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Estimation of positioning error from an array of automated omnidirectional receivers in an artificial reef area

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Abstract

Artificial reefs (AR) have been shown to harbour increased numbers of fish compared to adjacent areas. To assess whether this is due to attraction through artificial structures or providing permanent habitat for the occupants, the behaviour of fish within ARs needs to be examined in more detail. Automated omnidirectional receivers and miniaturized pingers were applied to determine the hydrophones' detection range and study the variability of detections recorded at different distances, and to estimate pinger positioning error throughout the AR study area. Throughout the study site, positioning design and respective detection ranges of five receivers created 17 regions of overlap between two to five receivers. The detection range of the hydrophones was found to be 500 m. Weighted means of modified detection numbers were used to calculate the pinger's position in the study area. Pinger positioning error (Pe) was defined as the distance between the calculated geographical coordinates and the real ones. The artificial reef characterization results showed that the position error is related to the number of receivers overlapping. Minimal positional error was found in regions with four and five overlapping receivers (Pe is 54±24 m). The "barrier effect" of an artificial structure on signals detection depends on the distance between obstacle and transmitter. The omnidirectional hydrophones were unable to record any signal when the pinger was set inside the artificial structures. But, when the pinger was at least 1 m outside the pyramid, the positioning accuracy was found to be 132±54 m.

Introduction

Artificial reefs (AR) are submerged structures placed on the seabed deliberately, to mimic some characteristics of a natural reef (Jensen, 1998). They are being used worldwide for multiple purposes, but aim mainly at increasing fish production and protecting sensitive habitats (Bombace, 1997; Santos *et al*., 1997). For three decades, scientific literature has been reporting successes and limits of AR but the question whether they contribute to attract or produce new fish biomass is still unresolved (Bohnsack, 1989; Lindberg, 1997). The attraction–production debate has provided the impetus to start studies dealing with the ecological processes (Miller, 2002) and fish behaviour (Santos *et al*., 2002; Relini *et al*., 2002; Workman *et al*., 2002) in the artificial reef areas with the employment of more efficient monitoring techniques.

Since 1950s, telemetry has been considered a powerful tool consisting in the attaching of transmitters to animal bodies and "tracking" them in their natural environment by means of hydrophones (Ireland and Kanwisher, 1978). Generally, telemetric techniques have been employed for studying behavioural ecology (migration, home-range, habitat utilization, activity and movement, etc…) of marine and freshwater animals in different habitats (Bégout and Lagardère, 1995; Bridger *et al*., 2001; Taverny *et al*., 2002). The usefulness of tracking and habitat-use-data in telemetric studies depends on the accuracy and precision of tagged fish location estimates. Biased location estimates are often the result of the presence of physical obstacles (e.g. submerged vegetation, bottom topography) and of the oceanographic conditions (e.g. water flow, thermocline, turbidity) (Pincock and Voegeli, 1990). Hence, telemetry studies should be preceded by accuracy and precision assessments (Braun *et al*., 1997).

Low cost automated receivers are commonly deployed to study habitat utilization, by using simple presence/absence data within the range of each receiver (Klimley *et al*., 1988; Heupel and Hueter, 2001; Bridger *et al*., 2001; Lacroix and Voegeli, 2000; Voegeli and Starr, 2000; Voegeli *et al*., 2001). Recent application, based on overlapping automated receivers detection ranges, has increased the accuracy in locating fish throughout small areas (Arendt *et al*., 2001). Simpfendorfer *et al*. (2002) estimated tagged fish location by means of an algorithm which uses the number of detections recorded by the overlapping receivers. The authors also highlighted the importance of a correct arrangement of receivers throughout the study area to increase the positional accuracy. However, an unsolved question remains on the limit of accuracy of location estimates of this telemetric system, due mainly to the interference effects of natural (Simpfendorfer *et al*., 2002) and artificial obstacles on signal detection.

The Gulf of Castellammare (NW Sicily) is one of the largest Italian artificial reef area. Studies on the AR of the Gulf, have provided data on benthic and fish assemblages, the trophic relationships and the fishing yield, but no study has been aimed at the movements and activities of the AR fishes (Badalamenti *et al*., 2000). Few papers deal with the application of ultrasonic telemetry in the artificial habitats mainly due to the interference of the artificial structures on signal propagation (Collins *et al*., 2000; Smith *et al*., 2000).

In 2000, a research program started with the final goal of studying long-term fish movement by means of an array of automated omnidirectional receivers (D'Anna and Badalamenti, 2003).

In this paper we present the results of the application of automated omnidirectional receivers, aimed to:

1. determine the hydrophone detection range and study the variability of the number of detections recorded at different distances (Free-Water characterization);
2. estimate the positional error of calculated pinger positions throughout the study area, quantifying the interference effect of the single artificial structures (Artificial Reef characterization).

Materials and methods

Study site

The Gulf of Castellammare (Fig. 1) is a broad, crescent-shaped bay on the NW coast of Sicily (38° 03' N, 12° 52' E). The sandy seabed of the central gulf part is interrupted by the presence of *Cymodocea nodosa* patches (12-14 m depth) and two artificial reef areas. The largest artificial reef, chosen as the study site, is located off Alcamo Marina, 1 km offshore. In this area, 27 artificial structures are distributed over an area of 0.2 km^2 at depths between 14.5 and 21 m (Fig. 3). Each structure is built as a three-layer pyramid of 14 concrete blocks (total volume 150 m^3) (Badalamenti *et al*., 2002).

Five automated omnidirectional VR2 receivers (Vemco Ltd, Halifax, Canada) were deployed in the study area. Coded V8SC-1L, ultrasonic transmitters were deployed at known locations to assess the detection range of the hydrophones and accuracy of calculated positions upon number of detections.

Free-Water Characterization

To analyse the variability of the number of detection (*Nd*) versus the distance and to determine the hydrophones' detection range, an unobstructed line-of-sight (termed "Free-Water") between receivers and pingers was used.

Detection range & *Nd* variability – A total of 10 replicates were carried out, during which the environmental conditions were measured. Samples carried out during thermocline conditions and high water turbidity were not considered for the analysis. Size of Δt was fixed to 25 minutes, as a result of pre-survey tests upon pinger variability in the signal emission time (D'Anna and Badalamenti, 2003). Five hydrophones acoustic receivers were independently suspended 15 m from each other,

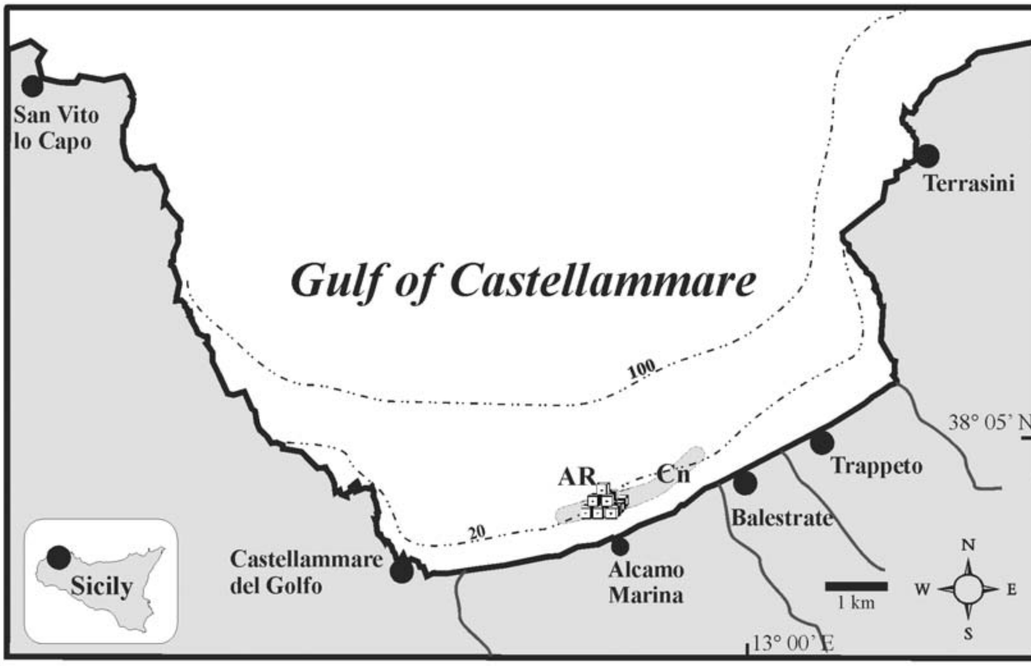

Fig. 1 – Map of study site in the Gulf of Castellammare showing the Artificial Reef (AR) area and the *Cymodocea nodosa* (Cn) patches

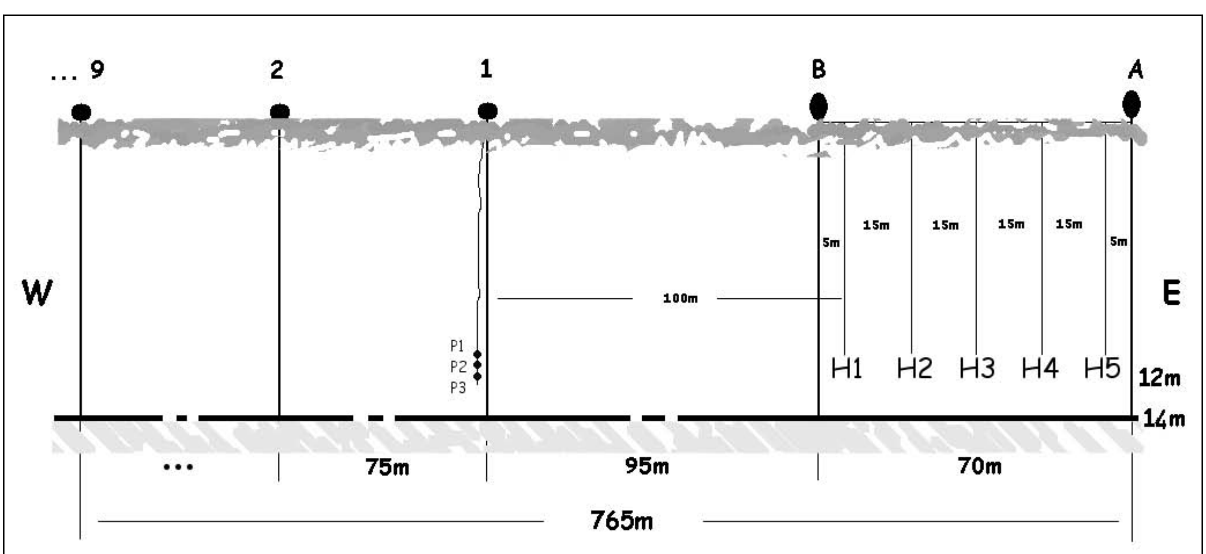

Fig. 2 – Sampling design for Free Water experiments. W = West, E = East; A, B, 1, 2,...9 = surface buoy; H1,…H5 = Hydrophones; • = Pinger (P1, P2, P3)

from east to west at a depth of 12 m (2 m above the seabed). Starting at 100 m from the westernmost receiver, 3 transmitters were suspended at the same depth for 25 minutes and moved to the west at consecutive distance intervals of 75 m (Fig. 2). During each trial 45 *Nd*-distance couples were recorded. The average *Nd* values from each pinger at different distances were tested with a two-way ANOVA using pinger (three levels) as random factor and distance (30 levels) as a fixed one.
ANOVA was carried out using "Gmav5" software after checking the homogeneity of variance with Cochran test. When differences were found, a-posteriori comparisons were made using the Student-Newman-Keuls (SNK) test (Underwood, 1997). A 10 percent detection threshold was chosen to assess the hydrophone detection range.

Artificial Reef Characterization

Three experiments were performed in order to estimate system error in calculated pinger position when placed (i) in the centre of each region of overlap (Study area tests), (ii) randomly inside the artificial reef area (Artificial reef area tests) or (iii) close to (out/inside) a single artificial reef structure (Pyramid "barrier effect" tests).
Based on the free-water experiments results, five receivers were deployed around and inside the artificial reef area (0.2 km^2) (Fig. 3). Each receiver was moored 2 m above the seabed, fixed to a thin rope anchored with a 4 kg lead barrel. A submersible plastic float was attached 3 m above the receiver to help it maintain a vertical orientation in the current, while a buoy was attached to the rope at the surface. The first receiver, called "C", was moored in the centre of the artificial reef area. The other receivers, labelled "N", "S", "E" and "W", were located 400 m, North, South, East and West of "C". This configuration resulted in the creation of 17 regions of overlap between two to five receivers and four zones, each unique to a particular receiver (N, S, E and W), covering a total area of 1.5 km^2.
Each recorded number of detections during Δt was replaced with the mean value of the respective *Nd* class according to free-water experiment results.

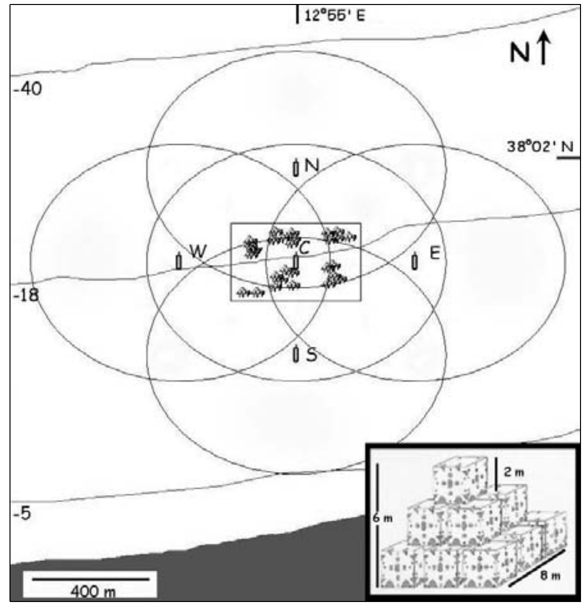

Fig. 3 – Receiver positioning design: circles represent the receivers (C, N, E, S, W) detection range, the square indicates the artificial reef area. In the corner a schematic picture of a single artificial pyramid.

The following weighted arithmetic mean was used to calculate the X- and Y- geographical coordinates of the pinger positions:

$$\overline{X}_{\Delta t} = \frac{\sum_{i=1}^{n} Nd_i X_i}{\sum_{i=1}^{n} Nd_i} \qquad \overline{Y}_{\Delta t} = \frac{\sum_{i=1}^{n} Nd_i Y_i}{\sum_{i=1}^{n} Nd_i}$$

where n is the number of receivers, *Nd* is the replaced number of detections for the *i*th receiver during Δt, X_i and Y_i are the X and Y coordinates of the *i*th receiver (based on Simpfendorfer *et al*. 2002). The pinger positioning error (Pe) was defined as the distance (in meters) between the calculated geographic coordinates and the recorded ones.
In all the experiments, a maximum of four pingers were used at the same time in order to avoid any code collision events (Lacroix and Voegeli, 2000). Pingers were independently attached to a thin rope, 2 m above the seabed. A 2 kg lead weight barrel

was useful to prevent drifting. A sub-surface styrene float and a little white buoy were attached to the rope, 2 m above the pinger and on the sea-surface end respectively. A 25-minute time interval was chosen for each position in all tests.

A multi-probe and currentmeter were used to verify that the experiments were carried out under similar environmental conditions of those carried out in the Free-Water characterization. A non-differential handheld Global Positioning System (Garmin GPSII-plus) was used to locate pingers throughout the study area.

Analyses of variance of Pe estimates were carried out using "Gmav5" software after checking the homogeneity of variance with Cochran test. When differences were found, a-posteriori comparisons were made using the Student-Newman-Keuls (SNK) test (Underwood, 1997).

Study area tests – To estimate calculated position accuracy in overlapping areas the pingers were deployed in the centre of the 17 regions of overlap and Pe was calculated for each position. In order to detect differences in Pe between the overlap regions, an equal number of Pe values per region were randomly sorted (12) from the database then, a one-way ANOVA was applied with the factor location, fixed and orthogonal, and four levels (2, 3, 4 and 5) overlapping receivers.

Artificial reef area tests – We estimated the artificial structures' influence on position accuracy with pingers placed close (3 m) and far (at least 10 m) from the pyramids. Pe estimates from pingers located close to and far from the pyramid, were compared with one-way ANOVA with the factor location, fixed and orthogonal, and two levels (close and far).

Pyramid "barrier effect" tests – The most central pyramid with regards to each of the peripheral receivers was chosen to test whether the system was able to detect transmitters inside the pyramid. First, a scuba diver placed a pinger 1 m from each side of the pyramid. Then, the pingers were moved inside the pyramid among the concrete blocks. We then compared the estimated positioning error when the pinger was outside and inside the pyramid. This procedure was repeated 3 times.

Results

Detection range and Nd variability

The hydrophones' detection range was found to be 500 m (*Nd*=10 percent). Distance intervals over 535 m were not consider for ANOVA test because *Nd* values recorded were always under the 10 percent threshold. Significant differences (p<0.001) were found between distance intervals, while non-significant difference was found among pingers (p=0.96) and for the interaction between pingers and the distances (p=0.77). Post-hoc pairwise comparison highlighted five groups of distance intervals within which *Nd* does not vary significantly. The first group includes distances in the range between 0-265 m, the second group 266-310 m, the third 311-415 m, the fourth 416-490 m and the fifth group 491-535 m (Fig. 4). For each group, an averaged *Nd* value was calculated as shown in Table 1.

Table 1 – For each distance group, distance ranges and number of detection (*Nd*) class were found. Mean *Nd* values were calculated for positional estimation algorithm.

Distance group	1	2	3	4	5
Distance range (m)	0-265	266-310	311-415	416-490	491-535
Nd class	23-18	17-15	14.8	7.4	3.1
Mean *Nd*	21	16	11	6	2

Study area tests

The highest values of Pe were estimated in regions with two overlapping receivers (269±158 m), the lowest in the region with five overlapping receivers (36±32 m) as showed in Table 2. Pe among different overlap regions differs significantly (ANOVA, p<0.001). The Student-Newman-Keuls test showed that Pe values were equal in regions with 2 and 3 and with 4 and 5 overlapping receivers, with 2=3 > 4=5.

Table 2 – Mean values of Positioning error (Pe) and standard deviations (s. d.) calculated for each overlap region.

overlap with	Pe (m)	s. d.
2 hydr/5	269	158
3 hydr/5	197	139
4 hydr/5	71	57
5 hydr/5	36	32

Artificial reef area tests
Positioning error of pingers located close and far from the pyramid was 130±59 m and 54±24 m respectively. ANOVA found significant differences (p<0.001) in Pe between the two locations.

Pyramid "barrier effect" tests
All receivers recorded *Nd*=0 when the pinger was inside the artificial structure and no estimated position and Pe were calculated.

When the pinger was placed outside the pyramid at a distance of 1 m from the blocks, Pe=132±54 m and the receiver on the opposite side of the pyramid with respect to the pinger, always recorded *Nd*=0.

Discussion

The results presented in this paper demonstrate that, using an appropriate arrangement of the receivers, it is possible to estimate the low-cost automated receivers' error in locating transmitters in an artificial reef area. Simpfendorfer *et al.* (2002) used an automated receiver system to estimate the location of tagged animals.
They applied an arithmetic mean of each receiver's geographic coordinates, weighted by the *Nd* recorded at a fixed time interval. However, that calculation algorithm is based on the assumption

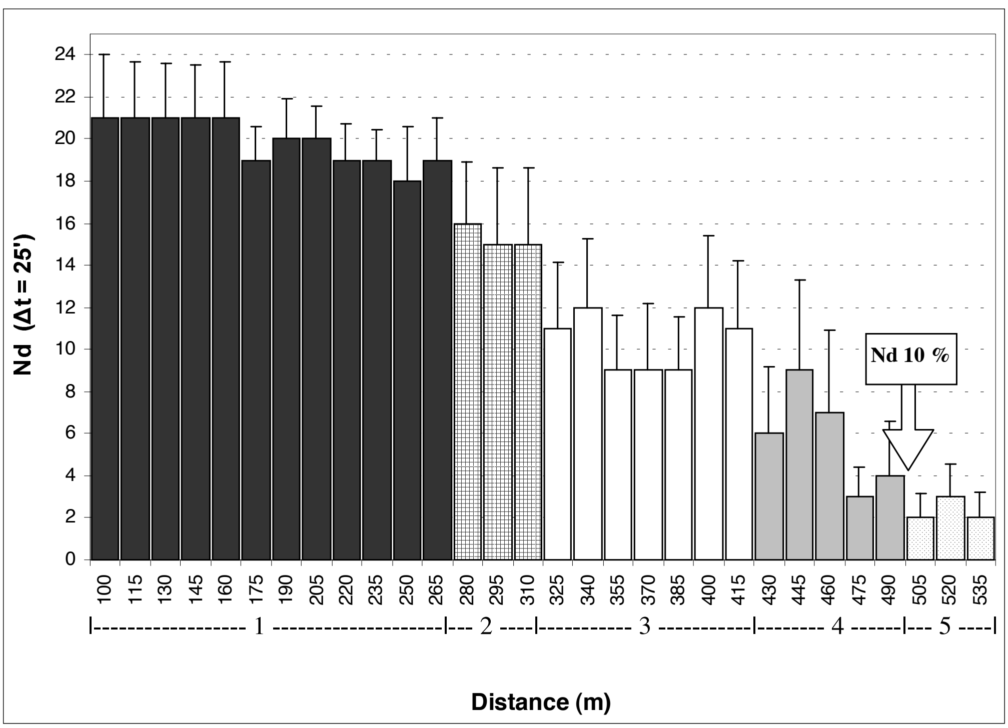

Fig. 4 – *Nd* means and standard deviation (s.d.) recorded at 15 m distance intervals. 1, 2, 3, 4, 5 = distance groups from Student-Newman-Keuls analysis.

that a linear relation exists between *Nd* and distance from receivers even if the inverse-square law precisely relates sound intensity to distance from the transmitter (Ireland and Kanwisher, 1978). Moreover, a previous study conducted in the Gulf of Castellammare, confirmed a non-linear relation between the number of detections (*Nd*) recorded in a fixed time interval (Δt) and the distance between pingers and receivers (D'Anna and Badalamenti, 2003).

In fact, many environmental factors can strongly affect the *Nd*-distance relation, modifying the ultrasonic pulses strength and spreading (Pincock and Voegeli, 1990). Within a receivers array, the acoustic wave from transmitter creates different lines-of-sight for each receiver. Each line-of-sight could be differently affected by the intensity of single factors (i.e. water flow, submerged vegetation, presence of a fish shoal or artificial structures). As a consequence, two hydrophones would record different *Nd* values even if the pinger was located at the same distance from them. In this case, assuming a linear relation between *Nd* and distance, those values will correspond to different distances and their weight in the calculation algorithm will reduce the positional estimates accuracy. For this reason, we adopted the arithmetic mean *sensu* Simpfendorfer (2002) to calculate the pinger's geographic location but we applied a modification to the number of detections based on our *Nd* variability study. The main advantage is that different *Nd* values that are included in the same distance group are replaced by the *Nd* mean value of that group so that they have the same weight in the calculation algorithm. This finding represents a new approach in calculating the geographical coordinates of pinger positions taking into account the variability in the number of detection due to environmental factors effect.

The recognition of the importance of a correct receiver arrangement throughout the study area and of the resulting effects on the power of any telemetric system, has been highlighted by many authors (Stasko and Pincock, 1977; Lagardère *et al*., 1996; Braun *et al*., 1997; Simpfendorfer *et al*., 2002). The first application of a specific receiver placement design was based on the overlap between two receivers (Arendt *et al*., 2001). The authors created two reception zones, one for each receiver and a third common reception zone resulting from the overlap of the two receivers. Tagged animals were located by the receiver(s) that could detect any single pinger signal. This receiver arrangement contributed in reducing the area where the animal could be located.

The optimal receiver arrangement will vary depending on environmental characteristics of the study area and on the objective of research. In our case, with the presence due to artificial structures, increasing habitat complexity was likely to affect signal detection (McLeave, 1978; Matthews *et al*., 1990; Pincock and Voegeli, 1990; Smith *et al*., 1998). Our receiver placement design created seventeen overlap regions. This allowed us to locate pingers throughout the whole study area and, above all, to evaluate how Pe can be reduced through the increase of the number of overlapping receivers. In fact, in a region with five overlapping receivers, Pe was less than 85 percent when compared to Pe calculated in regions with only two overlapping receivers. The high values of Pe estimated in regions with two overlapping receivers (Pe=269 m) is due to a limit of the algorithm. In fact, the mean-position estimates always fall within the minimum convex polygon (MCP) described by the receivers location (Simpfendorfer *et al*., 2002). Thus, if we deploy a pinger outside the MCP, as in the case of our experiment (Fig. 3), the algorithm will locate it as if it was inside the MCP. This increases both the mean and the standard deviation values of Pe.

Another advantage of our receiver arrangement is that the AR area coincides with the region of highest overlap (four and five receivers, see Fig. 3). Our tests, conducted in the AR area, demonstrated that it is unlikely to detect pingers placed inside a pyramid. The limitations of such a system to detect signals, when the pinger is placed directly inside a physical structure, has been documented by other authors in previous studies (Matthews *et al*., 1990; Collins *et al*., 2000; Smith *et al*., 2000; Connolly *et al*., 2002). Nevertheless, when the pinger was placed 1 m outside the pyramid, its geographic location was calculated with Pe=132±54 m. This value decreased significantly to 54±24 m when the pinger was placed at least 10 m away from any artificial structure. The difference between these Pe values (78 m) can be named as the "barrier effect" of artificial structures.

The results of this demonstrative study can represent the base for future long-term research on fish activity patterns, home-range, and their use of artificial structures. The correct arrangement of high-overlap-based receivers, the temporal sequence of locations and the knowledge of positioning error estimates, could be helpful in discriminating different positions of tagged animals: (i) inside/outside the AR area, (ii) inside/near/outside a single structure. All this information could also contribute to better understand the role and the efficacy of artificial habitats.

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