ESA Discovery and Preparation – OSIP

Campaign on Remote Sensing of Plastic Marine Litter

BLUE

Brillouin – backscatter - fluorescence **L**IDAR research for **U**nderwater **E**xploration of marine litter

Executive Summary Report

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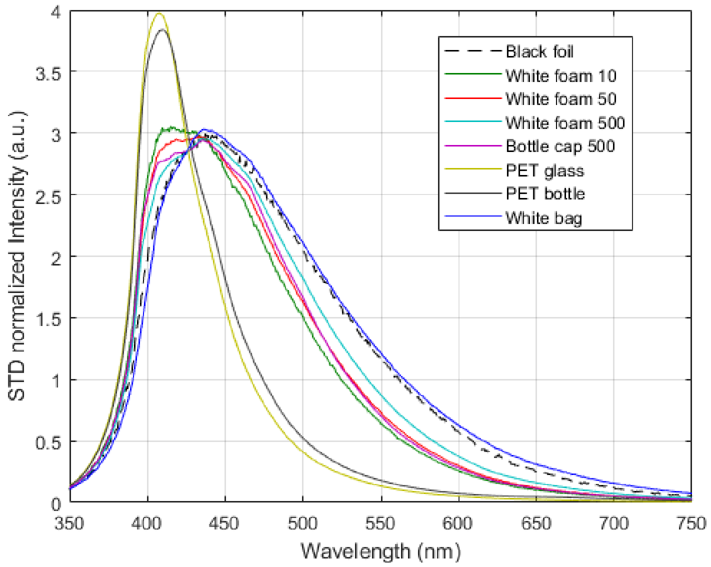
The **BLUE project** has investigated the potential of diverse LIDAR techniques (fluorescence, backscatter, Raman LIDAR) from different platforms – space, airborne and ground-based – to address plastic litter detection in the water column and its identification against other types of marine litter.

Recent studies have stressed how plastic litter at the sea surface represents only a small fraction of plastics entering the sea. Hence, the major contribution of our idea has been to investigate remote sensing methods with the potential to provide information on submerged plastics, including microplastics. Until now, the contribution of LIDAR to ocean plastic remote sensing has been almost unexplored, except for sporadic bathymetric data from airplane to detect large items such as wood logs or ghost nets. Meanwhile, spaceborne elastic LIDAR has already been used to detect algal blooms in oceanic waters, while fluorescence LIDAR has already been suggested for plastics characterisation in different contexts, mainly related to plastics manufacturing.

The approach we adopted was four-fold: (1) study the elastic backscattering properties of microplastics and compare them with those of other particles (e.g. plankton, mineral sediments) commonly found in sea waters in order to investigate the potential of elastic backscatter LIDAR from space to detect changes in the optical properties of the water column due to microplastics; (2) process backscatter LIDAR bathymetric data - acquired over the Great Pacific Garbage Patch by using the bathymetric Teledyne airborne LIDAR – in order to investigate the potential of this technique to detect macroplastics; (3) investigate the potential of fluorescence LIDAR to detect and characterise submerged plastic items by carrying out targeted LIDAR experiments in the laboratory and a measurement campaign at sea; (4) study the capability of Raman spectroscopy to identify different types of plastics – even heavily fouled - and the possibility of using a LIDAR system in standoff operation to detect Raman spectra of plastics.

For the first time, the BLUE project has provided a valuable insight to the potential of the LIDAR technique for the detection and identification of plastics litter in a marine scenario. During these two years, we carried out several experiments - both in the laboratory and in marine environment - that offered very interesting outcomes suggesting the capability of the LIDAR technique not only to provide a valuable tool for the detection of marine plastics litter, but also for its identification, at least for some of the plastic types investigated in this study. In addition, several promising research paths and lessons learnt for future research have been provided both by the experiments conducted in the laboratory, by the analysis of LIDAR dataset acquired on Great Pacific Garbage Patch and by the simulations done with the aim of a preliminary evaluation of the expected LIDAR performances in real case scenarios from different platforms.

Fluorescence LIDAR measurements in the laboratory – carried out by using an in-house developed fluorescence LIDAR instrumentation on a wide choice of both raw plastics and ocean-, beach- and river-harvested plastics – highlighted a remarkable capability of the fluorescence LIDAR technique to contribute to the detection of plastic litter and its identification against the fluorescence signal of the dissolved organic matter naturally present in surface waters as well as the Raman scattering signal due to the water molecules. Beside different type of raw and weathered plastics (gathered from marine, beach and riverine environment), the technique showed a very interesting potential for the detection of plastic microfibers suspended in natural water (with a considerable dissolved organic matter content), down to concentration of 0.04 gr/L by deploying the LIDAR system from a distance of about 11 m.



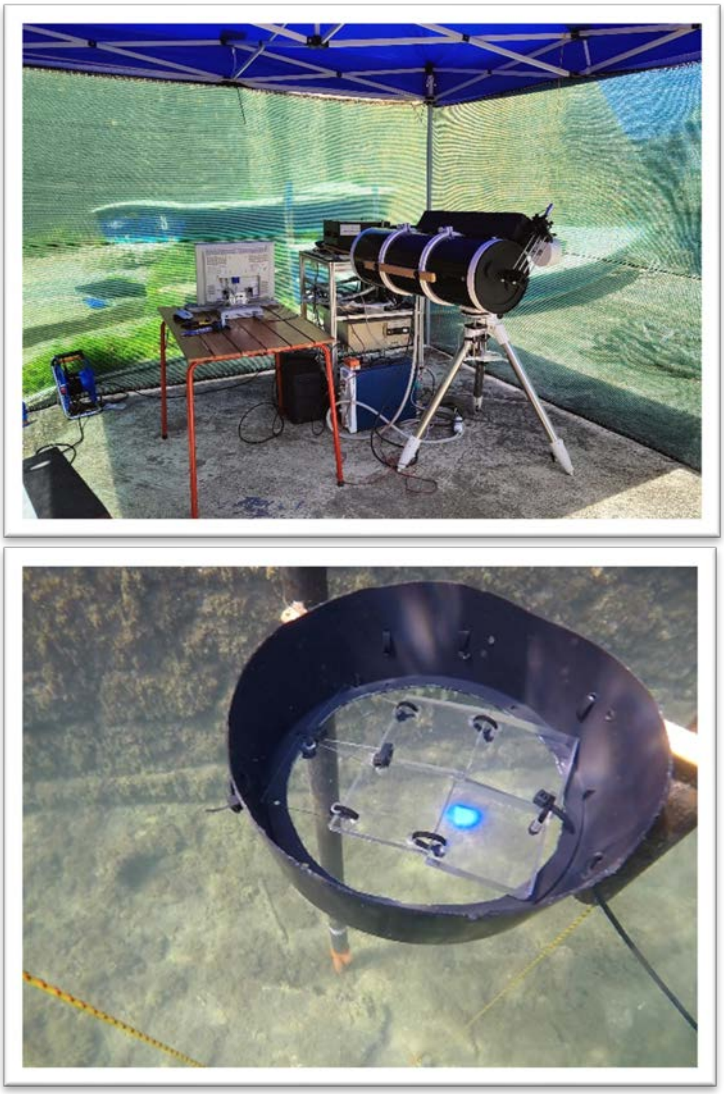
Fluorescence LIDAR spectra of different types of commercial plastics. The spectra are normalised to the standard deviation (STD) in order to make it easier the comparison. Laser excitation: 355 nm. Distance of the LIDAR sensor from the target: 11 m.

Most of the investigated plastic samples showed a very good fluorescence efficiency: among these, PET- and nylon-containing samples were the most strongly fluorescent ones. A remarkable difference in the spectral distribution of the fluorescence of some types of plastics also suggested the possibility of the characterisation of different types of plastics as well as the identification of plastics against other types of litter, such as wood or vegetation.

Remarkable photobleaching effects due to laser irradiation were also clearly observed both for raw and weathered plastic samples. The same effect was also observed when the samples were irradiated while immersed in the water, although to a less extent. This effect, however, is not considered of particular interest with respect to the detection and characterisation of plastic marine litter in a real case scenario since we expect that only few laser pulses hit the plastic item.

Another aspect pointed out by the experimental results obtained on samples of the same plastic type - but of different thicknesses - is that the samples could sometimes show different fluorescence efficiency and spectral distribution, depending on the thickness. The differences observed could not be merely due to reabsorption effects, due to the behaviour not consistent as the thickness increases; rather, this can be ascribed to the presence of additives used to make it easier the manufacturability of thin sheet of material. Some weathered samples gathered in marine/riverine/beach scenario also showed additional fluorescence contributions that could be ascribed to the presence of dyers or other additives in the plastics. Interestingly, heavily-weathered plastics like the riverine samples did still show characteristic fluorescence features of the plastic compound (PET), despite the extensive fouling they were subject to.

Fluorescence hyperspectral LIDAR imaging was also successfully tested on weathered samples: the technique is very promising for the characterisation of different types of plastics by using dimensionality reduction methods. The technique allowed to identify – within the same beach-harvested item – the presence of a different type of plastic to implement the eyelet of this piece of plastics.



Fluorescence LIDAR measurement campaign at sea (July 2022). Up: CNR-IFAC Fluorescence LIDAR system deployed during the measurement campaign from the harbour deck. Bottom: Laser-induced fluorescence of PET raw plastics plunged in the water column at sea (approximately 1-m depth). Laser excitation: 355 nm. Distance of the LIDAR sensor from the sea surface: 22 m.

Fluorescence LIDAR measurement campaign at sea, carried out in July 2022 by deploying the fluorescence hyperspectral LIDAR from the deck in a small harbour (*Porticciolo San Leopoldo*, *Accademia Navale di Livorno*, Italy), confirmed the results obtained in the laboratory and provided the opportunity to test the technique in a realistic scenario, which was representative of operation in conditions of very limited sea roughness, yet with relatively high content of coloured dissolved organic matter and phytoplankton. During the campaign, we could easily detect the fluorescence features of several types of plastics floating on the surface or below it. Some types of PET-containing plastics could be detected down to a depth of about 2.4 meters (seafloor in the harbour). Detection of floating plastic items dragged on the water surface could be easily performed also by observing the abrupt decreasing of the Raman scattering signal while the item was crossing the optical path of the LIDAR system and, in case of a fluorescent plastics, the simultaneously increase in the fluorescence bands typical of the plastic compound.

Fluorescence LIDAR data simulations provided a preliminary insight on the feasibility of PML detection from airborne and spaceborne platforms. Fluorescence measurements on the raw plastic samples in wet conditions executed in the laboratory were used to estimate the fluorescence conversion efficiency of the different types of plastics. These were used as input to the procedures for the simulation of the fluorescence signal acquired by a fluorescence LIDAR instrumentation deployed in different operational scenarios, airborne operation and satellite operation. For airborne operation, we considered a LIDAR system operated from an airplane flying at an altitude from 400 m up to 1000 m, with a speed of 200 km/h and at-ground spot diameter of 0.5 m, and as an excitation source, a commercial, rugged Nd:YAG laser - manufactured by Quantel - with emission wavelength at 355 nm, output energy of 70 mJ and pulse repetition rate of 100 Hz. SNR values are definitely high, especially for PET and PA6-XT plastic types. In principle, fluorescence from low-fluorescent samples like HDPE and PVC could be also detected, provided a good coverage of the measured area. Strongly fluorescent plastics like PET can be detected even in the case of a very limited fractional coverage (1%). From satellite, the very low atmospheric transmission at 355 nm is the main factor strongly hindering the application of the fluorescence technique for PML detection. In the case study, we considered LIDAR system parameters compatible with the ALADIN system onboard the AEOLUS mission. Due to the strong attenuation of atmosphere in the UV spectral region, however, the expected SNR is very poor. As a consequence, higher energy laser source (and/or higher repetition rate) would be needed in order to efficiently excite fluorescence at the sea surface.

Further aspects concerning the **fluorescence LIDAR technique** worth of being investigated in the future can include:

- definition of an operational procedure for the detection and characterisation of PML; the procedure, in fact, can be also affected by the operational scenario (e.g.: shallow waters, optical thick waters, clear waters with laser extinction).

- extensive measurements in real case scenarios, whose results would be beneficial both for the definition of an operational procedure and for the analysis of diverse interfering phaenomena, such as: highly trophic waters, waves, natural debris.

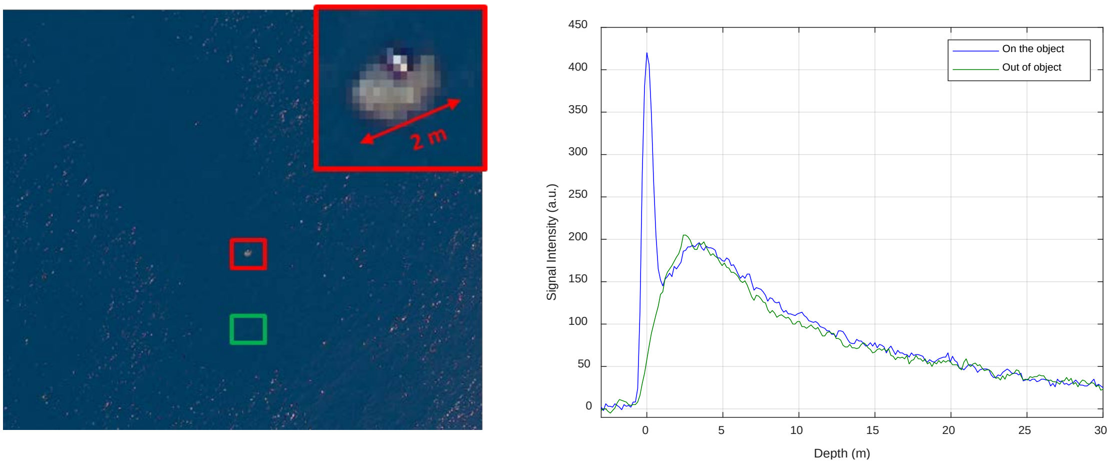
- further studies to investigate the feasibility of detecting microplastics (type of microplastics, concentrations, effects of CDOM and phytoplankton).

- the effect of fouling on fluorescence-based detection of plastics.

- feasibility study of a tailored fluorescence LIDAR system for PML detection and characterisation; this should also include the definition of the targeted operational scenario, including the platform.

Backscatter LIDAR technique from airborne platform was primarily investigated thanks to the availability of large dataset acquired by TOC on the Great Pacific Garbage Patch by using the Teledyne airborne bathymetric LIDAR in October 2016. During the expedition, two transects, each 600-km long, were acquired. The LIDAR had a ground sampling distance (GSD) of 2 m and 1 m for the "deep" and "shallow" channels, respectively. The swath of the LIDAR system during data collection was approximately 290 meters. Besides LIDAR backscatter profiles, the dataset included coregistered RGB data. The data volume of the dataset includes approximately 6600x2 "deep channel" and "shallow channel" data cubes, plus 6600 RGB images. The dataset was provided already preprocessed by OPTECH so that 3D point clouds and relevant depth-resolved LIDAR profiles were not available, but only a single ‘average’ LIDAR vertical profile for each sampling point.

A first aspect we investigated by processing the LIDAR dataset and by comparing it with the RGB data was the feasibility of **detecting macroplastics**. In fact, the limited spatial sampling of the LIDAR system deployed during the campaign limited the performance of the technique to the detection of only large plastic items (of the order of 1 m). The research, however, allowed to highlight several interesting aspects as lesson learnt for future research on this topic: remarkable effects of the LIDAR acquisition geometry (whiskbroom, in this specific case), which required additional correction procedures; the impact of wave motion, which – joint to poor spatial sampling - could affect the detection even of large items; systematic effects introduced by both the instrumentation used and the raw data pre-processing procedures required to create the vertical profile images.



Bathymetric LIDAR campaign on the Great Pacific Garbage Patch (October 2016). On the left: RGB image of the sea with a red-squared area corresponding to a floating object (in the inset, a 2-m wide floating marine debris) and a green-squared area corresponding to an area free of floating objects. On the right: average backscatter LIDAR profiles corresponding to the two squared areas of the RGB image.

A second aspect we investigated addressed the retrieval of the **water attenuation coefficient** from the LIDAR profiles. Based on the development of a model for the LIDAR signal and of pre-processing procedures to correct additional systematic errors, we calculated the average value of the attenuation coefficient for each image of the two transects, both for the deep and for the shallow channel, and compared its variation along the transects with the trend of the number of marine litter objects as detected by RGB data. Interestingly, we found a good agreement between the two trends, with some abrupt changes in the number of objects corresponding to rapid changes in the attenuation coefficient. We also observed that there is a good agreement between the trend of the RGB-detected quantity of very large (> 1 m^2) objects and small (<1 m^2) objects, suggesting a potential correlation between the number of macro-litter and the quantity of micro-litter in the water, which might also lead to infer a correlation between the quantity of RGB-detected objects and the overall quantity of plastics in the waters (the latter affecting the attenuation coefficient). The trend of the attenuation coefficient along the transects was also analysed as a function of the binning used to evaluate the spatially-averaged value of the attenuation coefficient. In general, a good correlation was found when averaging the attenuation coefficient over a leg of 50 km, with a R^2 value of 0.7 and a p-value less than 0.05, indicating a statistically significant correlation. Averaging the attenuation coefficients over longer legs resulted in higher, but less statistically significant, correlations, while averaging over shorter legs significantly decreased the correlation between the attenuation coefficient trend and the number and position of the detected objects. This aspect, of course, requires further investigation, especially if we consider that backscatter LIDAR simulations - yet with several limiting assumptions - for typical concentrations of microplastics did not provide the grounds for its detection through backscattering techniques.

Backscattering properties of microplastics were also investigated and compared with those of the most common particles that can be typically found in sea waters, such as plankton and mineral particles. The simulations took in consideration the main characteristics and typical concentrations of such particles from the literature (e.g. we assumed a microplastics density of 10^2 particles m^{-3} with (monodisperse) radius 500 - 1000 µm and refractive index 1.2). The results obtained showed that the backscatter LIDAR measurements are expected to be strongly dominated by plankton, which represents the higher concentrated particulate in sea water. Plastics instead represents the less concentrated source of particulate and, as a consequence, the determination of microplastics by scattering is very difficult due to the huge amount of other natural (non-plastics) particles present in the water.

Simulations of the **polarisation factor** P for monodisperse particles by varying wavelength, scattering angle and polarization were also performed. Simulations obtained for a backscatter signal using horizontally linearly polarized incident radiation (scattering angle 180°, horizontally linearly polarization representative of one of the two polarization scheme adopted by CALIOP) showed a spectral variability of the polarization factor and also peaks for specific particles' types. This behaviour, however, can be ascribed to the assumption of monodisperse particle distributions, while in a real case scenario of polydisperse particles such peaks are expected to be wider and overlapping, making very difficult the identification of microplastics. In the specific case of monodisperse distribution, however, some peaks of the spectrum of P for plastic particles might be exploited for discriminating the presence of microplastics in seawater. The preliminary simulations done so far showed that, in some specific cases, it could be worth investigating the possibility of discrimination of monodisperse microplastics against other types of particles by using specific wavelengths. In addition, auxiliary data such as chlorophyll values retrieved from remotely sensed reflectance data, could be further exploited to discriminate variations in the signal due to the phytoplankton against those due to microplastics. In general, it can be concluded that the main factor preventing microplastics detection by backscatter LIDAR extinction measurements remains the very low concentration of microplastics in seawater, considered also that microplastics shares refractive index and size distribution similar to the one of the other natural suspended particles.

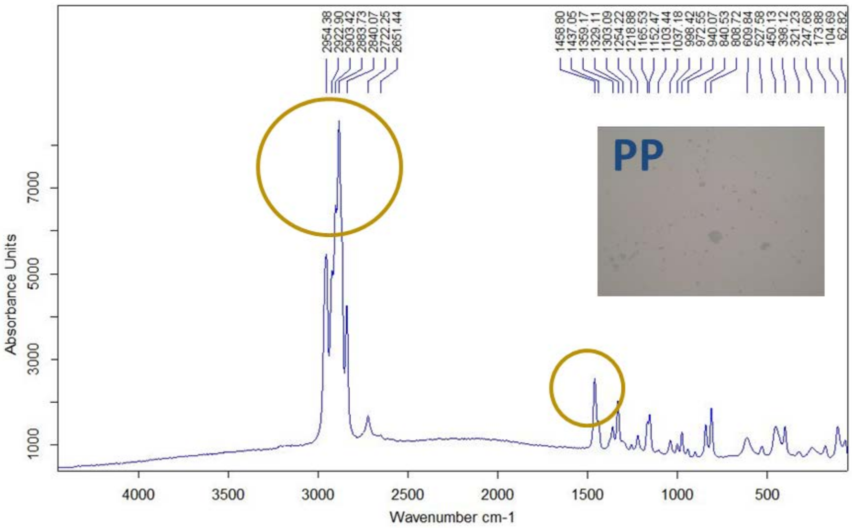
Further studies on the **backscatter LIDAR technique** can include:

- execution of backscatter LIDAR data measurement campaign by deploying LIDAR sensors featuring high spatial resolution aimed at the detection of macroplastics – both floating or submerged - and its 3D quantification.

- further investigation on the water attenuation coefficient as a proxy of the overall quantity of plastics in water and on the correlation between macro-litter, micro-litter and microplastics in the water column. This can also imply a bibliographical survey to better understand the impact – and correlation – with other interfering particles like plankton and sediments.

- as for depolarisation techniques, it might be worth to further investigate the possibility of discrimination of monodisperse microplastics - against other types of particles - by using specific wavelengths and with the support of ancillary data (e.g. Chl concentration estimates).

Raman spectroscopy measurements in the laboratory showed that all the investigated samples could be identified by their characteristic wavenumbers, with XPS samples the most difficult to be analysed. In addition, we noticed that black-coloured samples were more difficult to be analysed and that the shape can influence the resolution of the Raman spectra. In general, the alternate use of green and red lasers made it possible to obtain spectra from samples of different colours and shapes.



Raman spectra of raw PolyPropilene (PP) plastics acquired in the laboratory with Micro-Raman Senterra Bruker instrument.

Plastic samples with different levels of biofouling were also measure in order to investigate the effects of the layer of organic biofilm (2-3 mm max.) on the Raman measurements since such layer could produce strong fluorescence and hinder Raman detection. Nonetheless, we observed that a thick but porous layer of organic film – although making the Raman measurement more difficult - did not prevent the detection of the Raman signal, even in presence of the fluorescence from organic substances.

Raman signal simulations provided a preliminary insight on the feasibility of the Raman- based identification of plastics by means of Raman signal detected with a LIDAR system in standoff configuration. In general, on the grounds of the simulations carried out, both PP and HDPE plastics are expected to show good SNR in most investigated scenarios, even from a distance of 100 m. Only if the plastics is very thin (0.1 mm thick, approximately) and the sensor is deployed at distances of the order of 100 m, the detection of the Raman signal is expected to be difficult. It can be also noted that a thick plastic item would make it easier the identification of the plastic object, as expected.

Further studies on Raman scattering should possibly include experiments under controlled conditions in order to assess an actual feasibility of the Raman LIDAR remote sensing of plastics and its identification based on the specific compounds present in the sample. This could also imply the need of using a different type of laser source/LIDAR system with respect to the one employed in the BLUE project.

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