

Seeing Plastic from Space: A Spectro Polarimetric Approach to Ocean Litter Detection

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ABSTRACT

Plastic pollution in the world’s oceans is a major environmental issue, but the global-scale monitoring of plastic waste discharged by rivers and waterways into seas and oceans, and their transport towards open seas has never been included in the scientific objectives of an Earth observation satellite mission. The broad, but adjacent, research domain of “ocean color” is supported by flagship missions, such as OLCI/Sentinel-3, or OCI/PACE, which exhibit valuable spectroscopic and radiometric capabilities, but at a too coarse spatial sampling. The ESA OSIP project PLASMO (Plastic Litter Assessment and Surveillance via Monitoring from Orbit) addresses this gap by developing a spaceborne imaging spectro-polarimetric instrument concept for detecting floating plastic. This work presents the scientific background, mission requirements, and initial instrument design. Key requirements were derived from recent laboratory, airborne, and satellite studies, highlighting the importance of combining visible (VIS) and shortwave infrared (SWIR) bands to detect partially submerged plastics via characteristic polymer absorption features. Additionally, polarimetric measurements, particularly the degree of linear polarization, provide extra contrast between plastic and seawater. To meet these requirements within a small satellite platform in very low Earth orbit, PLASMO investigates an acousto-optical tunable filter (AOTF)-based payload, offering rapid wavelength tuning, polarization selectivity, and high robustness. Radiative transfer simulations define signal-to-noise and polarization accuracy needs, while preliminary design trade-offs confirm the feasibility of covering relevant SWIR bands with adequate performance. These results demonstrate the technical viability of an AOTF-based spectro-polarimeter for future dedicated satellite monitoring of marine plastic debris.

Keywords: AOTF, PLASMO, plastic debris, VLEO, remote sensing

1. INTRODUCTION

Plastic pollution in the world’s oceans has emerged as a critical environmental and societal challenge, with far reaching impacts on marine ecosystems, climate processes, and human livelihoods [1]. Despite increasing awareness and numerous in situ and airborne measurement campaigns, a global understanding of floating marine plastic debris is not fully achieved yet [2]. The primary limitation lies in the lack of dedicated spaceborne observation systems capable of reliably detecting, discriminating, and quantifying plastic litter on the ocean surface under realistic environmental conditions.

Current Earth observation missions are not optimized for this task. Conventional multispectral imagers, like Sentinel-2 [3, 4] achieve high spatial resolution (up to 10m), but lack the spectral specificity required to distinguish plastics from natural floating materials such as macroalgae, driftwood, or sea foam. Hyperspectral systems like OLCI/Sentinel-3, or OCI/PACE, do have the needed spectro-radiometric capabilities, but at the cost of a coarser spatial resolution (hundreds of metres). In addition, most instruments do not exploit polarization information, despite its demonstrated potential to enhance contrast between man-made materials and natural ocean surfaces [5, 6]. These limitations motivate the need for a dedicated sensing concept that combines tailored spectral coverage, polarimetric sensitivity, and sufficient spatial and temporal resolution.

The PLASMO (Plastic Litter Assessment and Surveillance via Monitoring from Orbit) project addresses this gap by proposing a novel remote sensing strategy based on imaging spectro polarimetry [7]. The approach is driven by a set of key observational requirements derived from recent experimental and modeling studies. First, the spectral domain must include visible (VIS) wavelengths, which provide high radiometric contrast and spatial detail, together with shortwave infrared (SWIR) bands that capture characteristic absorption features of common polymers [8, 9]. These SWIR features

are essential for robust material discrimination, particularly for partially submerged or weathered plastics. Second, the system must be capable of measuring the degree of linear polarization, which provides an additional observable sensitive to surface roughness and refractive index differences between plastics and seawater [6]. Finally, these measurements must be achieved with sufficient signal to noise ratio and radiometric stability to ensure reliable detection under varying illumination and atmospheric conditions.

Meeting these requirements within the constraints of a small satellite platform, particularly in very low Earth orbit (VLEO), presents significant challenges for instrument design. Constraints on mass, volume, power consumption, and mechanical robustness limit the applicability of conventional dispersive spectrometers or mechanically scanned filter systems. Furthermore, the need for rapid spectral sampling and polarization selectivity calls for an architecture capable of flexible, high-speed wavelength tuning without moving parts.

In this context, the use of an acousto optical tunable filter (AOTF), based on the interaction between light and acoustic waves in anisotropic crystals, allows wavelength selection through electronically controlled radio frequency signals [10]. This mechanism provides several advantages that directly address the mission requirements. First, AOTFs offer rapid, programmable spectral tuning over a broad wavelength range, enabling adaptive selection of bands in both the VIS and SWIR domains. Second, due to their intrinsic birefringent properties, AOTFs provide polarization selectivity, facilitating the retrieval of polarimetric observables without the need for additional bulky optics [11]. Third, the absence of moving parts enhances mechanical robustness and reliability, which are critical for operation in the harsh environment of space and particularly advantageous for compact VLEO platforms.

The optical design of the spectro polarimetric payload is therefore centered around a TeO₂ based AOTF, chosen for its high acousto optic figure of merit and suitability for operation in the targeted spectral range [12]. The design process involves detailed tradeoffs between spectral resolution, tuning range, angular acceptance, and diffraction efficiency. These parameters directly impact the achievable signal to noise ratio and polarization accuracy and must be balanced against system level constraints such as detector sensitivity and available radio frequency bandwidth. Particular attention is given to optimizing the instrument throughput in the SWIR region, where radiance levels are lower but spectral discrimination of polymers is strongest.

To validate the design requirements, radiometric and polarimetric performance assessments are conducted using coupled atmosphere–ocean radiative transfer simulations. These simulations provide estimates of top of atmosphere radiance and polarization signatures for both clean and plastic polluted water surfaces, enabling the derivation of minimum performance thresholds for detection. The resulting requirements feed directly into the optical and electro optical design of the AOTF based instrument.

In summary, this work introduces a spectro-polarimetric sensing concept specifically designed for the detection of floating plastic debris from space, with a strong emphasis on system requirements and optical design. By using the unique capabilities of AOTF technology, the proposed instrument aims to overcome the limitations of current Earth observation systems and is a first step in the conceptual design of a dedicated satellite mission for global monitoring of marine plastic pollution.

2. PLASMO REQUIREMENTS DEDUCTION

In order to design the PLASMO instrument, dedicated requirements have to be derived, based on the detection of plastic. The International Ocean Colour Coordinating Group (IOCCG), involved in the research related to ocean colour science, focusses also on marine litter remote sensing. Several fundamental papers have been published, related to the state of the art in marine litter and plastic debris measurements, as well as summarizing the scientific questions, together with defining optimal instrument requirements [13 – 15].

One of the studies evaluated the capability of the MultiSpectral Imager (MSI) aboard Sentinel-2 to detect the spectral signatures of different types of plastic patches [16]. The results showed that the Visible–Near InfraRed (VIS–NIR) bands of Sentinel-2 are insufficient for clearly distinguishing plastic litter from natural materials such as sea snail and pollen. However, improved discrimination can be achieved by combining spectral information into indices like the Normalized Difference Vegetation Index (NDVI) and the Floating Debris Index (FDI) [17].

Another challenge comes from the weathering of plastic surfaces during long exposure at sea. In the visible range, aging leads to a darkening of the plastic material. Processes such as biofouling and Ultra-Violet (UV) degradation reduce reflectance in the blue portion of the spectrum, while changes in the Near-Infrared (NIR) region remain relatively small.

Additionally, partial submersion of plastic debris significantly affects detection. Water strongly absorbs radiation in the Short-Wave InfraRed (SWIR) domain, and even a few centimeters of submersion can effectively suppress the SWIR reflectance signal. As noted in other studies [18], this absorption can obscure much of the spectral response, as shown by Figure 1.

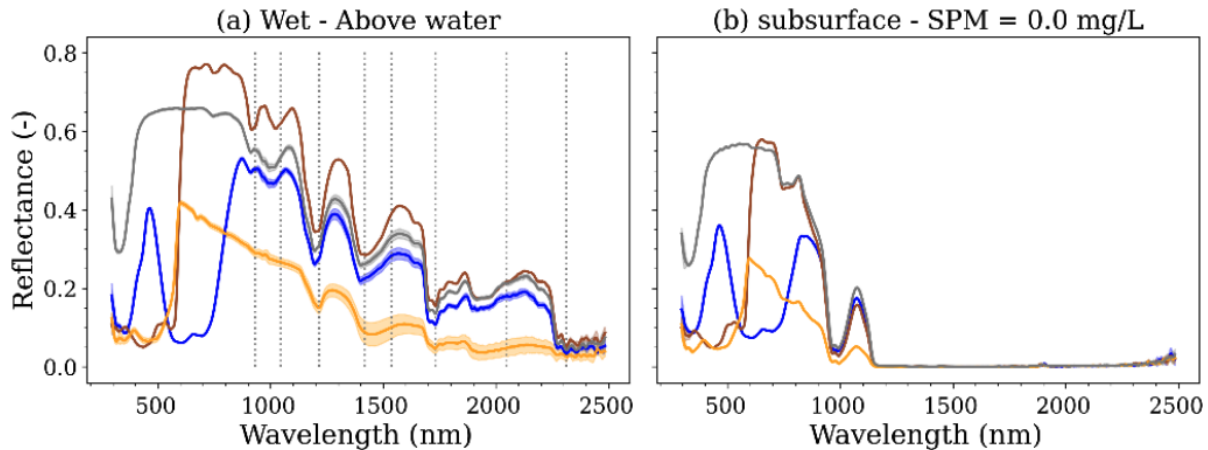


Figure 1. (a) Reflectance spectra of wet polypropylene objects, and placemats; (b) Same objects submersed by 2.5 cm. [Adapted from [18]].

The characterization of reflectance spectra for the most common plastic materials under real-world conditions is an active area of research, as distinguishing plastics from natural materials relies on their specific absorption features. Research on the reflectance of plastics of various composition and colors across the VIS–SWIR range showed that different plastic types share similar absorption bands in the SWIR region, specifically near 930 nm, 1215 nm, 1400 nm, and 1730 nm [21]. Color is in general not a discriminant term in this region.

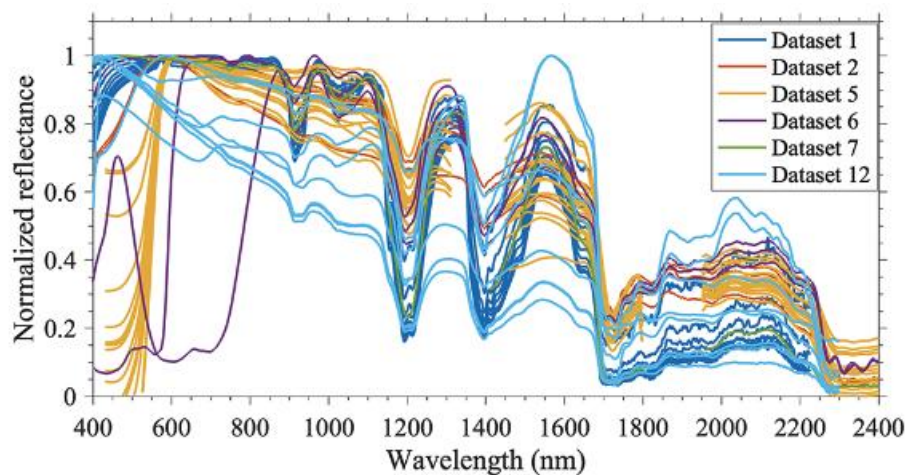


Figure 2: Measured reflectance spectra of various samples of polypropylene-based plastic debris [reproduced from [21]].

Recent research has also explored the use of light scattering polarization properties to detect macroplastics [19]. Beyond their spectral absorption features, plastic surfaces can be distinguished through measurements of the Degree of Linear Polarization (DoLP). A field study [17] demonstrated that incorporating polarimetry can enhance the discrimination performance of a standard RGB camera. In this experiment, images were captured using four linear polarizers oriented at 0°, 45°, 90°, and 135°, enabling pixel-level computation of the DoLP. By analyzing the correlation between the RGB

channels and the DoLP, the authors observed a strong decorrelation between polarization information and conventional color data. These findings indicate that polarimetric measurements provide complementary information, improving the identification and classification of objects.

Most studies focused on macroplastics, typically found near coastal sources, whereas large oceanic accumulation zones are dominated by microplastics (particles smaller than a few millimeters). Field measurements indicate that buoyant polymers, such as polyethylene and polypropylene, are found near the surface due to their low density. For satellite observations, only near-surface microplastics are relevant, as detectable radiation must traverse a limited path in water. This makes their absorption and scattering properties key, although they remain poorly characterized compared to other ocean constituents.

Modelling studies show that microplastics can significantly influence ocean optical signals [5, 20]. They tend to depolarize the water-leaving radiance and can induce measurable changes in near-infrared Top-Of-Atmosphere (TOA) radiance at sufficiently high concentrations, suggesting their potential detectability from space.

Field studies have demonstrated that macroplastic accumulations can be detected using the Sentinel-2 MSI instrument, which provides a spatial resolution of $10 \times 10 \text{ m}^2$. When floating at the water surface, even if wet, plastic debris can be identified through characteristic absorption features in the VIS–SWIR range. In addition, measuring the DoLP offers complementary information and should be considered alongside spectral indices such as NDVI or FDI. In contrast, monitoring microplastics near the ocean surface is unlikely to benefit from SWIR measurements due to strong water absorption. Instead, significant depolarization of the water-leaving radiance is expected, making DoLP a key observable. Furthermore, high concentrations of plastic particles can alter the TOA radiance in the VIS–NIR range by several percent, allowing detection instruments having a signal-to-noise ratio above 100. The resulting PLASMO instrument requirements are summarized in Table 1.

Radiative transfer model (RTM) simulations have been performed to determine typical levels of radiometric fluxes above a dark ocean surface, and above a plastic scene. The SASKTRAN2 vector RTM [22, 23] was used, assuming various illumination conditions at the spacecraft, and various viewing angles towards the ground. The model is capable of solving the equations of RT for a spherical atmosphere with full propagation of the Stokes vector representing the state of polarization of the solar light being scattered, absorbed, or reflected along its path through the atmosphere. A standard atmospheric composition was used, including the key absorbers such as O_3 , O_2 , and H_2O . A shallow layer of marine aerosols ($\text{AOD}=0.1$) was also included. Currently, the simulations treat the surface (the ocean, or the plastic scene) as a Lambertian surface with an albedo spectrum. The following examples (Figure 3, Figure 4) show the top-of-atmosphere (TOA) radiance spectrum for a 300km-high spacecraft, looking 16° off-nadir (viewing zenith angle $\text{VZA}=164^\circ$) at azimuth 45° from North, whereas the solar zenith angles (SZA) at the spacecraft is 30° , at an azimuth of 135° . Two plastic scenes simulate a dry polypropylene (PP) rope frame, and plastic bottles, whose reflectance spectra were extracted from [24]. In both plots, the dashed purple curve represents the scene albedo.

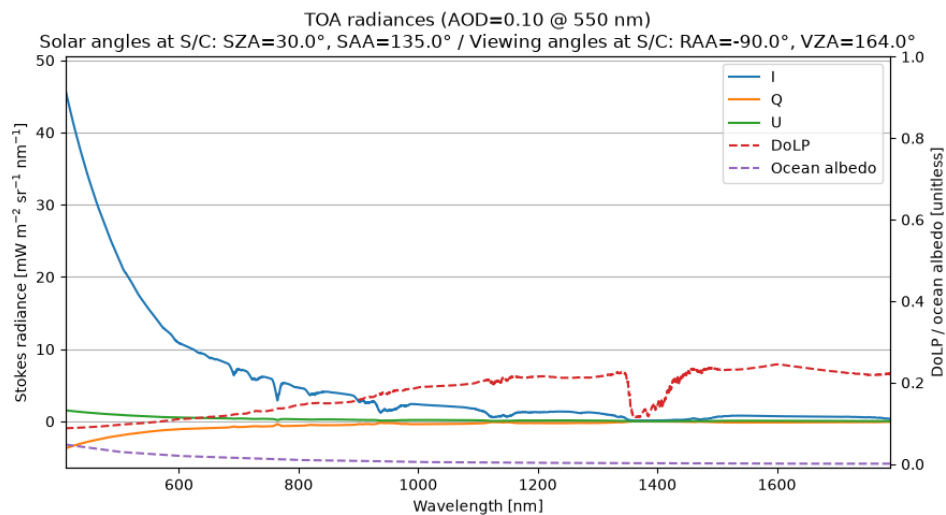


Figure 3: I, Q, and U radiance spectra at TOA above the dark ocean.

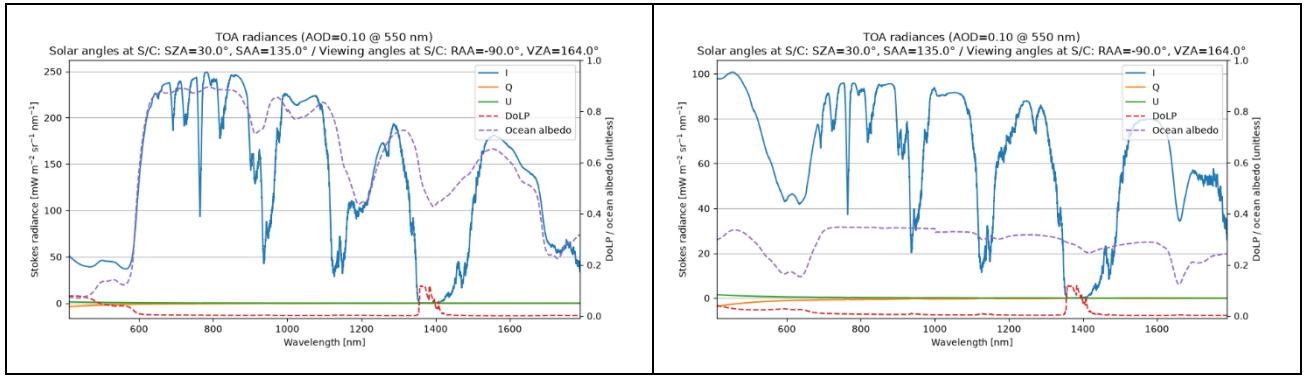


Figure 4: I, Q, and U radiance spectra at TOA above a plastic scene: Left: a dry PP rope frame, right: a dry plastic bottle.

As can be seen, while the albedo of the ocean quickly plummets to 0 already from the red end of the visible spectrum, a much higher radiance can be observed above plastic compounds throughout the NIR/SWIR domain. The characteristic absorption bands of polymers are clearly visible from their reflectance spectrum, but the water vapor bands will make the unambiguous detection more difficult. The 1200nm, 1400nm, and 1700nm bands are clearly standing out from the examples, although the middle one will likely be hidden by the water vapor signal.

In terms of radiance contrast, a SNR of 100 at the key wavelengths should allow to design a “plastic index” such as those presented in [16, 21] which should support the plastic signal identification.

Table 1. PLASMO requirements.

Item	Requirement	Justification
Orbit	VLEO-orbit	PLASMO study requirement imposed by ESA. Low altitudes allow the finest surface sampling
Ground sampling distance	10 m	On par with MSI/Sentinel-2, compatible with plastic patches size.
Swath width	Above 10 km	Resolving sub-mesoscale filaments of plastic debris in high seas
Revisit time	Less than 1 week	Enables tracking large scale dynamic processes
Spectral bands (central wavelengths)	ON: 930, 1215, 1730 nm OFF: 850, 1100, 1300, 1620 nm	Target the main polymer's absorption bands ([21])
Spectral resolution	10 nm	Enables the resolving of polymer's absorption features
Signal to noise ratio	Above 100	Based on absorption bands contrast, and simulated plastic scenes
Polarimetry	Radiance measured in 4 linear polarizations: 0°, 45°, 90°, 135°	The DoLP enables enhanced discrimination of plastics

3. OPTICAL DESIGN TRADE-OFF

The PLASMO instrument is conceived as an imaging spectro-polarimetric system operating in the visible to short-wave infrared spectral range. The entrance optics collect the radiation reflected by the observed scene and form the image for spectral and polarimetric analysis. To retrieve the linear polarization state, the incoming beam is divided into two channels by a beam splitter. Each channel passes by an AOTF, which simultaneously performs wavelength selection and separates the two orthogonal linear polarization components defined with respect to the AOTF orientation. The two resulting polarization states are then imaged onto a detector. The AOTFs in the two channels are rotated by 45 degrees with respect to each other, allowing the simultaneous measurement of the radiance components at 0 and 90 degrees in one channel, and at 45 and 135 degrees in the second channel. These measurements provide the information required to derive the linear Stokes parameters and the Degree of Linear Polarization.

The optical design is driven by the angular acceptance of the TeO₂ based AOTF. In an imaging AOTF configuration, the incidence angle inside the crystal directly affects the wavelength selected by the acousto-optic interaction. Consequently, the limited angular acceptance of the filter imposes a stringent constraint on the cone angle of the incoming beam. The optical system must therefore operate at a sufficiently large f-number to ensure that the angular distribution of rays remains compatible with the AOTF acceptance range.

This constraint leads to a fundamental trade-off between a telecentric architecture and a more classical imaging configuration. An image-space telecentric design is attractive because the chief-ray angle is kept nearly constant over the full field of view. This reduces field-dependent spectral shifts within the AOTF and supports a more uniform spectral and polarimetric response across the swath. However, the large f-number required by the AOTF implies a long effective focal length. Combined with the required ground sampling distance, this can result in a relatively large optical assembly and may challenge the volume constraints of S/C platform.

A classical imaging system can provide a more compact implementation and offers additional freedom to balance focal length, detector format, and field of view. Its main drawback is the variation of the chief-ray angle with field position, which may introduce a wavelength shift and potentially a variation in diffraction efficiency across the image. The final optical architecture must therefore balance compactness against spectral uniformity, while ensuring that both marginal and chief rays remain within the angular acceptance of the AOTF over the complete instrument field.

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