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Medium-Scale Measurement Campaign for Floating Macroplastic Detection in a Realistic Environment at X-Band Frequencies

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***Abstract*—In this paper we assess the possibility of detecting floating plastics in a medium-scale realistic environment using microwave (MW) and RADAR technology at X-band. The measurement campaign performed in the "25 de Abril" bridge over the Tagus River allowed for distances of around 100 m between the antennas and the targets. Several different targets with sizes of 1 m^2 were tested and detected. The use of objective metrics also allowed to see which of the targets presented a higher response. This is an encouraging step towards the implementation of such detection techniques onboard drones or airplanes.**

***Index Terms*—backscattering, macroplastics, measurements, propagation, remote sensing, rough surface.**

I. Introduction

The increase in plastic pollution in the world's oceans has become a critical environmental issue, posing significant threats to marine life and human health. Plastic debris, accounting for 87% of all marine litter, has led to harmful impacts on marine species through ingestion, entanglement, and smothering [1]. This growing accumulation stems from both land-based (80%) and marine-based (20%) sources, such as discarded fishing gear, which adds approximately 640,000 tons of plastic to the oceans annually [2], [3]. By 2010, an estimated 4.8 to 12.7 million metric tons of plastic entered the oceans, a figure projected to increase tenfold by 2025 without intervention [4].

The formation of garbage patches, notably the Great Pacific Garbage Patch (GPGP), which contains over 79,000 tons of plastic across 1.6 million square kilometers, underscores the severity of the issue [5]. Detecting and monitoring these large-scale pollution zones is essential for mitigation efforts. Satellite-based remote sensing offers a viable solution, with microwave (MW) and radio frequency (RF) technologies showing particular promise due to their ability to be less affected by weather conditions that hinder optical methods [6].

Optical satellite systems like Sentinel-2 have demonstrated success in identifying macroplastics in coastal waters by analyzing reflectance in the near-infrared spectrum [7]. However, these methods face limitations in deeper ocean regions and under cloudy conditions. Synthetic Aperture Radar (SAR) systems, which operate at MW frequencies, have emerged as a potential solution by detecting surface anomalies that may indicate floating debris [8]. Initial studies utilizing SAR data from satellites such as Sentinel-1 and COSMO-SkyMed have identified plastic-related sea slicks in remote ocean areas, though challenges remain in distinguishing plastics from other materials.

While progress has been made, the field of marine litter detection using MW technology is still emerging, with limited research focusing on plastic detection. Further exploration of C- and X-band frequencies and the development of higher-resolution SAR systems are needed to enhance detection capabilities [9]. The deployment of satellites equipped with these sensors present a promising path toward the continuous and large-scale monitoring of oceanic plastic pollution.

This paper aims to contribute to the growing body of work by presenting medium-scale measurements of floating plastic detection using MW technology. Building on previous studies that explored small-scale feasibility [10], this work extends the measurement range to 100 meters in a more realistic environment. The remainder of this paper is structured as follows: Section II reviews the metrics for detecting floating macroplastics, Section III describes the measurement

setup and methodology, while Section IV presents and discusses the results. Finally, Section V provides conclusions and outlines future work.

II. Metrics for detection

In order to evaluate the detection of plastics floating in water, some metrics were developed to quantify this detection. In this section, a metric based on a transform from the frequency to the time domains will be presented as a basis for detection. This study is followed by a metric based on the total energy scattered by the objects in the scenario that will return a scalar from which it can be inferred if there was detection or not. Lastly a more statistical approach based on the Kolmogorov-Smirnov test applied to the measurement results is presented.

The first metric described herein is the one based on the matched filter method. This method allows, from the backscatter frequency response ($S_{\text{ij}}(f)$) of the scenario in study, to evaluate the detection of floating objects in the distance domain. To achieve this however, for each case, two measurements need to be considered: one measurement without and one measurement with the floating targets. Note that each measurement contains several samples. One of the samples from the measurement without plastics (henceforth called reference) will be used in the normalization of the data. This normalization is attained by subtracting each frequency point of the normalization sample from the respective frequency point of the measurement.

Thus, the final frequency response that will be used in further calculations can be obtained using Eq. 1:

$$S_{ij}(f)_{final} = S_{ij}(f)_{measurement} - S_{ij}(f)_{norm}, \quad (1)$$

where $S_{ij}(f)_{final}$ is the normalized to reference frequency response, $S_{ij}(f)_{measurement}$ and $S_{ij}(f)_{norm}$ are the frequency responses of the measurement in consideration and the normalization sample, respectively.

The normalized frequency signal is then used in a matched filter calculation to transform the response of the scenario from the frequency domain to the distance domain. This will allow to see at what distances the plastics are in comparison to the antenna. The fact that multiple sequential samples are taken also provide the vantage of being able to see the movement of the targets in the time axis. The calculation to transform the data from the frequency to distance domain is as shown in Eq. 2 [11]:

$$s_{ij}(d) = \sum_{fmin}^{fmax} (S_{ij}(f)_{final} \times Window(f) \times \times \exp\left(\frac{1j \times 2\pi \times f \times d}{c}\right)), \quad (2)$$

where $s_{ij}(d)$, corresponds to the backscatter response in the distance domain, $Window(f)$ is the Hamming window, f represents the frequency, d is the distance being analyzed and c is the speed of light in vacuum ($3 \times 10^8 m/s$). The array of distances can be defined to have more or less spatial resolution. Lastly, $fmin$ and $fmax$ correspond to the minimum and maximum frequencies of the frequency sweep in each sample, respectively. This process allows for the detection of the plastic visually, as it should be possible to see the responses of the scatterers according to distance. To these plots we call scattergrams, where the abscissa represents the distance from the antennas to the water surface, while the ordinate corresponds to the successive time samples.

However, more objective metrics can be employed to verify if there is detection. One such metric can be one based on the energy scattered by the objects present in the water. This metric uses as basis the distance domain response of the scenario obtained by the matched filter method presented in the previous section. Using this data, the total energy for each measurement sample can be calculated by summing all the distance components, as shown in Eq. 3:

$$total_{energy} = \sum_{dmin}^{dmax} |s_{ij}(d)|^2 \times d_{res}, \quad (3)$$

where $total_{energy}$ represents the total energy of one sample $s_{ij}(d)$ and d_{res} corresponds to the spatial resolution used in the matched filter response calculations. The variables $dmin$ and $dmax$ are the minimum and maximum distances considered, respectively.

Having the total energy of each measurement sample, one way to assess if there is detection is by calculating the ratio between the average total energy of measurement with plastic objects against the average total energy of the measurement without said objects, as in Eq. 4:

$$EnR = \frac{\overline{total_energy_{measurement}}}{\overline{total_energy_{ref}}}, \quad (4)$$

where EnR is a scalar value that represents how much difference there is in the measurement with plastics against the measurements without. For detection purposes, a threshold needs to be calculated to verify if the energy scattered by the objects is significant when compared to the background. To achieve this value, we calculate the EnR metric between different references instead of comparing the energy between a reference and a measurement with floating targets. This allows for the determination of the maximum value of EnR between references meaning that values above this indicate detection.

The last metric presented herein that will be employed in the study of plastic detection is a statistical one based on the Kolmogorov-Smirnov test (KSTest). which allows to determine the probability that two sets of measured samples follow the same unknown probability distribution [12]. This test is used to com-

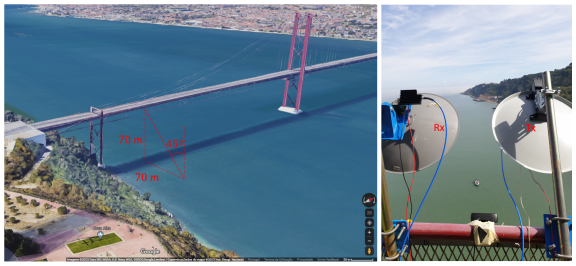


Figure 1: "25 de Abril" bridge measurement locale overview and antennas mounted in the bridge.

pare the distribution functions associated with reference and litter. High values of the maximum absolute difference between the two cumulative distribution functions should be indicative of litter presence. Being based on distribution functions, this approach opens further possibility for target classification based on the distributions shape parameters, something that is not possible with the EnR metric.

These metrics in conjunction will allow for the determination if there was detection of plastic in the measurement.

III. Measurement Setup and Equipment

This measurement campaign was performed on the "25 de Abril" Bridge looking down to the Tagus River (Fig. 1). It also shows the experimental setup mounted on the edge of the walkways directly under the bridge, looking into a patch of water surface with an incidence angle of around $45°$. This scenario was chosen to enable measurement distance of about 100 m. Besides, this allows having access to a moderately uncontrolled rough water surface with the wind and currents effect, while benefiting from a stable and accessible platform to fix the equipment and have the team close to control the measurements, pre-processing and video recording. A spot was chosen about 70 m away from the river bank, to benefit from the visual queue to identify the antenna footprint location.

The measurements were scheduled for the day of the Lisbon Marathon, the only day of the year where the Bridge is closed to vehicles, but open to thousands of athletes which cannot be perturbed. Therefore all the setup had to be mounted in the short period between the closure of the bridge (for four hours) and the start of the Marathon. Also a professional company was hired to maneuver the boat safely in the river, and use their experience to help the team laying the targets on the river, which was not a simple task given the strong currents.

This setup involved two V-polarized reflector antennas with approximately 33 dBi and 30 dBi gain for the transmitter (Tx), and receiver (Rx) antennas, respectively. The transmitting antenna was connected to a 23 dB gain amplifier, whereas the receiving antenna was followed by a 42 dB amplifier. The antennas were mounted at height of 70 m.The antennas were

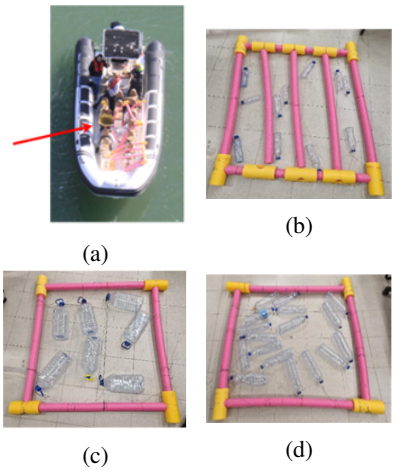


Figure 2: "25 de Abril" bridge measurement campaign targets: (a) trihedron on the boat, (b) foam frame with bottles and vertical foams (Frame A), (c) foam frame with seven 5 L water jugs (Frame B) and (d) foam frame with 18 1.5 L bottles (Frame C).



Figure 3: Photographs from the "25 de Abril" bridge measurement campaign: look up view of the boat towing a rope with a target and close up of a floating target.

connected to ports 1 and 2 of a portable P5004B VNA that measured the transmission parameter S_{21}. The VNA measured the frequency interval between 9 and 10.5 GHz with 2401 frequency points, and each sweep took about 1 s. These settings correspond to an unambiguous range of approximately 232 m.

We measured four types of targets: 50 cm-side trihedron used as a radar corss-section reference (Fig.2a), a foam frame with bottles and vertical foams (Fig. 2b), foam frame with seven 5 L water jugs (Fig. 2c) and foam frame with 18 1.5 L bottles (Fig. 2d). For simplicity we will call these targets Frame A, Frame B and Frame C, respectively. The length of the frames is approximately 1.2 m and the diameter of each tube is about 8 cm.

The wind strength was very mild (not quantified) and the wave height was of the order of 5 to 10 cm. It is possible to qualitatively guess this value looking at the photos taken *in situ* by looking at the photos in Fig. 3.

The team was divided into two groups: one was on the bridge controlling the measurement equipment, whereas the other group was on a boat controlling the targets placement within the field-of-view (FOV) of the antenna. The targets were tied by a rope and

towed by the boat until they were in the footprint of the antenna. Doing so was not easy because of the unstable current of the Tagus river and, therefore, it was difficult to ensure that the target was permanently within the footprint.

IV. Result analysis

As explained in previous sections, reference measurements (*i.e.* without target) were taken in order to account, as much as possible, with the fluctuations of the tide, currents and wind along the day. After the reference measurement was finished, the bridge team would signal the boat team to place the targets within the FOV. For the reasons explained above, some measurements labeled as "target" did not actually capture the target response. That explains why some of the results presented in the following figures do not show a consistent target response along time. However, for the calculation of metrics, we only used the measurement samples where the objects can be seen in the scattergrams. By doing this, we assess the metric values when we know that the target is present in the FOV of the antennas, allowing us to understand if the metrics work as intended.

The first measurement to be carried out was the measurement with a trihedron target. The main goal of this measurement is to assess the area of the FOV and, thus, have an idea of the position where to place the floating macroplastics targets in the subsequent measurements. Since the trihedron has a large radar cross section (RCS) (around $2.6 \times 10^3\ m^2$ at 10 GHz), it is a good calibration target. Figure 4 shows the reference and target scattergrams, respectively. In both measurements, a team member on the boat held the trihedron in place to generate the strongest scattering response possible.

Looking at the scattergram with the target we can clearly identify the trail caused by the trihedron drifting within the FOV. The response of the trihedron was not at constant distance, because the boat was constantly try to adjust its position according to the variable current pull of the water.

Moreover, a camera was also installed between the Tx and Rx antennas (visible in Fig. 1) to have an image for each frequency sweep and, thus be able to verify and define the area corresponding to the antennas FOV. This way it was possible to see when the targets were inside the footprint and outside. The measurements with the trihedron were also utilized for this purpose as, due to the trihedron's high RCS the footprint was easily located.

In Fig. 5 the course of the boat (where the trihedron was) is presented by the colored points, where the colors correspond to the maximum intensity observed in the scattergram for the respective measurement. From this tracking is also possible to outline the FOV of the antennas. This is the footprint that will be used in the rest of the analysis.

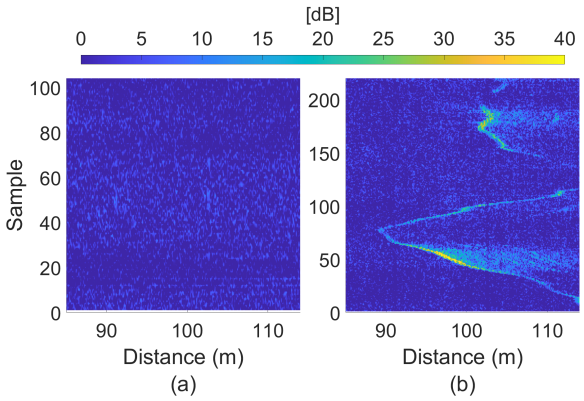


Figure 4: Scattergram of measurement with trihedron: (a) reference and (b) measurement with target.

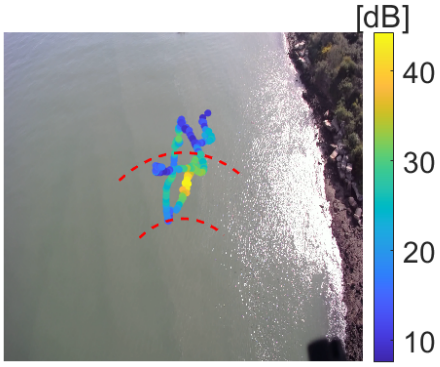


Figure 5: Footprint assessment from the trihedron measurement.

This particular measurement yielded metric values of $EnR = 12.46$ and $KSTest = 10.2\%$. As stated previously we need to have a threshold value to say we have detection. To obtain this value we calculated the metrics by comparing all the references of this measurement campaign and took the greater value, meaning that if the metric values of a measurement is higher then the higher difference between all the references, we can say that we have detection. By performing this analysis we obtained thresholds of 1.02 and 1.1% for the EnR and KSTest metrics, respectively. This means that the trihedron is clearly detected, as the metric values far exceed the threshold values.

Having defined the threshold values and the footprint of the antenna, we can now analyse the measurements with the three frames. Figure 6 shows the scattergrams obtained in the measurements of the three frames, where detection can be observed. For Frame A, we see trails between samples 50 to 100, 150 to 200 and 500 to 550. However, by analysing the trajectory of the boat and the target, we observe that the first (and stronger) response comes from the boat and not from the target. So for the metric calculations only the other two will be considered. For Frame B, we can clearly see the trail, as this was the measurement in which

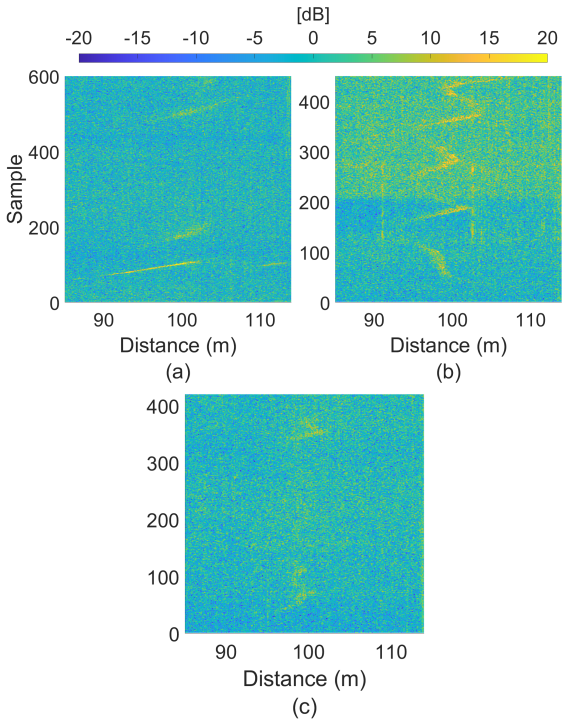


Figure 6: Scattergram of measurement with frames: (a) Frame A, (b) Frame B and (c) Frame C.

the target was more stable inside de antenna FOV. The difference in distance corresponds to the movement of the target as the team on the boat tried to compensate the effect of the currents. Lastly, for Frame C, detection is still visible, albeit more tenuous, between samples 50 to 150 and between 350 to 400. Tracking of both the boat and the frame shows that for these samples, the frame was inside the FOV and the boat was outside.

The metrics resulting from these three cases were compiled in Table I, where detection was also obtained for both metrics when we take into account the previously defined thresholds.

Table I: Metric values for measurements with frame targets.

	EnR	KSTest (%)
Frame A	1.20	4.7
Frame B	2.11	21.8
Frame C	1.19	5.1

V. Conclusion

This paper presents the results of a medium-scale measurement campaign on the detectability of floating macroplastics over the Tagus River. We used microwave frequency technology in the X-band to try to detect targets with a size of 1 m^2 over 100 m distance in a realistic scenario, with uncontrolled wind and waves. We started by using an object known for having a high RCS to evaluate the possibility of detection and antenna FOV. Subsequent measurements with less detectable objects yielded positive results, allowing the detection of both visually and using objective metrics previously defined. These results show that it is possible to detect floating small macroplastics (compared to the antenna footprint) even at higher distances when compared to previous work by the authors even when using bandwidth as small as 1.5 GHz.

Future work will address the possibility of scaling up the measurement scenario and adding equipment movement, such as on board a drone or plane.

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