Monitoring fish communities at drifting FADs: an autonomous system for data collection in an ecosystems approach

Patrice Brehmer[1*], Gorka Sancho[2], Erwan Josse[3], Marc Taquet[4], Stratis Georgakarakos[5], David Itano[6], Gala Moreno[7], Pierre Palud[8], Vasilis Trygonis[5], Riaz Aumeeruddy[9], Charlotte Girard[10], Christophe Peignon[11], John Dalen[12], Laurent Dagorn[10]

[1] University of the Aegean/Co IRD-UR109, Centre de Recherche Halieutique méditerranéenne et tropicale, Avenue Jean Monnet, BP 171, 34 203, Sète, France
[2] College of Charleston, Grice Marine laboratory, 205 Fort Johnson Road, Charleston, SC 29412, USA
[3] IRD, US004 ACAPPELLA, Centre de Bretagne, BP 70, 29 280, Plouzané, France
[4] Ifremer, Ressources Halieutiques, Centre de Recherche Halieutique Méditerranéenne et Tropicale, Avenue Jean Monnet, BP 171, 34 203, Sète, France
[5] University of the Aegean, Fisheries and Sonar Laboratory, University Hill, 81100 Mytilini, Greece
[6] University of Hawaii at Manoa, 1000 Pope Road, MSB 312, 96822 Honolulu, Hawaii, USA
IRD-UR109, Centre de Recherche Halieutique Méditerranéenne et Tropicale, 1 Avenue Jean Monnet, BP 171, 34 203, Sète, France
[7] AZTI - Tecnalia, Txatxarramendi ugartea z/g, 48395 Sukarrieta, Spain
[8] Simrad Europe France, Parc Technologique de la Soye, Espace Créa, 15 rue Gallilée, 56270 Ploemeur, France
[9] Seychelles Fishing Authority, PO Box 570, Victoria, Seychelles
[10] CLS, 8-10 Rue Hermès, 31520 Ramonville Ste Agne, France
[11] IRD, 101 Promenade Roger Laroque - Anse Vata BP A5 - 98848 NOUMEA Cedex, Nouvelle Calédonie
[12] Institute of Marine Research, P.O. Box 1870, Nordnes 5817, Bergen, Norway

* Corresponding author: Patrice.Brehmer@oceanraise.com ; tel (33) 672730048; Fax (33) 499573295

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Abstract –

An increasing proportion of landings by tuna purse seine fishing vessels are taken around drifting Fish Aggregating Devices (FADs). Although these FADs and their use by the fishing industry to capture tropical tuna have been well documented, operative tools to collect data around them are now required. Acoustic, video, photographic and visual data were collected on fish aggregations around drifting FADs in offshore waters of the western Indian Ocean. Multibeam sonars, multifrequency echosounders, pole-mounted digital video camera and an automated 360° rotating digital photographic camera were deployed from a vessel in the vicinity of FADs, and their observation capability evaluated with underwater visual census made by divers. Two prototypes of instrumented buoys equipped with scanning sonar were tested providing positive results on their feasibility and operability as pelagic observatory. Acoustics methods combined with digital underwater video represent interesting possibilities to remotely study the composition and behaviour of these fish aggregations. The acoustic methods allowed the accurate description of the spatial organisation and dynamics of individual fishes, schools and biotic scattering layers around the FAD, but species identification was difficult. *In situ* visual, photographic and video observations systems permitted species identification within a range of 0 to ~ 25 m. However, scuba divers observations were more efficient compared to the photographic and video cameras at detecting the presence of certain fish species around FADs. Obviously both methods are complementary, since the acoustic methods could not identify most fish species and could not detect the presence of small fishes found less than 5 meters under the FAD. These fishes represent a small part of the overall biomass of fish aggregations but they are part of the biodiversity of pelagic ecosystems and may play a major role in ecological processes associated with FADs. The opportunity to incorporate observation tools into the development of future autonomous instrumented drifting buoys for remotely monitoring fish diversity and abundance in the pelagic ecosystems is presented. The perspective of autonomously collecting large amounts of basic information useful for ecological and fisheries studies in an ecosystemic approach for open sea or coastal pelagic environment is emphasized.

Keywords: Visual and video Fish census / Acoustics / Buoy system / Pelagic species / Monitoring / Observatory.

Résumé : Une part importante des captures de poissons par les thoniers senneurs sont réalisées autour des Dispositifs de Concentration de Poissons (DCP). Ces DCP et leur utilisation par l'industrie thonière sont bien documentés mais des outils opérationnels sont désormais requis pour l'acquisition de données écologiques autour de ces objets. Des données d'origines acoustiques, vidéographiques, photographiques et visuelles ont été collectées sur les agrégations de poissons autour de DCP dérivant au large dans l'océan Indien occidental. Nous avons déployés à partir d'un navire à proximité de DCP des sonars multifaisceaux, des échosondeurs multifréquence, une camera montée sur une perche, et un système photographique numérique à 360°, et comparé les observations faites avec celles obtenues en plongée sous-marine. Deux prototypes de bouées instrumentées avec un sonar à balayages ont été testés et ont fourni des résultats positifs quand à leurs faisabilité et opérabilité. Les méthodes acoustiques combinées à des observations vidéo numériques offrent des possibilités intéressantes d'étude à distance de la composition spécifique et du comportement de ces agrégations de poissons. Les méthodes acoustiques permettent une description précise de l'organisation spatiale et de la dynamique des poissons individuels, des bancs et des couches planctoniques autour des DCP mais l'identification spécifique reste difficile. Les observations visuelles, photographiques et vidéographiques permettent quant à elles une identification spécifique à une portée de 0 à ~ 25 m. Les observations visuelles sous-marines sont toutefois plus efficaces pour détecter la présence d'espèces de poissons a proximité des DCP que les observations photographiques et vidéographiques. Les deux méthodes visuels et acoustiques apparaissent complémentaires car les dernières ne permettent ni la discrimination spécifique de nombreuses espèces présentes ni la détection des petits poissons directement inféodés au DCP (distance de 0-5 m). Ces derniers représentent une très faible part de la biomasse en poissons mais peuvent jouer un rôle essentiel dans les processus écologiques associés au DCP. En outre ils constituent une part de la biodiversité des écosystèmes pélagiques. L'opportunité d'incorporer les méthodes d'observations dans le développement de futures bouées dérivantes instrumentées et autonomes, pour la surveillance à distance dans les écosystèmes pélagiques de la diversité en poissons et leur abondance, est présentée autour de notre cas d'étude. La perspective de collecter de manière autonome un grand nombre d'informations élémentaires à l'usage d'études écologiques et halieutiques sur les agrégations de poissons au large comme sur le littoral est soulignée.

Introduction

The aggregation effect of floating objects has been recognized and exploited by fishermen for a long time, as a first scientific description of such natural aggregations was made by Hunter and Mitchell (1967). Fréon and Dagorn (2000) and Castro et al. (2002) formulated different hypotheses to explain the behavioural motivations of fishes to associate with floating objects, commonly named Fish Aggregating Devices (FADs). However, none of them have been validated so far, except for small species hiding in the structure of the FADs (Taquet et al. 2007). The deployment and exploitation of drifting FADs has become a common fishing strategy for industrial fisheries targeting tuna in tropical pelagic waters since 1980 (Fonteneau et al. 2000, Ménard et al. 2000). However, tuna are not the only species associating to floating objects, and fish aggregations (Pitcher 1983) around FADs commonly comprise 10 to 40 species (Romanov 2002; Taquet et al. 2007). Most of those species have no commercial value for industrial fishing fleets and are discarded as by-catch (Hall et al. 2000). But some associated species could be of great interest to small-scale fisheries exploiting coastal anchored FADs, while other species could play an important role in the initial aggregation process around floating objects (Taquet et al. 2007). Moreover, collection of scientific data of fish communities around drifting FADs is needed in order to characterize and understand their role in pelagic ecosystems, including potential adverse ecological impacts (Hallier and Gaertner 2008). However, collecting data on FAD aggregations is difficult for several reasons. First, drifting FADs deployed by tuna purse seiners are usually found far from coastlines and dispersed over wide areas (Hyrenbach et al. 2000). Second, while studying FAD populations though commercial catches is possible (Romanov 2002), using fishery-independent methods is preferable as (i) they do not cause the mortality of animals associated to the studied FADs, (ii) they provide complementary data to commercial catches, which are influenced by the selectivity of the fishing gear employed (Gaertner et al. 1999).

Observing fish aggregations around FADs with non intrusive methods can be done from research vessels using *in situ* visual (Taquet et al. 2007) and acoustic surveys (Josse et al. 1999, 2000; Doray et al. 2006; Moreno et al. 2007a; Brehmer et al. 2006a). However, these protocols require large human and financial efforts, extended research cruises, and do not allow for simultaneous monitoring of multiple FADs. In order to collect large and simultaneous data sets of FAD associated communities, there is a need for the use autonomous monitoring systems. Such autonomous systems are pre-requisites to develop large-scale research projects to (i) improve our understanding of the effects of FADs on tuna and other fish species, (ii) develop methods to reduce by-catch around FADs, and (iii) build the foundation for future scientific observatories of pelagic ecosystems using autonomous platforms.

In this study we evaluated the operability and efficiency of various observation tools based on visual observations and active underwater acoustics that could be autonomously deployed on FADs, by comparing them to proven monitoring methods based from research vessels. Visual underwater fish censuses are extensively used to identify species, but are commonly limited in space and time (Jones and Thompson 1978; Kimmel 1985; Michalopoulos et al. 1992). Standardized acoustic survey methods which can be conducted repeatedly and more extensively provide reliable biomass data, but lack accurate species recognition (Fréon and Misund 1999; Simmonds and MacLennan 2005). Combining both methodologies during daytime observations in clear waters is a very effective way to characterize fish communities associated with FADs.

Materials and methods

We distinguished two categories of instruments/methods: those that in their current configuration need to be operated from a research vessel (category 1), and those that can be deployed and work autonomously (category 2).

FAD surveys

In October 2004, two drifting FADs were surveyed during a research cruise operated in the frame of the EU project FADIO (EU Project 'Fishing Aggregating Devices as Instrumented Observatories of the pelagic ecosystems; ; web: http://www.fadio.ird.fr). They were deployed by the French tuna purse seine fleet in the western Indian Ocean, around the Seychelles Islands (Fig. 1a). The first FAD (ID 484: 52°22' E - 5°10' S; 13/10/2004) was a bamboo raft with hanging netting panels, and the second FAD (ID 958: 56°16' E - 4°01' S; 16/10/2004) consisted of a floating coil of thick rope (Fig. 1b, 1c). We reached the FADs using a 34 m vessel (M/V Indian Ocean Explorer) and used onboard (category 1) and autonomous (category 2) survey systems to monitor the fish communities around the FADs (see below). A sonar buoy prototype (category 2) which could not be safely deployed from the vessel on these drifting FADs due to bad weather conditions was tested at the end of the survey on an anchored FAD near Mahé Island. Lastly, a second test of a sonar buoy prototype was performed in August 2006 in a Spanish bluefin tuna cage.

Acoustic monitoring

Ship-based equipment

The ship-based acoustic equipment (category 1) consisted of a multibeam high resolution lateral sonar, a multifrequency echosounder and an omnidirectional sonar (Fig. 2abc).

The lateral sonar, a RESON Seabat™ 6012 was on pole-mounted at amidships at two meters depth. It emitted at a frequency of 455 kHz in a vertical plane from the surface to 90° with 60 beams of 1.5°*17° at a range of 50 m (Gerlotto et al. 1999; Guillard et al. 2006). The sonar TVG (Time Varied Gain) function was set in 20 Log R (where R is the distance to the target), the gain put between 4 and 6 dB and the pulse length was 0.67 ms. The video sonar detection was recorded on a digital videotape recorder and the raw digital one on a hard disk via a dedicated data acquisition software (Gerlotto et al. 1999). The data analysed were the voxel delivered by the sonar central unit, with a beam size of 1024 elements and a data precision of 7 bits. The lateral sonar software analyzed this digital sonar data and produced detailed 3D images of the schools. The sampling methodology consisted in performing with the vessel several passes close to the FAD, keeping a vessel FAD distance of 50 metres.

The multifrequency split beam scientific echosounder employed in this study was a SIMRAD EK60 (38, 70, 120 kHz) and was deployed on a pole in a similar way as the lateral sonar (see above; Fig. 2abc). We used it over a diameter of 0.8 nautical mile in the horizontal plane and on 250 meter depth (see Moreno et al. 2007a for details).

Finally, an omnidirectional Simrad SP90 sonar mounted in the hull of the vessel at four meters depth (Fig. 2ad) was a used at a frequency of 24 kHz. The sampling methodology consisted first in using the omnidirectional sonar to detect precisely the FAD aggregation position. Then the vessel started a drifting operation at a distance of 50 to 300 meters to the FAD to monitor large fish school (for more details, see Brehmer et al. 2006a, 2007).

Autonomous equipment

The autonomous acoustic equipment (category 2) consisted of a prototype of a sonar buoy system manufactured by Martec-Serpe designed for observing pelagic fish schools. This instrumented buoy system was equipped with a scanning sonar system (model: Simrad SL 35; frequency 90 kHz) and a radio beacon system (WIFI: frequency 2.6 GHz; data rate transfer 6 Mo.s^{-1}), which directly transmitted the sonar data to the vessel. The buoy settings could be remotely adjusted from the vessel though the WIFI. A detailed plan of this first prototype is presented in Appendix 1. The second prototype build by the same company following the preliminary analysis of the data presented in this paper, maintaining the Simrad SL35 scanning sonar, and changing the radio beacon system by a satellite one (Iridium). This last prototype was also equipped of solar panels and a web of 4 underwater cameras (see Fig. Annex 2A).

Visual monitoring

Two visual survey methods were used from the vessel (category 1). The first one consisted in visual surveys performed by SCUBA divers equipped with an underwater digital video camera system. The survey consisted in a diver census starting with the fishes present directly under the FAD structure within a 25 meter radius and down to 15 meters depth, followed by a dive down to 30 meters depth to count deeper fishes, all performed in 30 minutes (see Taquet et al. 2007 for details). The second visual method tested was an underwater video system (Sea-Viewer™). It was a Sea-Drop Camera model 650 Series (dimensions: diameter of 7.6 cm and length of 18.4 cm. Focal distance 5 1/2” to infinity), mounted on a pole along the side of the vessel (Fig. 2d), the camera being at 2 m under the surface. The system was specifically optimized for the marine applications such as underwater wildlife videos and habitat monitoring. The video camera allowed permanent monitoring in PAL-B Video standard, stored on an S-VHS videotape recorder. The analogical video data were post-digitalized with a video card (Brehmer et al. 2005). The sampling methodology was to perform several passages close to the FAD keeping a distance of 50 metres (same procedure than for the pole-mounted lateral sonar monitoring).

The autonomous visual system (category 2) tested was an Aquapix SeaSnap photographic system, consisting of a Nikon CoolPix 5400 digital camera (focus 28 mm) electronically controlled by a Harbotronics Snap360 turntable, all enclosed in a boro-silicate transparent underwater housing (www.aquapix.net/seasnap360.php). Panoramic views of 360° consisted of ten overlapping digital images of 5 megapixels each, shooting 1 picture every 4 seconds. This autonomous underwater imaging system was originally developed to monitor benthic communities and obtain panoramic photographs of benthic habitats while deployed on the bottom. For monitoring fishes around FADs, the Aquapix system was suspended from a buoy hooked to the FAD (with an elastic rope for absorption of the swell movement) at 3 meters depth. A vane was attached below the casing to avoid erratic drift and spinning of the suspended camera.

Results

Results obtained during this cruise with ship-based multifrequency echosounders and omnidirectional sonar are detailed in Moreno et al. (2007a) and Brehmer et al. (2007), respectively. Corresponding underwater visual surveys are also described in (Taquet et al. 2007). Therefore, in the present paper they are shortly described in order to further discuss the interest of the novel data obtained through the use of (i) the Martec-Serpe autonomous buoy system, (ii) the RESON lateral multibeam sonar, (iii) the Aquapix 360^{o} rotating digital photographic camera and (iv) the pole-mounted video camera (Sea Viewer).

Using the RESON sonar data, a tri-dimensional representation of an underwater scene around a drifting FAD was produced, discriminating the FAD from the fish schools surrounding it (Fig. 3a). However, while the 3D positions and structures of the schools could be determined, neither the species or the size of the individual fishes of these schools could be assessed from the data, nor the school biomass.

The vertical multifrequency echosounders recordings provided accurate acoustics characteristics and position of the fish schools, the individual fishes and the different planktonic scattering layers present in the water column. An important observation is that acoustic responses from the planktonic scattering layers varied with the frequencies used. For example, shallow layers were well observed at 70 and 120 kHz, while deeper layers were best observed at 38 kHz (Fig. 3b). The 120 kHz appeared as the best for tuna detection but was the worst for observation of planktonic layers. On the other hand, the multifrequency methodology permitted to obtain a better extraction of fish school characteristics from the echogram and estimate their relative biomass (Moreno et al. 2007a).

The recordings by the hull-mounted omnidirectional sonar allowed for monitoring the behaviours (kinematics and spatial structure) of large fish schools and marine mammals around the FADs, in a horizontal plane, at a much higher range (max. 300 to more than 1200 m) that all the other methods (Brehmer et al. 2007) (Fig. 3c).

The experimental trials with the first sonar buoy around the anchored FAD produced positive results as it successfully recorded acoustic data on fish schools around the FAD. Horizontal locations of fish school all around the FAD were observed dynamically and transmitted directly to the vessel positioned at several hundred meters from the FAD. The possibility to transmit directly data on the vessel platform by the radio system was validated. The ability to set the sonar buoy parameters from the vessel (wireless control) was also confirmed. The second buoy prototype, deployed on a bluefin tuna school in a Mediterranean farming cage, effectively detected the tuna school and the net around it (see Fig. Annex 2B).

Three pole-mounted video fish observations were made at the first drifting FAD (ID 484), recording one trigger fish school (*Canthidermis maculatus*) with about 100 individual fish, and two other fish species, which could not be identified from the recordings (Table 1). On the second FAD (ID 958), the pole-mounted video recorded eight fishes: one shark *Carcharinus falciformis* (80 to 100 cm), one Carangid (species unidentified), four *Kyphosus sp.* and five unidentified fishes (adding up to around 40 individual fish). Comparatively, a total of more than 600 individuals of 11 species and more than 13000 individuals of 15 species were observed respectively for FADs 484 and 958 by SCUBA divers (Taquet et al. 2007). All the species observed with the pole-mounted video camera were also recorded during the SCUBA surveys (Table 2). There is a poor correlation between fish composition (number of identified species) and abundance (number of individual fish) data collected with the pole camera and the SCUBA divers surveys (Fig. 4; Table 1). Intermediate results were provided by the autonomous Aquapix system, which recorded 207 individual fishes from 8 identifiable species and multiple unidentified fishes at FAD 958 (Fig. 4). Three species were identified from Aquapix images at FAD 484 (98 individual fish recorded), along with numerous fishes that could not be identified (Fig. 4). Observations from the Aquapix system are still less efficient than observations performed by SCUBA diver team, particularly on the number of individual fish.

Lastly we can notify that no fish species inventoried on the IUCN red list of threatened species (IUCN 2008) are commonly found around both drifting FADs.

Discussion

The results are discussed in three parts, (i) on the acoustics observations, then (ii) the visual systems to monitor fish community, (iii) the interest to combine visual and acoustics methods, and lastly (iv) the perspective of autonomous system to monitor pelagic environments, combining both previous methodologies.

The acoustics observations

Echosounder detections have permitted to obtain information not only on individual fishes and fish schools around FADs (Josse et al. 1999, 2000), but also on the planktonic scattering layer (Bertrand et al. 1999; Brierley et al. 2006; Doray et al. 2006). In order to avoid misleading descriptive interpretations when plankton scattering layers occur, echosounder data must be studied using multifrequency analyses (Moreno et al. 2007a), which needs at least two complementaries frequencies e.g. in our case study 38 kHz and 70 kHz.
The echosounders had a narrow sampling volume (*vs*. multibeam sonar) below the vessel (Fig. 5), but it could efficiently correct the pitch and roll effect from the vessel experienced in rough seas during the survey of the both FADs. Nevertheless, sea surface reverberation produced misleading echoes at the surface and numerous acoustic parasites generated by subsurface air bubbles on the lateral sonar detection. The high nearest neighbour distance (NND) (Belckman 1993) between individual fish inside fish aggregation and inside tuna schools did not allow producing a single target: in this case the software solution did not permit the generation of useful 3D images. In order to avoid these signal limitations, an alternative method would be to analyse raw sonar video data (Brehmer et al. 2006b).
The medium range omnidirectional sonar allows to detect fish school up to 800 m (Brehmer et al. 2006a; Brehmer et al. 2007), but has high power consumption. In the FADIO project, we limited the buoy system instrumentation to small scanning sonar coupled with fixed simple video cameras, which was considered a reasonable compromise between gaining scientific information on FAD fish communities, power consumption and low cost objectives.

The visual observations

The goal of our experiment was to check their operability at sea and potential of each visual devices with respect to further development of autonomous observatories. We can remark that the number of species observed from the pole-mounted video and from the autonomous camera (Aquapix system) are significantly lower than those estimated *in situ* by SCUBA divers. Many factors can explain those results. The duration of observations were different: while SCUBA divers were staying 30 minutes in the water to conduct their visual surveys, the pole-mounted camera was used during 15 minutes more per survey, and the autonomous camera did multiple 1 minute scans (10 pictures) in both surveyed FAD. Also, while the divers surveyed the FAD community dynamically from the surface to 30 m depth, the pole-mounted camera was located 2 meters below the surface turning around the FAD, and the autonomous camera three meters deep, fixed under the FAD. Other factors that could explain the poor results produced by the pole-mounted camera was fish avoidance reactions to the moving vessel (Olsen et al. 1983; Fernandes

et al. 2000; Brehmer 2004) and a small visual range due to a narrow focal optic. However, we consider that the pole-mounted camera provided some interests since it can provide visual information simultaneous to acoustic data and help in identifying species from specific acoustic targets.
The autonomous photographic camera (Aquapix) tested in our study appears to constitute the best compromise between a pole-mounted video and diver surveys. The number of fishes and species observed were less than those observed by SCUBA divers, but much higher than from the pole-mounted video. We hypothesize that with a more appropriate sampling protocol (i.e. longer duration of observations, greater number of images taken), such system could approach the performances of SCUBA divers at short and medium distances from the FAD. This system would (i) reduce human risks (conducting SCUBA diver surveys in offshore environments is a difficult and risky task), (ii) not depend on human performance, (iii) be autonomous (vs. both other visual methods which involves experienced divers or the use of vessel), (iv) and can be made regularly and simultaneously at multiple FADs. Consequently we decided to add a video system with 4 cameras at 90° from each other, which would obtain similar information to that of the Aquapix rotating photographic camera in the second autonomous buoy prototype developed.

Combining visual and acoustic observations

At the present time the combination of video with simultaneous sonar data records is not yet operational for species identification, as the range of detection by the high resolution sonar (50 m) was too wide i.e. the range was 50 m in a 90 ° plane and the visual detection range of the pole-mounted video was around 5 to 20 m, using a narrow focal. Nevertheless experimental studies could lead to fish identification using acoustics (Guillard et al. 2006). Synchronized acoustics detection with fish video identification sampling the same volume of the water column could be a way for such purpose and efficient new methods appear as it will be reported in the future ICES CRR coordinate by Erik XXXX. A few video species identification associated with acoustic records were observed during the survey using the lateral sonar and multifrequency echosounder. We determined that fish recognition when the video camera was mounted in the vertical plane (i.e. as the echosounder) is more difficult than when the video system samples in the horizontal plane (i.e. as for the lateral sonar (Fig. 2d)). Combining visual and acoustics is a way to facilitate the acoustic discrimination of fish species, which is a key to the reduction of by-catch (Bailey et al. 1996, Holland et al. 2003) and the take of undersize tuna species (Brehmer et al. 2005; Miquel et al. 2006) by the fishing industry.

The sampling area covered by each sampling method encompassed different scales (Fig.5). Moreover the information on the fish aggregations delivered by the different active acoustic methodologies were highly complementary (Brehmer et al. 2002): from a few small individual fishes located just below the FAD (Taquet 2004) visually observed by divers [Range (omnidirectional): 0 to 30 m, maximum 50 m], to the large schools of tuna [Range (omnidirectional): 5-800 m, maximum 1200 m] all around the FAD (Fig. 4c) detected by omnidirectional sonar, and the individual fishes as the planktonic layers observed by the multifrequency echosounders [Range (vertical): 3-200 m, maximum 600 m]. Fish of some centimetres directly present under the FAD could not be detected by our acoustics devices because they were present in the near field of the sonars and the multifrequency echosounders, or because they were below the range resolution of the transducers.

Perspectives in autonomous pelagic observatories

A drifting monitoring buoy system appears to be a valid observational platform since it may naturally act as a FAD and therefore allow for long term monitoring of pelagic fish communities without human disturbances. These buoys could also potentially cover large areas while being displaced by surface currents and winds. Purse seine fishermen are already working with autonomous non-scientific acoustic buoys that remotely provide information on relative biomass estimates using commercial echosounders and satellite transmitters (Moreno et al 2007b), which shows the value and the operability of such systems. Future refinements to both buoy prototypes are needed before a final autonomous buoy reaches the production stage. Hardware power consumption is still the main challenge for building autonomous instrumented drifting platforms with acoustic and video surveying capabilities in offshore environments. The rate of data transfer through satellite transmissions does not constitute a technical limitation as the buoy manufacture (Stolte 1994). Video systems have shown their operability in remote harsh conditions, plus they have low power consumption which allows them to be mounted additionally to sonar systems. Our second autonomous buoy prototype (figure Appendix 2) with four web quality cameras provides 360° underwater view (4*90°) around the buoy. Data can be transmitted though radio or satellite communication modules (e.g. Iridium or Immarsat) which provide short to long distance real time data transmission. An alternative is to store data on a hard disk in the buoy (Wilson 1998; Godø and Totland 1999), which increases power economy, but requires the recovery of the device to access the recorded data. However, the recovery of drifting buoys after long deployments in the open ocean where purse seiner fishing fleets operate is very unlikely (Moreno et al. 2007a). To further increase power economy, video cameras could be only activated during daytime hours and triggered according to particular acoustics detection characteristics (e.g. changes in acoustic intensity and reflectivity indexes of the targets) or when certain movement patterns are acoustically detected (i.e. fish passage in the camera detection field) (Spruijt et al. 1992). Fish tracking by video can also be envisaged to increase the fish species recognition (Kirkpatrick et al. 1991; Noldus et al. 2002). The power limitation will be inversely proportional to the buoy size (battery compartment size). A certain critical buoy size is needed to implement renewable energy generators such as solar panel, wind turbine or fuel cells, which would allow adding all kind of valuable instruments and sensors to the buoy such as acoustic doppler current profilers ADCP (Brierley et al. 2006). In our case of drifting FAD ecological studies, atmospheric and oceanographic sensors (rain, wind, air and water temperature, water conductivity and turbidity, etc.), hydrophones (sea state, bioacoustic noises) and acoustic listening stations (Ohta and Kakuma 2005; Dagorn et al. 2007), do not need heavy technical adaptation even expense and can provide the valuable information.

Apart from the devices used in our project, an interesting possibility would be to use remotely operated vehicles (ROV) and autonomous underwater vehicles (AUV) with the buoy as a power and data transmission platform. Fernandes et al. (2003) have shown that such equipment could be equipped with acoustics devices and produce high quality results. The main interest is that the AUV equipped with physical, acoustic and video sensors could make surveys around the FAD at several depths, could track particular individuals, or lead inter-FAD transect. A limitation could be the avoidance by fishes of underwater vehicles, shown to occur in some deep sea fish species (Trenkel et al. 2004).

This work paves way to provide interesting perspective for fisheries and ecological studies in the pelagic environment. Dagorn et al (2007) underline the interest to study top predators using buoy observatory, because they have natural aggregative behaviour around the buoy. The interest to use web of instrumented buoy at large scale was a perspective of the Fadio project (Dagorn 2005; Dagorn et al. 2007). Future project are already planed using several buoys clustering in a web, which could be led at the level of an ecosystem, e.g. firstly by installing echosounders on weather buoys which already are scattered across all the oceans (Olivier Maury and Patrick Leodey, pers. com.), in the interest to set and validate planktonic production models. Future studies which necessitate an ecosystem approach (e.g. Godø and Tenningen 2009), need adapted experimental sampling scheme, using ad hoc methodologies and devices. An important goal using such autonomous tools, in particular in such open sea pelagic environments seldom surveyed but which need to be regularly monitored, will be to look for consistent indicators (Josse 2008) of the ecosystem ecological status.

Conclusions

These results refined our methodology for characterizing fish aggregations and will help with the study of dynamic fish aggregations in association with drifting FADs as well as to monitor pelagic fishes in an ecosystems approach, including seabirds, marine mammals and plankton communities. Visual fish censuses by divers were limited in space and time, while acoustic methods were not. Acoustics methods are well standardized and are not dependant on underwater visibility. On the other hand SCUBA diver fish surveys allow accurate fish species identification and collection of detailed information on the FADs characteristics. Catching fishes from FAD aggregations with commercial purse seiners remains a valid way to obtain detailed fish inventories and abundance estimates around drifting FADs, though this method does not produce data on fish behavioural dynamics nor the presence of small fishes that swim through the net mesh or more simply not catchable by the fishing practice.

The underwater acoustics and video autonomous buoy system, drifting or fixed, linked with satellite communication, radio link (near a reception centre) or high memory storage recoverable systems will be in a near future an operative tool for monitoring fish behaviour, abundance and biodiversity. Indeed a combination of video and acoustic observations recorded simultaneously from the same instrumented buoy structure will provide large quantities of basic information useful for ecological and fisheries studies on fish aggregations in the open sea, as in our case study, or coastal pelagic environment. In the context of global warming, biodiversity conservation and overexploitation of natural resources, such tools could provide *in situ* data and consistent indicators crucial to making ecological studies in the pelagic ecosystems.

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Dugornay and Bertrand Wendeling for conducting underwater visual and video surveys. The M/V Indian Ocean Explorer has been seized by Somali pirates between Assumption and Aldabra in April 2009; we hope a safe issue and dedicated this work to all the crew.

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FAD	Species		Number of visual observation Aquapix	Pole camera
958	*Carcharhinus*	*falciformis*	38*	1
958	*Canthidermis*	*maculatus*	2*	-
958	*Elagatis*	*bipinnulata*	26*	-
958	*Acanthocybium*	*solandri*	2	-
958	*Naucrates*	*ductor*	1	-
958	*Thunnus*	*albacares* or *obesus*	20*	-
958	*Kyphosus*	*vaigiensis*	3	4
958	*Uraspis*	*helvola*	22	-
958	Unidentified Carangidae			4
958	Unidentified species		93*	30*
484	*Canthidermis*	*maculatus*	10*	100
484	*Elagatis*	*bipinnulata*	36*	-
484	*Acanthocybium*	*solandri*	2	-
484	Unidentified species		50*	5

Table 1. Fish Identification made after post watching from Aquapix Digisnap 360 image sequences and from the pole-mounted video camera on both studied drifting FAD. (*) Overestimation due to probable repeats as the fish identified could turn around the FAD. The unidentified fish species number does not represent the total unidentified fish species but the total number of their visual observation.

			Number		Minimum		Maximum	
Family	Genus	Species	958	484	958	484	958	484
Kyphosidae	*Kyphosus*	*vaigiensis*	>>1000	100	10	15	10	15
Carangidae	*Elagatis*	*bipinnulata*	>>5000	20; 300	30	75; 45	30	75; 45
Carangidae	*Carangoides*	*orthogrammus*	1	0	35	-	35	-
Carangidae	*Uraspis*	*helvola*	30	8	30	25	30	25
Carangidae	*Decapterus*	*macarellus*	>500	0	35	-	35	-
Carangidae	*Caranx*	*sexfasciatus*	0	9	-	7	-	7
Carangidae	*Seriola*	*rivoliana*	3	5	25	30	25	30
Coryphaenidae	*Coryphaena*	*hippurus*[+]	5	6	60	60	60	60
Balistidae	*Canthidermis*	*maculatus*	>>5000	300	10	25	10	25
Scombridae	*Acanthocybium*	*solandri*	3	2	100	100	100	100
Scombridae	*Thunnus*	*obesus**[+]	200	0	75	-	75	-
Scombridae	*Thunnus*	*albacares**[+]	>>1000	0	50	-	50	-
Scombridae	*Katsuwonus*	*pelamis**[+]	>>1000	0	45	-	45	-
Carangidae	*Naucrates*	*ductor*	10	1	30	25	30	25
Carcharhinidae	*Carcharhinus*	*falciformis*	100	2	70	100	70	100
Pomacentridae	*Abudefduf*	*vaigiensis*	1	40	1	1	1	1

Table 2. List of fish species seen during the survey by SCUBA diving around the two studied drifting FADs 484 (13/10/2004; 09:40 to 10:40) and 958 (16/10/2004; 14:00 to 14:40). The maximum and minimum size estimate are in cm. (*) Fish species exploited by the professional fishing fleets and (+) per the small-scale fisherman.

Fig. 1. (a) Map of Indian Ocean the survey was carried out off Mahé Island in Seychelles (ellipse) situated in the western part of the Ocean. The photo shows an example of a man made drifting FAD, using (b) a raft of bamboo and piece of fishing net (Copyright Fadio/IRD-IFREMER/E. Josse); (c) another example a natural one, in this case an immerged truck (Copyright Fadio/IRD-IFREMER/M. Taquet).

Fig. 2. (a) Underwater view of the active acoustic devices used to monitor marine biomass around the drifting FAD: (b) an omnidirectional sonar hull-mounted and (c) three echo sounders, as (d) a high resolution sonar associated with an under water video camera, which where both pole-mounted aside the vessel (Copyright Fadio/IRD-IFREMER/M. Taquet).

Fig.3. (a) 3D representation of several small fish schools detected near a drifting FAD. In red the sonar volume insonified (at a range of 50 m), the green windows cross at the FAD position, starting from the surface (455 kHz; range 50 m). (b) Echosounder view detecting individual fish and scattered layers (i.e. plankton), below the FAD at 38, 70 and 120 kHz from the right to the left, showing different acoustic responses of the planktonic layers according to the frequencies used. The echotrace in 'V' shape is characteristics of tuna detection (range 120 m depth). (c) Detection all around a drifting FAD, situated in the middle of image, on the right a large fish school, as revealed by the omnidirectional medium range multibeam sonar (24 kHz; horizontal diameter range 1600 m).

Fig. 4. Graphic of species visually observed by SCUBA diver (in black), the Aquapix system (in hatched) and the pole video camera (in white) around drifting FAD. The fish not identified, only found on the two last devices are not presented.

Fig. 5. Scheme of sampling distance for data collection around drifting FAD. The drifting buoy system transmits wireless data (by satellite or by radio HF near a relay) to a data storage centre, which could share scientific information using the World Wide Web. (A) Buoy video system allows fish identification at short range [20 m], (B) SCUBA diver observation sample a greater area [diameter ˜ 50 m]. The acoustic methods allow large, well standardized and continuous observation below the FAD using (E) echosounder [depth 200 to 600 m], at 3D high resolution using (C) lateral multibeam sonar [range 50 to 100 m], and at long horizontal distance using (D) omnidirectional or scanning sonar [range 300 to 1200 m]. The local depth is usually up to 2000 meters.

Appendix

Conceptual scheme of the autonomous buoy system equipped of scanning sonar Simrad SL 35, a web of underwater camera and a module of data transmission (according Palud 2005). The sonar parameters could be set and the data transmitted at short distance (WIFI transmission module) or at long distance (satellite transmission module) from a platform close to the buoy using a WIFI connection (first buoy prototype : Appendix 1) or from the land using satellite communication (second buoy prototype: Appendix 2).

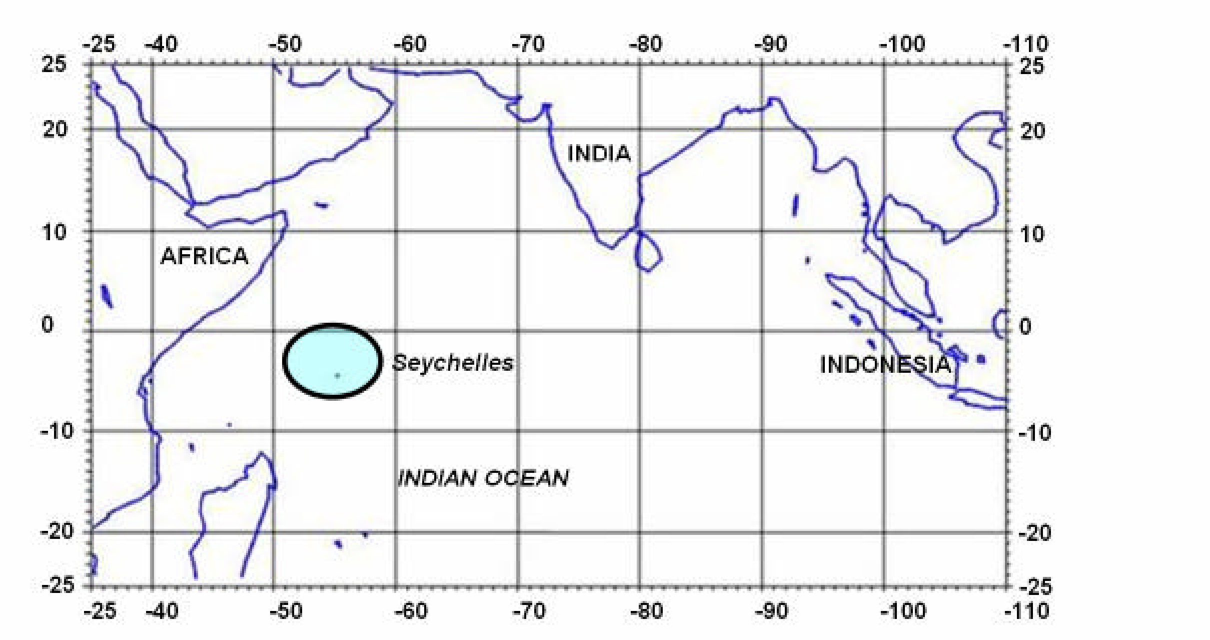
Figure Appendix 1 HERE

Figure Appendix 2 HERE

Figure Appendix 1. Block diagram. Technical legend of the main Fadio buoy component, linked (wireless transmission/reception) to a PC control. 1: Alimentation 24 volt. 2: Connection RJ 45 (Ethernet). 3: Antenna connector. 4: Fan less motherboard (PCB PC). 5: Module power manager (12V, 8V, 5V). 5b: Module data converter analog/digital, transmission signal. 6: Battery (floating mode); plumb, 2V by element. 7: Web of underwater camera D-link system. 8: Transducer, scanning sonar model Simrad SL35 (200 kHz); motion sensor. 9: Multiplexer USB data. 10: N-port serial interface (1510-IP). 11: N-port optical module (1510-IPO). 12: Antenna; modularly WIFI (e.g. 2.6 GHz) or satellite (e.g. iridium).

Figure Appendix 2. (A) Photography of the last buoy prototype using wireless satellite system (iridium transmission), solar panel and a web of under water camera. (B) Example of detection led in a tuna farming cage, we can distinguished the tuna schools and the circular net of 60 m diameter.

(a)


-25
-40
-50
-60
-70
-80
-90
-100
-110
25
20
10
0
-10
-20
-25
AFRICA
INDIA
Seychelles
INDONESIA
INDIAN OCEAN

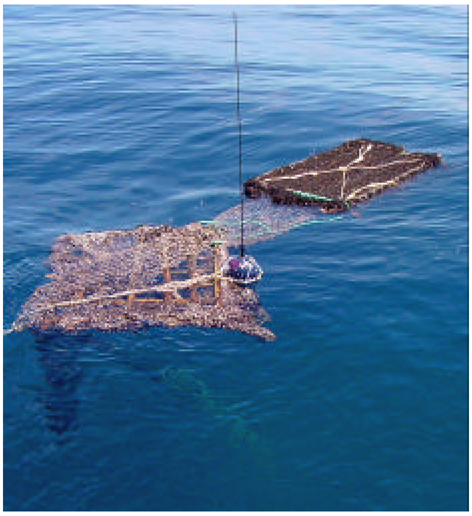
(b)  (c) 

Fig. 1.

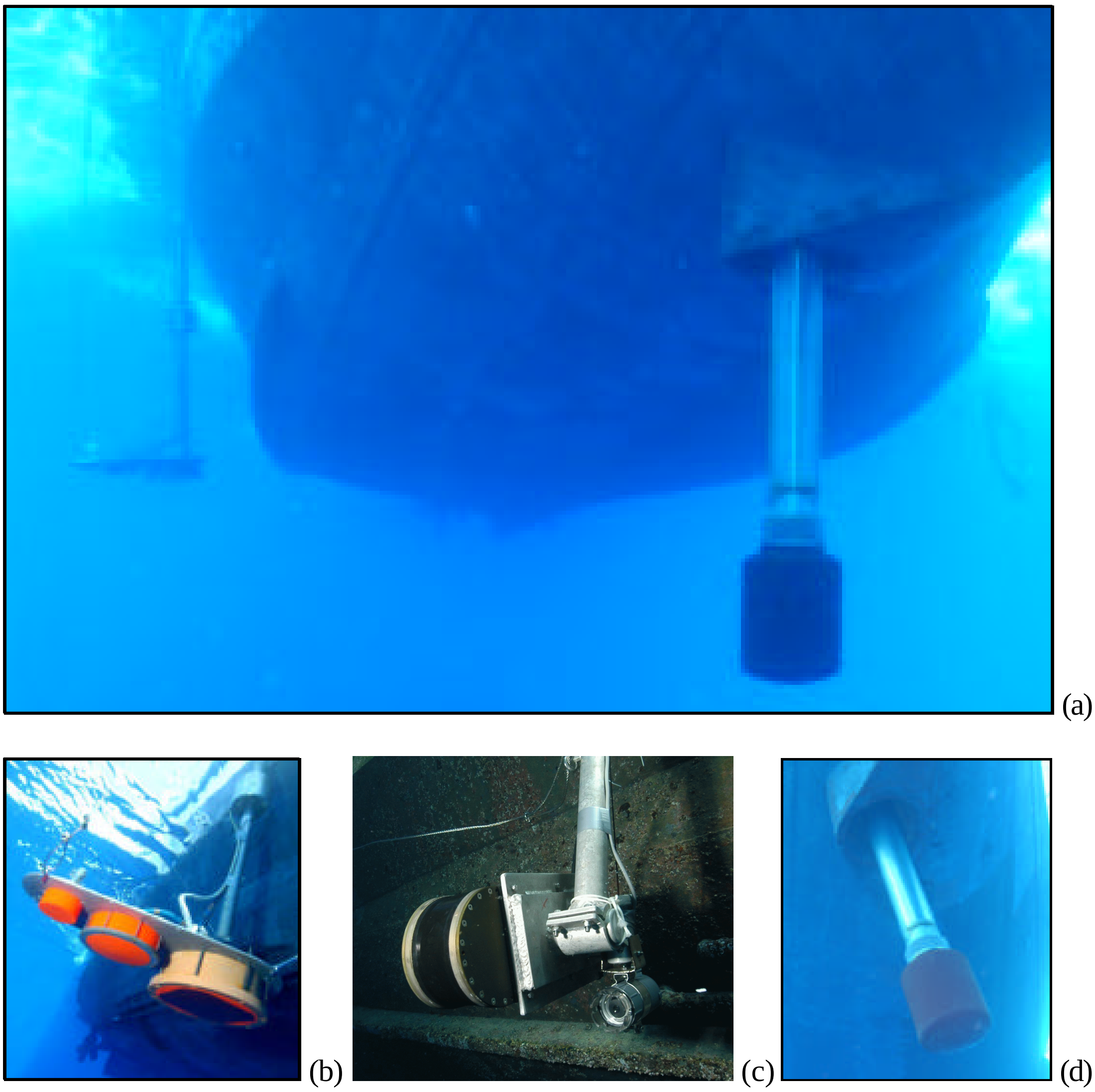


Fig. 2.

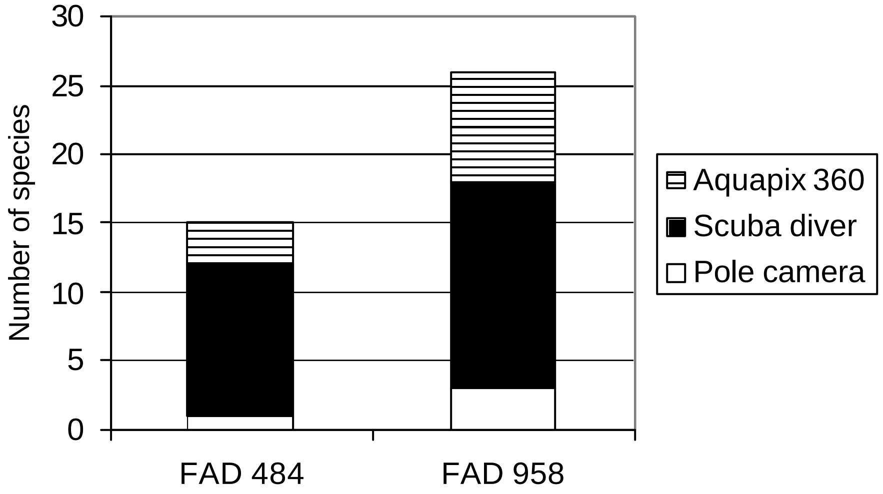
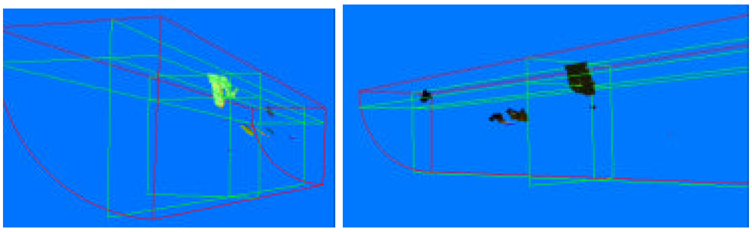
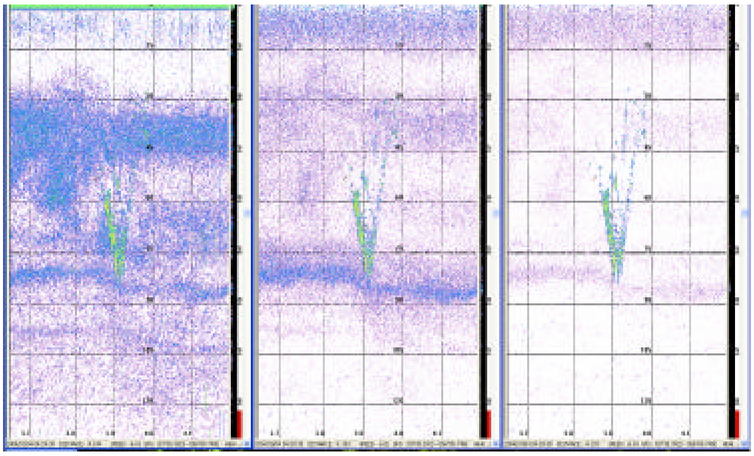

30
25
20
15
10
5
0
Number of species
FAD 484
FAD 958
Aquapix 360
Scuba diver
Pole camera

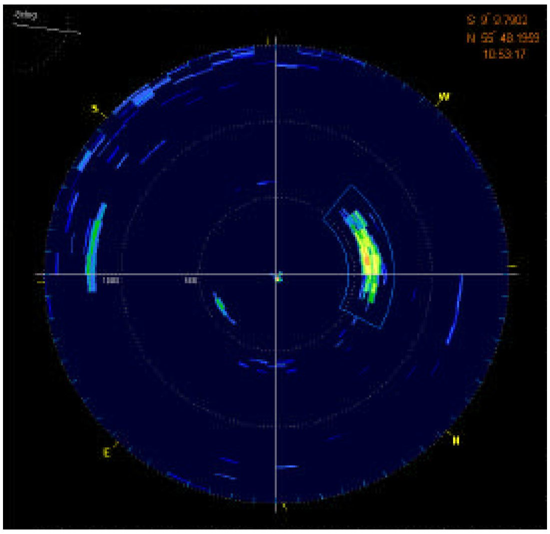
Fig. 3.



(a)



(b)



(c)

Fig. 4.

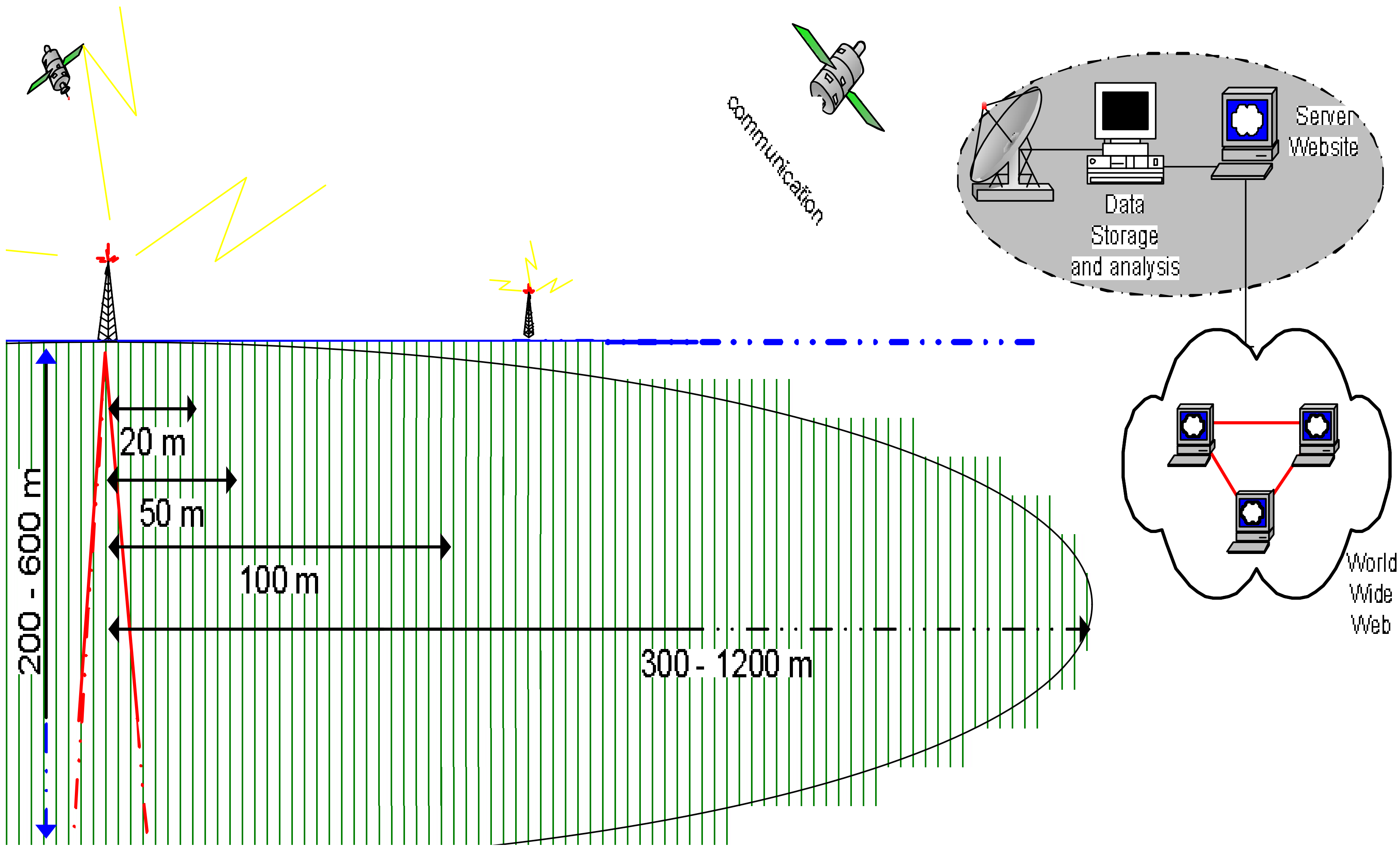
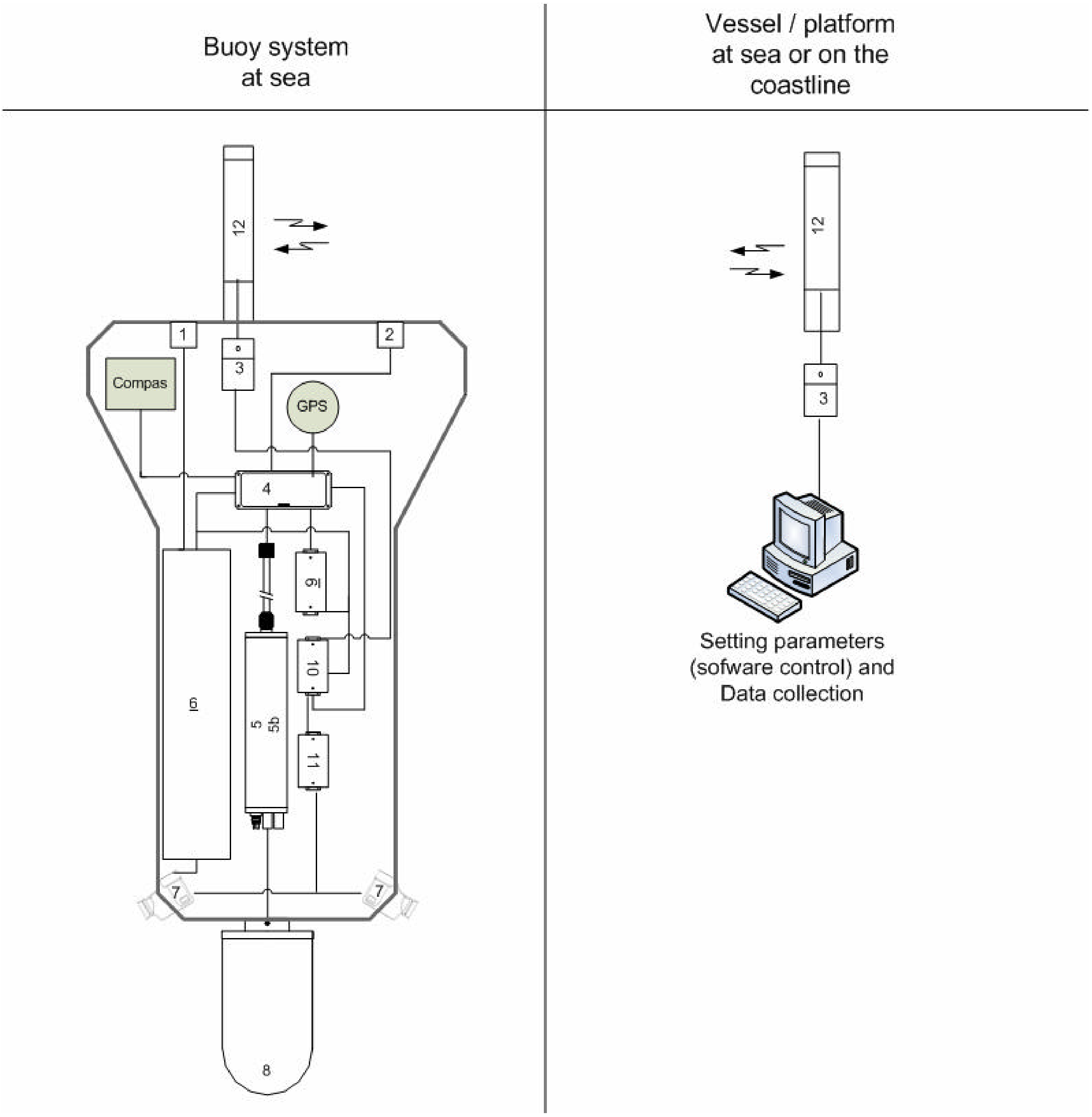
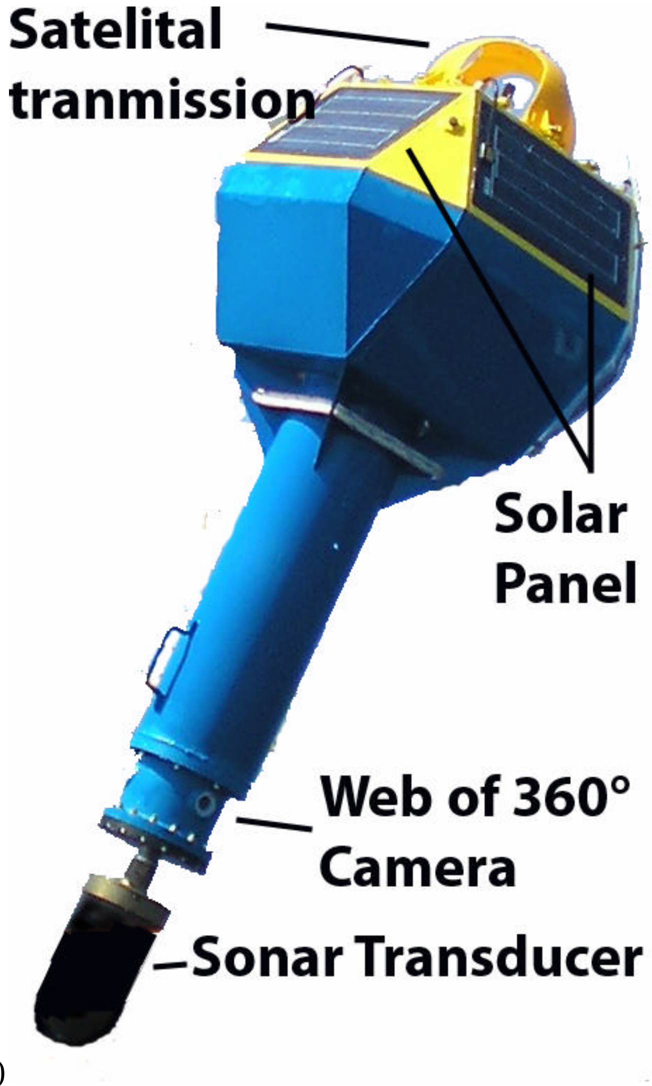

communication
Server
Website
Data
Storage
and analysis
20 m
50 m
100 m
200 - 600 m
300 - 1200 m
World
Wide
Web

Fig. 5.



Buoy system
at sea
Vessel / platform
at sea or on the
coastline
12
1
2
3
Compas
GPS
4
6
9
5
5b
10
11
7
7
8
12
3
Setting parameters
(sofware control) and
Data collection

Fig. Annex 1


Satelital
tranmission
Solar
Panel
Web of 360°
Camera
Sonar Transducer

(A)

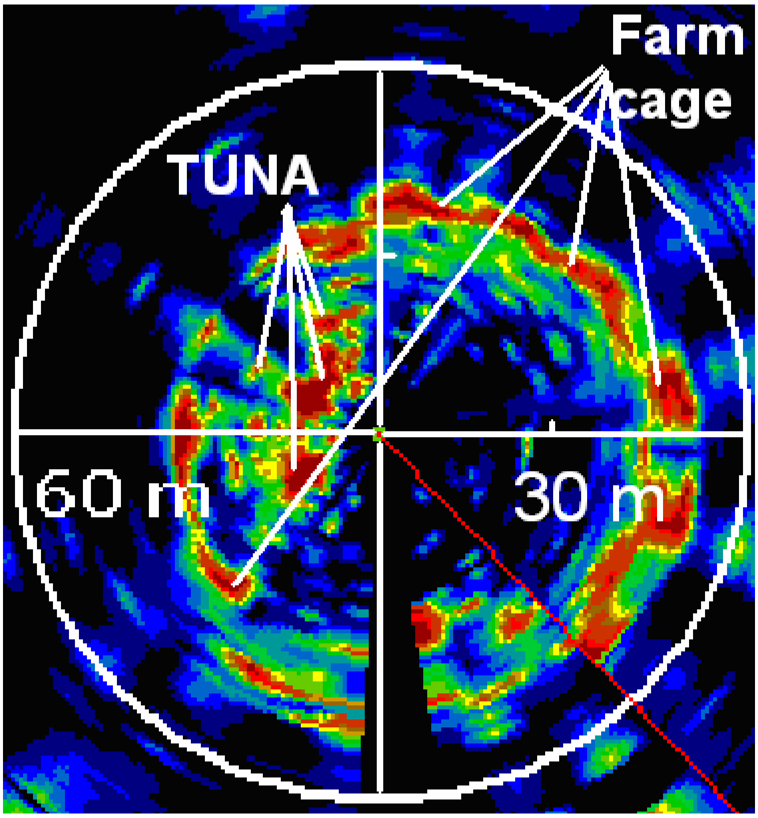
(B) 

Fig. Annex 2