

Aerospatial remote sensing as catalyst of an operational marine fishery (halieutic) science

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Abstract. A brief balance of the attainments and limits in the modern halieutic (fishery biology and economy) field is stricken and shows off the gap between the present management structure and the present problems. The surface tuna fishery case is thoroughly studied, considering its specificity and its economical importance. From there, it appears that conclusive strides will be made by halieutic science through the knowledge of the relationship between tuna and its environment. Some tuna environment studies are presented through typical remote sensing examples and introduce the basis of a coherent theory of tuna behaviour which can be schematically summarized by this basic general hypothesis; namely, that if tuna are present in a zone they will be inclined to aggregate close to any anomalies (gradients) of parameters in their environmental sensing field. From there, several models are presented in order to assess or forecast surface tuna stocks. A second part analyses the potential and contribution of the aerospatial remote sensing in the halieutic field through several original examples which point out clearly that this technique is one of the only tools able to visualize some essential concepts in oceanography and halieutic science. Last, we propose a study in several countries within the framework of several activities to integrate remote sensing tools in the fishery management structure, and to establish the data acquisition system in remote sensing satellites. From this study, a true operational halieutic field can be created.

1. Introduction

In the most concrete and the most general meaning of the word, a fishery is just a zone in the ocean, found by fishermen, where there exists a spatial and/or temporal concentration of living substances, a supply of necessary proteins or gastronomic ingredients, or currency. The halieutic science or fisheries theory is the science which searches for optimization tools for the efficiency of these fisheries. So, halieutic science includes fishery biology and economics.

2. The problem

2.1. *Brief assessment of inputs and problems in modern halieutic science*

Before introducing the operational halieutic concept, it is necessary to draw up a short and very schematic table of fishery exploitation mechanisms to diagnose the status of fisheries methods.

The behaviour of fishermen, who are more or less encouraged by the lack of legal restraint does not change, so the fishery is very often ruthlessly exploited. While the increase in fishing was, at most, proportional to the increase of catches this was not of great importance, but for many fisheries in the last fifty years, the increase of fishing has clearly surpassed the increase in catch and in many cases we have seen production

collapse for lack of stabilization. Consequently, there are a number of economic problems which generally generate some management laws without scientific basis, a call for scientific proposals, and eventually new laws arising from the first results of scientific programmes.

We may note that this scheme, in spite of its extreme simplification, remains even now very general indeed. Fisheries which adopt scientific management are rare, relatively recent and operate in traditionally unexploited zones for harvested species; for example, shrimps in the Persian Gulf or lobster in Western Australia.

By analogy with the terrestrial ecosystems laws, it has been possible to find the parameters—the symptoms—of the fishery state in considering the marine ecosystem characteristics; for example, the very high natural mortality rate (egg number is very often important). Because the goal of research is to evaluate the stock level, the population dynamics experts have elaborated the concept of the fishery unit or population (Laurec and Le Guen 1981) relatively independent of external events (isolation criterion) and without subpopulations having very different characteristics (homogeneity criterion). To assess the population abundance, it is necessary to know or to estimate the following data, which can be classified into three groups:

- (1) (a) species distribution field, statistical catches, and unit effort. To determine, for example, whether there could be two populations within two fields, or whether the same stock could be exploited by two different fisheries.
(b) data about size (age) composition of catches.
- (2) (a) spawning zones,
(b) biology and physiology characteristics.
- (3) the species behaviour in its environment.

Research efforts have developed in different ways, thereby generating a separation between the studies and the experts.

For thirty years, mathematical investigations and computer technology have encouraged models which try to find the mathematical equation (E) to express the relation between recruitment, growth, natural mortality and fishing mortality (Beverton and Holt 1957, Diemientieva 1971, Laurec and Le Guen 1981). Generally, fishery data and tag data are used. For each piece of research in a new field, the marine population dynamics gave outstanding results and allowed the diagnosis of the status and productive capacities of fisheries. However, like the deductions based on recent ecological information made by Dickie *et al.* (1987) we suggest that although current fishery assessment methodology has captured the main features of fishery production, it may not anticipate well the effects of early natural mortality or major changes in fishing.

Biology studies, while continuing classically, also indicated some elements which aided the evaluation of the same parameters of the mathematical equation (E). Studies of behaviour, or of direct assessment (count) have been neglected because of the difficulty of getting data. This difficulty was inhibitory until recent times for pelagic species.

2.2. *Industrial surface tuna fishery*

The industrial surface tuna fishery followed comparable evolution with its own specificity until the end of the 1970s; the problem changed for several reasons. First of all, from the point of view of the fishery industry, it was important to obtain a stock assessment for each year. Because of a dramatic increase in exploitation cost it has

become necessary to forecast the potential of fishing grounds, in order to maintain an acceptable energetic efficiency (in terms of harvested living matter per spent energy unit).

In the second place, international management has given way in part, to individual country responsibility because of the establishment of exclusive economic zones (EEZ). This is how international organizations such as the International Commission for Conservation of Atlantic Tunas (ICCAT), the Inter-American Tropical Tuna Commission (IATTC), and the Commission du Pacifique Sud (CPS) have declined in influence. To be convinced, one only has to analyse the proceedings of the electronic conference organized by the South Pacific Commission (SPC) on EIESnet (Telenet), following the text from Hilborn and Silbert entitled 'Is international management of tuna necessary?'

Lastly, to cope with problems of restructured technology (Japan), geopolitics (USA, Mexico) or stock abundance decreasing (French-Ivorian-Senegalese fleet), it seemed absolutely necessary to survey and, above all, to assess the halieutic stocks in virgin zones, i.e. without fishery data. Without such data, it has been necessary to develop environmental and behaviour studies. Even at this level, aerospatial remote sensing has been a first-rate tool to calibrate methods for fishing forecasting and directly assessing fishing potential.

This point of view can be illustrated by two examples.

2.2.1. *Aerial radiometry and tuna survey (ARTS) experiments in the South Pacific*

In the South Pacific the vastness of the area occupied by fisheries very often inhibits any classical study of oceanography or fishery biology. The rapid changes which have been observed in the tuna halieutic field in this region often make these studies unsuitable or decrease their interest. For instance, the important tagging programme realized by SPC since the end of the 1970s required with its methodology several years before getting some conclusions on the overall zone (Kearney 1978, Kleiber *et al.* 1987). The importance and the interest of this programme should not be questioned but its regional innovation created some difficulties, however, in dealing with socio-economic problems of the SPC countries which looked at these changes.

Between 1979 and 1984, ORSTOM developed an important programme of aerial remote sensing in the South Pacific French territories, in Vanuatu and New Zealand. The New Caledonia administration signed with ORSTOM a contract to realize aerial radiometry and tuna surveys between 1979 and 1982. The first aim of this research, paid by Fond d'Investissement Economique et Social (FIDES) and the Ministry of the Sea, was to assess the tuna resources potential in the area of New Caledonia, Wallis and Futuna EEZ with a view to developing industrial fisheries. In these areas, as in the whole South Pacific, the sea surface temperature was at this time not very well known and the fishing activities were simply Japanese pole and liners. As early as 1979 the first results of our programme were presented to the SPC tuna conference. This generated requests for similar experiments in some South Pacific countries. So ORSTOM signed contracts with the administrations of Vanuatu in 1980 and French Polynesia in 1982. Finally, in 1983 New Zealand asked ORSTOM to install aerial radiometry equipment with its methodology on the search commercial aircraft for US seiners operating in New Zealand waters. The principal aim in this case was direct fishing assistance.

All in all, not less than 2400 hours were flown in the South Pacific area. A general view of the material and method was given in numerous reports (Petit and Henin

1982, Petit and Kulbicki 1982). We can note that the ARTS method has been used, in aggregate or in part, for a long time by several French (ORSTOM, Institut français de recherche pour l'exploitation de la mer (IFREMER), university, weather service) and foreign (Japan, U.S.A., Australia) laboratories.

In short, the *modus operandi* is as follows: the flight path is determined after the analysis of various historical data (general hydrology, fishing statistics), some SST data (satellite and merchant ships) and earlier flight results (SST, catches, weather). Then the survey zone is defined but the path within this zone, can be changed during the flight because of thermal or weather changes. It is essential to find the optimal survey conditions for the success and efficiency of flights.

During the flight (altitude between 90 and 450 m), we record every 5 min or for each event (by 'event' we mean tuna schools, logs, fish aggregative devices (FADs), SST gradient, sea colour changes, cetaceans birds or fishing boats).

The records are as follows:

- nature of event
- time
- cloud
- cloud level for atmospheric correction
- sea surface temperature after correction
- position
- heading
- sea state and colour
- wind speed and direction
- distance between plane path and spotted tuna schools.

By finding thermal anomalies on surface water, aerial radiometry focuses the aerial spotting on the best zones where tuna seem to gather. Thus, this method gives three kinds of results which concern tuna ecology, abundance, assessment and distribution and, in real time, the evaluation of the fishing richness potential in the survey area (Petit and Henin 1982, Petit and Kulbicki 1982).

Thus, it has been confirmed that, in the South Pacific, when frontal zones and tuna are present, tuna aggregate near these zones. The aggregative effect of islands and sea mounts has been shown. The whole set of observations has allowed us to elaborate a coherent theory of tuna behaviour (Petit 1986).

The halieutic potential assessment, in real time, for the aerial survey area and direct fishing assistance have been made several times during these experiments. In New Zealand, for example, with US seiners, in Tahiti with local trolling boats, and with local and Japanese pole and liner companies in New Caledonia.

The principal results of these studies are the perfecting of an assessment method for surface tuna stock, and putting the method into practice. This method (Petit 1984) integrates a mathematical model (using non-parametric statistics) which attempts to take into account the influence of the different parameters (time, sea surface temperature, clouds, sea state, distance from land, distance between schools, season, etc.) as well as the discontinuous character of the sightings (tuna schools, birds, whales and porpoises, etc.). The concept of mathematical distance δ , which allows the data to be reduced to a single dimension, is used. By fitting a curve to these data we can compute the relationship between δ and the spot probability which is used as an index of abundance. Then, using an estimate of the school size and surveyed area, we can also compute the relationship between δ and the tuna density. We found that the

Tuna potential estimation from aerial radiometry and tuna survey (ARTS) data for the New Caledonia and Vanuatu areas (Petit 1984).

Area	Prospected surface (miles)	EEZ surface (from SPC) (km ²)	Estimated surface stock in prospected surface		Estimate surface stock in EEZ surface (tonnes)
			weight (tonnes)	density (tonnes/km ²)	
New Caledonia 14°30'–26°00 S 158°00'–175°00 E	222 309	1 540 000	88 848 (51 988–126 055)	0.117 (0.068–0.165)	154 566 (90 440–219 295)
Vanuatu 12°50'–22°00 S 165°00'–147°00 E	121 431	670 000	47 910 (27 971–68 032)	0.115 (0.067–0.163)	67 663 (39 502–96 082)

two functions are exponential, with a statistic security coefficient of 0.001. Finally, using this estimated density the surface tuna potential of the New Caledonia–Vanuatu area was evaluated (see the table): New Caledonia EEZ between 90 000 and 220 000 tonnes; Vanuatu EEZ between 40 000 and 96 000 tonnes.

The density is about 0.12 tons/km² in both cases. This value is very close to the SPC tuna programme value (0.10 tons/km²) found for all the stock (surface and depth). Figure 1 shows the different strata, and in particular those which have a strong power in aggregating tuna.

2.2.2. PREVIPECHE model used in the tropical Atlantic

This model is developed in detail by Stretta (1991). From the analysis of water mass history and by computing SST charts (GOSSTCOMP-METEOSAT) between 1982 and 1985, this model provided forecasting bulletins to French–Ivorian–Senegalese (FIS) fleet (Stretta and Slepoukha 1983, Stretta and Petit 1989).

2.3. Halieutic research context and the operational halieutic context

As one can foresee from the preceding sections, the industrial surface tuna fishery is a typical case where the answer of classical halieutic methods is not satisfactory. The changes, seen in the fisheries world-wide distribution, such as moving the FIS and Spanish fleets from the Atlantic Ocean to the Indian Ocean, or moving the American fleet from the East to the West Pacific, or the restructured technology of the Japanese fleet, should encourage us to develop a really operational halieutic method. Indeed, it is obvious that during the coming years fishery management will not be satisfied to add some points to the catch per unit effort (CPUE) curves. The character of the halieutic resource is limited. The world-wide expansion rate decreased from 7 to 1 per cent during less than ten years (Troadec 1982). Exploitation costs are raising and the EEZ laws are problematic. It is better, therefore, that the aim of modern operational halieutic programmes should not be confined to present-day problems, but rather should aim to develop a research programme, with the aid of aerospatial remote sensing, which will provide for the future the maximum amount of resources data.

3. Analysis of potentialities and limits of aerospatial remote sensing

As indicated above, the aim of tuna study is to know and to understand the dynamics of schools by the evaluation of their number, their aggregation and their movements. As it is difficult or impossible to observe these phenomena directly, the

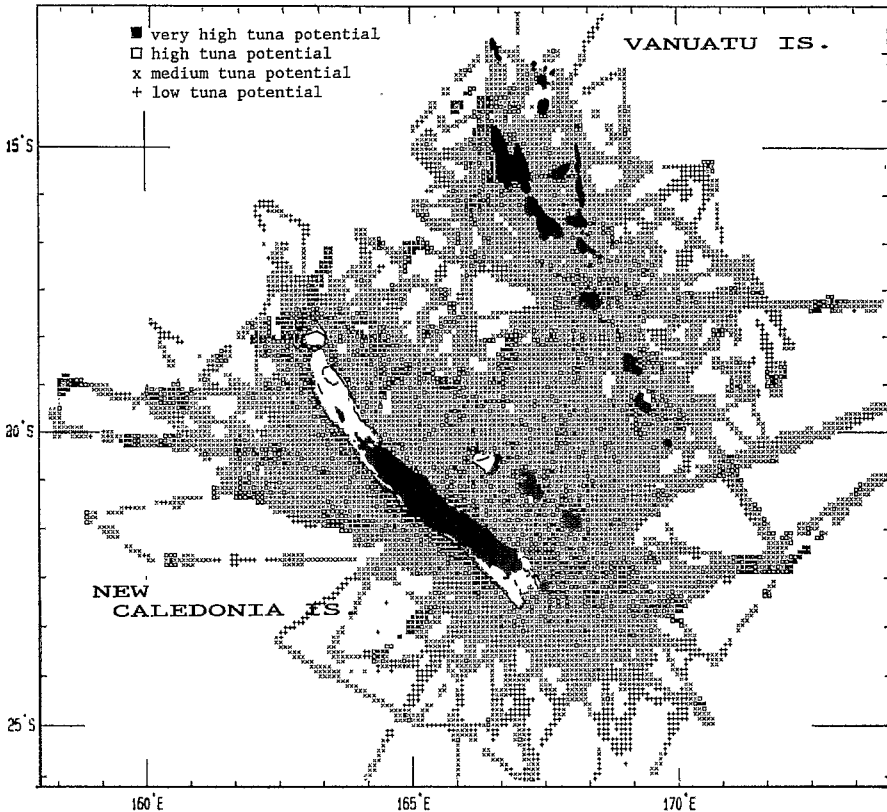


Figure 1. Assessment of surface tuna potential in New Caledonia and Vanuatu area from aerial and tuna survey (ARTS) data (Petit 1984)

studies are interested in determining the physico-biological mechanisms which govern them. Most of the time the models (Maugham 1972, Petit 1976, Stretta and Slepoukha 1983, Petit 1986, Mendelsohn and Roy 1986) are reduced to the study of the optimal cells or volumes in which tuna schools are distributed and find euphoric (optimal) conditions of life (Postel 1969). In this way, the migrations are reduced just to a movement of these cells which can come from: a physical movement of the water volume in three dimensions, and/or a continuous change of the optimal conditions in time, and/or a continuous movement of the optimal conditions in space.

Of course aerospace remote sensing is not and cannot be the panacea which should solve all the problems. Because of its own methodology, remote sensing does not provide directly usable data. It is here that the model concept known as Previpecche, comes in. These models simultaneously analyse principal and secondary data, in real time, and historical data. This kind of integration is operational in meteorological science and must henceforward prevail in halieutic sciences. Because the spatial scales of remote sensing are in line with the study zones, we now have a tool that on the one hand is useful for scientific study and on the other hand is a powerful aid to the tuna fishing industry. The two examples are now classical experiments. We are going to try to show here, through some original examples, the

possible evolution of this technique, its applicability to the current problems and, finally, its potential to catalyze the emergence of an operational halieutic method.

3.1. *Example 1: VARANS-S RADAR (SAR) in halieutic studies*

The high-resolution imaging radar has been developed by CNES with IFP support. It is implemented by CNES onboard an IGN aircraft within the framework of GDTA. This is a side looking airborne radar (SLAR) using synthetic aperture radar (SAR) mode within the X band (9375 MHz). Its antenna is stabilized in pitch, roll and yaw and can be used with vertical or horizontal polarization. Ground incidence is around $45^\circ \pm 20^\circ$, geometrical resolution is close to $3\text{ m} \times 3\text{ m}$ in the one-look mode, or $9\text{ m} \times 9\text{ m}$ in the nine-looks mode. All these parameters have been carefully chosen with a view to simulating potential future images from satellites.

This radar has flown since 1985—in the SAR mode—and a large number of different terrestrial and aquatic fields have been studied (agriculture, forest, geology, etc.). Recordings of oil pollution and slicks have been carried out in the Channel, in the Atlantic Ocean and in the strait of Gibraltar. The oyster-beds and small-scale fishing tackles in the Languedoc–Roussillon coast in France have been investigated. Some stationary and internal wave studies have been performed in the Gibraltar zone and bathymetric evaluations have been realized in the Pas-de-Calais area. Some radar data about swell and waves have been recorded to improve the definition of numerical models in the Atlantic ocean. This brief list of the VARAN-S applications shows well all the interest in this sensor for the studies at sea (see Wadsworth 1991).

The technical characteristics of this radar equipment are such that the tuna schools, in their surface behaviour, and associated sightings (birds, cetaceans, floating logs) could be detected from 6000 m altitude, within a 10 nautical miles swath; and up to 20 knots wind speed. Thus, the potential of this radar for detecting sea surface deformation, makes it a very efficient tool for drawing up a complete inventory of fishing effort (boats, nets, traps) in a small-scale fishing field. With a view to checking the potential of this radar we have proposed the HAREM experiment (halieutic radar experiment Mediterranean sea). In this experiment (figure 2) we wish to study precisely the relation between the radar signal and Mediterranean bluefin schools (HAREM-thon), and on the other hand small-scale fishing tackle (figure 3) in the Languedoc–Roussillon Lagoon (HAREM-Etang). The aim, beyond this experiment *sensu stricto*, is to restate a direct method for assessing tuna resources from surface sampling as an alternative to classical assessment methods which are always dependent upon fishery statistics and which are not available in unfished areas. This experiment was conducted during August 1989, with DLR radar (E-SAR) and not VARAN-S for technical reasons, and the results are reported by Petit *et al.* (1990).

3.2. *Example 2: SPOT as an oceanographic satellite*

It is necessary to spot the sea state and surface, not only to develop fundamental knowledge of oceanographic phenomena, but chiefly from an economic (navigation, oil platform, fishery) point of view. Until now, the visualization of this surface from satellites has principally been performed by radar sensors (SAR, SIR-A, SIR-B) which aimed sideways at the sea surface and provided data about the surface roughness (waves). In addition, within the visible band (MSS then TM) Landsat has very occasionally allowed the observation of oceanographic phenomena or the sea state. However, it was a real surprise to establish that the SPOT-1 satellite in spite of expectations or even simulations, was able to provide very good images of ocean surface.

These unexpected performances have been described elsewhere (Wadsworth and Petit 1987, Wadsworth 1988). The high resolution of SPOT would seem of great interest, but in fact it is not so important in considering oceanographic phenomena. What plays the essential role in the surprising SPOT efficiency is the possibility of tilting the sensor, i.e. to aim not only in a vertical but also oblique plane, with as much as a 29° angle of incidence. The multispectral images we can obtain in an east sighting, close to the specular reflection effect, allows us to detect oceanographic surface phenomena. With Landsat or with SPOT in vertical sighting, we obtain all the information from the sea colour. That is also true with SPOT in oblique sighting; thus, the signal is very clear and correlated in three bands even in the infra-red band which allows absolutely no water penetration. These, then, are the surface effects which are observed. In addition, the detected signal has a similar morphology with a radar signal. So, it is certain that the east oblique SPOT sightings come from local variations of the sea surface roughness which is modulated by deep oceanic phenomena, as we know from aircraft radar studies. The SPOT field of view ($4^\circ 13'$) is narrow and allows homogeneous detection over a swath of about 60 km. This is a good scale for ocean studies. In addition, numerical processing, necessary within vertical sighting images because of the low sea image density, is not necessary with oblique sightings.

Wadsworth and Petit (1987) and Wadsworth (1988) gave numerous SPOT images to illustrate detection of waves, internal waves, fronts, eddies, boats tracks, oil slicks. As a direct application of this SPOT potential, sea mounts detection has been recently

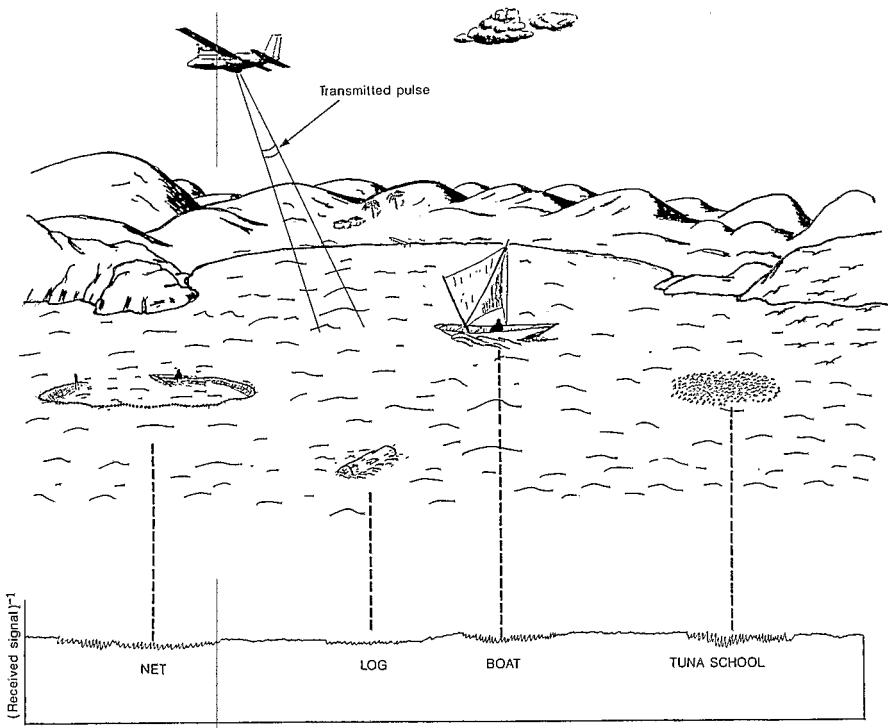


Figure 2. Synoptical view of HAREM (halieutic radar experiment in Mediterranean sea).

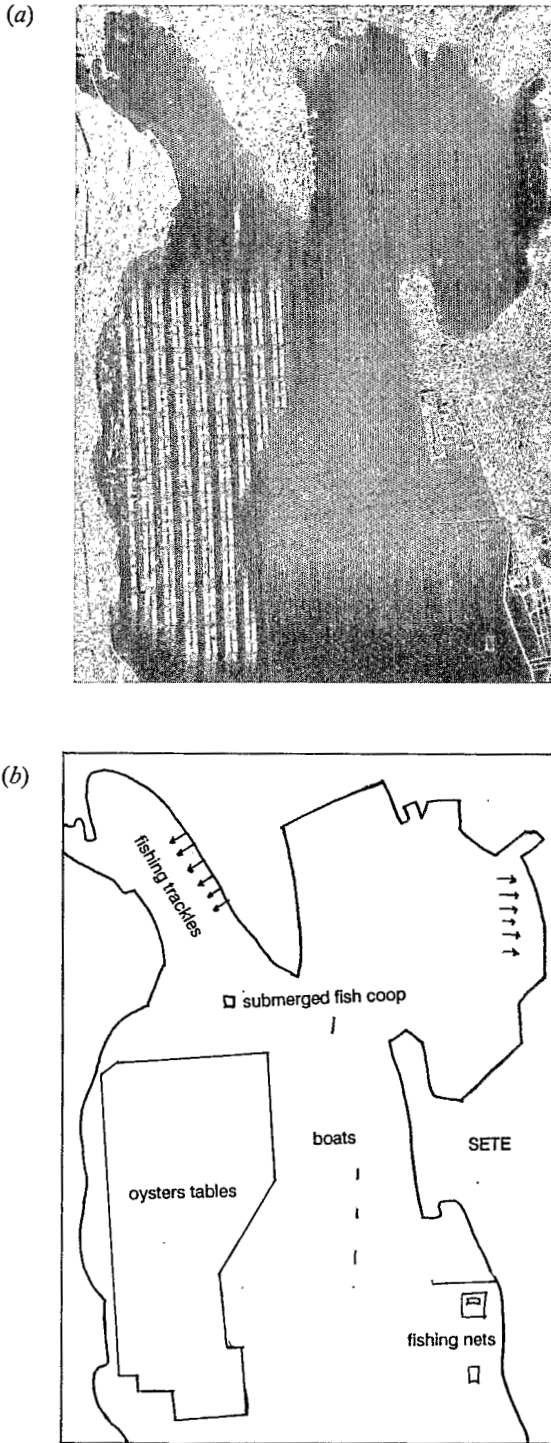


Figure 3. Results of HAREM's pre-experiment: a VARAN-S radar image has been (a) recorded, and (b) interpreted in the SETE (Mediterranean coast) region (Wadsworth, personal communication 1986).

shown (Petit *et al.* 1989). In this study, the SPOT image presented is near a volcanic sea mount, the coral top of which is at about 10 m depth. The oceanic surface anomaly, which is shown by very simple SPOT image processing, spreads 20 km wider. The importance of such sea mounts to increasing the richness of water masses is known (Boehlert and Genin 1987), and the interest for tuna fisheries is evident.

Of course, SPOT has its own limits. First, no useful data can be obtained when it is cloudy or at night, as can with a radar satellite. Then to observe the surface roughness it is necessary to obtain a minimum roughness, i.e. minimum wind force, that is not really restrictive. However, if the wind speed is too high (force 6), breakers hide the roughness variations.

We emphasize the fact that nobody was expecting this kind of performance from SPOT over the sea: SPOT Image Corporation does not record sea images systematically because, until now, the requirements concern mostly terrestrial zones. So for oceanographers the possibility of obtaining SPOT sea images is a real asset and it will not cause conflicts with the satellite recording programming.

3.3 *Primary production with visible multispectral satellites (Nimbus-7)*

One of the keys of halieutic methods in the next few years will be to understand how the euphoric environment of harvested species is distributed, is modified and moves. This will be true particularly for tuna species. So the forecasting of rich zones concerning primary production will be a very important crossroad for operational oceanography and halieutic methods. From the following example, we understand to what extent aerospatial remote sensing can help in perfecting and overturning classical concepts.

Tropical seas are major sites for extensive cyanobacteria (blue-green algal) developments. The oceanic nitrogen fixation caused by such blooms may be of relatively great importance with regard to the global nitrogen budget.

Dupouy *et al.* (1988) found a large phytoplankton bloom (90 000 km²) within a Nimbus-7 Coastal Zone Colour Scanner (CZCS) image on 4 January 1982 around New Caledonia and the Vanuatu archipelago, located east of Australia in the Coral Sea (165° E, 20° S). The bloom was caused by cyanobacteria, presumably *Oscillatoria* (*Trichodesmium*) spp. which occur systematically in this region. This assertion was not confirmed by simultaneous sea truths, but several indications and current knowledge of the region indicate that our hypothesis is reasonable. By using the CZCS image, an estimate is made for the nitrogen fixation of the bloom. It suggests that such a biological event plays a significant role in the global nitrogen oceanic budget.

4. **Synthesis and conclusions**

From the preceding examples it is now possible to come to some conclusions.

Aerospatial remote sensing allows us to quantify, and helps us to visualize, oceanographic and halieutic concepts. Thus, it can assist in spatio-temporal surveys.

High-seas oceanography and the tuna halieutic studies have similar requirements in the spatio-temporal scale for surveys and the essential parameters of their research. For the next ten years, several satellites will be launched (ERS-1, JERS-1, Radarsat, EOS) which are, to a large extent, dedicated to high-seas studies. So it seems that with these new space tools a new age for oceanography and halieutic studies is coming in the very near future; these changes must be conducted on a planetary scale and should emerge into operational oceanography and halieutic methods.

However, these developments will be obtained only if the sea observation strategy, the satellite data selection and their commercialization, and finally the data transmission, are integrated.

To emphasize these conclusions, it is necessary to keep in mind the fishery context.

A purse seiner, a tuna fishing boat, is a real production unit with just twenty people on board and is worth 8–9 million ecu. The world-wide annual fish catch is approaching 80 million tons and represents one of the most important sources of animal proteins. More than two hundred million people are living on the marine biological resources, and the fisheries business corresponds to about 30 per cent of marine activities. In spite of that, advances in fishery came mainly from the accumulated experience of fishermen, and the difficulty in developing efficient and scientific methods for operating boats and managing resources is considerable.

In spite of the economic importance of fisheries and the fact that remote sensing is becoming adult, the remote-sensing investigation in halieutic fields has stayed on a very limited basis, with some experiments in the U.S.A. for tuna, albacore and salmon, or in Europe for tuna and albacore too. However, two exceptions are to be noted, the fishing aid bureau (BAP) of ORSTOM in the Ivory Coast (between 1978 and 1984) and the programme now realized in Japan by JAFIC (Japanese Fisheries Center), reported by Doumenge (1987) have run or are running on an operational basis.

We think that it is the time to become conscious of this reality, particularly in Europe, and to promote integrated studies within an international framework.

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