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Letter

X-Band Radar for Cetacean Detection (Focus on *Tursiops truncatus*) and Preliminary Analysis of Their Behavior

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Abstract: Cetaceans are protected species all over the world, most of them are vulnerable, endangered, or data deficient (according to International Union for Conservation of Nature - IUCN red list). X-band radars detect the echo of the electromagnetic signal reflected by an obstacle or a ship (target). The application of X-band radar to the detection of cetaceans is a new and innovative field of research that could improve the automation of marine mammal data collection, and this is the first time in the Mediterranean Sea. The aim of this work was to test the capability of X-band radar installed along the coast (ground-based) to detect and track cetaceans in a range of approximately 2.5 nautical miles from the radar antenna. Data collection included a part of field work, implemented through the acquisition of photographic images and target's radar detection (by the panoramic terrace Santa Maria in Corniglia), and a part, performed in the laboratory, of data analysis. The work was undertaken between May and November 2018. During this period, 30 days of monitoring were carried out (about 300 h) and about 10,000 radar images were recorded. The first results showed that we were able to recognize the target "cetacean" from the other common targets (boats, buoys, etc.) detected by the radar. In particular 70 dolphins were sighted by visual census; 12 of them were recognized on radar images. Radar images allowed extraction of dolphin dive time (between 2 and 15 s). The next step will be to allow the radar to identify the presence of marine mammals itself since it also works at night and with low visibility. This technique could complement the protection measures of cetaceans, highlighting their presence at sea even if it is impossible with waves higher than 0.8 m and over distances greater than 2.5 km.

Keywords: X-band radar; monitoring; marine mammals; *Tursiops truncatus*; Lgurian Sea

1. Introduction

Marine mammals belong to Cl. Mammalia, Eutheria; in this paper we focused on cetaceans (cetartiodactyla) mammals completely adapted to aquatic life. Cetaceans are hard to access species due to their habitat and behavior (visibility at sea, superficial behavior, apneas time). That is why specifical monitoring campaigns are needed at sea to study cetaceans using several types of platforms (planes, boats) that require a lot of funds and time too. Research on these animals is essential, especially to learn about the impact of humans on the biology and behavior of these species, so the automation of data collection on the presence of cetaceans is becoming increasingly significant in a context of strong marine and coastal anthropization. The X-band radar instrument, through specific algorithms, allows monitoring of a large stretch of sea with the aim of characterizing the wave motion, measuring the surface current field, and obtaining information on the topography of the seabed etc. The high resolution of this instrument seems to make it suitable also for detecting and tracing the passage of marine mammals below the coast. Study experiences and research activities of this type have been carried out in the North Atlantic [1]. McCann and Bell's work used for the first time an X-band radar to detect marine mammals at Orkney islands with positive results. This work on Killer Whales lays the foundations for a new research methodology on marine mammals using non-invasive remote sensors for their habitat. The continuous monitoring of cetacean presence and passage within the Cinque Terre Marine Protected Area could be extremely relevant for protection and conservation measurements on these animals. In particular, this technology could be used to prevent collisions with boats, since the area is affected by high ship traffic. The activity carried out in the study area would be considered a pilot study whose analysis methods can be exported to other areas of the archipelago (from land and/or boats basis). The Pelagos Sanctuary (Figure 1) is continuously crossed by large ships equipped with radars, that could contribute to the creation of an extensive monitoring network capable of providing valuable information on the presence, distribution, and behavior of cetaceans. For the first time in the Ligurian Sea this work, based on these data, aims to test the ability of an X-band radar installed along the coast (ground-based) to identify and trace cetaceans in an area of approximately 2.5 nm (nautical miles) from the antenna. To this end, the radar network implemented as part of the RITMARE project was exploited and includes numerous devices (in X and HF bands) installed along the Italian coast. The instrument used was located in Corniglia and it allowed recording of the passage of marine mammals in the sea portion of the Pelagos Sanctuary included within the Cinque Terre Marine Protected Area. This preliminary experiment, given the absence of precedents in the Mediterranean, represents a new field of study to monitor the presence of marine mammals in the sea. Although the data collected are therefore completely preliminary, they are encouraging and would seem to represent a valid basis on which to test the effectiveness of the radar instrument.

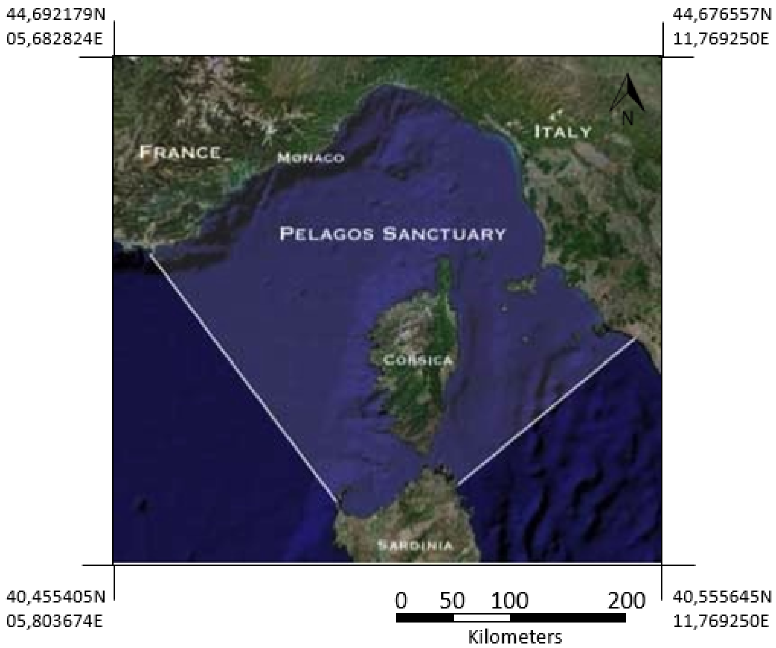

Figure 1. The image shows the Pelagos Sanctuary with the detail of the borders. Boudaries: West boundary line: Punta Escampobariou (near Toulon: 43°01′70″N, 006°05′90″E)—Capo Falcone (NW Sardinia: 40°58′00″N, 008°12′00″E). East boundary line: Capo Ferro sulla (NE Sardinia: 41°09′18″ N; 009°31′18″E)—Fosso Chiarone (Tuscany coast: 42°21′24″N; 011°31′00″E).

The work focuses on the species *Tursiops truncatus* (Montagu, 1821), considered common in the Mediterranean [2–5] where it has coastal habits [4,6]. Due to this, it is subjected to strong anthropic impacts.

2. Materials and Methods

The monitoring activity was conducted from the panoramic terrace Santa Maria, Corniglia (44.11 °N, 9.70 °E). The area is easy to access and the elevated position (about 90 m·asl) allowed monitoring of a rather large area of sea. In the Cinque Terre Natural Marine Protected Area the continental shelf is very extensive: the 100 m isobath runs at an average distance of 12 km from the coast. The entire area is usually frequented by the bottlenose dolphins [5,7]. Data collection included field work, implemented through data acquisition days conducted in the May–November 2018 period, and data analysis was performed on computer.

The days chosen for monitoring were planned in weather and sea conditions corresponding to Beaufort 3 or lower and with good visibility; good weather and smooth sea are important to optimize the quality of both the photographic images collected and the radar images recorded. With wave height above 80 cm the background noise does not allow the correct identification of small targets. The radar works on the backscattering due to the ripples of the sea surface. The reflected signal produced by high waves is very intense and masks the possible presence of cetaceans [8]. Similarly, the presence of rain masks the radar signal reflected by the sea and, consequently, reduces the ability to detect targets [9].

The radar instrument has always been used for monitoring purposes. The X-band equipment used for this work is a 25 KW Consilium SRT model with a 9′ antenna, approximately 2.74 m in length. Table 1 shows the X-band radar configuration parameters.

Table 1. X-band radar configuration.

Parameter	Data Set
Radar Rotation Period (Δt)	2.45 s
Radar Image Sampling (Δx)	9 m
Minimum range	200 m
Maximum range	4.6 km
Actual Angular Sector	190°
Antenna Height Over Sea Level	60 m

A radar image (Figure 2) is a spatial representation on a color scale (from blue (weak) to red (intense), in the images presented in this work) of the intensity of the signal transmitted by the antenna and reflected by a target. The more the target (ship, coast, metal objects) is reflective, the greater the intensity of the reflected signal received by the antenna and the more its color will tend to red. Less reflective targets (marine mammals, sea, birds, etc.) will be represented with green or blue colors in the radar images present in this work.

The purpose of this work is to define an algorithm able to discriminate the common target from the cetacean starting from the consideration that the cetacean has a typical oscillatory behavior on the surface of the sea that translates, in the radar image, into a hiccup track: a track that shows an alternation of peaks and values near 0. To this end, photographic images were collected to identify the presence in the radar field of cetacean targets in addition to that of common targets. Method of target identification: starting from the radar images and camera visual observations, sub-areas (patches) of 200 $\times$ 200 pixels were extracted from the radar data containing both the cetacean target and the common target relative to a boat.

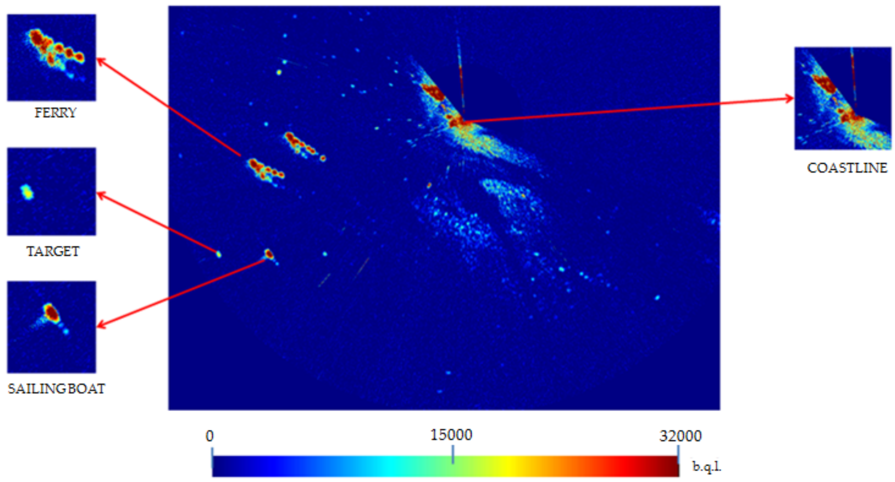

Figure 2. Example of a radar image. Various elements are recognizable on the basis of the color with which they are represented by in the image: a ferry (top left), a marine mammal (central left), a sailboat (bottom left), the coastline (top right). Below is the color scale indicating the reflectivity of the targets (unit of measure: bit quantization level, b.q.l.) and ranging from a minimum of 0 (dark blue) to a maximum of 32,000 (dark red).

During the data analysis the computing time was in real-time because the proposed algorithm is relatively simple; the required memory can be found in a basic computer with standard performance in processor and RAM. The step-by-step description of the radar data analysis algorithm (Figure 3) is shown below:

(1) Target identification on the radar images, through the photos (Figure 4); photos are essential for the presence of spatial and temporal references that ensure the target identification. To identify the patch of interest on the radar image, in addition to the photographs, the position of some spatial references near the cetaceans were detected in the field with the compass.
(2) Extraction of the sub-areas (200 × 200 pixels) containing the vessel and cetacean target (see Figure 5a,b).
(3) Maximum measurement, SM (i) (with i as image index), calculated by extracting the maximum intensity value detected for each patch of an image sequence (see Figure 5c,d).
(4) Application of a threshold on the signal amplitude of 45% to eliminate the background noise of the radar image. We used a manual thresholding method. The 45% threshold, identified by trial and error, cleans the signal from the background noise and allows correct identification of the target. The threshold was used for all data analysis.
(5) Calculation for the vector SM (i) the value of standard deviation, STDEV, and peaks frequency Fp.

Table 2. STDEV and F_P of Figure 5c (cetacean) and Figure 5d (boat).

STDEV cetacean	**FP cetacean**
6279.8	0.08
STDEV boat	**FP boat**
2294.6	0.41

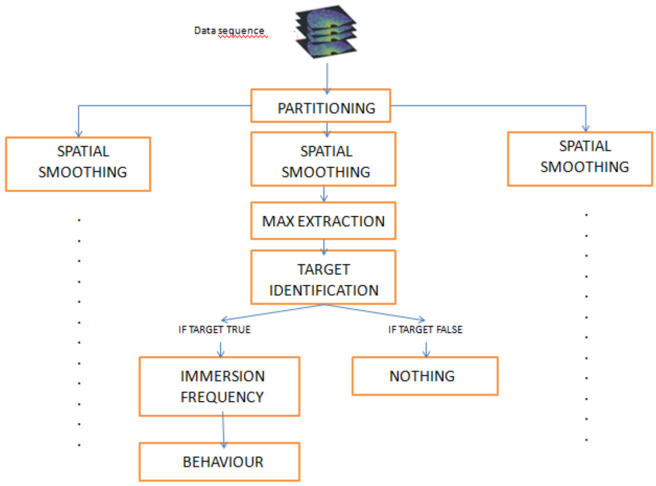

Figure 3. The figure shows the flowchart of the algorithm used for the radar data analysis. In this image the step by step data analysis procedure is shown.

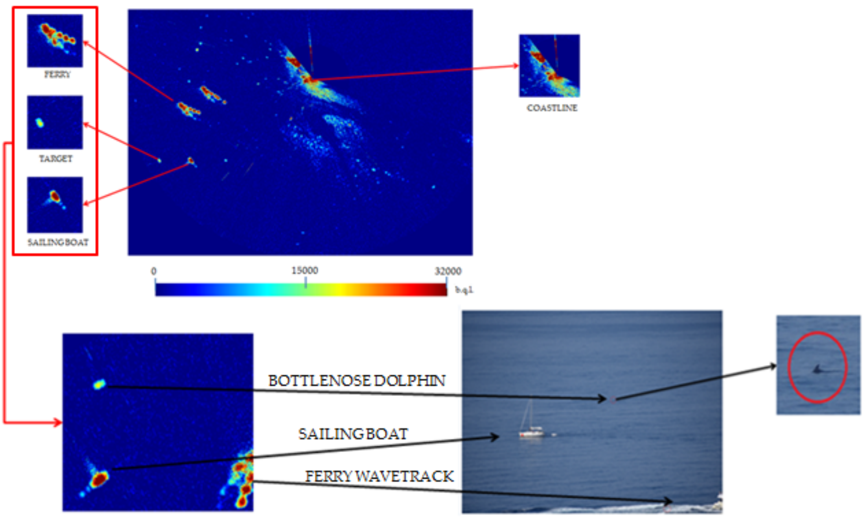

Figure 4. Practical application of the procedure reported in Figure 3. The photographs were used to recognize the targets of interest on the radar images by identifying precise spatial references.

The arithmetic mean used for calculating the STDEV was extracted after cleaning the trace from the background noise (threshold at 45%). The Fp data was normalized for the Δt, used by the radar to record two consecutive images. Both of these parameters were used as a decision maker to characterize the target and distinguish a cetacean from a boat. Due to the breathing, cetaceans immerse and emerge with a uniform frequency producing a characteristic hiccup "radar signature" that clearly distinguishes it from a boat's radar signature that is much more uniform as demonstrated by the following values of radar intensity standard deviation (STDEV) and Peak frequency (Fp) relative to the cetacean and boat (Table 2):

$$Fp = \frac{n}{i} \; / \; \Delta t \tag{1}$$

In the Peak frequency equation n indicates the total number of peaks (above threshold) produced by the target, i indicates the total number of images from which the time sequence is composed, and Δt (2.4 s) represents the time needed for the radar to record two consecutive images.

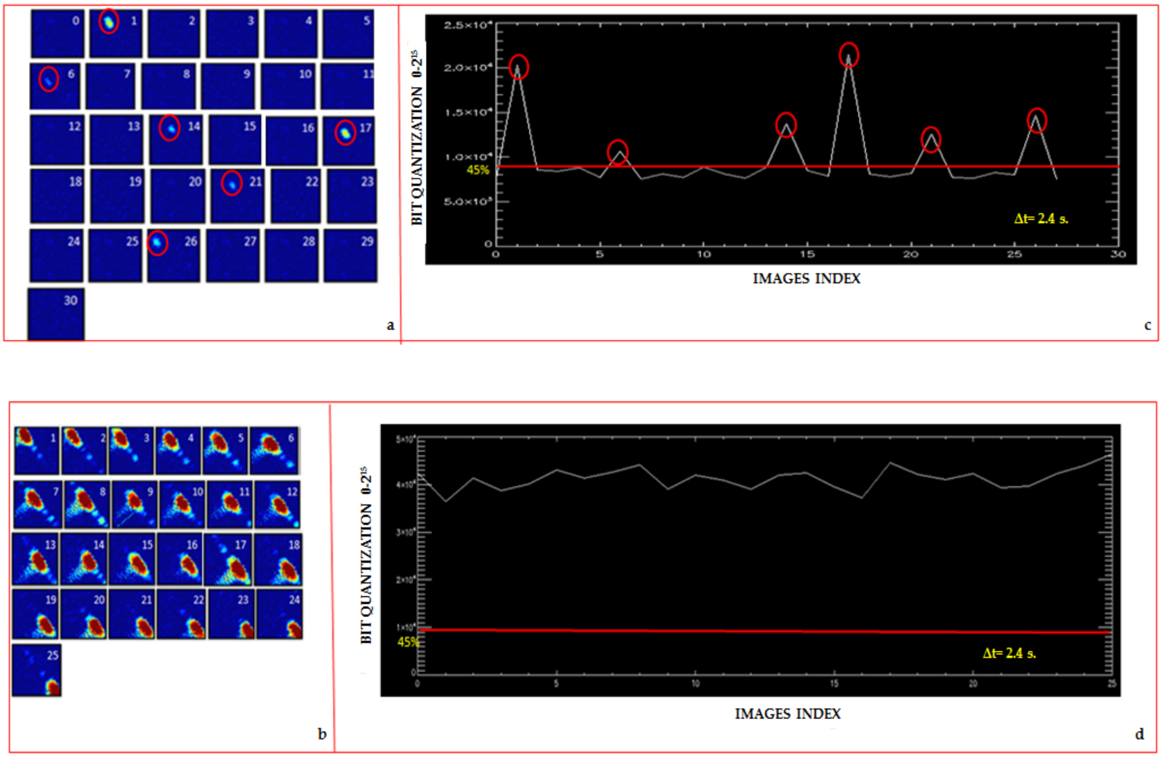

Figure 5. (**a**,**b**) show the temporal sequences of patches extracted from a sub-area of interest on the radar image shown in Figure 4. Sequence (**a**) refers to an alleged cetacean target; sequence (**b**) refers to a sailboat. Graphs 5c and 5d show the maximum measurement (SM) (I) for the both presumed cetacean (**c**) and boat (**d**) target sequences. The y-axis shows the quantization value of the radar signal (between 0 and 32,000); the x-axis shows the images index: the number of images that make up the extracted time sequence. The red line corresponds to the 45% threshold identified to clean up the radar signatures from the background noise. The Δt point at bottom right, and equal to 2.4 s, indicates instead the time taken by the radar to record two consecutive images.

3. Results

The analysis algorithm was applied to a certain number of targets, cetaceans and boats, previously identified with the camera and independent from each other. Between May and November 2018, 30 days of monitoring were carried out, about 300 h in total. There were successful sightings on 12 of the days. Only two times, during the summer months, the dolphins went very close to the coast at a distance of about 250/300 m, letting them be observed with the naked eye. About 70 individuals (adults and young) were spotted and around 10,000 radar images were recorded.

From the analysis of the radar images, 12 isolated interest targets were identified in sub-sequences. The visual comparison of the sequences and the extraction of the track led to confirm the targets as a "cetacean target" (see Figure 4). From the comparison with the common targets, it was shown that the radar detects the typical movement of alternation of the dolphin's apneas with respect to the fixed targets. Moreover it sees in a very distinct way the two types of targets: the dolphins are detected with a rather low intensity due to the organic surface with low reflecting power, while the boats and the buoys are seen with a much higher intensity since the their inorganic surface gives the object a high reflectivity.

The STDEV and the Fp values were calculated for all target tracks (Table 3). Bottlenose dolphin traces have very high STDEV values due to the continuous alternation of peaks and values close to zero (linked to the alternation of apneas). The tracks of common targets, with a lower oscillation, produce small STDEV values. The Fp produces lower values for the marine mammal traces, due to their apneas which determine a lower speed of peak formation. The tracks of common targets generate instead bigger values as objects always present in the radar field. In fact, their continuous presence determines a greater speed of peak formation because their reflexivity is constant.

Table 3. Comparison between radar signal standard deviation (stdev) and peaks frequency (fp) of the tracks recorded for t truncates and.

Experimental Name	Targets	Stdev (l.q. 0–2^{15}) [1]	Frequency (Hz) (Equation (1))
TT1	*Tursiops truncatus*	8859.15	0.09
TT2	*Tursiops truncatus*	7363.66	0.09
TT3	*Tursiops truncatus*	7219.38	0.1
TT4_TT5	*Tursiops truncatus*	4838.52	0.09
TT6	*Tursiops truncatus*	6279.81	0.08
TT8	*Tursiops truncatus*	7502.72	0.09
TT9	*Tursiops truncatus*	4874.13	0.2
B2	Fixed target	3490.66	0.41
B3	Sail boat	2294.66	0.41
B4	Fishing vessels	3863.6	0.41
B5	Sail boat	2349.22	0.41
B7	Ferry	2584.19	0.41
B8	Fixed target	3369.99	0.41

1. l.q. indicator of bit quantization level that characterizes the radar signal. This parameter is used to put a continuous signal in a scale of finite values.

The dolphin traces allowed extraction of information on the breathing times of the animals as shown in Table 4. The emersions were carried out in a time between 2 and 15 s and all the dolphins made at least 5–6 emersions before diving and disappearing from the area swept by the radar. The breathing times obtained for the registered animals are in line with what is reported in the literature: in general, the times of emersion for the bottlenose dolphin are between 2 and 15 s while the dives can last even between 8 and 10 min [10–12].

Table 4. Diving time of a bottlenose dolphin calculated from the radar track.

Bottlenose Dolphin	Dive Time (s)
Δt_1	2.41 s
Δt_2	9.64 s
Δt_3	16.87 s
Δt_4	4.82 s
Δt_5	7.23 s
Δt_6	9.64 s

4. Discussion

The X-band radar would seem to be an extremely valid and effective tool for monitoring and collecting data on the bottlenose dolphin (presence/absence, breathing times, direction of movement, bathymetry, etc.). Despite the instrument limits (optimal weather/sea conditions and distance between the targets greater than 6 m for the correct identification of the cetacean) the results obtained, although preliminary, are satisfactory. The observation of the radar images already shows clear differences between a cetacean target and a common target such as a boat or a fixed obstacle confirmed by the calculation of the STDEV and peak frequency.

An area of about 1.2/1.3 nm from the coast (lower than the overall area that can be swept by the radar: 2.5 nm) was analyzed to correctly identify the cetacean target and to obtain the maximum resolution in the images acquired. In fact, at a distance greater than 1.3 nautical miles it is no longer possible to correctly distinguish a small target. The radar's inability to perceive two targets at a distance of less than 6 m as separate implies that there is the possibility that some targets represent two dolphins swimming side by side.

For this first and preliminary work, the presence of an operator on site was necessary to validate the data recorded. The operator collected data on the species, on the number of individuals, and, when possible, on dolphin behavior. Breathing times calculated in this work accords to the data obtained from numerous authors [10–12]. Dive time analysis could give information about dolphin behavior; for example, long diving should be linked to hunting.

The distance from the coast is between 800 m and 1.5 km, confirming the predominantly coastal habits of this species in the Mediterranean Sea [4]. This coastal behavior is typical of the bottlenose dolphins which has often been observed during the summer in waters with bathymetry of less than 15 m [13–16].

Monitoring was conducted in the morning between 08:00 and 14:00. However, we cannot exclude the presence of individuals in the area even in the other time slots in the afternoon, evening, and night.

The distance of the site from which the observation was conducted did not allow us to accurately determine the behavior exhibited by the targets; only on one occasion it was possible to observe and identify dolphins in trawling (dolphins follow fishing boats to feed from nets [17–20]). This is the typical opportunist behavior of the bottlenose dolphin [21], which leads them to seek and follow food even in heavily populated and disturbed areas.

Although a manual approach was used for this work, this preliminary activity allowed us to lay the basis for the development of a completely automatic technique for identifying and tracking cetaceans. For this goal it is essential to be able to highlight differences from species both at the level of radar and behavioral tracks. Therefore, we started to work on an algorithm that lets the radar automatically detect and validate the presence of the cetacean target. Although the presence of an observer is necessary, for the moment, to validate the species, the number of individuals, and their behavior, using X-band radar for the detection of cetaceans could improve their protection. In particular to prevent collisions with boats: the capability of this instrument to work even in conditions of low visibility and/or at night could be a first alarm signal if installed near areas concerned by high ship traffic. The settings of these instruments on ferries or large boats would allow course changes, preventing collisions and reducing the noise produced by engine, and obtaining information on other cetacean species in the Pelagos Sanctuary. The recognition of the species, especially for what concerns the fixed radar stations near ports or points of intense naval traffic, can be obtained by coupling the radar detection to presence of hydrophones. In fact, every cetacean species emits characteristics and distinct sounds. The results obtained in this work are directed towards the implementation of the X-band radar capabilities. A single instrument capable of collecting interdisciplinary data would allow working simultaneously on multiple scientific fronts, reducing costs.

5. Conclusions

This experiment represents a new field of study through which monitoring the presence of marine mammals in the Mediterranean sea is possible, supporting the direct collection of data and cost reduction too. Although the results obtained in the six months of work represent only a preliminary analysis of the problem, they are encouraging and would seem to demonstrate the validity of the project and above all the potential that this device can offer in the field of cetacean monitoring and in understanding their behavior. During this work 12 dolphins were recognized in the radar images and, despite the small number of identified targets, they showed clear and recognizable differences compared to other targets like sailing boats or ferries.

To improve this goal, it will be necessary to continue the work starting from the results obtained and extend it to longer periods of time to collect a larger amount of data that is needed to refine the analysis of images and radar tracks. The extrapolation of a greater quantity of biological information is essential to create a non-exclusive automatic identification algorithm for small cetaceans, but which allows the radar to discriminate between small and large cetaceans.

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