Evaluating receiver contributions to Acoustic Positional Telemetry: A case study on Atlantic cod around wind turbines in the North Sea

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Evaluating receiver contributions to Acoustic Positional Telemetry: A case study on Atlantic cod around wind turbines in the North Sea

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Abstract

Background: An important aspect for the correct interpretation of Acoustic Positional Telemetry (APT) data concerns the effect of individual receiver contributions to animal positioning. The present study evaluated the contribution of each receiver within two APT designs to set-up efficiency and position accuracy of free-ranging Atlantic cod, through sequential single receiver removal. The two APTs were deployed around offshore wind turbines at which 27 individual cod were tagged and released, 50 km offshore, at depths of 20-30 m.
Results: Results indicated that removal of an APT receiver, positioned within the movement area of
the individual fish, reduced the efficiency and position accuracy of the set-up the most, with a
maximum of 34% position loss per fish, and an increase in core area of 97.8%. Removal of a single
receiver in general was shown to potentially lead to considerably altered swimming tracks.
Additionally, removal of a specific receiver that was deployed within 50 meters from a turbine (i.e.
reflective barrier) actually improved fish position accuracy.

Conclusions: An explorative, small-scale study like the one presented is recommended, before
embarking on any larger scale APT study. Exploration of receiver contributions to set-up performance
allow to test the suitability of a receiver set-up for the specific movement patterns and local tracking
conditions for a particular target species. Data from receiver arrays from which a receiver was lost
should be treated with care, as results revealed that changes in triangulation outcome can lead to
considerable shifts in swimming tracks and animal home range estimates.

Keywords
Acoustic telemetry, position triangulation, behaviour, Atlantic cod, offshore structures, wind power

1. Introduction
Acoustic Positional Telemetry (APT) is an established method for fine-scale aquatic animal
positioning to study fish behaviour and movement and a large spatial and temporal scales [1,2]. In an
open marine environment, acoustic receivers for APT are often placed in regular squared- and
triangular grids [3] or in a circular constellation [4,5], depending on the location and research
questions at stake [6]. The chosen design furthermore depends on the species-specific behaviour of the
target species. Movement behaviour of crabs, for example, is quite different from that of demersal fish,
and some fish species exhibit a high residency and site fidelity, while others are much more mobile,
which calls for a different receiver set-up for optimal tracking [7]. Even within species, movement
patterns may vary with life stage, personality traits and subpopulations [8,9]. The design of an acoustic
receiver set-up, i.e. the receivers included and their spatial distribution, determines the outcome and reliability of any APT study.

The performance of a receiver set-up for an APT study in a marine open-water system will be affected by local habitat conditions [10] and by the dynamic nature of environmental factors [11,12]. The difference in time of arrival of the transmitter signals at various hydrophones is used in the positional algorithm. Any factor influencing, or interfering with, speed-of-sound and signal propagation in the water will therefore affect APT performance [13,14]. Habitat-specific features such as vegetation type and density, bottom characteristics and presence of rocks and/or (man-made) obstacles can block signal propagation [15]. Furthermore, natural events like currents and surface waves can influence receiver detection range [12,16] and can even lead to signal propagation interference through receivers getting temporarily buried or even lost [17]. If the latter occurs, an APT set-up may suffer significantly in terms of performance efficiency (number of tag signals detected) and position accuracy, and thus in terms of scientific value of the obtained results. The scientific impact of losing a receiver in an APT study often remains unknown, since information stored on the missing receiver is usually no longer available after the event. Furthermore, in the design of any APT study, typical trade-offs exist between area covered and set-up performance, and between money spent on as large a number of receivers as possible and other research expenses. It is therefore a relevant exercise to explore receiver removal and finding out about which receiver to drop if needed (i.e. one that influences the results the least).

Atlantic cod (*Gadus morhua*) at offshore wind farms in the North Sea form a good model system to explore the contribution of individual receivers on spatial data collection and processing form an APT design. Atlantic cod is an economically important species, and it’s behaviour at offshore wind farms is well-studied [17–19]. In summer, it spends extended periods of time residing on or close to the scour bed for feeding and shelter [17,19–22]. In addition, in the wind farms in the Belgian Part of the North Sea (BPNS), no fishing or shipping is allowed, which makes them an ideal study location, because the risk of losing tagged fish or receivers to bottom-trawling fisheries is therefore lower than at other wind farms in neighboring countries. Despite that there are several cod tagging studies at wind farm locations available, there are no data yet confirming receiver network suitability for high-resolution
spatial tracking of individuals around a turbine, nor is there any exploration reported on the impact of losing or dropping a receiver from an operational network.

In the current study, the contribution of individual receivers on the detection and positioning precision within two Acoustic Positional Telemetry (APT) designs, was evaluated for Atlantic cod at a wind farm in the BPNS. The study aims to answer the following questions: Do individual receivers contribute equally to the spatial data collection and position accuracy?, Which local factors explain variation among individual receivers?, And to what extent are fish swimming tracks affected by individual receiver removal? APT data was explored by quantifying the effects of sequential single receiver removal and by zooming into the changes in fish swimming tracks of cod with high site residency. Study results will potentially provide insights into how positional array designs can be improved for future studies into the spatial response and activity changes of fish in response to disturbance by anthropogenic noise (e.g. pile driving, seismic surveys) and will reveal the consequences of removing or losing a receiver from a particular set-up.

2. Methods

2.1 Study site

This study was performed in the offshore wind farm Belwind (51.670°N 2.802°E), situated on a sand bank about 50 kilometres off the Belgian coast (fig. 1A, and Brabant et al., 2013). The 55 turbines (fig. 1B) in the wind farm have steel monopile foundations, surrounded by a scour bed protection layer consisting of stones of various sizes (information obtained from Van Oord Dredging & Marine Contractors). The monopile turbines and the scour beds have a diameter of 5 m and of ~40 m, respectively; scour bed covering varies, but covers approximately 500 m² per monopile [24]. The seabed between turbine scour beds predominantly consists of medium-grained sand dunes, formed by the tidal currents. The water depth at the study site was between 20 – 30 m, including tidal fluctuations [23].

Fig. 1 Location of Belwind wind farm in the Belgium part of the North Sea. A) Grey lines outline the countries land and water boarders (e.g. EEZ’s). Contours of the offshore area designated to wind farm construction in
black, red indicates the location of the Belwind. B) Overview of monopile turbine positions at the Belwind.

Orange turbines are the two around which APT’s were deployed. Depth around the turbines varied between 20 - 30 meters (bathymetry data obtained from “European Marine Observation and Data Network” (EMODNet)).

2.2 Acoustic Positional Telemetry set-up design

VR2AR (Innovasea, Halifax, N.S. Canada) acoustic receivers were used. Two APT designs were deployed from July 4th until September 28th 2017 around two wind turbines: the northern F05 and the central C05 turbine (fig. 2A and fig. 3A). The set-up around turbine F05 included 8 receivers, 6 of which were placed in a ‘circular’ shape with similar spacing (150 m on average), the remaining 2 inner receivers being positioned at approximately 50 m from the edge of the turbine base (fig. 2A). At turbine C05, 10 receivers were placed in a ‘triangular’-grid configuration, with 150 m up to 200 m spacing between adjacent receivers (fig. 3A). Detection probability at these distances has been tested in the same environment and under similar environmental conditions [12] and remained above 70%, even during harsh environmental conditions. During the deployment period, receiver C05-8 was lost on the 21st of September. This was not part of the study plan, but due to an accidental release by another research team, which was only found out at the end of data collection and recovering of all receivers. All other 17 receivers remained functional for the entire deployment period until their scheduled recovery. They were bottom-moored as described by Reubens et al. [12].

2.3 Fish tagging

In total, 27 Atlantic cod (total length range 33-43 cm) were caught and tagged with V13AP transmitter tags (Innovasea, Halifax, N. S. Canada) between July 4th and September 1st 2017 (table 1). Fish were caught, using hook and line, from up to 30 m depth and slowly reeled in to prevent barotrauma. Individuals were kept in a holding tank for observation. If fish displayed any sign of serious discomfort or abnormal behaviour (e.g. being unable to keep buoyancy or swimming at the surface), they were not used for tagging. An individual was sedated using clove oil (0.03 ml/L). Upon losing equilibrium, it was placed on its back in a holder at a slight angle, keeping its mouth and gills submerged in oxygenated seawater. An incision (2-3 cm) was made on the ventral side through which the acoustic tag was slid into the abdominal cavity. The incision was closed using three monofilament
sutures. Next, fish were measured and tagged with an additional T-bar Floy tag in front of the dorsal fin for individual identification (fish ID) in case a fish was re-caught. After tagging, taking 5 minutes on average, the animal was placed in a recovery tank. Upon resuming normal swimming behaviour, the cod was released at the catch site (i.e. turbine F05 or C05). Fish were tagged in two rounds, with two groups of tags set at different transmission intervals (table 1). A transmitter’s interval delay was set for a period of 30 days to a random delay varying between 40-80 s or 30-60 s (table 1).

**Table 1 Number of cod tagged per turbine and signal transmission delay**

| Catch and tag date | Turbine | Cod tagged (#) | Random transmission interval between (sec) |
|--------------------|---------|---------------|------------------------------------------|
| 4-17 Jul 2017      | F05     | 8             | 40-80                                    |
| 13 Jul 2017        | C05     | 6             | 40-80                                    |
| 23 Aug 2017        | F05     | 5             | 30-60                                    |
| 1 Sep 2017         | C05     | 8             | 30-60                                    |

### 2.4 Raw receiver data analysis

The data recovered from the receivers was uploaded to the European Tracking Network (ETN) data platform (lifewatch.be/etn). Per positional set-up, a linear time correction of raw detections was performed (on the online Fathom Position platform, position.fathomcentral.com), followed by a position triangulation that used the Time-Difference Of Arrival (TDOA) of a coded signal by three or more receivers to calculate transmitter positioning. This yielded a dataset per APT set-up design (i.e. F05 and C05) containing: information on the number of detections per fish and receiver, and triangulated positions with set-up-specific position accuracy estimates. The indicator of position triangulation accuracy provided is called the Horizontal Position Error (HPE) [25]. HPE is a dimensionless estimate of position precision based on the relationship between theoretical position error sensitivities and observed measurement errors for synchronization tags [25], calibrated to the local environmental conditions (water temperature: 17-19 °C; salinity 33.2 ppt). HPE is set-up-specific and cannot be compared between different set-ups, but can be used to compare positions calculated through multiple receiver combinations within the same set-up [26,27]. The lower the HPE, the higher the expected position accuracy.
Data of the first day after tagging were excluded from the analyses to avoid possible impact of catching and tagging on fish movement behaviour. The data-set was scanned for stationary tags (i.e. tags remaining stationary for longer periods of time while acceleration remained 0 m s\(^{-2}\)), as these tags might have been expelled by the fish or indicate that a fish had died. Since none of the tags were stationary, all data were considered to concern tags in live fish. No prior position filtering based on the set-up-specific indication of accuracy (e.g. Horizontal Position Error [25]) was applied since individual receiver contribution on the triangulation of all positions was required.

2.5 Individual receiver contribution to APTs

Individual contribution of a receiver to fish positioning was calculated by sequential removal of single receivers from each APT. The following assumption was made: when no receiver was removed, and thus all receivers were included in the positional analysis, the number of fish positions detected within that set-up was 100% and the triangulated positions were the ‘base’ fish positions. This provided the possibility to determine two metrics for each APT performance: set-up efficiency and position accuracy [1,15], for each single receiver removal option (i.e. eight or nine for F05 and C05 respectively). Set-up efficiency was calculated as the proportion (%) of daily successfully calculated positions by the APT (i.e. \(\frac{\text{number of positions when a receiver is removed}}{\text{number of positions when all receivers are included}}\)). Position accuracy, represented the variability in position precision as the standard deviation of the mean daily relative HPE. These metrics were calculated and averaged to give a daily value for both set-up designs, per single receiver removal option for all fish (27 fish in total), including all days with at least 100 detections for that fish.

2.6 Fish residency

Additionally, the effect of single receiver removal on shifts in the triangulated positions of fish with a high residency was evaluated, to illustrate the effect of receiver loss. To identify fish with high residency, the hourly Residence Index (RI) was used. The hourly RI was calculated by dividing the hours an individual fish was detected by the total number of hours between first and last day of detection (maximum of 30 days = 720 h). A value of 0 indicated no residency and a value of 1
permanent residency [28,29]. Four fish (two at turbine F05 and two at turbine C05) that were detected for more than 10 days and had an RI > 75%; were considered to show high residency at that turbine.

Fish core and extended spatial use were calculated as the Kernel Utilization Distributions (KUDs) [30]. KUDs are a common approach to estimate the activity space of animals from telemetric tracking data [31,32]. The core 50% and extended 95% KUDs in square meters (m²) were also estimated for the four resident cod (R package ks, [33]). All calculations were performed in Rstudio version 4.0.0.

3. Results

3.1 Individual Receiver contribution to APTs

All fish positions, 76,743 at turbine F05 and 31,202 at turbine C05, were used to test set-up performance when a single-receiver was removed. To evaluate position accuracy, a sub-set of position data was used that included positions that could be calculated in all single-receiver removal options, resulting in: 62,240 and 23,916 positions for turbines F05 and C05, respectively.

Single receiver removal from the APT around turbine F05 reduced the daily set-up efficiency by 4-14% on average (fig. 2C) and position accuracy changed with HPE shifts of 0.02 SD 0.35 to 0.66 SD 1.24 (fig. 2D). Removal of receiver F05-8, one of the centre and most central receivers with respect to fish spatial area use (fig. 2B), reduced the percentage of positions the most, followed by F05-3 and F05-4, two receivers east of the turbine. The accuracy of positions was especially reduced when receiver F05-3 was removed, as this was a critical receiver for many positions of fish that moved to and from the reefballs (fig. 2B), but improved for part of the positions when either of the centre receivers, F05-7 or F05-8, was removed (i.e. HPE difference<0, fig. 2D).

Single receiver removal from the APT around turbine C05 had a variable effect on the lowered daily percentage of positions between 0-34% (fig. 3C), but a moderate effect on position accuracy with HPE shifts between 0.01 SD 0.11 and 0.44 SD 0.64 (fig. 3D). Receivers that had a high contribution to the percentage of positions triangulated were both centre receivers, C05-5 and C05-6: when either of these was removed, daily set-up efficiency reduced by 34% or 22% respectively. Also receivers C05-2 and C05-3, on the south side of the turbine, had a relatively large contribution to the set-up efficiency (fig.
3C), which may be due to the higher number of cod positions on the southern side of the monopole.

Receiver contribution to accuracy revealed a similar pattern, reflecting the general proximity of fish to the turbine: accuracy of positions reduced the most when the centre receiver, C05-5 or C05-6, was removed, and to a lesser extent when the southern C05-2 or northern C05-9 receiver was removed (i.e. HPE difference > 0 fig. 3D).

Fig. 2. Set-up overview and data from turbine F05. A) Overview of the complete APT set-up; and B) all derived fish positions: colour indicates HPE associated with the position: the lower the HPE, the higher the expected position precision. Positions of receivers and reef balls are indicated with black dots and burrowed electricity cables are represented by grey lines. Effect of single receiver removal on the spread of the daily: C) set-up efficiency (% of positions calculated) and D) position accuracy (difference in HPE).

Fig. 3. Set-up overview and data from turbine C05. A) Overview of the complete APT set-up; and B) all derived fish positions: colour indicates HPE associated with the position: the lower the HPE, the higher the expected position precision. Positions of receivers are indicated with black dots and burrowed electricity cables are represented by grey lines. Effect of single receiver removal on the spread of the daily: C) set-up efficiency (% of positions calculated) and D) position accuracy (difference in HPE).
3.2 Effect of receiver loss on fine-scale fish tracks & KUD

Results showed that the total derived positions reduced due to single receiver loss was between 4-14% and 0-34% for APT’s F05 and C05, respectively (table 2). The location of the triangulated position based on the same fish tag signal showed in some cases, large shift when a particular receiver was removed. For example, for fish 6, a core area (50% KUD) of 390 m$^2$ changed into an area of between 300-780 m$^2$, depending on which receiver was removed from the APT at turbine F05 (table 2). In this example, receiver loss could result in a core area estimate of almost twice the size compared to when all receivers were present. To demonstrate the extent to which the same triangulated fish positions could shift in space when one receiver from an APT was lost, the same 3-h tracks were plotted along with the core spatial area (50% KUD) of four fish (fig. 4).

Table 2. Effect of single receiver removal for four resident cod. RI = Residence Index. KUD = Kernel Utilization Distribution.

| Fish with RI>75% | Wind turbine | Receiver removed | Positions (#)* | KUD 50% (m2)* | KUD 95% (m2)* |
|------------------|-------------|------------------|---------------|--------------|--------------|
| 6                | F05         | None             | 13908         | 393.3        | 3912.7       |
| 6                | F05         | F05-1            | -579          | +22.3        | -250.8       |
| 6                | F05         | F05-2            | -814          | -95.8        | -1201.2      |
| 6                | F05         | F05-3            | -1559         | +384.8       | +4138.1      |
| 6                | F05         | F05-4            | -813          | +31.2        | -942.2       |
| 6                | F05         | F05-5            | -307          | -67.5        | -464.5       |
| 6                | F05         | F05-6            | -398          | -31.6        | -114.9       |
| 6                | F05         | F05-7            | -321          | +64.1        | -228.7       |
| 6                | F05         | F05-8            | -1862         | -37.7        | -342.5       |
| 18               | F05         | None             | 28601         | 341.5        | 5393.9       |
| 18               | F05         | F05-1            | -1626         | +50.4        | -34.4        |
| 18               | F05         | F05-2            | -816          | -6.2         | -1649.6      |
| 18               | F05         | F05-3            | -572          | +0.7         | -61.1        |
| 18               | F05         | F05-4            | -1271         | +82.1        | -542.3       |
| 18               | F05         | F05-5            | -2306         | +95.7        | -199.3       |
| 18               | F05         | F05-6            | -1638         | +14.2        | -257.1       |
| 18               | F05         | F05-7            | -472          | +56.5        | -618.3       |
| 18               | F05         | F05-8            | -1603         | +10.5        | -960.2       |
| 10               | C05         | None             | 16427         | 194.5        | 1925.2       |
| 10               | C05         | C05-1            | -27           | -9.8         | -39.6        |
| 10               | C05         | C05-2            | -1380         | +59.6        | +528.3       |
| 10               | C05         | C05-3            | -2080         | +30.1        | -189.4       |
| 10               | C05         | C05-4            | -14           | +4.6         | +18.4        |
|    |     |     |     |    |    |
|----|-----|-----|-----|----|----|
| 10 | C05 | C05-5 | -1977 | +63 | +583 |
| 10 | C05 | C05-6 | -2143 | -22.2 | -625.2 |
| 10 | C05 | C05-7 | -319 | +19.4 | -513.5 |
| 10 | C05 | C05-9 | -341 | +23.8 | -59.4 |
| 10 | C05 | C05-10 | -163 | -5.7 | -216.9 |
| 27 | C05 | None | 5197 | 336.6 | 2630.3 |

*+ or – indicates change from no receivers removed

**Fig. 4.** The same 3-hour tracks (grey lines) and 50% core Kernel Utilisation Distributions (KUD in red) of four resident cod. When no receiver was removed (left column: ‘None’) and when a single receiver was removed, that caused the smallest (middle column) and largest (right column) spatial changes in fish positions.

### 4. Discussion

This Acoustic Positional Telemetry (APT) study revealed considerable variation in receiver contributions to the detection and position accuracy within two receiver network designs. Critical factors explaining the variation were the location of the core area of fish activity, the direction of specific journeys outside the receiver set-up area, and the receiver proximity to the turbine, of both outer-edge and inner-circle receivers. Receivers that overlapped with the spatial distribution of the tagged cod, who’s core area was concentrated at the turbine base, contributed most to the APTs performance. Consequently, removal of single receivers closest to the turbine reduced the percentage of positions derived the most. This was especially the case when the outer-edge receivers were positioned at a distance of more than 200 m from the turbine (as was the case for the outer receivers at APT C05), and less so when this distance was around 150 m (as was the case for all receivers at APT F05). Additionally, the presence of the reefballs north east of turbine F05, lead to a high contribution of receiver F05-3 to both set-up efficiency and position accuracy as removal of this receiver, also
removed positions detected outside of the APT array (fig. 2B). Dropping the data of a single receiver, furthermore, resulted in variable changes of fish movement-tracks and spatial area use. Again loss of the receivers closest to the core area with most fish positions, had the largest effect on the fish swimming track and home range.

4.1 Lessons for an optimal APT design

The aim of most behavioural APT studies is to understand the movement behaviour of individually tagged animals at a fine scale [1,2]. However, the choice for a particular APT set-up design, will also influence the resulting individual animal movement patterns. Between the two locations of the current study, results showed distinct patterns in position distribution and cod movement. Cod at turbine C05 constrained their movements mostly around the turbine, while cod at turbine F05 made frequent excursions towards the adjacent reefballs. Cod residing in offshore windfarms, have been shown to occasionally move between turbines [19] and the relative proximity of the reefballs to turbine F05 (~250m) most likely resulted in a clear capture of this movement behaviour by the APT. This resulted in very different patterns in position accuracy and receiver contribution of single receivers, between the two APT set-ups. When receivers are positioned too far from the animals core area, they will be less likely to pick up tag signals [11]. Consequently, understanding how a target species will use a spatial area is fundamental to the study outcome and may accordingly require adjustments to the receiver set-up. This underlines the need for exploratory pilot studies, like the current one [c.f. 34], to understand the area use of the target species as well as receiver detection range, before starting a large scale experimental study.

Our results furthermore demonstrated that removal of either one of the two receivers closest to turbine F05 (i.e. F05-7 or F05-8 at ~50 m from the turbine), slightly improved HPE values for fish positions and thus position accuracy. This was not the case for either of the two receivers closest to C05, as these were positioned further from the turbine at ~150 m. This difference between the two set-ups is likely due to proximity-dependent impact of the monopole on signal propagation. The monopile forms a reflective barrier in the middle of the receiver set-up which can cause tag signal reflections and result in multiple arrivals of the same fish tag signals at a nearby receiver [25]. This phenomenon of signal
reflection by barriers (e.g. water surface, air bubbles, sediment or obstacles) is called ‘Close Proximity Detection Interference’ (CPDI) [35,36]. Consequently, when designing an APT around a reflective barrier, position accuracy can be improved or stabilised by keeping enough distance between the reflective barrier and the receivers surrounding it.

Another factor that can influence receiver contribution to APT performance is the local bathymetry. Bathymetry can influence sound propagation [37] and therefore affect signal detection at receivers. In the present study, receivers were moored on a sand bank with dune-like bathymetry (depth may have varied with 1-3m, EMODNet). The structure and position of these ‘dunes’ can vary under the influence of current direction and strength, and can cause acoustic shadow effects of receivers behind ‘dunes’ (i.e. blocking part of the receiver listening angle). Additionally, currents can affect the angle at which a receiver is standing (i.e. it’s tilt), which can result in an additional directional bias of the receiver’s listening angle. Receiver tilt is one of the main influencers of detection range [12] and, together with water flow noise, can hamper detectability [16]. At this study site, the semi-diurnal flood and ebb currents flow to the north-east and south-west, respectively, with current speeds typically reaching up to 1 m/s during the turn of the tide [38]. Change in receiver listening angle could have influenced the spatial distribution of fish positions to be more towards the west side of both turbines (which is likely more sheltered from the current by the turbine), either because of a true spatial preference of the fish or because of a higher detectability of signals. The receiver listening angle in environments with high current speeds can be improved by fixing the receiver in a solid construction above the seabed [39].

4.2 Consequences of receiver loss

A receiver loss event was mimicked through sequential removal of a single receiver from the APT set-ups, which allowed for an evaluation of the consequences of actual loss through drift, damage or burial of receivers. Receiver loss is unfortunately quite common, particularly when receivers are deployed for long periods in harsh environments such as offshore areas [17,40], but also in more shallow coastal areas [41,42, current study]. Results showed that the effect of receiver loss depended on how well an APT is covering the spatial area used by the target species. If the array is larger than the home range of the species, losing one receiver might not have a very large effect on the information recovered.
However, considerable shifts in the estimated swimming tracks may occur if you lose a receiver close
to the core area of activity or in the direction of frequent journeys outside the set-up range. This
exploration provided insights into improved receiver network design and potential consequences of
receiver loss for future studies into the spatial response and activity changes of fish due to human
disturbance (e.g. effects of anthropogenic sounds on fish movement [43,44]).

5. Conclusions

The results confirmed that a set-up of receivers around a turbine, separated by distances tailored to
local propagation conditions (detection range), provides a sufficient APT design for resident cod in the
BPNS. In case extra receivers are available, increased resolution for fine-scaled positioning can be
achieved by placing extra receivers within the array. However, locations in close proximity to the
turbine should be avoided, as this lowers the position accuracy. Data from receiver arrays from which
a receiver was lost should be treated with care, as results revealed that changes in triangulation
outcome can lead to considerable shifts in swimming tracks and home ranges. As a final take-home
message, an explorative, small-scale study like the one presented is recommended, before embarking
on any larger scale APT study. A small-scale exploration like the current one allows testing the
suitability of a receiver set-up for the specific movement patterns and local tracking conditions for a
particular target species.

Abbreviations

BPNS: Belgian Part of the North Sea; CPDI: Close Proximity Detection Interference; ETN: European
Tracking Network; HMM: Hidden Markov Models; HPE: Horizontal Positioning Error; KUD: Kernel
Utilization Distribution; RI: Residency Index; TDOA: Time-Difference-Of-Arrival; VeDBA: Vector
Dynamic Body Acceleration; VPS: Vemco Positioning System

Ethics approval and consent to participate
Catching and tagging treatment of free-ranging animals was performed under the approved ethical certificate number EC2017-080, in line with official guidelines for animal welfare in Flanders.

**Consent for publication**

Not applicable

**Availability of data and materials**

The datasets generated during the current study are available through the European Tracking Network (ETN) repository, http://www.lifewatch.be/etn, upon reasonable request. Further information on the analyses used can be obtained from the corresponding author.

**Competing interests**

The authors declare that they have no competing interests.

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**Authors’ contributions**

JR, HS, HW, TM and IvdK conceived the ideas and designed the methodology; JR, HW and IvdK performed the fieldwork and collected the data; IvdK analysed the data; IvdK led the writing of the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

Location of Belwind wind farm in the Belgium part of the North Sea. A) Grey lines outline the countries land and water boarders (e.g. EEZ’s). Contours of the offshore area designated to wind farm construction in black, red indicates the location of the Belwind. B) Overview of monopile turbine positions at the Belwind. Orange turbines are the two around which APT’s were deployed. Depth around the turbines
varied between 20 - 30 meters (bathymetry data obtained from “European Marine Observation and Data Network” (EMODNet)).

Figure 2

Set-up overview and data from turbine F05. A) Overview of the complete APT set-up; and B) all derived fish positions: colour indicates HPE associated with the position: the lower the HPE, the higher the expected position precision. Positions of receivers and reef balls are indicated with black dots and burrowed electricity cables are represented by grey lines. Effect of single receiver removal on the spread of the daily: C) set-up efficiency (% of positions calculated) and D) position accuracy (difference in HPE).
Figure 3

Set-up overview and data from turbine C05. A) Overview of the complete APT set-up; and B) all derived fish positions: colour indicates HPE associated with the position: the lower the HPE, the higher the expected position precision. Positions of receivers are indicated with black dots and burrowed electricity cables are represented by grey lines. Effect of single receiver removal on the spread of the daily: C) set-up efficiency (% of positions calculated) and D) position accuracy (difference in HPE).
The same 3-hour tracks (grey lines) and 50% core Kernel Utilisation Distributions (KUD in red) of four resident cod. When no receiver was removed (left column: ‘None’) and when a single receiver was removed, that caused the smallest (middle column) and largest (right column) spatial changes in fish positions.