FEASIBILITY ASSESSMENT OF A DEDICATED SATELLITE MISSION FOR MONITORING MARINE MACROPLASTICS

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ABSTRACT

Marine plastics is a major environmental problem which requires systematic monitoring. We investigated to feasibility of detecting marine macroplastics using a dedicated satellite mission. After consulting a diverse group of stakeholders, three primary use cases were selected for which satellite monitoring would have high impact, be feasible, but is not yet covered by current missions. The use cases are: 1) monitoring of beach litter, 2) monitoring litter accumulations in coastal/estuarine fronts and coastal windrows and 3) landfill detection (source of marine plastics).

They are best covered using an optical high resolution superspectral instrument with a set of up to 26 narrow spectral bands covering the VNIR and SWIR, a spatial resolution of 1m to 3m and a high SNR. As only selected areas need to be imaged, with infrequent updates, a swath of 10km is sufficient.

The proposed instrument concept include a telescope with 45cm front mirror, dedicated frame sensors for VNIR and SWIR, equipped with spectral filters. Spatial resolution of 1m (VNIR) and 3m (SWIR) can be achieved with 11km swath. By using pitch steering, longer integration times enable good SNR. With a suitable platform, a mission with a total dry mass 150kg range would meet all requirements.

1 INTRODUCTION

1.1 Marine Litter Problem

Marine plastics is widely recognized as a major and urgent global environmental problem, with a major negative impact on marine life and leading to global economic loss, as well as posing risks on human health [1]. In March 2022, the 5th UN Environment Assembly adopted a historic resolution named to end plastic pollution and forge an international legally binding agreement by 2024 [2]. It was acknowledged that monitoring, reporting and review mechanisms are critical for the success of such a global plastics treaty.

Annually, millions of tonnes of plastic debris end up in the seas, causing the worldwide amounts of marine plastics to increase to ever more alarming levels. Surprisingly, the magnitude of the problem is poorly quantified. Current operational methods cannot yet provide a good overall view on the global distribution of marine plastics [3]. More extensive monitoring is needed with systematic sampling over time.

Macroplastics (with sizes >0.5cm) are not only a major fraction of the total marine plastic pollution, they also decay into microplastic, which is much harder to detect or remove. Therefore, it is crucial to perform timely detection of macroplastics. Current local methods largely underestimate macroplastics because often they focus on a limited range of sizes, so rarer larger pieces often remain undetected. To quantify the abundance and size distribution of larger debris, larger areas need to be monitored.

Unmanned aerial vehicles are widely adopted as tools for surveying water surface and coastal regions, and image analysis is being used to estimate debris concentrations from the resulting imagery. At a larger scale, detection based on satellite images is the most efficient way of covering larger areas. However current and planned satellite missions are either designed for low resolution ocean colour applications or for land applications so their capabilities are not optimal for marine litter detection [4].

1.2 Scope and approach of the study

The have conducted an ESA PRODEX study to investigate the opportunity to contribute to the monitoring of marine litter with a dedicated earth observing satellite mission, assess the feasibility of creating such mission. The approach of the study was the following:

- gather an overview of the problem and relevant policies
- identify & understand the needs of stakeholders through interviews
- compile a set of primary use cases with observational requirements for addressing them
- derive a set of technical requirements for an instrument and mission, covering the use cases
- define an instrument concept in line with the requirements to assess its feasibility
- define a mission concept in line with the requirements to assess its feasibility

Different sensing techniques have been applied to the problem of marine plastic detection. SAR imaging has shown great promise for microplastics, but its application to marine macroplastics is still in its infancy [5]. Thermal imaging appears to be useful to detect marine litter [6], but only under certain conditions, so it can be best employed as an additional technique, providing complementary information. In this study, we focus on optical imaging in the range 400nm -2400nm, which many studies have identified as a preferred technique to monitor marine plastics.

2 USE CASES AND FEASIBILITY

2.1 Selection of use cases

The most important aspect is the added value a future marine litter satellite mission could bring, therefore it was essential in our approach to gain a good understanding of user needs. We started by interviewing a sizeable group of about 30 stakeholders and experts from a variety of companies and organizations (interest groups, policy makers) from different countries to gather a representative view on the user needs. The interviews resulted in a longlist of potential use cases.

These use cases were further assessed according to three criteria:

1) impact and added value which a dedicated mission could bring
2) technical feasibility
3) complementarity: we prefer application not yet covered by other methods or missions

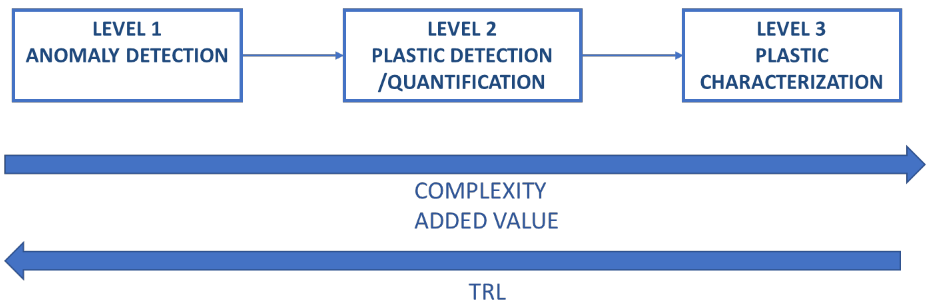

Figure 1: Levels of detection with respective complexity

technical feasibility was assessed through literature review, own analysis and discussions with the experts. Complementarity was assessed by literature, while for the importance and potential impact of the use cases / the impact the information gathered in the interviews was decisive.

This process resulted in a set of three primary use cases, which we will present discuss next. For each use case, different levels of detection can be considered, as presented in Figure 1. The basic level is anomaly detection. In the second level plastics are distinguished from other types of litter, while in the third level, also the presence of different types of plastics is also estimated. The higher levels provide additional value, but also increase complexity, and solutions are still less mature.

It is instructive to compare the use cases to those identified in the earlier RESMALI study [7]. The authors used a different approach in which all locations where plastic litter is found were considered, where we focused on selected use cases with high impact instead. Moreover the authors did not exclude use cases for which satellite monitoring is already possible. As a result, they did not consider landfills, found beach litter detection not to be a feasible use case, but found monitoring concentration of litter at global scale feasible instead. Still, they also identified the monitoring of accumulations as a good use case. The observational requirements were quite different: focusing on large coverage instead of very detailed spatial resolution.

5.2 Monitoring Beach Litter

Beaches are the locations where the effect of plastic litter are most visible to the general public. Litter tends to accumulate on beaches, where it has a direct impact on the environment, but also gives a strong indication of litter at sea. Identification of potential litter accumulations (level 1 detection) would provide strong added value to support clean-up actions on the beach. If plastics can be discriminated from other beach litter (level 2 detection), the added value becomes much higher. It then can contribute to understanding the mass balance and pathways of litter, and provide support for relevant policies. If characterization of plastic types could be achieved (level 3 detection), this would even provide greater values, but this remains unproven. For all levels the impact is high because no systematic monitoring.

Plastic detection on beaches is challenging because for typical satellite spatial resolutions, the plastic only covers small fractions of a pixel [8]. The observed spectra will be a mixture of plastic and sand. The samples are often wet but not submerged in water. In our own experiments using a multispectral VNIR drone camera, a vast majority of plastic pixels could be correctly detected (see Figure 2).

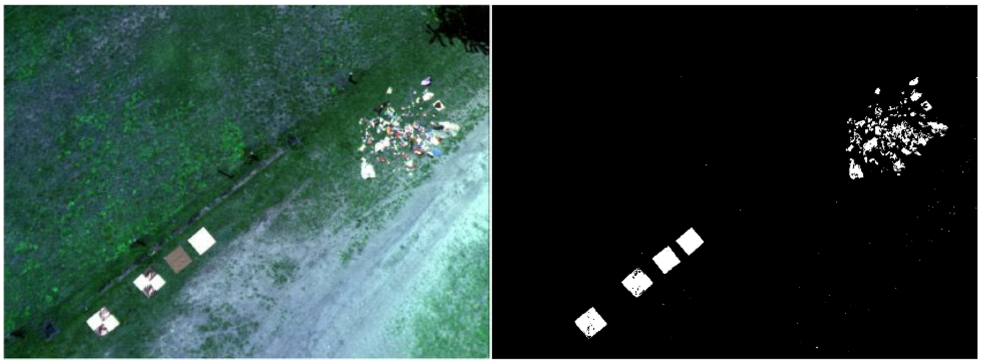

Figure 2: Left: drone image with plastic litter, Right: Binary map with litter in white

Multiple studies [5] [7] have shown that the SWIR range contains very clear spectral features that characterize plastic, allow to discriminate it from other debris, and possibly discriminate plastic types. SWIR narrow band features are seen as crucial to perform such detection for mixed pixels.

We conclude that discrimination of plastics from a sandy/grass background is realistic, provided at least 2–8% of the surface is covered with plastic. The discrimination between plastic types is remains to be proved, especially when different types are mixed.

Observational requirements for beach litter monitoring were set and summarized in Table 1

5.3 Monitoring litter accumulations in coastal/estuarine fronts and coastal windrows

Density fronts capture pollutants such as oil slicks and litter and draw them down into the water column [9]. They are present on continental shelves, observed within 10 km from shores and detected in satellite sea surface temperature images. The term litter windrow is used to refer to aggregations of floating litter, seafoam, seaweed and plankton in scales <10 km. [10].

Litter windrows can provide important information on the flux of plastic from land based sources into the marine environment and are seen as key to improve waste management in coastal environments [11]. level 1 detection helps to understand the plastic mass balance. With direct plastic detection (level 2), more advanced policy support becomes possible, while detailed plastic characterization (level 3) (different polymers, detection of fishing gear…) would bring additional value..

Direct detection can exploit the high contrast in NIR and SWIR reflectance between water and floating material, which has been reported using Sentinel-2 images in several publications [12] [13]. Discrimination of litter/plastics from foam, white caps and sun glint remains a challenge, but may be realized using additional spectral bands [14]. Discrimination of plastics vs. floating algae and vs other materials such as seaweed, timber, foam have also been explored [15][16].

Observational requirements for monitoring of litter accumulations were set and summarized in Table 1

5.3 Landfill detection

Landfills contains large quantities of litter of various types and sources and can pose serious pollution risks. Landfills close to water are a major source of marine pollution through flooding events and leachate of liquids. In many areas, uncontrolled or informal landfills are a widespread phenomenon. Knowledge on the location of landfills (level 1 detection) is essential for preventing pollution. If the plastic content (level 2 and 3) can be revealed, this helps to understand the pathways of marine plastics, yielding policy support.

Finding anomalies on land is definitely feasible, but distinguishing landfills from other areas which similar properties can be challenging. Complementary sensing (SAR) or analysis techniques (shape, texture,…) can help to reduce false positives. In [17] landfill detection was studied using multiple methods and datasets. The detection of plastic in landfills was found to be possible but challenging because the plastic debris are small, degraded, stained and mixed with other materials. To achieve success, detailed spatial and spectral imaging is needed, which is difficult to combine with monitoring of very large areas. However, large scale level 1 detection of landfills has already been demonstrated. The prototype of the "Global plastic watch" initiative [18] gives an idea of the current state of the art. Such a system could give excellent preselection of areas that a worthwhile to image and investigate in more detail.

Observational requirements for landfill detection and monitoring were set and summarized in Table 1

3 OBSERVATIONAL REQUIREMENTS

We collected observational requirements for the three primary use cases and combined them into a common consolidated set of requirements, listed in Table 1

All use cases need a very high resolution in the range of 1 to 3m, while a small swath of 10km is enough to cover selected areas. Pointing capability is necessary to be able to reach any area within a reasonable time For all use cases, meaningful results can be obtained with only a monthly or even seasonal update. This allows to cover larger areas by acquiring them gradually with each pass.

The spectral requirements differ somewhat per use case, so we combined them to an overall optimal set of 26 narrow spectral bands, shown in Figure 3 including their bandwidths. In a further iteration, this number may be reduced by omitting the least useful bands. The Signal to Noise Ratio (SNR) should be high to allow small signal differences, including the detection of lower abundances, and to enable good discrimination between plastic and other litter (level 2 detection).

Table 1 Observational requirements

characteristics		Beach	accumulations	landfills	consolidated	unit
Spatial resolution	GSD	1-3m	anomaly: 5-10m plastic: 1-3m	1-5m	1-3 m	m
Coverage	Swath	Selected coastline areas	known areas, close to shores and river mouths	Preselected likely areas	10	km
Spectral range		VNIR + SWIR	VNIR + SWIR	VNIR + SWIR	400-2400	nm
Spectral bands		bands at specific locations	VNIR: ocean colour SWIR: 9-12	VNIR + detailed SWIR	20-26 bands identified	
Spectral resolution	FWHM	10-20nm	2.5-20nm	10-20nm	2.5-20	nm
Radiometric resolution	SNR	High (200)	High (200)	Medium (100)	200 (average)	
Temporal update		monthly/ Seasonal	monthly/seasonal	monthly/seasonal	monthly/seasonal	

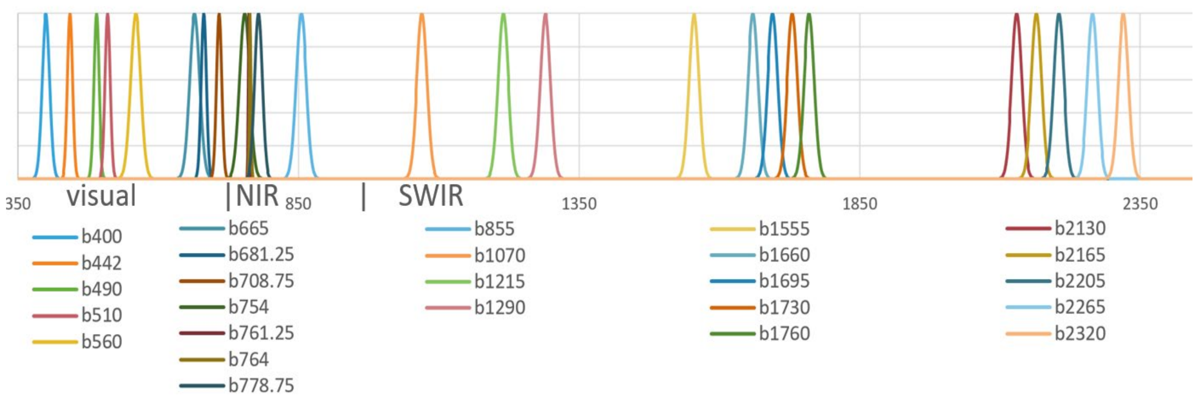

Figure 3 optimal set of spectral bands for marine litter detection

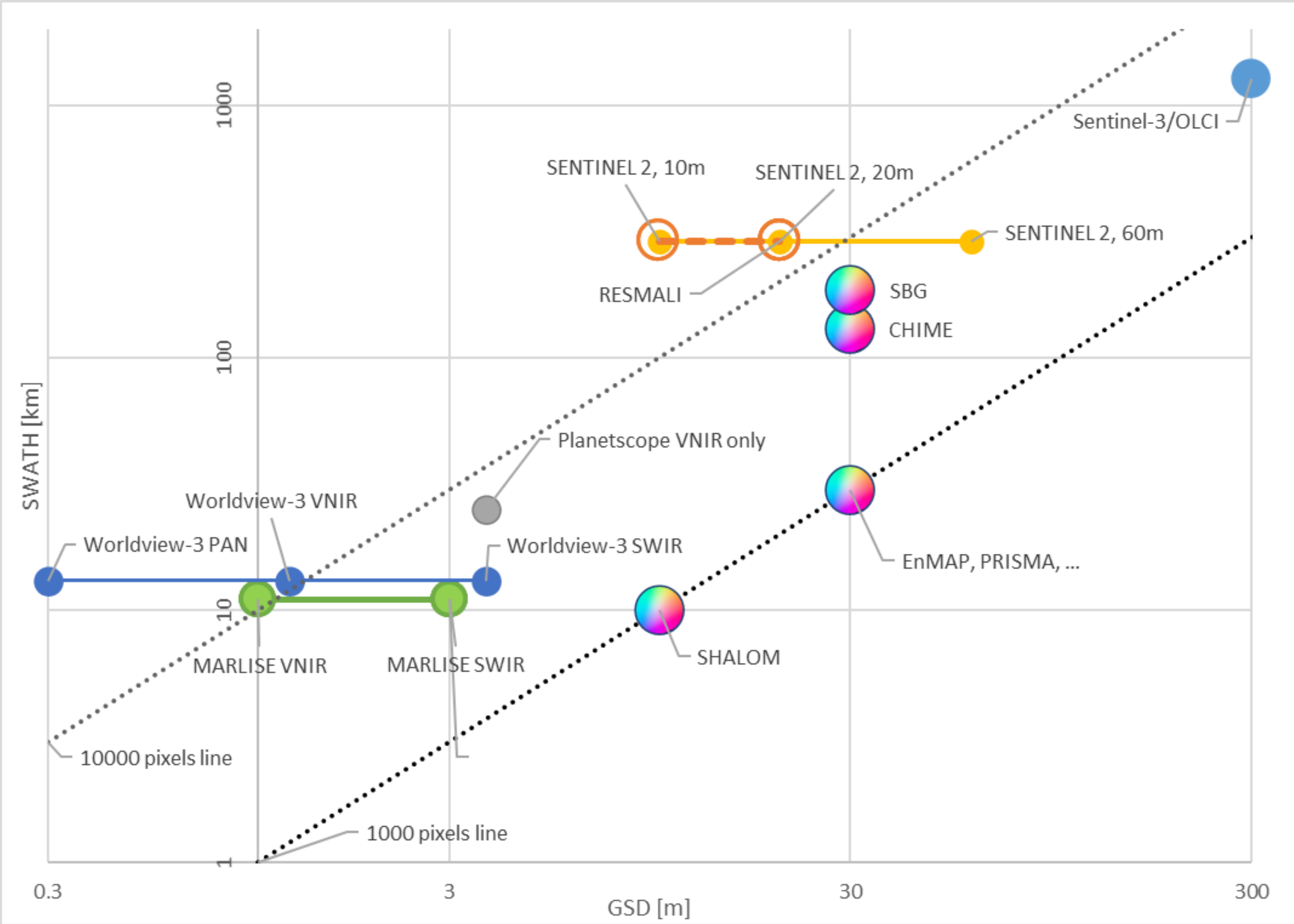

Figure 4 swath vs GSD for the proposed mission vs RESMALI and existing missions

We compare the requirements to the characteristics of some existing and upcoming missions. We concentrate only on missions with good SWIR coverage and make an overview plot of GSD vs swath with most important missions with proven towards plastic detection.

The plot in Figure 4 shows:

- **ocean color missions**: superspectral, focusing on large coverage of open oceans with low spatial resolution (Sentinel-3 OLCI).
- **hyperspectral missions** : (upcoming) main missions will achieve a full spectral coverage in the VNIR-SWIR range, with a typical spatial resolution corresponding to GSD= 30M. Of these the PRISMA mission is already operational, while EnMAP has just been launched. A special case is the SHALOM mission which aims at GSD=10m.
- **Sentinel-2**: large coverage multispectral mission with a cleverly chosen GSD between 10m and 60m. It has very broad usability, also due to its fast revisit time and free availability.
- **Commercial high resolution missions**: only Worldview-3 has good SWIR capability. Planetscope was also added to the graph: these missions have no SWIR coverage, but because of their combination of GSD=3.7m and excellent coverage (by using a large constellation), they have been used in multiple marine litter studies.

While the RESMALI proposed marine litter mission closely matches the GSD and swath of Sentinel-2, the outcome of this study (MARLISE) arrives at specifications which are close to those of Worldview-3. This commercial mission is already past its planned operational lifetime and its successors no longer offer SWIR imaging, so it is not a future long term supplier of similar imagery.

4 INSTRUMENT CONCEPT

A superspectral instrument has been defined, maximally in line with the requirements. The total mass of the payload is estimated at 45kg, including 25kg for the telescope. The optics consist of a Ritchey-Chrétien telescope including a primary mirror of 45cm and 166cm focal length. A possible mounting of the telescope is shown in Figure 5. Dedicated large VNIR and SWIR frame detectors are used, each equipped with spectral filters. This results in an imaging capacity of 9km swath with a GSD = 1m (VNIR) and GSD= 3m (SWIR).

To obtain a high SNR in line with requirements, additional measures are foreseen:
- Platform pitch movement 5form +15° to -15°) to reduce the apparent ground speed, allowing much longer integration times (10x or more)
- Digital TDI in which multiple images are stacked
- Optionally a 2x2 binning of the VNIR pixels

The total mass of the payload is estimated at 45kg, including 25kg for the telescope.

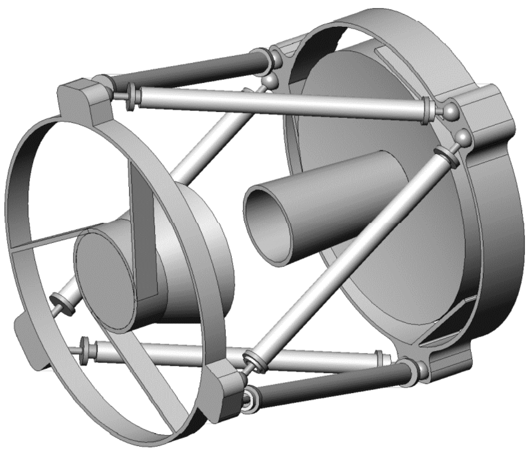

Figure 5: possible mounting for the telescope

5 MISSION CONCEPT

The proposed instrument can be accommodated by a range of commercially-available spacecraft platforms. The spacecraft is compatible with most launchers as a primary payload. A baseline satellite altitude of 500 km (SSO) allowing a swath of 11 km is selected. A baseline LTAN of 10h30 is proposed as it is a relatively popular ensuring multiple launch opportunities. Smart tasking approach (including roll off-pointing upto +-30°) should be put in place to maximize the number of useful acquisitions, mainly focusing on coastlines. If the maximal amount of imaging is enabled, the total imaging area per day ranges between 25000 km^2 and 40000 km^2, resulting in and 253 Gbytes/day payload data (uncompressed). Thus, the main challenge is the amount of imaging data to downlink, and therefore it is recommended to include an efficient data reduction strategy.

6 CONCLUSION

We presented the results of a feasibility study on detecting marine macroplastics using a dedicated satellite mission. By focusing on three primary use cases, we derived a consistent set of observational requirements. To cover them we proposed an optical high resolution superspectral instrument with a set of up to 26 narrow spectral bands covering the VNIR and SWIR. It can image selected areas with an spatial resolution of 1m for the VNIR and 3m in the SWIR range, with an 11km swath. The instrument concept includes a telescope with 45cm front mirror and dedicated frame sensors for VNIR and SWIR, equipped with spectral filters. A key element to enable imaging with good SNR is the ability to perform pitch pointing during acquisitions, so longer integration times can be used. With a suitable platform, a mission with a total dry mass 150kg range can meet all requirements.

The concept as proposed is a first iteration. A refinement of the concept can be used as a starting point for the development and full deployment of a marine plastics monitoring satellite system. Such a system can fill a large gap in the knowledge on the amounts, sources and pathways of plastic litter, because current efforts only assure partial observations, and can only be part of a multisource marine debris observing system [19]

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