Experimental research and fish aggregating devices (FADs) in French Polynesia

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by P. Bach [1], L. Dagorn [1], E. Josse [2], F.-X Bard [1], R. Abbes [3], A. Bertrand [2] & C. Misselis [3]

Introduction

Floating natural or man-made objects are often encountered at sea. Fishermen themselves deploy such devices because they know that small or large pelagic fish are likely to gather around them and that fishing there is likely to be productive. Artisanal fleets in South-east Asia have been using this technique to catch small pelagics for many years. Where the larger pelagics are concerned, purse-seine fishing around floating objects has intensified over the past 20 years in all the world's oceans. Fonteneau (1992), in a review of tuna fisheries, wrote that the main area in which fishing is carried out around floating objects is the western central Pacific, where catches associated with such devices account for approximately 50 per cent of landings. In 1995, 42 per cent of the French purse-seine catch and 65 per cent of Spanish purse-seine landings in the Atlantic Ocean came from fishing around floating objects. These figures rise to above 70 per cent in the Indian Ocean (Stretta et al., 1996).

Fish aggregating devices (FADs) moored near the coast are an aid to artisanal fleets targeting large pelagics such as tunas in many island states. Historically, the FAD testing area of the 70s was the Pacific, with the guidance of the South Pacific Commission. As was stressed by Holland (1996) in this bulletin, FADs are now used world-wide to support or develop artisanal or sport tuna fisheries. French Polynesia began its FAD deployment programme in 1981. Technological progress on materials, giving moorings a longer lifespan, has had an impact on the programme. The latest type of FAD used in French Polynesia was recently discussed (Leproux & Desurmont, 1996) in this bulletin.

Scientists have been recording observations on tuna behaviour near FADs for about the past 10 years (Cayré & Chabanne, 1986; Holland et al., 1990a, 1992; Cayré, 1991; Cayré & Marsac, 1993; Marsac et al., 1996). Whatever the merits of observing, however, understanding is better. Despite the extensive experimental work already carried out in all the world's oceans and consequent wealth of available information, Holland (1996), concluded that a great deal remain to be learned on the mechanisms (including the role of biological factors) affecting the relationship between tunas and FADs.

Why do tunas aggregate around FADs? How long do tunas remain near FADs? Why do some FADs seem to be more effective in attracting tunas than others? These are some of the questions facing scientist from EVAAM [4], IFREMER [5] and ORSTOM [6], who are working together in the ECOTAP [7] programme in Tahiti.

These issues affect the resource at various levels of perception (individual specimen, school, aggregation) and on various time-scales from one day to

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7. ECOTAP: Étude du Comportement des Thonidés par l'Acoustique et la Pêche (Tuna Behaviour Study through Acoustics and Fishing)

several months. To find the answers to these questions, science needs to call upon a range of tools and methods: sonic tagging, active acoustics, coupling of sonic tagging and active acoustics, Artificial Life modelling.

Initially, this paper will discuss the two main tools used by the ECOTAP programme: ultrasonic telemetry and acoustic surveys. These tools were either used separately or together depending on the goals of the activities concerned. The second part of the paper will address implementation methods, with some comments on the initial results being given in each case. Lastly, some planned analytical and experimental work will be discussed.

Tools used as part of the ECOTAP programme

Sonic tagging

The first fish tracking by sonic telemetry was carried out in the late 50s (Trefethen, 1956 in Yuen, 1970). Much more research has been carried out for the purpose of describing fish movements in their natural environment since that time, through the rapid development of telemetry, in other words, the distant transmission of a signal carrying the result of measurement work, which has been made possible by technological progress achieved in electronics and in particular the miniaturisation and improvements in the range and lifespan of transmitters.

Since the work carried out by Yuen (1970) on tunas, many sonic tagging experiments have been performed out in all the oceans. Holland (1996) has produced a synopsis of the results so far published of tuna tagging near FADs (Cayré & Chabanne, 1986; Holland et al., 1990a, 1992; Cayré, 1991; Cayré & Marsac, 1993; Marsac et al., 1996).

Under the ECOTAP programme, tuna tracking by sonic telemetry was performed using two different devices.

The first, which was used in the first series of experiments, comprised a VEMCO V-10 bearing (directional) hydrophone fitted to a paravane towed by the boat. This hydrophone was connected to a VEMCO VR-60 decoder which converted the value of the raw signal transmitted by the tag into the value of the variable measured (depth, in the case of our experiments). The boat position was recorded on a global positioning system (GPS) receiver every five minutes.

Concerning the second, which has been in use since 1996, signal reception was by the "VEMCO V-41 Bearing Hydrophone" system fitted to a towed paravane. In this case, four basic hydrophones, each having its own listening angle, were used. Four zones were defined for the horizontal plane: forward, rear, port and starboard. All the hydrophones were connected to a VEMCO VR 28 receiver by an electromechanical cable. This receiver was equipped with a control module making it possible to select which of the four areas was to be listened to. The receiver was connected to a micro-computer through an RS232 link. This micro-computer was also connected to a GPS through a second RS232 link.

The "TRACK" software package used on the micro-computer made it possible to record:

- signals transmitted by the tag and decoded by the receiver every second, and
- GPS data every five seconds.

Two methods were used to attach the tag to the fish. The most widely used method for tunas, which has been described in this bulletin by Holland (1996) involves attaching the tag using two nylon straps inserted through the muscle behind the dorsal fin. This method is difficult to use on specimens weighing over 30 kg. In such cases, it is preferable to tag the fish in the water in the same way as with billfish (Holland et al., 1990b; Brill et al., 1993). The sonic tag is attached to a flexible tag developed as part of a billfish tagging experiment. A pole with a stainless steel arrowhead is used. The hydroscopic nylon head of the hollow flexible tag is pushed through the fish's muscle by means of the arrowhead. A ring fitted to the pole two or three centimetres behind the tip acts as a stop, preventing the nylon head from penetrating too far. A rubber band secures the tag to the pole to prevent it being misplaced during preparations for tagging (Figure 1).

Active acoustics

There are two different main acoustic survey methods:

- active acoustics where the basic information comes from the echoes returned by the targets from a signal generated by the sonic equipment, and
- passive acoustics performed by analysing noises spontaneously emitted by organisms or the environment.

The use of active acoustics to detect fish (acoustic surveys) was first referred to in the scientific literature in 1929 (Kimura, 1929 in Johannesson &

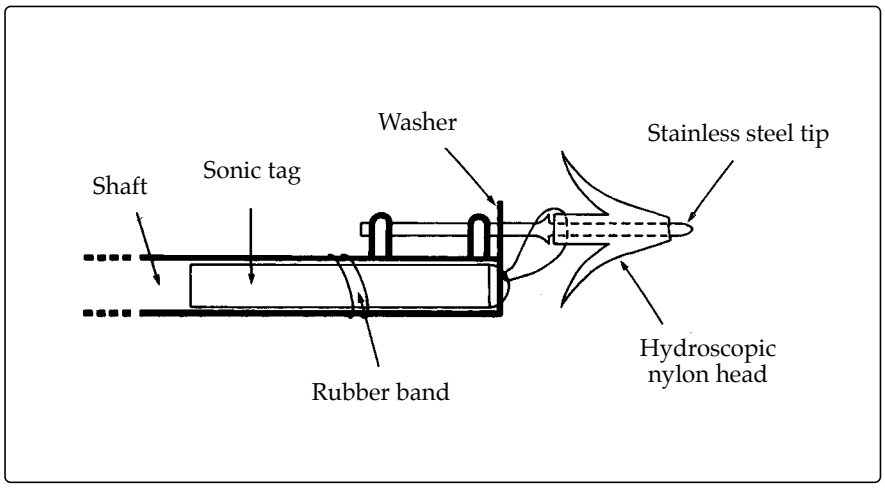

Figure 1

Sonic tag attachment device for specimens weighing over 30 kg

Mitson, 1993). Not until the 1960s did the first electronic integrators appear, making it possible to process fish echoes (echo-integration). Quantitative fish stock estimates then made rapid progress (Johannesson & Mitson, ibid.). There are various types of sounders which differ in their operating principles and the kind of information they collect.

Only vertical sounders were used in the ECOTAP programme. The Biosonics 102 model, using two frequencies, 38 kHz and 120 kHz, was used first either in normal mode (single beam) to make quantity assessments or in dual beam mode to determine the target strengths (TS) of individual subjects. The echo-integration data collected with the Biosonics sounder were analysed using the INES-MOVIES software package (Diner, 1990). From 1995 onwards, observations were carried out with a SIMRAD EK500 sounder, operating on two frequencies, 38 kHz and 120 kHz. This is a compact sounder including an echo-integration module and a TS analysis system. The 120 kHz transducer is a single beam transducer whereas the 38 kHz is a split beam transducer.

Results of some experiments

Movements of tunas tagged near FADs

Tuna tagging experiments near FADs in French Polynesia began in November 1985 (Cayré & Chabanne, 1986) and continued in 1992 as part of the EVAAM FAD programme, in 1993 as part of the ECOTAPP experimental programme (Abbes et al., 1995) and then in 1995 under the ECOTAP programme. Nine tunas have been tagged near FADs since 1992 (8 yellowfin, *Thunnus albacares* and 1 bigeye, *Thunnus obesus*), four of which are the subject of this report. Three involved conventional ultrasonic tagging while the fourth was an association of acoustic survey and ultrasonic tagging.

Yellowfin tagged on 2 September 1992

A yellowfin tuna 48 cm in fork length was caught by trolling near a FAD located 20 nautical miles (nm) east-south-east of the Tahiti peninsula (see Figure 2 on next page). Tagged in the morning (09:11, local time), this fish was tracked for almost 28 hours. After being tagged, this fish stayed close to the FAD for approximately four hours before heading south (between 12:30 and 16:30) then south-west (from 16:30 to 18:00). At sunset, it was located 1.5 nm from the FAD and then veered west and subsequently north. It then started swimming back towards the FAD, which it swam past at a distance of 0.5 nm, before exploring the zone to the north of the device.

From the middle of the night to dawn, this animal's horizontal movements were not very extensive in an area which it would again favour in mid-morning, after a period of rapid movements towards the FAD. The fish was lost at 11:11 and then relocated two hours later at the FAD. During the tracking period (28 hours) the fish did not move more than 2.1 nm away from the FAD.

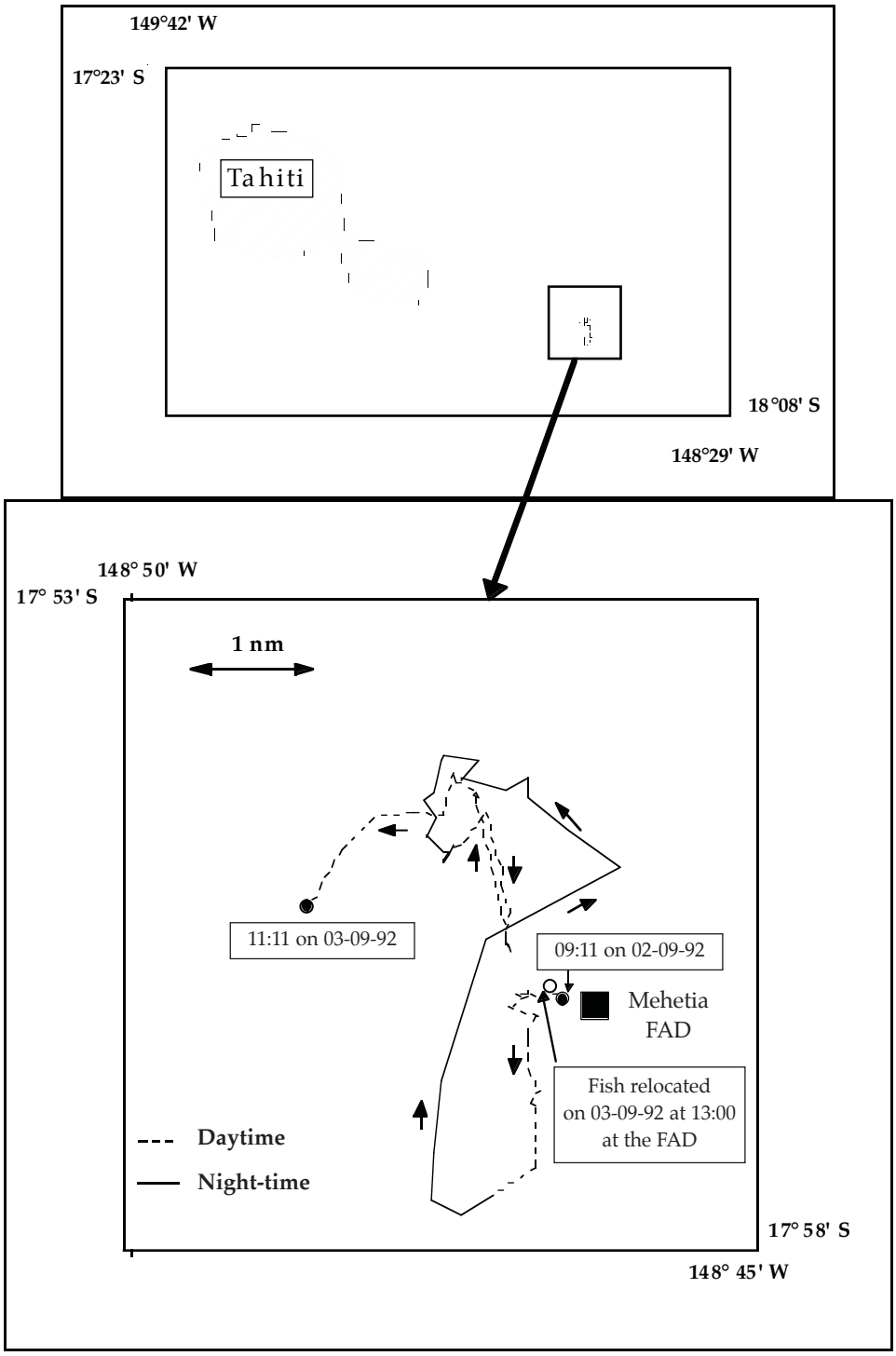

Figure 2

Horizontal movements of the 48 cm fork-length yellowfin tuna tagged on 2 September 1992 and tracked for 28 hours

Vertical movements during the diurnal phase were mostly limited (between 180 and 260 m) except two brief deep dives to 430 m in the morning and 470 m in the afternoon (Figure 3). The fish moved up nearer the surface early in the night (50–120 m) before commencing a phase of wide depth variations (50–250 m). During the morning of the second day, the fish remained between 150 and 250 m, in an identical manner to the first day.

Yellowfin tagged on 2 March 1993

A yellowfin tuna 51 cm in fork length was caught on a trolling line near FAD no. 165 (Punaauia FAD) located 5.2 nm from Tahiti's west coast (see Figure 4 on next page). This specimen was tagged at 18:35 (local time) and tracked for approximately 64 hours. It left this FAD just after being tagged and swam parallel to the coast for the first night towards FAD no. 179 (Paea FAD) located 6.4 nm from the previous one. Little movement was recorded between 09:30 and 12:30, and the fish remained within a semi-circle 1.5 nm in radius from the FAD. In the middle of the day, its movements turned southwards towards a third FAD (FAD no. 170, known as the Papara FAD) located 9.2 nm from the second and 15.6 nm from the first. It continued swimming towards this FAD all night to reach a point approximately 0.8 nm from it at first light. During the day and in the early evening, it remained relatively far from the FAD, returning towards it in the middle of the night (maximum distance from the FAD = 7.8 nm).

Early in the morning (07:00 local time), it was located under the FAD and remained there until 09:30 when tracking ended. A synopsis of these results reveals that the fish swam between the FADs on the first two nights and came back to the third FAD during the third night, having swum away from it at the end of the second day. The diurnal phases were spent in areas close to FADs.

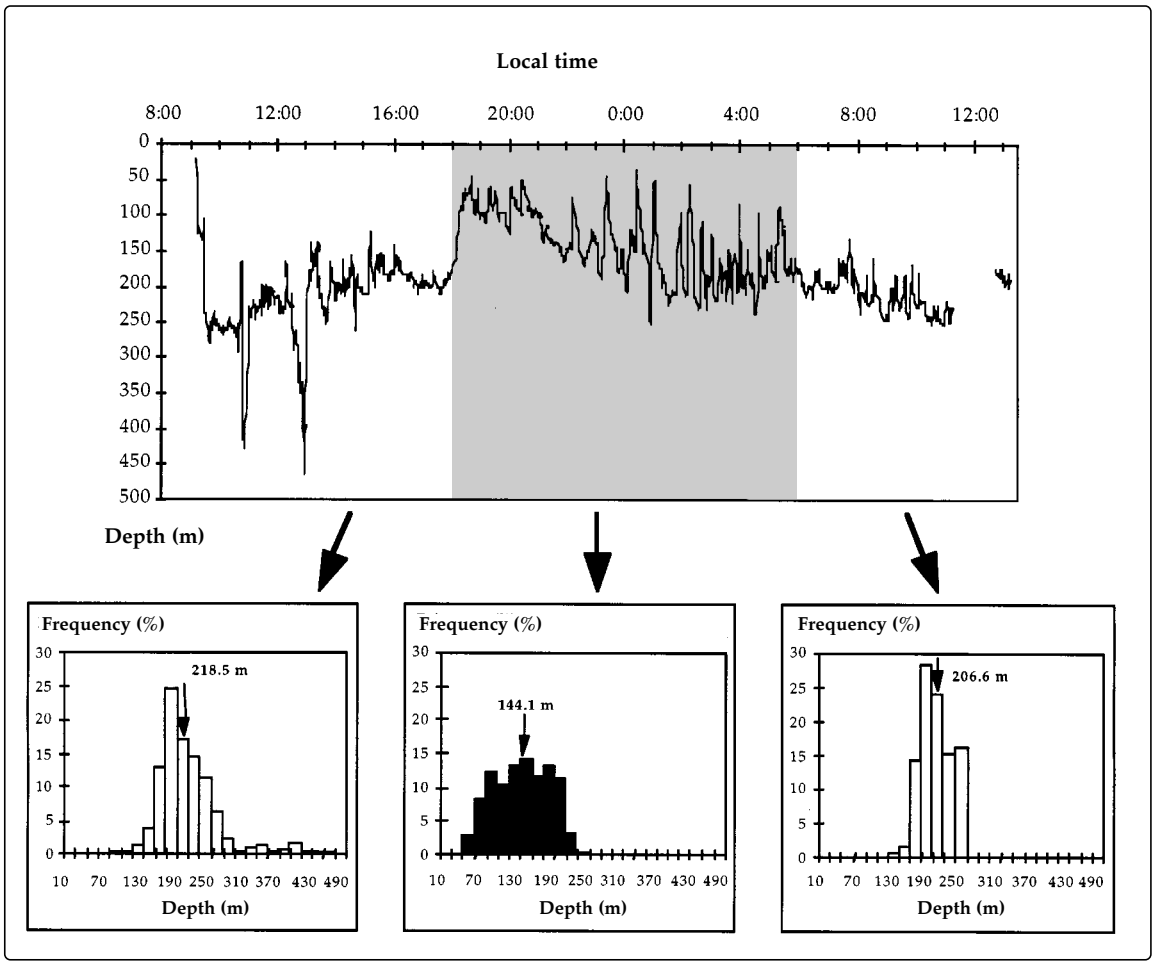

Figure 3

Vertical movements of the 48 cm fork-length yellowfin tuna tagged on 2 September 1992

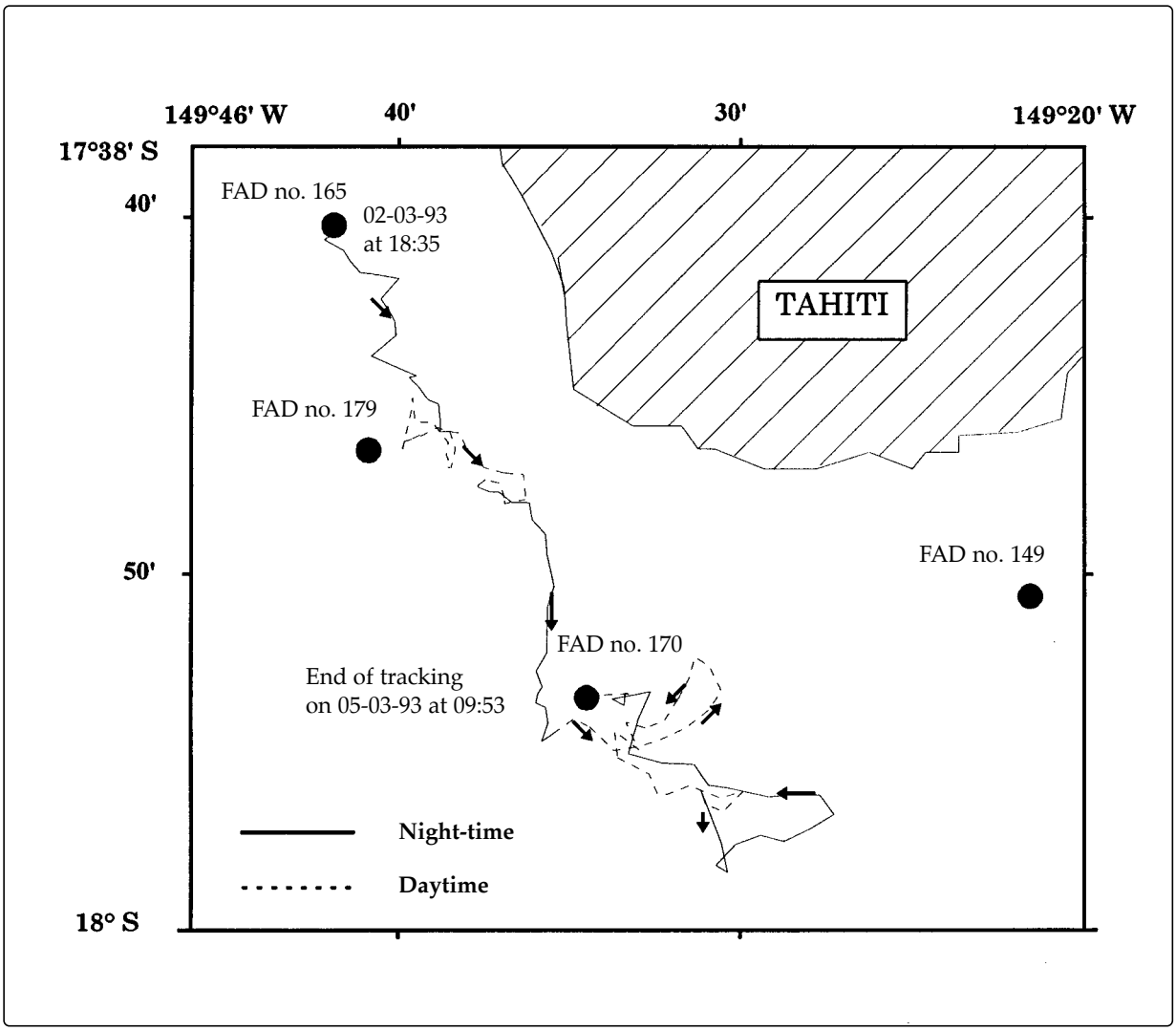

Figure 4

Horizontal movements of the 51 cm fork-length yellowfin tuna tagged on 2 March 1993 at FAD no. 165 (Punaauia) and tracked for 64 hours

The average speed-frequency distributions per thirty minute period calculated during the nights and days of tracking show that these speeds fluctuated over time (Figure 5). From being relatively stable over the first two nights and the first day of tracking (average speed approximately = 0.9 knot or 1.7 km/h), they increased during the second day (average = 1.4 knots or 2.6 km/h) and the third night (average = 1.6 knots or 3 km/h) to reduce at the beginning of the third day when the fish was near the FAD (average = 0.4 knot or 0.7 km/h).

The vertical movements show that on the first night, the fish occupied the water layer between the surface and a depth of 120 m with a dive to 250 m in the middle of the night (Figure 6). On the other hand, during the next two nights, it mostly remained in the top 80 m. During the first diurnal phase, the fish showed a preference for depths of between 100 and 140 m while swimming between the surface and 210 m during the second. This difference in diurnal vertical movements was in both cases observed when the fish was swimming close to a FAD.

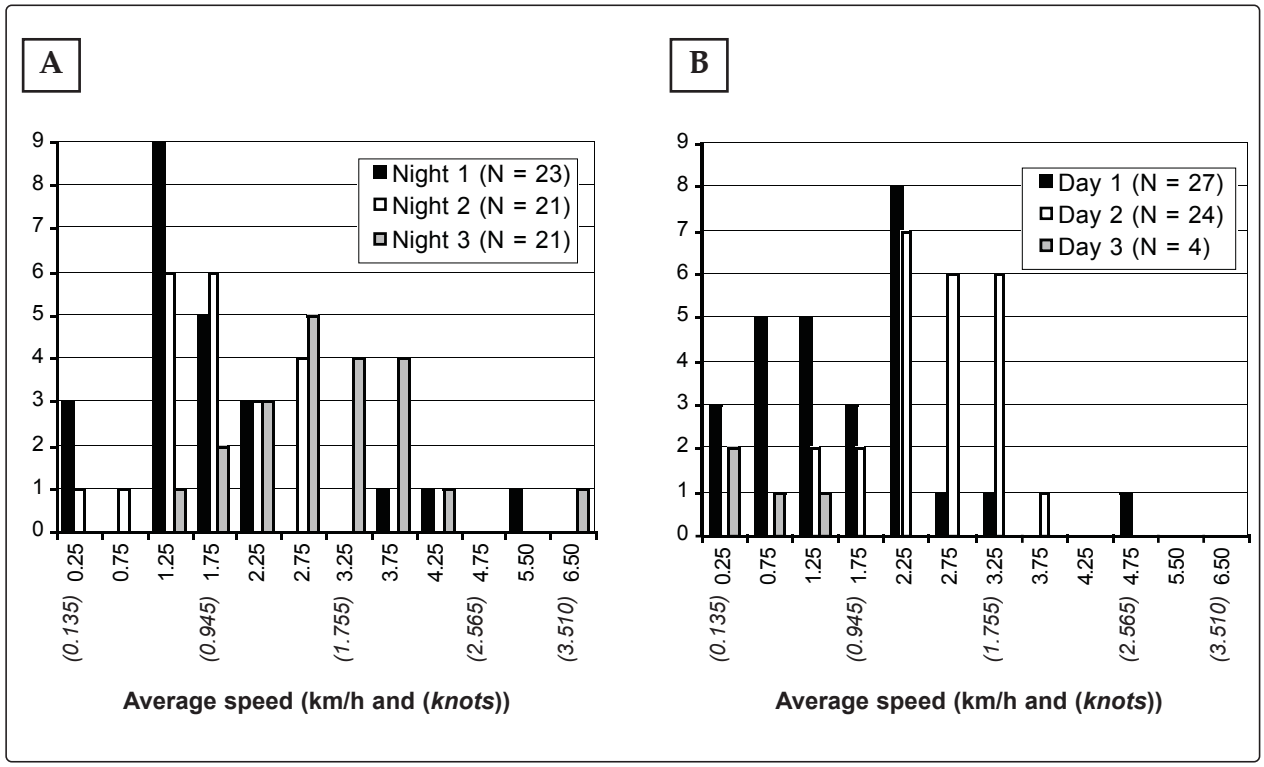

Figure 5

Average speed-frequency distributions per 30-minute period observed at night (A) and during the day (B) in the course of tracking

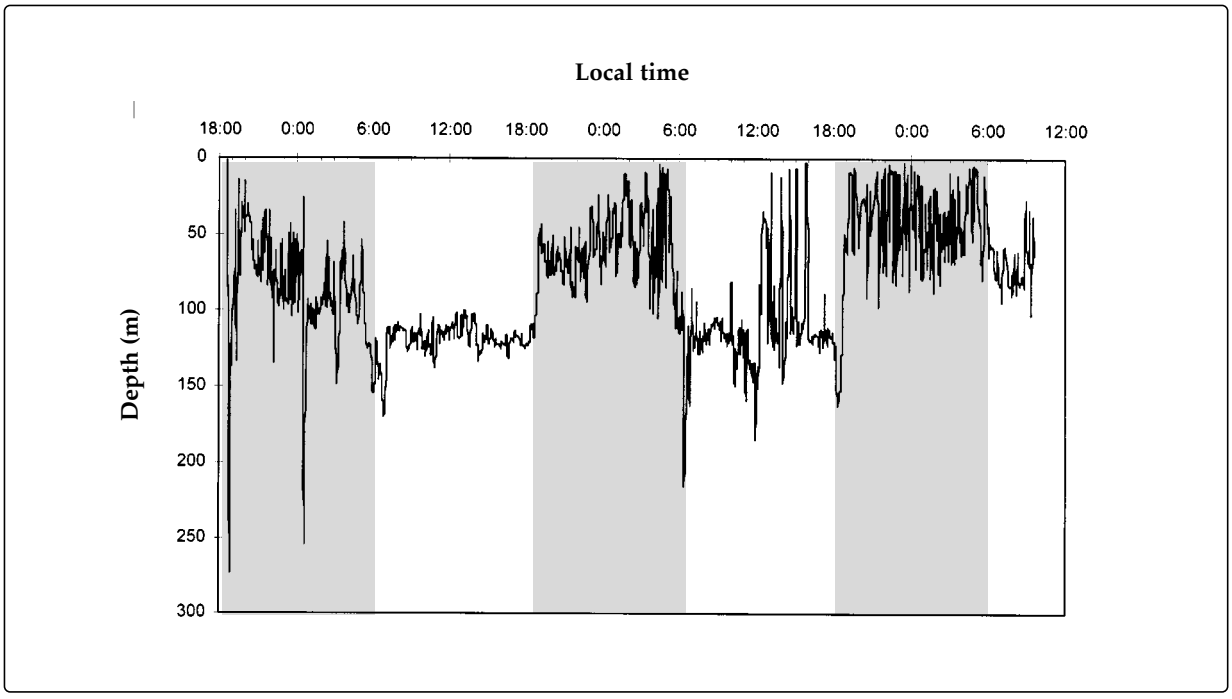

Figure 6

Vertical movements of the 51 cm fork-length yellowfin tuna tagged on 2 March 1993

Yellowfin tuna tagged on 2 March 1996

A 90 cm fork-length yellowfin tuna was caught on a vertical longline (drop-stone fishing, Moarii & Leproux, 1996) near FAD no. 204 (Papeete FAD) located 14.2 nm off the northern coast of the island of Tahiti (Figure 7).

During tracking, which lasted almost 81 hours, the fish always remained at a distance of less than 1 nm from this FAD. This tagging experiment shows that the fish did not leave the FAD for at least 81 hours or approximately 4 days.

The vertical movements oscillate between the surface and 165 m (this depth interval corresponds to a temperature interval between the 28.5°C and 23°C values). No significant difference between diurnal and nocturnal movements was recorded (Figure 8).

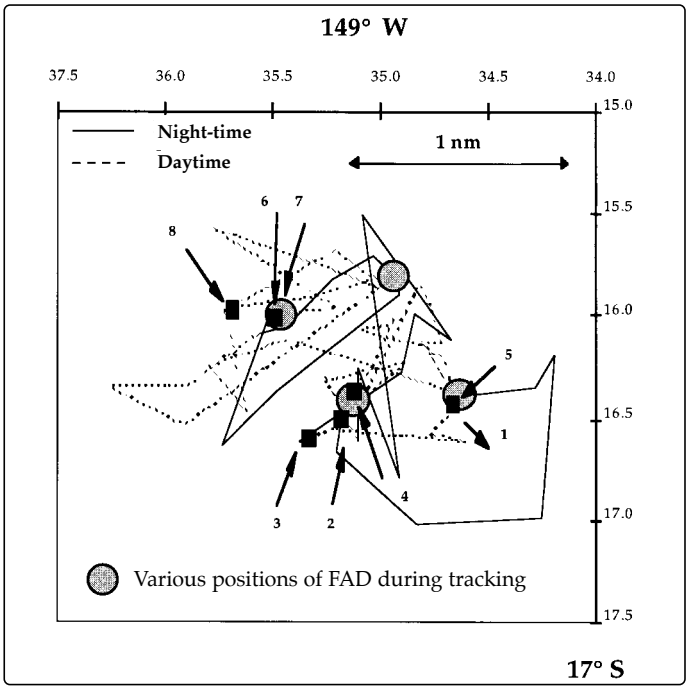

Figure 7

Horizontal movements of the yellowfin tuna in the vicinity of the Papeete FAD from 09:13 on 2 March 1996 to 18:00 on 5 March 1996

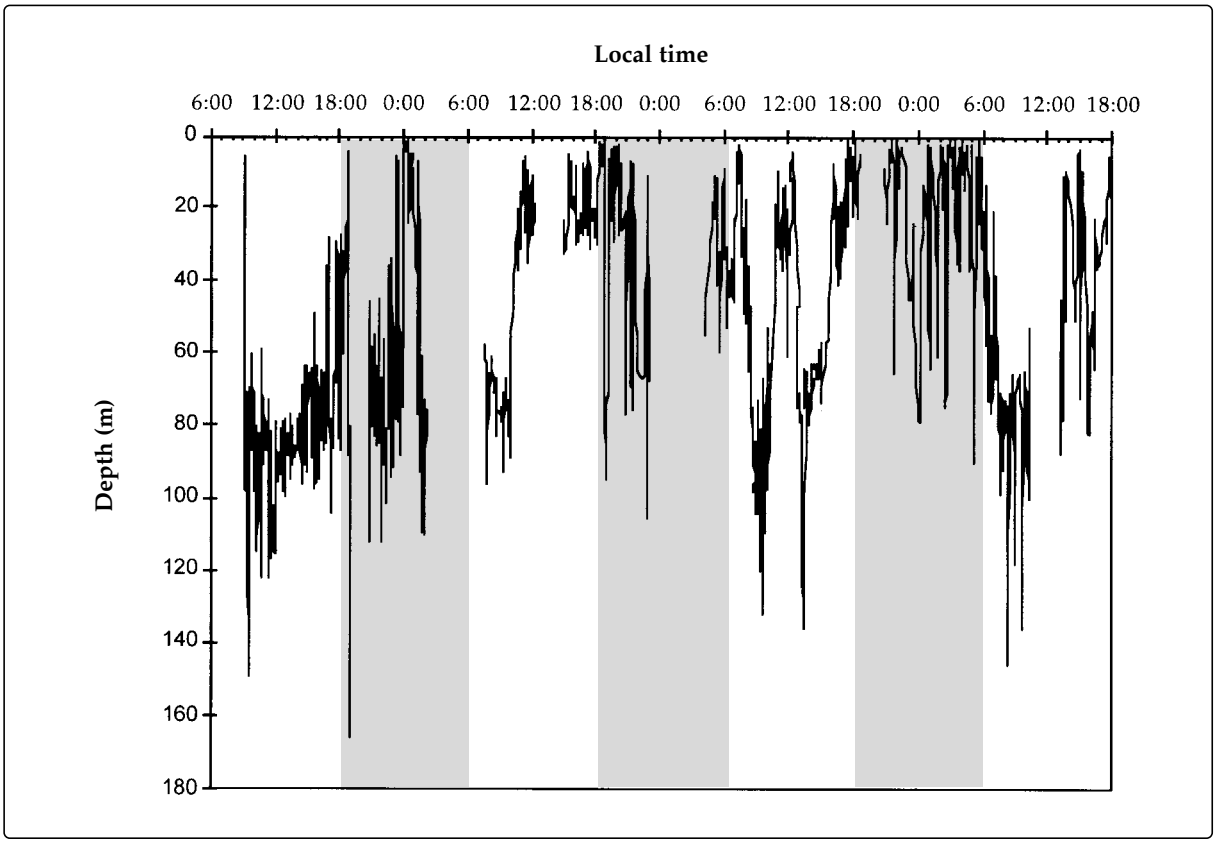

Figure 8

Vertical movements of the 90 cm fork-length yellowfin tuna during the 81 hours of tracking

Coupling of acoustic surveys and ultrasonic tagging

The use of active acoustics together with a sonic tagging experiment made it possible to observe the biological environment inhabited by the tracked fish. In the same way as with the physical environment (temperature, dissolved oxygen) it becomes possible to consider this biological environment as an explanatory factor for vertical and horizontal tuna movements (Josse et al., 1997). The tagging experiment described below illustrates the wealth of information that such a dual method can provide.

Yellowfin tuna tagged on 27 October 1995

A 60 cm fork-length yellowfin tuna was caught by vertical longlining near FAD no. 177 (Maupiti FAD) moored near the island of Maupiti (16°27'S and 152°17'W), (Figure 9). This fish's horizontal movements can be divided into four periods:

(i) association with the FAD just after tagging;
(ii) gradual movement away from the FAD until sunset (the maximum distance from the FAD was 3.3 nm at 17:14);
(iii) gradual return to the FAD until 23:00; and
(iv) gradual movement away from the FAD parallel to the coast from 23:00 onwards.

Two periods characterise the vertical movements :

(i) under the mixed layer during the day, and
(ii) in the mixed layer for the nocturnal period observed.

Within an oligotrophic environment, a sound scattering layer (SSL) was observed (Figure 9), using the SIMRAD EK500 sounder. SSLs were sampled several times during pelagic trawling, revealing that they are formed of tuna prey. The fish crossed this layer a first time during the day (see Figure 10 on next page) and a second time at night (see Figure 11 on next page). During the second crossing, this fish changed its vertical movement: it swam in the mixed layer at night and left to enter the prey aggregation, probably for feeding purposes. The horizontal movements would appear to be more due to the attraction exerted by this layer than by an association with the FAD.

Synopsis of the four taggings described in this document

The last tagging experiment coupled with an acoustic survey revealed the need to observe the biological environment in the same way as the physical and chemical environments in order to better understand the behaviour of tunas near FADs.

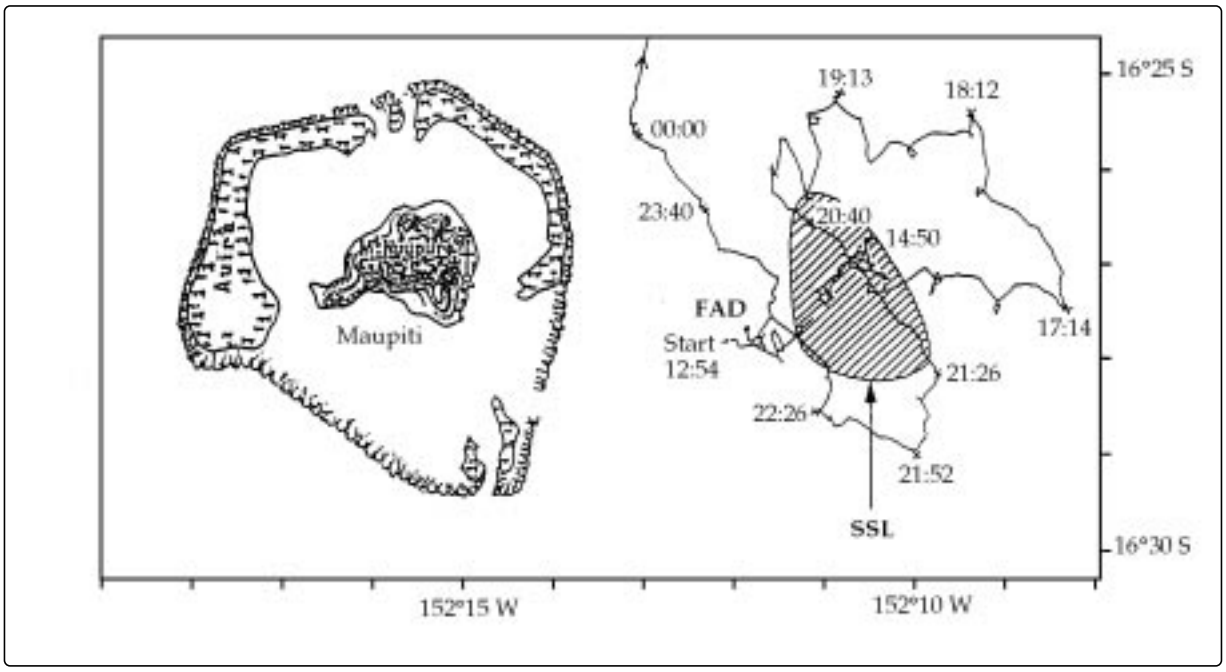

Figure 9

Horizontal movements of the 60 cm fork-length yellowfin tuna caught and tagged at a FAD moored near the island of Maupiti. Superimposition of the sound scattering layer (SSL) on the horizontal movements

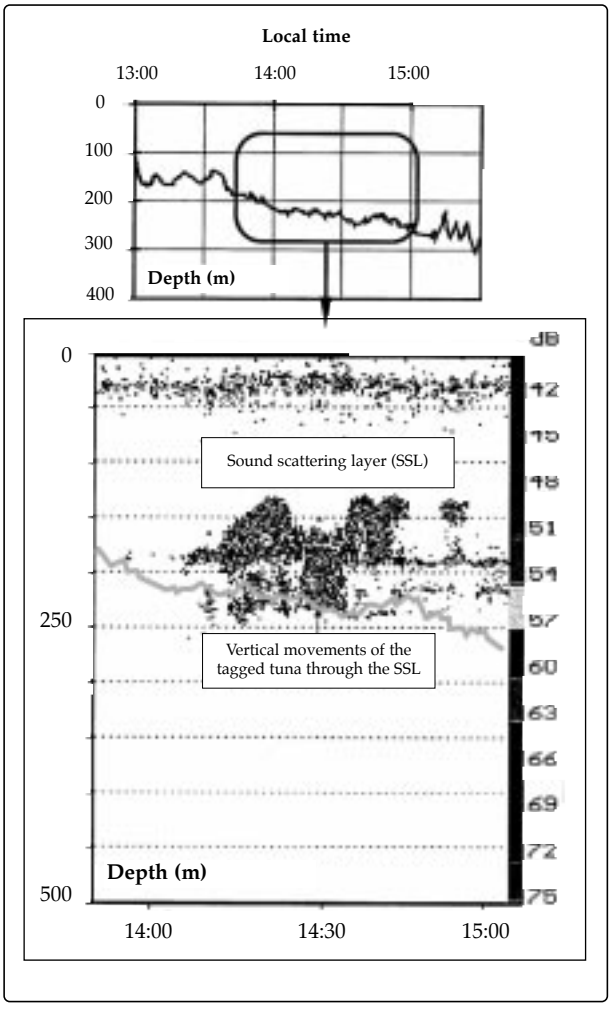

Figure 10

Vertical movements of the yellowfin tuna in the daytime between 13:30 and 15:00 (local time) and relationship with the sound scattering layer (SSL)

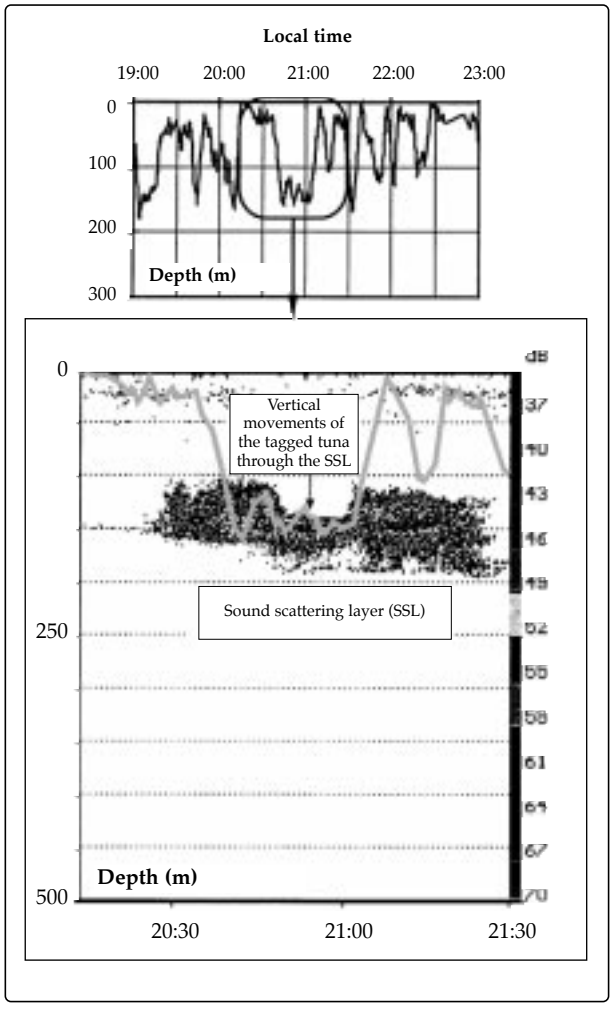

Figure 11

Vertical movements of the yellowfin tuna in the night-time between 20:15 and 21:30 (local time) and relationship with the sound scattering layer (SSL)

In addition, these four taggings showed that it is not possible to define a single kind of association (in term of duration or horizontal and vertical movements). The first and third tunas remained near the FAD during tracking whereas the second and fourth tunas left the FAD close to which they had been caught to visit other FADs or follow the outline of the coast. Similarly, the vertical profiles did not make it possible to show any particular trend as to vertical movements near FADs.

Use of acoustic survey methods to study the daily variability in aggregations

In analysis of tuna-FAD relationships, sonic tagging with tracking only yields information on these relationships at the level of the individual fish. Multiple ultrasonic tagging (up to 20 specimens) with a network of receivers installed on neighbouring FADs makes it possible to analyse the group's degree of cohesion, the strength of its relationship with a FAD and the exchange mechanisms between FADs on a time scale which will be determined by the lifespan of the transmitters (Klimley & Holloway, 1996).

Acoustic surveys around FADs make it possible to consider the associated aggregation. The purpose of the experiments carried out in Tahiti (see Depoutot, 1987 and Josse, 1992, for some initial results) was to study the horizontal and vertical extensions of aggregations and their variations on a one-day time scale. Acoustic surveys, in a star formation around the FAD (Figure 12) were carried out several times per day in order to do so.

The results presented here concern a series of acoustic surveys performed with the Biosonics 102

sounder in July 1993 around a FAD moored off the island of Nuku Hiva in the Marquesas Group (FAD moored 1.5 nm from the coast at a depth of 450 m). These are preliminary results and take into consideration overall acoustic response values irrespective of individual target strengths (TS). Six operations were carried out over a 24-hour period but only the results of three of them will be presented here for clarity reasons.

Acoustic density values were calculated by depth stratum (10 strata each 25 m in width between the surface and 250 m) taking into account distance from the FAD (4 distance strata of 0.2 nm).

During the night-time acoustic surveys (Figure 13A), the high acoustic responses in the first 50 m (strata 25 and 50) are due to the presence of a nocturnal deep scattering layer (DSL). Under this layer, some strong response values correspond to detections of single fish situated between 75 m and 150 m. The first daytime trip (Figure 13B) reveals the disappearance of the night deep scattering layer which had migrated deeper, beyond the echosounder's vertical range. Small schools of fish are present vertically beneath the FAD to 125 m, as are isolated fish at greater depths (between 175 m and 250 m), 0.3 nm from the FAD. Early in the afternoon (Figure 13C) the aggregation would appear to be more compact close to the FAD. Detections are also observed at greater depth (125 m and 150 m) further from the FAD.

An appraisal of the previous results made it possible to reveal the high response to nocturnal acoustic surveys associated with the presence of a deep scattering layer in the top 50 m. At night, if the 0–250 m water layer is considered in its entirety, the intensity of this response thus creates background noise which masks any vertical variations in acoustic response dependent on other organisms such as tunas. In order to discriminate between these two sources of acoustic response (DSL, and predators apart from DSL) two depth strata were considered individually, a 0–50 m stratum and a 50–250 m stratum.

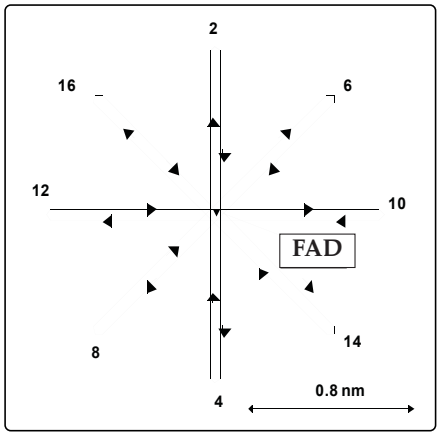

Figure 12

Star pattern acoustic survey work around FADs

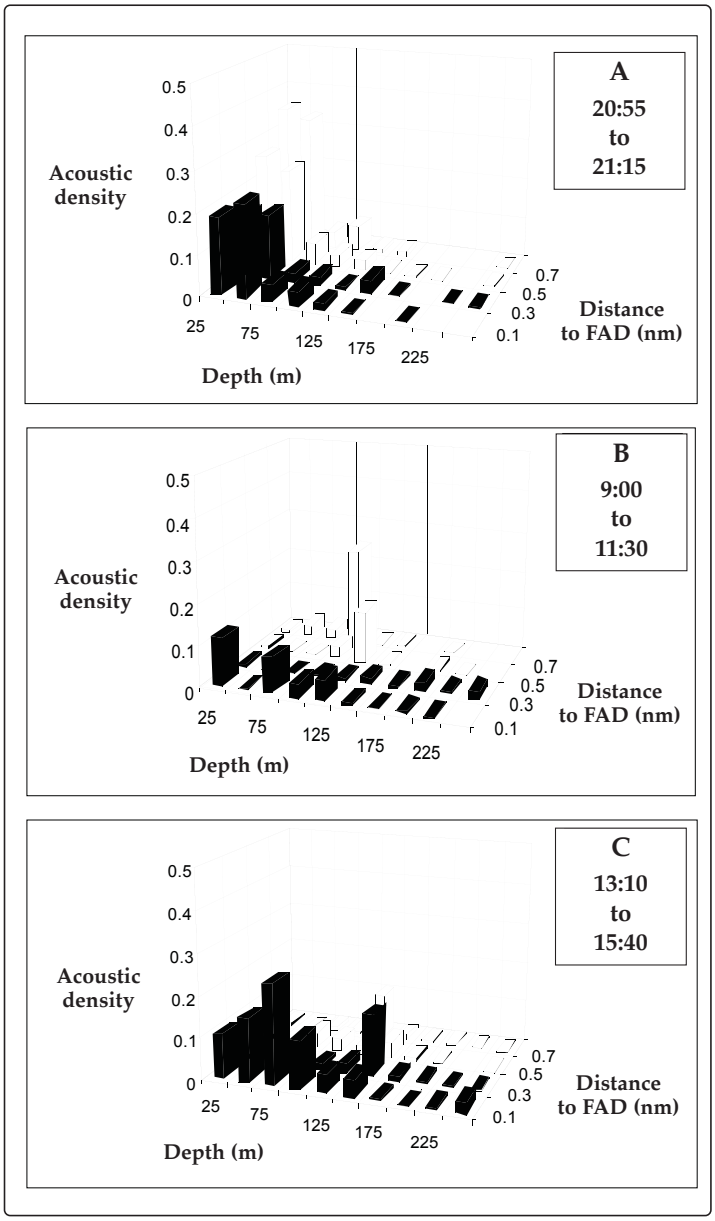

Figure 13

Acoustic response density distributions by depth stratum (25 m stratum) according to distance from FAD (0.2 nm stratum) observed during successive acoustic surveys around the Nuku Hiva FAD (Marquesas Group).

During the night-time, between 0 and 50 m, acoustic responses are high and located offshore rather than close to the coast (Figure 14A). In the daytime, the acoustic response densities observed in this layer are low with the exception of some areas located near the FAD and, in this case, the highest values are located between the FAD and the coast (Figure 14B and C).

The spatial distribution of acoustic responses between 50 and 250 m differs from that observed for the upper layer (Figure 14D, E and F). Where night-time acoustic surveys are concerned (Figure 14D), no particular trend can be noted as to the orientation of acoustic response intensities. On the other hand, this trend does appear with daytime surveys. In the same way as for the 0–50 m stratum, high acoustic densities are recorded near the FAD, as well as along certain radials (Figure 14E and F). These radials are always located between the FAD and the coast (north-east and east radials of Figure 14E, south-east radial of Figure 14F). The high values near the FAD correspond to two small schools located in the top 100 m and to some isolated fish echoes identified to a depth of 250 m and a distance from the FAD of 0.45 nm (Abbes et al., 1995). Vertical longlining over these isolated echoes yielded young yellowfin tuna at depth of between 100 and 150 m.

This spatial heterogeneity could be due to the fish positioning themselves in relation to a current. The acoustic responses recorded at the greatest distance from the FAD are thought to be able to be attributed to detections close to the sea floor which is at a depth of approximately 200 m at the end of the east radial. These detections probably relate more to the demersal than to the pelagic fish resource.

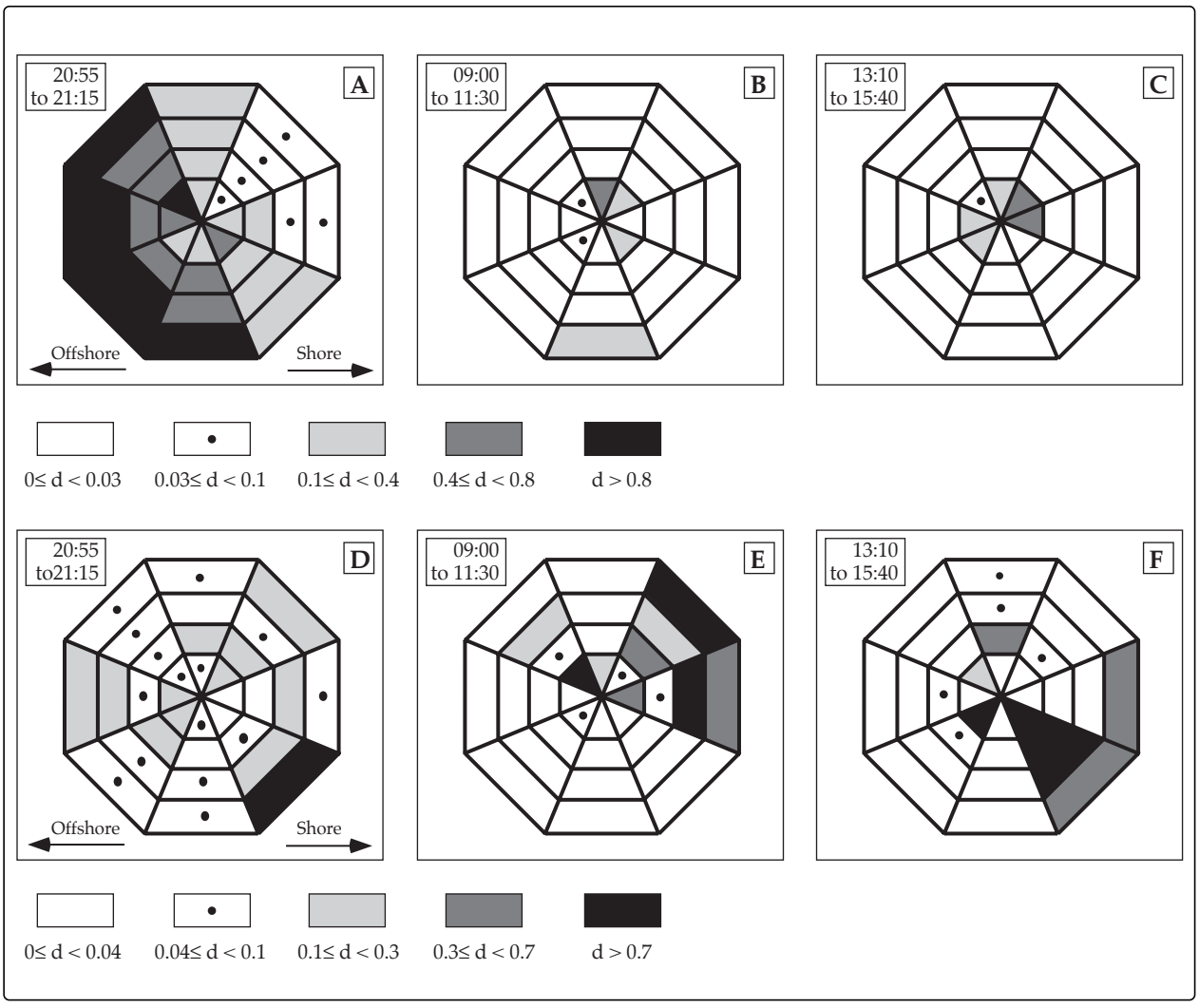

Figure 14

Spatial distributions of acoustic response densities by 0.2 nm intervals as observed in the 0–50 m stratum (A, B, C) and in the 50–250 m stratum (D, E, F) during a series of acoustic surveys carried out around the Nuku Hiva FAD (Marquesas Group).

Discussion

The results presented in this paper and those under analysis show that no real trends exist which would make it possible to define the behaviour of tunas in relation to FADs in simple terms.

At the scale of the individual specimen, the published results (Cayré & Chabanne, 1986; Holland et al., 1990a; Cayré, 1991; Marsac et al., 1996; Marsac & Cayré, 1997) as well as those presented in this document demonstrate the variability of tagged tunas' horizontal and vertical movements in the vicinity of FADs. Concerning horizontal movement, tunas assumed to be associated with a FAD swim at a variable distance from it, up to 5 nm in the daytime and 7 at night (Marsac & Cayré, 1997). Tracking for several successive days showed that some tunas remained under the FAD all the time, while others stayed close to the FAD in the daytime and swam away from it during the night, returning towards the FAD on the following day or leaving it in a horizontal movement pattern tied to the coast, or offshore, or attracted by other objects such as a new FAD. In other cases, a tuna could return to a FAD several months later after an initial association with it (Klimley & Holloway, 1996).

Tagged tunas' vertical movements close to a FAD vary in a given geographical area. The only constant factor in these movements concerns the nycthemeral variation, with movements generally taking place close to the surface at night rather than in the daytime. This trend would appear to be independent of the tuna's relationship with the FAD, since it is observed with specimens not associated with FADs. However, some authors (Holland et al., 1990a; Cayré & Marsac, 1993) have shown the influence of FADs on tunas' vertical movements.

One piece of information which makes it possible to justify the heterogeneity observed in the behaviour of tunas near FADs can be provided by our observations as represented on Figure 9. This result suggests that the spatial structure of the biological environment could be one of the explanatory factors in the diverse ways in which the relationships of tunas to FADs express themselves, a theory which have not yet been put forward.

It is difficult to draw conclusions about the structure and spatial organisation of FAD-generated aggregations. Also, results differ regarding fauna composition determined from the observation of FAD-related catches. This difference should be related to the diversity of fishing techniques used. Skipjack (*Katsuwonus pelamis*) and small yellowfin tuna, generally swimming in mixed schools, (Depoutot, 1987; Cayré et al., 1991; Sims, 1992; Cillauren, 1994) account for the major proportion of catches from trolled aggregations. In French Polynesia, handlining has almost entirely replaced trolling around FADs (Josse, 1992). The albacore (*Thunnus alalunga*) accounts for approximately 80 per cent of catches and is taken with lines 140 to 270 m in length (Asine, pers. comm.). When artisanal fishermen target yellowfin, they usually use shorter lines (approximately 90 m long). These handlines are set at random around the FAD within a radius of approximately 0.5 nm and their success would not appear to be connected with distance from the FAD.

Current knowledge does not make it possible to deduce the specific composition of schools from acoustic responses. However, with results recently obtained on target strength of tunas (Bertrand et al., 1997), future analysis of acoustic surveys carried out around FADs should make it possible to characterise aggregation composition more accurately.

The results gained from acoustic surveys around FADs provide a partial image of the aggregation in its vertical and horizontal extensions. These results depend on the sampling methodology (means used and protocol). Depoutot (1987), using acoustic survey techniques sampling the top 100 m of the ocean, demonstrated that aggregations showed major spatial and temporal variability, with acoustic responses diminishing during the day and increasing during the night. During the diurnal phase, the acoustic responses increase with decreasing distance from the FAD without a clear trend as to their orientation in relation to the FAD. At night, the acoustic responses are higher and increase with distance from the shore.

These results concur with those presented in this paper for the 0–50 m stratum. In contrast, we have shown that fish echoes were identified down to a depth of 250 m and up to a distance of 0.3 nm from the FAD. In the case of sonic tagging, fish echoes could be recorded at a distance of 5 to 7 nm from the FAD and at depths of over 250 m. Maximum echo distance corresponds to the length of the radials carried out : 0.6 nm for Depoutot (1987) and 0.8 nm for the observation described in this paper, which shows the limits of this kind of experiment for addressing the aggregation in every dimension.

It can be seen therefore that the issue regarding tuna aggregation dynamics around FADs, often addressed by scientists, has not for the moment found a satisfactory response. This answer is nevertheless the one the most keenly awaited by fishermen and coastal fishery managers using FADs to maintain and develop both artisanal and sport fisheries. This situation can be explained by two main reasons.

The first, as we have seen, is connected with the spatial and temporal limits of ultrasonic tagging operations and acoustic surveys. In this connection, Kleiber and Hampton (1994) stressed that: 'These tracking studies deal with individual animals perhaps in the vicinity of one or a few FADs. They typically cover a time scale of days and a spatial scale of tens of kilometres. It is not clear how to extrapolate the findings to longer term movements within a population of tunas in a large area occupied by a given spatial arrangements of many FADs.' Multiple-tagging with listening stations (Klimley & Holloway, 1996) improves the coverage in space and time of the results of tuna-FAD relationship studies.

The second reason is connected with the restrictions imposed by the issue of the relationship between an aggregation and a FAD. To provide answers supposes that all the mechanisms governing a relationship between the two factors should be taken into consideration. In particular, it is essential that the spatio-temporal observation scale should be higher than or equal to that in which these mechanisms act.

We believe that it is essential to distinguish between two spatio-temporal windows for fish likely to gather around FADs (Figure 15): firstly, a window corresponding to the FAD's radius of attraction (window A); secondly, a window which can be referred to as a comfort window (Postel, 1966; Legett, 1977; Balchen, 1979; McKeown, 1984) which is defined by the biological quality of the environment (window B). The results of ultrasonic tagging show that a FAD attraction radius is approximately 5 nm in the daytime and 7 at night (Marsac & Cayré, 1997), which could correspond to the size of window A. The edges of the comfort window (window B) will be determined by the environment's capacity to meet fishes' needs, in particular their food needs. One B window could contain several A windows (a number of FADs). In this way, a fish can satisfy its needs within a given A window, which would explain their back-and-forth movements close to a FAD or why they remain associated with a FAD. If a fish cannot meets its needs within an A window, it leaves the A window, while remaining within a B1 comfort window (see Figure 15), where it may meet other FADs (A windows). If this B1 window does not enable it to satisfy its needs, it may go to a B2 window and be able to associate itself with FADs if these are present in that window (Dagorn, 1994). Thus, when Klimley and Holloway (1996), observe a time interval of 114 days before a tuna returns to a FAD, this tuna might have remained, during the period in question, within the same comfort window, while it might or might not have associated itself with other FADs, swum within another comfort window—with or without an association with FADs—and then again returned to the FAD where it was tagged.

This working hypothesis is under test in the ECOTAP programme. A modelling tool has been selected and the approach used calls upon recent developments in the sphere of Artificial Life modelling.

The tridimensional biological environment (window B = comfort window) of the tunas in the model, comprises various A windows (FADs) 10 to 12 nm apart. This biological environment corresponds to a prey environment based on acoustic observations carried out during ECOTAP.

Tuna's movements are modelled by using artificial neurone networks. In fact, an artificial tuna consists of variety of internal and external sensors and interprets the data from these sensors over time, which makes it possible to determine its behaviour (swimming speed, direction and depth) on the basis of stimuli perceived around itself (prey, FADs).

This model is still under development. However, the initial results obtained concur with the results of movements observed during ultrasonic tagging (Dagorn et al., 1997). This approach therefore makes it legitimate to study the relationships between tunas and FADs at space and time scales superior to those conventionally used so far. This kind of simulation, which calls upon the results of acoustic surveys and ultrasonic tagging is an avenue of work which is currently being developed in order to propose a fishery management plan based on FAD deployments (distance from the coast and FAD network density).

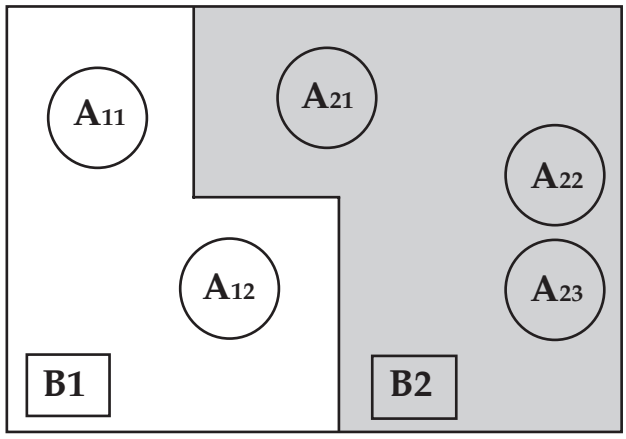

Figure 15

Example of FAD window layouts (Aij) around two different Bi comfort windows.

Conclusion

Research on the theme of the relationships between tuna aggregations and FADs has made considerable progress over the past ten years. A range of tools has been developed within the ECOTAP programme to improve knowledge in this area.

The results obtained from ultrasonic tagging agree with those already published. The use of acoustic surveys and sonic tagging in a coupled arrangement has made it possible to reveal the important role played by the biological environment on tunas' horizontal and vertical movements. A similar association has made it possible to carry out the first target strength measurements for tunas and thus future acoustic survey analysis will make it possible to qualify and quantify aggregation more accurately.

Acoustic observations of the biological environment played a determining role in all our experiments. They lead us in particular to address the relevance of the scale of study of the relationship between an aggregation and a FAD. Thus, we believe that issues such as tunas' 'faithfulness' to a FAD, exchange mechanisms between FADs and the attraction of a FAD should be considered on a scale taking into account a spatio-temporal window which can be referred as a comfort window. The edges of this window correspond to the environment's capacity to satisfy the needs of the resource. This working hypothesis is currently being tested using an artificial life modelling approach.

On the experimental level, future observations within the study of the relationship between tunas and FADs will need to take into consideration space and time scales greater than those so far used. In addition, then, to the instruments described in this paper, those used in future will need to make it possible to include the following scales: network of echo-sounding buoys, network of listening posts, pop up tags, conventional tagging and high-definition satellite station.

At a time when the exploitation of tuna resources around floating objects is expanding considerably without it being yet possible to evaluate the consequences of this type of fishing on stocks, research on the relationships between tuna and drifting and anchored floating objects is becoming more important than ever.

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