Chapter 2

Telemetry

2.1 Animal biotelemetry

Telemetry is an increasingly applied technique to investigate the behavioural ecology of aquatic animals in the wild and has benefited substantially from miniaturization and software development (Hussey et al., 2015). The word 'telemetry' is derived from the Greek tele, which means (from a) distance, and metron, meaning measurement. As such, telemetry involves collection of data on organisms from a distance.

Telemetry allows researchers to analyse animal behaviour at the individual level. By linking environmental and/or physiological data to the obtained telemetry data, researchers can get a better understanding of ecosystem functioning (Hussey et al., 2015; Lennox et al., 2017). This can help to assess the effects of anthropogenic disturbance by, for instance, man-made constructions (Piper et al., 2017; Reubens et al., 2014; Winter et al., 2007) and thus can deliver the necessary insights for efficiently managing, restoring and conserving aquatic species and habitats (Hussey et al., 2015; Lennox et al., 2017). The resulting data and knowledge form the scientific basis for international policies and directives, such as the Common Fisheries Policy and the Integrated Maritime Policy, Natura 2000, Marine Strategy Framework Directive and the Water Framework Directive, among others (Hussey et al., 2015; Lennox et al., 2017).

Multiple biotelemetry techniques are available to track aquatic animals, each with its specific applications and limitations. Passive integrated transponder (PIT) telemetry, for instance, does not use an internal battery, since the emission signal is generated via an external antenna through which the transmitter needs to pass (i.e. a loop). The main advantage is the production of very small transmitters (< 1 cm in length), but the disadvantage is that antennas need to be built. This is feasible in small river stretches and to some extent in larger rivers (e.g. the NEDAP Trail System® which is a derivation of PIT telemetry), but it is impossible to apply this method in large estuaries and at sea. Other techniques require internal batteries in the transmitter, substantially increasing the transmitters' size. Transmitters applied in radio telemetry transmit radio waves and can be detected by antennas. However, radio waves rapidly attenuate in salt water, restricting the method to freshwater systems. Transmitters of acoustic telemetry on the other hand, emit acoustic signals which can be transferred to ALSs in salt water as well. This may partly explain why it is one of the most popular techniques to track aquatic animals and generate detailed spatio-temporal observations of their movements (e.g. dispersion, migration and homing) and habitat use (Hussey et al., 2015). Obviously, this telemetry technique is appropriate to track diadromous species which move between freshwater and marine environments.

Next to transmitters, some techniques use data storage tags which store environmental data via sensors. Based on these data (mostly water temperature, light and pressure/depth), the tagged animal's trajectory can be estimated (Bonfil et al., 2005; Righton et al., 2016). To retrieve data from data storage tags, the tag needs to be retrieved. However, satellite archival tags have the ability to transmit the collected data to the ARGOS satellite (http://www.argos-system.org), which in turn transmits the data to the processor of the researcher. Since not all aquatic animals surface, pop-up functionalities have been developed for both conventional data storage tags and satellite archival tags. This facilitates that tags wash ashore and can be found by beachcombers and -goers (especially for data storage tags) or that the data are transmitted to the ARGOS satellite when non-surfacing animals are studied. This technique allows long-distance tracking of animals where the mooring of listening devices (e.g. acoustic telemetry, see 1.2) is impossible. However, the pitfall of the technique is that in order to estimate the trajectory of a tagged fish, based on measured environmental variables, high-resolution spatio-temporal data of the environment is a prerequisite. This is rarely the case in freshwater systems. For example, in a polder area in Flanders (see chapter 5), environmental data is measured at most two locations. Also environmental data in the Belgian Albert Canal lacks resolution (i.e. not all environmental variables are measured at all canal sections) or quality (see Chapter 6). Finally, there are electronic tags that combine features of different tags, such as radio-acoustic transmitters (Niezgoda et al., 1998) or the recently developed data storage tags with acoustic emissions.

Since eels move between freshwater and marine environments, and we were interested in environments which are often not monitored at a high spatio-temporal resolution, we decided to apply acoustic telemetry to answer our research questions.

2.2 Applicability of acoustic telemetry in aquatic systems

Acoustic telemetry uses ALSs which detect tagged animals autonomously by registering the transmitter ID, date and time (and sensor data when applicable) (Fig. 2.1). Consequently, this passive technique results in an Eulerian data approach (i.e. fixed stations detect a moving object (Merki and Laube, 2012)), unless active tracking or a dense, fine scale positioning system is applied (Roy et al., 2014). Transmitters come in variable sizes (both length and diameter), ranging from one to several centimeters, dependent on the acquired battery life time, which is related to the research question (e.g. long term vs short term tracking). Battery life time is also dependent on the transmitter settings, such as the minimum and maximum signal emission rate, sensors (e.g. pressure, temperature, accelerometer and predation sensor) and energy output (low or high). Transmitters are preferably surgically implanted in the abdominal cavity to avoid transmitter loss, lesions or biofouling leading to infections, yet this is not always possible dependent on the species (see Chapter 10 for an example of external tagging).

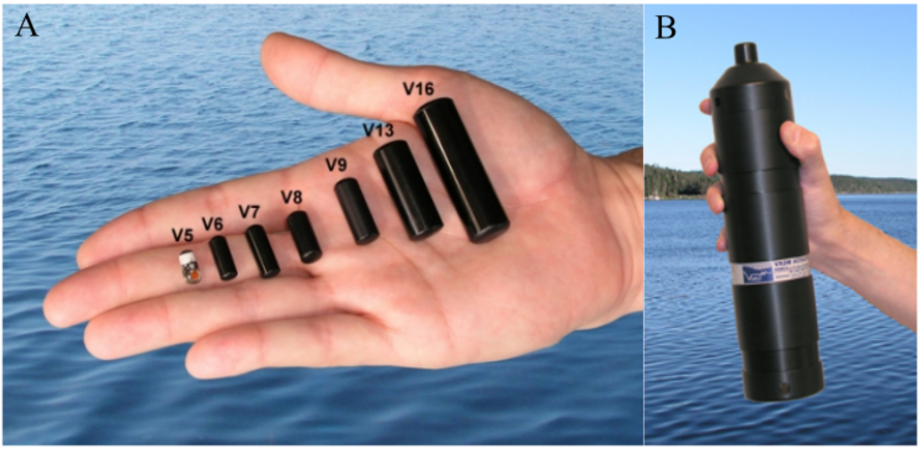

Figure 2.1: Different models of acoustic tags (A) and an acoustic listening station, model VR2W (B) from VEMCO Ltd (Canada) (Photo credit: VEMCO Ltd).

To tag the eels, we followed the protocol by Thorstad et al. (2013): first, fish are placed in a basin with an anaesthetic (e.g. clove oil, MS222 or phenoxyethanol; in this PhD dissertation, 0.3 ml L^{-1} clove oil was applied). When sedated, an incision is made to reach the abdominal cavity (Fig. 2.2). After implanting the transmitter, three stitches with non-absorbable monofilament close the wound. Subsequently, the wound is disinfected with isobetadine and the fish is placed in a reservoir for recovery, which takes approximately 30 min. Although we strived for a transmitter weight : body weight ratio of 2%, higher ratios do not lead to significant differences in swim speed (Brown et al., 1999). Yet, this led to the fact that we only tagged relatively large, female eels, as males are smaller than the minimum size handled in this study (<450 mm (Durif et al., 2005)). Further, transmitter expulsion is possible via the incision, an intact body part or the digestive system (Jepsen et al., 2002), but occurred in only 12% of the eels in a study by Thorstad et al. (2013).

Figure 2.2: Acoustic transmitters are surgically implanted in the abdominal cavity (A) and the wound is subsequently closed with three non-absorbable monofilament threads (B). Eels recaptured after ± 1 year indicated they healed well from the surgery (C).

2.3 The need for aquatic telemetry networks – The Belgian case

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P. Verhelst contributed to writing and generation of the figures.

2.3.1 Abstract

Aquatic biotelemetry techniques have proven to be valuable tools to generate knowledge on species behaviour, gather oceanographic data and help in assessing effects from anthropogenic disturbances. These data types support international policies and directives, needed for species and habitat conservation. As aquatic systems are highly interconnected and cross administrative borders, optimal data gathering should be organized on a large scale. This need, triggered the development of regional, national and international aquatic animal tracking network initiatives around the globe. In Belgium, a national acoustic receiver network for fish tracking was set up in 2014 with different research institutes collaborating. It is a permanent network with 163 acoustic receivers and since the start, over 800 animals from 14 different fish species have been tagged and generated more than 14 million detections so far. To handle all the (meta)data generated, a data management platform was built. The central database stores all the data and has an interactive web interface

that allows the users to upload, manage and explore (meta)data. In addition, the database in linked to an R-shiny application to allow the user to visualize and download the detection data. The permanent tracking network is not only a collaborative platform for exchange of data, analysis tools, devices and knowledge. It also creates opportunities to perform feasibility studies and PhD studies in a cost-efficient way. The Belgian tracking network is a first step toward a Pan-European aquatic tracking network.

2.3.2 Background

Telemetry is an increasingly applied method to investigate the behavioural ecology of aquatic animals in the wild. Multiple biotelemetry techniques are available to track aquatic animals and generate detailed spatiotemporal observations of their movements (e.g. dispersion, migration and homing) and habitat use. This information is needed to understand ecosystem functioning and dynamics. The biotelemetry techniques have already proven to provide cost-efficient crucial oceanographic data (Block et al. 2016), help in assessing the effects of anthropogenic disturbance by, for instance, man-made constructions (Reubens et al., 2014; Verhelst et al., 2018c; Winter et al., 2010) and thus deliver the necessary insights for efficiently managing, restoring and conserving aquatic species and habitats (Abecasis et al., 2014; Afonso et al., 2016). The resulting data and knowledge form the scientific basis of international policies and directives for species and habitat conservation (Hussey et al., 2015; Lennox et al., 2017), such as the Common Fisheries Policy and the Integrated Maritime Policy, Natura 2000, Marine Strategy Framework Directive and the Water Framework Directive, among others.

Aquatic systems are highly interconnected, linking different environments to one another and enable species to move over large distances, crossing administrative borders. This has triggered the development of large scale regional, national and international tracking network initiatives around the globe (e.g. IMOS Animal Tracking in Australia (Steckenreuter et al. 2016), OTN in Canada (Whoriskey and Hindell, 2016) and ATN in the United States (Block et al., 2016)). Each network not only entails the development and maintenance of physical networks of devices, but also the set-up of collaborative platforms for data exchange, analysis tools, devices and knowledge. Clearly, these coordinated, large scale and integrated approaches offer the users valuable opportunities to: 1) scale-up the study area and questions at stake by improving data gathering and sharing among stakeholders; 2) increase funding opportunities and; 3) encourage industry commitment to ensure compatibility between brands and technologies (Hussey et al., 2015; Lennox et al., 2017). In Belgium, scientists collaborated in the set-up of a permanent acoustic receiver network for fish tracking, by merging several local networks of smaller fish tracking projects of different institutes. Here we discuss the rationale behind the network, the current status and data-flow, the opportunities and the integration in a European tracking network.

2.3.3 The Belgian tracking network

Rationale

The Belgian tracking network resulted from a collaboration between Ghent University, the Research Institute for Nature and Forest (INBO) and the

Flanders Marine Institute (VLIZ) in the framework of LifeWatch (http://lifewatch.eu/).

The LifeWatch consortium, which was established in 2012 as part of the European Strategy Forum on Research Infrastructure (ESFRI), works as a virtual laboratory and is meant to support biodiversity research, for climatological and environmental impact studies, to support the development of ecosystem services and to provide information for policy makers in Europe. This large European research infrastructure consists of several biodiversity observatories, databases, web services and modeling tools. It integrates the existing systems, upgrades them and develops new systems. Since 2017, LifeWatch is fully operational and will run for at least 20 years, aiming at long term series of observation data.

As part of the Belgian contribution to LifeWatch, a national marine-freshwater-terrestrial observatory was constructed (http://www.lifewatch.be/) (Fig. 2.3). Many kinds of devices for automated data gathering were installed. The acoustic receivers, used to track fish in their natural environment, are one type of devices. The Belgian tracking network includes the physical network of acoustic receivers and the data management system. The latter involves the database, the data portal and the data explorer.

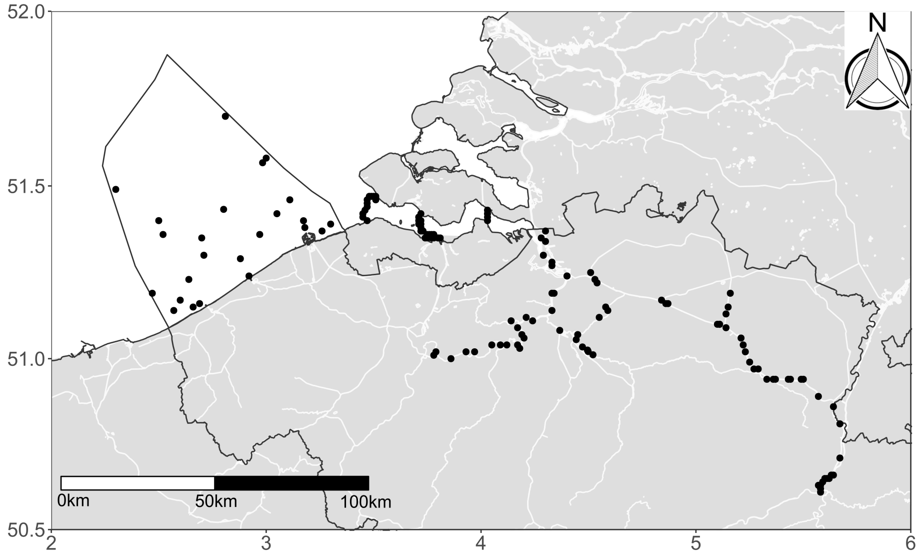

Figure 2.3: The Permanent Belgian Acoustic Receiver Network. Each dot represents a receiver station. National borders as well as the Belgian part of the North Sea are indicated with black solid lines and rivers with white solid lines.

The physical network

The Permanent Belgian Acoustic Receiver Network (PBARN) consists of 163 permanently installed receivers: 25 in the BPNS; 79 in the Schelde river basin (of which 39 in the Westerschelde, and 40 in the Zeeschelde, Nete, Rupel and Dijle), 43 in the Albert Canal and 16 in the Meuse river. The coverage of the permanent network allows tracking of fresh water, marine and diadromous fish in different environments, which are in a greater or lesser extent regulated by human activities. Studies on the permanent network involve PhD studies as well as government or internationally funded projects. The PBARN is, in times, extended by temporary receiver networks. These networks are deployed in the framework of specific projects or studies with a more local focus (e.g. a wind farm, a river stretch, a marsh area). In these projects higher resolution data or additional environments/geographic areas are required for the questions at stake. The number of receiver stations in the temporary projects, and the duration of their deployments depend on the project outline and duration. This manuscript uses the permanent network.

Different types of acoustic receivers of VEMCO Ltd (Canada) are used (i.e. VR2W, VR2Tx, VR2C and VR2AR) and the type depends upon the environment and mooring opportunities. Receivers are moored on navigation buoys, ship wrecks, man-made structures (i.e. reefballs, wind turbines and shipping locks) and along river and canal banks. When attached to buoys, the receivers' hydrophones point downward. When attached to river or canal banks, the receivers are moored near the bottom in upward position. Depending on the type of mooring, the environment and the oceanographic and meteorological conditions, the detection probability of the receivers will differ. We refer to (Reubens et al., 2018) for detailed information on this issue.

Since the start of the network in 2014 over 800 animals have been tagged (Fig. 2.3). In total 767 animals of 13 species have been detected: 166 Atlantic cod (*Gadus morhua* L.), 95 Atlantic salmon (*Salmo salar* L.), 2 common carp (*Cyprinus carpio* L.), 4 common dab (*Limanda limanda* G.), 3 European chub (*Squalius cephalus* L.), 392 European eel, 8 European flounder (*Platichthys flesus* L.), 3 European plaice (*Pleuronectes platessa* L.), 1 lemon sole (*Microstomus kitt* W.), 30 river lamprey (*Lampetra fluviatilis* L.), 2 sea lamprey (*Petromyzon marinus* L.), 35 Twaite shad (*Alosa fallax* L.), 6 common roach (*Rutilus rutilus* L.) and 20 welsh catfish (*Silurus glanis* B.). Several eels from acoustic telemetry projects in The Netherlands and Germany have been detected on the PBARN (Huisman et al., 2016), which explains the higher number of observed versus tagged eels.

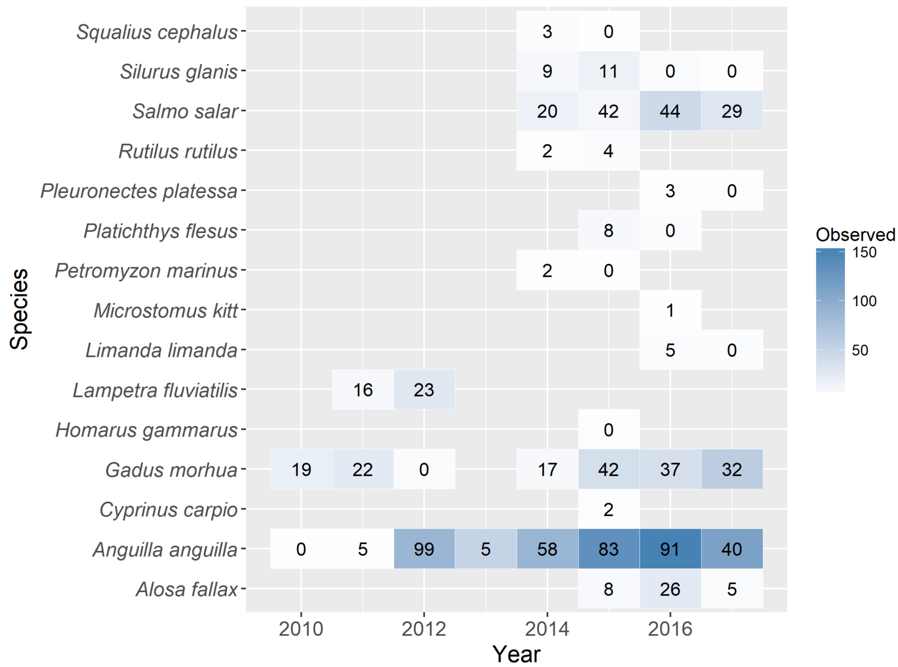

Figure 2.4: Information on tagged species. The numbers indicate the number of tagged individuals per species and per year. The colour gradient indicates the number of individuals per species and per year detected by the Belgian acoustic receiver network.

So far, the PBARN generated more than 14 million detections. Most of these detections occurred at receiver stations in the rivers, canals and the Westerschelde estuary (Fig.2.5). This is, however, strongly correlated to the tagging location and number of specimens per species tagged. The BPNS on the other hand had most of the occurrences from eels tagged abroad (Huisman et al. 2016). These results indicate that each part of the PBARN renders valuable information.

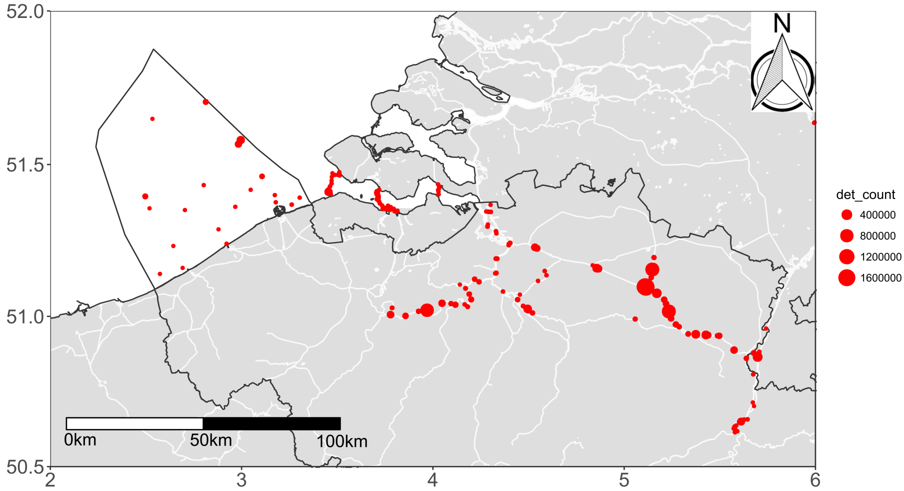

Figure 2.5: Indication of the locations where species have been detected. Size of the dots indicate the number of detections that occurred at that station.

Data management

Next to a physical network, proper data management is needed for a successful telemetry network. All data are stored in a central PostgreSQL database hosted by VLIZ. The database stores both the occurrences (i.e. detection data) and the metadata related to tags, animals, receivers, deployments and projects. An interactive online web interface (http://www.lifewatch.be/etn), developed in PHP using Symfony framework, gives access to all detection- and metadata stored in the database and allows to manage and explore it. Upload of the detection and metadata into the database occurs in a semi-automated way. Several quality controls, to minimize the chance on human errors and maximize the data quality, are performed on the data. There is a data policy (see http://www.lifewatch.be/etn) with moratorium rules in place to ensure that 1) data ownership is protected and 2) data becomes open access to the public at large after the moratorium period ended. We refer to the manual (http://www.lifewatch.be/etn/assets/docs/ETN-DataManual.pdf?1.0) for detailed information about the data management platform.

To explore, visualize and download the detection data an R Shiny application was developed (http://rshiny.lifewatch.be/ETNdata/).

Opportunities

In addition to the advantages mentioned in section 1, the PBARN has proven to create opportunities. One of these is the ability to perform a feasibility study in a cost-efficient way. For some species it is difficult to assess whether acoustic telemetry will be the most suitable technique for a specific research question.

With the presence of a network, a feasibility study can be performed with a limited number of acoustic tags. Such a study can render information on the type and amount of data that will be gathered, and on the geographical and temporal coverage. This can also aid researchers to decide on number of receivers and tags needed and to place receivers at strategic points to maximize detection of the species of interest. Breine et al. (2017) for instance, could test a modified external tagging technique on twaite shad. Shads are very sensitive to handling and stress, rendering the species rather unsuitable for electronic tagging studies. However, the authors of this study succeeded in the development of an external attachment procedure for twaite shad. Through the availability of an extensive array of receivers in the Schelde Estuary, this study could be performed with a limited amount of resources. Further, several pilot studies, which will use the PBARN, are currently initiated for European sea bass (*Dicentrarchus labrax* L.) and starry smooth-hound (*Mustelus asterias* C.). Similarly to pilot studies, the existence of the permanent network can aid PhD studies, as the resources for PhDs are often limited to a bench fee that does not allow to cover the equipment and logistics needed for large experimental set-ups. The PBARN reduces the equipment needs and costs related to logistics and maintenance. Three PhD studies, making use of the BARN, are currently ongoing : two on European eel (Huisman et al., 2016; Verhelst et al., 2018a,b,c,d) and one on Atlantic cod.

Next to providing infrastructure, a coordinated network also stimulates cooperation between researchers on national and international level. In 2014 and 2015, European eels from different river catchments in Western Europe (i.e. Belgium, The Netherlands and Germany) were detected on the PBARN. So far, it was assumed eels use the Nordic migration route over Scotland. However, these detections revealed that at least a part of the population uses another route. Although the different studies were independently organized and focused on different research questions, it resulted in a peer-reviewed publication (Huisman et al., 2016), describing this novel insight in eel spawning migration. Another ongoing study on silver eel escapement in The Netherlands resulted, once again, in detections on the PBARN.

Further, not only infrastructure and data, but also expertise can be exchanged. Telemetry experts from Belgium are currently involved in several projects in The Netherlands and Germany to train their colleagues (unpublished data).

2.3.4 Towards a European Tracking Network

The PBARN is a national showcase proving the value of coordinated networks. However, this national network is just a first step towards a larger, international aquatic telemetry network. Several large scale initiatives are already active in different parts of the world (e.g. IMOS Animal Tracking in Australia, OTN in Canada, ATAP in South-Africa and GLATOS in the Great Lakes) (Cooke et al., 2011; Cowley et al., 2017; Hoenner et al., 2018). These networks address crucial scientific, conservation and management questions on a larger scale.

So far, Europe was lagging behind in these large-scale initiatives. To meet the demand for a Pan-European aquatic telemetry network, the European Tracking Network (ETN) was launched in 2017 in the framework of the European project AtlantOS (https://www.atlantos-h2020.eu/) (Abecasis et al., 2018).

The data management system developed for PBARN will be used as the central data repository for ETN (http://www.lifewatch.be/etn). The necessary adaptations and extensions, required to cover European needs, were implemented recently and the system can now handle large amounts of data. With ETN, Europe will be positioned in the global arena of already existing aquatic telemetry network initiatives (Abecasis et al., 2018).

2.4 Methodological limitations

Obviously, acoustic telemetry has certain constraints, the detection probability being the most important one. The detection probability is highly variable depending on the system with a stable environment leading to a more constant detection probability. However, in dynamic systems such as estuaries and the marine environment, detection probability can vary substantially depending on the environmental conditions (Section 2.5). Also, the geomorphology of the system can have a serious impact on the detection probability. In the Albert Canal for instance, fish were detected over a distance > 1 km, likely attributed to the transmitter signals being scattered over large distances against the concrete embankments (INBO unpublished data). Another constraint of acoustic telemetry is the dependency on detection stations. When there are no mooring opportunities (i.e. no physical structures for attachment or administrative permission), no ALS can be deployed. In freshwater systems this is often not a big problem, but it is logistically impossible to cover large surfaces such as the Belgian part of the North Sea (BPNS). Yet, technological improvements such as built-in acoustic releases allow more flexibility when no fixed mooring opportunities are present. Moreover, even with a sparse network leading to a low number of detections, important results can still be obtained (Chapter 8).

2.5 Environmental factors influence the detection probability in acoustic telemetry in a marine environment: results from a new setup

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For the supplemental material, we refer to the online version of the article: https://doi.org/10.1007/s10750-017-3478-7
P. Verhelst contributed to the data analysis, generating the figures and writing the text.

2.5.1 Abstract

Acoustic telemetry is a commonly applied method to investigate the ecology of marine animals and provides a scientific basis for management and conservation. Crucial insight in animal behaviour and ecosystem functioning and dynamics is gained through acoustic receiver networks that are established in many different environments around the globe. The main limitation to this technique is the ability of the receivers to detect the signals from tagged anim-

als present in the nearby area. To interpret acoustic data correctly, understanding influencing factors on the detection probability is critical. Therefore, range test studies are an essential part of acoustic telemetry research. Here, we investigated whether specific environmental factors (i.e. wind, currents, waves, background noise, receiver tilt and azimuth) influence the receiver detection probability for a permanent acoustic receiver network in Belgium. Noise and wind speed in relation to distance, the interaction of receiver tilt and azimuth, and current speed were the most influential variables affecting the detection probability in this environment. The study indicated that there is high detection probability up to a distance of circa 200 m. A new setup, making use of features that render valuable information for data analysis and interpretation, was tested and revealed general applicability.

2.5.2 Introduction

The use of acoustic telemetry has been growing a lot in recent years and acoustic receiver networks are being established around the globe in many different aquatic environments. Consequently, our understanding of the ecosystem functioning and dynamics (e.g. migration routes, spatio-temporal habitat use and movement behaviour of key species) in these environments has significantly improved in recent years. This knowledge provides a scientific basis for fisheries management (Hussey et al. 2016), species conservation, marine spatial planning (Abecasis et al., 2014; Afonso et al., 2016) and environmental impact assessment (Reubens et al., 2014; Winter et al., 2010). In 2014, a permanent acoustic receiver network was set up in the Belgian part of the North Sea (BPNS), the Westerschelde (The Netherlands) and several rivers and canals in Belgium in the framework of a long-term European project 'LifeWatch' that aims at automated monitoring of biodiversity (http://www.lifewatch.be). The Belgian network currently consists of 177 receiver stations in the marine, estuarine and freshwater environment (Fig. 2.6). It is a dynamic network and receiver stations can be added or removed according to the requirements of the projects involved (see http://www.lifewatch.be/etn/login for the most recent update of the network). Such a network of receivers allows detailed observations of animal movement and behaviour in the aquatic environment.

Although acoustic telemetry is a cost- and labour-efficient method able to generate extensive datasets in a short time period, it also suffers some limitations (Gjelland and Hedger, 2013; Hobday and Pincock, 2011; Kessel et al., 2014) which are often less understood (Huveneers et al., 2016) or not taken into account. The most important limitation is related to the ability of a receiver to detect the signals from tagged animals in its vicinity. This so-called detection probability depends on many factors, which are linked to the physical characteristics of sound propagation through the water column (Gjelland and Hedger, 2017; Medwin and Clay, 1997), and can change over space and time. As a consequence, the successful application of acoustic telemetry and the correct interpretation of detection and movement data depend upon proper knowledge of the detection range (i.e. the relationship between detection probability and the distance between the receiver and tag) (Gjelland and Hedger, 2017; Kessel et al., 2014). It is therefore important to know the environment one is working in and the factors that could influence the applicability of the technique. Therefore, before a study is initiated, the applicability of receiver arrays or networks to the questions at stake should be carefully reviewed. Thus, extensive range tests should be performed. The results of such range tests can be used to improve the setup and the design of the receiver arrays and/or to adapt the questions that can be answered (Hayden et al., 2016; Hobday and Pincock, 2011; Kessel et al., 2014; Selby et al., 2016; Steckenreuter et al., 2017; Stocks et al., 2014).

It is well known that the detection probability will depend upon several factors related to transmission parameters (frequency, signal strength) and sound attenuation properties in the water (absorption, scattering, spreading and reflection). These attenuation properties depend upon specific characteristics of the water mass and the geomorphology of the system (e.g. temperature, salinity, substrate type, vegetation, suspended particulate matter) (Gjelland and Hedger, 2017; How and de Lestang, 2012; Jensen et al., 2000; Kessel et al., 2014). In addition, both anthropogenic and natural sound sources may mask the signal as the signal-to-noise ratio becomes too low (de Jong et al., 2011; Huveneers et al., 2016). The BPNS, for instance, is a shallow ocean basin with sandy sediments and strong tidal currents and winds (Baeye et al., 2013; Fettweis et al.). In addition, intensive shipping traffic and offshore industry result in high anthropogenic noise generation (e.g. dredging and disposal, deepening of navigation channels, offshore wind farm construction) (Douvere et al., 2007). Both the environmental characteristics and the anthropogenic noise generation can influence the detection probability within the acoustic receiver network present in the BPNS.

Range tests can be performed in many different ways. Several options are available for the setup and duration of the test. Most used setups (a) are in situ, short term (i.e. a couple of hours to one day) range tests performed during the study, and (b) use a setup with single tags at different distances from a fixed receiver. We refer to Kessel et al. (2014) for an extensive literature review on this topic. In this study, a new setup was applied, which has the advantage that it tests detection probabilities over a prolonged period of time at fixed distances, using a multitude of sentinel tags. VR2AR receivers (VEMCO Ltd, Canada) were used. These receivers contain a hydrophone to record detections, a built-in transmitter which renders information on the exact transmission times, an acoustic release, and several sensors which monitor tilt angle, temperature, depth and noise. The tilt sensor is the most interesting sensor in relation to range tests as it gives an indication of the receiver angle. The latter may have a profound influence on the detection probability through the angle between the incoming sound wave and the hydrophone (Bergé et al., 2012), as well as through potential shadowing by the receiver body or the mooring frame. In addition, it is expected that different meteorological and oceanographic variables influence the receivers' detection probability through time.

In this study we assess whether specific environmental factors influence the performance of acoustic receivers in a part of the Belgian receiver network (Fig. 2.6). More specifically, we assess 1) the influence of wind, currents, waves, background noise, receiver tilt, azimuth and distance on the detection probability; and 2) the average detection range in this environment. In addition, the applicability of the new setup for range tests is evaluated.

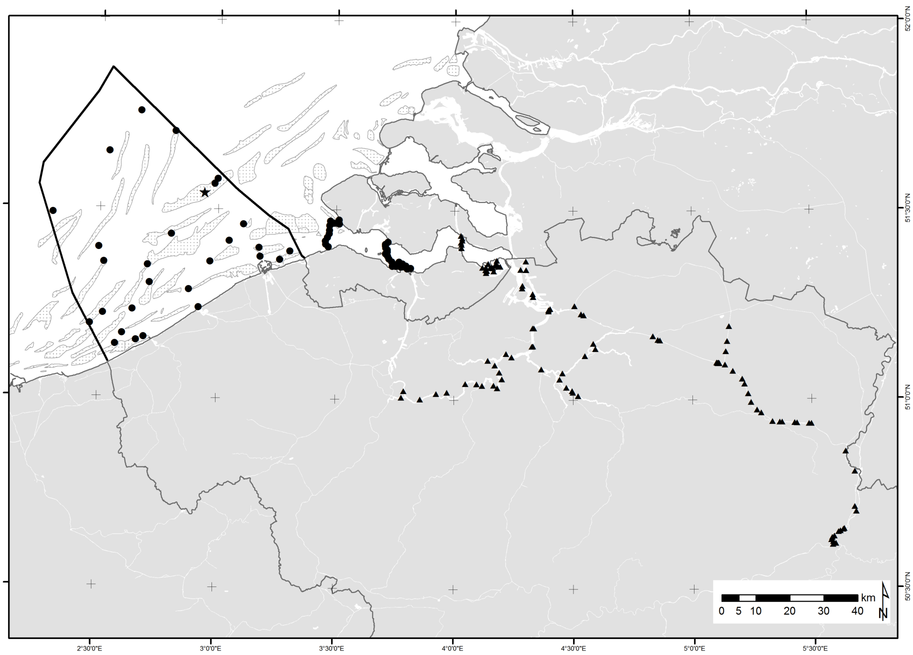

Figure 2.6: The Belgian acoustic telemetry network. The dots and triangles represent the 177 receiver stations currently in operation; the dots are those stations to which the results of the range test are assumed to be applicable; the black star indicates the location of the range test study. Bold black line delimits the BPNS, light-grey shading represents sand banks.

2.5.3 Material and methods

Study area

The study was performed at an offshore wind farm in the BPNS (Fig. 2.6). It is situated on the Thornton bank, a natural sandbank about 27 km off the Belgian coast. The sandbanks in the BPNS are created by the strong tidal actions, which also results in a high turbidity (Otto et al., 1990). Water depth varies between 18 and 24 m in the area and the substratum consists of medium sand (Reubens et al., 2014). This site was specifically chosen as it is closed for all types of fishing, which effectively protects the receivers against bottom disturbance due to trawling activity and thus against damage and loss. The site represents typical conditions in the BPNS (i.e. shallow depths, sandy sediments and high current velocities). Thus, although the study was performed in a small area, it is assumed that the results are applicable to most of the network's receivers in the BPNS and the entrance of the Westerschelde (black dots in Fig. 2.6), except for receivers positioned in the freshwater-salt water transition area, where boundary transitions may have a profound additional effect on detection probability.

Study design and data collection

Deployment of receivers

Seven VR2AR acoustic receivers of VEMCO Ltd (Canada) were used. These receivers have a built-in transmitter (with several transmission power and delay options), sensors that measure tilt, depth, temperature and noise, and an acoustic release. These features make them favourable for range tests. The receivers recognize the tag IDs from the transmitters and log the detections together with a timestamp. The receivers were deployed at fixed distances, spaced between 50 and 350 meters from one another (Fig. 2.7). This setup results in 49 distances (i.e. 7 receivers each with 7 distances), ranging from zero (logs of built-in tags) to nearly 700 m, with approximately 50 m increments between the receivers and the transmitters (Fig. 2.7). Exact distances were based on GPS positions taken during deployment (ranging from 0 to 683 m, see also Table 2.1). Transmission power of the built-in transmitters was set at 148 dB, with a random transmission delay between 60 and 120 seconds to avoid signal collisions.

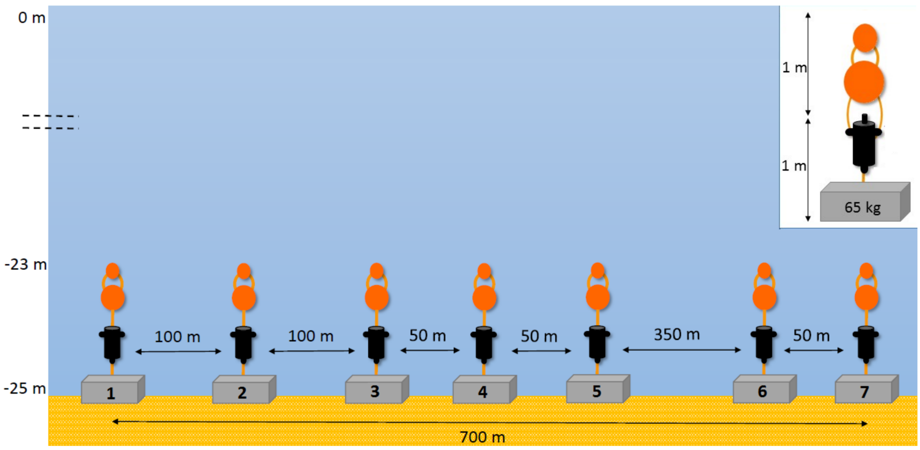

Figure 2.7: Setup of the range test. Seven acoustic receivers with a built-in transmitter were used. Distances range between 0 and 700 m, with 50 m increments. Tidal influence on depth is not taken into account.

The receivers were moored on the sea bottom with a block of bluestone of approximately 65 kg. Two hard plastic floats (280 and 180 mm diameter) were connected with polypropylene rope to the receiver to keep it in upright position (hydrophones pointing to the surface). Floats were positioned ca 1 m above the hydrophone to ensure that the detection field of the hydrophones was not blocked. No surface floats were used to avoid ship collisions. For detailed information on mooring design, see Vemco (2016a).

Table 2.1: Distance matrix (in meter) between receivers and built-in tags.

	R1	R2	R3	R4	R5	R6	R7
T1	0	85	176	232	281	631	683
T2		0	97	150	199	548	600
T3			0	59	106	455	507
T4				0	49	399	451
T5					0	350	402
T6						0	52
T7							0

Monitoring environmental parameters

Several oceanographic (current speed, current direction and wave height) and meteorological (wind speed and wind direction) parameters were measured during the study. Wind speed and wind direction data were obtained from 'Meetnet Vlaamse Banken', from station MOW 0 (51.33° N, 3.22° E) at 31 km from the study area. Wave height was also obtained by 'Meetnet Vlaamse Banken' but from station Westhinder (51.38° N, 2.44° E) at 39 km distance, as this data was not available at MOW 0. Current data was calculated from a 2D hydrodynamic model from the Operational Directorate Nature of the Royal Belgian Institute for Natural Sciences. The modelled currents are based upon astronomical tides and meteorological influences (i.e. wind and atmospheric pressure). In addition to these measured and modelled environmental parameters, the tilt measurements from the VR2AR built-in sensor were used as well. Although tilt is not an environmental parameter, it may potentially influence detection probability if this is not perfectly omnidirectional, and was therefore taken into account. This parameter was logged for the duration of the study with a ten-minute interval.

In addition, we calculated the azimuth (i.e. the angle) between the transmitter-to-receiver bearing and the current direction, scaled to 180°. This parameter provides additional information related to the angle between the receiver and the incoming signal, which may reveal e.g. shadowing effects caused by the receiver body. An azimuth of 0° indicates that transmitter-to-receiver bearing and current direction have the same bearing, while at 180° they have a completely opposite direction.

Temperature, salinity, depth and sediment type were not taken into account for the modelling, as receivers and tags were all present in the same environment and at very similar depths. No thermoclines nor haloclines are present in the area as the water column is well mixed.

The study ran for 22 days (from 18-02-2016 to 10-03-2016). This period encompassed varying environmental conditions (Table 2.2), making it possible to assess the influence of the different parameters on receiver performance and detection probability. Temperature varied between 6.5 and 8.0°C and average water depth was 23 m. Wind speed varied between 0.25 and 21 m s^{-1}, while current speed ranged between 0.13 and 0.92 m s^{-1}. Wave height varied between 0.30 and 2.54 m, tilt between 0 and 25 °. The study was performed in winter time, allowing for harsh environmental conditions (i.e. strong winds and high waves).

Table 2.2: Minimum and maximum value of the different environmental parameters and the tilt. An overview of the different data collection methods and stations is provided.

Variable	Method	Station	Min. value	Max. value
Wind speed (m s^{-1})	Measured	MOW 0	0.25	20.95
Wind direction(°)	Measured	MOW 0	0.14	359
Current speed (m s^{-1})	Modelled	/	0.13	0.92
Current direction (°)	Modelled	/	0.07	359
Wave height (cm)	Measured	Westhinder	30	254
Tilt (°)	Measured	Built-in sensor	0	25
Noise (mV)	Measured	Built-in sensor	105	903

Data analysis

At the end of the study, data was downloaded from the receivers and was uploaded into the European Tracking Network database (http://www.lifewatch.be/etn). A dataset, containing the 442,856 transmissions from the built-in transmitters detected by the seven receivers, was created.

Detection data were binned per half hour (as the weakest resolution of the environmental data was per half hour) for each receiver-tag combination (hereafter referred to as events), and linked to the environmental parameters for the same time period. All events in which no detections were encountered were also added to the data frame, as we were not only interested in presences, but also absences. This resulted in 49,098 distinct events. As receiver clocks are sensitive to time drift, detection data were accounted for possible time drift using the linear time drift correction available in the VUE software of VEMCO Ltd. It was assured that PC clock time was correct at the moment of initialization of the receiver and upload of the data. The effects of the environmental variables on the detection probability were assessed. First, the data were checked for outliers (defined as data points below Q1 – 1.5×IQR or above Q3 + 1.5×IQR) followed by a collinearity analysis (Zuur et al., 2010). If correlations were found, one of the covariates was excluded from the analysis (Dormann et al., 2013).

To determine which environmental variables contributed to the detection probability, a generalized linear model was applied. The covariates were scaled by applying a z-transformation:

$$x = \frac{x - mean(x)}{sd(x)}$$

The model was tested for overdispersion and zero-inflation. Overdispersion was tested using the vuong test from the pscl package in R (R Development Core Team 2017) . As the vuong test revealed that the negative binomial distribution performed better than the Poisson distribution, it could be assumed that overdispersion did occur and thus the negative binomial distribution should be used. A histogram showing the number of detections per event revealed that the data were zero-inflated. Due to the random transmission delay of the tags, the number of transmissions a tag emitted per half hour time bin differed through time. To account for this, an offset was used in the model (Zuur et al., 2009). The offset was defined as the logarithm of the number of transmissions sent out by the built-in tag per event. Based on the result from the above tests, it was decided to use a zero-inflated negative binomial (ZINB) distribution with an offset for the model development. For more details on ZINB models we refer to Zuur et al. (2009). The package pscl of the R environment (R Development Core Team 2017) was used. Based on Forstmeier and Schielzeth (2011) and Hegyi and Garamszegi (2011) it was decided to work with the full model.

In addition, to estimate the average detection range within our study site, the detection probability per distance was calculated for the half hour time bins. This probability was calculated as the number of transmissions received, divided by the number of transmissions sent out.

2.5.4 Results

Variables influencing detection probability

The large temporal variation in detection rate (Fig. 2.8) indicates that environmental factors influence the detection probability. Under favourable oceanographic conditions, transmissions can be received much further (even beyond 400 m). On the other hand, in unfavourable conditions, transmissions can be missed even at very close distances. Collinearity analysis revealed a high correlation between wave height and wind speed (0.72). We decided to remove wave height since wind information consists of two components (direction and speed), each of which can be informative. The model revealed that several environmental parameters influence the detection probability. The interactions of noise and distance, and of wind and distance contributed most, followed by the interaction between tilt and azimuth, and current speed (Table 2.3). It should be kept in mind that there still is a lot of unexplained variation. At close distances, the detection probability is not much influenced by noise or wind. However, at larger distances, noise and wind negatively influenced the detection probability (Fig. 2.9, Fig. S2). The influence of the azimuth depended upon the receiver tilt. At no or low receiver inclination, the detection probability increased with increasing azimuth; while at higher receiver inclination, azimuth negatively influenced the probability. The detection probability decreased only slightly between minimum and maximum current speed (Fig. 2.9), hence the current speed only has a limited impact on the detection probability.

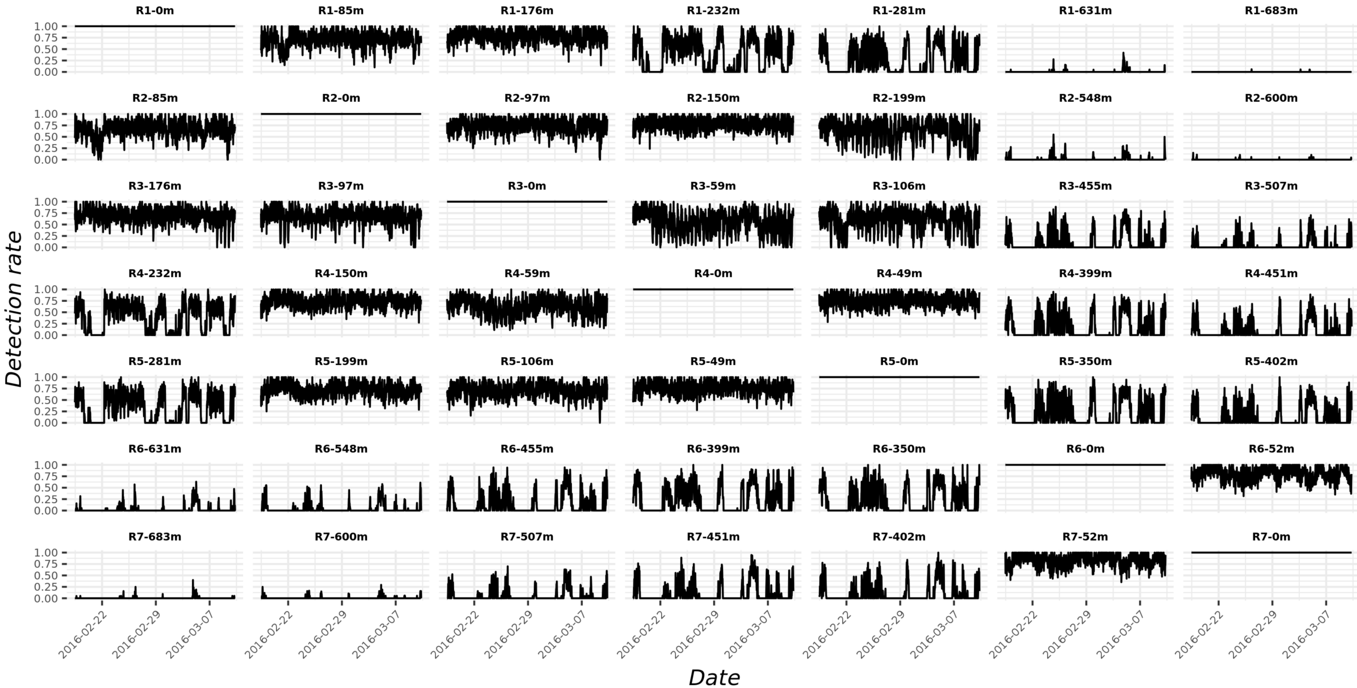

Figure 2.8: Detection rate for all distances for the seven groups for the duration of the study. Each group represents the detections over time of one receiver linked to seven transmitters.

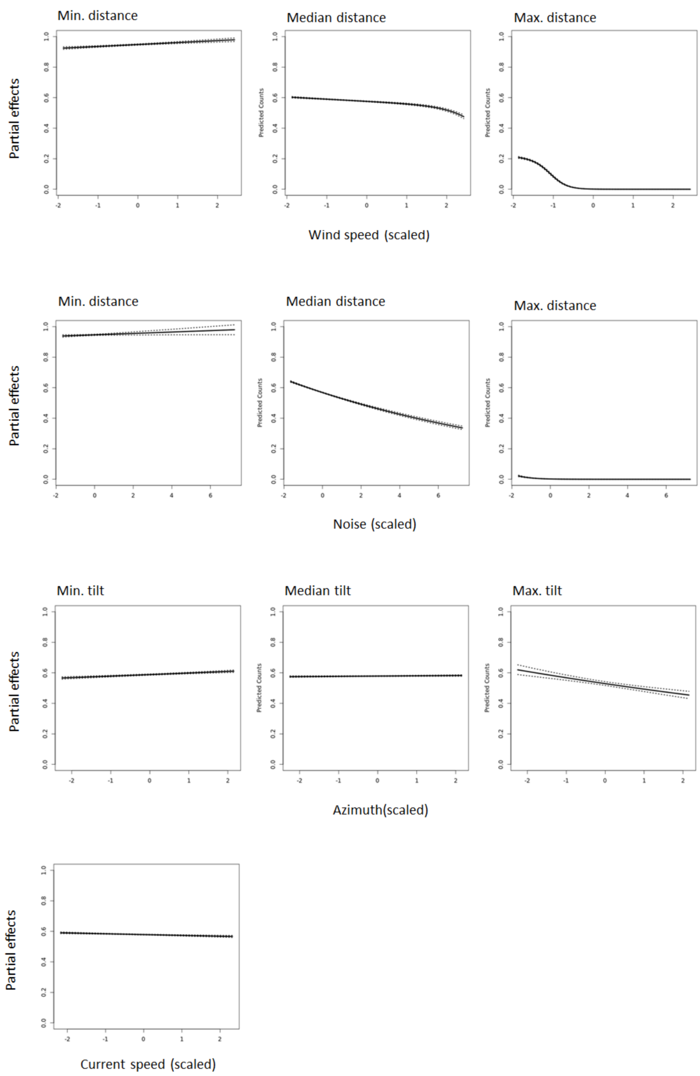

Figure 2.9: Summary of the partial effects of the environmental parameters on the detection probability. For interaction effects, the minimum medium and maximum value for distance and tilt are shown. Dashed lines indicate the 95% confidence intervals.

Table 2.3: Zero-inflated Poisson model summary.

	Estimate	SE	z value	p-value
Count part: *Negbin with log link*				
Intercept	-0.75	0.00	-211.95	< 0.001
Wind speed	-0.04	0.00	-10.05	< 0.001
Distance	-0.57	0.00	-149.79	< 0.001
Wind direction	-0.01	0.00	-4.07	< 0.001
Tilt	-0.02	0.00	-7.21	< 0.001
Azimuth	0.00	0.00	-0.81	0.42
Noise	-0.10	0.00	-32.83	< 0.001
Current speed	-0.01	0.00	-4.25	< 0.001
Current direction	0.00	0.00	0.64	0.52
Wind speed*Distance	-0.04	0.00	-10.69	< 0.001
Tilt*Azimuth	-0.01	0.00	-7.14	< 0.001
Noise*Distance	-0.08	0.00	-27.68	< 0.001
Log(theta)	13.63	9.54	1.43	0.15
Inflated part: *Binomial with logit link*				
Intercept	-5.15	0.04	-129.81	< 0.001
Wind speed	2.46	0.04	59.44	< 0.001
Distance	5.58	0.07	80.45	< 0.001
Wind direction	-0.04	0.02	-1.90	0.057
Tilt	0.34	0.03	10.51	< 0.001
Azimuth	-0.03	0.03	-0.99	0.32
Noise	0.29	0.03	8.31	< 0.001
Current speed	0.23	0.03	7.72	< 0.001
Current direction	0.03	0.02	1.44	0.15
Wind speed*Distance	1.24	0.04	29.17	< 0.001
Tilt*Azimuth	-0.05	0.04	-1.33	< 0.18
Noise*Distance	0.47	0.04	12.02	< 0.001

Detection range

Figures 2.8 and 2.10 reveal that the average detection probabilities are high (i.e. above 70%) until a distance of ca. 200 m, whereafter they quickly drop to (near) zero at a distance of 350 m. These results indicate that there is a limited detection range within this dynamic environment. However, there is considerable temporal variation in detection probability, and thus in detection range.

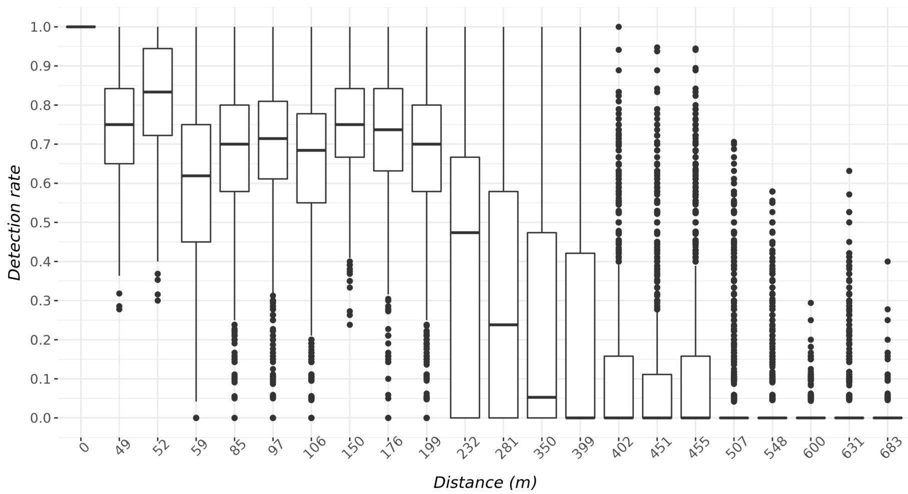

Figure 2.10: Boxplots of detection probability in relation to the distance between receiver and transmitter. Dots represent outliers.

2.5.5 Discussion

Variables influencing detection probability

Our results demonstrate that detection probability is not static and can change considerably over time. It was mainly influenced by noise and wind speed in relation to distance, the interaction between tilt and azimuth, and to current speed; which is in agreement with Gjelland and Hedger (2013); Huveneers et al. (2016). In contrast, Stocks et al. (2014) listed wave height as the principal factor affecting detection range. However, wave height was highly correlated with wind speed, hence our study does not contradict the results of Stocks et al. (2014).

The influence of wind can be attributed to both the noise generation itself and to the air bubbles that are mixed into the water column (Gjelland and Hedger, 2013). Scattering of signals in strongly wind-influenced surface layers will, due to air bubbles (Medwin and Clay, 1997) and multi-path (Dol et al., 2013), increase the sound attenuation in these layers, but also contribute to increased background noise levels, even at larger depth.

The interaction effects of noise with distance, and of wind with distance can be explained by the signal-to-noise ratio (SNR). At close distances, the SNR is still high, hence the transmitted signal strength dominates over the ambient noise (including wind-generated noise) present in the environment. At higher distances, the transmitted signal has already lost part of its strength due to attenuation and interference, and therefore negatively influences the SNR (Vemco, 2015).

The present study was performed in an offshore wind farm, and although it is expected that ambient noise in this area is lower than in the surrounding environment because no shipping or industrial activities take place here, noise still significantly influenced the detection probability. Both anthropogenic and natural sound sources may mask the transmission signal (de Jong et al., 2011; Gjelland and Hedger, 2017; Huveneers et al., 2016), and it is difficult to attribute the impact to a specific sound source. As the sound sources, and thus the SNR, strongly vary in both spatial and temporal context, the influence of noise on the detection probability may strongly differ between receiver stations in the Belgian network.

The influence of currents, on the other hand, can be attributed to both flow noise and tilt angle of the hydrophone. Flow noise refers to changes in pressure and the creation of eddies around the hydrophone under high flow conditions, and can be caused by movement of the hydrophone in the water column (Martin et al., 2013). In addition, the hydrophone can also receive strumming noise from ropes under tension. As flow noise generally occurs below 1 kHz (Martin et al., 2013), this does not cause problems for acoustic receivers. However, the eddy creation may cause sound attenuation. The tilt angle of the hydrophone presumably better explains the variation in the detection probability than current in itself (Fig. S3). The higher the current velocity, the higher the tilt angle becomes. If the tilt angle becomes too high, the hydrophone no longer has an unobstructed view and shadow zones are created (Vemco, 2016a), which can adversely affect the detection probability. However, this is also influenced by the azimuth as, the interaction effect between tilt and azimuth indicated. The azimuth is defined as the angle between the transmitter-to-receiver bearing and the current direction, which changes over time. At some moments in time, the receiver may be tilted towards the focus transmitter, resulting in a higher detection probability. With changes in the current direction, the receiver is tilted away from the transmitter, causing reduced detection probability due to shadowing.

In addition, the present results reveal that the detection probability does not decline linearly, but shows some inconsistencies at close distances. Although the receiver-transmitter distance was within the same range between 49 and 59 m, the detection probability differed considerably. This might be related to small local differences in the environment, as mentioned earlier. However, it can also be related to close-proximity detection interference (CPDI) or tag code collision. As stated by Kessel et al. (2015) and Gjelland and Hedger (2017), CPDI occurs when reflective barriers (e.g. water surface, air bubbles) result in multiple pathways from transmitter to receiver. As these multipath signals have the same frequency, they contribute to the background noise. Code collision is a function of the number of transmitters within range of the receiver, the signal duration and signal delay (Binder et al., 2016). At larger distances there is a reduction in code collisions as transmissions are attenuated.

Besides environmental variables, sediment characteristics and topography, also the mooring design, the transmission characteristics of the tags, the transmitter attachment on the fish and the configuration of the receivers can all influence the detection probability (Clements et al., 2005; Dance et al., 2016; Heupel et al., 2006; Hobday and Pincock, 2011; Simpfendorfer et al., 2008). For this range test, transmission power output was set at 148 dB, and the receivers were moored near the bottom with the hydrophone pointing in an upward direction. Different setups or tag specifications will undoubtedly affect the results. Many of the receivers deployed in the BPNS and the Westerschelde are moored near the surface (using navigation buoys) with the hydrophone pointing downward. As wind action significantly influences detection probability, it can be expected that receivers near the surface will be more negatively influenced by wind than receivers near the bottom. On the other hand, the range test was performed in winter, when more extreme weather events such as storms and high waves occur. In the whole of 2016, the maximum wind speed was 25 m s^{-1} at MOW 0, with a peak of 21 m s^{-1} during our test period, while the largest wave height measured in 2016 was 3.8 m, compared to 2.54 m during our test period. High wind speeds and wave heights were mainly measured in quarter 1 of 2016. As a result, most of the year, detection range may be higher than what we found in this study.

Detection range

The present study demonstrates that there is a good detection probability up to 200 m, but it quickly reduces beyond this distance. This detection range is in the range of previous reports, which encompass both higher (Hobday and Pincock, 2011; Huveneers et al., 2016) and similar range values (Cagua et al., 2013; Stocks et al., 2014; Welsh et al., 2012). Some other publications have reported a broad range of distances within the same study (Cagua et al., 2013; Gjelland and Hedger, 2013; How and de Lestang, 2012). Although the detection ranges differ extensively between the cited studies, they all concluded that detection range strongly depends upon meteorological and oceanographic environmental variables, on sediment characteristics, and on the environment's topographic complexity; factors which all influence sound propagation in water. As environmental conditions and topography differ largely between areas, detection ranges will do so as well. Even in environments that look comparable at first sight, small local differences can have large effects on the detection probabilities and thus also on the detection ranges.

Coping with variation in detection probability

Of similar importance as knowing which factors influence the detection probability, is to know how to account for this variation in detection probability (Gjelland and Hedger, 2013, 2017). Performing adaptations at the level of data-analysis, mooring and receiver setup, and/or research questions can partly overcome the problem. Changes to the setup or the questions to be answered can only be made if there is some a priori knowledge on the influencing factors. On many occasions, influences on detection probability only become clear once data-analysis has started. This underlines the importance of reliable data analysis when dealing with the specific situation where the factors influencing the detection rate may bias the results towards false negatives (absences of recordings on specific moments despite fish being present). Data analysis should take this increased likelihood of false negatives into account. This can, for instance, be done by including a prevalence-adjusted performance criterion. Such a criterion contains an adjustable parameter that corrects for false negatives (Mouton et al., 2009a). The performance criterion can vary as a function of the influencing environmental parameters and thus allows incorporation of ecological relevance in the model optimisation process (Mouton et al., 2009b) to more accurately model the fish movement behaviour.

The present study revealed that current speed and azimuth influence the detection probability. This indicates that the mooring design could be improved. By fixing the receiver (e.g. on a frame), the hydrophone wouldn't be able to tilt anymore. As a result, the 'line of sight' between receiver and transmitter wouldn't change in function of the current direction. Although not empirically tested, this would probably reduce the statistical noise in the data.

Applicability of the range test setup

In Belgium, several short-term (i.e. hours up to a few days) range tests have previously been undertaken (but were never published) in both marine and freshwater environments. The current study is the first extensive range test in Belgian offshore waters and the setup used has, to our knowledge, never been used before. The research field of acoustic telemetry is characterized by fast technological improvements and new developments are launched regularly (Whoriskey and Hindell, 2016). The VR2AR receivers used in this study are a relatively new type of receivers that combine a regular receiver with a built-in transmitter, an acoustic release, and several sensors which monitor tilt angle, temperature, depth and noise (Vemco, 2016b). There are several aspects that make such a type of receiver favourable for range testing. First, the transmission events from the built-in tag are logged in the memory of the receiver. They don't actually listen to their self-transmissions, but simply record the date and time that they transmitted, thus allowing the researcher to know the exact number of transmissions in a specific time period. This is a practical feature if the transmitters are programmed to send their signal in random delay modus or in situations where there is a high chance for echo detections due to the characteristics of the environment (e.g. in areas with hard substrates or ice cover). Secondly, the available sensors give in-situ information on receiver tilt and an estimate of the presence of noise in the environment (Vemco, 2016b). Although it doesn't give detailed information, this data can already inform researchers about possible environmental features conflicting with the transmissions. Further, with a limited number of units, many different distances between receiver and tags can be created, resulting in detailed information on the relation between detection probability and distance. Lastly, the built-in acoustic release allows for easy retrieval, without the need for surface marker buoys. This reduces complexity of the setup, and thus considerably reduces the chance of recovery failure of the mooring.

2.5.6 Conclusion

When interpreting acoustic telemetry data, it is important to keep in mind how the characteristics of sound propagation through water relate to environmental factors (i.e. meteorological, oceanographic and topographic) and interfere with other sound sources (both natural and human). It is important that scientists understand these influencing factors, consider their contribution, and adjust for them where possible, when interpreting the results. We encourage performing range tests for each study area, and when possible, for the entire duration of a study. If the latter is not possible, the range test period should at least cover a time span that is sufficient to assess the influence of varying environmental conditions on detection probability.

The setup tested in this study made use of features (e.g. transmission event and tilt data) that render valuable information for data analysis and interpretation of the results. The setup is easy to deploy and retrieve. These aspects make it a comprehensive technique with potential for general applicability.