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The efficiency of using remote sensing for fisheries enforcement: Application to the Mediterranean bluefin tuna fishery **

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Abstract:

This paper analyzes the impact of applying vessel detection technology using satellite images (vessel detection system, VDS) to complement air patrols for fisheries enforcement and control. Due to limited fisheries enforcement budgets there is the need to allocate costs efficiently among competing control tools. This paper focuses on assessing the benefits of using VDS jointly with VMS (vessel monitoring system) and air patrol surveillance to improve effectiveness of controls. A statistical model to estimate the number of inspections was developed and was used with enforcement costs data as reported by a number of EU countries. The result of applying VDS in fisheries enforcement is presented in one of the most demanding fisheries enforcement contexts: the Mediterranean bluefin tuna (BFT) fishery.

Highlights

► Reduced fisheries enforcement budgets require more efficient control tools ► VDS can complement VMS and aircraft inspections ► Development of a statistical model to measure the efficiency of VDS ► Application of the model to the Mediterranean bluefin tuna fishery with real data ► Results indicate that savings of 10–12% can be obtained through the use of VDS.

Keywords: Vessel detection system ; Synthetic Aperture Radar ; Illegal fishing ; Cost–benefit analysis; Bluefin tuna

** CAVEAT: The opinions expressed in this paper do not reflect the European Commission's positions or policy.

1. Introduction

Fisheries enforcement of fisheries management systems is typically quite costly relative to the gross value of the fisheries. Available empirical estimates put the cost of fisheries enforcement at somewhere between 2 and 8 % of the gross value of landings [1]. In the Mediterranean this percentage is estimated at 1 to 10% [2,3].

As the total value of landings by the EU fleet is estimated to be more than seven billion Euros, the cost of fisheries enforcement might well be between 150 and 600 million Euros per annum. It is likely that these funds could be more effectively used. A recent study conducted on a number of fisheries worldwide, suggested that the optimal enforcement system maximizing social benefit, expressed in terms of enforcement tools and their optimal intensity, seems to be very far away from the current situation [4].

Naturally, the enforcement effort is affecting the cost of enforcement. As predicted by the theory, most fisheries confirmed that an increase in the enforcement level will increase the compliance and the social benefits up until the point where the costs of enforcement outweigh the benefits [4-8]. Consequently, a better allocation of resources in different enforcement tools is needed so that the optimal level of control is achieved at lower costs.

Fisheries inspections can take place at sea using patrol vessels or aircrafts, or at port or even at later stages of the market chain. However, not all types of inspection can detect the same type of irregularities or illegal activities. For example, inspections at landing ports can detect mainly the presence of undersize fish, forbidden species or excesses in the quotas, while inspections by aircraft are mainly used to detect vessels fishing illegally.

Often aircraft inspections are used in conjunction with automated systems that monitor the vessel positions and activity. The most important system of this type is the Vessel Monitoring System (VMS). VMS is used widely worldwide, while it is mandatory for all EU fishing vessels above 12 meters in length [9]. The fishing vessels having this device on board transmit GPS-derived positions by satellite to their national Fisheries Monitoring Centre (FMC) at regular intervals.

Although VMS is a powerful tool for fisheries enforcement, it assumes cooperative behaviour by the fishers. Moreover, not all fishing vessels are equipped with this system while VMS boxes can also malfunction, or be switched off or be manipulated to report wrong positions. In contrast, the Vessel Detection System (VDS), another type of automated system, allows for an independent identification of vessel positions through the analysis of satellite Synthetic Aperture Radar (SAR) imagery. In this way, it can also detect non-cooperative vessels. Over the last few years the VDS through SAR imagery has evolved and has become relatively mature technology with applicability to the maritime context at the operational level. VDS relies on polar orbiting satellites carrying SAR instruments, which can detect vessels at sea under most conditions – day, night and through clouds.

Therefore, VDS is used to determine independently the number of vessels and their position in a given area. The vessel positions detected by VDS are then cross-checked with vessel positions as provided by VMS. In this way, VDS flags the possible presence of suspicious fishing vessels from which no position reports have been received through VMS [10, 11]. Image delivery time (necessary for VDS) will depend on the capability and geographic location of the satellite receiving station and normally can vary from just a few minutes to one hour, if near-real-time was requested. Thus, the use of VDS has the potential to increase the efficiency of aircraft controls, because inspections can be directed towards areas where suspected targets are identified (i.e. when vessels appear on the VDS image that do not match with vessels reporting through VMS).

However, satellite images are still relatively expensive. Considering that fisheries enforcement budgets are limited, VDS should only be used if it can be proven that it is useful for fisheries enforcement. Accordingly, EU countries are required to ensure the operational use of satellites for fisheries control and enforcement in contexts where cost-benefit can be established [9, 12].

For what concerns the BFT fishery, praised for its high valued flesh, tuna has become one of the most important target species in fisheries worldwide. It has been fished in the Mediterranean waters since at least the 7th millennium B.C. In modern times, annual catches in the Mediterranean increased dramatically after the mid 80’s, from less than 10,000 tons up to more than 30,000 tons in the mid 90’s. Introduction of annual quota regulations in 1998 leveled these numbers below 25,000 tons in subsequent years, reaching 12,500 tons in 2009 [13].

However, , the ICCAT assessment of bluefin tuna stock status for eastern Atlantic and Mediterranean reported a strong decline in number and biomass of adult fish (spawning stock) since 1993. There is consensus [14] that among 26 tuna populations worldwide, eastern Atlantic bluefin tuna can be assigned the lowest status, i.e. “overexploited”.

Satellite technology has been widely used by fleets as an aid to fishing. Tuna fisheries were the first to use satellite technology (back in 1971 - US tropical Pacific tuna fleet) to search for tuna schools as discussed in Santos [15]. With this technology fleets reduce the searching time, and consequently the fuel consumption and their costs. While the fishing industry has been using satellites to reduce costs for years, this work aims at demonstrating that it can also reduce the costs of fisheries enforcement.

In order to measure the impact of VDS to reduce the cost of fisheries enforcement, a statistical model that estimates the probability of detecting position infringements is proposed. As explained in the following sections, this model takes into account the two main types of position infringements depending on whether vessels had or did not have VMS on board (if they had VMS, because it was switched off or was malfunctioning). The model allows for the quantitative assessment of the contribution of VDS to reduce the cost of airborne fisheries enforcement, based on the reduction in the number of air patrol hours to reach the same level of infringement detection.

The paper is structured as follows: The first part provides a description of the model and the assumptions considered, and is followed by an overview of the different enforcement modalities and their estimated costs. The paper then continues with the application of the model to the Mediterranean bluefin tuna fishery and discusses the results. Finally, the paper concludes with an assessment of the ability of VDS to increase efficiency of fisheries enforcement by reducing its costs.

2. Methodology

To measure the efficiency of VDS we estimate the required cost necessary to perform the same level of infringement detection, with and without remote sensing to support current enforcement means. This is done with a model that calculates the probability of discovering position infringements based on VMS data as well as the capability of the airplane to discover the actual position of the targets as vessels move into its radar footprint.

2.1. Assumptions

This section discusses the assumptions that have been made for the development of the model.

Infringements: In general two different position infringement types are considered. The first type is due to vessels that are broadcasting either intentionally or unintentionally erroneous information about their position (these are VMS positions that could not be correlated to a satellite-derived target); this is called **positional infringement** and N^{i}_{vms} is the number of vessels that are reporting these erroneous positions. A second type of infringement is committed by vessels that have switched off their VMS or lack VMS equipment (it is not possible to distinguish between these two cases) but carry out illegal fishing; such vessels are detected by the radar but cannot be correlated to any VMS signal. We call this behaviour action infringement; and N^{i}_{nvms} is the number of vessels that commit such position infringements.

Note that there are other types of infringements not related to vessel positions but to licensing, fishing authorisations, use of illegal gears, catching of non-authorized species, non respect of other technical measures etc. These are not considered by the model, as they are not detectable though VDS' SAR technology. Even if the above seem to constitute the majority of reported infringements, it is logical to assume that a vessel conducting ‘positional infringement’ is more likely to conduct other types of infringement as well.

A Priori Knowledge: It is assumed that surveillance is planned (before being executed) based only upon VMS information (this is in fact valid in areas far away from any coastal or patrol radar available to enforcement authorities). It is also accepted that all VMS tracks are treated evenly and there is no special targeting of vessels (e.g. inspecting only vessels of a certain nationality or fitted with a given type of gear). Therefore distinction is only made at the level of "whether a vessel is committing an infringement or not".

Spatial Distribution: The model assumes that the targets are evenly distributed and the time that a plane employs to check each target is constant, which allows achieving statistically representative results at a general level [16-18].

Discovery of New Vessels: Since patrol planning is only based on VMS, it is when the plane arrives to the inspection area and moves to check the VMSs positions that it starts detecting the actual number of vessels that are present in the area, regardless of the number of initial VMSs that were available before taking off. Some of these vessels will also be taken into account thus modifying the initial plan of the inspection. Since it has been assumed that vessels are evenly distributed, the number of vessels that are discovered on the spot will depend on the coverage of the radar and it is assumed to be a proportion of the total number of vessels that a plane can check during a flight (due to the limited time that the plane is in the air).

Accuracy of the VDS: The images used in this study have 25 m resolution (this is the minimum distance that allows distinguishing between two close targets), however in terms of detection it is possible to detect targets under the resolution size provided that they have a high radar reflectance (e.g. man-made objects such as vessels). This feature allows the detection of vessels well under the limit of the resolution size; as an example, in the course of VDS campaigns, the correlation between VDS targets with VMS and AIS data allowed JRC to verify the detection of vessels of 17 m length with 25 m resolution images.

Regarding errors, VDS false positives (detections without vessels) has not been taken into account. VDS errors are normally a very small fraction of total detections, but they can increase in case of rough weather conditions or in coastal areas where high degree of azimuth ambiguities can occur.

2.2. The model

Taking into account the above assumptions, it is possible to assign the probability of detecting a certain number of VMS infringing vessels (k_{vms}) and non VMS detected vessels (k_{nvms}) as:

$$P(\chi_{vms}=k_{vms},\chi_{nvms}=k_{nvms})=\frac{\binom{N^{i}_{vms}}{k_{vms}}\binom{N^{ni}_{vms}}{P_{vms}\cdot n-k_{vms}}}{\binom{N_{vms}}{P_{vms}\cdot n}}\cdot\frac{\binom{N^{i}_{nvms}}{k_{nvms}}\binom{N^{ni}_{nvms}}{P_{radar}\cdot n-k_{nvms}}}{\binom{N_{nvms}}{P_{radar}\cdot n}}=Pk_{vms}\cdot Pk_{nvms}$$

where $\binom{}{}$ is the combination operator. $N_{vms}=N^{i}_{vms}+N^{ni}_{vms}$ is the total number of vessels that are sending VMS messages, obtained from the addition of infringing vessels (indicated by i) and vessels not doing infringement (indicated by ni). $N_{nvms}=N^{i}_{nvms}+N^{ni}_{nvms}$ is the number of non VMS targets (vessels only detected on satellite images ,i.e. vessels with no VMS equipment or intentionally being switched off), also divided between vessels committing or not position infringements. Parameter n gives the number of vessels that are checked by the plane. K_{vms} and K_{nvms} are the number of infringing vessels to be found, these committing positional and action respectively that are to be found. Finally P_{vms} and P_{radar} reflect the proportion of vessels that will be uniquely discovered by either VMS or the aircraft radar and which are intrinsically related to the total proportion of vessels equipped with functioning VMS system during the time in which the action is taking place. The condition $P_{vms}+P_{radar}=1$ holds in order that the number of discovered vessels $n\cdot P_{vms}+n\cdot P_{radar}$ remains n, total number of inspected vessels.

The situation is similar to the classical problem where a known number of black and white balls (infringing and non infringing vessels) are in a bag and we try to calculate the probability that a ball is black (infringing vessel) given a certain number (n) of extractions from the bag.

When combining the two terms: the first one takes into account preliminary information of VMS data (Pk_{vms}); and second, when the non VMS vessels that are to be discovered enter into the plane radar footprint (Pk_{nvms}), the already described probabilistic mixed model arises.

This model allows us to calculate the number of vessels to be checked (n) in order to achieve a given level of enforcement efficiency, which is done by detecting a certain number of infringing VMS (k_{vms}) and non VMS (k_{nvms}) with a certain probability threshold (P_{th}). Therefore try to minimize n such as:

$$P(\chi_{vms} \geq k_{vms}, \chi_{nvms} \geq k_{nvms}) = \sum_{k_{vms}}^{N_{vms}^{i}} \sum_{k_{nvms}}^{N_{nvms}^{i}} Pk_{vms} \cdot Pk_{nvms} \geq P_{th}$$

Once n is set, then it is possible to associate a cost of achieving this level of enforcement and study the case when VDS data is incorporated. This can be done by simply taking into account that when VMS-VDS correlation is provided, identification of most of the VMS positional infringing vessels is possible thus resulting in reducing the population N_{vms}^{i} by a certain coefficient (and by extension this also changes k_{vms}). The ability of VDS to reduce the value N_{vms}^{i} depends on the quality of the VDS and the proximity of the image acquisition time to the provided VMS positions. These will vary according to the image type employed to analyse, the size of the vessels and also according to some external factors such as the weather conditions at the image acquisition time.

2.3. Satellite images

Due to its ability to measure the electromagnetic properties of the targets, its all-weather, night-and-day and wide area coverage, SAR imagery is one of the most appropriate remote sensing techniques used in maritime applications. SAR satellites that were available and regularly used (when this study was conducted) for fisheries and environmental sea monitoring purposes: RADARSAT-1/2 and Envisat ASAR. Envisat's lifetime ended recently, but other SAR sensors are now available for this purpose: TerraSAR-X and COSMO-SkyMed constellations. And shortly, the new satellite called Paz will be launched.

By varying the incidence angle satellites can operate in several modes: from wide coverage at low resolution to narrow coverage at higher resolution. To choose the appropriate mode, a balance between spatial coverage and resolution needs to be found, depending on the size of the vessels to be detected and the area to be covered. A resolution increase can only be done at the expense of reducing the spatial coverage; this means that in order to detect small vessels (where higher resolution is required) the total surface covered by the image is reduced. This is determined by the satellite swath, which is the distance swept by the satellite footprint as it moves along its orbit during the acquisition.

Therefore, VDS costs will depend mainly on the type of vessels that needs to be monitored, as this requirement will define the resolution of the image to be employed. Then the size of the area required to control will allow us to calculate the total number of images needed. Table 1 presents a summary of the characteristics and costs of the most commonly used SAR satellites for fisheries enforcement at the time of the study.

Table 1. Characteristics and costs of sensor images for VDS for fisheries control (year 2008).

		Resolution	Coverage			Monitoring costs	
Satellite	Image mode	(in m)	Swath (in km)	Km2	Nm2	Unit price (Euro)	Cost per 100 Nm2
RADARSAT-1[1]	ScanSAR	50	300	90,000	26,400	3,174	12
	Standard	25	100	10,000	2,916	3,174	**109**
	Fine	8	50	2,500	729	3,174	435
Envisat	Image mode	25	60	6,000	1,749	N/A	N/A

For example, in North-East Atlantic (NEAFC waters), the most suitable RADARSAT ScanSAR mode was chosen, with 50m resolution and the swath covered is 300Km, since fishing vessels operating there are larger than 50m. In the Mediterranean, the fishing vessels are smaller, therefore RADARSAT Standard mode was chosen, with 25m resolution and a swath of 100km per image or Envisat ASAR image mode with equivalent resolution.

Table 2 presents a summary of characteristics and costs to be used in the Bluefin tuna fisheries enforcement scenario for the new alternative sensors available, in 2011.

Table 2. Characteristics and costs of sensor images for VDS for Bluefin tuna fisheries control (year 2011).

		Resolution	Coverage			Monitoring costs	
Satellite	Image mode	(in m)	Swath (in km)	Km2	Nm2	Unit price (Euro)	Cost per 100 Nm2
RADARSAT-2[2]	Standard	25	100x100	10,000	2,916	3,488	**120**

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[1] Using the current official price list for Radarsat-1 (http://gs.mdacorporation.com/SatelliteData/Radarsat1/Price.aspx) in effect since 2007 (the price used is 4,950$ Canadian dollars and is composed of image price plus NRT fee). The price is converted to euro using the official exchange rates for 2008 (1EUR=1.5594 CAD), extracted from the European Central Bank (http://sdw.ecb.europa.eu/browse.do?node=2018794).

COSMO-SkyMed[3]	ScanSAR Wide	30	100x100	10,000	2,916	2,450	**84**
TerraSAR-X[4]	ScanSAR	18	100x150	15,000	4,374	3,450*	**79***

With these new sensors, for the Mediterranean scenario, the choice would be: RADARSAT-2 Standard, COSMO-SkyMed ScanSAR Wide and TerraSAR-X ScanSAR. In 2011 the mean cost per 100Nm2 of those was 94 Euros (using table 2), around 2,800 Euros for a 100x100Km2 scene.

During the last few years, image providers have become more active in taking into account maritime surveillance requirements (e.g. Near Real Time services) and develop a different market model approach for maritime surveillance. The fact that maritime images lose the value of the information they contain more rapidly compared to inland images (where an image can be used in seasonal and even yearly studies) combined with the ease of accommodating sea customers' requests within their image acquisition plan (lack of conflicts due to less concurrent customers) has driven providers to adopt a more competitive stand[5]. JRC’s experience is that providers can offer competitive image package discounts for maritime surveillance that are proportional to the volume of images ordered by customers (typically these are Agencies at the EU or global level, government authorities, etc). It can be concluded that for the case where large campaigns are organised (such as BFT-tuna joint deployment plans (JDP) by EU Agency EFCA - typically, more than 100 images are purchased per JDP) or for regular services (such as CleanSeanet for oil spill detection offered by EU Agency EMSA) competitive discounts are possible thus lowering the surveillance cost. A sensitivity analysis of impact of image price variation on cost savings is included in the cost analysis section of this paper.

2.4. Aircraft surveillance costs

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[2] Using the official price list for Radarsat-2, (http://gs.mdacorporation.com/SatelliteData/Radarsat2/Price.aspx), the price used is 4,800 Canadian dollars and is composed of image price and NRT fee). Price is converted to euro using the official exchange rates for 2011 (1 EUR=1.3761 CAD), extracted from the European Central Bank (http://sdw.ecb.europa.eu/browse.do?node=2018794).

[3] For CosmoSkyMed in the official price list (http://www.e-geos.it/products/pdf/prices.pdf) the image price is 1,650 € and the NRT fee is 800 €.

[4] For TerraSAR-X, in the international price list issued in 2011 (http://www.astrium-geo.com/files/pmedia/public/r463_9_itd-0508-cd-0001-tsx_international_pricelist_en_issue_03.pdf) the image price is 2,750 €, but the NRT fee is not available. Since the NRT fee is not available in 2011 price list, 700 € (as in the 2012 price list) has been used.

[5] For example, TerraSAR-X has lowered its price to 1600 € during 2012 to celebrate its anniversary (http://www.astrium-geo.com/en/4214-terrasar-x-5-years-of-precision-reliability-celebrate-with-us-).

The analysis of aircraft surveillance costs for fisheries enforcement was carried out, based on data collected at the end of 2008 from several European countries: Belgium, Finland, France, Iceland, Ireland, Italy, Latvia, Malta, Sweden, Poland and United Kingdom, therefore representing inspection costs in the North Sea, Baltic Sea, Mediterranean and North East Atlantic.

Air surveillance costs depend very much on fuel consumption, and consequently vary a lot depending on the type of aircraft used and the area to be monitored (extension, distance from coast and density of vessels activity). An average cost per flight hour has been estimated at 3,800 Euros; on the average 4h50min flight hours are needed to monitor an area of about 10,000 Nm^2. Thus, we estimated a cost of around 170 Euros per 100 Nm^2.

3. Mediterranean bluefin tuna application

Each fishery has specific fisheries control and enforcement problems, depending mainly on the main species to be controlled, characteristics of the vessels and gears involved on that fishery, as well as the presence of support vessels or reefers.

In this section we apply the model presented to one of the most demanding fisheries in terms of IUU fishing enforcement: the Bluefin tuna fishery in the Mediterranean [19,20]. Bluefin tuna prices are relatively high and the fishery offers high potential catch, which have attracted many countries in the fishery, some of them coming from outside the Mediterranean basin. Moreover, there are many landing ports where catches are landed and near-shore farms where tuna is towed [21] hundreds of kilometres in large net-cages (also visible on SAR images). Figure 1 shows the distribution of overall vessel length per different gear from the VMS data received in 2007. This indicates that EU fishing vessels in the Mediterranean are not very large, maximum around 50m length and majority around 20-30m length. The capability of detection of vessels on a SAR image, well under its resolution limit (see discussion on paragraph “Accuracy of VDS” in section 2.1) and its balance with surface coverage (maximum extension desired) deemed the selection of 25 m resolution as adequate to detect the majority of vessels involved in the Mediterranean tuna fishing campaign.

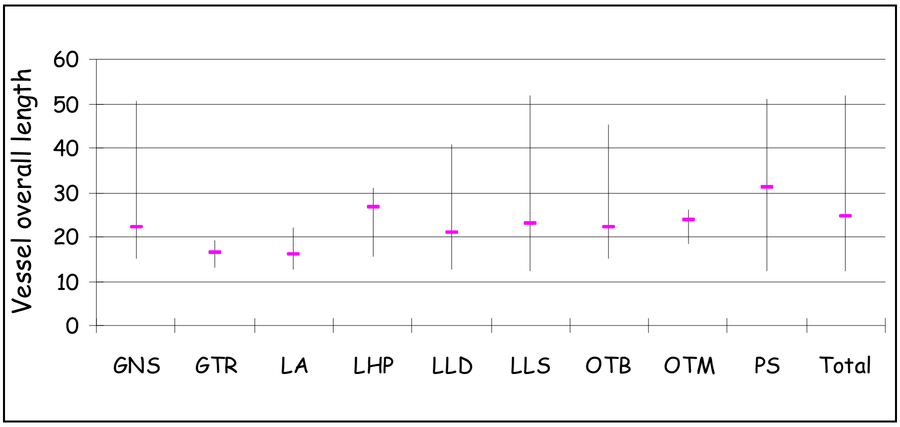

Figure 1: Distribution of vessel length per different vessel gear.[6] (Source: EU fleet register. Fleet register from EU countries involved in Bluefin tuna fishing in 2007)

The Joint Research Centre (JRC) of the European Commission in cooperation with different national FMCs has been running VDS campaigns, mostly in near-real-time, in European and international waters since 1999. In particular, large VDS campaigns were organised in 2007 and 2008 to support inspections in the Mediterranean bluefin tuna fishery. Data from both campaigns were used to estimate the efficiency of VDS use for fisheries enforcement. We report two different cases, first the use of VDS on a given day to show exactly how this method works, and then the use of VDS for the whole of the 2007 Central Mediterranean campaign.

3.1. Case 1: One typical day on the bluefin tuna fishery in Central Mediterranean in 2008

In this case, the analysis corresponds to a 3-framed image (Figure 2) from a single satellite pass on the Central Mediterranean on 6th of June 2008. This example has been chosen because it is a clear example of the bluefin tuna fishery, when a lot of fishing activity takes place.

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[6] *GNS: set gillnets (anchored); GTR: Trammel nets; LA :lampara nets; LHP: handlines and pole-lines (hand operated); LLD: drifting longlines; LLS:set longlines; OTB: bottom otter trawls; OTM: Midwater otter trawls PS: purse seines*

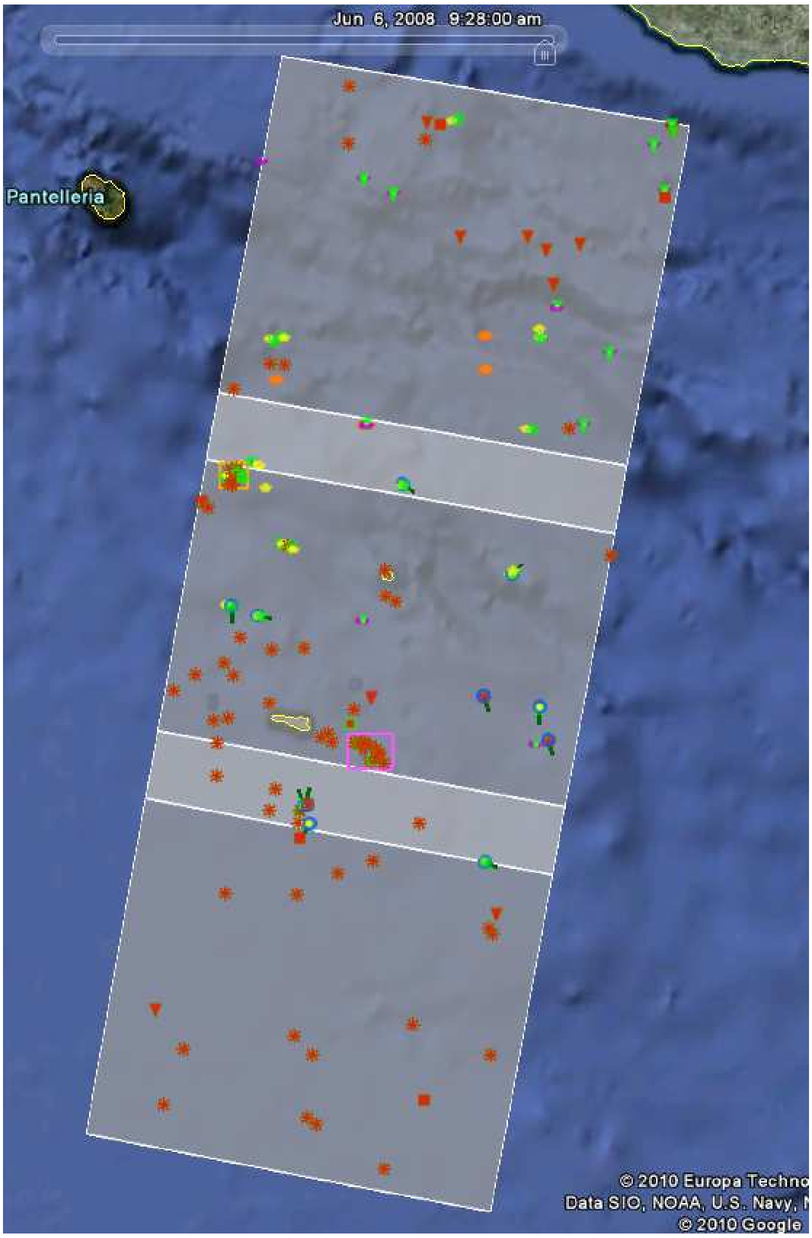

Figure 2: VDS correlation results for images acquired in the Central Mediterranean on the 6th of June 2008.

The red asterisks represent the VDS targets that are potential fishing vessels and could not be matched against any VMS position. Yellow small boats represent VMS positions that match VDS targets and orange small boats (there are three) are VMS positions that could not match any target. Triangles represent big vessels, too large to be Mediterranean fishing vessels. See also the clusters of fishing activity on the orange and purple rectangles in the central image. Blue circles indicate tuna cages being towed by a vessel (these are also detectable from SAR images [21]) and squares indicate vessels of intermediate size.

On Table 3 there are summarized the VMS-VDS enforcement statistics. The total number of potential fishing vessels (small signature size) detected by VDS was 104 (represented as asterisk). The number of fishing vessels in the area with VMS available was 21 (reported as "*number of VMS*" on table 3); of these 21 vessels, for 18 of them correlation VDS-VMS could be established (those VMS positions are represented by a small yellow boat and the corresponding VDS target with a green asterisk and reported as "*Correlations VMS-VDS*" on table 3). Finally, a set of 86 suspicious vessels (red asterisk in the figure and reported as "*non correlated VDS-targets*" on table 3) remained to be inspected. In the case VDS was not used more vessels should be checked, all potential fishing vessels (104). Table 3 gives the summary of the data.

Table 3: VMS-VDS statistics for the 1 day Mediterranean application (3 images)

Number VDS targets	**Number of VMS**	**Correlations VMS-VDS**	**Non correlated VDS targets**
104	21	18	86

In order to apply the model it is necessary to make some assumptions:

1. The percentage of infringements is required. According to the European Fisheries Control Agency (EFCA)[7] the average overall infringements found at sea inspections in 2009 was 16% [22][8]. For this case a conservative estimate of 15% was adopted[9].
2. Also the distribution of the "positional" and "action" infringement is not available. Weights of 20% and 80% of the total infringement have been assumed respectively, based on previous experiences.
3. Finally, the model will be asked to predict how many inspections or checks (number of samples, n) a plane will have to do in order to find all the infringing vessels with a certain degree of probability. A value of 80% was set for the study ($P(\chi_{vms} \geq N^{i}_{vms}, \chi_{nvms} \geq N^{i}_{nvms}) = 0.8$).

Introducing these parameters (taking integer numbers from Table 3: 104 as the number of VDS targets and 86 as non correlated VDS targets) in the model and searching for the number

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[7] Previously called Community Fisheries Control Agency (CFCA).

[8] It should be noted that overall infringements detected in 2009 slightly decreased from 2008 [23].

[9] Arnason et al., [1] estimate total IUU fishing in volume between 12.5% and 32.5% of the total marine production [24].

of inspections, results can be summarised with the following plot (Figure 3) of the cumulative probability of detecting infringements:

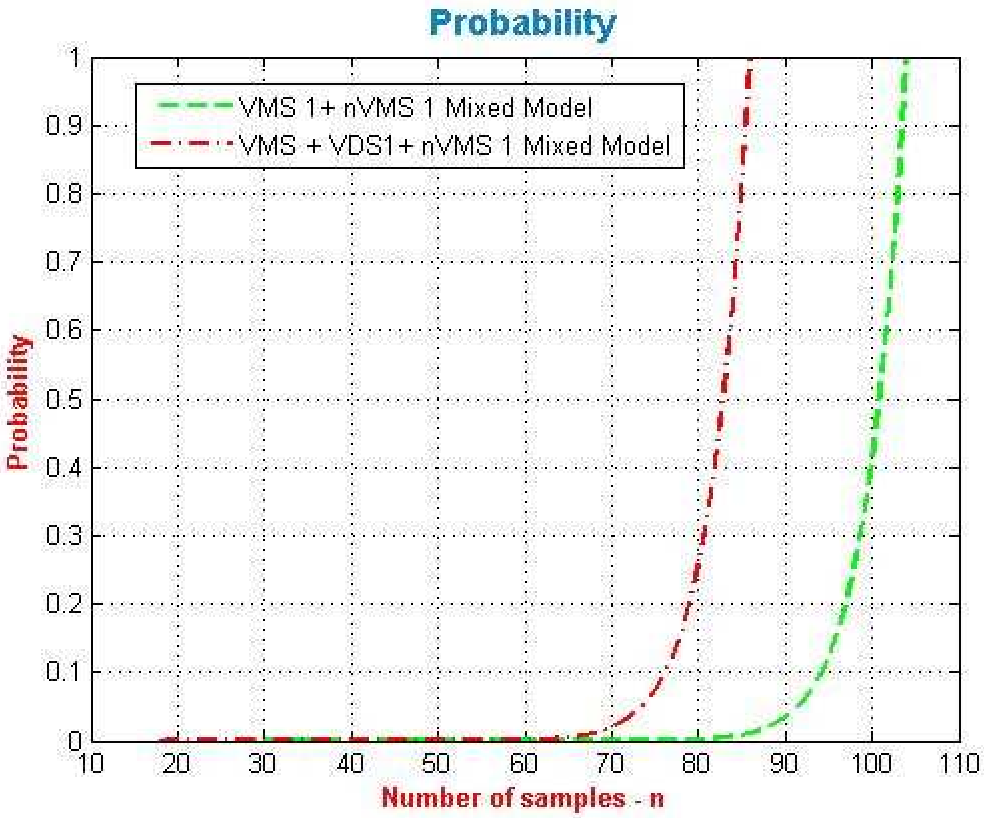

Figure 3: Cumulative probability of detecting infringements without (green) /with (red) VDS for Mediterranean data for 6th of June 2008.

The number of inspections required to obtain a certain probability to detect all infractions, using only VMS or VDS+VMS, are shown in Figure 3. When using VMS+VDS, in order to achieve 0.8 probability to detect positional plus action infringements only 85 inspections are required, whereas 103 inspections are needed if only VMS is considered. Therefore confirming that with a significant (17%) reduction in the number of inspections thanks to the use of VDS, the same infringement detection can be achieved.

3.2. Case 2: The whole 2007 season in Central Mediterranean

71 images were acquired for the 2007 bluefin tuna fishery campaign on the area covering the Central Mediterranean (from the Sicilian Channel to South Malta) from the 21st of May until the 27th of July 2007.

On Table 4 there are displayed the 2007 bluefin tuna campaign VMS-VDS enforcement statistics (only considering the targets detected on the images that are potential fishing vessels). On the first row, data refers to the whole set of images analyzed in the area (71 images); while on the second row there are reported the average values per image.

Table 4: VMS-VDS statistics for Mediterranean 2007.

Number of Images	**Number of VDS targets**	**Number of VMS**	**Correlations VMS-VDS**	**Non correlated VDS targets**
71	1788	320	253	1535
Average per image	25.2	4.5	3.6	21.6

For the 2007 Mediterranean bluefin tuna campaign, there were detected from the images 1788 potential fishing vessels (very big SAR signatures have been excluded). From these potential vessels, 320 different VMS positions were reported inside the images at the time of the image acquisition. So, 1535 VDS targets could not be correlated to any VMS position.

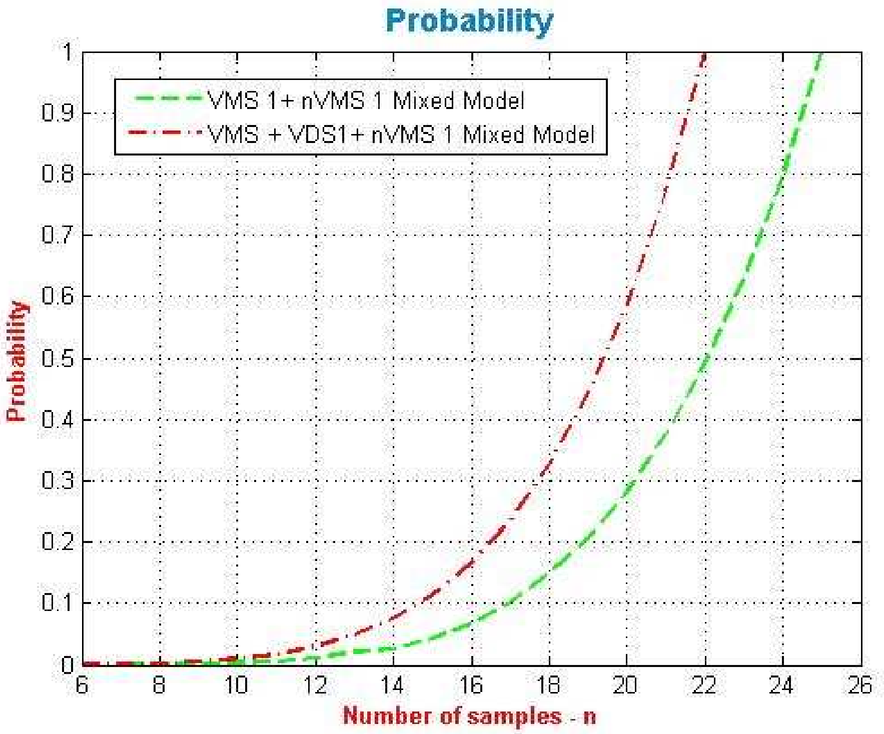

Figure 4: Cumulative probability of detecting infringements without (green curve) and with (red curve) VDS for the 2007 bluefin tuna campaign in the Mediterranean.

Results of the number of vessels to be checked in order to reach the required cumulative probability of detection of infringement are presented on Figure 4. In this case, it can be appreciated that the number of vessels that the plane will need to check is 24 (without VDS) and 21 when using VDS (left curve) in order to achieve 80% probability to detect all illegal vessels. This represents a 13% reduction.

3.3. Incorporating the monitoring costs

On this section, we compare the costs of air patrolling with and without the use of VDS needed to reach the same level of infringement detection from the results of the model in the previous section.

Table 5 shows the costs of monitoring in both cases, when using or not VDS in conjunction with VMS and aircraft controls. The total number of flight hours needed to achieve the defined level of infringement is the number of vessels to be checked (values coming from each case respectively) divided by the number of average checks per flight hour[10]. The aircraft control costs are then estimated by multiplying the total number of flight hours by the average cost per flight hour (3,800 Euros per hour, as estimated on section 2.4). This calculation should be carried for both air patrolling with and without use of VDS; the difference is the need of less flight hours when using VDS due to the need of checking less vessels. Moreover, one needs to add to the aircraft costs when using VDS the costs of the VDS images themselves (from table 1, but only Standard RADARSAT images have been used). Finally, the difference between these two expenditures is the relative saving of complementing air patrolling with VDS.

Table 5: Savings from the use of VDS on the bluefin tuna fishery Central Mediterranean (2008).

Case	N of aircraft checks per trip	Using only VMS			Using VMS and VDS					Savings (%)
		N vessels to check	N flights hours needed	Aircraft cost (Euro)	N vessels to check	N flights hours needed	Aircraft cost (Euro)	VS images cost	Total costs	
1	14	103	37	140,600	85	30	114,000	9,522	123,522	12.1
2	11	24	11	41,800	21	9	34,200	3,174	37,374	10.6

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[10] The difference between both cases is due to the different average flying time to reach both areas.

Therefore, comparing the costs of air patrolling with and without the use of VDS needed to detect a similar level of infringement, it can be seen that by using VDS there can be obtained savings of 12.1% and 10.6%, respectively.

Figure 5 shows a sensitivity analysis on how the savings on fisheries control vary depending on potential price increase (on the left hand) or, what it is more probable, on price decrease (on the right hand). The reference price here at x-axis zero is 2008 price of satellite images (table 1), 3,174 Euros which reach savings of 12.1% and 10.6%. In the sensibility analysis the other surveillance costs (i.e. patrol costs) are considered constant; while it is expected that patrol costs may increase overtime with oil price increases. According to JRC experience, large volume purchases (for surveillance campaigns or services) and more competitiveness in maritime surveillance products result in price discounts; as an example, a hypothetical discount of 20% will increase the savings up to 13.5% and 12.1% respectively for case study 1 and 2. Even in the improbable case that satellite image prices increase significantly, still important savings on the total cost of enforcement can be achieved.

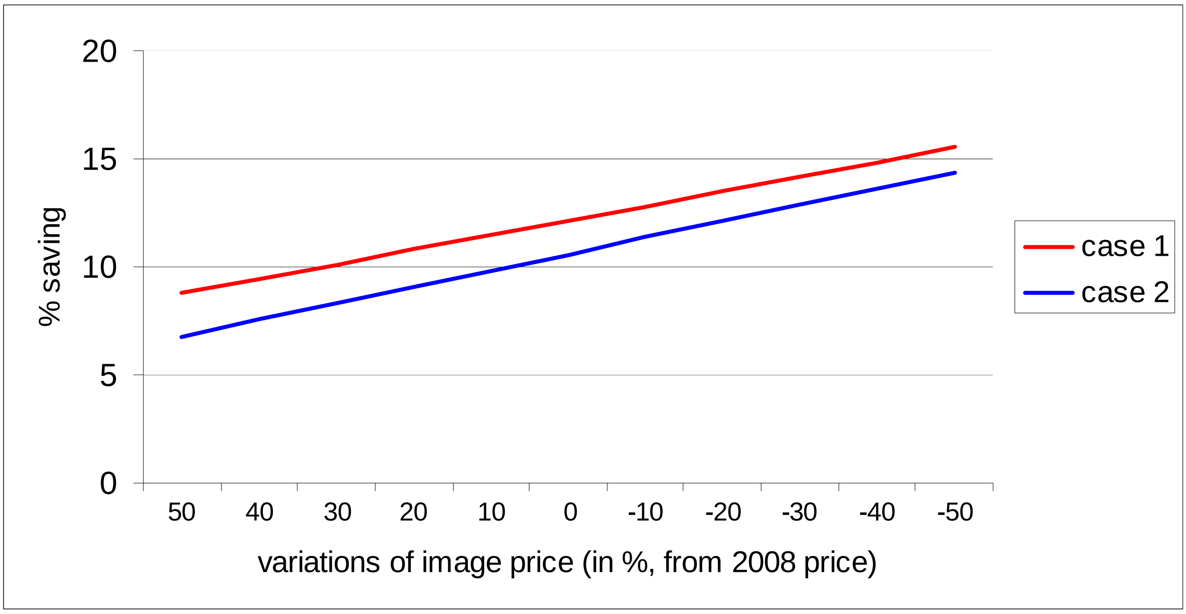

Figure 5: Sensitivity analysis of the control cost savings in relation to the image prices

Hence, use of VDS can reduce the cost of the inspections because it reduces the number of vessels that need to be checked, and therefore the number of flying hours needed In fact, in the cases analysed for the year 2008, VDS images represent only between 7.7% and 8.5% of the total enforcement cost when using VDS in conjunction with the other enforcement tools.

4. Concluding remarks

In this paper, a quantitative model that estimates the minimum number of inspections required to detect a given level of illegal fishing has been proposed. From the results obtained with this model we can compare the aircraft inspection costs, with and without the use of VDS, as needed to reach the same level of infringement detection, and in this way we can estimate whether cost savings can be obtained using VDS.

The model is based on assumptions that are applicable in the majority of fishing scenarios. In addition to this, the fact that the model is probabilistic means that the model can be adapted to other scenarios and assumptions. The applicability of the model has been demonstrated in this paper in two real case studies of using VDS in the Mediterranean tuna fisheries, obtaining positive results.

Assuming a conservative value of 15% for positional and action infringement together (the remaining percentage being all other types of infringements) the application of the model to the data in the Mediterranean results in savings in the range of 10.6% to 12.1%. With higher levels of infringement the use of VDS is expected to be more effective. Unpublished work by the authors indicates similar savings also for other areas (NEAFC, North Sea and Baltic Sea).

VDS can help to increase the enforcement level while keeping the same level of enforcement resources. Even if the cost of the images is high, the total cost of VDS imagery represents a small proportion of the air surveillance cost. In the two cases analysed they accounted for 7.7 and 8.5% of the total enforcement cost, respectively, when using VDS in conjunction with other enforcement tools. Moreover, the upgrade of VDS use to a proper service for monitoring fishing activities is expected to result in further cost reductions because of larger image quantity acquisitions. In fact, the purchasing of large volume of images to be used in large maritime surveillance campaigns and/or service provision often results in pricing discounts from the providers that increase the savings obtained from completing air surveillance with SAR remote sensing.

According to the proposed model, the greatest benefit can be achieved when the vessels are spread across a wide area (e.g. NEAFC and the Mediterranean cases), with the maximum possible number of VMS data available (this improves the probability of detecting vessels with no VMS, and so aircraft routing inspections can be optimised to focus on detected satellite targets that could not be correlated to reported VMS vessels) and also far away from the patrol base (less inspections possible and with a higher cost).

During the analysis the spatial distribution was not taken into account. However, an uneven spatial distribution of the vessels is likely to occur. In fact, Druon et al., [25] have established that Mediterranean bluefin tuna schools are not randomly encountered with the same likelihood, but that they tend to congregate in certain marine regions following a seasonal pattern. As a result, fishing fleets targeting tuna are not uniformly scattered in space and time, only randomly seeking a school, but rather tend to concentrate in areas of high tuna abundance. Thus, the fishing footprint is characterized by an uneven spatial distribution.

This uneven distribution will likely increase the benefit of using VDS. This is because many of the vessels are not detected by the plane until they enter into its radar footprint. By the time this happens, even though there might be targets that are worth checking, it may not be possible to do so due to flight limitations (i.e. not enough fuel due to the distance of the targets). If air patrolling could take into consideration both VMS and VDS results - rather than only VMS - when planning the flight, this problem could be avoided. Furthermore, the flight plan could be optimised in order to investigate suspicious vessels that not only do not match with VMS, but also vessels that might present some special pattern (like the fishing clusters indicated in Figure 2). In such a way, inspections will be maximised and will cover more vessels, therefore improving the benefit even further. This was indeed the situation in JRC’s VDS campaigns in coordination with the Icelandic coast guard in the NEACF area where patrolling normally takes place very far away from the coast (it takes several hours to arrive to the inspection area) with very positive results according to the Icelandic authorities.

In addition to increasing the efficiency of aircraft inspections by providing information to the inspection units, the use of VDS can also help to provide an overview of the situation on days when surveillance flights do not take place. Importantly, VDS represents the only source of data for fisheries monitoring in places that are not accessible to patrol vessels or airplanes, and therefore VDS is a very valuable tool to obtain an estimate of irregular or illegal fishing activity in such areas. Despite our imperfect knowledge - uncertainties in human values, fisheries systems, economic value of ecosystem preservation, and statistical methodologies will always be there to be challenged - action to improve enforcement needs to be taken and this paper highlights one of the possible ways to do it.

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