Near real-time detection of low-frequency baleen whale calls from an autonomous surface vehicle: Implementation, evaluation, and remaining challenges

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JASA ARTICLE

Near real-time detection of low-frequency baleen whale calls from an autonomous surface vehicle: Implementation, evaluation, and remaining challenges

Mark F. Baumgartner,[1,a)] Keenan Ball,[2] Jim Partan,[2] Léo-Paul Pelletier,[2] Julianne Bonnell,[3] Cara Hotchkin,[4] Peter J. Corkeron,[3,b)] and Sofie M. Van Parijs[3]

[1]*Biology Department, Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, Massachusetts 02543, USA*

[2]*Applied Ocean Physics and Engineering Department, Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, Massachusetts 02543, USA*

[3]*Northeast Fisheries Science Center, National Oceanic and Atmospheric Administration, 166 Water Street, Woods Hole, Massachusetts 02543, USA*

[4]*Naval Facilities Engineering Command Atlantic, 6506 Hampton Boulevard, Norfolk, Virginia 23508, USA*

ABSTRACT:
Mitigation of threats posed to marine mammals by human activities can be greatly improved with a better understanding of animal occurrence in real time. Recent advancements have enabled low-power passive acoustic systems to be integrated into long-endurance autonomous platforms for persistent near real-time monitoring of marine mammals *via* the sounds they produce. Here, the integration of a passive acoustic instrument capable of real-time detection and classification of low-frequency (LF) tonal sounds with a Liquid Robotics wave glider is reported. The goal of the integration was to enable monitoring of LF calls produced by baleen whales over periods of several months. Mechanical noises produced by the platform were significantly reduced by lubricating moving parts with polytetrafluoroethylene, incorporating rubber and springs to decelerate moving parts and shock mounting hydrophones. Flow noise was reduced with the development of a 21-element hydrophone array. Surface noise produced by breaking waves was not mitigated despite experimentation with baffles. Compared to a well-characterized moored passive acoustic monitoring buoy, the system greatly underestimated the occurrence of sei, fin, and North Atlantic right whales during a 37-d deployment, and therefore is not suitable in its current configuration for use in scientific or management applications for these species at this time.
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I. INTRODUCTION

The need to manage interactions between human activities and marine mammals has spurred the development of near real-time passive acoustic monitoring from autonomous platforms (Van Parijs *et al.*, 2015). These platforms are capable of long-term continuous operation in virtually all weather conditions, making them a potentially valuable supplement to visual monitoring efforts conducted from shore, ships, and airplanes. Passive acoustics has been employed for several decades as a means to remotely monitor the occurrence of marine mammals *via* the detection of the sounds they produce (Mellinger *et al.*, 2007; Van Parijs *et al.*, 2009). Recent advancements in *in situ* sound detection and classification from low-power instruments have made near real-time passive acoustic monitoring from power-limited autonomous platforms possible (Clark *et al.*, 2005; Klinck *et al.*, 2012; Matsumoto *et al.*, 2013; Baumgartner *et al.*, 2013; Baumgartner *et al.*, 2014; Baumgartner *et al.*, 2019; Baumgartner *et al.*, 2020). As these technologies mature, they are increasingly being used to augment visual monitoring for management applications. This is especially true for mitigating threats to the endangered North Atlantic right whale (*Eubalaena glacialis*) on the east coasts of the United States and Canada, such as ship strikes, fishing gear entanglements, and noise exposure from wind farm construction (Van Parijs *et al.*, 2015). As new autonomous platforms and passive acoustic systems are developed, it is vital that their performance be rigorously evaluated before they are trusted for mitigation applications.

To date, near real-time passive acoustic monitoring for low-frequency (LF) baleen whale calls has been successfully demonstrated with moored buoys (Clark *et al.*, 2005, Baumgartner *et al.*, 2019) and buoyancy-driven gliders (Baumgartner *et al.*, 2013; Baumgartner *et al.*, 2020). Buoys allow monitoring in a fixed location over long time scales,

[a)]Electronic mail: mbaumgartner@whoi.edu
[b)]Current address: Kraus Marine Mammal Conservation Program, Anderson Cabot Center for Ocean Life, New England Aquarium, Central Wharf, Boston, MA 02110, USA.

typically six months (Clark *et al.*, 2005) to over one year (Baumgartner *et al.*, 2019). Buoyancy-driven gliders are autonomous underwater vehicles that alternately become more and less dense than the surrounding seawater to descend and ascend in the water column, respectively, while short wings provide lift to propel the glider forward (Rudnick *et al.*, 2004; Schofield *et al.*, 2007). Electric gliders move forward slowly, typically 0.15–0.20 m s^{-1}, and are therefore difficult to navigate in strong currents. Autonomous surface vehicles (ASVs), such as the wave glider (Liquid Robotics, Inc.), Saildrone (Saildrone, Inc.), and Datamaran (Autonomous Marine Systems, Inc.), move much faster than buoyancy-driven gliders and therefore are very attractive platforms for passive acoustic monitoring over large areas with strong currents ($>0.2\,\mathrm{m\,s^{-1}}$). All of these autonomous platforms, including buoys, gliders, and ASVs, are or can be equipped with communications packages that allow the transfer of passive acoustic data (i.e., audio, sound snippets, representations of sound, or sound detection classification information) from the platform to shore, so all are capable of near real-time monitoring. Like buoys, ASVs have a permanent surface expression, so are capable of true real-time monitoring with an appropriate full time satellite communication connection. However, such connections currently (1) are very challenging to implement because of the need for directional antennas, (2) consume significant power, and (3) are expensive.

The success of any autonomous platform for passive acoustic monitoring depends almost entirely on the level of noise produced during the operation of the platform. The moored near real-time buoys described by Clark *et al.* (2005) and Baumgartner *et al.* (2019) were purposefully designed to minimize platform noise by using stretch hoses, urethane-jacketed chain, and straking and hairy fairing to minimize hose and electromagnetic cable strum, respectively. The mooring design described by Baumgartner *et al.* (2019) places the hydrophone at the sea floor, as far from the surface as possible where noise from breaking waves is prevalent. Buoyancy-driven gliders have moving parts that make noise, including the buoyancy pump (to change the vehicle's physical volume, and therefore its density), pitch motor, and rudder, but these are infrequently activated so that the glider remains mostly silent during descent and ascent (Baumgartner *et al.*, 2013; Baumgartner *et al.*, 2014; Baumgartner *et al.*, 2020). For example, the buoyancy pump only activates as the glider nears the sea floor to initiate a climb or as the glider nears the sea surface to initiate a dive; throughout the rest of the water column, the buoyancy pump remains inactive. Because the glider spends much of its time away from the surface, the effect of surface noise on the recorded or processed audio is minimized. However, the glider must return to the surface to communicate with a shore-side computer, and LF passive acoustic monitoring is difficult during these surfacing intervals because of wave noise as well as electromagnetic noise caused by radio transmission.

ASVs have great promise for real-time or near real-time passive acoustic monitoring of LF whale sounds, but they are challenged by several sources of noise. By their very definition, ASVs have a component of the vehicle that remains at the surface, which produces noise by interacting with waves. Unlike moored buoys that can affix the hydrophone to the sea floor or buoyancy-driven gliders that can descend away from the sea surface, passive acoustic monitoring systems on surface-bound ASVs must explicitly incorporate solutions to hull slapping noise as well as surface wave noise (i.e., noise generated by breaking waves). Some ASVs also generate mechanical noise by the operation of passively-driven rotating wings or motor-driven rudders that must be quieted. For hydrophones towed from ASVs, cable strum can be an important source of LF noise. Finally, because ASVs move quickly (which makes them so promising for monitoring over large or high-current areas), flow noise is a significant problem for detecting LF sounds.

During 2014 and 2015, we incorporated the digital acoustic monitoring (DMON) instrument (Johnson and Hurst, 2007) running the LF detection and classification system (LFDCS; Baumgartner and Mussoline, 2011; Baumgartner *et al.*, 2013) into the Liquid Robotics wave glider with the goal of conducting near real-time passive acoustic surveys for baleen whales over long periods (3–4 months) in the waters off the northeast United States. The DMON/LFDCS has been successfully incorporated into moored buoys and Slocum gliders (Baumgartner *et al.*, 2013; Baumgartner *et al.*, 2019; Baumgartner *et al.*, 2020) for near real-time passive acoustic monitoring of several baleen whale species, including fin (*Balaenoptera physalus*), blue (*Balaenoptera musculus*), sei (*Balaenoptera borealis*), humpback (*Megaptera novaeangliae*), bowhead (*Balaena mysticetus*), and North Atlantic right whales. Archival passive acoustic recording from wave gliders has been described by Bingham *et al.* (2012) and Darling *et al.* (2019) for humpback whales in central Pacific waters, but no work has been done to date with wave gliders to detect species that call at lower frequencies than humpbacks (e.g., fin, blue, sei, right, and bowhead whales) or to conduct near real-time detection. During 2015–2017, we made several modifications to our wave gliders and the DMON hydrophone housing to address mechanical, surface, and flow noise, but not all were successful. In this paper, we describe and evaluate our approaches to mitigating these noises and discuss outstanding challenges to using ASVs for real-time or near real-time passive acoustic monitoring for baleen whales.

II. MATERIALS AND METHODS

A. Wave glider and near real-time passive acoustic monitoring system

Two Liquid Robotics SV2 wave gliders were acquired and augmented for near real-time passive acoustic monitoring for this study. The wave gliders consisted of two parts, the float and the sub, each connected to the other by a 7-m tether with integrated conductors that allowed the passage of power and digital data between the sub and the float (Fig. 1).

Wings on the sub rotated freely such that the sub would move up and forward whenever the float was carried up by the surface waves, and down and forward whenever the float was carried down by the surface waves. The float housed a global positioning system (GPS) receiver and a computer that steered the constantly forward-moving wave glider toward waypoints by activating a rudder on the aft end of the sub. The float also housed an Iridium modem capable of sending and receiving short-burst data (SBD) messages to a shore-side computer so that navigation and engineering data could be transmitted to shore, and navigation and operational commands could be sent from shore to the wave glider. Electrical power for all system components was supplied by a 665 W-hour lithium-ion battery pack that was recharged during daytime with two 40-Watt solar panels.

For all of the wave glider deployments described below, one or more DMON instruments were mounted to the underside of the sub (Fig. 2). Despite the challenges of quieting the moving parts on the sub, we chose to mount the DMON on the sub because we intended to operate the wave glider for periods of several months at a time to monitor for baleen whales in the Gulf of Maine off the coast of the northeast United States where there is abundant fixed fishing gear. We considered using a towed hydrophone, but estimated that the risk of the tow cable becoming fouled in fishing gear was very high; hence, we would not be able to achieve our goal of months-long deployments.

We developed a separate wave-glider payload to house a custom-built electronic device equipped with a GPS receiver, Iridium satellite modem, flash memory, and a dedicated GPS/Iridium antenna; this device was developed at the Woods Hole Oceanographic Institution (WHOI). The DMON (mounted on the sub) transmitted detection and status information to this device (housed in the float) *via* RS485 serial communications through the wave glider's tether. The device stored the DMON data and once every 2 h, transmitted these data to shore *via* the Iridium satellite modem using the router-based unrestricted digital internetworking connectivity solutions (RUDICS) protocol (Fig. 1). Other than the power supplied from the wave glider, this system was wholly independent of the wave glider's control and communication systems and is identical to that used in the near real-time passive acoustic buoys described by Baumgartner *et al.* (2019).

The DMON and LFDCS are described in detail in Baumgartner *et al.* (2013), Baumgartner *et al.* (2019), and Baumgartner *et al.* (2020), and the DMON/LFDCS used in this study was identical to that used in Baumgartner *et al.* (2019) and Baumgartner *et al.* (2020). Briefly, the DMON consists of a programmable digital signal processor, flash memory, and integrated low-, mid-frequency (MF), and high-frequency (HF) hydrophones packaged in an oil-filled urethane housing (Fig. 1). For this study, the LFDCS sampled and continuously recorded audio from the LF hydrophone, a WHOI custom-built end-capped cylinder with Navy type II ceramics with the following characteristics: 8–7500 Hz bandwidth, 36 dB re μPa/$\sqrt{}$Hz noise floor at 2 kHz, and -169 dB re V/μPa sensitivity at 2 kHz (Baumgartner *et al.*, 2013). The LFDCS sampled audio at 2000 samples per second, created spectrograms in real time (512 sample frame, Hann window, and 75% frame-to-frame overlap, resulting in a spectrogram frequency resolution of 3.9 Hz and a time step of 64 ms), equalized the spectrograms, and identified and characterized tonal sounds using a pitch tracking algorithm (Baumgartner and Mussoline, 2011). Pitch tracks were classified by comparing attributes of each pitch track to the multivariate distribution of those same attributes for a variety of call types in a call library using quadratic discriminant function analysis (Baumgartner and Mussoline, 2011). Pitch tracks and their associated classification information were transferred from the DMON to the wave glider's independent payload *via* serial communications, but the amount of pitch track data sent each hour was limited to 8 kilobytes (kB) to constrain the cost of sending the data and the time and cost of reviewing those data back on shore. As mentioned above, the wave glider transferred these data to shore during Iridium satellite communication sessions once every 2 h.

Pitch track and classification data were assessed on shore to determine the occurrence of right, humpback, sei, and fin whales using the human-review methods described in Baumgartner *et al.* (2019) and Baumgartner *et al.* (2020) (Fig. 1). The presence of species-specific calls in the pitch tracks was taken as evidence of the occurrence of one or more whales of that species. Upcalls, a frequency-modulated upsweep from ∼100 to 300 Hz (Schevill *et al.*, 1962; Clark, 1982, 1983), were used to identify North Atlantic right whales, LF downsweeps (34–82 Hz; Baumgartner *et al.*, 2008) were used to identify sei whales, and 20-Hz pulses (17–25 Hz downsweeps; Watkins *et al.*, 1987; Morano *et al.*, 2012) were used to identify fin whales. No single call was used to identify humpback whales; instead, recognizable patterns of variable notes that comprise humpback whale song (e.g., Payne and McVay, 1971; D'Vincent *et al.*, 1985; Clark and Clapham, 2004) were used to identify this species. We refer to the review of detection information over a time interval (e.g., a day) as producing an estimate of whale occurrence (i.e., presence or absence). We recognize that these estimates may be biased low because of silent animals and missed detections, but this bias will typically be reduced with longer time intervals that afford whales more opportunity to call and be detected.

B. Reducing flow and surface noise

During 2014–2017, numerous dock tests and 1-d sea trials were conducted to characterize platform noises and evaluate noise mitigation efforts. Wave gliders were also deployed on four occasions for long-duration missions (1–3.5 months; Table I) to (1) evaluate the endurance and navigability of the platform in Gulf of Maine waters and (2) determine how well the noise mitigation efforts performed. Two of the significant noise sources that we identified during these tests were flow noise and surface noise.

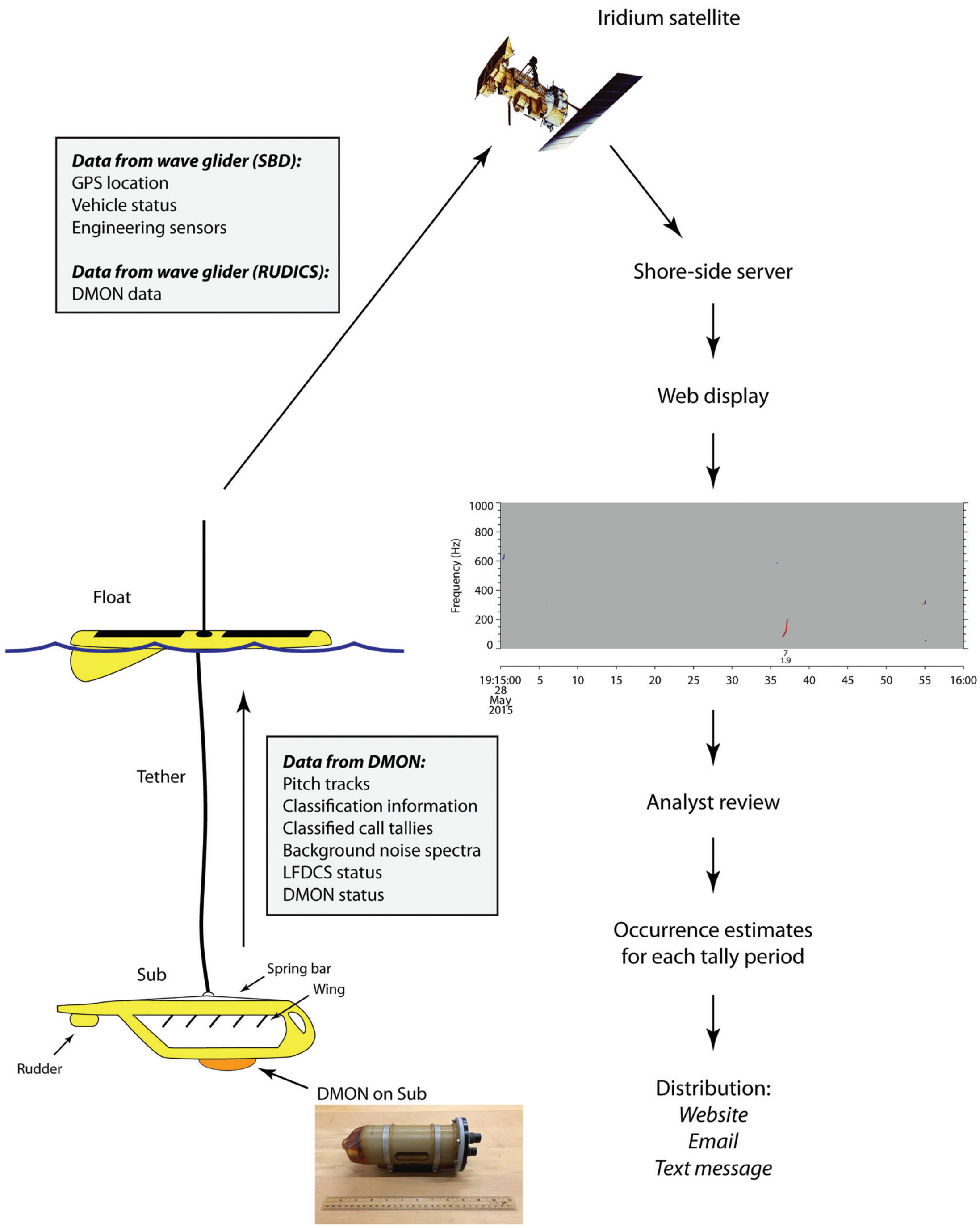

FIG. 1. Diagram of data flow from the DMON affixed to a wave glider sub to a shore-side server *via* the Iridium satellite service (both SBD and RUDICS services). These data are displayed on a website (Baumgartner, 2012), and pitch tracks and classification information are reviewed by an analyst to produce species-specific occurrence estimates for each monitored tally period. Occurrence estimates are then distributed to users *via* the same publicly accessible website as well as email and text messages. Web display in the figure shows a pitch track of a single North Atlantic right whale upcall. The DMON with integrated hydrophones is shown packaged in an oil-filled urethane housing.

The turbulence that induces flow noise can be thought of as many eddies that each influence a small area at any given time. Two hydrophones that are separated by a distance that is larger than the typical size of these eddies would be influenced by two separate eddies simultaneously (Sherman and Butler, 2007). These two eddies would be incoherent, so the LF pressure fluctuations caused by the eddies that are transduced by the two hydrophones would be uncorrelated. If these two hydrophones are separated by a distance that is considerably smaller than the wavelength of a LF whale call (meters to tens of meters) such that the call arrives at the two hydrophones virtually simultaneously, then averaging (or summing) their outputs will increase the signal to noise ratio of the whale call by a factor of $\sqrt{2}$, because averaging uncorrelated noise with zero mean reduces its variability (measured as root mean square) by a

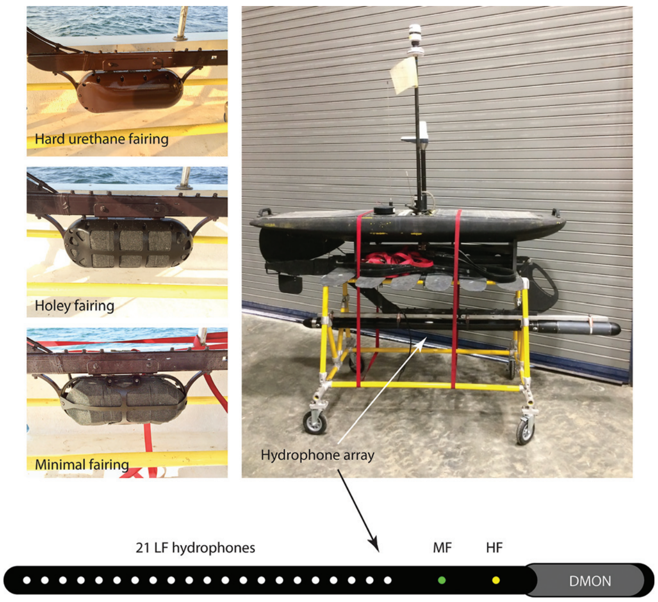

FIG. 2. Configuration of DMON instruments used in this study. Fairings on the left hold open-cell foam that, in turn, hold DMON electronics and LF, MF, and HF hydrophones encased in an oil-filled urethane housing (shown in Fig. 1). The photograph on the right shows the hydrophone array affixed to a wave glider sub, and the diagram at the bottom shows the 21 LF, 1 MF, and 1 HF hydrophones installed in an oil-filled polyurethane tube.

factor of $\sqrt{2}$. This suggests a linear array of n appropriately spaced LF hydrophones can increase signal-to-noise by a factor of up to $\sqrt{n}$ when challenged by flow noise.

During 2016, we designed a hydrophone array consisting of 21 acceleration-canceling LF hydrophones whose outputs were combined into a single input to a DMON electronics board. The array was fabricated by GeoSpectrum Technologies, Inc. (Canada) and was designed to be omnidirectional for the LF signals of interest. The array also had a MF and a HF hydrophone that were used as separate inputs into the DMON (not used in this study). The LF hydrophones were separated by 5 cm (total hydrophone array length was 1 m) and housed in an oil-filled 7.6-cm diameter polyurethane tube. The DMON electronics were contained in a housing that attached to the end of the tube so that the entire array and DMON were self-contained (Fig. 2). This 2.1 m long instrument was attached to the sub using rubber mounts to mechanically isolate the hydrophones from the sub. The 21 hydrophones theoretically could improve the signal-to-noise ratio of whale calls by a factor of $\sqrt{21}$ or 4.58.

To address surface noise (i.e., hull slapping and noise generated by breaking waves), we conducted tests with air-filled baffles placed over faired DMON instruments (not the array) in an attempt to deflect acoustic energy emanating from the sea surface. Baffles consisted of either a $61 \times 19 \times 2.5$ cm block of closed-cell foam or several 61-cm long $\times$ 3.8-cm diameter stainless steel hollow cylinders stacked in a $61 \times 16.5 \times 7.6$ cm volume that were placed 15 cm above a faired DMON.

C. Evaluation of near real-time estimates of baleen whale occurrence

To evaluate the performance of the wave glider as a platform for near real-time detection of baleen whales, a DMON-equipped wave glider was navigated continuously around a DMON-equipped moored buoy near Nomans Land Island, Massachusetts for 37 days during spring 2017 [Fig. 3(c)], and the near real-time estimates of baleen whale occurrence were compared between the two platforms. The wave glider circled the moored buoy at a nominal distance of 300 m [Fig. 3(c) inset], so the whale detection information between the two platforms was directly comparable. The moored DMON/LFDCS was attached to an aluminum frame just above the sea floor in 35 m water depth. The performance of the DMON-equipped moored buoy is well characterized (Baumgartner *et al.*, 2019) and therefore was considered an appropriate standard against which the DMON-equipped wave glider could be benchmarked. Pearson correlation analysis of daily detection rates from the wave glider and buoy was conducted for each of the monitored species. Daily percentages were transformed for the correlation analysis using the arcsine square-root transform: $\hat{X} = \sin^{-1}[\sqrt{X/100}]$ (Sokal and Rohlf, 1995). Axes of transformed values were back-transformed into percentages for clarity in the figures.

To quantitatively assess the performance of the wave glider, confusion matrices were constructed for each species comparing the near real-time estimates of baleen whale occurrence between the wave glider and buoy. Missed and false detection rates derived from these confusion matrices (see Fig. 4 in Baumgartner *et al.*, 2019 for equations) could be used to characterize the performance of the wave glider only if the buoy had perfect performance (i.e., missed and false detection rates of 0%). Baumgartner *et al.* (2019) observed false detection rates for right, humpback, sei, and fin whales of 0% on daily time scales, but the buoy was not perfect with respect to missed detections, having missed detection rates of 12%–42% on daily time scales. Equations were developed to account for the buoy's missed detections (Fig. 4) and the resulting estimated missed detection rate for

TABLE I. Summary of long-duration wave glider deployments. LF is an abbreviation for low-frequency.

Date	#Days	Area	Hydrophone configuration	Archival DMON without fairing	Figures
04/26–07/20/15	85	Great South Channel	Single LF hydrophone in minimal fairing	No	Figs. 3(a), S1a
08/08–11/29/16	113	Gulf of Maine	Single LF hydrophone in minimal fairing	Yes	Figs. 3(b), S1b
03/31–05/09/17	39	Nomans Land Island	Hydrophone array	No	Figs. 3(c), S1c
07/31–10/06/17	67	Gulf of Maine	Hydrophone array	Yes	Figs. 3(d), S1d

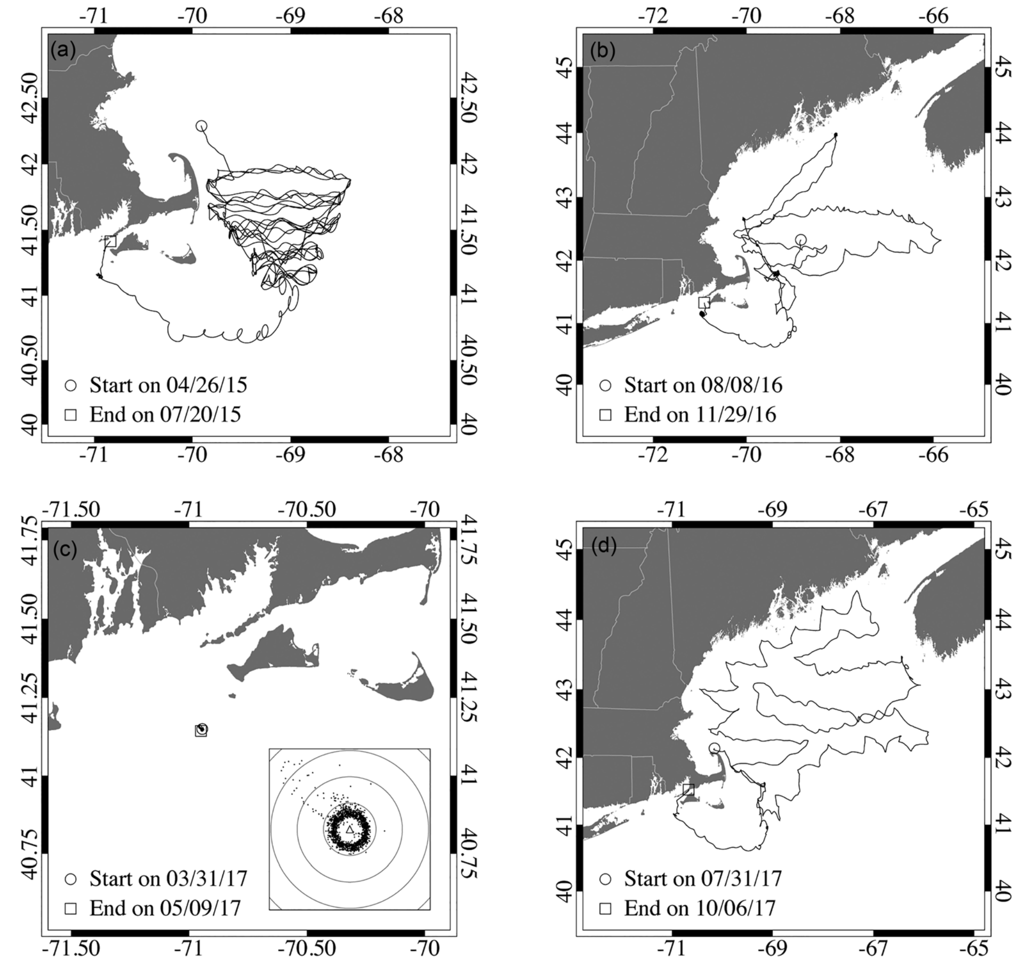

FIG. 3. Tracks of wave gliders for each of the long-duration deployments (a) in the Great South Channel (southwestern Gulf of Maine) during 04/26–07/20/15, (b) in the Gulf of Maine during 8/08–11/29/16, (c) near Nomans Land Island, MA during 03/31–05/09/17, and (d) in the Gulf of Maine during 07/31–10/06/17. Inset in (c) shows wave glider locations (small dots) in proximity to a DMON-equipped moored buoy (triangle); concentric circles are 0.5 km apart.

the wave glider (m_{wg}) for each species is reported below. For the purposes of estimating the missed detection rate, the wave glider was assumed to have a false detection rate of 0% because this provides the most optimistic (i.e., lowest) missed detection rate possible. As the false detection rate increases, the missed detection rate does as well (note F_{wg} in the equation for m_{wg} in Fig. 4); therefore, the missed detection rates for the wave glider reported here are considered minimum (i.e., best-case) estimates.

III. RESULTS

A. Mitigating noise produced by the vehicle

During spring 2014, an off-the-shelf SV2 wave glider was modified by (1) applying polytetrafluoroethylene (PTFE; Teflon brand, DuPont/Chemours) to all parts that pivoted or rubbed against one another, including the spring bar on the sub (a shock absorber where the tether meets the sub; Fig. 1) to reduce friction, and (2) attaching a DMON instrument to the sub. The DMON was placed in open-cell foam and a rubber frame to separate the hydrophone from mechanical shocks induced by the sub. Submersible cameras (GoPro, Inc.) were attached to the float and the sub to help attribute recorded noises to specific motions of the autonomous vehicle. The wave glider was deployed during calm conditions on May 21, 2014, off Race Point, Massachusetts, and again during windy conditions on May 28, 2014, in Buzzards Bay, Massachusetts. Tonal noise regularly produced by the activation of the rudder was plainly audible and apparent in the spectrograms (Fig. 5). During calm conditions, a LF impulsive sound was apparent [Fig. 5(a)], and it became much louder and broader in frequency during windy conditions [Fig. 5(b)]. An analysis of the camera footage indicated that this impulsive sound was associated with vertical acceleration of the tether (hence we dubbed it tether noise), which in turn was believed to be causing movement where the tether inserted into the float. A LF squeak was also apparent in the audio and spectrograms during windy conditions [Fig. 5(b)], which we preliminarily attributed to friction in the spring bar.

The mount point where the tether inserted into the float was replaced with a custom design that attempted to decelerate the tether with a strong spring and to cushion its impact with the float at the base of the mount. Additional PTFE was applied to the spring bar. These modifications appeared to be successful, as a sea trial on October 2, 2014,

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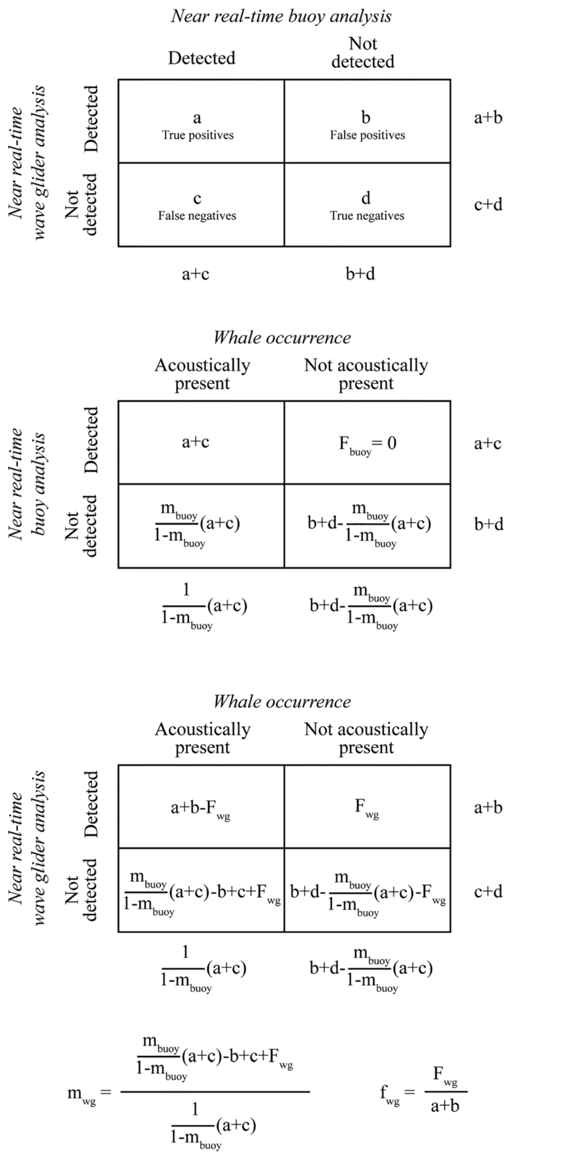

FIG. 4. Equations to derive the missed (m_{wg}) and false (f_{wg}) detection rates of the wave glider assuming the buoy had a missed detection rate of $m_{\rm buoy}$ and a false detection rate ($f_{\rm buoy}$) of 0%. $F_{\rm buoy}$ and F_{wg} indicate the number of false positives for the buoy and wave glider, respectively. Acoustically present is defined as one or more whales that are present and making detectable sounds (i.e., the whales are available to be detected by the buoy and wave glider).

during windy conditions showed no sign of tether noise or the LF squeak. However, additional noises became apparent during this test, including broadband impulsive noises [Fig. 6(a)] and a LF whooshing noise that we attributed to flow noise [Fig. 6(b)]. Analysis of camera footage synchronized with the audio indicated that the impulsive noises occurred when the wings reached the extent of their motion in the upward direction [i.e., when the sub moved downward; Fig. 6(a)]. We attributed these noises to the wings rotating hard against their stops and later remedied this noise by inserting rubber cushions between the wings and the stops to more gently decelerate the wings as they neared the stops. Mitigation of flow noise was more challenging and is described in detail below.

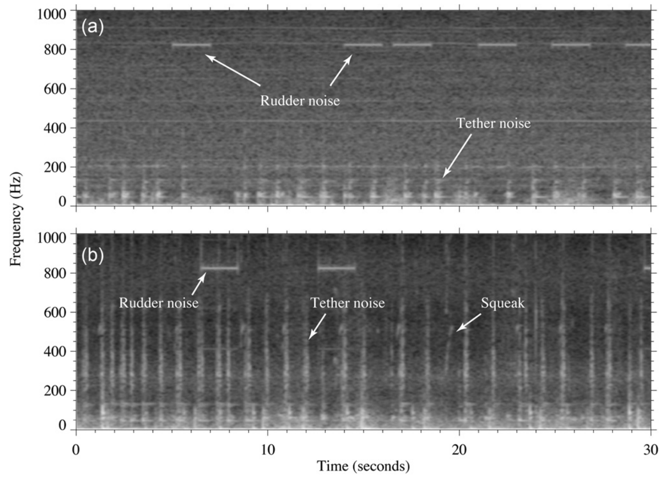

FIG. 5. Spectrograms of audio from a DMON shock mounted in foam and attached to a wave glider sub during (a) very calm sea conditions off Race Point, MA on May 21, 2014, and (b) choppy seas with abundant whitecaps (20–25 knot winds) in Buzzards Bay, MA on May 28, 2014. Noises referred to in the text are labeled.

In 2015, two wave gliders were painted with black anti-fouling paint (Interlux) in preparation for several long-duration missions (see supplementary Fig. S1).[1] We anticipated that biofouling as well as mechanical wear would limit the endurance of the vehicle; the application of this paint was intended to minimize biofouling so that the vehicle could achieve endurances of several months. While the paint worked well at anti-fouling, its application created a new platform noise source that took over a year to discover. Paint was inadvertently applied to the region where the wings inserted into the sub frame such that whenever the wing rotated, the paint would catch on the frame and produce a LF ticking sound. This seemingly small impulsive sound source appeared to be amplified by the sub frame acting as a resonator. The source of this sound was only discovered when the sub was suspended in air and the wings were rotated manually. Removal of paint at the insertion points remedied this source of noise.

B. Mitigating flow noise

Flow noise was important to mitigate in order to be able to detect whales that produced LF sounds, including sei, fin, and North Atlantic right whales. Flow noise is caused by turbulence in the immediate vicinity of a hydrophone; the very small eddies associated with the turbulence cause LF pressure fluctuations that are transduced by the hydrophone. We first attempted to mitigate flow noise with a variety of fairing designs intended to isolate the hydrophone from these pressure fluctuations. All of the fairings were designed to house a DMON instrument (Fig. 1) placed in open-cell foam to mechanically isolate the hydrophone from the wave glider sub (Fig. 2). Different fairings were made of different materials and enclosed the open-cell foam to different degrees. Materials included hard and soft urethane as well as rubber and were fabricated into full fairings (i.e., fully enclosing the foam), "holey" fairings (hard urethane shell

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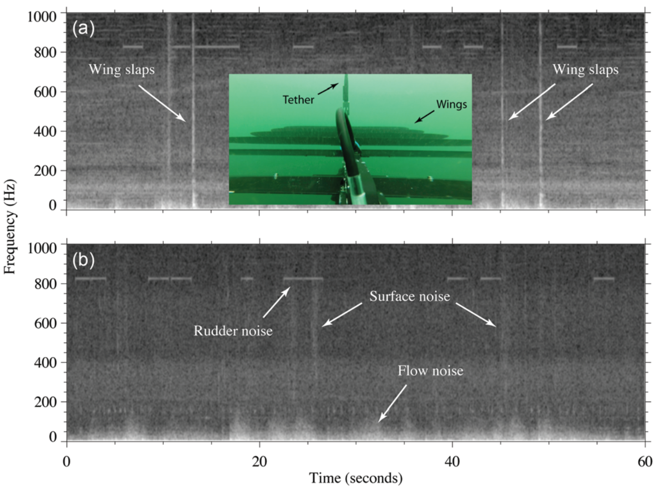

FIG. 6. Spectrograms of audio from a DMON shock mounted in foam and attached to the wave glider sub in Vineyard Sound, MA on October 2, 2014. Conditions during the deployment were 2–3 ft seas and 20+ knot winds. Noises referred to in the text are labeled, and the inset in (a) shows the position of the sub wings when the wing slap sounds were detected. Video frame taken from a camera mounted on top of the sub just above the rudder.

with large holes in it), or "minimal" fairings (hard urethane bracket with only enough support to hold the open-cell foam in place) (Fig. 2).

At sea tests designed to allow comparisons of multiple fairings were conducted but were difficult to interpret because only one fairing could be affixed to a glider sub at any given time (hence environmental conditions were not the same for each fairing). Hard mounting a reference DMON to the sub (i.e., without fairing or foam) along with the faired DMON was helpful for comparisons but did not allow adequate control for environmental conditions. Dock tests were also conducted where faired hydrophones and a reference DMON were affixed to a rope and allowed to free fall from the surface to the sea floor to generate flow over the fairings. While many of these tests were conducted to determine which fairing afforded the best reduction in flow noise, we learned that none of them satisfactorily reduced flow noise such that it would no longer impact the detection of distant, LF, low-amplitude whale calls. Based on these tests, we concluded that a fairing alone was not going to reduce flow noise adequately, so we developed the hydrophone array described in Sec. II B.

The hydrophone array was used during two long-term deployments (Table I). For one of the deployments, a bare DMON instrument was attached to the wave glider sub to allow comparison to the hydrophone array (see supplementary Fig. S1d).[1] The bare DMON was not mechanically isolated from the sub; therefore, it transduced many more mechanically-generated impulsive noises than the hydrophone array (Fig. 7). Specifically, there were impulsive sounds likely generated by a "catch" in the wings from residual anti-fouling paint or some other cause. These sounds were transmitted mechanically to the bare DMON [Fig. 7(a)], but because rubber mounts were used to attach the hydrophone array to the sub, these sounds were absent in the array audio [Fig. 7(b)]. The use of the 21 hydrophones in the array successfully reduced flow noise relative to the bare DMON (Fig. 7). For the example shown in Fig. 7, the array audio was approximately 14 dB quieter at 105 Hz [Fig. 7(c)]. Theoretically, the maximum reduction in flow noise should be 6.6 dB ($10\log_{10}[\sqrt{21}]$), but the mechanical isolation provided additional noise reduction over the hard-mounted bare DMON. Although the noise was significantly

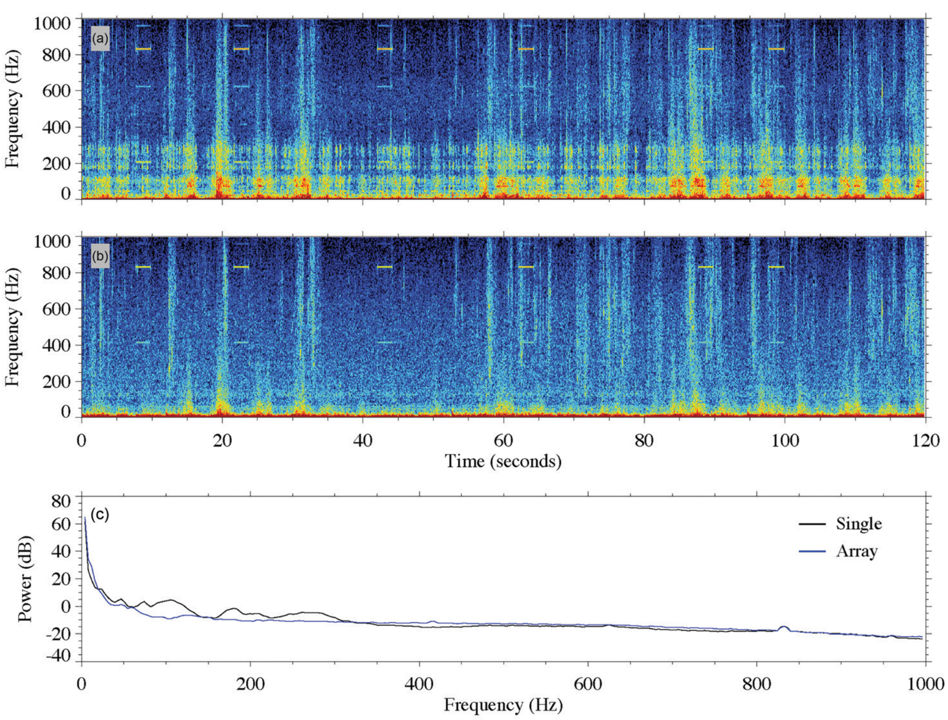

FIG. 7. Spectrograms of simultaneous DMON recordings from (a) a single hydrophone and (b) a 21-element hydrophone array collected during the wave glider deployment on 07/31–10/06/17 (photograph of configuration is in the supplementary Fig. S1d[1]). (c) Average spectra over the 120-s period for the bare single hydrophone (black) and the 21-element hydrophone array (blue). Neither the single hydrophone nor the array were calibrated, so the array spectra were adjusted to match the single hydrophone spectra in the frequency band of a common local source: the rudder noise (833 ± 20 Hz).

reduced for the array, there was still evidence of flow noise, and both the array and the bare DMON recorded a great deal of surface noise.

C. Mitigating surface noise

The baffles we designed produced no noticeable reduction in the surface noise recorded by the DMON during our tests. Baffles are commonly used to absorb or diffract sound for noise or reverberation reduction indoors in air (e.g., in a recording studio). The size of the baffle should be comparable to the wavelength of the sound intended to be reduced, but wavelengths for sounds of a particular frequency are much longer in the ocean than in air owing to the much higher speed of sound in seawater. Therefore, larger baffles are required in water than in air to reduce sounds of the same frequency. For example, noise at 500 Hz has a wavelength of 0.7 m in air (sound speed of 344 m s^{-1}), whereas in seawater, its wavelength is 3 m (sound speed of 1500 m s^{-1}). We suspect our baffles were much too small to effectively diffract 200–1000 Hz surface noise away from the DMON's hydrophone.

D. Evaluation of near real-time estimates of baleen whale occurrence

Most persistent mechanical noises produced by the wave glider were eliminated with the strategic application of PTFE and rubber, although new noises occasionally were detected that were likely produced by small, repetitive impulsive shocks to the sub (e.g., from wings catching as they rotated). Flow noise was reduced, but not eliminated, by the 21-element hydrophone array, and surface noise was not mitigated at all by the inclusion of baffles. While flow, surface, and some mechanical noises remained, detection of LF baleen whale calls was possible in the DMON recorded audio (see supplementary Fig. S2).[1] During a 3+ month deployment in the Gulf of Maine [Table I; Fig. 3(d)], the DMON recorded fin whales (see supplementary Fig. S2a[1]), right whales (supplementary Fig. S2b[1]), and humpback whales (Fig. S2c[1]). Many of these calls were also successfully pitch tracked in real time by the LFDCS and were recognizable when these pitch tracks were transmitted to shore and reviewed in near real time (see Fig. S3[1]). However, noise often interfered with the pitch tracking algorithm as well as confounded the interpretation of the pitch tracks when reviewed by an analyst on shore in near real time.

To evaluate the accuracy of the DMON/LFDCS-equipped wave glider when estimating baleen whale occurrence in near real time, we deployed a wave glider near a DMON/LFDCS-equipped moored buoy during spring 2017 [Fig. 3(c)] and compared the near real-time estimates of baleen whale occurrence between the two platforms. Example spectrograms of audio recorded simultaneously by the moored buoy and the wave glider on April 12, 2017, illustrate the challenges of identifying whale calls from the wave glider in the presence of surface and flow noise (Fig. 8). Despite relatively low wind speeds at the time of the recordings (<10 knots), the shallow depth of the DMON hydrophone array on the wave glider made it susceptible to recording individual breaking waves that interfered with call detection [Fig. 8(b)]. Flow noise still present in the array recording similarly interfered with the identification of LF whale calls [e.g., sei whale calls in Fig. 8(a)]. Comparison of the two platforms suggested that intermittent surface noise was likely 10–20 dB louder than background, while flow noise was 15–35 dB louder than background [75th–95th percentiles in Fig. 8(d)]. Because of these challenges, daily occurrence rates for all species were lower for the wave glider than for the moored buoy (Fig. 9), although the magnitude of this reduction varied by species. For right, sei, and fin whales, daily occurrence rates derived from the wave glider were substantially lower than those from the buoy [Figs. 9(a), 9(c), and 9(d)], whereas much closer agreement between the two platforms was observed for humpback whales [Fig. 9(b)].

There was no correlation between daily occurrence rates derived from the wave glider and the buoy for right whales [Pearson correlation analysis, $p = 0.3042$; Fig. 9(e)]; the missed detection rate for the wave glider when compared directly to the buoy was 85% for right whales, and the estimated best-case missed detection rate for the wave glider after taking into account the buoy's missed detections was 83% (Table II). Daily humpback whale occurrence rates from the wave glider were significantly correlated with those of the buoy [$r^2 = 0.596$, $p < 0.0001$, Fig. 9(f)], while the wave glider missed detection rate relative to the buoy was 26% and the best-case missed detection rate after accounting for the buoy's missed detections was 43% (Table II). Sei whale presence was missed completely by the wave glider until calling activity increased at the end of the evaluation period [Fig. 9(c)]. Daily sei whale occurrence rates from the wave glider were significantly correlated with those of the buoy [$r^2 = 0.695$, $p < 0.0001$, Fig. 9(g)], but the wave glider missed detection rate relative to the buoy was 63% and the best-case missed detection rate after accounting for the buoy's missed detections was 70% (Table II). Finally, there were no near real-time detections of fin whales from the wave glider at all, whereas the buoy reported the presence of fin whales on several days [Fig. 9(d)]; accordingly, no correlation analysis could be conducted [Fig. 9(h)] and both observed and estimated best-case missed detection rates were 100% (Table II).

IV. DISCUSSION

The integration of the DMON/LFDCS with the Liquid Robotics wave glider allowed the detection of baleen whales in near real time; however, outstanding issues with surface and flow noise remain to be resolved before the system could be used reliably and operationally to monitor the occurrence of whales that produce LF sounds. The platform is clearly capable of long-endurance missions. We found that wear in the tether bushings limited the endurance of the vehicle to three to four months. If recovered before

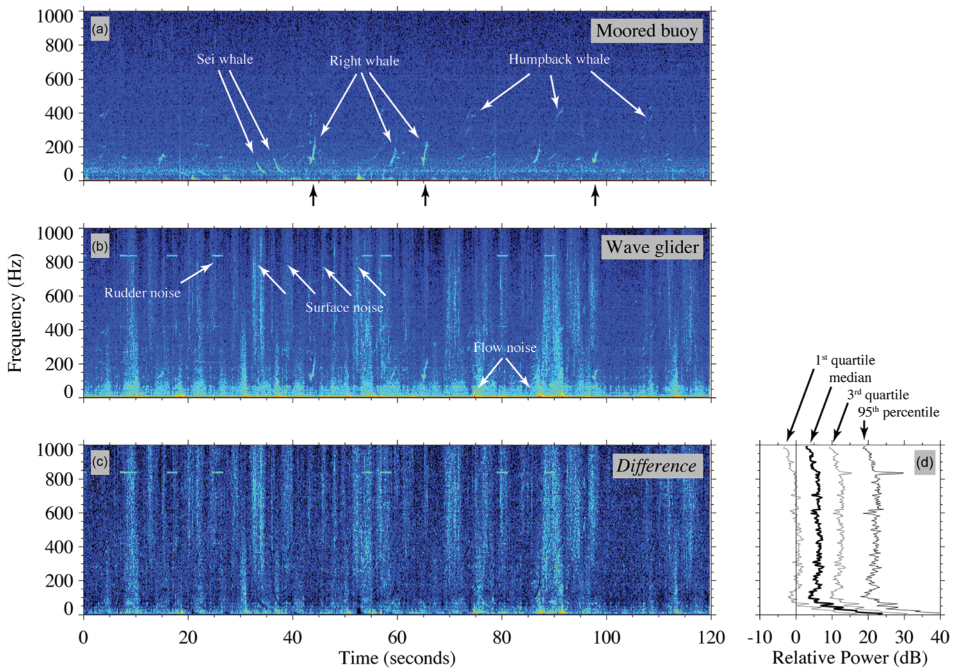

FIG. 8. (a) and (b) Spectrograms of audio recorded simultaneously at roughly the same location by (a) a DMON mounted near the sea floor (DMON at 34 m in 35 m water depth) and (b) a wave glider equipped with a DMON and an attached hydrophone array suspended at 7 m depth. The wave glider circled the moored DMON at a nominal distance of 300 m [Fig. 3(c), inset], and the wind speed was approximately 8 knots at the time of these recordings as measured at a meteorological station 15.5 miles to the north of the moored DMON. Note that the surface and flow noise in (b) mask many (but not all) of the whale sounds. (c) Spectrogram (power in dB) of moored buoy audio in (a) subtracted from the spectrogram (power in dB) of wave glider audio in (b). Since the hydrophones were not calibrated, the spectrograms were intercalibrated by making the relative power in each spectrogram equal for the three right whale calls indicated by arrows in (a); while received levels can differ because of receiver depth alone (7 vs 34 m), propagation modeling (not shown) suggested that these differences were quite small (a few dB). (d) Distribution of differences shown in (c) with frequency.

four months, these inexpensive bushings could be easily replaced, but after three to four months the bushings would no longer protect the tether termination from metal-to-metal contact and the tether would begin to wear. Replacing the tether is very expensive. Biofouling does occur on the vehicle, but this was mitigated with anti-fouling paint and did not limit the vehicle's endurance. We found the transit speeds of the wave glider to be sufficient to successfully navigate it in areas with strong currents, including in strong tidal currents within certain regions of the Gulf of Maine. For long-duration missions, we were able to navigate the wave glider to within 15 miles of our home port in Woods Hole, Massachusetts, for recovery (Fig. 3).

We had success in quieting many of the noises produced by the wave glider by lubricating moving parts with PTFE, adding rubber padding to decelerate moving parts, or re-engineering some wave glider components (e.g., tether mount). The use of underwater video was extremely helpful in identifying noise sources, as was suspending the sub in air and manipulating different moving parts. The sub frame acts as a resonator for many impulsive shocks, so even small sound sources, such as the wing "catches," can be acoustically amplified and (or) transmitted mechanically to the DMON hydrophone(s). Isolation of the hydrophone(s) from the sub using shock mounts (open cell foam, rubber isolators) was critical to reducing or eliminating these impulsive noises. Flow noise was a persistent problem that was improved measurably by the use of a 21-element hydrophone array, but was not eliminated altogether. Finally, surface noise was also a persistent problem for which our solution of baffles was not successful.

Whales could be identified from pitch tracks transmitted in near real time from the wave glider (Fig. 9, see also supplementary Fig. S3[1]), but calls were often missed for several reasons. First, noise obscured calls to the extent that either they were not detectable (e.g., Fig. 8) or the resulting pitch tracks did not faithfully represent the true frequency and amplitude modulation of the calls. Second, after pitch tracks were transmitted to shore, pitch tracks of noise confounded the assessment of context (defined as the sounds that are in temporal proximity to a sound of interest) that an analyst relies on to accurately identify a species' calls (e.g., Fig. S3[1]). Third, pitch tracks of noise often caused the DMON/LFDCS to reach its 8 kB per hour limit of pitch track data in only a few minutes, thus severely limiting the system's monitoring time (once this limit is reached, no pitch track data is sent to shore until the start of the next hour of monitoring). Monitoring was most effective when environmental conditions helped to reduce both flow and surface noise, such as during very calm weather, but these conditions are uncommon in all but summer off the northeast United States.

The comparison of near real-time occurrence estimates from the wave glider and moored buoy allowed us to characterize the extent to which calls were missed in near real time by the wave glider. Over daily time scales, Baumgartner

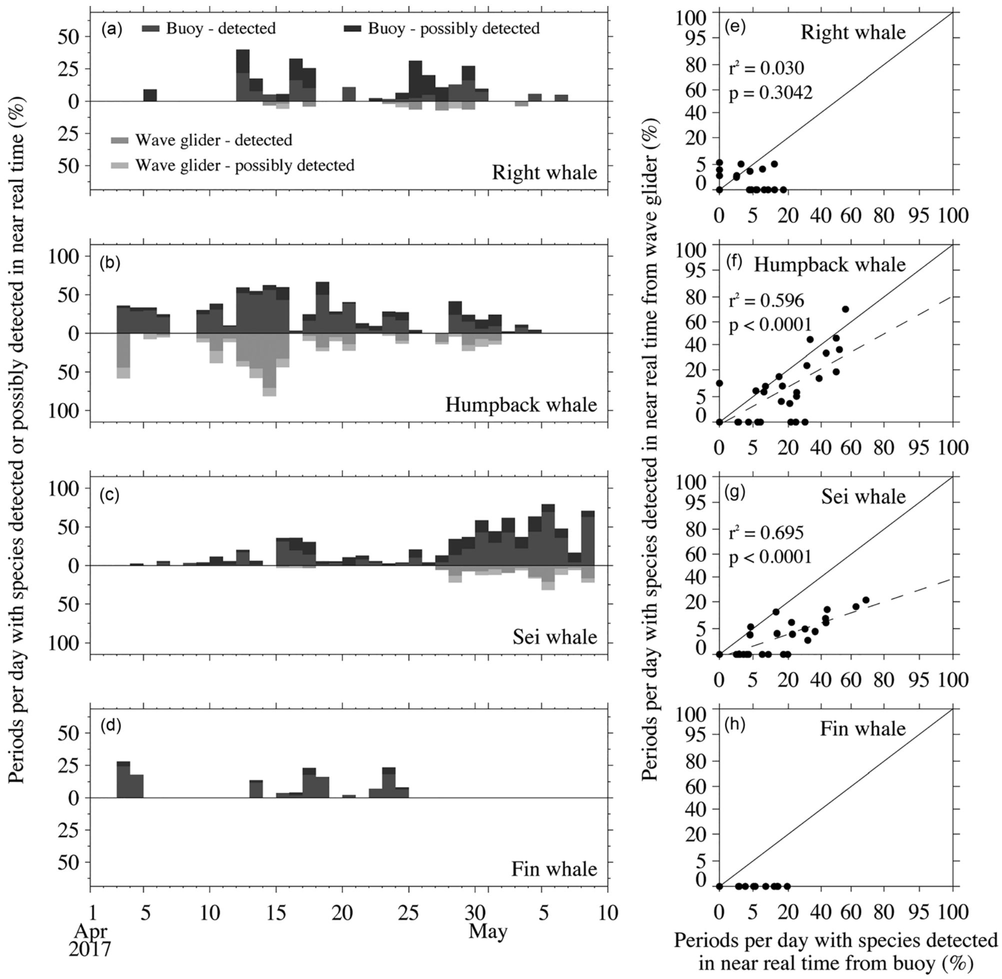

FIG. 9. Comparison of near real-time whale occurrence estimates from the collocated DMON-equipped moored buoy and a DMON-equipped wave glider for (a) right, (b) humpback, (c) sei, and (d) fin whales. Detections and possible detections are shown for both platforms. Scatterplots of daily detection rates for (e) right, (f) humpback, (g) sei, and (h) fin whales. Coefficients of determination (r^2) and associated p-values are shown as well as a 1:1 line (solid) and simple linear regression line (dashed).

et al. (2019) found that the moored buoy had 0% false occurrence rates, but modest missed detection rates of 27%, 37%, 42%, and 12% for right, humpback, sei, and fin whales, respectively. For the wave glider, we estimated that the daily missed detection rates were at least 84%, 43%, 70%, and 100% for right, humpback, sei, and fin whales, respectively (Table II). The wave glider's estimated best-case missed detection rates for right, sei, and fin whales were substantially higher than the buoy, whereas the humpback whale estimated best-case missed detection rate was much closer to the buoy (albeit with the assumption of a wave glider false detection rate of 0%). Better agreement between the two platforms for humpback whales was observed because many humpback whale calls (but not all) are generally higher in frequency than the other species (and therefore not affected by flow noise) and occur in patterns called song that are easier to identify among noise (Payne and McVay, 1971; Clark and Clapham, 2004; Vu *et al.*, 2012). Because of the high missed occurrence rate of the system, we do not believe the wave glider as configured in our study is acceptable for operational near real-time monitoring applications. Further work is needed to reduce flow and surface noise.

Both Bingham *et al.* (2012) and Darling *et al.* (2019) describe archival passive acoustic monitoring for humpback whales from wave gliders in central Pacific waters. Like the present study, both of these studies successfully recorded humpback whales. Bingham *et al.* (2012) used measured noise characteristics and humpback whale detections to suggest that the wave glider is suitable for passive acoustic monitoring of marine mammals, but their evaluation dataset was short (6 days) and collected in calm conditions (average wind speeds of less than 10 knots). Darling *et al.* (2019) recorded humpback whales from a wave glider, but noted that self-noise precluded the use of automated detectors to aid in the review of the audio. Spectrograms presented by Darling *et al.* (2019; see their Fig. 2) appear to illustrate the same noise issues described in our study. While manual review of archival recordings collected by wave gliders is possible *via* viewing spectrograms and listening to audio (as in Darling *et al.*, 2019), the persistent presence of noise complicates the review and can fatigue the analyst, which in

TABLE II. Confusion matrices comparing near real-time analyses for the moored buoy and wave glider for right, humpback, sei, and fin whales over daily time scales for 37 days. The variables m_{buoy} and f_{buoy} indicate the missed and false detection rates for the buoy, respectively, and m_{wg} and f_{wg} indicate the missed and false detection rates for the wave glider, respectively. For each species, the first confusion matrix (labeled "Near real-time buoy analysis") shows the observed performance of the wave glider versus the buoy; if the buoy's performance was perfect (i.e., $m_{\text{buoy}} = 0\%$ and $f_{\text{buoy}} = 0\%$), then this confusion matrix can be used to compute m_{wg}. Since the buoy's actual performance was not perfect, the second confusion matrix (labeled "Whale presence") evaluates the wave glider's performance against the expected whale presence if the buoy had the missed and false detection rates observed in Baumgartner *et al.* (2019) and the wave glider's false detection rate (f_{wg}) was 0%. Equations to derive the second confusion matrix from the first are shown in Fig. 4.

		Near real-time buoy analysis		*Whale presence*	
	Near real-time wave glider analysis	Detected	Not detected	Acoustically present[a]	Not acoustically present
Right whale	Detected	2	1	3	0
	Not detected	11	23	15	19
$m_{wg} = 84.6\%$ if buoy is perfect; for $m_{\text{buoy}} = 26.9\%$, $f_{\text{buoy}} = 0\%$ and $f_{wg} = 0\%$, then $m_{wg} = 83.3\%$					
Humpback whale	Detected	20	1	21	0
	Not detected	7	9	16	0
$m_{wg} = 25.9\%$ if buoy is perfect; for $m_{\text{buoy}} = 27.0\%$[b], $f_{\text{buoy}} = 0\%$ and $f_{wg} = 0\%$, then $m_{wg} = 43.2\%$					
Sei whale	Detected	11	0	11	0
	Not detected	19	7	26	0
$m_{wg} = 63.3\%$ if buoy is perfect; for $m_{\text{buoy}} = 18.9\%$[b], $f_{\text{buoy}} = 0\%$ and $f_{wg} = 0\%$, then $m_{wg} = 70.3\%$					
Fin whale	Detected	0	0	0	0
	Not detected	6	31	7	30
$m_{wg} = 100.0\%$ if buoy is perfect; for $m_{\text{buoy}} = 11.6\%$, $f_{\text{buoy}} = 0\%$ and $f_{wg} = 0\%$, then $m_{wg} = 100.0\%$					

[a]Acoustically present is defined as one or more whales that are present and making detectable sounds over the course of 1 day (i.e., the whales are available to be detected by the buoy and wave glider).
[b]The observed m_{buoy} from Baumgartner *et al.* (2019) is larger than what was used here. Using the observed m_{buoy} resulted in whales being present for more than 37 days. m_{buoy} was computed such that the total number of days whales were acoustically present equaled 37 days.

turn increases the chances of missed detections (e.g., Fig. 8). Neither the Bingham *et al.* (2012) study nor the Darling *et al.* (2019) study assessed missed detections, so while both demonstrate that humpback whale detection is possible, it is not clear from these studies if noise issues cause so many missed detections as to make the platform inappropriate for scientific or management applications.

The use of the hydrophone array to reduce the effects of flow noise on the DMON audio shows significant promise. We did not conduct an exhaustive hydrodynamic study of how many hydrophones are needed and what the ideal spacing of the hydrophones should be, as the flow field around the sub is undoubtedly complicated. We suspect that a design with additional hydrophones that are configured to be mostly omnidirectional at frequencies below 1000 Hz when combined together would further improve reductions in flow noise. Surface noise is more challenging to address; we can think of three possible approaches. The first involves further exploration of a sub-mounted baffle design that can diffract sound emanating from the surface away from the hydrophone(s). This baffle will likely be very large to allow diffraction of frequencies as low as 200 Hz, and therefore may impede the propulsion mechanism of the wave glider. The second approach is to extend the wave glider tether so that the sub is deeper in the water column and further from the surface. Our 7-m tether was clearly too short to mitigate surface noise. While longer tethers are available, there is a limit to how long the tether can be because of its drag on the wave glider; Liquid Robotics has produced 20-m tethers in the past that could be tested for passive acoustic monitoring. The third approach is to tow a hydrophone from the sub with an appropriate depressor weight to sink the hydrophone(s) to a depth sufficiently far from the surface. Towed hydrophones have their own challenges, including strum noise from the tow cable, wrapping around the sub and tether in storms, and getting entangled in fixed fishing gear.

The lessons we learned while incorporating a near real-time passive acoustic monitoring capability in the wave glider are applicable to any ASV. Autonomous sailing vessels like the Saildrone or Datmaran do not have a component of the vehicle that is submerged in the same manner as the wave glider's sub, so the only way to mitigate surface noise is by towing a hydrophone. Based on our experience, attaching a hydrophone directly to the hull will result in unacceptable levels of surface noise, rendering the audio unusable for whale detection except in the calmest of conditions. Like the wave glider, autonomous sailing vessels move fast (faster than the wave glider), so flow noise will be a similar (or bigger) challenge. Until high-volume data transmissions are feasible for autonomous platforms, audio must be processed on board the autonomous platform rather than transmitted to shore in order to detect and characterize sounds. Both surface and flow noise pose serious challenges to this processing, and therefore must be mitigated to allow reliable and accurate detection in nearly all weather conditions. While ASVs have great promise as survey platforms, additional research and development is required before they are capable of reliable real-time or near real-time passive acoustic detection of the LF calls produced by baleen whales.

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[1]See supplementary materials at https://www.scitation.org/doi/suppl/10.1121/10.0004817 for photographs of wave glider as configured for the long-duration missions, as well as example spectrograms and pitch tracks for fin, right, and humpback whale calls detected from a wave glider.

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