Use of radar detectors to track attendance of albatrosses at fishing vessels

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Abstract: Despite international waters covering over 60% of the world's oceans, our understanding of how fisheries in these regions shape ecosystem processes is surprisingly poor. Seabirds are known to forage at fishing vessels, with potential deleterious effects for their population, but the extent of overlap and behavior in relation to ships are poorly known. Using novel biologging devices, which can detect radar emissions to record the position of boats and seabirds, we measured the true extent of the overlap between seabirds and fishing vessels, and generated estimates of the intensity of fishing and distribution of vessels in international waters. During breeding, wandering albatrosses from the Crozet islands patrolled an area of more than 10 million square kilometers and as much as 79.5% of birds equipped with loggers detected vessels, at distances up to 2500 km from the colony, modifying their natural foraging behavior to attend boats. The extent of this overlap has widespread implications for bycatch risk in seabirds and reveals the areas of intense fishing throughout the ocean. We suggest that seabirds equipped with radar detectors are excellent monitors of the presence of vessels in the southern ocean, offering a new way to monitor fisheries. The method used opens new perspectives to monitor the presence of illegal fisheries and to better understand the impact of fisheries on seabirds.

Introduction

Today there is a serious concern about the potential impact of fisheries by-catch on the marine megafauna (Lewison et al. 2004; Lewison et al. 2014). Seabirds have been attracted to vessels for centuries (Coleridge 1895), before the development of industrial fisheries. Today, they attend fishing vessels in large numbers to feed on offal or bait, where their high mortality is the main threat to populations worldwide (Croxall et al. 2012; Phillips et al. 2016) . Ship-based studies have shown how albatrosses react to the presence of vessels (Hudson & Furness 1989; Weimerskirch et al. 2000), and the use of Argos transmitters or GPS, combined with Vessel Monitoring System (VMS) data from fishing vessels (Votier et al. 2010; Witt & Godley 2007), allowed quantification at an individual level of attendance pattern to vessels and behavioural responses (Bodey et al. 2014; Collet et al. 2015; Granadeiro et al. 2011; Torres et al. 2011)..

However, interactions with vessels can only be derived from declared vessels whose position are occasionally known within Exclusive Economic Zones (EEZ), rarely in high-seas areas (Witt & Godley 2007). Thus little information is available on the fine scale attendance of seabirds outside EEZs, i.e. 66% of the oceans, and limited information is available within EEZs. Being able to detect the presence of vessels through a species' range is essential to derive comprehensive encounter, attendance and mortality rates (Tuck et al. 2015) and detect changes in foraging behaviour triggered by the presence of vessels. Any change in movement, such as the use of Area Restricted Search (ARS) by foraging seabirds is generally interpreted as an answer to the direct, or indirect, presence of prey (Weimerskirch et al. 2007), but recent evidence shows that change in foraging movements may also occur in the presence of vessels (Bodey et al. 2014; Torres et al. 2011). This has very important implications in terms of interpreting behaviour, but also for conservation, as seabird foraging areas are used to propose or designate Marine Protected Areas (Lascelles et al. 2016).

Here we used newly-developed GPS loggers that record radar emissions from vessels. The logger was fitted on wandering albatrosses (*Diomedea exulans*) foraging from the Crozet Islands. Our aims were (1) to estimate the efficiency of this new technique to detect vessels at sea by comparing radar detections with VMS data of a declared long-line fishery operating around Crozet and (2) to estimate the extent of overlap with vessels over their entire foraging range of the species.

Methods

The study was carried out at Possession Island (46°S 51°E), Crozet Islands in January-March 2015 and 2016. A total of 53 incubating individuals was fitted with XGPS radar loggers with tape on back feathers: 6 in 2015 and 47 in 2016. The loggers (35g, i.e. 0.3 to 0.4% of the bird body mass) were well below the recommended mass to avoid potential deleterious effect on the foraging behaviour of flying seabirds (Phillips et al. 2003). Birds were caught by hand as they were relieved from their incubation shift by partners and departed to forage. Devices were recovered on their return to the nest after a foraging trip at sea. 43 loggers were recovered and data downloaded and the other10 loggers were either lost at sea (4, detached from back feathers) or recovered but we were unable to collect data from the logger (6).

The XGPS logger (Sextant Technology; Figures S1, S2 and S3) has been designed to detect interactions between animals and ships at sea by measuring radio emission in the 9.41GHz X radar band which is used in marine radars. The radar signals emitted from vessels are detected by an omnidirectional micro-strip antenna integrating the signal over a programmed interval (1 or 2min. every 5min.). The XGPS is composed of a 77mm x 23mm x 4mm main board and an independent 3.7V LiPo battery, scalable depending on the species (2000mAh in this case). The board combines a radar detector, a low power Sirf IV GPS and low power NOR FLASH and FRAM memory chips to store the data. The radar signals emitted from the vessel radar are picked up by the loggers using an

omnidirectional micro-strip antenna tuned at 9.41GHz (Supplementary Information figure S1,S2,S3) connected to a high frequency temperature compensated Schottky diode acting a as a peak detector. The 9.41GHz radar bursts are then converted into a lower frequency signal (3.3V max) proportional to the strength of the radar electro-magnetic field that the animal is exposed to. The power indicator signal could be measured accurately with a fast analogue to digital converter, however this solution would result in excessive power consumption, instead the power indicator signal is compared sequentially every 100ms with 4 reference voltages (1.65V, 0.825V, 0.412V, 0.206V). Every time the power indicator signal is greater than the reference voltage, a digital pulse is generated by a high frequency comparator and then counted by the MSP430 micro-controller chip in low power mode.
The radar level power index is calculated accordingly to the following formula: radar_power_level_index = sqrt(C3*8+C2*4+C1*2+C0) with C3 corresponding to the number of pulses counted by the micro controller greater than 1.65V, C2 >.825V, C1>.412 and C0>.206V. The XGPS were programmed to provide locations at 1-2 min intervals, giving a lifespan of the battery of 25 days.

The behaviour of birds associated with radar detection was characterised according to movement of birds and radar detection patterns. *Fly-past* occurred when few successive radar detections were recorded (1-5) and no significant change in the route of the bird. *Follow* corresponded successive radar detection aligned with a linear movement of a flying bird. *Attendance* corresponded to successive radar detections with typical of area restricted search movements where the bird alternate flying and sitting on the water periods.

We used data from VMS (vessel GPS locations recorded hourly) for French long-liners operating within the Crozet and Kerguelen EEZ, provided by the Pecheker database hosted at the Museum

National d'Histoire Naturelle, Paris (Martin & Pruvost 2007). The data correspond to 7 vessels fishing under license over the Crozet and Kerguelen shelves, and surrounding seamounts. VMS data and albatross radar detection GPS data were imported into Google Earth (https://www.google.fr/earth) to analyse spatio-temporal coincidence of radar detections by XGPS and VMS data. Distances between locations of VMS equipped boats and bird GPS locations were calculated, and associated with Radar signal intensity.

The Préfet des TAAF and Comité de l'Environnement Polaire, together with CNPN (National Committee for the Protection of Nature) approved the field procedures for the study on wandering albatrosses at the Crozet islands under IPEV programme N° 109 (Arrêté n° 2015-103, 4Septembre 2015).

Results

A total of 43 foraging trips were obtained with the XGPS in 2015 and 2016, seven of which were incomplete. The birds travelled between Antarctica and sub-tropical waters and between the South Africa and central Indian Ocean, covering an estimated 10 million km^2 (Fig. 1). 79.5 % of the birds recorded contact with vessel radar, over periods between 1min and 23.9 h continuously (Table 1). Detections were particularly numerous over the Crozet shelf edge (39.6% of detections), but also over the Del Cano rise west of Crozet, and the eastern and northern Kerguelen shelf edge (Fig. 1). In these areas long-liners fishing for Patagonian toothfish *Dissostichus eleginoides* were operating, mostly French vessels for which matching VMS locations were available.

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When combining VMS and XGPS data, it appears that all VMS equipped vessels in proximity to birds (<5km) were detected by the XGPS, except for one vessel encountered for a few minutes at >4km. The distribution of distances between a VMS equipped vessel and a XGPS-equipped bird indicates that radar was detected mainly at distance of 0.2 to 2km, and up to 5.5 km (Figure SI 4), with weaker signals received at distances greater than 2km (Figure SI 5). The detections other than from VMS equipped boats (29%) were recorded to the north of the Crozet Islands over a wide longitudinal band between 38°S - 30°S (Fig. 1), especially over the western Indian Ocean ridge and seamounts south of Madagascar.

The duration of radar contacts (all behaviours combined) represented between 0 and 57.6% of the entire foraging trip (average 6.6±11.3%, n=39). There were no differences between sexes in the proportion of time attending or not attending vessels (χ^2_1=0.76, P=0.321, Yates corrected, 16 out of 22 females, 16 out of 18 males), nor in the type of behaviour when attending (χ^2_3 Pearson = 4.61, P=0.202). Females interacted with vessels at more northerly latitudes ($F_{1,28}$=5.4, P=0.025), and at slightly greater distances from the colony ($F_{1,28}$=3.4, P=0.055) than males (Fig. 1) whereas there was no sex-specific difference in maximum range or southernmost latitude of the entire foraging trips.

The behaviour of birds in the presence of vessels can be derived from the GPS track of birds and radar detections (Table 1). Birds either arrived at a vessel, but continued on their way (*Fly-past*), followed steaming ships (*Follow*), or remained at vessels (*Attendance*) by either continuously sitting on the water nearby, or alternating periods sitting on the water with short bouts in flight, probably to follow a vessel moving between fishing locations (as verified when VMS data were available, Fig. 2). *Fly-past* represented 23.9% of radar detection events. Birds frequently *followed* steaming vessels, with a maximum of 15.5 h continuously during daylight over 334 km (Fig. 2). The most frequent radar detections were those followed by *attendance* behind vessels. (Table 1).

Discussion

The major result of this study shows that wandering albatrosses from Crozet overlap to a very large extent with vessels in the western Indian Ocean, with nearly 80% of birds having contact with vessels detected by XGPS loggers. This is a minimum estimate, since some birds may have encountered vessels at distances greater than 5 km which would not have been detected there: indeed wandering albatrosses can change their behaviour and approach vessels from distances up to 30 km (Collet et al. 2015). However once birds have changed their route toward a vessel, they generally approached at close range (<3km) and XGPS appeared to detect most of these interactions based on the comparison of VMS and XGPS data. Generally birds spent extended periods behind vessels, suggesting real interactions after attraction, instead of simple spatial overlap (Collet et al. 2015; Collet et al. 2017).

The high encounter rate highlights the propensity of wandering albatrosses to be attracted to vessels. Fishing vessels may operate in traditional foraging zones of albatrosses. The edge of Crozet and Kerguelen shelves were visited by albatrosses before the development of fisheries and are now also exploited by long-line fishing vessels (Weimerskirch 1997). The co-occurrence of vessels and albatrosses over sub-Antarctic shelf edges does not mean that they are fishing for the same prey, since wandering albatrosses mainly feed on squids in these zones (Cherel & Weimerskirch 1999), and the occurrence of Patagonian tooth-fish in their diet is recent, indicative of opportunistically exploitation of fishery discards (Cherel et al. 2017; Weimerskirch et al. 1997). The reason why albatrosses are attracted so strongly to vessels is not clear particularly as attending sailing vessels has been reported for more than two centuries, with little nutritional reward expected prior to commercial fishing. In the Crozet toothfish fishery, vessels provide feeding opportunities, as vessels discard fish waste primarily. The extensive rate of encounter could also be explained by the birds' opportunistic "curiosity", or attraction to specific signals such as smell or seabird aggregations (Collet et al. 2017; Nevitt et al. 2008; Silverman et al. 2004).

Over oceanic waters, encounters occurred only in northern latitudes, over seamounts such as those south of Madagascar, where fisheries are known to operate; or in sub-tropical oceanic waters where there is a high bycatch risk in oceanic longline tuna fishing (Tuck et al. 2015). These fisheries represent one third of the encounters by Crozet wanderings albatrosses, and put at risk females, but also young age classes of wandering albatrosses that occur there (Weimerskirch et al. 2014). Our results also demonstrate that males and females interacted with vessels in distinct areas. Males interacted mainly with vessels over the edges of the Crozet and del Cano shelves, close to the colony, while females additionally encountered many vessels over sub-tropical oceanic waters that are their traditional foraging grounds (Weimerskirch et al. 2014). These sex specific and age specific differences have considerable consequences in terms of conservation, because no seabird bycatch mitigation is implemented in subtropical longline fleets (Anderson et al. 2011), contrary to those operating in sub-Antarctic waters. Our findings support the observed higher mortality in breeding females that has far-reaching demographic consequences (Weimerskirch et al. 2014), but also for young birds that have a high mortality rates during the juvenile and immature phase (Fay et al. 2015).

The XGPS worked efficiently to detect the presence of vessels, since all but one of the VMS-equipped vessels that was approached within 5km was detected. Vessels actively fishing can be easily distinguished from cruising vessels, as albatrosses attending a vessel during fishing appear to

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have very sinuous ARS movements over a restricted area with radar detections (Fig. 2), different from large scale ARS in natural foraging conditions that are less tortuous (Weimerskirch et al. 2007). Our study shows that albatrosses encountered fishing vessels over a wide range of the ocean basin, where fleets from many countries operate, and whose distribution is generally known only at coarse resolution from Regional Fisheries Organisms (Tuck et al. 2015; Witt & Godley 2007). Thus the XGPS is a a promising tool to not only study the foraging behaviour of seabirds in the presence of vessels, but also to detect vessels in particular areas. Given the large direct and indirect impacts fishing vessels have on seabirds (Bicknell et al. 2013; Cury et al. 2011; Pauly et al. 2005; Votier et al. 2004) these devices could become a crucial tool for monitoring marine ecosystems. The ongoing development of XGPS which can be relayed by Argos or Iridium systems will further allow real time monitoring of the presence of vessels anywhere in the range of seabirds, which could thus become patrollers of the southern ocean, allowing better monitoring of fisheries, as well as seabird-fishery interactions. For example, on one occasion in the EEZ around Crozet, a XGPS-equipped albatross detected an undeclared radar signal, i.e. probably an illegally fishing vessel. With such an integrated communication system, it could thus potentially inform authorities in real time of the location of illegal fishing vessels.

Presently, there is an extensive effort to estimate the degree of overlap between seabirds, particularly albatrosses and petrels, and fisheries, especially long-line fisheries that operate over entire oceanic basins in the case of tuna fisheries, and represent the main threat for these seabirds (Croxall et al. 2012). This effort has only been able to estimate potential overlap between fisheries of RFMOs or national fisheries (Richard & Abraham 2015) and seabirds at very course resolution. In the Indian and Atlantic Ocean RFMOs provide long-line fishing effort at the scale of 5° squares of longitude and latitude, which is obviously insufficient to measure overlap and suggest efficient conservation measures. With the deployment of XGPS at large scales it becomes possible to measure exactly overlap with fisheries for each population where loggers have been deployed, thus estimate interactions at the population or individual level (according to sex, age), and therefore better understand and measure the effects of fisheries on seabird populations. Furthermore our approach is fishery independent and covers the ecological scale of risk to individual birds. The impact of fishing described for seabirds also applies broadly to other marine megafauna such as marine mammals and turtles (Hays et al. 2016), and our approach may have some utility for these taxa as well.

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Table 1 – Behavioural types of movements derived from XGPS tracks and radar detection of vessels

	Mean duration (h)	Range (h)	Frequency %	% of time in contact with Radar
Fly-past ship	0.03	0.01-0.025	23.9	0.2
Follow cruising ship	2.9	0.2-15.5	8.8	11.4
Attend ship	4.3	0.06-24.9	64.7	45.2

Figure 1 – a) Map of the southern Indian Ocean showing the movement patterns of wandering albatrosses tracked in 2016 (males: orange lines, females yellow lines) b) enlargement of the zone showing the movements and location of radar (green dots) c) enlargement of the Crozet shelf. The location of the colony is indicated by the red square.

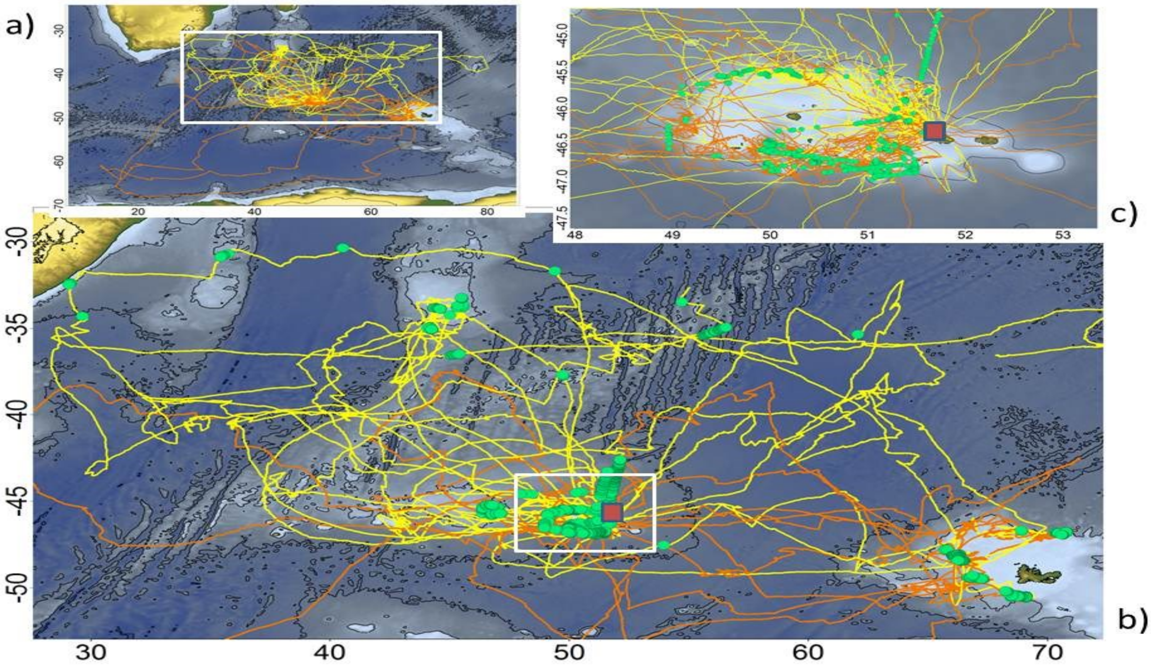

Figure 2 – Movement pattern recorded by GPS (yellow/orange lines) with detection of radar (green circles) with a) *Attend* behaviour behind a Japanese fishing vessel (identity determined from Globalfishingwatch.org), b) *Fly-past* and c) *Follow*, the red lines indicates track of VMS equipped vessel.