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# Automatic real-time GPS tracking of tagged cetaceans to conduct controlled exposure experimental protocols at sea

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## Abstract

**Background** In addition to recording whale behaviour, animal-attached tags enable real-time tracking of a focal experimental subject—required for positioning a sound source to achieve a desired exposure design. Tracking has typically been accomplished with visual observers spotting the tagged whale, aided by radio signals from the tag, and recording its range and bearing. Here we describe an automatic system for near real-time GPS tracking of multiple tagged whales, developed to enable execution of long-duration exposure sessions in a behavioural response study.

**Results** Real-time GPS tracking was automatically accomplished by intercepting satellite transmissions from a Lotek F6G 149 series GPS-Argos unit attached to a whale within a suction-cup multisensor tag, and decoding the data packets on the source vessel. Testing and refinement using a custom high-performance antenna demonstrated tracking of killer whales (*Orcinus orca*) and humpback whales (*Megaptera novaeangliae*) to the horizon and confirmed the benefit of specific tag placement flat on the body between the blowhole and dorsal fin. The system was successfully deployed in a behavioural response study testing how killer and humpback whales respond to continuous and pulsed sonar exposures over durations used by Navies. With receiving antennas placed 23 m above sea level, positions were reliably received < 10 min after they were recorded on the whale out to distances up to 17 km—the distance to the horizon, and at a somewhat slower rate at even greater distances. A MATLAB program was developed to plot automatic GPS positions and plan vessel movements in the sonar controlled exposure experiments. Using this system, we were able to carry out a challenging experimental protocol which required two approaches to within 1 km of each tagged whale subject over an 8-h period, while maintaining a distance of ~ 10 km between approaches. A publicly available PAMGuard module to plot GPS locations is also available to support smaller scale experimental efforts.

**Conclusions** Automatic GPS tracking represents a fundamental advance that enables at-sea experiments with marine mammals to be conducted without continuous visual tracking, substantially lowering cost and expanding contexts in which controlled exposure experiments can be conducted, including during darkness or rough weather.

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**Keywords** GPS telemetry, Cetacean, At-sea experiment, Tracking, Controlled exposure experiment, Behavioural response study, Suction-cup tag

## Background

At-sea experiments which quantify the behavioural responses of free-ranging cetaceans to natural and anthropogenic sounds has been a powerful tool to identify the types of responses exhibited by the animals, as well as the acoustic received levels and distances at which behavioural responses begin to occur [1, 2]. Controlled exposure experiments (CEEs) were defined by Tyack et al., 2003 [3, pg 41 therein] as: “A field procedure in which controlled doses of an acoustic stimulus are applied to focal animals for the purposes of assessing their behavioural and/or physiological responses. The stimulus, which may either be generated by the noise producing object itself, or reproduced electronically from recordings using an underwater sound projector, will be under the control of the experimenter”. CEEs are a central component of behavioural response studies (BRS) which seek to address an applied research question that is helpful for quantifying the potential impact of the noise source on the behaviour of a study subject.

The specific goals of a BRS are typically driven by management requirements, and the need to fill gaps in knowledge to enable more complete risk assessment of the potential impact of a disturbance on the natural behaviour and population health of free-ranging animals. Early research on the effects of sonar on marine mammals aimed to describe the variety of responses that can occur due to sonar exposure [4], validate experimentally that the sonar signal itself indeed can be a driver of behavioural responses [5], and determine dose-response relationships that specify the probability of a negative response given exposure to a sound at a particular received level [6]. The experimental nature of assessing responses of a free-ranging subject to an anthropogenic sound has notable similarities to ‘playback experiments’ which tend to focus on how a subject responds to natural sounds [1]. Indeed, several BRS studies included playback of natural predator sounds of killer whales to contrast responses to anthropogenic vs natural sounds [7, 8]. This has been a powerful tool to describe how responses to anthropogenic sounds vary across species likely shaped by acoustic interspecific interactions, and susceptibility to predation, among the cetaceans [9]. Partly because the research questions addressed so far have not implied the need to expose the animals over an extended period, and partly to the challenges of positioning a source near a subject whale, most transmission periods (exposure sessions with active transmissions) within each experiment have tended to be <1 hr [2, 5]. Ongoing experiments in the 3S4 BRS (‘3S4’ refers to the 4<sup>th</sup> phase of the Sea

mammals, Sonar, Safety collaborative study; [10]) aim to expose animals to more realistic exposure durations, but still in a controlled manner using a strict experimental design [11, 12].

### Real-time tracking: a key requirement for conducting CEEs

A key field approach which has been particularly effective in the conduct of CEEs testing effects of natural or anthropogenic sounds on free-ranging cetaceans has been the temporary attachment of sound and movement recording tags to subject whales [1, 13]. The animal-attached tag itself continuously records high-resolution data on the movements and behaviour of the tagged animal, which otherwise would not be possible due to their visual absence during diving. Acoustic recordings on the device enable accurate measurement of received level from the recorded stimulus signal, so that behavioural changes can be related directly to received signal characteristics. While many BRSs have been accomplished using short-duration suction attachment of sound and movement recording tags, the use of movement only tags that telemeter diving or positional information via the Argos satellite system have also been employed effectively [5, 14]. Received sound levels in those cases are typically modelled [15, 16]. A recent BRS demonstrated the ability to test effects of sonar on shallow-diving delphinids without the use of tags, instead relying on drone follows and visual observations to quantify behaviour and position the sound source [17].

A sometimes overlooked, but key capability required to carry out a CEE is effective positioning of the sound source relative to the position of the subject animal [3]. Positioning the source relative to the subject is necessary to achieve the desired exposure at the subject animals, enabling specific evaluation of the applied research question of how animals respond to specific characteristics of the received signal (e.g., distance from the source [2]). In some studies, positioning of the source relative to the movement direction of the subject whale can also be important to control the spatial context of the animal hearing the stimulus [4]. Controlled positioning of the source requires regular updates of the subject animal’s position in real-time during the experimental procedure, so that the position of the vessel carrying the source (‘source vessel’) can be optimized to match the goals of the CEE. In most BRS research to date, subject animals were tracked using visual observers that noted the position of the tagged animal when it surfaced, supported by the transmission of a VHF signal from the tag to confirm the correct animal was being sighted [1, 18]. Direct

visual sighting of the tag itself on the animal's body also aids confirmation that the correct whale is being tracked. Visual observations also enable documentation of additional behavioural patterns such as group size and spacing (e.g. [19]).

Typically, tracking the focal whale is conducted independently from a separate observation vessel because of requirements related to source positioning [4], but has been carried out from the source vessel itself in some cases (e.g., [2]). While effective, the need for visual tracking tends to limit experiments to daytime periods in sufficiently calm seas or to the larger cetacean species most visible at the surface, to enable reliable tracking of the tagged subject. Visual tracking can also be quite inaccurate [20] and is costly in terms of required personnel and a dedicated observation vessel for tracking, and specialized tracking equipment such as automatic-direction finder systems that indicate the direction to an incoming very high frequency (VHF) radio signal [21].

Here, we report on the development and use of a novel automatic GPS tracking system, which provides near real-time positional information of a tagged whale without using visual tracking. The immediate scientific need which drove the development of this automatic tracking method was the question of how dose-response studies over short experimental timelines, typically <1hr, can be extrapolated to real-world sonar activities which tend to last for many hours [11, 12, 22]. We designed a BRS with killer and humpback whales to address this question with the field design to approach each tagged subject twice, once near the start of the 8-hr exposure session, and again roughly 4–5 hrs into the session. By approaching the whales twice over the 8 hr exposure sessions, our study seeks to quantify whether whales' responsiveness to sonar changes over time periods more representative of actual naval use of sonar than the relatively short exposure sessions used primarily to date. Given our use of a 214 dB re 1 $\mu$ Pa m source in the 1–2 kHz band, we aimed to approach each focal tagged whale to within ~1 km to achieve received levels greater than 142 dB re 1 $\mu$ Pa, which was determined by Miller et al. [6] to be the received level at which 50% of killer whales began avoidance movements to sonar in exposure sessions of 30–50 min duration. This design therefore allows assessment of whether and how the long-duration sonar transmission period might alter how whales respond to sonar, with greater responsiveness indicating sensitisation to the sonar stimulus and lesser responsiveness indicating habituation. This protocol requires effective tracking and monitoring over 24 hr periods, including in darkness, with a sufficient accuracy that the source vessel can approach the tagged subject(s) within a distance of 1 km.

Tracking whales using signals from tags has been accomplished using Argos positions provided by satellite

tags [14, 16, 23]. However, Argos locations typically have much poorer accuracy than GPS [24] which limits the effectiveness of the placement of the source except in circumstances when the source-animal distance is very large [23]. Heide-Jorgensen et al. [25] used Argos relay of GPS positions recorded on the animal, which was effective for their study, but entailed a necessary delay between the time the location was recorded on the animal and when it was received by the research team. Reliance on Argos also means that tracking is only possible when sufficient Argos satellites are available to compute a location or to relay signals received from a tag, and when researchers on the source vessel are able to access the internet to obtain information from Argos.

Rather than relying on transfer via the Argos satellite system, the new automatic whale tracking system described here intercepts GPS snapshots encoded within Argos signals from the tag using a standard Collecte Localisation Satellites (CLS; <https://www.cls.fr/>) goniometer receiver and custom non-directional antenna tuned to the Argos transmission frequency band. This approach was inspired by a similar method by [26], to track difficult-to-sight harbour seals using snapshot GPS receivers on each seal with data telemetered using ultra-high frequency radio signals. A GPS snapshot (a.k.a. Fastloc GPS or FastGPS) records sufficient data from GPS satellites to compute a position once the snapshot data is linked to GPS ephemeris data which describes the relative positions of the GPS satellites. As in [26] GPS satellite ephemeris data to decode the animal GPS positions were collected using a u-blox GPS receiver ([www.u-blox.com](http://www.u-blox.com)). This avoids any need to connect to the internet for tracking functionality, enabling a fully remote tracking capability that can be widely used in a variety of field settings and locations.

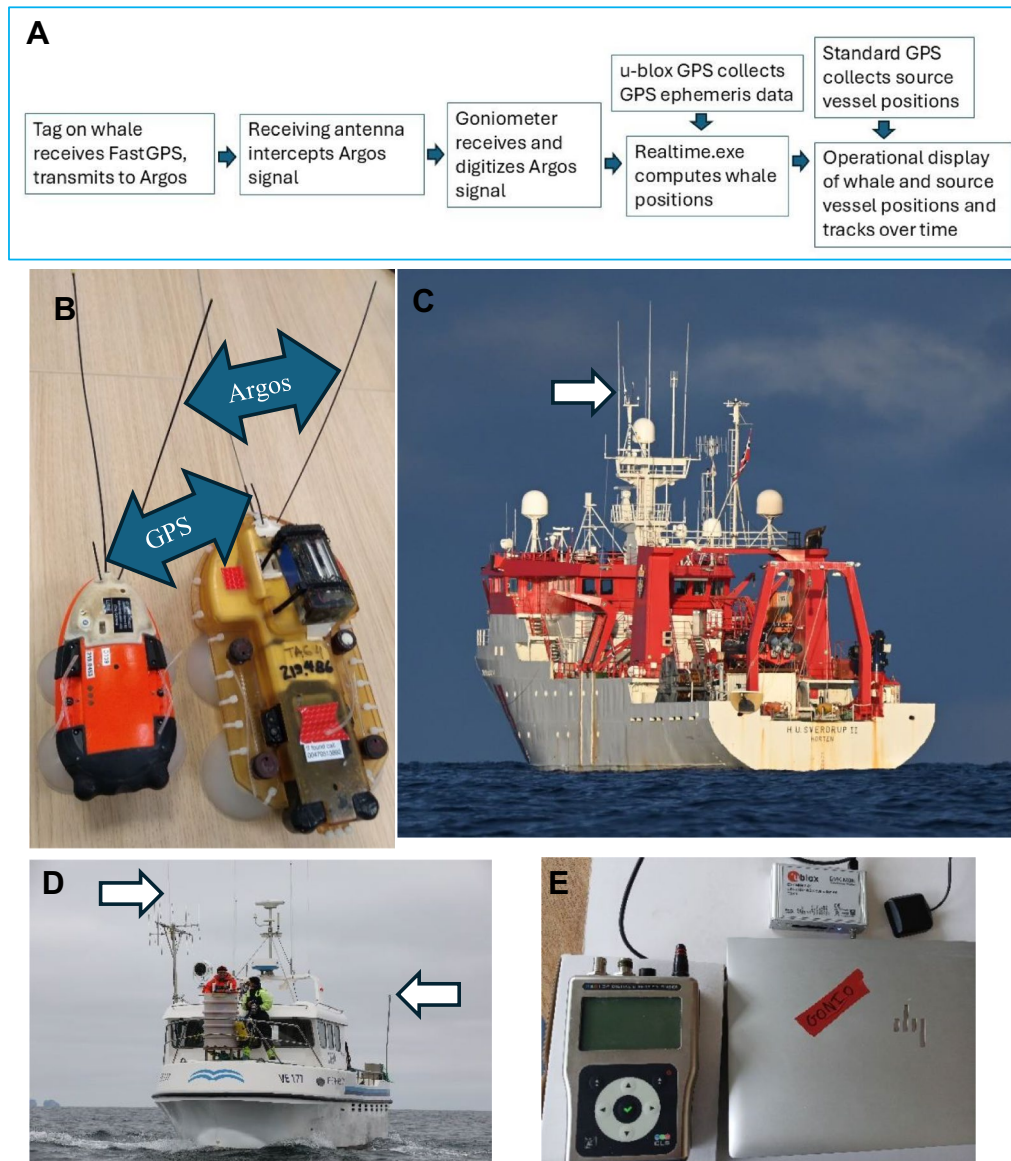
## Materials and methods

Development and demonstration of the new automatic GPS tracking system was carried out in two phases with fieldwork conducted in two locations, both focusing on tagging and tracking killer whales and humpback whales feeding upon herring. The system was developed and tested during fieldwork in waters near the Westman Islands archipelago, south-east Iceland, in a spawning location for Iceland Summer Spawning herring, with fieldwork conducted in the summer months of 2021–2024, with demonstration of the PamGuard visualisation software (described below) in 2024. The system was deployed for full operational use during the 3S4 BRS research trials in northern Norway during October–November 2023 and 2024, using CEE Tool (described below) for visualisation [11, 12].

The Iceland field research consisted of a 6 m tagging vessel (Golli) and a 12 m dedicated tracking vessel

(Marine Vessel (MV) Friðrik Jesson; Fig. 1; panel D). In Iceland, tagging from the smaller vessel was attempted first, and the tracking vessel was only used during dedicated tracking session for a subset of the tag deployments. During the Norway fieldwork, tagging was conducted from a tag boat deployed by crane from RV HU Sverdrup II, which was the principal tracking station as well as the source vessel for CEEs (Fig. 1; panel C).

In both locations, two different tracking antennas were used. One was the standard directional goniometer antenna ( $-2$  dB gain) supplied with the CLS goniometer receiver, and the other was a custom omnidirectional antenna ( $+5$  dB gain). To place antennas as high as possible, 25m extension cables were used for both systems. Both antenna types were used for GPS tracking in the early testing phases in Iceland. However, during Norway fieldwork, only the custom  $+5$  dB antenna was used for



**Fig. 1** Components of the real-time tracking system. Panel A: Block diagram of overall system; Panel B: Multi-sensor suction-cup tags used in development and deployment of the system. On the left is an integrated-Dtag, and on the right is a custom modular-Mixed-Dtag. Both tag types carried a Lotek (<https://www.lotek.com/>) F6G 134D device that receives GPS signals via the shorter GPS antenna, and relays position data to the Argos satellite system via the longer Argos antenna. The third longer antenna is a VHF transmitter. Panel C: Research Vessel HU Sverdrup II used as the tracking and CEE source vessel in Norway fieldwork during the 3S4 CEE trials. White arrow indicates placement of both tracking antennas. Antenna height was measured to be 23 m above sea level. Panel D: MV Friðrik Jesson used as the tracking vessel in the Iceland fieldwork. White arrows indicate placement of the tracking antennas, which were 5 m above sea level. Panel E: A CLS goniometer receiver digitizes signals from the antenna, which are transferred to a computer for processing. A u-blox GPS receiver is connected to the computer for acquisition of ephemeris data required for decoding positions

receiving and decoding GPS locations while the directional  $-2$  dB antenna was used to obtain real-time bearing estimates. The signal from the custom  $+5$  dB antenna was first connected to a filter and low-noise amplifier in a waterproof box that removed energy outside of the ARGOS signal band, before connecting to the goniometer receiver.

Signals from each antenna were received using standard CLS goniometer receivers (both models RXG134 and RXG234 were successfully used). Goniometers were set to 'USB mode' to transfer digital data via a serial-over-USB Universal Serial Bus) connection to the analysis computer, with the hexadecimal identifiers (IDs) of tags to be tracked set as 'favourites'. A u-blox EVK-M8N GPS receiver was also connected to the same computer to obtain GPS ephemeris data, required to decode the FastGPS signals, the u-Blox GPS antenna was mounted outside with a 3 m connector cable. The digital signals were accessed using a command line program called 'FastGPS\_Realttime.exe' (version 2.0.5) which was written by Lotek. The software polls the received antenna for signals from specified transmitter IDs, and simultaneously collects GPS satellite ephemeris data from the u-lox GPS

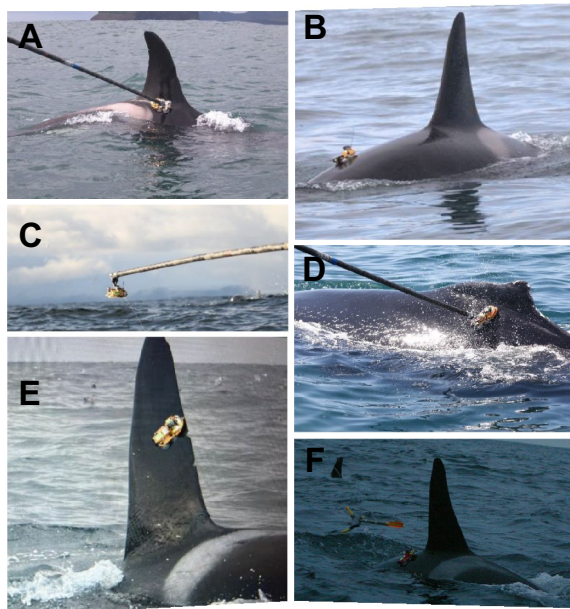
receiver. Please see supplementary material for a complete installation manual.

#### Tag design and placement on the whale body

Two types of suction cup-attached multisensor tags were used in automatic tracking in this study, with the common key component of a Lotek F6G 134 series GPS-Argos module. Integrated-Dtags (Fig. 1, panel B) provided by the University of Michigan also contain a Dtag core unit that records sound, depth, 3-axis magnetic field and 3-axis acceleration as well as a VHF transmitter. A larger modular form of the Dtag ('Mixed-Dtag' [21]) developed by PJOM also includes a Little Leonardo DVLW1300M130-VD3GT-4R that records wide-angle video, as well as depth and 3-axis acceleration (both at 10 Hz). Both tags have sufficient buoyancy that they float after detaching from the whale, and can be reused once data are offloaded and batteries recharged.

These short-term (1–2 days maximum) multisensor tags were attached to individual killer and humpback whales using suction cups. Whales were approached using the tagging vessel and tags were attached using 5 m carbon fibre poles, or a pneumatic aerial remote tag system (ARTS). Specific projectiles holding the tags have been developed for this system, enabling aerial launchings with 2–3x farther tagging distances compared to traditional pole tagging [21].

Effective suction-cup tagging with killer whales has long been accomplished by placing tags just under the dorsal fin with the antennas pointing backwards using a straight attachment system ([27] as in Fig. 2, panel A). As described in the Results section, this tag placement did not always lead to successful GPS tracking, so we changed our target tag-placement location to the flat part of the body between the dorsal fin and blow hole using a  $90^\circ$  attachment system (Fig. 2, panel C). For humpback whales, we started with a target tag placement high on the dorsal fin in Iceland (Fig. 2, panel D) while in Norway we targeted the flat part of the body between the dorsal fin and blowhole using the same  $90^\circ$  attachment system as was used for killer whales.



**Fig. 2** Tag placements for effective automatic tracking performance. Panel A: deployment oo23\_184a represents a typical tagging location for killer whales, just under the dorsal fin using a straight attachment system—for which automatic tracking was not successful. Panel B: whale oo23\_181b tagged in Iceland which had optimal automatic tracking performance. Panel C: illustrates the  $90^\circ$  attachment system used in Norway designed to enable tag placement as in Panel B. Panel D: deployment mn23\_193a had excellent tracking performance. Panel E: excellent tracking was achieved for this tag placement on whale oo23\_305a tagged in Norway. Panel F: excellent tracking was achieved during deployment oo24\_291a using the ARTS launching system in low light conditions. Note the vertical orientation of the antennas

#### Lotek F6G 134 series GPS-argos configuration

The F6G 134D uses a salt-water switch to indicate when the device is out of the water (thus with a view of the sky) and refers to a programming schedule for recording GPS snapshots and sending the most recent snapshot to the Argos satellite system. Given the short time available in a single surfacing for our study animals as well as most cetaceans, only one of those actions can be reliably performed, and the device will prioritize acquiring a GPS snapshot over transmitting an Argos message. Therefore, it is recommended to use a faster rate for Argos transmissions than GPS snapshots to assure that Argos

transmissions will be prioritized during sufficient animal surfacing events for snapshot data to be relayed. The device also archives each GPS snapshot, which can be downloaded after recovering the tag.

For the high-intensity tracking used in this study with killer and humpback whales, we scheduled acquiring a GPS snapshot every 5 min and transmitting an Argos message every 2 min. The GPS-Argos software also allows a certain number of snapshot GPS 'retries,' which we set to 2. A final useful feature enables the device settings to change after a given period of time. The manufacturer estimates the F6G 134D can make ~2000–2200 transmissions until battery depletion. To aid with tag recovery, we reduced the duty cycle to 25% after 28 hr, which extends the battery life over many days if necessary to recover the tag while it is floating after detachment from the whale.

#### Software to estimate and visualize whale positions

The 'FastGPS\_Realttime.exe' program created by Lotek polls the proprietary data stream incoming from the goniometer receiver, and identifies signals from a user-specified list of Argos Platform Transmitter Terminals (PTTs; including hexadecimal and decimal IDs). Received FastGPS signals from these Argos IDs are then processed to obtain the GPS position solutions, making use of the GPS satellite ephemeris data obtained using the u-blox GPS receiver. The real-time tracking software exports a string of data for each successful whale position fix to a text file which is formatted as an automatic identification system (AIS) position report. Thus, the positions can be read by standard chart plotter software such as OpenCPN (<https://www.opencpn.org/>). This software was used to plot locations during the early development phase in Iceland. However, such software is not well-suited for dynamically tracking multiple animals and conducting experiments at sea. Therefore, two different software packages were developed, 'CEE Tool' and 'PamGonio'.

To conduct CEEs according to the experimental design, a custom program CEE Tool was developed in MATLAB [28], version 2022b, that graphically displays bathymetry (depth contours), coastlines, own ship track, AIS tracks of other vessels, and the positions of tagged whales. Whale positions are derived from a combination of Argos satellite data (i.e., Argos-quality positions with associated error ellipses), the automatic GPS tracking system described herein, whale bearings from the goniometer receiver and directional antenna, and manual inputs such as visual sightings. The tool also allows users to manually place position markers on the map and measure range and bearing between two points selected on the geographic map. Data recorder functions were designed

and used to decode, filter and record GPS, AIS and Argos data in real-time.

Automatically received GPS positions for each tag were identified in the log file generated by 'FastGPS\_Realttime.exe' by filtering entries using the corresponding tag ID every 30 s. The vessel AIS recorder function decoded and recorded AIS data in real-time, capturing essential information such as Maritime Mobile Service Identity (MMSI), vessel name, latitude, longitude, speed over ground, and course over ground. The Argos recorder retrieved Argos data from the CLS server via internet, storing the data in an XML (eXtensible Markup Language) file for further processing. Though requiring access to the internet, these systems within CEE tool collectively ensured that the GPS, Argos, and AIS data were continuously recorded and stored in an organized manner, providing a reliable source of information for further analysis and application.

The CEE tool operates across two screens. The first screen provides a geographic overview of all relevant data and includes interface tools for editing. The second screen functions as a closest point of approach (CPA) calculator, which supports planning vessel movements to achieve the desired exposure levels. This dual-screen setup enables CEE operators to navigate the vessel efficiently while ensuring adherence to the experimental design. The CPA tool is especially valuable for adjusting the vessel's course to maintain the intended range to the tagged whales, thereby ensuring precise control over exposure conditions. The CEE tool also contains a night mode feature that is used for bridge operations during nighttime and a status monitor to display the real-time state of data streams and GPS signal quality. This status monitor proved particularly useful, providing insight into the distance to tags and the strength of the GPS connection for each whale.

Additionally, a module was developed for the open source PAMGuard software ([29]; see <https://doi.org/10.5281/zenodo.17965495> for a Zenodo repository) that also plots decoded FastGPS data generated by the FastGPS\_Realttime.exe program. This operates in a similar way to the CEE tool in that it polls the output files from FastGPS\_Realttime.exe for updates every five seconds but does not require access to the internet. Updated files are decoded and the whale positions added to a PAMGuard data stream which can be plotted on the PAMGuard map display and stored to the PAMGuard structured query language (SQL) database. Inclusion in PAMGuard means that the FastGPS positions can be displayed on the same map as sightings information entered into PAMGuard user forms. Ultimately this software would also enable display of acoustic tracking data should passive acoustic tracking be implemented in future studies. As well as displaying data on the map, the PAMGuard module can be

used to launch and manage the FastGPS program (which has several command line options). Source code and built releases for the PAMGuard module are available at <https://github.com/douggillespie/pamgonio>.

## Results

### Development and testing in Iceland (2021–2023)

During initial tests of the system in 2021 and 2022, automatic GPS tracking of tagged whales was only intermittently successful, with a maximum distance of 2.0 km. However, we were able to successfully track the F6G 134D unit when it was mounted on the tagging vessel (Golli), with consistent tracking to distances of 13.3 km for the custom +5 dB antenna, and to 7.2 km for the standard -2 dB goniometer antenna. These tests indicated that the custom +5 dB antenna would provide longer distances, but that either GPS reception on the whale or effective transmission from the whale limited our ability to track tagged whales.

Reliable automatic GPS tracking of tagged whales was first accomplished in 2023 for four out of five Mixed-Dtag deployments in Iceland, including for one tagged humpback whale, with GPS receptions at rates of 7.7–13.0 per hour though not all receptions had a new GPS position. The time between when a GPS snapshot was recorded on the whale to when it was processed ranged between 7–16 min, at maximum reception distances of 6.3–10.9 km for antennas placed 5 m above sea level (note: distance to horizon for 5 m elevation is 8.0 km). While both antenna types were effective for receiving GPS snapshots, the custom +5 dB antenna was the most effective. It was in 2023 that we finalized the Lotek software settings (see Methods) to ensure sufficient Argos-priority surfacings, and that change was likely a key factor in the successful tests in Iceland in 2023.

One key result from the Iceland 2023 trial was the unusually strong performance of tag deployment oo23\_181b (Fig. 2, Panel B). By chance this animal was tagged in an unusual location on the body (until 2023 we targeted placing the tag on the lower dorsal with antennas facing backwards; Fig. 2, Panel A). Tag oo23\_181b stayed attached for 24 h, and was tracked very successfully using MV Friðrik Jesson on two different days to a maximum distance of 10.9 km with an average update rate of 7 min. This flat placement on the front half of the whale's body leads to ideal upward orientation of both the receiving GPS and transmitting Argos antennas and minimizes potential GPS shadowing effects of the large dorsal fin of killer whales.

### Successful automatic GPS tracking during the 3S4 BRS in Norway (2023–2024)

The system operated highly effectively throughout both the 2023 and 2024 BRS research trials in Norway. Most

tags were deployed onto killer and humpback whales using a handpole with the suction cups pointing 90° perpendicular to the pole, effectively placing tags on the body in front of the dorsal fin by lowering the pole (Fig. 2, Panel C). In 2024, several tag deployments were made successfully using the ARTS launching system [21]. In some cases, killer whales were tagged on their dorsal fins with antennas angled upward (Fig. 2, Panel E), and good tracking was also obtained in those cases.

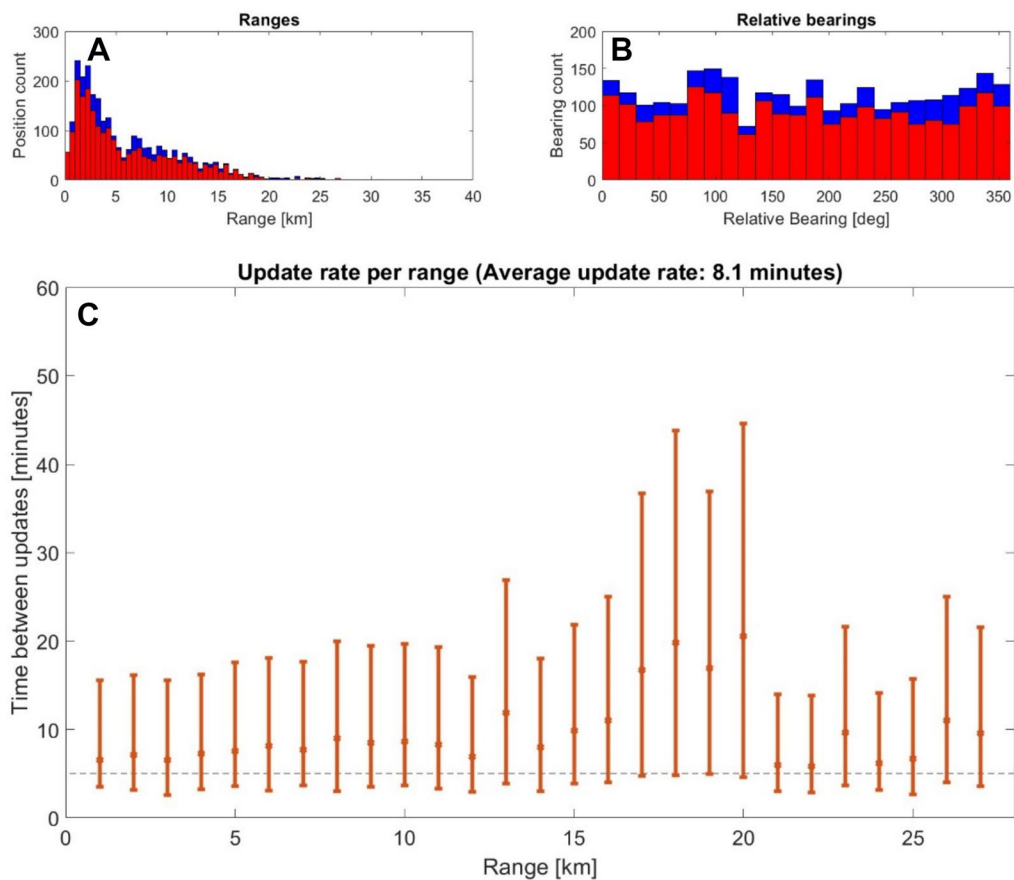
Automatic GPS tracking was not successful for tags that were unintentionally attached too low on the body (e.g. oo23\_299b), or that slipped to non-effective positions during the tag-attachment period. Those rare negative outcomes could be quickly determined in the field by the lack of GPS position receptions for a deployed tag. In those cases, position information was received again once the tag detached from the whale and floated to the surface. Indeed, position information was obtained for all tags after they detached, which greatly aided tag recovery by indicating their position while floating.

To demonstrate the performance of the method for effective tag placements, we quantified the performance of the system for 25 tag deployments totalling 510.8 h of on-animal tag time, which included all deployments that were subjects during CEEs (Fig. 3). Of this total, 21 deployments (427.9 hr) were on killer whales and 4 (82.9 h) were on humpback whales. Poles with the 90° attachment system were used for 14 killer whale deployments, and all the humpback whale deployments. The ARTS launching system (see example in Fig. 2 Panel F) was used for seven killer whale deployments of 153.3 h duration.

The results demonstrate the great effectiveness of tracking during these deployments, with positions received over distances to the horizon (17 km) and some even further (Fig. 3, panel A). Positions were received from all orientations around the vessel (Fig. 3, Panel B). There was no noticeable difference in performance between killer whales vs. humpback whales. The near real-time reception of position was confirmed by an average wait time of 8.1 min from when the tag recorded the position of the whale to the time it was received on the vessel (Fig. 3, Panel C).

### Successful accomplishment of 3S4 CEE design in 2023 and 2024

Overall, the CEE Tool plotting automatic GPS positions was the key critical asset for successful completion of the 3S4-2023 and 3S3-2024 trials, supporting accurate whale tracking, and effective execution of experimental vessel approaches. Figures 4 and 5 illustrate an example experiment conducted in 2024 (CEE24-02) during which three tagged subjects were exposed to an 8hr duration continuous active sonar transmission. Note that the position of the vessel was only controlled for up to two



**Fig. 3** Performance of the automatic tracking system on the RV HU Sverdrup based on 510.8 h of tracking tagged killer (427.9 h) and humpback (82.9 h) whales in 2023 and 2024. Top two panels show ranges (panel A) and bearings (panel B) from which GPS locations were received (killer whale data in red, humpback whale data in blue). Panel C shows the rate at which GPS position rates were received as a function of range. The mean time between updates is shown, with error bars indicating the 95% confidence interval using a Poisson distribution. The dashed grey line indicates the 5 min update interval between GPS locations. Note that 17 km was the distance to the horizon for an antenna placed 23 m above sea level

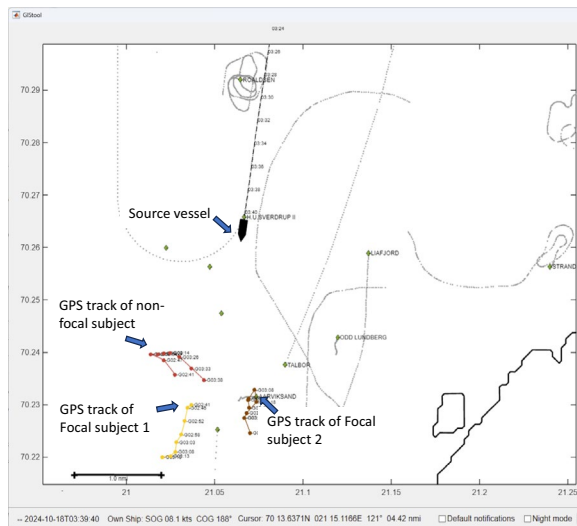
focal whales per experiment, and the distance to non-focal tagged whales was not controlled. The CEE Tool software displayed a map showing the most recent positions of selected tagged whales, the source vessel, and other nearby vessels (Fig. 4). The distance projection window in CEE Tool (Fig. 5, top-right panel), was useful for the experiment operators to predict the closest point of approach to the tagged animals based upon planned trajectories while approaching the whales' locations.

In the illustrated experiment, the source vessel was steered successfully to achieve two approaches to ~1 km distance from the two focal whales (Fig. 5, bottom panel), perfectly matching the desired protocol for the CEE. The field team relied on this automatic GPS tracking system visualized with CEE Tool to accomplish numerous CEEs in 2023 and 2024. Using this method, the team successfully accomplished 10 CEEs over eight weeks of fieldwork with a total of 15 focal and four non-focal animal subjects [11, 12].

## Discussion

The automatic GPS tracking system described here is a highly effective and economical way to track tagged whales in near real-time, with outstanding update rates to distances even somewhat beyond the horizon (Fig. 3). The combination of GPS-quality locations and regular updates enables very fine-scale tracking likely even more accurate than visual tracking (see [20]). By bypassing the need for signals to be received and transferred by the Argos satellite system, positions are received closer to real-time (typically <10 min after GPS reception on the whale; Fig. 3) and the system functions when Argos satellite coverage is not available.

The automatic GPS tracking system presented here, supported by CEE Tool to visualize data and design experiments, enabled our team to efficiently conduct long-duration CEEs that would have not been possible to conduct without it (Figs. 4 and 5). The field setting in Norway during October has limited daylight, precluding the use of visual tracking for more than brief periods. More broadly, visual tracking limits experiments to



**Fig. 4** CEE execution and outcome using the automatic tracking system. Illustration of CEE Tool for the second experiment conducted during 3S4-2024 on 18 October 2024, at time UTC 03:39:40 during the second controlled approach to the tagged subjects. Note the HU Sverdrup (in black) approaching the tagged whales' locations, while the tracks of other nearby vessels derived from AIS data are shown in grey. Tagged whales' locations are displayed as coloured dots with the yellow, brown and red dots corresponding to focal subject 1 (oo24\_291c), focal subject 2 (oo24\_291b) and a non-focal subject (oo24\_291a), respectively

daylight hours in relatively good weather conditions – which has the potential to constrain the variety of contexts in which it is possible to use CEEs to study effects of naval sonar [30]. While favourable weather conditions are still required to place a tag on a whale at sea, the automatic GPS tracking method reported here, enables the experiments to be carried out in rough weather and at night, which greatly expands the contexts in which it is possible to conduct CEEs.

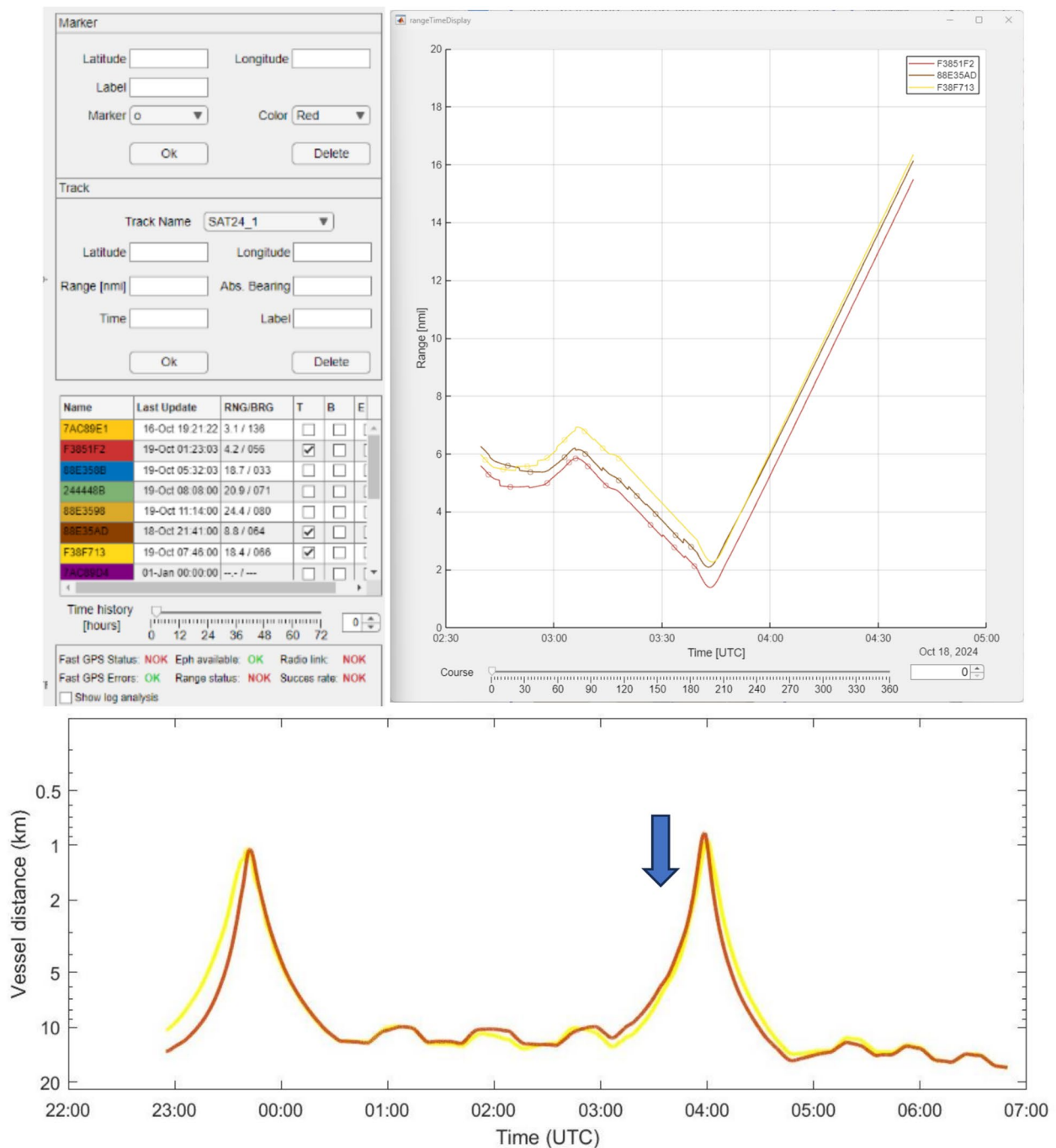
Visual tracking has usually required a separate dedicated observation vessel (e.g. [18]), whereas we were able to conduct CEEs using just the source vessel. This has the important scientific benefit of eliminating any concern that the following observation vessel might influence how the subject responds to the experimental stimulus. Another advantage of the automatic GPS tracking system reported here is a substantial saving in cost of the observation vessel and human effort to carry out visual tracking. Visual tracking is a labour-intensive activity, requiring constant lookouts using binoculars and VHF receivers to locate the tagged whale, which requires sufficient staff. The strong performance of the system in the 3S4-2023 CEE trial [11] enabled us to decrease the number of visual observers staffed for the 3S4-2024 trial, increasing staff numbers for other tasks [12]. A final benefit is that GPS locations from a floating tag, after detaching from the whale, greatly shorten the time taken to recover tags and prepare for a subsequent experiment.

Controlled exposure experiments using high power acoustic sources are subjects to a thorough permitting process and visual observers are still needed on the source boat to monitor the vicinity of the source to mitigate the risk that focal animals or other animals gets too close and risk hearing impairment [11, 12]. During the 3S-experiments, the visual observers were equipped with thermal binoculars which enabled visual monitoring of the mitigation zone also in the dark [31].

All of the hardware components of the tracking system are commercially available. By using a u-blox GPS receiver to gather GPS ephemeris data, the automatic GPS tracking system operates autonomously, with no connection to the internet required. We used the rechargeable Lotek F6G 134D GPS-Argos unit (Fig. 1), but the FastGPS\_Realttime.exe command line program is compatible with all F6 model devices supplied by Lotek. Both of the two receiving antenna types tested (Fig. 1) were functional to receive and decode GPS positions. However, the custom +5 dB antenna was found to be somewhat more reliable for receiving positions than the standard -2 dB goniometer antenna, so the custom +5 dB antenna is recommended to maximize GPS tracking distances. However, smaller-scale tracking experiments can rely upon the standard antenna supplied with the CLS goniometer. To maximize the usability of the system reported here, an installation manual is included as supplementary material.

The software CEE Tool is recommended for complex experiments with numerous data inputs (including Argos positions, visual sightings, and goniometer bearings) and a requirement for careful operational planning of source vessel movements [11, 12]. The PAMGuard module Pam-Gonio is a simpler, yet robust plotting system that also enables integration of AIS data from other vessels and visual sightings with a functionality similar to the widely used Logger 2000 software produced by IFAW [32]. Note that the PAMGuard visualization system does not require access to the internet, while CEE Tool does require access to the internet to retrieve Argos-only locations.

To date, we have only used the system with two species: killer and humpback whales. For effective tag placements (Fig. 2), the performance of the system did not appear to differ across these two species (Fig. 3). Killer and humpback whales are relatively large-bodied marine mammals, which could benefit performance of the system by raising a well-placed tag high out of the water for a long period of time during each surfacing event. Though we expect the system should work with other marine mammals (e.g. [26]), further testing is recommended with any new species, particularly with smaller-sized marine mammals that might have very brief surfacings that don't raise the tag high out of the water. Tests tracking the transmitter on a boat ('boat-to-boat tests') are strongly



**Fig. 5** Top left panel shows additional features of CEE Tool, including an interface to add manual markers or track, status of display for different tags, display history, and status of reception system. Top right panel shows the distances to the tagged whales' locations (in Fig. 5) projected by CEE Tool based upon the planned trajectory of the source vessel. Bottom panel shows a successful experiment outcome with two source vessel approaches to ~ 1 km distance from the two focal whales (yellow for Focal subject 1, brown for Focal subject 2). Note the non-linear Y-axis. The vertical arrow indicates the time illustrated in Fig. 4 (UTC 03:39:40)

recommended to assure the reception system is operating, before attempting to track tags attached to animals.

While tag placement can be optimized for animals that can be temporarily captured (e.g. [25, 33], see Fig. 1 in [34]), it is impossible to fully control the placement of tags during remote tagging at sea. In this study, we

demonstrated that using poles with 90° attachment orientation (Fig. 2, panel C) and the ARTS launching system (Fig. 2, panel F [21]) worked effectively. We expect that tags attached from above using novel UAV drone attachment systems (e.g. [35]) have good potential to lead to

effective tag placements for use of this automatic tracking system.

### Limitations, conclusions and future research

Our goal in this paper is to describe our demonstrations of this automatic, near real-time system for relaying GPS positions from free-ranging cetacea to a vessel within line-of-sight, and to provide sufficient details for its use by the research community. Future studies making use of the system could improve on some of the limitations in our work to date. For example, we did not aim to quantify the accuracy of the GPS positions obtained over the system. The positions provided using this method matched expected quality for GPS, for example test deployments on the HU Sverdrup and visualized in CEE Tool matched the vessel position closely, so we consider that the accuracy of this system will be similar to the accuracy of the GPS loggers themselves. Wensveen et al. [20] quantified the accuracy of an earlier version of these GPS loggers, and found that the number of GPS satellites used to calculate a location is a key determinant. A key challenge for quantifying the accuracy of locations is that the true position of a free-ranging animal is difficult to obtain; even visual observations can have more error than GPS locations [20]. The location quality was effective for our research goals which required placing the research vessel ~1km from the tagged subject whale. However, more evaluation of the location accuracy of the system could be warranted for other research questions (e.g. within group inter-animal spacing, [36]).

Another limitation of this study is that we did not quantify how weather conditions might impact how often GPS fixes can be obtained on a free-ranging animal. Performance could potentially be affected by direct wave action on the whale or receiving vessel, and/or by changes in surfacing behaviour of tagged whales. During the 3S4 experiments, the system worked well enough to conduct the controlled exposure experiments as planned in weather conditions up to Beaufort 4–6 (8–14 m/s wind) and sea state 4–5 (1–3m wave height) [11, 12]. Though we did observe the system worked well on occasions when weather conditions worsened (compared to when tags were attached), we were not able to address this quantitatively.

Ultimately, effective performance of the system seemed to depend most strongly upon placement of tags in ideal positions to receive GPS signals and transmit Argos signals to the antenna on the tracking vessel (Fig. 2). Placement cannot be fully controlled for remotely deployed tags, and suction-cup tags can also slide and move during attachment periods. We experienced cases where tracking did not work at all due to bad initial tag placement (oo23\_299b), and we noted that tracking quality tended to decline later in some of our >20hr duration

deployments, which we attributed to tags moving on the whale body. Movement of the tags to low positions on the tagged whale's body would, of course, also negatively affect visual tracking methods as the tag cannot be seen nor VHF signals received.

Additionally, any local features that affect global navigation satellite system (GNSS), including GPS reception (such as high mountains nearby, or unusually low surfacings by whales during certain behaviours) will also directly impact the effectiveness of the system described here. As GNSS-jamming becomes more common due to military conflicts, we expected those may also impact performance in areas close to areas where GNSS jamming may take place. Even with the influence of these limiting factors, however, the system has worked effectively to enable completion of the exposure protocol in the 3S4 BRS program. We recommend consideration of its use in similar future CEE efforts, as well as for smaller scale playback experiments (e.g. [8, 37]) that require accurate placement of an experimental sound source relative to the animals under study. If desired, the system can be effectively combined with visual tracking, which can have the additional benefit of enabling visual observation of group-level behaviour [19] not recorded by animal-attached tags.

### Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40317-026-00450-8>.

Additional file 1 (PDF 2033 KB)

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### Author contributions

Conception: PM, PW, KAS, CH Design of the work: PM, PW, LK, KAS, CH, PdSL Acquisition of data: PM, EH, PW, FS, SvIJ, MvR, CvdS, FPL, PK, LK Analysis and interpretation: PM, PW, SvIJ, MvR, CvdS Creation of new software: CH, SvIJ, MvR, CvdS, DG All authors read and approved the final manuscript.

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### Data availability

The datasets and software programs used and/or analysed during the current study are available from the corresponding author on reasonable request.

## Declarations

### Ethics approval and consent to participate

Animal tagging and experiments in Norway were carried out under permit from the Norwegian Animal Research Authority (permit no 23/110085). Fieldwork in Iceland was conducted under a Marine and Freshwater Research Institute (Hafrannsóknastofnun) institutional permit. Research protocols were approved by the U of St Andrews Animal Welfare and Ethics Committee.

### Consent for publication

Not applicable.

### Competing interests

The authors declare no competing interests.

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