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The 3S3 experiment data report

— using operational naval sonars to study the effects of continuous active sonar, and source proximity, on sperm whales

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Summary

The 3S project is an international collaborative effort with the aim to investigate behavioral reactions of cetaceans to naval sonar signals. The objectives of the third phase of the project (3S3) were to investigate if exposure to continuous active sonar (CAS) leads to different types or severity of behavioral responses than exposure to traditional pulsed active sonar (PAS) signals, and to investigate how the proximity of the source to a whale affects behavioral responses. This report summarizes the method and data collected during the 3S-2016, 3S-2017 and 3S-2019-OPS research trials.

We worked on and off the shelf break between Harstad and Tromsø in Norway. Sperm whales and pilot whales were the primary target species. When a target species was localized, a tag boat was launched and DTAG or mixed-DTAGs deployed. The mixed-DTAG contained a GPS, an Argos satellite transmitter, in addition to the core DTAG unit with triaxial accelerometers and magnetometer sensors, stereo acoustic sensors and a pressure sensor. In addition to the tags, additional acoustic data were collected by two moored acoustic buoys, for assessment of potential vocal responses and avoidance of the exposed area. Tagged whales were subject to controlled sonar exposure experiments (CEE). The experimental design involved dose escalation at different ranges and maximum source levels using operational sources towed by the FFI research vessel H.U. Sverdrup II (HUS) or the Norwegian Navy frigate KNM Otto Sverdrup (OSVE). The experiments were conducted under permit from the Norwegian Animal Research Authority, and all procedures were approved by the Animal Welfare Ethics Committee at the University of St Andrews. A separate risk assessment and management plan was developed for the trial to minimize risk to the environment and third parties.

During a total of 9 weeks at sea we tagged 33 sperm whales and collected 630 hours of tag data. We conducted 24 controlled exposure experiments with 71 sonar or control sessions. 7 CEEs with 16 sessions were conducted using the frigate OSVE as the source vessel. In addition, 8 long-finned pilot whales were tagged, but tag durations were generally short and only 2 CEE sessions were conducted. Only the sperm whale data is reported here. Data plots of all collected data are presented, with a summary of key experimental outcomes. Further analysis and interpretation of the data will be presented in already published or scientific papers in preparation.

We expect that the data collected will be sufficient to achieve the objectives of the 3S3 project and answer the questions of CAS versus PAS and received level versus range conclusively for sperm whales. This knowledge will increase our ability to do risk assessment on new CAS technology and to assess how experimental data from CEEs using scaled sources can be used to predict responses from real naval sonar scenarios. Remaining questions for future research include how CAS affects the behavior of other species, particularly species more sensitive to PAS, and whether habituation or sensitization might occur during longer duration exposures that are more realistic.

A video showing the activities during the 3S3 experiments can be seen following this link.

Sammendrag

3S-prosjektet er et internasjonalt forskningssamarbeid som undersøker hvordan hvalers atferd påvirkes av militære sonarer. 3S-prosjektet er nå i sin tredje fase (3S3) der målsettingene er å undersøke om moderne kontinuerlige sonarer (CAS) har større innvirkning enn konvensjonelle pulsede sonarer (PAS), og å undersøke om avstanden mellom sonarkilden og dyrene påvirker terskelen for respons. Denne rapporten oppsummerer metodene og dataene som ble samlet inn under toktene 3S-2016, 3S-2017 and 3S-2019-OPS.

Data ble samlet inn langs Eggakanten fra Harstad til Tromsø. Spermhval og grindhval var studieobjekter. Når en hval ble oppdaget, ble de merket med DTAG eller Mixed-DTAG ved hjelp av en lang stang fra mob-båt. Mixed-DTAG inneholder GPS og Argos satellittsender i tillegg til DTAG-enheten som inneholder treakse akselerometer, treakse magnetometer, stereo hydrofoner og dybdesensor. I tillegg til disse merkene ble det også samlet inn data fra to akustiske bøyer som ble satt ut i operasjonsområdet. Merkede dyr ble eksponert for sonarpulser på en kontrollert måte. Det eksperimentelle designet innebærer en dose eskalering ved ulike avstander og til ulike maksimale lydnivåer ved hjelp av operative sonarkilder tauet av FFIs forskningsfartøy H.U. Sverdrup II (HUS) eller den norske fregatten KNM Otto Sverdrup (OSVE). Tillatelse til å gjennomføre eksperimentet er gitt av Mattilsynet og den etiske komiteen ved Universitetet i St. Andrews. En egen risikovurdering ble gjennomført i forkant av toktet for å redusere risikoen for miljøeffekter eller negative effekter for tredjepart (fiskeri og hvalsafari).

Etter totalt 9 uker på sjøen har vi merket 33 spermhval og samlet inn 630 timer med data. Vi har gjennomført 24 kontrollerte eksperimenter med til sammen 71 sonar- eller kontrolleksponeringer. 7 eksperimenter ble gjennomført med fregatten OSVE som kildefartøy. I tillegg merket vi 8 grindhval, men fordi merkene falt av før tiden, ble det bare gjennomført 2 eksponeringer. Derfor er bare spermhvaldata presentert i rapporten. Dataplott fra samtlige eksperimenter på spermhval er presentert sammen med et sammendrag av resultatene. Videre analyser og tolkninger vil bli eller er allerede presentert i vitenskapelige tidsskift.

Det innsamlede datasettet er forventet å være tilstrekkelig til å oppnå prosjektets målsettinger og besvare spørsmålene om moderne CAS påvirker hval på en annen måte enn konvensjonell PAS, og om avstanden mellom sonarene og dyret påvirker responsen. Denne kunnskapen gir oss større generell forståelse av hvordan militære sonarer påvirker hval, og øker vår evne til å bruke eksperimentelle data til å si noe om hvordan reelle øvingsscenarioer vil påvirke dyrene. Gjenværende spørsmål for fremtidig forskning inkluderer studier av hvordan CAS påvirker andre arter, spesielt arter som er mer sensitive til PAS. Videre bør man undersøke om dyrene habitueres eller sensitiveres når de utsettes for sonar over lengre tid enn korte eksperimentelle eksponeringer.

En video som viser aktivitetene under 3S3 eksperimentene kan ses om man følger denne linken.

Contents

Preface

The 3S3-project has been a multidisciplinary and international collaborative effort to investigate behavioral reactions of cetaceans to naval sonar signals. The main partners in the project have been:

The Norwegian Defense Research Establishment (FFI), The Netherlands Organization for Applied Scientific Research (TNO), Sea Mammal Research Unit (SMRU) at the University of St Andrews Scotland, UMRAE Cerema, France. In addition, Life and Environmental Sciences (University of Iceland), University of Oslo (Norway), Institute of Marine Research (IMR) (Norway), LK-ARTS Norway, Marine Science and Communication (The Netherlands) also made significant contributions to the project through their association with one or several of the main 3S-partners. The 3S3 research project was funded by:

US Naval Facility Engineering Command / Living Marine Resources research program, The Netherlands Ministry of Defense, Defense Science and Technology Lab (UK Ministry of Defense), DGA (French Ministry of Defense). The Royal Norwegian Navy supported the project by supplying access to the ASW frigate KNM Otto Sverdrup.

The achievements of each sea trial conducted as part of the project have been reported in separate cruise reports, including some examples of the data collected. This report presents the methodology used and the complete dataset collected during every experiment conducted under the 3S3-project. While a summary of the outcome of each experiment is presented, this report does not contain higher level analyses and interpretations. Such analyses have already or will be published in peer-review literature in the coming year. The report concludes with a short discussion of the status of knowledge and a list of already published and planned publications from the 3S-program, and some future prospects.

Horten, 18 March 2021
Petter Kvadsheim

1 Introduction

Modern long-range anti-submarine warfare (ASW) sonars transmit powerful sound pulses which might have a negative impact on marine mammals. Behavioral response studies (BRS) conducted by research groups in the US (the AUTEC, SOCAL and Atlantic BRS projects; Tyack et al. 2011, Southall et al. 2012, Southall et al. 2019) and in Norway (the three phases of the Sea Mammals and Sonar Safety 3S-projects; Miller et al. 2011, Kvadsheim et al. 2015, Kvadsheim et al. 2021) over the past 10 years have indicated large differences in responsiveness across different species, as well as substantial variation within a species depending on the behavioral context of the animals, and probably also other factors. Behavioral responses such as avoidance of the sonar source, cessation of feeding, changes in dive behavior and changes in vocal and social behavior have been observed, and response thresholds quantified. Results from BRS have helped navies to comply with international guidelines for stewardship of the environment, as well as rules and regulations within Europe and the USA.

The current third phase of the Sea Mammals and Sonar Safety project was initiated in 2016 (3S3), and three successful sea trials have been conducted to collect data on sperm whales and pilot whales (Lam et al. 2018ab, Kvadsheim et al. 2020) and on northern bottlenose whales (Miller et al. 2017). In the first two phases, 3S1 (2006-2010) (Miller et al. 2011) and 3S2 (2011-2015) (Kvadsheim et al. 2015), we looked at behavioral responses of six species of cetaceans to naval sonar signals, and we addressed specific questions such as sonar frequency specificity of behavioral responses (Miller et al. 2014) and the efficacy of ramp-up (Wensveen et al. 2017). A key output from these studies was dose-response functions describing the relationship between the acoustic received levels (RL) associated with observed responses. Sonar dose response functions for four species; killer whales (Miller et al. 2014), pilot whales (Antunes et al. 2015), sperm whales (Harris et al. 2015) and humpback whales (Sivle et al. 2015) have been established and compared (Harris et al. 2015, Sivle et al. 2015).

Such functions can be used to define a putative affected area around a source and estimate the cumulative effects of sonar operations on marine mammal populations. However, it is not obvious which measure of sonar dose best predicts responsiveness. The received RMS sound pressure level (SPL) is the most commonly used metric, but accumulated Sound Exposure Level (SEL) has also been used. The source levels of most BRS sources have been lower than the source levels of operational sonar sources. Using received level thresholds alone to predict impact of naval operations therefore implies that there is no effect of distance, i.e. that whales respond only to sound levels and are not influenced by how far away the whale judges the source to be. However, recent studies indicate that response to sonar may be influenced by the distance from the source (DeRuiter et al. 2013; Moretti et al. 2014; Southall et al. 2019). More empirical data on whether and how source-whale distance might influence the SPL or SEL thresholds at which cetaceans behaviorally respond to sonar is necessary to predict and better manage unintended environmental consequences of sonar usage, while avoiding unnecessary restrictions on naval training activity.

Importantly, all BRS research so far has been conducted using pulsed active sonars (PAS), typically transmitting 5-10% of the time (a short pulse followed by a much longer period of listening). Recent technological developments imply that in the near future naval sonars will have the capability to transmit almost continuously (Continuous Active Sonar, CAS). This technology leads to continuous illumination of a target and therefore more detection opportunities (van Vossen et al. 2011). In many anti-submarine warfare scenarios CAS will give a tactical advantage with increased probability of detection, and therefore there is a strong desire to implement this technology in operational use. This raises imminent questions about the environmental impact of such future sonar systems.

1.1 Objectives of the 3S3-research project

In the third phase of the 3S-project we addressed the following 2 specific research questions:

1. Does exposure to continuous-active-sonar (CAS) lead to different types or severity of behavioral responses than exposure to traditional pulsed active sonar (PAS) signals, and does the CAS feature of high duty cycle lead to behavioral responses that indicate masking?

2. How does the distance to the source affect behavioral responses?

Figure 1.1 Tagging sperm whales to conduct controlled exposure experiments.

Photo; Jacqueline Bort.

In 3S3 we addressed these questions by conducting controlled exposure experiments (CEE) to sperm whales and pilot whales. This document reports on the datasets collected during three sea trials in 2016, 2017 and 2019:

- The 3S-2016-CAS trial off the coast of Northern Norway to study the effect of CAS and PAS in sperm whales and pilot whales (Lam et al. 2018a).
- The 3S-2017 trial off the coast of Northern Norway to study the effect of CAS vs PAS and effect of range on sperm whales (Lam et al. 2018b).
- The 3S-2019-OPS trial off the coast of Northern Norway to study the effect of range and received level in sperm whales using an operational sonar source. (Kvadsheim et al. 2020).

Only 2 CEE sessions were conducted on pilot whales, therefore, only the sperm whale data are reported here.

2 Materials and Methods

Conducting controlled sonar exposure experiments on free ranging cetaceans at sea requires a variety of sophisticated equipment and expertise. The main platform of the trials was the FFI R/V HU Sverdrup II (HUS) with a regular ship's crew of 7. The research team consisted of 15 scientists with a multidisciplinary background, including experts in biology, underwater acoustics, oceanography, electronics, mechanical engineering, environmental science and operational sonar use. During the 3S-2019-OPS trial R/V HU Sverdrup II was supported by KNM Otto Sverdrup (OSVE), an ASW-frigate from the Royal Norwegian Navy. The contribution of a naval combat vessel to biological research is unique, and the value of the data collected particularly high, since it allowed testing of behavioral responses to an actual operational system. Detailed descriptions of data collection, procedures and equipment can be found in the cruise reports from each of the three trials; 3S-2016 (Lam et al. 2018a), 3S-2017 (Lam et al. 2018b), 3S-2019-OPS (Kvadsheim et al. 2020).

2.1 Risk management and permits

Experimental exposure of marine mammals to high levels of sound implies some risk that animals could be negatively affected (that is why it is important to study it). The experiments reported here were conducted under permits from the Norwegian Animal Research Authority (permit no 2015/223222 and 18/126201), and experimental procedures were approved by the Animal Welfare Ethics Committee at the University of St Andrews. Separate risk assessment and management plans were developed for the trials to minimize risk to the environment and third parties, specifying suitable mitigation measures, endpoints and responsibilities.

2.2 Experimental design

The experimental design was developed to quantitatively compare differences in responses to continuous active sonar (CAS) versus pulsed active sonar (PAS) signals, and to characterize the importance of the distance to the source in predicting responses. Two different sonar sources were used; the SOCRATES source on HUS and the CAPTAS source on OSVE. During the CEEs to sperm whales, different sonar transmissions schemes with CAS or PAS pulses at different maximum source levels and ranges were used (figure 2.1).

Tagged whales were subjects in rigorously conducted controlled exposure experiments (CEE). To avoid habituation or sensitization from previous experiments, for the 24h following an exposure CEEs were never conducted within 20 nmi of the previous exposure when 201-214 dB max source level was used, or within 30 nmi when max source level of >214 dB was used . These distances were based on expected response threshold and propagation loss.

One tagged whale was deemed the 'focal whale' and was tracked by HUS throughout the experiment. Any additional tagged whale(s), beyond the focal whale, were considered non-focal subjects. They would be exposed at the same time as the focal whale, but the position of the source vessel was determined by the movements of the focal whale, and therefore the distance and levels of the non-focal exposures were more variable. The track of both focal and non-focal whales could be reconstructed afterwards using the GPS logger on the mixed-DTAG in combination with pseudotrack reconstruction of movements underwater using the DTAG sensors (Wensveen et al. 2015).

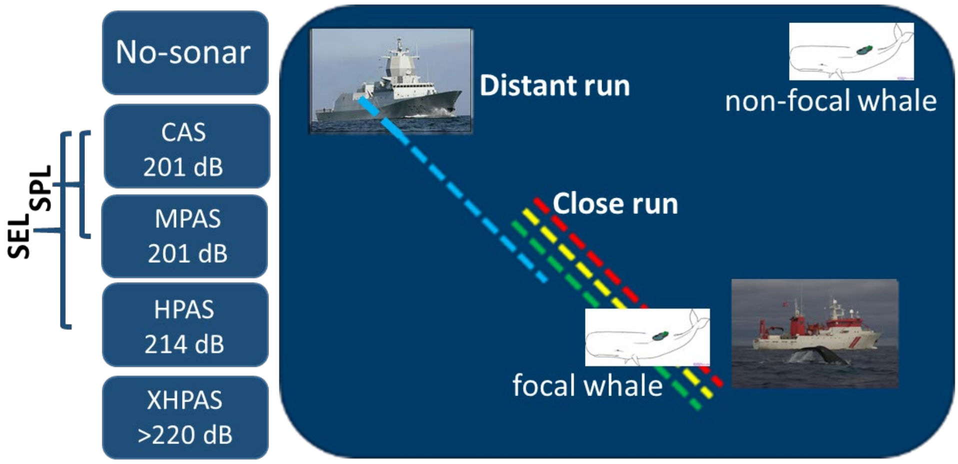

Figure 2.1 Experimental design. Focal and non-focal whales were tagged with DTAGv3 or Mixed-DTAGS. Each focal whale was approached up to 4 times, first a no-sonar control session, then three sonar sessions at planned ranges using CAS or PAS sonar signals transmitting at defined source levels using the SOCRATES source on HUS or the CAPTAS source on OSVE

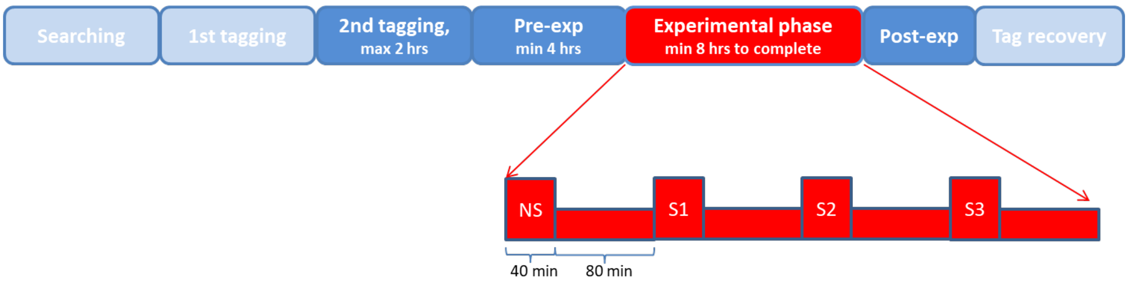

Figure 2.2 Timeline of the 3S3 CEE experiments. Each experiment started with search and tagging phases, followed by a pre-exposure phase for collecting baseline data before the experimental phase with up to 4 different exposure sessions each lasting 40min, with at least 1 hr 20 min between sessions. Finally each experiment ended after a post exposure phase and tag recovery. The first exposure was a no-sonar control (NS), whereas the following exposures used different signals (S1, S2, S3) depending on the research question addressed. The signals used in each experiment are specified in table 2.1. The order of S1-S3 were rotated to maximize contrasts between exposure conditions.

After the pre-exposure baseline period of at least 4 hrs, the source vessel approached the focal whale from a distance of 4nmi (CLOSE exposure sessions) or 8nmi (DISTANT exposure sessions). The vessel trajectory approached the estimated position of the focal whale at the start of each exposure session, intercepting the whale's path at a 45° angle to the front. The approach speed was 8 knots and the course constant throughout exposure sessions. Exposure sessions lasted 40min, first 20 min of ramp-up, then 20min of full power exposures. A maximum of 4 sessions was conducted, typically a no-sonar session first, and then up to 3 sonar exposures using different transmission schemes (figure 2.2). The order of the sonar exposures were rotated to maximize contrasts between CAS and PAS and between different levels and ranges.

Table 2.1 Hypothesis table for different drivers of behavioral responses. During the 3S3-experiments animals were exposed to different treatments of Sound Pressure Level (SPL), Sound Exposure Level (SEL), sonar duty cycle and animal-source ranges. The darkness of the colors illustrates expected relative variation in response intensity (the darker the shading, the greater the expected behavioral response intensity) if the different drivers (left column) were the main driver for behavioral responses. Details of each exposure condition can be found in figure 2.3 and table 2.2.

Driver/Signal	**NoSonar Close**	**CAS Close**	**MPAS Close**	**HPAS Close**	**XHPAS Close**	**HPAS Distant**	**XHPAS Distant**
Sonar-SPL_{max}							
Sonar-SEL_{cum}							
Sonar-Duty cycle							
Animal-source range							
Ship							

This experimental design enables us to determine response thresholds and characterize the severity of response to different stimuli (table 2.1). The no-sonar approach enables us to separate responses to the approaching ship alone from responses caused by the sonar signals. By contrasting response threshold, type and severity of responses during CAS-exposures to the threshold, type and severity of responses seen during PAS-exposures, we can compare the effects of continuous active sonar versus pulsed sonar. Similarly, by contrasting the response to MPAS, HPAS and XHPAS at different ranges we can investigate the effect of range, because these experiments are designed to achieve the same received levels at different ranges. With the multiple tag deployment design, the focal whale was subject to a precisely designed dose escalation experiment (figure 2.1). The position of the non-focal whale relative to the source was more random, expected to be further away, providing a broader coverage of range versus received level doses. However, since each animal was exposed several times to different signals, we have to account for any potential exposure order effects. Therefore, the order of the three different sonar exposure sessions was alternated. The no-sonar sessions were always conducted first to avoid any potential sensitization to the ship and associated sonar before any effect of the approaching ship was tested. After the final exposure session, we collected post exposure data until the tag detached, to determine time to recovery to normal behavior.

2.3 Data collection

Data was collected on sperm whales (*Physeter macrocephalus*) along and off the shelf edge between Harstad and Tromsø (from Langnesegga to Fugløy deep), 69.0-70.5° Northern latitude by 12.5-19.5° East longitude. We searched for whales using both visual observers and the Delphinus acoustic array. When the target species was localized and conditions allowed, a tag boat was launched to deploy 1 or 2 standard DTAGv3 or mixed DTAGs using the cantilever pole. We aimed to deploy two tags on two separate animals, but if a second animal was not available the second tag could be deployed on the same animal to reduce risk of having to cancel part of the experimental program if the first tag falls off prematurely. On two occasions more than 2 animals (3 or 4) were tagged simultaneously. The mixed-DTAG contained a GPS Fastloc sensor from Lotek and an Argos SPOT transmitter from Wildlife computers, in addition to the DTAG3 core unit containing triaxial accelerometer, triaxial magnetometer, stereo acoustic and pressure sensors. The core DTAG units were supplied by Alex Shorter at the University of Michigan. Tag release time was set at 8 to 34 hours, to release at least 4 hours after the final scheduled exposure session.

From tag-on until tag-off, focal animals were tracked using target localization based on daytime visual sightings supported by an automatic direction finder (DF-Horten, LKARTS Norway) to give the bearing to the VHF beacon on the tag, combined with acoustic tracking using the Delphinus system from HUS. During nighttime, tracking was accomplished without visual observations, but aided by target motion analysis based on the VHF tracking (Kvadsheim et al. 2020). If we had tagged more than one animal, one focal whale was tracked real-time, whereas the others (non-focal whales) were always equipped with mixed DTAGs containing a GPS logger which allowed retrospective track reconstruction without visual fixes. During tracking HUS sailed in rough 'boxes' of 2-3nmi by 2-3 nmi, trying to keep the focal whale inside the box. This sailing pattern seemed to be the optimal compromise between the visual effort, target motion acoustic tracking, VHF tracking range, and the desire to not affect the behavior of the focal animal by the close presence of the ship. Marine mammal observers (MMOs) recorded position of the focal whale and other animals in the area at each surfacing in Logger, created and provided by the International Fund for Animal Welfare.

In addition to the tags attached to subject whales, acoustic data was also collected by two moored acoustic buoys, providing supplementary data to assess potential vocal responses and/or avoidance of the exposed area. Two Loggerhead Instruments DSG-ST Ocean Acoustic Datalogger (sampling at 144 kHz) with an aluminum housing were deployed using an IXSEA Oceano 2500S universal acoustic release. The two buoys were placed 27nmi apart at 1200-1500m depth in known hot spots for sperm whales within our operation area. The idea was that they would monitor the vocal activity of sperm whales along a gradient from any exposure site. Only the tag data is reported here.

2.4 Sonar exposure

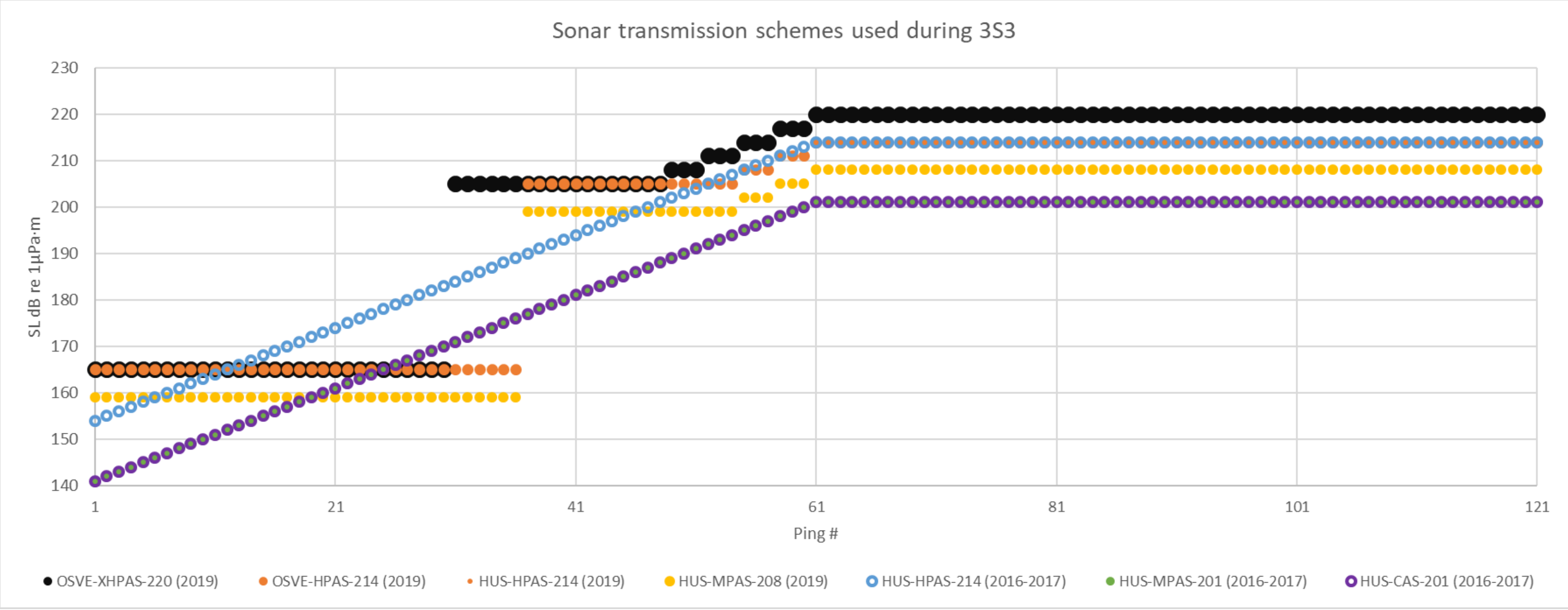

Figure 2.3 Transmitted source level and ping no (pulse repetition time was 20s) of the different sonar transmissions schemes used to achieve the 6 sonar exposure conditions presented on Table 2.1. Transmissions always started with a 20min ramp up followed by 20 min of full power transmissions. Ramp-up used in 2016-2017 with the SOCRATES source started at -60 dB, then +1 dB/pulse to full power in 20 min. This ramp-up scheme had to be modified in 2019 due to limitations in the CAPTAS system of OSVE. This modification was also implemented for SOCRATES source experiments conducted in 2019, to match the frigate Ramp Up. Further details of the transmitted pulses are given in table 2.1. Note that purple circles and green dots are overlapping entirely.

Table 2.2 The sonar transmission schemes used during the sonar exposures of sperm whales. Two sonar systems were used, the SOCRATES source on HUS and the CAPTAS source on OSVE (2019 only). During the trials in 2016-2017 pulsed active sonar signals (PAS) and continuous active sonar signals (CAS) were used to compare matching SPL and SEL levels. In 2019 full power and -6dB PAS levels of both systems were used. In 2016-2017 the pulses used with SOCRATES were 1000-2000 Hz bandwith and the minimum source level was 60 dB below max levels. In 2019 this was slightly modified to match the bandwith and minimum source level available in the CAPTAS system of OSVE. In addition to the sonar exposures, no-sonar control approaches matching the CLOSE approach geometry and speed were also used. Sonar exposures always started with a 20min ramp-up and then 20 min of full power. During all exposures source depth was 100-120m and approach speed was 8 knots. Approach distance started either 4 nmi from the animal during CLOSE exposures or 8 nmi during DISTANT exposures.

SONAR SOURCE	**SOCRATES on HUS**					**CAPTAS on OSVE**	
SONAR SIGNAL (year)	**HUS-HPAS-2014 (2016-2017)**	**HUS-MPAS-201 (2016-2017)**	**HUS-CAS-201 (2016-2017)**	**HUS-MPAS-208 (2019)**	**HUS-HPAS-214 (2019)**	**OSVE-XHPAS-220 (2019)**	**OSVE-HPAS-214 (2019)**
Min-Max Source level dB re 1µPa·m	154 - 214 dB	141 - 201 dB	141-201 dB	159 - 208 dB	165-214 dB	[1] 165 - 220 dB	[1] 165 - 214 dB
SEL_{20s} dB re 1µPa·s	154-214 Db	141 - 201 dB	154-214 dB	159 - 208 dB	165-214 dB	[1] 165 - 220 dB	[1] 165 - 214 dB
Pulse duration	1s	1s	19s	1s	1s	1s	1s
Pulse repetition time	20s	20s	20s	20s	20s	[2] 21-24s	[2] 21-24s
Pulse frequency	1000-2000 Hz	1000-2000 Hz	1000-2000 Hz	1280-1920 Hz	1280-1920 Hz	1280-1920 Hz HFM	1280-1920 Hz HFM
Sonar pulse form	HFM UpSweep	HFM UpSweep	HFM UpSweep	HFM UpSweep	HFM UpSweep	HFM UpSweep	HFM UpSweep
Approach distance	CLOSE=4nmi	CLOSE=4nmi	CLOSE=4nmi	CLOSE=4nmi	CLOSE=4nmi, DISTANT=8nmi	CLOSE=4nmi, DISTANT=8nmi	CLOSE=4nmi

[1] The maximum source level of the frigate is restricted information. The max level of the CAPTAS system on OSVE was used and given to be >220 dB. Here we assume that it was 220 dB. During reduced power transmissions the sonar system uses an attenuation factor (e.g. max attenuation -55 dB is then assumed to be 165 dB source level).

[2] The pulse repetition time of the CAPTAS system on OSVE is set automatically by the system to optimize search within a set range. It therefore changes slightly with sound speed profile.

2.5 Data processing

Depth, heading and pitch were calculated using established techniques (Johnsen & Tyack 2003). Swim speed during dives of each tagged animal was calculated following a method that regressed the acoustic flow noise in the 22.4-28.2 Hz frequency band to kinematic speed estimates during ascent and descent periods (pitch>60°) (Wensveen et al. 2015). The horizontal turning angle was calculated as a centered moving circular average of heading with a +/- 1 min window size. Horizontal tracks of the tagged whales were reconstructed to 1 s resolution based on 1) the tag-derived movement data and visual and GPS position fixes using a state-space model implemented in a Bayesian framework (Wensveen et al. 2015), or 2) linear interpolations between visual and GPS position fixes when tag-derived heading data were not available due to noisy magnetometer readings (lower-resolution method).

The acoustic recordings from the DTAGs were aurally and visually inspected on spectrograms using Adobe Audition software (Blackman-Harris window, FFT length: 4096) to identify sounds produced by the tagged sperm whale, sounds produced by conspecifics or other species present in the area, and sonar sounds received by the tagged whale. Typical sperm whale vocalizations were identified and included regular echolocation clicks and buzzes associated with foraging behavior (Miller et al. 2004), and other types of sounds associated with social behavior (slow echolocation clicks, codas, clangs and trumpet sounds) (Frantzis & Alexiadou 2008, Oliveira et al. 2013).

Incidental anthropogenic sonar, as well as sounds produced by other whale species in the research area, i.e. typically killer whales or long-finned-pilot whales (hereafter grouped as "blackfish" species), were annotated. Killer and pilot whales are considered as potential threatening stimuli for sperm whales as they represent potential food competitor and/or predator species (Weller et al. 1996, Reeves et al. 2007).

The acoustic dose of the experimental sonar received by the tagged whales was quantified from the recordings of those sonar signals on the tags using the method established by Miller et al. 2011 and Sivle et al. 2015. For each sonar pulse, the received maximum sound pressure levels (SPL_{max}) was determined using a sliding window of 200 ms, and the received cumulative sound exposure level (SEL_{cum}) was measured since the start of the sonar exposure session. Both received level metrics were analyzed in the 890-2240 Hz frequency band as it included the fundamental frequencies of the transmitted signal (the contribution of the harmonic frequencies on the broadband levels was determined to be negligible to the sound metrics we quantified (von Benda-Beckmann et al. 2018).

Simultaneously with visual recording of the tagged whale positions at the surface, a best estimate of group size, defined as the number of individuals within 200 m of the focal animal (Visser et al. 2014) during the surfacing period, was recorded. Visual data collection including the geographic position of the vessel, range and bearing to calculate whale re-sighting locations and group size was recorded using the software Logger. Moreover, sightings of blackfish species present in the area were reported (time and geographic position recorded).

3 Results

During the 3S-2016, 3S-2017 and 3S-2019-OPS trials we tagged 33 sperm whales and collected 630 hours of tag data in 9 weeks. We conducted 24 controlled exposure experiments with 71 sonar or control sessions (table 3.1). In addition, 8 pilot whales were tagged, but tag durations were generally short and only 2 CEE sessions were conducted (no sonar and CAS in 2016, Lam et al. 2018a). Only the sperm whale data are reported here. Data plots for all CEE sessions on sperm whales are presented in Appendix B.

Table 3.1 *Summary of tag deployments and controlled exposure experiment sessions during the three 3S3 trials. DTAG id (sw16_126 = sperm whale tagged in 2016 on 126 Julian date). HUS means exposures conducted using the SOCRATES source on RV HU Sverdrup II, OSVE means exposures conducted using the CAPTAS source on the RNoN frigate KNM Otto Sverdrup. PAS is Pulsed Active Sonar sessions at max source level of 201 dB (MPAS-201), 208 dB (MPAS-208), 214 dB (HPAS-214) or 220 dB (XHPAS-220). CAS is Continous Active Sonar sessions at max source level of 201 dB (CAS-201). For CLOSE exposure sessions the starting distance was 4 nmi, for DISTANT exposure sessions the starting distance was 8 nmi. Details of the sonar exposure regimes are given in table 2.2. Data plots for all CEE sessions are shown in Appendix B.*

Trial	DTAG ID	Sonar source Source Vessel	Date	Exposure sessions
3S-2016	sw16_126	SOCRATES HUS	May 5th 2016	BASELINE CAS-201-CLOSE MPAS-201-CLOSE HPAS-214-CLOSE
3S-2016	sw16_130	SOCRATES HUS	May 9th 2016	Baseline NoSonar-CLOSE MPAS-201-CLOSE CAS-201-CLOSE
3S-2016	sw16_131[2]	SOCRATES HUS	May 10th 2016	Baseline NoSonar-CLOSE
3S-2016	sw16_134a[2]	SOCRATES HUS	May 13th 2016	Baseline NoSonar-CLOSE
3S-2016	sw16_134b	SOCRATES HUS	May 14th 2016	Baseline NoSonar-CLOSE CAS-201-CLOSE HPAS-214-CLOSE MPAS-201-CLOSE
3S-2016	sw16_135	SOCRATES HUS	May 15th 2016	Baseline NoSonar-CLOSE HPAS-214-CLOSE CAS-201-CLOSE MPAS-201-CLOSE
3S-2016	sw16_136	SOCRATES HUS	May 16th 2016	Baseline NoSonar-CLOSE CAS-201-CLOSE MPAS-201-CLOSE HPAS-214-CLOSE

Trial	DTAG ID	Sonar source Source Vessel	Date	Exposure sessions
3S-2017	sw17_179a sw17_179b	SOCRATES HUS	June 28th 2017	Baseline MPAS-201-CLOSE HPAS-214-CLOSE CAS-201-CLOSE
3S-2017	sw17_180	SOCRATES HUS	June 29th 2017	Baseline NoSonar-CLOSE HPAS-214-CLOSE MPAS-201-CLOSE CAS-201-CLOSE
3S-2017	sw17_182a sw17_182b	SOCRATES HUS	July 1st 2017	Baseline NoSonar-CLOSE MPAS-201-CLOSE CAS-201-CLOSE HPAS-214-CLOSE
3S-2017	sw17_184	SOCRATES HUS	July 3rd 2017	Baseline NoSonar-CLOSE CAS-201-CLOSE HPAS-214-CLOSE
3S-2017	sw17_186a sw17_186b	SOCRATES HUS	July 6th 2017	Baseline NoSonar-CLOSE HPAS-214-CLOSE CAS-201-CLOSE MPAS-201-CLOSE
3S-2017	sw17_188a sw17_188b	SOCRATES HUS	July 7th 2017	Baseline NoSonar-CLOSE MPAS-201-CLOSE HPAS-214-CLOSE CAS-201-CLOSE CAS-201-CLOSE
3S-2017	sw17_191	SOCRATES HUS	July 11th 2017	Baseline NoSonar-CLOSE HPAS-214-CLOSE MPAS-201-CLOSE
3S-2019-OPS	sw19_241a sw19_241b	SOCRATES HUS	August 29th 2019	Baseline HPAS-214-CLOSE HPAS-214-DISTANT MPAS-208-CLOSE
3S-2019-OPS	sw19_243a	SOCRATES HUS	August 31st 2019	Baseline HPAS-214-DISTANT HPAS-214-CLOSE
3S-2019-OPS	sw19_244a sw19_245a	CAPTAS OSVE	September 3rd 2019	Baseline XHPAS-220-DISTANT XHPAS-220-CLOSE
3S-2019-OPS	sw19_248ab[1]	SOCRATES HUS	September 5th 2019	Baseline NoSONAR-CLOSE HPAS-214-DISTANT MPAS-208-CLOSE HPAS-214-CLOSE

Trial	DTAG ID	Sonar source Source Vessel	Date	Exposure sessions
3S-2019-OPS	sw19_250ab[1]	CAPTAS OSVE	September 8th 2019	Baseline XHPAS-220-CLOSE XHPAS-220-DISTANT
3S-2019-OPS	sw19_253ab[1,2]	CAPTAS OSVE	September 10th 2019	Baseline NoSONAR-CLOSE
3S-2019-OPS	sw19_253c	CAPTAS OSVE	September 10th 2019	Baseline XHPAS-220-DISTANT XHPAS-220-CLOSE
3S-2019-OPS	sw19_254a	CAPTAS OSVE	September 11th 2019	Baseline XHPAS-220-CLOSE HPAS-214-CLOSE XHPAS-220-DISTANT
3S-2019-OPS	sw19_255ab[1] sw19_255c Sw19_255d	CAPTAS OSVE	September 12th 2019	Baseline XHPAS-220-DISTANT XHPAS-220-CLOSE NoSONAR-CLOSE
3S-2019-OPS	sw19_259a[2] sw19_259b	CAPTAS OSVE	September 16th 2019	Baseline NoSONAR-CLOSE XHPAS-220-CLOSE XHPAS-220-DISTANT

[1]Two tags on the same animal. [2]Tag detached before any sonar exposure was completed.

4 Discussion

4.1 Collected data

During the 3S3 trials we tagged 33 sperm whales and collected 630 hours of tag recordings. We conducted 24 controlled exposure experiments with 71 sonar or control sessions, of which 16 sessions were executed with an operational naval vessel as the source vessel. Pilot whales were also a target species, secondary target species in 2016 and 2017, and primary target species in 2019. However, we only managed to do one single sonar exposure session, despite the fact that we tagged 8 pilot whales. Pre-mature tag detachment was the main reason why so few exposures were conducted on pilot whales. However, 3S has successfully tagged pilot whales before with similar tags (Miller et al. 2011), and the outcome therefore seems to be bad luck with unfortunate animal behavior with fast swimming resulting in early tag release. Overall, 3S3 must be considered highly successful in terms of data collection. The data are of high quality and we expect that based on the data we will be able to conclusively answer the 2 questions of whether behavioral responses to continuous active sonar (CAS) are different from those to pulsed active sonar (PAS), and how the range to the sonar source affects the whales' responsiveness.

Table 4.1 Summary table of all 3S data collected between 2005 and 2019 on fish (herring) and cetacean species (killer, long-finned pilot, sperm, minke, bottlenose and humpback whales). Killer whales, pilot whales, sperm whales and herring were studied as part of the 3S-project (2005-2010), minke whales, bottlenose whales and humpback whales were studied during the 3S2-project (2011-2015). The current 3S3-project focused on bottlenose whales, sperm whales and pilot whales (2016-2021).

	# TAGs deployed	# Sonar exp.	# Control exp.	Trials/year
Herring	0	38	25	3S-06, 3S-08
Killer whales	22	8	3	3S-05, 3S-06, 3S-08, 3S-09, ICE-09
Pilot whales	39	15	29	3S-08, 3S-09, 3S-10, 3S-13, 3S-16CAS, 3S-17CAS, 3S-2019OPS
Sperm whales	51	65	22	3S-08, 3S-09, 3S-10, 3S-16CAS, 3S-17CAS, Azores18, 3S-2019OPS
Minke whales	2	1	2	3S-10, 3S-11
Bottlenose whales	36	3	2	3S-13, JM-14, JM-15, 3S-16-ORBS
Humpback whales	37	20	41	3S-11, 3S-12, NO-16, NO-17
Total	**187**	**150**	**124**	

The combined 3S dataset collected between 2005-2019 (table 4.1.) has resulted to date in 55 peer review papers, of which 28 directly address the effect of naval sonar on marine life, 12 reports, and 3S data has been used in 22 theses. Four papers are currently submitted or in review, another four are in preparation. All 3S publications are listed in Appendix A.

4.2 Analysis and publication plan

We have now completed all data collection under the 3S3-project and this report presents methods, summary results, and data plots of all collected data on sperm whales. We are now focusing on analyzing the data and publishing results addressing the core objectives of the project. The project end date has been extended by 6 months to 30 June 2021, because of delays caused by the COVID19-pandemic. So far two major papers have been published to report on the results of the data collected under 3S3 (Wensveen et al. 2019 and Isojunno et al. 2020). Wensveen et al. (2019) reported that bottlenose whales in a pristine environment responded at similar received sound levels to both close and distant sonar, indicating that for this species in that habitat behavioral responses were not significantly modified by range to the source. This paper was supported by propagation modelling in Von Benda-Beckmann et al. (2019) in order to optimize estimates of received levels for whales with satellite tags (without acoustic recording). The bottlenose whale study on the effect of animal-sonar range was a pilot study conducted in the transition between 3S2 and 3S3, and 3S3 ended up being focused on sperm whales, even though pilot whales was also a primary target species during the OPS-trial in 2019. Isojunno et al. (2020) reported that received sound energy of sonar pings predicts sperm whale responses to both intermittent and continuous navy sonar, and that responses to CAS and PAS were similar when the received *sound exposure levels* were similar but responses to CAS were stronger when received *sound pressure levels* were similar. Further publications are currently in preparation or in the reviewing process to address the severity of behavioral responses in sperm whales exposed to CAS and PAS (Curé et al. in prep), empirical indication of masking of sperm whales exposed to 1-2 kHz CAS and PAS (Isojunno et al. in prep) and an analysis using theoretical modelling of masking potential in sperm whales exposed to CAS and PAS (von Benda-Beckmann et al. in review).

Analysis of all of the PAS exposures focusing on data from the 3S-2019-OPS trial will be used to address the question of how range to the sonar affects whale responsiveness. This will be achieved through a quantitative analysis of response threshold and response intensity (Wensveen et al. in prep), and a more descriptive analysis using severity scoring (Curé et al. in prep). All analysis and publications are expected to be achieved (submitted for publication) by 30 June 2021, which is the current end data of the 3S3 project.

All 3S publication are listed in Appendix A, including core papers in preparation.

4.3 Methodological improvements

Conducting controlled exposure experiments as part of behavioral response studies (BRS) of free ranging cetacean subjects is a complicated task, but the methodology is now well established (Southall et al. 2016). The first MFAS sonar CEEs conducted in 2005-2006 (e.g. Tyack et al. 2011, Miller et al. 2012) were exploratory and observational by nature, with low sample sizes. Recent CEE studies typically have a strict experimental design, and sufficient sample sizes allowing for statistical hypothesis testing (e.g. Wensveen et al. 2017, Wensveen 2019, Isojunno et al. 2020). However, new research questions require new technology and methodology. The major achievements made during the 3S project has been to establish multi scale CEEs, where detailed behavior is still recorded with DTAGs, but this is combined with satellite tags and acoustic recorders. This means that behavioral responses are recorded at larger temporal and spatial scale than before (e.g. Wensveen et al. 2019). This is particularly useful with very sensitive species like beaked whales. During the sperm whale experiments, satellite tags were mainly used to recover the DTAG unit, and not as sole sensors on the whale, because we did not expect behavioral responses to be detectable on such tags. However, acoustic recorders were used to monitor responses at larger distances from the source.

Another important technological improvement made during 3S3 is the development of the Mixed-DTAG which combined the core DTAG sensor unit, with a GPS fastlock logger and a satellite transmitter within the same tag unit. This combined unit was crucial to our design to deploy several tags at the same time, collecting data from several animals at different ranges from the source. Tags can be deployed and left to record behavioral data, including the whale movement track. The satellite transmitter was primarily used to recover the tag after detachment. The limitation of this technology is still that the real time tracking has low resolution in time and space. This was not a problem for us, since we used the VHF transmitter in combination with acoustic and visual tracking of the focal whale. Non-focal whales had an uncontrolled position relative to the sonar source in our design, and the detailed track could only be reconstructed afterwards, when the tag was recovered. For future CEE designs (see section 4.4) it would be another important step forward to receive real time GPS tracking via ARGOS or directly using goniometer receivers on a vessel. This would allow for more precise real time tracking of several whales simultaneously, including in rough weather and night time tracking in darkness.

The use of UAV drones to observe tagged whales is another new method to collect data during BRS, established during 3S3. Drones were primarily intended to observe near surface social behavior in pilot whales. We were able to demonstrate the feasibility of this method for that purpose, but we did not collect any such data during the actual CEE experiments. However, drones also turned out to be a useful tool for body condition measurements and photo id of sperm whales (Kvadsheim et al. 2020). Aerial drones are likely to be an important tool for future BRS projects.

3S has previously used the TNO developed SOCRATES sonar source during our CEEs. This source is an experimental source used by the Royal Netherlands Navy, considered to be an operational source. Even though the maximum source level is lower than for many combat sonar systems, many research questions related to the impact of naval sonar can be investigated using such a source. However, in order to fully investigate the effect of distance to the sonar on animal behavioral responses, it became important to utilize an operational source with realistic source levels that could expose animals to received levels expected to trigger responses at longer ranges than the SOCRATES source. The collaboration with the Royal Norwegian Navy, and their contribution to the project by making an ASW frigate with the CAPTAS system available was therefore crucial to our success. It took a lot of planning to make it happen, and we learned a lot from the planning process. We realize that it was a big commitment by the navy, and hope that we could find future opportunities to repeat the success.

4.4 Future perspective - 3S4?

The 3S3 project have achieve our objectives and added to our understanding of how marine mammals are affected by naval sonar. We have increased the knowledge about the impact of the new CAS technology in sperm whales, but this can not necessarily be extrapolated to other more sensitive species. We have also contributed to a better understanding of how animal to sonar range might affect dose response relationships, a research question also addressed by other research groups on other species. This knowledge will enable us to better extrapolate effect observed during controlled exposure experiments, using scaled sources, to real naval exercise scenarios. However, there remain important issues to fully understand how marine mammals are affected by naval sonar. Together with our sponsors, naval end users from 5 NATO countries (USA, UK, France, The Netherlands and Norway), the 3S research group has identified two important topics for which we can contribute to increase the knowledge further.

4.4.1 Topic 1 - Effects of continuous active sonar (CAS) on different species

All BRS research to date, except the third phase of the 3S-project (Isojunno et al. 2020), has been conducted using pulsed active sonars (PAS), typically transmitting at a 5-10% duty cycle. Recent technological developments imply that in the near future naval sonars will have the capability to transmit almost continuously (Continuous Active Sonar, CAS). This technology leads to more continuous illumination of a target and therefore more detection opportunities (van Vossen et al. 2011). In many anti-submarine warfare scenarios CAS will give a tactical advantage with increased probability of detection, and therefore there is a strong desire within navies to put this technology in operational use. This raises imminent questions about the environmental impact of such sonar systems. Robust but surprising results from sperm whales indicated that the severity of reduced foraging response is better predicted by ping-by-ping cumulative signal energy than by received sound pressure level (Isojunno et al. 2020), but knowledge from other species is needed. Of particular relevance are species that: 1) vocalize within the frequency band of the sonar (e.g. killer whales and humpback whales), since CAS has higher potential for masking, and 2) have been shown to be particularly sensitive to PAS (e.g. beaked whales). In a future study we propose to conduct CAS CEEs focused on killer whales, humpback whales and northern bottlenose whales for which 3S has previously collected PAS data for comparison.

4.4.2 Topic 2 - Understanding the effect of exposure duration to enable better extrapolation from BRS to real operational sonar scenarios

The biological relevance or severity of behavioral responses depends upon the duration of responses. Behavioral responses that last through the entire duration of the exposure, or longer, are considered more severe than equivalent responses that cease while the sonar is still transmitting (Miller et al. 2012). A key challenge exists to extrapolate results from short duration exposures used in BRS studies to the typically longer duration operational activities of navies using sonar. If animals habituate over time, the severity of behavioral responses based on BRS could be overestimated. Conversely, if animals sensitize over time, the severity would be underestimated.

We propose to address this key question experimentally by conducting longer-duration experimental exposure of 4-6 hours, getting closer to the duration of some operational scenarios. The proposed study species are two cetaceans previous shown to avoid the sonar source and cease foraging during exposure and either rapidly resumed foraging (humpback whales), or had more prolonged avoidance and cessation-of-feeding responses (killer whales). Using real-time GPS quality location data of multiple tagged subjects, we propose an experimental design in which the source vessel is moved to achieve repeated dose escalations above the level at which 25-50% of subjects are expected to respond. We propose to use 1-2 kHz signals as in previous 3S research, but CAS instead of PAS. Analysis will focus on quantification of habituation or sensitization trends in responsiveness over the duration of exposure to a sonar stressor.

4.4.3 3S4 objectives

The two specific objectives of the proposed phase four of the 3S project (3S4) would be to:

1) Investigate whether exposure to CAS leads to different types or severity of behavioral responses than exposure to traditional PAS signals in killer whales, humpback whales and bottlenose whales.
2) Investigate empirically whether responses to short duration CAS exposures can be used to predict severity of responses to longer duration and more operationally relevant CAS exposures.

The proposed 3S4 study will address CAS vs PAS (objective 1) and longer vs short duration exposures (objective 2) by doing both short and long duration CAS exposures to species for which the responses to short duration PAS have already been investigated (Miller et al. 2012, 2014, 2015, Sivle et al. 2015, 2016, Wensveen et al. 2017, 2019).

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Wensveen et al. (In prep). Quantifying the effect of range to the source on severity and dose-response relationships in the sperm whale. *3S white-paper B36*, expected submission by May 2021.

Appendix A – List of 3S publication

In chronological order

** core deliverable (publications directly addressing the main objectives of the project - effects of sonar on marine life.*

A.1 Peer review papers

Benti B, PJO Miller, M Biuw, C Curé (2021). Indication that behavioural responses of humpback whales to killer whale sounds are influenced by trophic relationships. *Mar. Ecol. Prog. Ser.* 660:217-232. doi: https://doi.org/10.3354/meps13592

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*Isojunno S, Sadykova D, DeRuiter S, Curé C, Visser F, Thomas L, Miller PJO, Harris CM (2017). Individual, ecological and anthropogenic influences on activity budgets of long-finned pilot whales. *Ecosphere* 8(12): e02044. 10.1002/ecs2.2044.

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*Wensveen PJ, Kvadsheim PH, Lam F-PA, vonBenda-Beckmann A, Sivle L., Visser F., Curé C., Tyack PL., Miller PJO (2017). Lack of behavioural responses of humpback whales (*Megaptera novaeangliae*) indicate limited effectiveness of sonar mitigation. *J. Exp. Biol.* 220: 4150-4161. doi:10.1242/jeb.161232

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*Doksæter L, OR Godø, NO Handegard, P Kvadsheim, FPA Lam, C Donovan and P Miller (2009). Behavioral responses of herring (Clupea harengus) to 1-2 kHz sonar signals and killer whale feeding sounds. *J. Acoust. Soc. Am.* 125: 554-564

A.2 Papers in preparation, submitted or in review

*Von Benda Backmann A, Isojunno S, Zandvliet M, Ainslie MA, Wensveen PJ, Tyack PL, Kvadsheim PH, Lam FPA, Miller PJO (in review). Modeling potential masking of echolocating sperm whales exposed to continuous 1-2kHz naval sonar. *Journal Acoustical Soc. America* (in review).

Hooker SK and Miller PJO (in review). Northern bottlenose whale, Hyperoodon ampullatus Forster, 1770. In: *Handbook of the Mammals of Europe.* Series Editors: Klaus Hackländer, Frank E. Zachos. Springer.

*Miller PJO, Isojunno S, Siegal E, Lam FPA, Kvadsheim PH, Curé C (submitted). Underwater soundscape of fear: anti-predator adaptations predict cetacean responses to anthropogenic noise.

Aoki K, Isojunno S, Bellot C, Iwata T, Kershaw J, Akiyama Y, Martin-Lopez LM, Ramp C, Biuw M, Swift R, Wensveen P, Pomeroy P, Narazaki T, Hall A, Sato K, Miller PJO (Submitted). Aerial photogrammetry and tag-derived tissue density reveal patterns of lipid-store body condition of humpback whales on their feeding grounds. *Proc Roy Soc B.*

* Curé C, S Isojunno, M Siemensma, PJ Wensveen, C Buisson, RR Hansen, B Benti, LD Sivle, PH Kvadsheim, FPA Lam, PJO Miller (In prep). Severity Scoring of Behavioral Responses of Sperm Whales (Physeter macrocephalus) to Novel Continuous versus Traditional Pulsed Active Sonar. *3S white-paper B37, expected submission in March 2021.*

*Isojunno et al. (In prep). Testing indicators for masking during CAS exposures in sperm whales. *3S white-paper B35, expected submission in March 2021.*

*Wensveen et al. (In prep). Quantifying the effect of range to the source on severity and dose-response relationships in the sperm whale. *3S white-paper B36, expected submission by May 2021.*

*Curé et al. (In prep). Scoring of the severity of sperm whale behavioral responses to close and distant naval sonar. *3S white-paper B46, expected submission in June 2021.*

A.3 Reports and proceeding papers

*Kvadsheim PH, Isojunno S, Curé C, Siemensma M, Wensveen P, FPA Lam, RR Hansen, B Benti, LD Sivle, A Burslem, L Kleivane, PJO Miller (2021). The 3S3 experiment data report – using operational naval sonars to study the effects of continuous active sonar, and source proximity, on sperm whales. *FFI report* (in press).

* Kvadsheim PH, FPA Lam, S Isojunno, PJ Wensveen, SP van Ijsselmuide, LM Martín López, MWG van Riet, EH McGhee, M Siemensma, J Bort, A Burslem, RR Hansen & PJO Miller (2020). Studying the effect of source proximity in sperm whales and the effect of continous sonar in pilot whales using operational sonars – the 3S-2019-OPS cruise report. *FFI report 20/01749.* https://publications.ffi.no/nb/item/asset/dspace:6827/01749.pdf

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Wensveen, P (2018). Northern bottlenose whales: The mysterious deep divers of Jan Mayen. *The Circle (WWF)* 3:2018

Berkowitz Héloïse & Dumez Hervé [eds] (2017). Racket in the oceans: why underwater noise matters, how to measure and how to manage it. Paris: Observatory for Responsible Innovation / Palaiseau (France): i3-CRG (CNRS – École polytechnique). (with 3S contributions from C Curé C and P Miller).

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*Kvadsheim P, Lam FP, Miller P, Wensveen P, Visser F, Sivle LD, Oudejans M, Kleivane L, Curé C, Ensor P, van Ijsselmuide S and Dekeling R (2014). Behavioural responses of cetaceans to naval sonar signals – the 3S-2013 cruise report. *FFI-rapport* 2014/00752**.** (http://rapporter.ffi.no/rapporter/2014/00752.pdf).

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Sivle LD, Kvadsheim PH, Ainslie M (2013). Potential population consequences of active sonar disturbance in Atlantic herring: Estimating the maximum risk. In: *Proceedings from The Effect of Noise on Aquatic Life 3rd International Conference, Budapest, Hungary, August 11-16 2013.*
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A.4 Theses with 3S-contributions

Hollers A (2020). Acoustic communication in male sperm whales: exchanging codas and slow clicks, and adjusting source volume based on receiver distance. *MSc thesis U St Andrews.*
Benti B (2020). Behavioural responses of two cetacean species to natural and anthropogenic sounds. *PhD U Strasbourgh*
Selbmann A (2019). Comparison of the pulsed call repertoires of killer whales (Orcinus orca) in Iceland and Norway. *MSc University of Iceland.*

Keller O (2016). A comparative approach to investigate the severity of humpback whale, *Megaptera novaeangliae*, movement responses to naval sonar, *MSc, University of Amsterdam.*
Wensveen PJ (2016). Detecting, Assessing, and Mitigating the Effects of Naval Sonar on Cetaceans. *PhD-thesis, University of St.Andrews.*
Dreteler K (2015). What is the effect of behavioral response on accumulated sound exposure? *MSc thesis, Leiden University*
Roos M (2015). Respiration timing and underwater activity in killer whales (Orcinus orca). *MPhil thesis, University of St Andrews.*
Isojunno S (2014). Influence of natural factors and anthropogenic stressors on sperm whale foraging effort and success at high latitudes. *PhD-thesis, University of St.Andrews.*
Visser F (2014). Moving in concert - social and migratory behavior of dolphins and whales in the North Atlantic Ocean. *PhD-thesis, University of Amsterdam*
Kuningas S (2013). Population dynamics and distribution of northern Norwegian killer whales in relation to wintering herring. *PhD-thesis, University of St.Andrews.*
Filbri CN (2013). The effect of boat noise on killer whale (Orcinus Orca) vocalization, *Bachelor Thesis, Leiden University*.
Kok ACM (2013). Put your money where your mouth is. Correlations between surface social, diving and acoustic behaviour in long-finned pilot whales (Globicephala melas). *MSc thesis, Leiden University*
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Wensveen PJ (2012). The effects of sound propagation and avoidance behavior on naval sonar levels received by cetaceans. *MPhil thesis, University of St. Andrews.*
Ammerlaan I (2011) A new algorithm for determination of interclick intervals. *BSc-thesis, Fontys University of Applied Sciences, Eindhoven.*
Doksæter L (2011). Behavioral effects of naval sonar on fish and cetaceans. *PhD thesis, University of Bergen.*
Hadley ML (2011). Tracking sperm whales using passive acoustics and particle filters. *PhD thesis, University of Southampton*
Samarra FIP (2011). Functional design and use of acoustic signals produced by killer whales *(Orcinus orca).* PhD-thesis, *University of St.Andrews*
Shepherd CE (2010). The three dimensional beam pattern of sperm whale usual clicks. *MSc thesis, University of Southampton.*
Marijke Olivierse M (2009). Behavioural responses of marine mammals in their horizontal movement as a result of exposure to sonar. *BSc-thesis, University of St.Andrews/SMRU.*
Podt A (2009). Effects of anthropogenic noise on killer whale vocalization. *Bachelor thesis, Leiden University* (In Dutch, with English summary)
Shapiro AD (2008). Orchestration: the movement and vocal behavior of free ranging Norwegian killer whales (Orcinus orca). *Ph.D. thesis, Massachusetts Institute of Technology, Woods Hole Oceanographic Institution.*

Appendix B – Data plots from 3S3

B.1 Figure legend

Since the figures are the same for all data records, common figure legends are given here. Symbol legends are inserted in each figure. Each tag deployment is represented with separate plots showing the entire record and zoomed views of the pre-exposure baseline period and each of the exposures. Data plots of the exposures include data from 60 min before the start of the exposure until 60 min after end of the exposure. Each tag deployment has one figure showing the tracks of the source boat (FFI RV HU Sverdrup II or during the frigate trials, KNM Otto Sverdrup) and the focal whale with experimental periods indicated, another figure with a close-in to the whale tracks only, and one figure with time series observations of group size, swim speed, heading and turning angle, pitch, depth and vocalizations.

Geographical plot: The track of the tagged whale (dark blue line) was either a high-resolution track estimated from tag-derived movement data and visual and GPS position fixes using a Bayesian track reconstruction method (Wensveen et al. 2015) extended to include acoustic estimates of source-whale range, or 2) a lower-resolution track based on linear interpolations between position fixes (when tag-derived heading data were not available). The temporal progression of the whale track during the exposure period was coded using a color gradient, with blue indicating the whale's position at the start of the exposure and red indicating the whale's position at the end of the exposure period. The same color coding was used to indicate the temporal progression of the source boat's track during the exposure period. For the 2016-17 trials, sightings of killer whales (OO) and pilot whales (GM) are indicated on the tracks as a line connecting the position of the vessel and the position of the sighting at that time. Sightings are numbered from the first to last. Killer whales or pilot whales were not sighted during the 2019 deployments.

Timeseries plot: The start and end of exposure periods are indicated with solid and dashed vertical lines, respectively. Group size represents the best visual estimate of the focal group size. The swim speed during dives was calculated using a method which regressed acoustic flow noise on the tag in the 22.4-28.2 Hz frequency band to kinematic speed estimates during ascent and descent periods (pitch>60°) (Wensveen et al. 2015). Depth, heading and pitch were calculated using established techniques (Johnson and Tyack, 2003). The horizontal turning angle was calculated as a centered moving circular average with a +/- 1 min window size. Acoustic signals from the tagged whale or whales nearby consisting of slow clicks, codas, buzzes, and periods of regular search clicks were manually identified by an experienced auditor and overlaid onto the dive profile. When present, the timing of killer whale and pilot whale sightings are indicated by red text (OO and GM, respectively) on the top panel. Vertical lines indicate pilot whale or killer whale (pink) or other delphinid (brown) sounds heard on the tag. Similarly, blue vertical lines indicate timing of incidental sonars heard on the tag (various frequencies 1-10 kHz).

The data plots can be downloaded in a separate file, following this link, the file is approximately 130 Mb.

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The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

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FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

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FFI turns knowledge and ideas into an efficient defence.

FFI's CHARACTERISTICS

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Forsvarets forskningsinstitutt ble etablert 11. april 1946. Instituttet er organisert som et forvaltningsorgan med særskilte fullmakter underlagt Forsvarsdepartementet.

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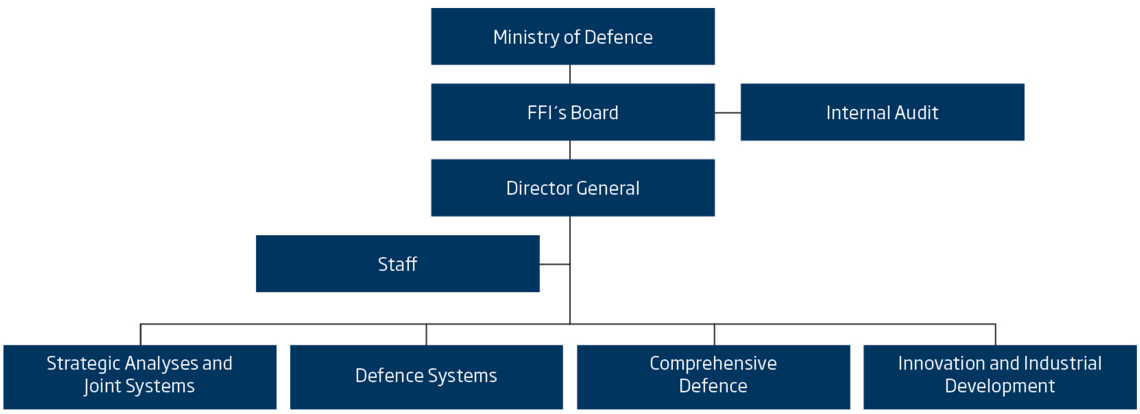

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