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The Design of a Global Oceanic Plastic Debris Monitoring System Using Imaging Spectroscopy Onboard Low-Flying Satellites

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***Abstract*—The distribution and behavior of the vast accumulation of plastic waste in the oceans, often referred to as the 'plastic soup', are heavily influenced by plastic debris coming from rivers and coastal areas. Currently, the location and dynamics of the oceanic 'plastic soup' is already well understood. However, the exact process behind the formation of this plastic soup remains incompletely comprehended. This knowledge gap can be linked, in part, to the absence of worldwide detailed spatiotemporal data collected from ground and space. This is specifically due to the lack of detection and imaging techniques with a high spatial and temporal resolution. To address this gap, an innovative concept is proposed based on imaging spectroscopy. The goal is to address and further improve the observed spectral signatures of different plastics by imaging the observed scenery. In order to distinguish between these different kinds of plastics, a dedicated optical filtering system with a high resolution and revisit time has to be designed. Therefore, the concept is based on an Acousto-Optic Tunable Filter (AOTF), specifically designed for remote sensing and imaging. In order to achieve a high temporal resolution, being able to capture the evolution and movement of plastic in the oceans, a constellation of satellites are foreseen. Therefore, a low flying platform and deployable optics are introduced. Flying at 300 km altitude instead of a typical > 600 km for Earth observation satellites, reduces the required imaging aperture.**

Keywords—Plastic debris, AOTF, low-flying platform, deployable optics, spectroscopy

I. INTRODUCTION

Plastic pollution, land- as well as sea-based, has emerged as a significant and highly important environmental issue. Known for their light weight and durability, the increased amount of plastics pose significant environmental problems when they become marine debris [1, 2]. Also the impact on human health is still unclear, but it is accepted to be potentially hazardous [3, 4]. The global presence and movement of extensive plastic waste in oceans (the 'plastic soup') are significantly shaped by plastic debris originating from rivers and coastal regions [5]. Although a comprehensive understanding exists of the current location and behavior of this oceanic plastic soup, the precise mechanisms responsible for its formation remain inadequately understood [6].

This gap in knowledge can be partly attributed to the limited availability of comprehensive spatiotemporal data collected from both ground- and satellite-based sources. Recent studies incorporate observations from ships, which include visual assessments and net trawls [7]. While these methods yield valuable data, interpreting the information becomes challenging in the face of complex aquatic dynamics [1]. Moreover, assessing the effectiveness of these efforts relies on the ability to monitor plastic pollution in specific areas. This proves to be a challenging task due to complex temporal and spatial distributions of debris, as well as the complexity of marine dynamics [1]. Recent advancements in remote sensing have highlighted the potential of employing satellite data to track plastic debris. Modern Earth observation satellites like Sentinel-2 have significantly enhanced the ability to utilize satellite data, thanks to improvements in both temporal and spatial resolutions [8]. Nevertheless, there is still a lack of advanced detection and imaging technologies capable of providing high-resolution spatial and temporal data. Utilizing this data can greatly assist in modelling the plastic soup and consequently help in finding effective mitigation policies.

In order to address this knowledge gap, we propose the design and development of an innovative concept based on imaging spectroscopy. The objective is to tackle and enhance the distinct spectral characteristics of various plastic materials through imaging. To effectively differentiate between different plastic types, it is necessary to develop a specialized optical filtering system, capable of observing at a high resolution and revisit time. The optical concept of an Acousto-Optic Tunable Filter (AOTF), is especially designed for remote sensing and imaging [9].

To attain a significant temporal resolution capable of capturing the evolution and movement of plastic debris, a constellation of satellites is envisioned. Depending on its size, this constellation of satellites can image specific areas of interest every hour or less, whereas global imaging with a single satellite has revisit times of usually multiple days. While costs for production, assembly and testing of satellites can be reduced for series of identical satellites and instruments, launch cost can become relatively expensive. Launch cost is linked to volume and mass of satellites. Moreover, space debris is a major issue as well which should be avoided for a constellation. Hence, the introduction of a low-altitude flying platform and deployable optics is proposed. Operating at an altitude of 300 km, as opposed to the usual > 600 km for Earth observation satellites, reduces

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the necessary imaging aperture by at least a factor two and ensures that dysfunctional satellites will de-orbit in a matter of months [10]. The technical challenge is to design robust attitude control and propulsion to compensate the relatively high atmospheric drag at this altitude compared to higher orbits.

The primary objective of this research initiative is to study a concept to generate high-resolution data, providing insights into the distribution of different kinds of plastic pollutants under several environmental conditions. The final goal is to extend this concept in order to create a precise and comprehensive worldwide map of plastic pollution using a space-based constellation.

In the next paragraphs, the current status of plastic debris detection using spectral signatures is explored. Consequently, the AOTF-principle is explained. Additionally the necessity of a space-based low-flying platform is introduced.

II. Spectral Signatures of Plastic Debris

The detection of plastic debris using spectroscopy is not new. The use of an airborne ShortWave InfraRed imager (SWIR) aboard an aircraft at a moderate altitude (400 m) showed already the potential to detect plastic debris in a limited coastal area [11]. Additionally, spaceborne instrumentation such as the Sentinel-2 Multi Spectral Instrument (MSI) comprises 13 spectral bands that cover a range from visible to near-infrared and short-wave infrared, each operating at different spatial resolutions [12]. The MSI is capable of detecting the spectral signatures of plastics, but at a very low resolution.

In the realm of plastic detection research studies explore the use of multi-spectral indices as features [13]. These indices are created based on the phenomenon that different materials reflect varying amounts of energy across different optical wavelengths. Essentially, a spectral index captures the correlation between reflectance values in different spectral bands, essentially representing the reflectance at various points within a material's signature.

Specifically, in the research field of plastic debris detection, a range of spectral indices has been employed. These include indices like the Normalized Difference Vegetation Index (NDVI). Additionally, novel indices such as the Floating Debris Index (FDI) and Plastic Index (PI) have been developed explicitly for plastic detection purposes [14, 15].

These indices take into account several parameters, such as changes in the atmosphere, and characteristics, such as aerosol type and thickness, solar angle, observation angle, and sun glint. This enables detection even in the presence of thin clouds or haze [14].

Current research enables the detection of different kinds of plastic debris based on the spectral signature. Features around in the Near InfraRed (NIR) and SWIR optical wavelength domain create the potential to be utilized in detecting plastics [11, 16]. More specific, features around 1215 and 1732 nm are promising [11, 17]. A differentiation can be made between objects such as vegetation, man-made structures, and debris, but also between wet and dry plastics. Additionally, already many different kinds of plastics can be categorized based on their spectral signature, e.g. PolyVinyl Chloride (PVC), PolyAmide or nylon (PA 6.6 and PA 6), Low-Density PolyEthylene (LDPE), PolyEthylene Terephthalate (PET), PolyPropylene (PP), PolyStyrene (PS), Fluorinated Ethylene Propylene teflon (FEP), terpolymer lustran 752 (ABS), Merlon, and PolyMethyl MethAcrylate (PMMA) [16].

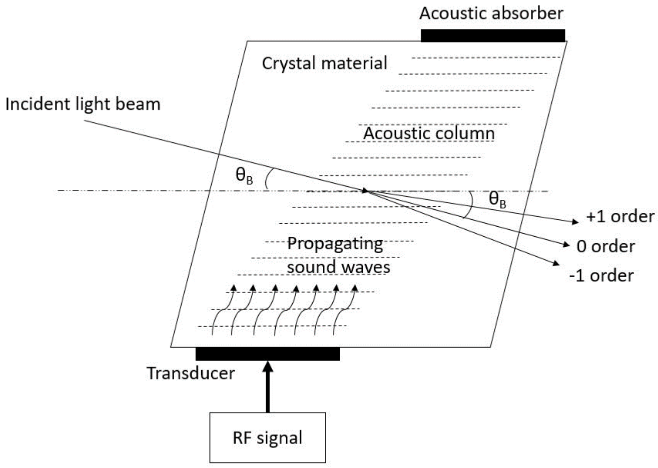

Fig. 1. The working principle of an AOTF. Reproduced with permission from reference [21] by OSA Publishing..

Nevertheless, the exact classification of plastics using indices and spectral signatures is still suboptimal. Effects like time, submerging and algae formation on plastics is not yet fully understood. In order to detect plastic debris using spectroscopy, the spectral signature of these plastics under specific temporal and environmental conditions has to be further improved. Martínez-Vicente et al. [17] indicated a list of requirements, specifically linked to detection from space. They showed the necessity of having a high spatial and temporal resolution in order to detect the different marine processes, such as river discharge, spills, shoreline accumulation and sub-mesoscale convergence filaments [17]. This distinction arises from the higher temporal variability in parameters affecting the movement of marine plastic debris in the water or on the shore.

Based on the shortcomings and requirements described above, a novel plastic debris imaging technique and accompanying instrumental concept is proposed in the next paragraphs.

III. AOTF-Based Imaging in Remote Sensing

AOTFs are used in multiple ground- as well as space-based applications [9, 18-20]. The working principle is based on the interaction between sound waves which propagate inside a birefringent crystal and incoming light (Fig. 1) [21]. In order to generate two first-order diffracted beams at the output of the crystal, the Bragg-condition (θ_B) has to be met [22]. Also the zero order beam exists inside the crystal. The sound within the AOTF is produced by the use of a transducer, which incorporates a piezoelectric layer responsible for generating mechanical vibrations and, consequently, sound waves. Activation of this piezoelectric layer is achieved through a Radio Frequency (RF) signal (Fig. 1). By applying this RF signal at a specific frequency, a specific wavelength of the incoming light spectrum is diffracted. The AOTF has a spectral transmission function, matching a sinc^2 shape [23]. The amplitude of this spectral transmission function defines the diffraction efficiency of the device. In order to achieve the maximum efficiency, each spectral wavelength is linked to a specific RF power level, following the equation:

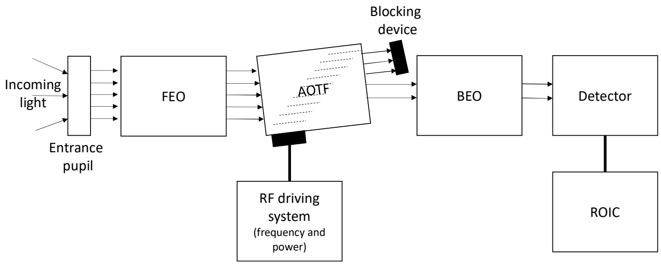

Fig. 2. The instrumental concept of the AOTF-based spectrometer for plastic debris detection. FEO: Front-End Optics, BEO: Back-End Optics, ROIC: Read-Out Integrated Circuit.

$$P_{OPTIMAL} \cong \frac{\lambda^2 H}{2\, L\, M_2} \quad (1)$$

In (1), L and H represent the actual length and height of the transducer, λ signifies the wavelength of the optical light beam, and M_2 denotes the figure of merit, which is contingent upon the material of the crystal [23].

The spectral scanning speed only depends on the flexibility of the RF driver and limitations of the detector. Due to recent developments in this field, a swift and accurate frequency and RF power switching is possible [24]. This creates the opportunity to perform prompt imaging at a specific wavelength and at a high efficiency, which is needed in the frame of a smooth identification of plastic debris.

The advantage of this passive AOTF-principle is its robustness for space and the accompanying space heritage [25], as well as the potential to conduct rapid spectral scanning in an imaging context. Spectral resolutions up to < 1 nm are possible, together with a spatial resolution in the centimeter range (depending on the observed area) [21, 20, 26]. It is clear that these advantages are particularly prominent for space-based remote sensing applications.

IV. Instrumental Concept

In the frame of plastic debris monitoring using remote sensing, the identification of plastic debris by spectroscopic analysis, combined with the AOTF technique described in the previous paragraph, is beneficial. The combination of knowing the specific spectral signatures of different plastics, together with the opportunities created by the AOTF technology, enables the design of a plastic monitoring system as depicted in Figure 2. The described instrumental concept has space heritage [25] and is also used to detect NO_2 [18] and the polarization of auroral light [20] in ground-based instrumentation.

The light enters the instrument on the left side, using an entrance pupil. Additionally, the incoming light continues through the Front-End-Optics (FEO). These optical elements consists of optical lenses and a polarizer. The light consequently enters the AOTF, which acts as an optical wavelength selector. The device is slightly tilted in order to fulfill the Bragg angle for the entering light beam. The activation of the AOTF is done by a dedicated RF chain. The applied frequency and accompanying power level determines which optical wavelength is selected and at what rate. The AOTF creates a zero and first order beam. Only the first order is of interests as it contains the selected optical wavelength. The zero order beam contains the rest of the optical spectrum and needs to be removed by an optical blocking device. The selected light beam continues through a polarizer and lenses (Back-End-Optics (BEO)) to end up at the detector. The images are captured by using a data Read-Out Integrated Circuit (ROIC).

TABLE I
AOTF-based Spectrometer – Instrumental Performance Parameters

Requirement	Value
Orbit	300 km
Aperture	300 mm
Spectral resolution	< 1nm
Frame rate	> 400 Hz (detector dependent)
FOV	3.8° x 3.8°
Ground Sampling Resolution (GSR)	4 m
Revisit time	1 hour locally (<1% of area)

The design parameters, specifically linked to the AOTF-based spectrometer setup, are summarized in Table 1. Having an AOTF, a common aperture for imaging is 10 mm x 10 mm [23]. For these devices a spectral resolution of < 1 nm is prevalent [23]. The monitoring system is capable of imaging at a rate of around 400 images per second, depending on the used detector and the data ROIC. This is a typical number for detector systems used in space [27]. In current AOTF-based spectrometer instruments, a FOV of around 5.7° x 5.7° and even 12° x 11° is possible [23, 28]. The RF driving frequency and applied power to the AOTF depends on the selected optical wavelength.

V. Low-Flying Platform Concept

Most Earth Observation satellites have structurally rigid telescopes and fly orbits above 600 km. For example, the reference Sentinel-2 satellite, introduced in section II, is flying at a Sun Synchronous orbit of 786 km [29]. Its MSI instrument has primary mirror of 442 mm x 190 mm and is able to provide a ground sample resolution of 10 m [30]. The full satellite is approximately 3.3 m x 1.6 m x 2.4 m in volume and 1225 kg in mass. For effective plastic monitoring, both ground sampling resolution and temporal resolution need to be improved. Innovative solutions need to be investigated to avoid that the overall system becomes unaffordable.

Introducing a deployable baffle and deployable secondary mirror can effectively decrease the volume of the instrument by a factor two [10]. Introducing state-of-the art technologies and innovative architectures can increase the (stowed) payload to spacecraft bus ratio to at least 50% [31]. An internal study for a thermal infrared imager has shown that a deployable telescope with a circular 30 cm primary mirror [10] is feasible in a 27-unit CubeSat with outer dimensions of 34 cm x 35 cm x 36 cm and a mass of less than 54 kg.

Flying at Very Low Earth Orbit (VLEO) can further enhance the ground sampling resolution at the same dimensions. Using electric propulsion, it is considered feasible to fly at 300 km for several years without the propulsion system becoming a driver in terms of mass and volume [10]. Air-breathing propulsion can potentially even enable orbits between 120-250 km [32] in the future, but its technology readiness level is still relatively low.

For the plastic monitoring experiment using Sentinel-2 imagery the Plastic Index (PI) was calculated using

TABLE 2
GROUND SAMPLING RESOLUTION AT CENTER WAVELENGTHS λ_C

λ_c [nm]	Sentinel-2 (ref. values) [m]	Distance @ 300 km, dif. Lim. [m]	Distance @ 150 km dif. Lim. [m]
665	10	0.8	0.4
842	10	1.0	0.5
1215	n/a	1.5	0.7
1732	n/a	2.1	1.1

wavelengths 842 nm (near infrared) and 665 nm (red) [15]. Also the Reversed Normalized Difference Vegetation Index (RNDVI), using the same frequencies, is useful to distinguish plastic. This study was able to detect a clutter of plastic bottles of 3 m x 10 m using a 10 m x 10 m ground sampling resolution. It should be noted that the MSI instrument on Sentinel-2 is not operated at its diffraction limit of its primary mirror; it has a 7.1 and 5.6 times lower ground sampling resolution for 665 and 842 nm than possible. This means that the detection of plastic may require a signal-to-noise limited design rather than a diffraction limited design. However, MSI's primary mirror is rectangular and approximately half the area of a circular mirror with the same width and the conducted experiment used a clutter of plastic of only one-third of the area of the ground sampling resolution. Using this data, the equivalent SNR as for MSI's experiment can be achieved using a binning 2 x 2 pixels for a diffraction limited telescope with circular aperture where the plastic occupies these full 2 x 2 ground samples.

Next to the 665 nm and 842 nm as used from MSI, the 1215 nm and 1732 nm are considered very useful for plastic monitoring [16]. A full radiometric analysis is still open for further analysis and for this study, diffraction limits are considered.

Taking the 30 cm aperture Deployable Space Telescope (DST) and an orbit of 300 km and 150 km altitude respectively, the achievable diffraction limited Ground Sample Resolution (GSR) are listed in Table 2. This means that a GSR of 1-2 m should be feasible if SNR is not limiting, and 2-4 m if the SNR of the MSI experiment is taken as a reference.

A good GSR for plastic monitoring is thus possible from a relatively small 27U CubeSat platform, making use of several state-of-the-art technologies and concepts. The initial investment cost for all these concepts can be fairly high and Rough Order of Magnitude (ROM) is 25-50 M€ to achieve a full and reliable operational status of a single satellite using all these innovative developments. These developments, such as deployable optics [10], VLEO capabilities [33, 32] and innovative architectural concept for enhanced payload volume [31] are however useful for many purposes and maybe developed independently. Also, while plastic monitoring may be a dominant driver in the payload design, some selected spectral lines in between may be added for different applications without becoming a design driver for the payload or platform design. Once a full satellite system, including payload, is developed the reproduction cost of the second and more can be relatively limited (ROM estimates of 1-2 M€ per satellite) and launch cost of a 27U CubeSat may come down to about 0.5 M€ in the future. Because the deployable space telescope design requires active in-orbit alignment detection and correction, this can inherently save on assembly, integration and testing cost [10]. This means that, not taking into account initial investment cost, the ROM estimate per satellite can be in the order of 2-4 M€ for a constellation. Using a constellation, the temporal resolution of the plastic monitoring can be improved significantly.

The revisit time for Sentinel-2 is 10 days. This will increase for a satellite with improved ground resolution with a smaller field-of-view. Therefore, in order to monitor plastic at a daily or higher frequency, the use of a constellation is required. Plastic moves at relatively high pace on rivers and at sea near the river estuaries. Once further down the seas and oceans, a monitoring every few days is deemed sufficient. Assuming that the satellites can be re-oriented by several tens of degrees to monitor the rivers and shores at the required higher pace, a constellation with a global nadir-pointing revisit time every few days and local monitoring down to once every hour is considered both feasible and adequate. Assuming that the AOTF technology develops such that a 5000 x 5000 pixel (25 Mpixel) sensor can be implemented, the local swath width will be 20 km for a 4 m GSR. A single satellite in a near polar orbit can have a revisit time around the equator of approximately 125 days. At other latitudes, this revisit time will be smaller. For a two-day global revisit time, an constellation using sun-synchronous orbits requires in the order of 60 satellites. When spread over 12 different orbital planes and properly phased-out, and assuming a sway of the attitude of each satellite up to 20°, the requirement of being able to monitor local areas of interest every hour can also be met. Assuming that these areas of interest is less than 1% of the global area, this can for a large part be done when satellites are passing land areas and/or when they ground traces overlap at North/South latitudes larger than 20°.

VI. CONCLUSION AND FUTURE WORK

The concept of having a global low-flying satellite constellation, using spectroscopic AOTF technology to monitor plastic debris was proposed. Using spectral signatures of different plastics serves as the baseline of plastic debris identification. Combined with a platform which can provide a high resolution and revisit time, creates the possibility of global plastic debris mapping.

The data eventually generated by this innovative space-based monitoring system will enable decision-makers with the necessary information to understand the threat posed by plastic pollution. Subsequently, this knowledge can drive the implementation of essential policies and measures to mitigate the environmental impact of plastic debris. The innovative combination of AOTF-technology, deployable optics and low flying satellites in a constellation will enable a cost-effective global space-based plastic debris monitoring system.

Future research is foreseen to improve the spectral signatures of plastic debris under different environmental conditions. Also, the concept of low-flying platforms and deployable optics needs to be worked out in further detail.

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