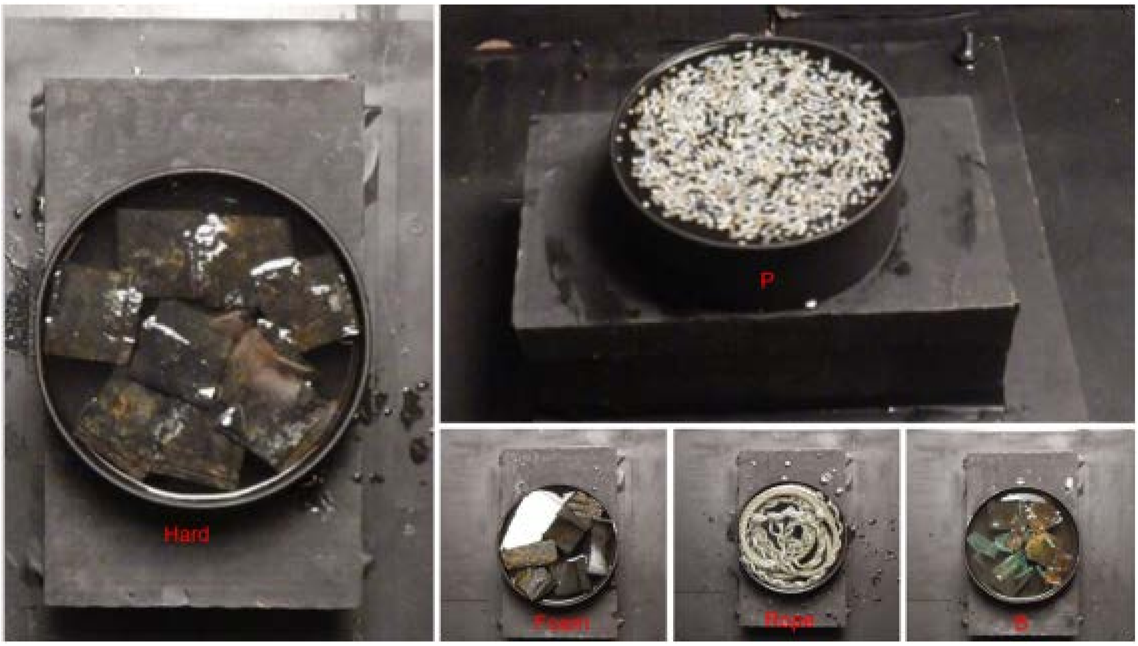

Figure 23: Indoor measurements for marine harvested samples.

4.1.3.1 Effect of sample colour on spectral reflectance

The bulk spectral reflectance properties of the samples exhibited variabilities that were related to the apparent colour of the objects over the measured wavelength range from VIS to SWIR (Figure 24, below). We observed that for the 100%-pixel coverage of HDPE pieces with different colours (orange, blue, white, purple, green, black) had spectral reflectance lower than 80%-pixel coverage HDPE of only white pieces.

For the white pieces a nearly flat but decreasing signal in the visible spectrum was observed whilst in the multi-coloured measurement the bluish, greenish and reddish peaks resulting from different colours were salient. Disregarding the 100% coverage signal, we observed a near linear trend at each wavelength correlating pixel coverage and spectral reflectance.

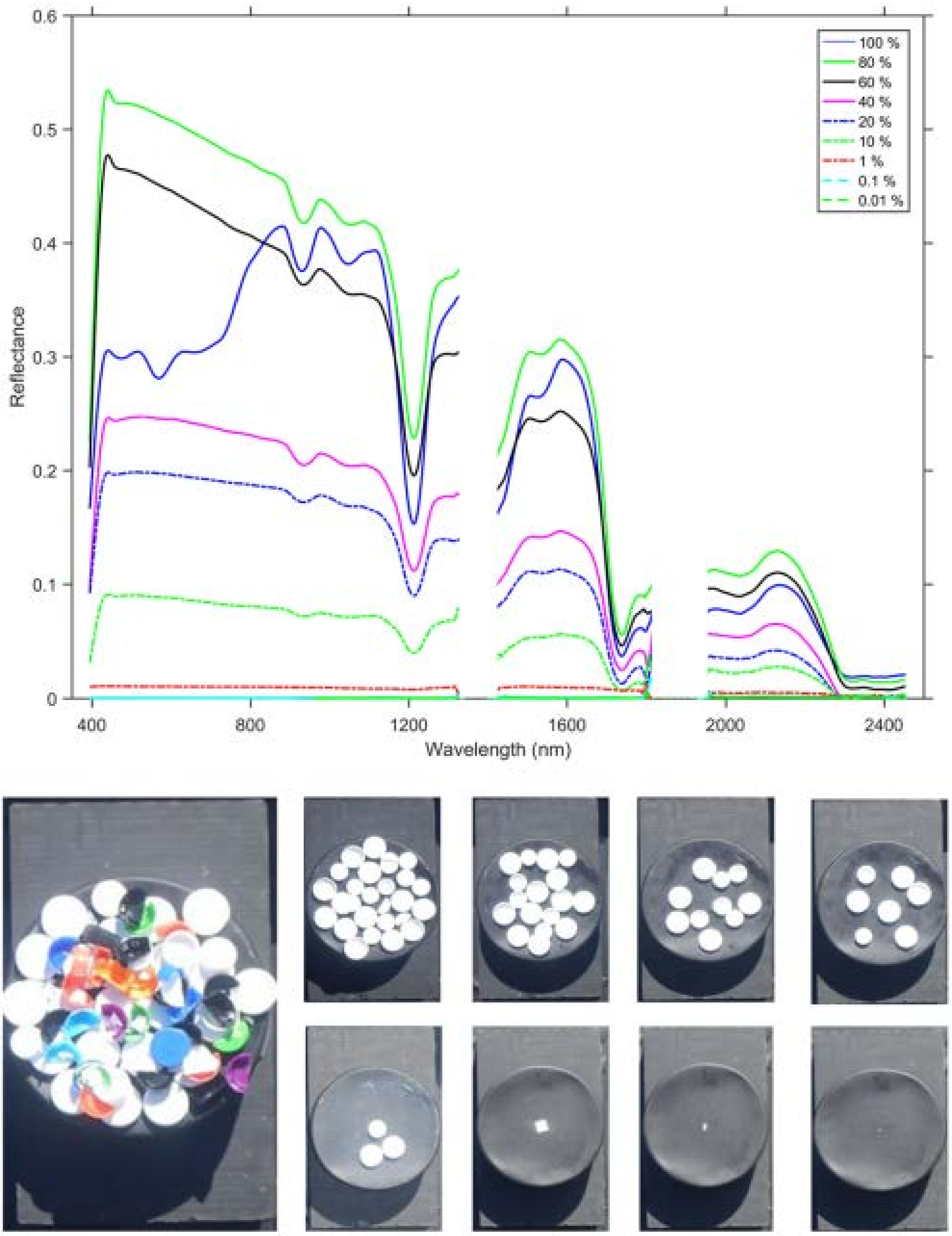

Figure 24: Spectral reflectance of dry HDPE measured outdoors and the corresponding pixel coverages with a black background.

4.1.3.2 Dry and wet plastics

In general, the dry raw samples had higher reflectance compared to the wet, which is consistent with prior studies (Garaba and Dierssen 2018; Garaba, Aitken, et al. 2018). Presence of a water layer on the samples results in a significant decrease in the reflectance of the object because water itself is a very strong light absorber.

All the wet samples were floating except for the LDPE, which was slightly submerged, this explain why the reflectance was lower than the other samples over the whole measured wavelength range. We used different objects made of HDPE for the dry and wet measurements. White bottle tops were used in the dry measurements whilst blue and white cut-out pieces were used for wet measurements. Although we expected a decrease in reflectance due to presence of water, the magnitude might be an effect of different colour of the samples as observed above (Figure 24). Dry LDPE at 100% had higher reflectance which can be explained by its transparent colour acting as a specular reflective surface, but once underwater or submerged water absorbs most of the light hence lower reflectance.

Detecting new plastics would therefore be possible but wet and clear LDPE litter would require a sensor with a high signal to noise ratio especially if debris is submerged. These new plastics are more water-repellent which means if they can float the reflectance detectable from any floating surface is not be highly affected by absorption of light by water. During the experiments, we kept our samples wet by using a spray bottle to simulate sea spray. PS presented the least loss of reflectance due to presence of water especially at 850 nm.

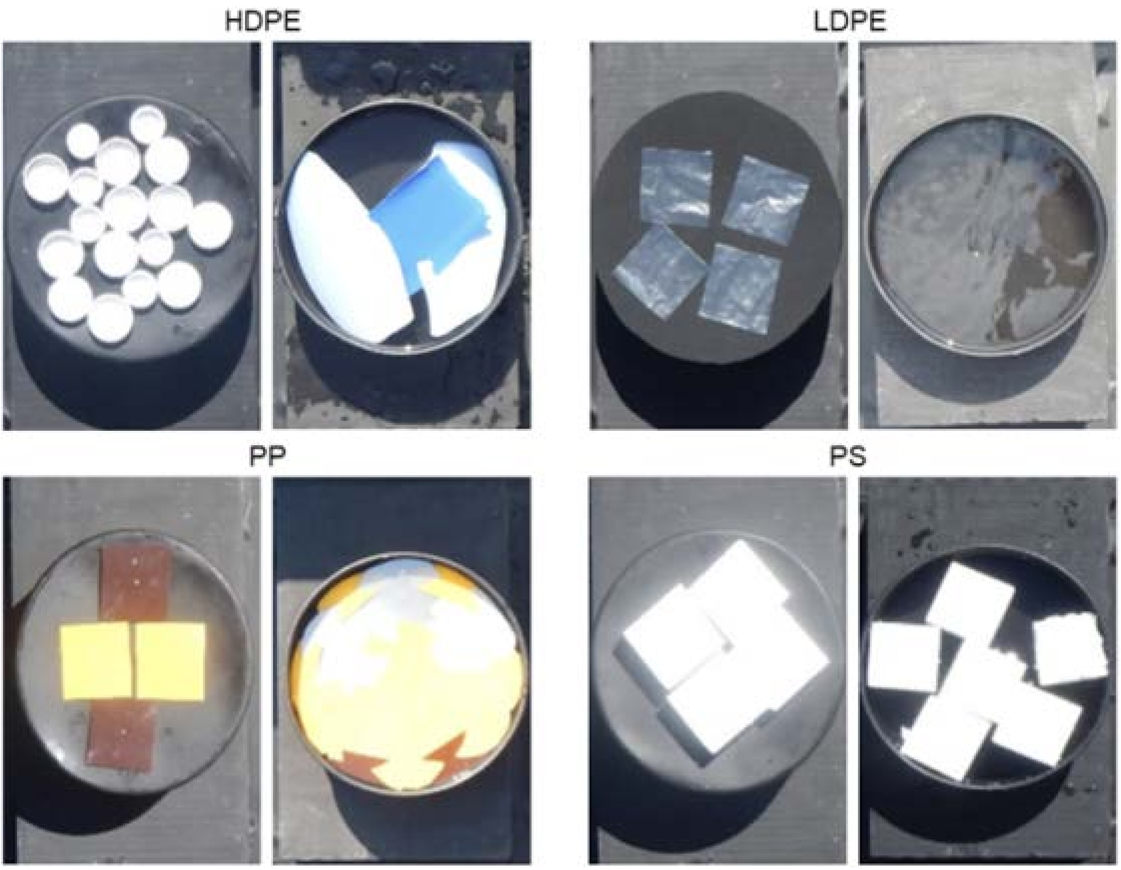

Figure 25: Example true-colour images captured before each spectral reflectance measurement of the dry and wet HDPE, LDPE, PP and PS samples observed at nadir angle =0°.

4.1.3.3 Marine-harvested plastics

The degree of biofouling on B and Hard needs to be investigated by measuring the reflectance after cleaning both samples and possibly further analysis with FTIR also before and after cleaning. Spectrally, we did not observe large differences for these samples although it seemed like B was a less bio-fouled version of Hard (Figure 23). It is also observed that detection of Hard samples at pixel coverage < 20% could be challenging as the reflectance is higher than expected which could also be an effect of smoothing and a very low signal reaching the sensor.

Reflectance of the wet marine harvested samples decreased with an increasing observation nadir angle. Unlike for the raw materials that were observed outdoors it could suggest that the assumed diffuse light conditions indoors were not similar and comparable to those of ambient sunlight. It is also evident that at 0° nadir the reflectance of all the samples was highest, more noticeable at 850 nm and less noticeable at 1732 nm.

4.2 Modelling exercise

After the experimental phase, a radiative transfer modelling exercise was carried out, in order to learn how floating plastics could look for a theoretical sensor over the sea surface.

In this case, simulation parameters have been set to try to represent the observational conditions of litter situated over the sea surface in open ocean conditions. This has been selected following recommendations from previous activities. These documents were generated during the first phase of this contract and involved the understanding of marine litter: its characteristics; spatial and temporal variability and patterns; the definition of the best observational possibilities; and the identification of the most suitable technologies for its observation.

4.2.1 Rationale of the simulation

The experimental parameters for the modelling have been selected according to what has been considered the best potential target for marine litter observation from space: ocean waters with low content on sediments and not affected by land aerosols, and with depths larger than Secchi disk depth, to prevent contribution from the sea bottom.

From the applications analysis, there are three main boxes where marine litter accumulates:

- The sea surface: Here, the debris accumulates a large scale in the ocean sub-tropical gyres, as result of the general circulation patterns of the ocean and by combination of wind-driven currents and wind dragging. This has been often reported in the scientific literature (Lebreton et al. 2018; Van Sebille, Wilcox, et al. 2015, for example).

- The sea bottom: It is estimated that only around a 15% (Giacovelli et al. 2018) of the total marine debris input remains at the surface, being the rest buried in the sea floor (70%), where is suspected accumulates, and the rest floating within the water column (15%). Remote sensing of this fraction falls beyond this study.

- Coastal areas and beaches, for which, unfortunately, there is not a good estimation of how much of the total litter accumulates there, but it is where litter is the most visible.

The main issue for the remote sensing of marine litter lies, not in the total amounts or relative concentrations, but in how it distributes spatially. Current estimations of concentrations are of those compatible with ocean colour applications. In principle, it could be possible to achieve measurement of marine litter by using plastics as a proxy, as it composes a vast majority of the total litter found in any of these three domains. These plastics are present in amounts equivalent to what we find in chlorophyll estimations from space (see Cozar et al. 2017 for further details). This is even more true for accumulation areas such as beaches or sea floors where these values can be significantly higher.

However, these concentrations of plastics are not a homogeneous mix. For instance, phytoplankton concentration is composed of large amounts of unicellular organisms that could be considered more or less well mixed in a given water volume, but plastics are usually present in a much smaller number of particles. Indeed, plastic particles distribution is poorly known at sub-millimetric scales, but current observations show that what the smaller size classes have in numbers, they lose it in terms of weight (Cozar et al. 2017). As consequence, a few plastic particles scattered in a given area will yield equivalent concentrations than phytoplankton in terms of mass, but not in terms of numbers. This could be rephrased as marine plastic litter does not reach the right density of particles to have an overall impact into the colour of the ocean waters.

Thus, to achieve detection of plastic litter in ocean waters using traditional optical techniques, much higher number of particles would be required, and those have been not yet observed. This imposes an extreme limitation in how the problem should be approached, and hence, one of the keys aspects to be covered is to understand what spectral bands are the most suitable ones for remote sensing of plastics, knowing that is necessary to measure what fraction of the surface observed shall be covered or contain plastics to have a noticeable effect in the observed water-leaving radiance.

The problem is even more challenging as we go closer to the coast or even over beaches. There a few reasons for that, like the presence of additional variables in the observation, as the Coloured Dissolved Organic Matter (CDOM) associated to productivity of the waters (and/or by input from rivers), sediments in suspension, aerosol optical thickness (AOT), etc. There is also a larger variety in terms of litter composition. Whist in ocean waters floating litter is made of low-density polymers by far (PP, LDPE and PS), close to coast the variety of items and polymers increases, reaching its maximum over beaches, where many non-natural materials can be found. In fact, in beaches there are items deposited by storms, dragged by the wind from sea or land, or directly abandoned there as result of human activity. Because of that, their nature can be multiple, both in composition, distribution and origin, which makes a remote sensing solution significantly more complex (Arias et al. 2017). All of these shall also be combined with the substantially large variety of background conditions, including but not limited to whether the coastal area is rocky or sandy, the size of the grains and stones, the composition of those, the slopes of the coast, etc.

Having into account all these limiting aspects, we consider that the best chances for detection are concentrated over waters not too close to coast and where litter could form accumulations or patches. Current studies about spatial distribution of litter have resolved global patterns (e.g. Eriksen et al. 2014 or Van Sebille, England, et al. 2012), but even so, they can differ significantly in terms of absolute concentrations (Van Sebille, Wilcox, et al. 2015). There is, however, very little information about how litter accumulates in the surface at microscale, or in general, at scales in which most EO optical sensors operate (below 1 km spatial resolution). Cozar et al. 2017 suggest that, under certain conditions, Langmuir circulation as result of superficial wind stress could lead towards the formation of the so-called windrows, acting as convergence zones in which floating material can aggregate for shorts periods of time, and at scales of tenths to hundreds of meters. Those have been observed in field campaigns in which the UCA participates. The same principle could apply to any convergence or frontal areas happening at compatible scales. These places would act as accumulators of litter, favouring the increase of concentration to levels that could be detectable. In fact, studies performed with Sentinel-2/MSI by ARGANS (as reported in section 3.4.2) prove that is possible to observe large accumulations of litter when the conditions are right. One of the caveats of this approach, however, is that we do not know how often these accumulations take place, and how representative they are of the total presence of litter. Diffuse contamination could be hard to detect unless a considerable improvement in sensitivity of sensors takes place. However, as part of this simulation, we were able to compare the impact that very small concentrations of litter can have over the water-leaving radiance, which could be well within the range of natural variability or background noise, preventing any detection despite improvement in the technology. Bottom line clearly lies on the SNR defined by the photon noise versus the signal caused by the litter.

The last point worth mentioning at this stage is about the spectral information. From our preliminary assessments (Bonnery et al. 2017; Cozar et al. 2017), it seems clear that identifying litter with optical sensors will require the use of bands able to classify unambiguously what is plastic from other components present in the sea water (e.g. floating seaweeds, foam and white caps, sediments, phytoplankton plumes, etc). Existing studies over plastic polymers point towards NIR/SWIR bands as optimal for plastic detection and identification. Not in van, FTIR methodologies are currently the state-of-the-art in terms of plastic identification, and they have been used for long by the industry for such task, especially for rubbish classification and urban wastes processing plants. It takes sense, henceforth, to check these regions of the spectrum to try to find plastic-specific features that could help in the discrimination exercise. Nonetheless, we anticipate that using these regions will be a limiting factor for what technologies could achieve in terms of detection.

In fact, this is also one of the reasons we also anticipate that hyper-spectral technologies would be of not much interest in LEO applications, as the bandwidths would be not narrow enough to discriminate between polymers, at the price of losing sensitivity. Thus, it makes sense to go for a multi-spectral solution with bands well located over the spectral features specific for the most common polymers found in the marine litter. Garaba, Aitken, et al. 2018 did an interesting study that shows clearly how these spectral features over raw materials are considerably close each other. This has been also supported in Goddijn-Murphy, Peters, et al. 2018, and later in a second publication (Goddijn-Murphy and Dufaur 2018). When trying to apply the theoretical model proposed in Goddijn-Murphy, Peters, et al. 2018 over field measurements obtained with an ASD, Goddijn-Murphy and Dufaur 2018 found that it was not possible to do proper estimations of the polymer composition and/or concentrations.

Regardless, in this simulation we have proposed a per-spectral line computation, so to obtain results in a similar manner than an ASD provides, which could show to be particularly useful to take into account atmospheric features.

4.2.2 Objectives for the study

Having into account this is considered a feasibility study, we have limited the analysis to a set of optimal and sub-optimal case studies, which help to delimit the best chances for a potential mission devoted to marine litter. The results help to delimit which case studies of those presented are the most realistic applications. Within this level of detail, we have also explored some factors that could be of relevance for any future mission, like impact of wind speed, observational geometry, and chlorophyll content.

The objectives are:

- Identify the minimum concentrations
- Find the optimal distance to target
- Recommend the best geometry for observation
- Isolate the operational spectral bands
- Check on additional environmental parameters

In addition to the above, we aim also to provide a first approach to understand the role some parameters have into the resulting water-leaving radiance. The main ones under our current scenario are chlorophyll concentration and wind speed. Both affect how light is reflected by the water's surface and its absorption.

4.2.3 Methodology

The simulation experiment nurtures of the existing knowledge about the spectral behaviour of marine litter, which is rather limited. The field experiment performed within the project has allowed to answer some of the key questions that were still open in this topic, but many remain unanswered and probably additional efforts will be required to solve them.

To comply with the objectives detailed in the previous chapter, the exercise is formed of three components, each one with its own limitations:

1. Generation of a water-leaving reflectance at BOA.
2. Radiative transfer problem from BOA to TOA.
3. Identification of SNR.

4.2.4 Results

Each of the potential scenarios has been simulated 10 times, including reference and littered ones. This, and considering all the varying parameters, it has implied to process a total of 3,600 scenarios.

Each of those scenarios has involved simulating 2,100 bands of 1nm, with 10^6 photons. Because this was very demanding in terms of RAM, the simulations were split in 4 intervals of 525nm each, meaning that a total of 14,400 simulations were performed.

According to the results obtained in the modelling phase, it would be possible in principle to develop a multi spectral mission devoted to the detection and monitoring of floating plastic concentrations at ocean. The results show significant values of SNRr at pixel coverages of 10% for the three polymers presented previously. Spectral differentiation from respect background is also achievable at concentrations around 1%, but this capability is pretty much lost when reaching coverages of 0.1%. This implies that measuring of low concentrations of microplastics in seawater is beyond reach for the current present concentrations, even if those are just on the surface, as per setup of this modelling activity. It is important to highlight that the field experiments run by TOC also show this specific limitation, with signature below 1%-pixel coverage lost due to the background noise. Therefore, results of the model and the measurements are matching, and thus, the most realistic scenario will be the observation of accumulation of plastic debris in the surface, for which the right combination of spatial resolution and sensitivity in the sensors for the selected spectral band will be necessary.

It is also important to note that instrumental set-up can substantially vary depending on the target. The results indicate that a spectral differentiation between the polymers could be achieved by means of a proper selection of the spectral bands and spectral disaggregation after measurement. However, this capability will require the definition of some narrow bands to prevent the overlapping of pikes within the same bandwidth, which shall be put against the requirements for sensitivity. On the other hand, the three polymers presented here share significant SNRr in some of the spectral regions, which could be used to define some relatively broad bands for plastic detection, allowing probably to increase the instrumental SNR for its detection. This choice would imply sacrificing the capability to discriminate between the polymers and obtain a relative quantification of each one but could be considered in order to achieve detection at lower concentration rates or with higher spatial resolution.

Other aspects that shall be considered in the need of having ancillary bands to discriminate or rule out false positives. For instance, it is well known that phytoplankton and seaweeds will deploy spectral features at some of the reported peaks, which will make difficult the identification of litter, especially in areas where floating seaweeds are very active (e.g. tropical and sub-tropical Atlantic Ocean), or phytoplankton blooms can have a meaningful signature at surface level, which could be confused with strands of litter in the surface. To help solving these limitations, additional bands shall be added to the instrumental set-up to monitor photosynthetically active organisms.

Moreover, it has also been reported that most of the plastic litter present at ocean is actually white or of pale colours, as result of production choices but also due to pigment decolouration from exposure to sun and eroding of the surface of the plastic within time. This means that bands in visible would help also to rule out some false positives by providing spectral information that could be used. This still could be a problem to run identification of litter under strong wind conditions when white caps appear. However, if there are bands for NDVI computation, white caps can be discriminated, especially if wind information is also provided as metadata for the acquisitions.

Related to the signature from BOA to TOA, it is observed that SNR and SNRr diminish with the altitude, as expected. However, for the most relevant observed pikes the impact is not enough to mask them, which means observation could be achieved at orbit level. Exact altitude for the mission will depend on the final GSD and the sensitivity requirements at sensor level. It is important that the pikes reported previously are having this into consideration. Some local maximums appear at lower altitudes than TOA, but those disappear or are not particularly interesting when reaching TOA. Henceforth, they have been not reported. The assessment could be repeated with a more precise estimation of the expected altitude for the sensor. Note that, however, little loss is observed beyond 32.5km in these simulations for a fixed fraction of plastics into a pixel (which in a real scenario would, of course, change according to the surface of the distance and the design of the sensor). This opens opportunity for different platform than satellites, whenever they can meet other technical requirements. Examples of it could be HAPS.

All in all, it seems from these results that marine litter monitoring can be achieved from space, given the right choice of bands and pending on the instrumental assessment. This monitoring, however, will have some limitations, especially in terms of concentrations, which means that only plastic accumulations will be observed under a medium spatial resolution (1-10m). However, if enough sensitivity is provided at even higher spatial resolutions, object detection could be feasible (e.g. 10% plastic coverages over 25cm spatial resolution would, in principle, provide observable anomalies in the measured L_w). Hence, such applications could also be open for more regional or dedicated missions with VHR targets. If sensitivity is pushed, even smaller fractions of pixel coverage could also be observed. Results at 1% are still meaningful, if well is true that the SNRr they provide is low in general terms and would make detection more complicated.

Proposed potential band centres are shown in Table 14. The list compiles all the pikes for the three polymers. Some are shared by the three plastic materials. In some other cases, however, only a single polymer has them. Measuring $L_w$on these spectral positions could help to not only detect, but possibly also identify what materials are composing the observed reflectance in a given pixel. However, in some cases these positions are really close to each other, with differences in NIR or visible of less than 10nm or 40nm in SWIR. Henceforth, any mission targeting their classification would require significantly narrow bands which could oppose to the needed sensitivity or GSD. In the fine approach a total of 19 bands are proposed, which should be complemented with additional bands in visible and NIR, so that to enable observation of non-plastic targets that could confuse the signal in the relevant pikes, as well as any band needed for atmospheric corrections.

On the contrary, the broad approach (see Table 15) could be used instead. This time, close bands are merged to favour broader bands but losing spectral definition. This alternative set of bands could be more efficient in detecting floating plastics but will have more difficulties to classify them. In this approach, only 10 bands for floating plastics are proposed, to be complimented as indicated in the fine selection.

λ (nm)	LDPE	PP	PS	Bandwidth (nm)
830	No	No	Yes	10
840	Yes	Yes	No	10
925	Yes	Yes	Yes	70
975	Yes	Yes	No	70
1150	Yes	Yes	No	40
1325	Yes	Yes	Yes	50
1490	Yes	No	No	10
1500	No	No	Yes	10
1510	Yes	Yes	No	10
1530	No	Yes	Yes	35
1570	No	No	Yes	40
1590	No	Yes	No	25
1610	Yes	No	No	40
1640	Yes	Yes	No	20
1785	Yes	Yes	Yes	70
2030	No	No	Yes	80
2040	No	Yes	No	40
2080	Yes	No	No	80
2250	No	No	Yes	170

Table 14: Fine selection of proposed band centres and bandwidths according to results observed in the simulation through the SNRr analysis.

λ (nm)	LDPE	PP	PS	Bandwidth (nm)
835	Yes	Yes	Yes	20
925	Yes	Yes	Yes	70
975	Yes	Yes	Yes	70
1150	Yes	Yes	No	40
1325	Yes	Yes	Yes	50
1510	Yes	Yes	Yes	65
1600	Yes	Yes	Yes	100
1785	Yes	Yes	Yes	70
2055	Yes	Yes	Yes	130
2250	No	No	Yes	170

Table 15: Broad selection of proposed band centres and bandwidths according to results observed in the simulation through the SNRr analysis.

4.3 Conclusions

In this chapter, the details of the executed experimental plan and its results are presented. From these results, a set of conclusions have been drawn and summarized below:

1. Field measurements of raw polymers and sea-collected polymers have not yielded significant spectral differences. The reasons behind this are probably related to the specific set-up and samples used. Whilst ocean plastics had certain amount of biofouling on them, it seems signature is only really affected if a large fraction of the surface is covered by it, which was not the case for most pieces. This can be due to the low productivity found in the North Pacific Sub-Tropical Gyre, which means that biofouling growth rate is very slow, plus the fact that pieces further covered by biofouling could sink, due to the ballasting effect of the organisms.

2. Field measurements showed large difficulties to obtain distinguishable signature of plastic litter with pixel fractions below 1%. This is confirmed by the modelling exercise, and the cause is related to the large effect of the photon noise compared to the signal, which shall not be confused with the SNR reached by the sensor itself.

3. Colour of the materials plays an important role in terms of reflectance level, especially in the visible bands, but also some dependency in NIR and SWIR has also been observed in the field measurements. This dependency can be associated to effect of the pigments used to provide colour to the polymers, but this has not been confirmed. The fact that most floating plastic is white or close to be, it is also an opportunity for the selection of visible bands to support discrimination between plastic and other materials that could have some common spectral features (e.g. floating seaweeds).

4. Not a clear dependency of the geometry of the observation has been observed in the measurements, which points towards a more Lambertian properties of the polymers when dealing with light. Geometry did have effect in the field measurements, but due the distance to

target and the relative size of the pieces with respect to the sensor, those can be due to a 3D effect that would be mainly lost at TOA. This particular aspect shall be further studied.

5. There is a strong effect of layers of water over the plastic pieces. This was expected, and actually, was already reported by Garaba and Dierssen 2018 and Goddijn-Murphy and Dufaur 2018. However, the latter reported that such strong attenuation could not be explained by very thin layers of water, as per the experimental setup performed by Garaba and Dierssen 2018. Similar behaviour has been found in the field measurements done in this project, which has triggered some investigation about this topic. It has been found that there are significant chances that refractive index in the plastic/air interface is very different from the one in the plastic/water interface, largely affecting in the angular dependency of light source and sensor position. Measurements performed by the team with wet polymers at different angles show similar behaviour than those reported by Voss and Zhang 2006, which points towards this particular issue. It could be necessary to further explore these dependencies to improve detection of sub-surface floating plastics.

6. Modelling exercise has been focused in Case I waters, which represent open ocean conditions and where detection of floating plastics is potentially easier. The three most frequent polymers have been studied (LDPE, PP and PS) in order to understand the signature, they can yield from BOA to TOA and with pixel coverages of 0.1%, 1% and 10%. The exercise has involved the development of combined BRDFs for seawater and floating plastics. No significant results have been found for fractions 0.1%, but possibilities are found for fractions of 1% and 10%.

7. As pixels in the simulation are dimensionless, the success on the detection for fractions at 1% and 10% should be revisited according to the SNR specific for the proposed sensor. These results have been obtained by producing an SNRr index which measures how distinct signature of pure ocean cases are from scenarios where litter is present. However, if enough sensitivity is reached, GSD could be adjusted accordingly to increase mapping capabilities.

8. It has been shown that detection and monitoring or low-level concentration of plastics per pixel (whether from microplastics or macroplastics) is not feasible because of the minimum concentrations required to have a measurable signature. This implies that any potential satellite mission will have the focus in the observation of plastic accumulations in the surface of the water, like associated to windrows, frontal zones, etc. The level of detail can be achieved will rely upon the GSD that can found compatible with floating plastic detection.

9. No special loss of signature in the relevant bands have been observed when propagating signature from BOA to TOA, if well at TOA level the number of potential bands diminishes as consequence of the atmospheric absorption and scattering.

10. A set of spectral bands have been defined as they have - pending on instrumental assessment - potential for floating plastic detection. Whilst these bands are rather numerous, they bring possibilities for floating litter detection and monitoring, if well classification could be difficult to achieve, as not all of them will have enough SNR for instruments, or they could require GSDs not compatible with the targets. There are, however, some good choices.

11. Geometries of the simulations have resolved that glint presence contaminates the 111 potential observations in a way that can make difficult to distinguish glint from plastic polymers. This can be mitigated by including specific absorption bands from the polymers, as already proposed in [D3]. Nonetheless, and similar to ocean colour, a Relative Azimuth Angle (RAA) between 40° and 60° shall be favour, as it provides a good combination of low glint levels but enough light intensity. It is worth to mention that glint can appear at higher spatial resolution as consequence of the

slopes in the sea surface caused by wave trains (usually < 100m). Additional deglint techniques could be required.

12. Results of the modelling have helped also to understand why Sentinel-2 is capable of certain degree of detection of accumulations of floating plastics. Bands at 842nm and 1610nm are found between the ones yielding SNR values of relevance for litter observation, if well specific band centres, bandwidths and GSD from Sentinel-2 are probably not fully optimal for marine litter observation.

13. Atmospheric correction will be one of the key points to tackle in the future. As per this experiment, most of the relevant signal from plastic polymers is found in NIR and SWIR bands, which quite often are used in ocean colour applications to perform vicarious atmospheric corrections and/or calibrations. For floating plastic observation, a different approach shall be found, as these techniques effectively remove signature in these spectral bands to correct information in the bands used for ocean colour.

5 Mission concept for RESMALI and way forward

5.1 Specifying a potential mission

The design of a mission concept requires significant amount of information coming from different areas. One of the key elements are the so-called Mission requirements, that have been broadly discussed already in the chapter 3 of this document.

Based in such information, the RESMALI team devised a set of experiments and modelling exercises, aiming to narrow the options and try to offer a more realistic approach about what an EO mission devoted to ML could be. These experiments and their results have been presented in Chapter 4 of this document.

The following sections address the effort the team has done in crystalizing all this knowledge and learnings in such mission concept. However, it is worth to mention that the specifications here provided are not necessarily final ones, and just a starting point that shall be revisited and polished with additional studies and effort. The team for the project has already identified a set of activities that could help to better define the mission concept and get closer to a final instrumental setup. In particular, important additional dedications could be offered in the retrieval methods, which is what finally would determine the needed sensitivity at the different spectral bands proposed for the observation of ML.

It is also worth to mention that the proposed instrument is not necessarily the only one that could have a role in the remote sensing of marine litter, but just the one the team considers as most promising. Passive multispectral sensors have some strong limitations like the presence of clouds, which effectively block electromagnetic radiation in most of the spectrum from UV till LSWIR. This means that the proposed approach will suffer of such limitations. However, techniques based on microwaves (e.g. SAR) have such no limitations, if well they suffer of other difficulties and limitations.

It is acknowledged that an optimal solution for EO of ML would probably imply combination of instruments. However, considering the resources and time window granted to this activity, the team decided just to focus on the presented approach. Investigation and exploration of alternative methods is encouraged and this is an area in which future works could focus on, having into account the potential synergies between the various technologies available.

5.2 Revisited applications and Mission requirements

The activities planned aimed to produce an iteration over the initial results. In section 3.3, a starting set of applications was identified, based in the input produced by the scientific community with interest in ML. In addition, a set of Mission requirements for each of those applications was also defined. As stated previously, the approach we have followed aimed to cross-verified Mission Requirements and applications, with special attention to the most realistic solution according to the assumptions and results obtained in the different tasks.

In this section, we revisit those applications and requirements, and we compare them against the technological approach and performance explored in this chapter. Thus, we now match the potential applications to the capabilities of the mission concept proposed, so to learn what this theoretical mission would cover.

5.2.1 Proposed Mission specifications

As per previous sections, a summary of the mission specifications can be found in the Table 16, below. These are not final characteristics, as some of them could be perfectly adjusted to further extend the applicability of the mission. However, they are a good starting point to address this question in the future.

It is worth to mention at this stage that many of the mission specifications are derived from Sentinel-2/MSI instrument. This is intentional, as we consider that a mission of such characteristics can achieve many of the objectives for a specific EO mission for ML. Nonetheless, different aspects could be reconsidered or evaluated again once further information of some of those key elements is available.

For instance, some of the parameters that could be subject to revision are the altitude of the satellite, which for the time being is set at the same orbit of Sentinel-2. However, there are reasons why reducing the altitude could be interesting. On one hand, it could help to improve the SNR, what could help to reduce the spatial resolution of the instrument, and thus, improve the applicability and validity of the measurements. Also, a lower orbit would mean that time used in each orbit would be minor, but at the same time the effective swath will be also reduced for the same number of detectors.

Also, it is known that Sentinel-2 is significantly impacted by glint, as this was not a mission with a specific objective for open ocean. As explained in this document, sun glint can be a source of considerable problem for the effective detection of accumulations of plastic at water's surface. Some parameters could be also revisited to minimize glint.

Instrument	Multi spectrometer
Field of View	20.6 degrees (290km projected over surface according to orbit)
Maximum view zenith angle	15 degrees
Orbit	Sun-synchronous at altitude 786 km (potentially reducible to improve SNR and reduce revisiting times) Mean Local Solar Time at descending node: 10:30 (optimum Sun illumination for image acquisition) Inclination of 98.62 degrees Period of 100.6 min
Geometric revisit time	Five days from two-satellite constellation (at Equator)
Spectral range	[0.4 µm -2.4 µm] (VNIR + SWIR)
# of spectral bands	13 in total. 10 in VNIR, 3 in SWIR

Spatial resolution	20m (with current technology) 10m (with next generation of sensors)
Minimum plastic content	1% of the pixel

Table 16: Proposed mission specifications for RESMALI.

5.2.2 Applications covered by the proposed mission

According to the inputs and indications provided in Table 16, we can now establish which ones of the proposed applications could be actually covered by this mission. One of the elements to have into account is that initial estimations situate the required sensitivity in 1% of the pixel coverage. This translates to objects or equivalent areas of $4m^2$ and $1m^2$, for the 20m and 10m resolution options, correspondingly. Those are minimums that could offer difficulties for detecting sparse objects that are not concentrated in specific areas. However, under the same rule, if spatial resolution reached 5m, then objects or equivalent surfaces of $0.25m^2$ could be detected. That would be possibly enough to detect plastic buoys drifting in the ocean. However, a resolution of such characteristics would require an extra technological development, not directly compatible with the next generation of MSI sensors.

Table 17 lists all the application and the key mission requirements. These are also contrasted against the different spatial resolutions that have been proposed. The term “Goal” means that the proposed mission specifications comply with the most restrictive MRs of the targeted application; the term “Threshold” means that the mission specifications comply with the minimum MRs; the term “No” means that the proposed mission cannot comply with them. Terms in parenthesis mean that these could be achieved by whether revisiting some of the mission parameters or improving technology.

Application	Parameters	20m	10m	5m
Detection and identification of large ML items at the ocean (section 3.3.3.1)	GSD	No	No	Threshold
	Revisiting time	(Threshold)	(Threshold)	(Threshold)
	Coverage	Goal	Goal	Goal
	AOIs	Goal	Goal	Goal
	Objectives	No	No	Threshold
Detection and quantification of concentrations of ML at global scale (section 3.3.3.2)	GSD	Goal	Goal	Goal
	Revisiting time	Goal	Goal	Goal
	Coverage	Goal	Goal	Goal

	AOIs	Goal	Goal	Goal
	Objectives	No	No	No
Detection and monitoring of hot spots and accumulation zones (section 3.3.3.3)	GSD	Goal	Goal	Goal
	Revisiting time	(Threshold)	(Threshold)	(Threshold)
	Coverage	Goal	Goal	Goal
	AOIs	Threshold (Goal)	Threshold (Goal)	Threshold (Goal)
	Objectives	Threshold (Goal)	Threshold (Goal)	Threshold (Goal)
Monitoring of river mouths as main input flow for ML at the oceans (section 3.3.3.4)	GSD	Threshold	Threshold	Threshold (Goal)
	Revisiting time	No (Threshold)	No (Threshold)	No (Threshold)
	Coverage	Goal	Goal	Goal
	AOIs	Goal	Goal	Goal
	Objectives	Threshold	Threshold	Threshold (Goal)
Detection, monitoring and quantification of ML at shores and beaches (section 3.3.3.5)	GSD	No	Threshold	Threshold (Goal)
	Revisiting time	No	No	No
	Coverage	Goal	Goal	Goal
	AOIs	Goal	Goal	Goal
	Objectives	No	No	No

Table 17: Applications vs Mission requirements and Mission Specifications relative to the discussed passive optical radiometric approach.

From above, it could seem none of the possible applications is compliant. However, there are certain levels of acceptance in some of them that would require some revision. For instance, "Detection and monitoring of hot spots and accumulation zones" could be fully achieved if revisiting time of the instrument is improved. In fact, in this particular case, it is already covered over the 30° in latitude, and assuming two twin satellites in orbit (as currently is the case for Sentinel-2). The same applies for "Monitoring of river mouths as main input flow for ML at the oceans", in which the limiting factor is the revisiting time, but a threshold level could be reached by use of multiple platforms, for example.

In the case of the "Detection and identification of large ML items at the ocean", the same limitation applies in terms of revisiting time, but that main difficulty is the lower limit of detectability. We estimate that this could be achieved by obtaining spatial resolutions of better than 5m, assuming that detectability is the only criteria.

For the application "Detection and quantification of concentrations of ML at global scale" most of the parameters are correct. However, the instrumental sensitivity that is required does not fall within acceptable values. According to our results, concentrations of ML below 1% are almost indistinguishable from the background photon noise, rendering this application as not feasible.

The "Detection, monitoring and quantification of ML at shores and beaches" has not been properly explored in RESMALI, as its complexity was considered too high for the resources and time available within the project. However, the exchanges with the parallel project OPTIMAL (which explored this possibility with some limitations) showed that satellites would have serious difficulties in detecting plastic in beaches, due to the strong radiometric contamination that sand, gravel and rocks produce. Indeed, the main advantage of using NIR/SWIR bands is the strong absorption of water in these bands, in comparison to the plastic polymers. But this advantage does not exist over beaches, as these other materials can be significantly more reflective than plastics, and the combination of wet and dry surfaces adds extra complications. Thus, we do not consider feasible to produce a specific multispectral satellite mission for these areas, if well other technologies could operate well in them (e.g. drones or VHR satellites operating in VIS).

5.3 Development plan

This section is a roadmap for technology developments aiming at raising the maturity of Marine Litter (ML) remote sensing techniques. The Development plan nurtures of the outcomes from the previous activities. The goal of this section is to specify a technical roadmap leading from the mission concept to higher TRL value and identify activities/areas in which additional effort would benefit the improvement of the proposed mission concept.

5.3.1 Pathway for a breadboard

RESMALI aims at demonstrating the observability of ML from space. In the perspective of building observational requirements for a future mission, the main outcomes of the study are:

- We have focused on ML surface concentrations in the open ocean. For this purpose, it has also identified the multispectral imagery as one of the most promising techniques, due to the high SNR needed for ML detection and the thus the need to optimise the instrument for the ML spectral bands.

- We have identified the candidate spectral bands for the detection and identification of floating plastic polymers commonly encountered in the open ocean, based on a thorough experimental campaign.

- We have shown that a concentration of 1% of floating plastic can be detected by a multispectral instrument, with a GSD of 20 m (with current Sentinel-2 mission) and down to 10 m (with the future generation of Sentinel-2).

5.3.1.1 Way forward

The work performed in the frame of RESMALI is the first comprehensive effort in performing the iteration between acknowledgement of the ML problematic, identification of scientific needs, mission requirements, observation requirements and preliminary performance assessment.

This iterative process is the natural path followed by Science space missions, as done for Ocean Colour missions or Green House Gases Monitoring missions for example (Figure 26).

Nevertheless, several such iterations will have to be performed before the implementation of a ML remote sensing mission will be decided, starting by the confirmation of the scientific objectives (i.e. floating ML in the open ocean, but maybe not limited to that), then in-depth feasibility analyses and better appraisal of the reachable performances, until the mission and technical requirements can be written by ESA.

An interesting outcome evidenced by the analyses performed in the frame of RESMALI, is that current observation techniques provide a good starting point in the goal of detecting and identifying floating ML. In the short term (i.e. unless further analyses demonstrate other kind of needs), the current technical roadmaps, in particular on the detector side, are covering the needs. The next generation of multispectral instruments (e.g. Sentinel-2, Figure 27) would be perfectly suited for a ML mission, provided that the proper bands and post-processing methods are worked out.

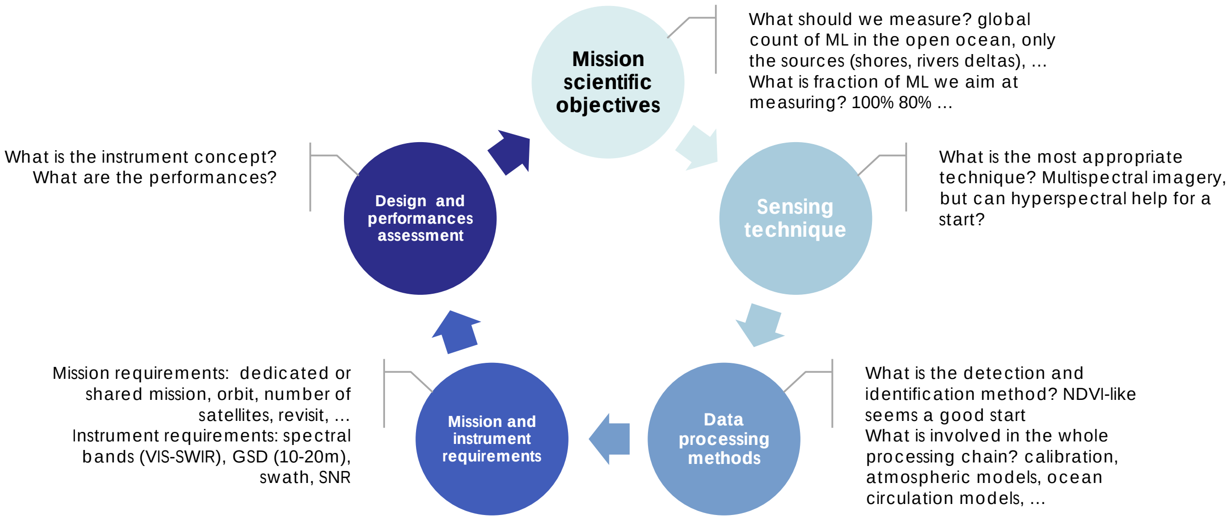

Figure 26: Iterations towards the definition of a ML mission. A first complete iteration has been performed in the frame of RESMALI. Other such iterations will be necessary, involving scientific / academic research, industry and ESA.

Figure 27: Sentinel-2 MSI VNIR detector with stripe filters associated to 10 spectral bands

The preliminary requirements derived from this study do not permit (and justify) the identification of technology development activities for the instrument technologies. One can reasonably think that the current roadmaps will provide natural candidate technologies for such a mission. In particular, two key technologies for these future missions will be:

- The detectors (VIS / SWIR)

- The spectral filters (VIS / SWIR)

Nevertheless, further studies are necessary to consolidate RESMALI results. In particular:

- Investigations on the indices used for ML detection. Some promising indices have been proposed, but more indices and possibly more complex indices, e.g. involving more spectral bands, would enable to decrease the required SNR or detect fainter concentrations than 1%. This work could be handled by Industry and typically Academic research. Synergies are possible with the Ocean Colour community, which has performed similar work in the field of observation of plankton for instance.

- Based on that work, or in parallel to, the exploitation of field data (e.g. Sentinel-2 imagery, similar to the work performed notably by ARGANS for ESA in the frame of the study "EO tracking of marine debris in the Mediterranean Sea from public satellites"), would be beneficial to the consolidation of the processing techniques and by simulation / extrapolation, to the testing of the detection methods (candidate indices, but not limited to), the false alarm removal methods, and possible identification methods. Since the start of RESMALI, two European hyperspectral missions have started operating: the DESIS instrument (DLR Earth Sensing Imaging Spectrometer, on the ISS, with a GSD of 30 m and a spectral resolution of 2.55 nm and including 235 spectral bands spanning from visible to near-IR) and the PRISMA mission (ASI PRecursore IperSpettrale della Missione Applicativa) that has just finished its commissioning phase at the time of writing. These missions offer opportunities for the testing of ML detection methods directly in the spectral bands of interest, probably limited to high concentrations of floating plastic (due to the GSD limited to 30 m). Interestingly, reflecting the path recently followed by The Ocean Cleanup towards addressing the ML issue at the source with their Interceptor concept, the observation of ML near the shores and in rivers deltas is an interesting field of investigation since the areas of interest are well known, the concentrations are very high, and there is much more available and actionable data (with Sentinel-2 in particular). Ultimately, like GHG monitoring missions, there might also be an interest to identify the ML sources in the frame of a polluter-pays policy.

- Once the requirements are consolidated, similar work as performed in the frame of RESMALI can then be conducted by Industry in the frame of a typical ESA Phase 0 / A study, to derive a mission and instrument design and performances. A relevant trade-off will be to compare multispectral and hyperspectral instrument concepts against these new requirements, at the light of the return of experience on the latest missions.

5.3.2 Scientific roadmap

According to the work performed during the project, a few limitations/caveats have been identified in the research field that could be subject to further exploration. In addition to those, the learnings of the project have also opened new opportunities for deepen our understanding of the remote sensing of marine litter, as well as opening some interesting question about the spectral characteristics of plastics polymers.

Furthermore, on the activities performed within this project, ARGANS has also led some other activities funded by ESA and UKSA in the exploitation of Sentinel-2 imagery for the study of marine litter in the environment. These activities have supposed a very good synergistic contribution to RESMALI, as it has allowed to understand better the limits of the existing capabilities at certain extend, and what shall be improved in order to achieve an optimal observational system. Some of the additional efforts that could be done in this area are also reflected in this roadmap.

Finally, it is also interesting to discuss about how the activities of RESMALI fit within the activities of the international community. The recent "Call for Ideas in Remote Sensing of Plastic Marine Litter", run by ESA through the new OSIP platform, is a good example of how the interest in the development of new techniques to study plastics in the environment is reaching Earth Observation and remote sensing in general.

In this chapter we are trying to cover the main topics that could be further explored in coming activities and that definitively are of interest to improve our knowledge about the remote sensing of plastics in the marine and aquatic environments, in general.

5.3.2.1 Requirements for basic research

During the execution of the Experimental and Modelling Plan (Chapter 4), a few limitations have been found, and areas that will require extra studies so to achieve the right level of knowledge. These areas go around to main concerns:

- The identification of the lower limit of plastic concentration in a pixel that is feasible with the current hyperspectral analysis capabilities.
- The understanding of the changing spectral properties of the plastic polymers in a sub-submersed situation or just covered by thin layers of water.

These two questions have not been possible to fully clarify within the reach of RESMALI and should be addressed in a proper context to solve them.

5.3.2.2 Expanding the modelling capabilities

Besides the potential advances that could be achieved in the previous section, and from which a modelling activity would automatically benefit, there are a set of aspects of the modelling presented in section 4.2 that could be revisited or expanded to bring further information. This could be required to close the current existing gap between the theoretical modelling presented so far in the project, and the reality of the instruments.

The main limitations of the performed modelling are as follows:

- Determining with more accuracy the impact of different types of aerosols, which was done in a simplistic way, as only marine aerosols were considered in the initial exercise, whilst for coastal applications could be of relevance to repeat some of the simulations with more complex aerosols.
- Properly cover mixing of different polymers over the same pixel, which was not done and could help to obtain additional information and explore possible techniques for spectral un-mixing, which could be necessary in the future to develop algorithms able to differentiate the different types of polymers and quantify them.

- Provide a finer resolution to the pixel coverages, which was done only in orders of magnitude and could require a finer grid in the fractions below 10% (as per previous points, this is an important area to really find the specific limit of detectability).

- Better understand the impact of wind conditions over the ocean's surface in terms of sun glint and lighting conditions. In the current exercise, wind speed was fixed but this could be revisited to identify till what a point sun glint could be a problem.

- Check the signature that floating algae (e.g. Sargassum), accumulations of leaves from marine phanerogams, and/or organic debris coming from land could have in the same experimental setup and see till what point they are causing false positives.

- Investigate the real impact of the uncertainties associated to the different parts of the model to understand their total contribution to the results.

In addition to those elements, there are other activities that would expand the current modelling effort and that would help to get closer to an optimal sensor. For instance:

- Introduce an end-to-end simulator that could transfer field measurements from artificial targets or real litter accumulations to space, so to simulate how they would be seen by existing instruments (e.g. Sentinel-2 MSI, PRISMA, Hyperion or VHR sensors). This could also be performed based purely in simulated BOA information (based in spectral libraries and water-leaving simulations) instead of in field measurements, if those were not available.

- Similar to the above, but according to a theoretical instrument, which could support the technological development before trying to physically breadboard. A good option could be to use the characteristics of the coming Copernicus HPM Chime satellite, as a proof of concept and to assess what this instrument could offer in the field of marine litter. This could also be valid for other instruments that are multispectral rather than hyperspectral, which also has some advantages.

- Combined at some extension with the above, investigate the development of reflectance indices that could be used in the future to detect, and potentially quantify and classify, the presence of marine litter at the ocean's surface.

For this last point, it is worth to mention that we have indeed done some effort already in this line. Some preliminary results based in a proposed set of indices were used in the elaboration of [AD-07]. Those, however, are rather preliminary and exploratory, as it was not an activity actually requested for this project.

From all of the above, there are a few overarching goals that would really support the further development of a mission:

1. Understanding better what are the errors and limitations of the models according to the existing knowledge. This, at the same time, will help to better refine the applications that a potential mission can have. Whilst modelling cannot be considered as a solution for everything, it is complimentary to actual measurements and serves to minimize the randomness of the choices done in the path towards higher TRLs.

2. Assessing better what are our actual capabilities for monitoring marine litter from space from existing sensors. In this particular, ARGANS has done extensive effort in the use of Sentinel-2 datasets, but this is necessary to be expanded to existing hyperspectral missions but also to other

coming multispectral missions. This, at the same time, will help the engineering component to better identify what technological push could be needed.

3. Refine the spectral lines and bands that could be used in a future mission and improve/propose spectral indices for marine litter detection from space, including a better understanding of the potential false positives reported by the community. This will help to prototype the software that will be needed to pass from L1b/c TOA reflectance values to L2 data.

Mind that even these goals could be a redundancy with the ones the RESMALI project has, the advantage is that now we know what aspects of these goals shall be specifically developed, whilst before RESMALI the question was if remote sensing of marine litter would be ever possible.

Other aspect to have into account is that the modelling effort would massively benefit of in situ data. One of the most challenging aspects we have faced so far is how to validate techniques and determine uncertainties. Activities like the deployment of artificial targets that are observed by remote sensing platforms, from drones to satellites, and passing by airplanes is a significant need to achieve the goals laid out above. So far, this effort has been mainly done to support investigation of capabilities for Sentinel-2, but consideration of the need for this data and in coordination with the existing remote sensing solutions is necessary to understand the limitations of the models. Field campaigns are in order and deployment of additional field instruments is also a strong need.

5.3.2.3 Learnings from the use of Sentinel-2 datasets

As indicated above, ARGANS Ltd has also done a significant effort to exploit the potential capabilities of Sentinel-2 to monitor marine litter. These activities have been performed in the frame of separated contracts, but their seed was born within RESMALI, and a strong interaction has taken place between those contracts and RESMALI, which has been very helpful to determine the current capabilities.

The team for RESMALI identified early in the project that, potentially, multispectral instruments could be enough to achieve detection of marine litter, and that probably the narrower bands but also noisier of hyperspectral instruments could be not so optimal for its observation. With that consideration, soon enough came the need to check if existing multispectral instruments could help on this matter. Sentinel-2 was rapidly selected as candidate, due to the combination of relatively high spatial resolution, but also for its spectral bands, some of which fall within the optimal regions for plastics (e.g. 841 and 1610 nm).

With that in mind, as previously already summarised, a feasibility study was funded by the UKSA during 2018, in order to explore if Sentinel-2 data could find accumulations of litter. At the time, we already suspected that microplastics or isolated plastic elements will be out of reach of the instrument, as signature associated to them could not be enough for detection. The paradigm of ocean colour is mainly based in the integral contribution of small particles over a volume of water, which in fact has impact into its colour. This change of colour is associated to the specific spectral characteristics of these particles, which gets combined with the signature from ocean water. This, however, relies on the identification of a specific “colour” for these particles, which could be unmixed from water’s signal. For microplastics, signature in the VIS part of the spectra is expected to be rather flat. We did not investigate that particular aspect in RESMALI but this was done by the parallel ESA project OPTIMAL. The issue relies on the fact that most plastic elements at sea are actually white, so their reflectance is quite homogeneous in all the visible bands. Because this brings a flat component to the signal, they will be confused with white noise whenever they are not present in quantities enough to make the change of water colour be noticeable as due to the existence of particulate matter. Further on this problem, little is known so far about the actual distribution of microparticulate contents in the water column. Inasmuch was deduced in Chapter 3, microplastics accumulate mainly in the surface of the ocean, and not much in the water column. This is not a problem if they are concentrated enough. However, whilst contents of plastic in the surface is comparable to phytoplankton till some extent, it is not so much in terms of numbers of particles for the same relative concentration. Plastic particles are usually larger in size and thus, they distribute less homogeneously within the pixel. As consequence, there is a strong frontier problem between the reflectance of these particles in the near surface and water itself, which again favours identify them as noise rather than signal. Results reported by OPTIMAL using laboratory setup confirmed our assumptions about the detectability of microplastics in suspension.

The final reason for their exclusion in the studies was also that reported distinguishable spectra for plastic polymers is only possible when observing NIR and SWIR spectral regions. By focusing in ocean colour, we were targeting plastic particles well mixed with water at some level, what renders nil the use of NIR and SWIR bands for their detection, significantly limiting the detection capability and the future exploitation of the data for classification and/or quantification.

Considering the above, the RESMALI team considered that most likely approach would be the detection of macro-litter, or moreover, accumulations of it in the surface of the ocean and other water masses. For such applications, Sentinel-2 could provide some information not yet explored. The goal of the SSGP project funded by UKSA was to precisely address this question: could Sentinel-2 spot litter accumulations? The answer was affirmative, and we reported to UKSA that this use was positive within some limitations, as Sentinel-2 was not tailored for this mission.

Proved this capability, ARGANS Ltd proposed to ESA via the Open Call of the EO4Society Program the development of a prototype EO data processor for Sentinel-2, able to report in these accumulations at coastal areas. The project aimed to combine information of Sentinel-2, the learnings from the previous SSGP project and also datasets from in situ observations (from University of Cadiz (Spain) and ISMAR-CNR (Italy)), both from natural accumulations and also of artificial targets (this part run by the University of Aegean, Greece), in order to prototype the processor (see example of intermediate output in Figure 29) and validate it up to certain level. The project called "EO Track of Marine Litter from public satellites in the Mediterranean Sea) run for 1 year and finished recently in last September 2019.

Besides the specifics of the EO data processor that was built in the project, the team for that contract had opportunity to further learn about the types of difficulties a future mission could run into. Those cover from some basic research in the area of remote sensing to the difficulties of developing spectral indices for this purpose. The list of challenges could be summarized as follows:

- Limitations of the existing atmospheric corrections.
- Difficulties to handle sun glint due to the scale of the size of the pixel *vs.* the waves.
- Removing false positives.
- Identifying the minimum fraction of the pixel by litter that triggers detection.
- Automatic detection of litter accumulations.

Some of these topics will be particularly challenging for almost any mission with a Sentinel-2 profile, and effort shall be done to better cover them in order to eventually have a workable mission, reason why this is very relevant for the objectives of RESMALI.

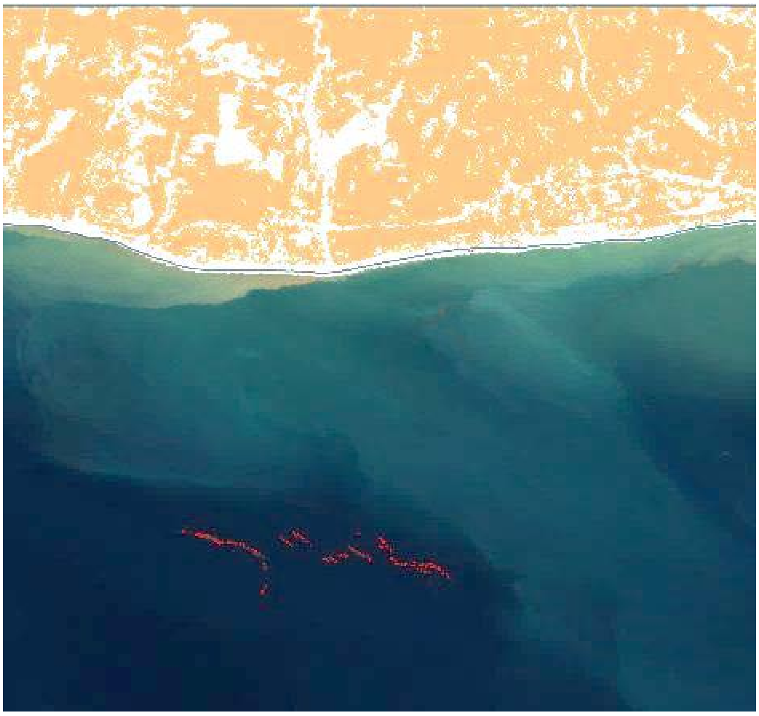

Figure 28: Example of marine litter windrows in the Southern Calabria Coastline, Italy (38.8, 16.7) on the 22nd October 2018. Sea mask has been removed to show visible RGB render of the sea surface. Floating MD targets highlighted red.

5.3.2.4 Known caveats

Because of the vast amount of possibilities, the RESMALI team decided to put the focus in the most promising aspects of remote sensing applied to marine litter. In the process, we have essentially focused in the spectral methods for its observation, with special emphasis in multispectral sensors, as in our view, they offer the best opportunities, even if it is true that we identify this application walks in the limit between multispectral and hyperspectral.

This decision has made the team to put less energy in evaluating alternative remote sensing technologies, like SAR or LiDAR. Those should still be properly explored when possible, even if chances are that results are more difficult to obtain with these technologies due to their mechanisms of operation, technical complexity or level of information provided by them.

Other caveats are referent to the areas of interest. In our case, the attention was provided for open ocean/coastal applications, and the proposed mission concept matches with it. We do not foresee applicability for beaches, due to the complex nature of the remote sensing paradigm from satellites in these areas, where there are many aspects identified in section 3.3 that make it far more complex to analyse and obtain results for a project of the size of RESMALI. It is possible that other technologies (e.g. drones) can offer better chances in these areas, as even VHR satellites have proved that can only provide very limited information over beaches (Acuña-Ruz et al, 2018).

However, even if we excluded them from the area of interest for RESMALI, they are still one of the regions where more interest is present, due to the impact litter has there both in tourism and natural ecosystems.

Finally, in terms of ranges of sizes, in RESMALI we have concluded that the best opportunity relies in the identification of plastic accumulations in the surface of the water masses. The exact size of these fractions will be limited by the SNR that can be afforded and the size of the pixel. Current capabilities have been reported in Chapter 5. In our view, detection of diffused microplastics (< 5mm) is not feasible, due to their spatial variability and spectral characteristics, which impose some limitations to the remote sensing. Nonetheless, this fraction is the most pervasive and with more potentiality to harm health of humans and of the organisms in the environment, if we exclude the ghost nets.

6 Impact, outreach and scientific contributions

6.1 Impact

The work done by the RESMALI team has been an important icebreaker in terms of the remote sensing applied to marine litter. When this project started, there was little knowledge in this area of research, and there was not much hope in the community that this approach would come out to be positive.

Now, after two years of intense work, there are evidences enough to think positively about the application of remote sensing to this environmental problem. And a significant amount of knowledge has been also generated in the process. The project has helped a lot to create momentum within the community to further explore alternatives to support detection and monitoring of litter from satellites, airplanes and drones. Witness of this explosion is the large number of ideas presented by the community in the ESA OSIP platform, under the call for marine litter.

This rapid expansion and growing interest come from a few facts:

1. The efforts done by RESMALI run by ARGANS and the parallel contract, named OPTIMAL and run by PML, have been definitively a serious impulse to our understanding of the remote sensing for marine litter.

2. In RESMALI, and with the support of additional studies performed by ARGANS Ltd., it has been possible to prove the preliminary feasibility of multispectral/hyperspectral techniques for the detection of marine litter from satellites.

3. The team has been working actively in promoting the activities of RESMALI in as many forums as possible, including numerous workshops and international conferences, from the starts in the workshop run at ESTEC, till the Living Planet Symposium 2019 in Milano (Italy), passing through the 6th International Conference in Marine Debris (San Diego, USA) in 2018.

4. In all this process, multiple contacts have been done with some of the most respected researchers in the area of marine litter, like Nikolai Maximenko (University of Hawaii, USA), Eric vanSebille (University of Utretch, Netherlands), Stefano Aliani (ICMAR-CNR, Italy), Francois Galgani (IFREMER, France), Heidi Dierssen (University of Connecticut, USA), Kara Law (NOAA, USA), Richard Thompson (University of Plymouth, UK), to cite some. The team also counted with some of those consolidated experts, including Andres Cozar (University of Cadiz, Spain) and Laurent Lebreton (The Ocean CleanUp, Netherlands) whom also are actively involved in the international community.

5. The team for RESMALI has also successfully participated in the IMDOS concept (Integral Marine Debris Observation System), which in turn become into a community paper within OceanObs 2019 and published in the Frontiers of Marine Sciences journal (Maximenko et al, 2019). This paper is a keystone for the development of remote sensing of marine litter in the coming years.

6. The team has also participated in a paper that has come out of the 1st workshop on Remote Sensing of Marine Litter organised at ESA-ESTEC, which establishes some ground basis about the observational needs of the community, and that includes inputs from OPTIMAL, RESMALIand the community (Martínez-Vicente et al, 2019).

7. In addition, ARGANS Ltd has done a substantial effort in further opening the area of research to the community, as proved by the various projects that the organisation has/is running with some

of these key members. These projects have been possible thanks to the foundations created by RESMALI, including the SSGP contract for the feasibility study of Sentinel-2 images as source of data for detecting marine litter (funded by UKSA), the EO Track of Marine Litter in the Mediterranean Sea (funded by ESA through the EO4Society Open Call program), the Copernicus Marine Service for marine litter transport in the North Sea (funded by CMEMS), and the project for the study of Beaching mechanisms of marine litter in the coastal areas of Corsica (funded by IFREMER). In those projects we work with many entities, from universities (e.g. University of Cadiz, University of Aegean, ICMAR-CNR), research institutes (e.g. IFREMER) to NGOs (e.g. The Ocean CleanUp, WWF Europe) and public organisations involved in environmental regulations (e.g. Environmental Agency in UK), and of course international integrators and industry (e.g. AIRBUS DS, ESA, UKSA).

8. In addition to this, the ACRI group to which ARGANS pertains have been also supporting the promotion of our activities through their own network and participation in conferences, plus promoting the incorporation of the citizenship to support science by means of the SAMPLEX app developed by a sister company of the group.

All of this has allowed to cooperate with many entities and members of the international community, from which we can proudly say we have now a solid position.

In terms of the future, this document lays out many elements that could be explored or are needed for the following steps towards a potential mission. Some of these were submitted to the Open Call for Ideas organised by the ESA Open Space Innovation Platform (OSIP) team. The list of approved ideas includes many of our current partners and collaborators, with which we plan to continue working with, whereas inside of the ideas ARGANS Ltd is leading in the proposal phase, or by exchanging information/looking for synergies with the teams these collaborators are setting up by themselves. This diversification will, with no doubt, substantially help to keep adding pieces to this puzzle and progress towards the future of RESMALI.

Other aspect to mention is that ARGANS Ltd has been identified as one of the European entities leading the research of plastics in the environment by many members of the community within the continent. Thanks to that, ARGANS is preparing currently a proposal for an ambitious H2020 project in which EC wants to stablish the basis for a world-leading laboratory in this area. The purposes of this laboratory are beyond the remote sensing paradigm, but ARGANS will provide this component to the laboratory if we are successful in this proposal to the EC.

All in all, the overarching goal of RESMALI is to encourage policies for the control of this environmental problem, goal to which ARGANS Ltd is fully committed to support from the Earth Observation and Ocean Modelling components.

The roadmap presented in this document collects important advances that could be done in various of the branches of research involved in the remote sensing of marine litter. Whilst not all of them have been identified purely in RESMALI, they have been considered of relevance for the future. The list is probably not exhaustive but at least reflects the main challenges that remain to be addressed. From the technical point of view of the TRL evolution of the proposed mission concept there is still activities to be performed that would help to realistically constrain the scenarios ins the pathway towards a dedicated instrument.

We hope that the coming publications associated to the outcomes of this project will foster additional initiatives and collaborations to support the additional needs, for which the consortium is keen to develop and investigate to move the milestone closer to the final goals of RESMALI.

6.2 Participation in international conferences, workshops and symposiums

The RESMALI team has been actively participating in international events of relevance I the context of Earth Observation and Marine Litter. This is witnessed by the following list:

- 1st ESA Workshop on remote Sensing of Marine Litter (30 November – 1 December 2017). ESTEC, Netherlands.
- 6th International Conference on Marine Debris (12 – 16 March 2018). San Diego, USA.
- Challenger Conference 2018 (10 – 14 September 2018). Newcastle, United Kingdom.
- AIRCENTER 4th High Level Dialogue (25 – 27 November 2018). Las Palmas, Spain.
- IEEE Workshop in Marine Litter (26 – 27 November 2018), Brest, France
- Litter Drone International Symposium (10 December 2018). Madrid, Spain.
- Med 2018 ESA Workshop (11 – 12 December 2018). Frascati, Italy.
- Atlantic from Space ESA Workshop (23 – 25 March 2019). Southampton, United Kingdom.
- ESA Living Planet Symposium 2019 (13 – 17 May 2019). Milano, Italy.
- ESA Phi-Week 2019 (9 – 13 September 2019). Frascati, Italy.
- OceanObs 2019 (16 – 20 September 2019). Honolulu, USA.

6.3 Collaborations

The activities of RESMALI have benefitted from an extensive collaboration with other entities beyond the ones included in the team. In particular, exchanges of information and networking activities have taken place with the following individuals:

- Dr François Galgani (IFREMER, France), in the context of the UNESCO GESAMP Group (http://www.gesamp.org/)
- Dr Nikolai Maximenko (University of Honolulu, USA) (http://iprc.soest.hawaii.edu/)
- Dr Stefano Aliani (ISMAR, Italy) (http://www.ismar.cnr.it/)
- Dr Eric van Sebille (University of Utretch, Netherlands) (https://www.erik.vansebille.com/)
- Dr Heidi Dierssen (University of Connecticut, USA) (https://marinesciences.uconn.edu/)
- Dr Richard Thompson (University of Plymouth, United Kingdom) (https://www.plymouth.ac.uk/)
- Dr Konstantinos Topouzelis (University of Aegean, Greece) (https://www1.aegean.gr/)
- Dr Victor Martinez-Vicente (Plymouth Marine Laboratory, United Kingdom) (https://www.pml.ac.uk/)

- Dr Laila Romero (IsardSat, Spain) (https://www.isardsat.cat/)
- Dr Dick Vethaak (DELTARES, Netherlands) (https://www.deltares.nl/en/)
- Dr John Hedley (Numerical Optics Ltd, United Kingdom) (https://www.numopt.com/)
- Dr Antoine Mangin (ACRI-ST, France) (https://www.acri-st.fr/)
- Heidi Savelli (UNEP GPA / Global Partnership on Marine Litter) (https://www.unenvironment.org/)
- Dr Georg Hanke (European Commission, Joint Research Centre (JRC), Ispra, Italy) (https://ec.europa.eu/info/departments/joint-research-centre_en)
- Dr Thomas Maes (CEFAS, United Kingdom) (https://www.cefas.co.uk/)
- Dr Delwyn Moller (RSS, USA) (https://www.remote-sensing-solutions.com/)
- Dr Atsuhiko Isobe (Kyushu University, Japan) (https://www.kyushu-u.ac.jp/en/)
- Claire Olsen (Marine Biology Association, United Kingdom) (https://www.mba.ac.uk/)

Additional contacts/interactions have taken place with the following institutions:

- Environmental Agency (United Kingdom) (https://www.gov.uk/government/organisations/environment-agency)
- Environmental Protection Agency (USA) (https://www.epa.gov/)
- World Wild Foundation Europe (http://www.wwf.eu/)
- SurfRiders Foundation Europe (https://surfrider.eu/)
- National Oceanography and Atmosphere Agency (USA) (https://www.noaa.gov/)
- AZTI (Spain) (https://www.azti.es/)

Further in collaborations, the RESMALI team has also had relevant with other existing working groups. In particular:

- SCOR WG153 "Flotsam", led by Dr. Stefano Aliani (http://scor-flotsam.it/)

Also, there have been direct exchanges with the following projects:

- SSGP-201802-17 "GeoInt Service for Marine Litter" (UKSA, United Kingdom)
- ESA Contract 4000124861/18/I-NB "EO tracking of marine debris in the Mediterranean Sea"
- CMEMS 1085-P1018-CMEMS-DEM4-LOT5_TECH "Litter TEP"

6.4 Scientific production

The RESMALI team is active in terms of scientific publications. As such, the following publications have been made directly associated to the project or as part of the external collaborations:

Maximenko, N., Corradi, P., Law, K. L., Van Sebille, E., Garaba, S. P., Lampitt, R. S., ... & Thompson, R. C. (2019). Towards the integrated marine debris observing system. Frontiers in marine science, 6, 447.

Martínez-Vicente, V., Clark, J. R., Corradi, P., Aliani, S., Arias, M., Bochow, M., ... & Echevarría, F. (2019). Measuring marine plastic debris from space: Initial assessment of observation requirements. Remote Sensing, 11(20), 2443.

Topouzelis, K., Papakonstantinou, A., & Garaba, S. P. (2019). Detection of floating plastics from satellite and unmanned aerial systems (Plastic Litter Project 2018). International Journal of Applied Earth Observation and Geoinformation, 79, 175-183.

The following scientific articles are currently under preparation:

Arias, M., Hennen, M., Delaney, J., Martin-Lauzer, F-R., Cozar, A. (2019) Evidence of observations of marine litter from space in Sentinel-2/MSI data. (Under preparation).

Arias, M., Garaba, S., Lebreton, L., Corradi, P. (2019) Radiative transfer simulations of plastic marine litter for an Earth Observation mission. (Under preparation).

Garaba, S., Lebreton, L., Arias, M., Corradi, P. (2019) Spectral library for in-situ plastic marine litter. (Under preparation).

Lochard, J., Bonnery, G., Arias, M., Cozar, A., Lebreton, L, Garaba, S., Corradi, P. (2019) Mission concept for the Remote Sensing of Marine Litter. (Under preparation).

6.5 Others

The team RESMALI has also been involved in educational and diffusion events. In particular, Manuel Arias (ARGANS) had opportunity to produce a TEDx talk in February 2019 (University Polytechnic of Valencia, Spain).

The complete talk is available in the following link (in Spanish):

https://www.youtube.com/watch?v=XLax8XuNUKc

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