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Campaign on Remote Sensing of Plastic Marine Litter

REACT

Crowdsourcing, Copernicus and Hyperspectral Satellite Data for Marine Plastic Litter Detection, Quantification and Tracking

Executive Summary

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ARPA PUGLIA

EUROPEAN SPACE AGENCY

CONTRACT REPORT

The work described in this Report was done under ESA contract.

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The work described in this Report was done under ESA contract.

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Acronyms

AI	Artificial Intelligence
ARPA	Environmental Prevention and Protection Agency of Puglia Region
ASI	Italian Space Agency
CNMF	Coupled Nonnegative Matrix Factorization
DL	Deep Learning
EU	European Union
GSA	Gram-Schmidt Adaptive
HS	Hyperspectral
HySure	Hyperspectral Superresolution
LGBM	Light Gradient Boosting Model
LDPE	Low-Density Polyethylene
ML	Machine Learning
MSFD	Marine Strategy Framework Directive
NOAA	National Oceanic and Atmospheric Administration
NIR	Near InfraRed
N/A	Not Applicable
OSIP	Open Space Innovation Platform
PAN	Panchromatic
PCA	Principal Componet Analysis
PET	Polyethylene Terephthalate
PRISMA	PRecursore IperSpettrale della Missione Applicativa
PS	Polystyrene
PVC	Polyvinyl Chloride
SDGs	Sustainable Developments Goals
SoW	Statement of Work
SSU	Spectral Signature Unmixing
SWIR	Short Wave InfraRed
VNIR	Visible and Near InfraRed

VHR Very High Resolution

Table of Contents

1 Scope of the document

This document is the Executive Summary for the REACT project, performed under ESA contract no. 4000131235/20/NL/GLC as awarded to a consortium led by Planetek Italia and comprising the following institutions:

- Planetek Italia s.r.l.
- National Technical University of Athens (NTUA)
- Environmental Prevention and Protection Agency of Puglia Region (ARPA Puglia).

The output of the REACT project consists of the following technical reports:

- D1.1 Users' Requirements
- D1.2 Technical Specifications
- D1.3 Report on Data Preparation
- D1.4 Report on the Algorithms Design
- D1.7 Report on Prototype Integration, Delivery, Assessment
- D1.8 Report on Methodology and Prototypes Testing and Validation

A compendium of the above technical reports is also available in the form of a Final Report (OP190296-35-v1).

The Final Presentation was held on September 24th, 2021, via telco because of the Covid-19 pandemic, with ESA, Planetek Italia, NTUA and ARPA Puglia.

1.1 Applicable Documents

AD1	ESA Contract No. 4000131235/20/NL/GLC	
AD2	Technical Proposal	pks100-286-1.0
AD4	Negotiation Points	pks100-300-1.0
AD4	MoM Negotiation Meeting	pks100-301-1.0

1.2 Project's Documents

PD1	Project Management Plan	OP190296-01-v0
PD2	Users' Requirements	OP190296-09-v1
PD3	Technical Specifications	OP190296-10-v1
PD4	Report on Data Preparation	OP190296-16-v1
PD5	Report on the Algorithms Design	OP190296-17-v1
PD6	Report on Prototype Integration, Delivery, Assessment	OP190296-25-v1
PD7	Report on Methodology and Prototypes Testing and Validation	OP190296-32-v1
PD8	Final Report	OP190296-35-v1

2 Abstract

Oceans receive solid waste from anthropogenic activities. A significant amount of the produced solid waste is made of plastics. The amount of plastic debris in the ocean and coastal areas is steadily increasing and is now a global major environmental problem. Accumulation of marine debris poses considerable threats to the livelihood of aquatic species and ecosystems and human beings as microplastics enter the diet of fish, shellfish, birds, and then our food chain. At the global scale, the 2030 Agenda for Sustainable Development, adopted by the United Nations in 2015, calls to action to conserve and sustainably use the oceans, seas and marine resources with the Sustainable Development Goal No. 14. Among the SDG 14 targets, the 14.1 calls to prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution. From the European perspective, the Marine Strategy Framework Directive (MSFD) requires the EU Member States to ensure that “properties and quantities of marine litter do not cause harm to the coastal and marine environment”.

For monitoring marine plastic litter, ground-based monitoring systems and/or field campaigns are limited, time-consuming, expensive, require great organisational efforts, and cannot provide information about the spatial and temporal dynamics of debris.

The key target user of the REACT project was ARPA Puglia, which is in charge of detecting and monitoring marine plastic litter in the framework of the European legislation (i.e., MSFD).

The critical target users’ needs can be summarised in reaching the capacity to:

- support field campaigns by environmental agencies to implement data collection plans by field operators;
- perform regular monitoring of marine litter over broad areas thanks to satellite imagery;
- provide spatial and temporal distribution of marine litter thanks to satellite data;
- forecast paths of floating litter;
- identify potential sources of plastic litter into the marine environment and forecasting possibly places of beached litter;
- achieve a cost-efficient, repeatable, and flexible methodology, from local to the country level.

Earth Observation by satellite can contribute significantly to marine plastic litter monitoring thanks to its global synoptic point of view. However, remote sensing of marine plastic litter is in its infancy, and it is a significant scientific and technological challenge. REACT was focused on presenting a Proof-of-Concept on remote sensing of marine plastic litter—the project aimed to develop a methodology to detect plastic litter offshore and onshore. The methodology exploited data fusion of multispectral (i.e., Sentinel-2, WorldView) and hyperspectral satellite data (i.e., PRISMA), together with in situ data collection, and took advantage of two different approaches. The first was based on spectral signature unmixing, and the second was based on artificial intelligence methodologies.

3 Objectives

The main objectives of the project are to:

- Assess how plastic litter can be detected and quantified with current and future remote sensing tools;
- Develop adaptive indices insensible to biases induced by sunglint on satellite radiometric products and indicate the constraints of current satellite missions under various atmospheric and illumination conditions;
- Exploit data fusion methods between remote sensing data with high spectral (PRISMA hyperspectral, Sentinel-2) and high spatial resolution (PRISMA panchromatic, WorldView) to increase the sensors' detectability of marine plastic litter;
- Explore spectral unmixing methodology for sub-pixel detection of floating marine plastic debris;
- Explore Artificial Intelligence techniques for detecting plastic litter;
- Conduct controlled experiments under real conditions to better understand the effect of the atmosphere and the illumination conditions on the spectral properties of marine plastics in visible and infrared wavelengths.

4 Controlled experiments

In the framework of the project, a few controlled experiments under real conditions were realised to understand better the effect of the atmosphere and the illumination conditions on the spectral properties of marine plastics in visible and infrared wavelengths.

The controlled experiments were realised in Mytilini and Koplos Geras, on the Greek island of Lesvos. 12 floating plastic targets were constructed for the experiment needs. Their sizes were selected according to the spatial resolution of PRISMA and Sentinel-2 data that were expected to be achieved by data fusion and pansharpening techniques, i.e. 5.1x5.1 m2 (about the resolution of PRISMA fused data), 2.4x2.4 m2 (nearly half of the resolution of PRISMA fused data), and 0.6x0.6 m2 (about 1/8 of the resolution of PRISMA fused data and very close to the resolution of Sentinel-2 fused data). For each one of these three different sizes of targets, four types/compositions of plastic materials with various colours were setup: 1) low-density polyethylene (tarps in white, yellow and green colour), 2) polyethylene terephthalate (transparent water bottles, green oil bottles), 3) polystyrene (sheets for building insulation in cyan colour), and 4) all the above materials in equal surface extent.

In-situ measurements using the spectro-radiometer were also carried out during the controlled experiments.

The controlled experiments were realised with the cooperation of the University of the Aegean.

Figure 1 Tsamakia beach in Mytilini (Lesvos Island, Greece)

Figure 2 Kolpos Geras (Lesvos Island, Greece)

Figure 3 Orthorectified UAV data collected over the plastic targets in Mytilini (Lesvos Island, Greece)

5 Outputs

5.1 Abundance maps of plastic litter

A single pixel's signal is often a mixture of several distinct electromagnetic signals that constitute a macroscopic composite, regardless of the sensor's spatial resolution. Spectral unmixing contributes to the extraction of information at a sub-pixel level. Its main scope is to detect the distinct spectra in the hyperspectral scene, which may represent materials, and to estimate their apparent quantification in a pixel in terms of a fraction. Endmembers, or pure pixels, correspond to these different signals, whereas abundances refer to the fractions of these endmembers that exist within a mixed pixel.

In this project, marine plastic litter detection was achieved by separating endmember spectra that best characterise plastic materials and water. Areas littered with plastics present high abundance values of the endmember labelled as “plastic” and low abundance values of the endmember labelled as “water”. The respective abundance maps are products of the unmixing methods and their observation leads to plastic litter detection.

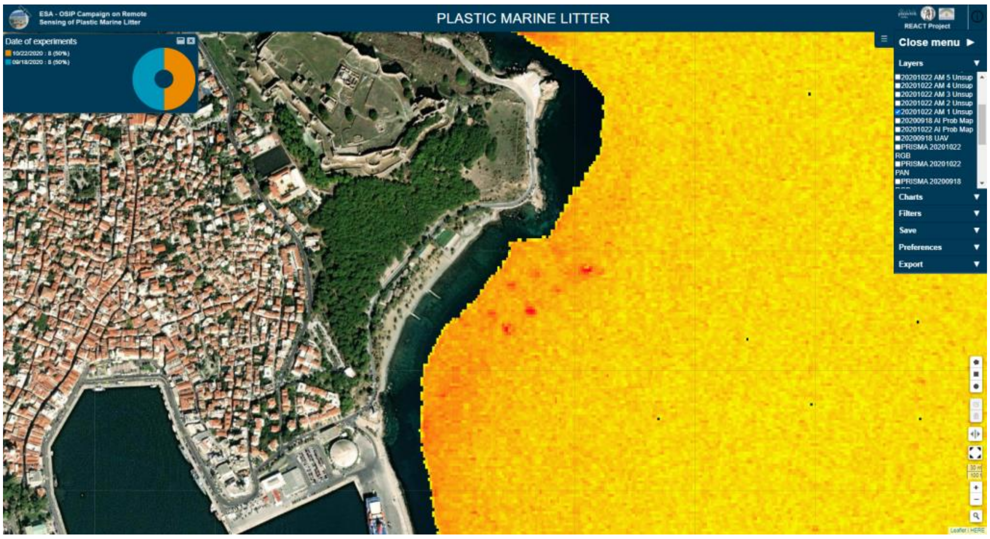

Figure 4 Map representing the fraction of each material (endmember or pure pixel) that appear in a mixed pixel

5.2 Probability maps of plastic litter

In this project, marine plastic litter detection was achieved by exploiting supervised and unsupervised ML algorithms. The output were probability maps representing the probability that a pixel contains plastic or not. For pansharpened PRISMA data, the probability map was a linear combination of supervised and unsupervised ML algorithms, while for fused Sentinel-2 + WorldView data only unsupervised ML algorithms were adopted for outputting the probability maps.

Figure 5 Map representing the probability that a pixel contains plastic or not

6 Findings

The main relevant findings of the project were drawn and summarised below:

- **Pan-sharpening methods of PRISMA data**

Similarity measurements between water and plastic target spectra were performed for every pan-sharpened image with the spectral angle distance (SAD) and correlation coefficient (CC). It was observed that

a) water and plastic signatures are significantly correlated in the original image, and
b) all the pan-sharpening methods generally present low SAD values and high CC values, which means that signatures, even after pan-sharpening, are pretty similar.

Pan-sharpening methods exhibiting the highest mean SAD value and the lowest mean CC value are the most appropriate for marine plastic detection. Based on this statement, PCA (Principle Component Analysis) and GSA (Gram-Schmidt Adaptive) methods present the most satisfactory results in terms of spectral discrimination between water and plastics. Apart from its spectral performance, the PCA method is straightforward and presents minor spatial distortions. Thus, it can be selected as the most appropriate pan-sharpening method for marine plastic detection.

- **Sunglint correction of PRISMA data**

Four sunglint correction methods were applied to the pan-sharpened image (Hedley et al., 2005[1]; Lyzenga et al., 2006[2]; Goodman et al., 2008[3]; Kutser et al., 2009[4]) produced by the PCA method since PCA produced the most satisfactory spectral separation between the water and the targets. Sunglint correction methods by Hedley et al., 2005 and Lyzenga et al., 2006 were not considered suitable for the PRISMA images, as far as the detection of floating plastic litter is concerned. Regarding the methods by Goodman et al., 2008 and Kutser et al., 2009, even though they managed to separate the targets from the water spectrally, they did not perform better than the initial pan-sharpened image; thus, their application was not considered necessary.

- **Fusion methods of Sentinel-2 and WorldView data**

According to the project's experiments, the data fusion methods based on matrix factorisation perform better than the deep learning methods. Indeed, plastic targets were not always distinguishable when deep learning methods were applied, and the fused images were quite noisy. Moreover, deep learning methods resulted in severe spectral distortions in the fusion product.

Among the several combinations of the WorldView bands that were employed in the matrix factorisation methods, the combination that includes all the VNIR bands yields the best results. CNMF (Coupled Nonnegative Matrix Factorization) method produced better results when plastic targets were placed offshore. When the land was masked, the fused image presented pixilation near the shore. When plastic targets were placed onshore, the HySure (Hyperspectral Superresolution) method presented slightly better results. In this case, the shape of the fused signatures was more similar to the original spectral signature and spectral and spatial distortions were not observed.

- **Spectral Signature Unmixing and plastic indexes**

Two methodologies for marine plastic litter were presented: the first is based on spectral unmixing analysis, and the second is on band indexes.

Considering the pan-sharpened hyperspectral datasets, some constraints arose due to the spectral inseparability between plastic targets and “shallow” waters. So, land and “shallow” water pixels should be masked out. Pan-sharpening and spectral unmixing can detect floating marine objects, but some tuning in the labelling step is required using more datasets.

Tuning is also required for the successful application of the indexes on PRISMA pan-sharpened hyperspectral imagery. Furthermore, it is concluded that the thresholds used for the final mask estimation need to be manually defined.

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[1] Hedley J. D., Harborne A. R. , Mumby P. J., 2005. *Technical note: Simple and robust removal of sun glint for mapping shallow-water benthos*. International Journal of Remote Sensing, 26:10, 2107-2112, DOI: 10.1080/01431160500034086

[2] Lyzenga D., Malinas N. and Tanis F., 2006. *Multispectral Bathymetry Using a Simple Physically Based Algorithm*. IEEE, Transactions on Geoscience and Remote Sensing, 44, 2251, DOI: 10.1109/TGRS.2006.872909

[3] Goodman J.A., Lee Z., Ustin Z., 2008. *Influence of Atmospheric and Sea-Surface Corrections on Retrieval of Bottom Depth and Reflectance Using a Semi-Analytical Model: A Case Study in Kaneohe Bay, Hawai*. OSA, Applied Optics, 47, F1, DOI: 10.1364/AO.47.0000F1

[4] Kutser T., Vahtmäe E., Praks J.A., 2009. *Sun Glint Correction Method for Hyperspectral Imagery Containing Areas with Non-Negligible Water Leaving NIR Signal*. Remote Sensing of Environment, 113, 2267, DOI: 10.1016/j.rse.2009.06.016

The CNMF fusion method and spectral unmixing analysis properly mapped the plastic and wooden targets using the multispectral dataset. All targets except one small were detected. Fused data with high spatial and medium spectral resolution provided very good results. In this case, only land masking is required.

Accuracy results were obtained from method validation. Overall, the results of this study are promising for the development of an automated algorithm for the detection of floating plastic and wooden objects in the marine environment.

- **Artificial Intelligence**

Two different kinds of algorithms were used to detect marine plastic litter on hyperspectral pan-sharpened PRISMA data. The first was an unsupervised machine learning algorithm among the Clustering methods (K-means); the second was a supervised machine learning algorithm among the Decision Tree methods (LGBM). Due to the insufficient number of pixels representing the plastic targets, an unsupervised method was used. On the other hand, supervised methods can create complex relationships between input data and ground truth automatically. For these reasons, both methodologies were applied to extract the final probability mask.

Overall accuracy results were obtained from method validation applied on trained algorithms.

The AI methodology developed for hyperspectral images is capable of extracting floating objects offshore, even if with little data for the training phase. However, if data have significant differences from those used for the training, the output could be meaningless. Increasing the training data, it was possible to significantly reduce the false positive and detect floating objects with more accuracy. This proved that, in the presence of further data to be used during the configuration phase, it will be possible to reach very good results in terms of extraction of floating objects and distinguish plastic targets offshore and other anthropogenic objects on the sea.

The input data were insufficient to decide if LGBM is better than the K-means, so additional satellite acquisitions with plastic targets offshore are needed.

No significant results were highlighted with the target onshore.

The AI methodology developed for fused multispectral images was able to highlight plastic targets offshore with high accuracy. Due to the lack of information, only unsupervised methods were tested. Some constraints arose due to the spectral inseparability between plastic targets and “shallow” waters. So, land and “shallow” water pixels should be masked out.

Finally, no significant differences were found between the images coming from fusion using HySure and CNMF so that both methods are valid to be used as input for the K-means methodology.

This work showed that detecting plastic targets onshore remains an open point and additional analysis is necessary.

- **End-user’s assessment**

Abundance maps and probability maps represent a valuable tool to support ARPA for the monitoring activities of the Descriptors 10 of the MSFD. The output of REACT can support the authorities (Environmental Agencies, Universities, Research Centres, etc.) responsible for the monitoring. In particular, maps of abundance and maps of probability can help the definition of monitoring plans, to evaluate the optimal position for a monitoring station.

In addition, maps of the spatial and temporal distribution of marine litter can be used in modelling the dispersal of plastic litter in aquatic systems from local to global scales. Indeed, the application of current data from remote sensing via satellite can become an efficient and reliable tool to monitor large marine areas.