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TELEMETRY CASE REPORT

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Factors affecting detection efficiency of mobile telemetry Slocum gliders

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Abstract

Background: Acoustic biotelemetry sensors have been fully integrated into a broad range of mobile autonomous platforms; however, estimates of detection efficiency in different environmental conditions are rare. Here, we examined the role of environmental and vehicle factors influencing detection range for two common acoustic receivers, the VEMCO mobile transceiver (VMT) and a VEMCO cabled receiver (VR2c) aboard a Teledyne Slocum glider. We used two gliders, one as a mobile transmitting glider and one as a mobile receiving glider during the fall in the mid-Atlantic coastal region.

Results: We found distance between gliders, water depth, and wind speed were the most important factors influencing the detection efficiency of the VMT and the VR2c receivers. Vehicle attitude and orientation had minimal impacts on detection efficiency for both the VMT and VR2c receivers, suggesting that the flight characteristics of the Slocum glider do not inhibit the detection efficiency of these systems. The distance for 20% detection efficiency was approximately 0.4 and 0.6 km for the VMT and VR2c, respectively. The VR2c receivers had significantly lower detection efficiencies than the VMT receiver at distances <0.1 km, but higher detection efficiencies than the VMT at distances >0.1 km.

Conclusions: Slocum gliders are effective biotelemetry assets that serve as sentinels along important animal migration corridors. These gliders can help elucidate the relationships between telemetered organisms and in situ habitat. Therefore, estimating the detection ranges of these common telemetry instruments provides an important metric for understanding the spatial scales appropriate for habitat selection inferences.

Keywords: Slocum glider, VMT, VR2c, Range test, VEMCO, Acoustic telemetry

Background

Acoustic biotelemetry is commonly used to monitor the presence and movement of organisms in aquatic environments [1], supporting both regional and international conservation efforts [2]. Location information for acoustic biotelemetry observations is tied to the location of the receiver and its detection range. The detection range of acoustic receivers depends on in situ listening conditions, which are linked to environmental conditions. Tides, currents, winds, stratification, and listening array configuration can impact detection efficiency, thus impacting the study of the presence and movement of organisms using acoustic biotelemetry [3–5].

The issue of acoustic range is further complicated by the use of telemetered autonomous underwater vehicles (AUVs) and other mobile platforms that transit different listening environments. While AUVs often measure environmental conditions that could impact listening conditions [6], moving platforms and dynamic environments create new range of testing challenges. One solution to this challenge is near-real-time triangulation of the acoustic signal using a combination synthetic aperture and known test tag locations [7]. Another solution is using a combination of stereo receivers and near-real-time particle filtering [8], and multiple AUVs to geolocate the acoustic tag on meter scales [9]. These approaches

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can be highly effective for geolocating acoustic signals, but require high-performance, propeller-driven AUVs that are able to precisely control their positions in the water. However, because these propellered AUVs require more energy to operate, they are limited to relatively short deployments due to battery life (<2 days). These propelled platforms are not designed to conduct continuous long-term searches, listening for telemetry signals of dispersed animals.

Observations of acoustically telemetered animals can be infrequent in the ocean environment; therefore, low-power AUVs such as Slocum and wave gliders can play the supporting role of environmental sentinel, targeting ocean features and discovering new areas used by telemetered organisms outside of fixed acoustic arrays with missions that last weeks to months [10–14]. Gliders are easily outfitted with externally mounted, self-contained VEMCO mobile transceivers (VMT) [10, 15], or with vehicle-integrated VEMCO cabled receivers (VR2c) [11, 14]. Critical to their sentinel role is the ability to associate in situ environmental data with acoustic detections, allowing inferences to be made about habitat associations [11]. However, this requires estimates of the range of acoustic detections over the large spatial scales (hundreds of km) covered by these long-lived AUV missions, which is difficult to obtain with moored test tags. In this study, we estimate the detection range of an integrated VR2c and externally mounted VMT on Slocum gliders during the fall along the mid-Atlantic Bight. We used a combination of vehicle attitude, in situ oceanographic data and meteorological observations from nearby NOAA buoys to determine which factors affected the detection efficiency of these common telemetry systems.

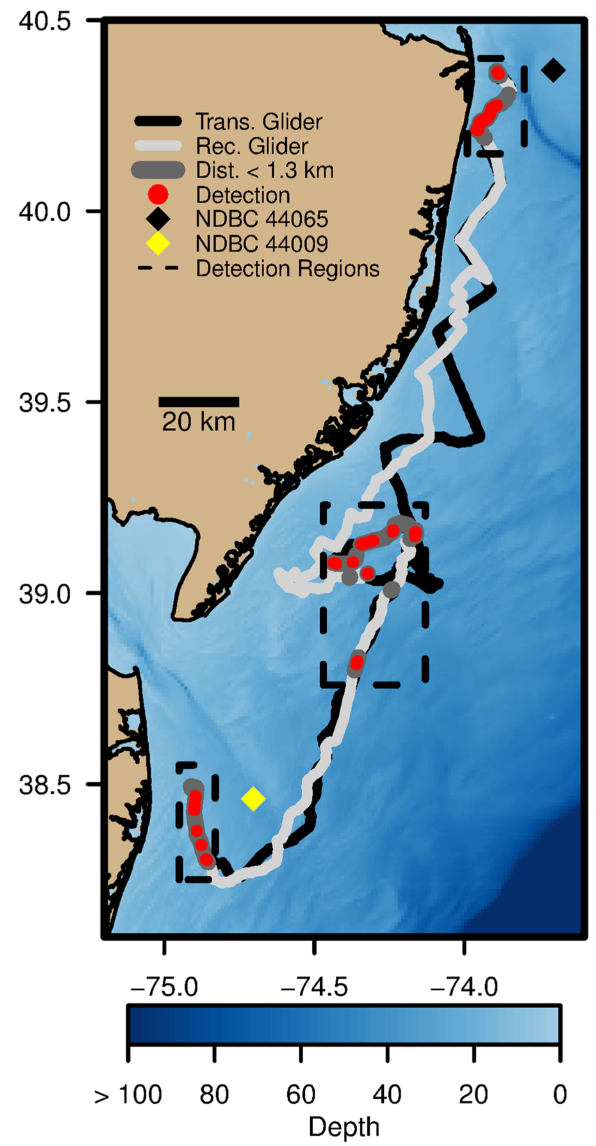

Fig. 1 Paths of the transmitting and receiving glider along New Jersey, Delaware, and Maryland coasts. The gliders transited very similar paths, but were not always close together. *Dark gray regions* indicate when the gliders were within 1.3 km of each other within study boxes, and *red dots* indicate when the receiving glider detected the transmitting glider. *The diamonds* are the location of NDBC buoys used to determine wind speeds. *Dashed boxes* indicate the three regions the receiving glider detected the transmitting glider

Methods

Glider deployments

Slocum gliders are buoyancy-driven vehicles that dive and climb at a nominal 26° angle and travel in a vertical "sawtooth" pattern between predetermined surface events [16]. While the glider is underway, it collects vertical profiles of physical (temperature, salinity), chemical (oxygen), and biological properties (chlorophyll-*a* fluorescence). Two Slocum gliders (Teledyne Webb Research) were deployed off of Sandy Hook, New Jersey, USA, on September 17, 2015, and were recovered off the coast of Delaware, USA, on October 7, 2015 (Fig. 1). For this 20-day mission in the mid-Atlantic coastal ocean, one glider (transmitting glider) was equipped with an externally mounted VEMCO mobile transceiver (VMT, VEMCO Ltd.) programmed to transmit coded acoustic signals (69 kHz, 156 dB) [10]. The second glider (receiving glider) was equipped with an externally mounted VMT programmed to only receive coded acoustic signals, and two hull integrated (1 top and 1 bottom) VEMCO VR2c acoustic receivers [11]. The hydrophones of the integrated VR2c's were normal to the major axis of the glider (pointed upward and downward), while the VMT hydrophone was mounted facing forward, and along the major axis of the glider (Fig. 2). The gliders record vehicle pitch, roll, depth, heading, and total water depth at

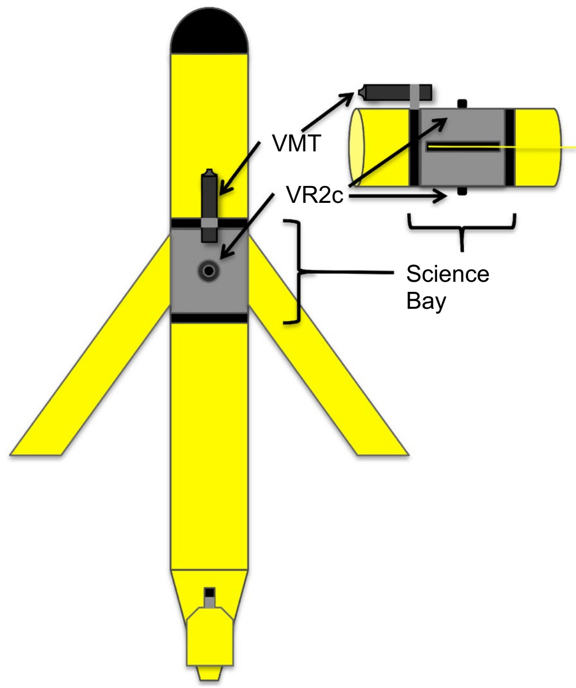

Fig. 2 The mounting orientation of the VMT and VR2c's on the receiving glider from the dorsal (*left*) and the lateral (*right*) view. Two VR2c's are integrated into the central science bay, one pointing up and the other down. The VMT was mounted in a bracket forward of the top VR2c, with its receiver pointing toward the nose of the glider. The transmitting glider had a VMT mounted in a same way

1 Hz throughout the mission. The gliders also estimate depth integrated water currents between surface events by comparing surface GPS locations with dead-reckoning subsurface navigation. The transmitting glider's primary mission objective was to measure full water column dissolved oxygen in the coastal ocean. The receiving glider, deployed at the same time and location, was testing an automated glider path-planning tool. Given these primary objectives, these gliders also served as mobile platforms of opportunity to test the influence of environmental and vehicle factors on acoustic signal detection in the mid-Atlantic coastal ocean. The receiving glider was within 1.3 km (the longest distance of detection between gliders) of the transmitting glider during three distinct time periods, each with different environmental conditions (Fig. 3).

Environmental and vehicle predictors of detection efficiency

The VMT mounted on the transmitting glider was scheduled to transmit a coded acoustic signal at 69 kHz (156 dB) on average every 110 s (range 70–150 s). We hypothesized that reception of coded acoustic signals by either the VMT or integrated VR2c's on the receiving glider would be affected by the distance between gliders, depth of the water, wind speed, current speed, depth of the receiving glider, water column density, pitch and roll of the receiving glider, and the bearing of the transmitting glider to the receiving glider. We computed the distance between the gliders using the rdist.earth function in the fields R package [17]. We used wind speeds measured at NDBC buoys 44065 and 44009 as proxies for wind speeds at the glider locations (Fig. 1). The wind records at these buoys are different, but strongly correlated ($r = 0.81$) (Fig. 3a). We used wind speed from NDBC 44065 as a proxy for wind speed for the northernmost region where the receiving glider was detecting the transmitting glider, and NDBC 44009 for the middle and southernmost regions. We derived water density using the equation of state (temperature, salinity, pressure) measured by each glider [18]. We estimated water column stratification by differencing surface and bottom density. We eliminated predictors that were highly collinear ($|r| > 0.7$). For example, depth of the glider was highly correlated to the altitude of the glider from the bottom because the gliders were in relatively similar depths throughout the mission. Also, the relative depths of the transmitting gliders were not considered because the vertical depth differences were only 2% (max of 30 m) of the horizontal depth differences of detection (up to 1.3 km).

Generalized additive mixed model analyses

To test which predictor variables influenced detection efficiency, we used a generalized additive mixed model (GAMM) framework in the R gamm4 package [19]. A GAMM sums smoother functions (penalized regression splines) to model the binomial presence/absence of telemetry detections compared to the expected number of detections from the transmitting glider. We implemented penalized shrinkage smoothers as an automatic alternative to model selection of environmental predictors. Shrinkage smoothers incorporate a penalty, which may shrink all of the coefficients to zero, effectively penalizing the variable out of the model [20]. We used penalized thin plate regression splines (ts) for non-cyclic predictors and penalized cubic regression splines for cyclic predictors (cc) using the mgcv package in R. We limited the number of knots for each smooth variable in our model to five to prevent overfitting. Model analysis was limited to mission times when the transmitting glider was within 1.3 km of the receiving glider. This was the furthest distance the receiving glider detected the transmitting glider. The receiving and transmitting gliders were within 1.3 km in three distinct regions (northern NJ, southern NJ, and Delaware coasts) (Fig. 1). Therefore, we added these locations as random effects to account for unknown differences inherent to these three locations that are otherwise unaccounted for in our analysis. Finally, we used fivefold cross-validation on these models to determine if the model was

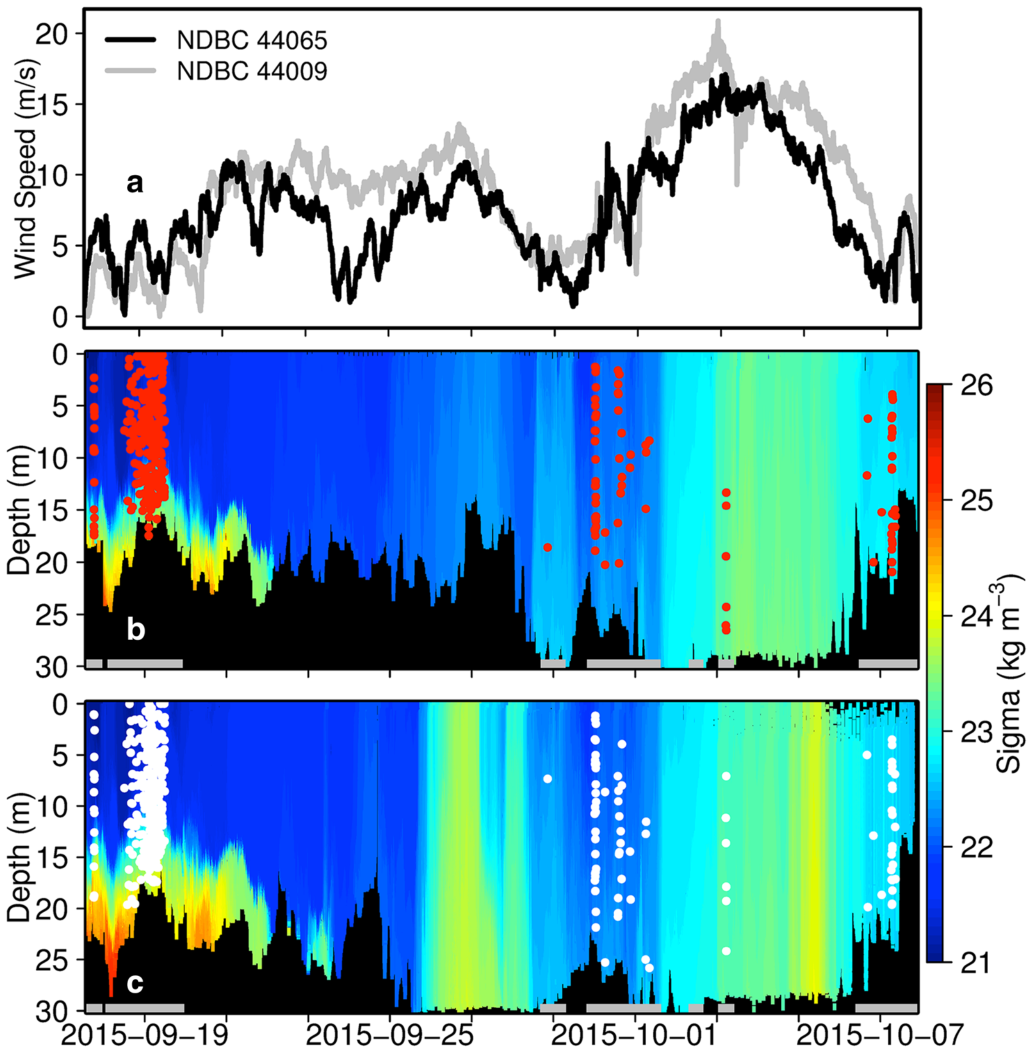

Fig. 3 **a** Wind velocities at the NDBC buoys during the deployment. Sigma (density-1000) cross section of the receiving (**b**) and transmitting (**c**) glider. *Points* indicate the depth of the receiving glider (*red*) and transmitting glider (*white*) when detections were recorded. *Gray bars* indicate when the gliders were within 1.3 km of each other

overfit and to test the performance of the model without each fold of data. This was done by splitting the data randomly into five subsets, reiteratively fitting the model to four of the five subsets (training dataset), and then predicting on the remaining subset (test dataset) to verify the robustness of the models [21]. We estimated the relative predictor importance of these cross-validated models using the BIOMOD2 package [22, 23].

Results

Environmental conditions

The transmitting and receiving gliders made similar, but not identical southward paths starting in coastal NJ waters and ending in DE waters (Fig. 1). These gliders encountered three prolonged wind events >10 m s^{-1} (Fig. 3a), presumably changing the subsurface noise conditions [3]. Stratification of the water column is most pronounced early in the mission, with up to a 4 sigma (4 kg m^{-3}) difference in density between surface and bottom waters. Data collected by the receiving (Fig. 3b) and transmitting (Fig. 3c) gliders show the erosion of the pycnocline and a general increase in density due to cooling over the study period. This erosion of the strong summer pycnocline is well known in this region as a result of seasonal cooling and storm activity [24].

Acoustic detections

The two gliders were within 1.3 km of each other for 90.7 h and got as close as 15 m. Within this distance range, the transmitting glider emitted 2177 coded acoustic signals. The VMT receiver successfully decoded 124 detections (5.6%) of the transmitting glider. The top integrated VR2c receiver decoded 188 detections (8.6%), while the bottom integrated VR2c receiver decoded 175 detections (8.0%). Forty-eight of the transmissions were detected by both the top and bottom integrated VR2c receivers. Treating the integrated VR2c receivers as a single receiving apparatus, removing double detection counts, the integrated VR2c receivers recorded 264 detections (12.1%) of the transmitting glider. There were six other tags detected during this experiment; however, these detections were not intermingled with the detections of the transmitting glider. Therefore, we believe that false-positive detections are not a major factor in this study.

Detection efficiency for the VMT receiver was highest when the distance to the transmitting glider was <0.1 km and decreased with distance (Fig. 4). At distances >0.4 km, VMT receiver detections were sparse. In contrast, the integrated VR2c receivers performed poorly at distances <0.1 km, but were comparable to or better than the VMT at the further distances. Peak detection efficiencies for the integrated VR2c receivers were at 0.2–0.3 km, but dropped markedly past 0.6 km. The low detection efficiencies at distances <0.1 km by the integrated VR2c receivers are likely a result of close proximity detection interference, where the power of the transmission (156 dB in our case) overwhelms the hydrophone and is known to occur in these systems. These detection efficiency patterns create different expectations for the distance of a received transmission by these two sensors known as the "doughnut effect" (Fig. 4) [25]. The integrated VR2c's have a much larger detection area, which scales with the square of the distance between the transmitter and receiver.

Environmental and vehicle attitude predictors of detections

GAMMs were developed for predicting both VMT and integrated VR2c detections using penalized smoothers for continuous predictors. We observed strong stratification during the first glider encounter, but the water column was thoroughly mixed for the rest of the experiment. Models predicting the presence/absence of detections on the VMT and the integrated VR2c receivers (Table 1) had AUC values of 0.96 and 0.89, respectively, indicating good model performance. Fivefold cross-validation of these models had AUC values of 0.95 and 0.89 indicating that these models were not overfit. Variable importance for these models followed similar patterns for the VMT and the integrated VR2c's (Fig. 5). Distance between gliders was the most important predictor of detections for both the VMT (54.2%) receiver and the integrated VR2c (69.6%) receivers (Fig. 5). Wind speed (19.0%) and water depth (15.3%) were similarly important for predicting detections on the VMT receiver; however water depth (16.5%) was more important than wind speed (4.4%) for

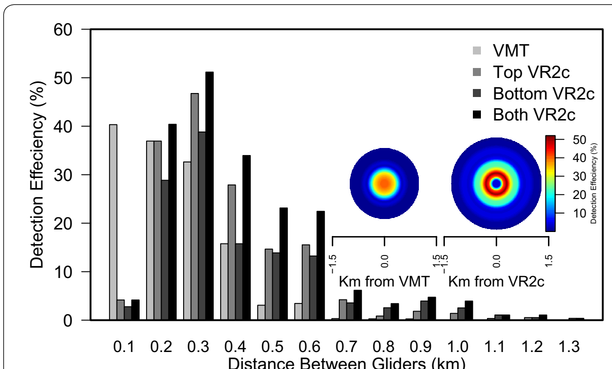

Fig. 4 Detection efficiency of the VMT and integrated VR2c receivers on the receiving glider at distance bins away from the transmitting glider. *The figure inset* is a visual aid for the circular distribution of detection efficiency for the VMT and both integrated VR2c receivers, illustrating the "doughnut effect" [25]

Table 1 GAMMs evaluated to predict the likelihood of acoustic transmission detection by a VMT and integrated VR2c receivers based on environmental conditions

	GAMMs (binomial, knots = 5, penalized smoothers)	Adj. R^2	AIC	AUC
VMT	VMT ~ s(Dist.) + s(Wind) + s(W. Depth) + s(Cur.) + s(Strat.) + s(Bearing) + s(Depth) + s(Pitch) + s(Roll) + s(Den.) + 1| Region	0.385	473.9	0.96
VR2c	VR2c ~ s(Dist.) + s(Wind) + s(W. Depth) + s(Cur.) + s(Strat.) + s(Bearing) + s(Depth) + s(Pitch) + s(Roll) + s(Den.) + 1| Region	0.277	1090.6	0.89

Dist. is the distance between gliders, Wind is wind speed from the nearest NDBC buoy, W. Depth is the depth of the water estimated by the receiving glider altimeter, Density is the density of the sea water measured by the receiving glider, Strat. is the difference between surface and bottom densities measured by the receiving glider, Cur. is the glider estimated depth integrated currents, Depth is the depth of the receiving glider, Pitch is the angle of descent of the receiving glider, Bearing is the bearing of the transmitting glider in relation to the receiving glider, Roll is the roll of the receiving glider, and Region refers to the three major geographic areas where detections occurred in Fig. 1

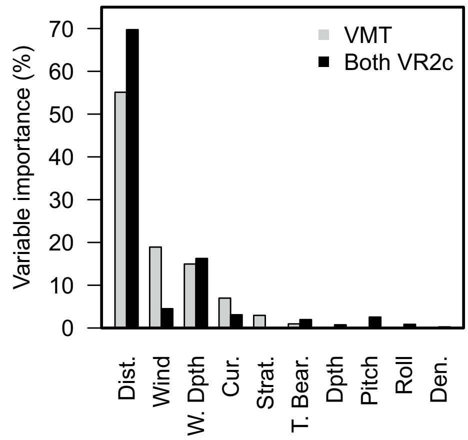

Fig. 5 The relative importance of environmental and vehicle attitude predictors affecting acoustic detections. See Fig. 1 caption for variable abbreviations

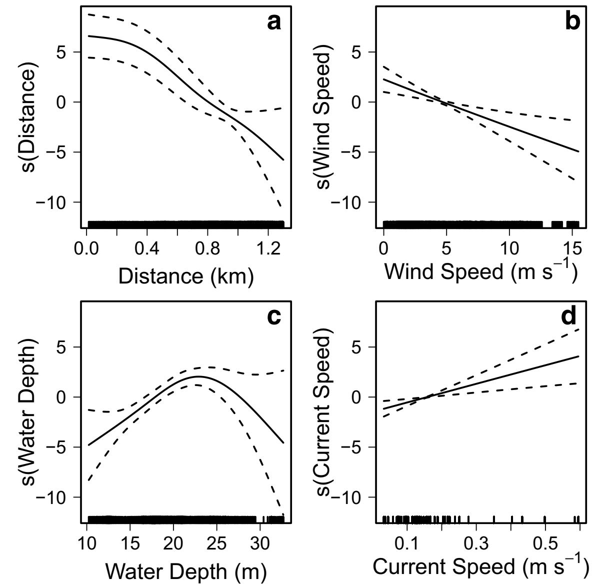

Fig. 6 VMT model response functions of the four most important variables (**a** Distance between gliders, **b** Wind speed, **c** Water depth, **d** Current speed) affecting likelihood of detections on VMT receiver. *Dashed lines* indicate confidence intervals, and *rug plots* indicate observations. *Positive values* indicate conditions that enhance detection efficiency, and *negative values* indicate conditions that suppress detection efficiency

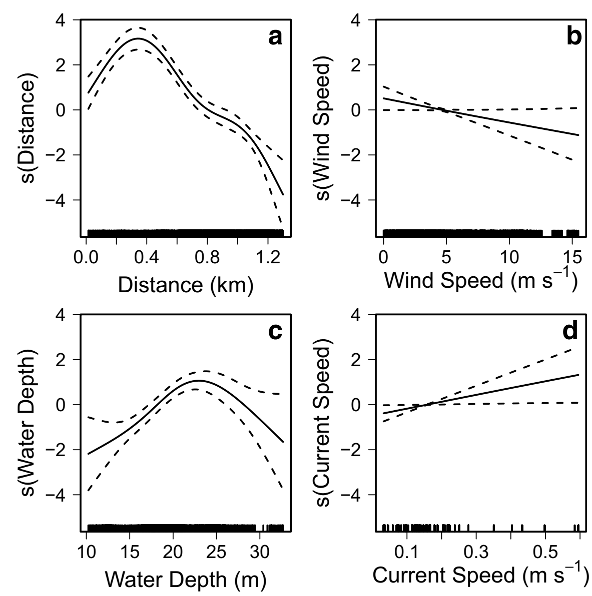

Fig. 7 Model 4 response functions of the four most important variables (**a** Distance between gliders, **b** Wind speed, **c** Water depth, **d** Current speed) affecting likelihood of detection on integrated VR2c receivers. *Dashed lines* indicate confidence intervals, and *rug plots* indicate observations. *Positive values* indicate conditions that enhance detection efficiency, and *negative values* indicate conditions that suppress detection efficiency

the VR2c model (Fig. 5). Current speed (7.5, 3.1%) was somewhat important for both models, with the rest of the predictors, including vehicle attitude, having less than 3% importance (Fig. 5). Distance, wind speed, water depth, current speed, stratification, and target bearing were significant ($p < 0.05$) predictors of VMT detections (Additional file 1: Table S1). For the integrated VR2c's all predictors were significant except for stratification, AUV depth, and water density (Additional file 1: Table S2).

The response curves of the four most important predictors of detections by the VMT (Fig. 6) and the integrated VR2c's (Fig. 7) exhibit different responses for these two acoustic telemetry systems, especially with respect to distance between the gliders. VMT model predictors showed the expected decline in detection likelihood as distance between the gliders increased (Fig. 6a); however, the VR2c model did not illustrate the same monotonic decline (Fig. 7a). Instead, the response curve showed that the VR2c's were not as effective at very close distances, similar to the results in Fig. 4. Both the VMT receiver and integrated VR2c receivers performed better at low wind speeds, indicating that noise generated by windy conditions might affect detection efficiency (Figs. 6b, 7b). However, confidence intervals around the partial residual plot of the effect of wind on detection efficiency for the VR2c receivers always encompass zero, and therefore, there is low confidence in this relationship. Both the VMT receiver and integrated VR2c receivers performed better as water depth increased; however, deeper than 20 m, the standard error estimates of the response curves increase substantially, making judgments about the response curve in deeper waters difficult (Fig. 6b). This is likely because only 2.5% of our observations were in waters deeper than 30 m, increasing the spread of the confidence intervals. In addition, the confidence intervals for the effect of current speeds on the detection efficiency of VR2c receivers always included zero, making interpretation of the effects inconclusive (Fig. 7d). Water column stratification played a statistically significant but minor role in VMT detections (Fig. 5; Additional file 2, Additional file 1: Table S1). Stronger stratification reduced the likelihood of VMT detection; however, the confidence intervals include zero, making it difficult to interpret the stratification effect. Vehicle attitude parameters in general were nonsignificant predictors of detection efficiency for the VMT, with the exception of the effect of target bearing being weak but significant (Additional file 1: Table S1). For the integrated VR2c's, vehicle roll, pitch, and target bearing were statistically significant, but weak predictors of detection efficiency (Fig. 5; Additional file 3, Additional file 1: Table S2).

Discussion

The major predictors of detection efficiency for both receiver assets were distance between transmitter and receiver, wind, and water depth (Fig. 5). This is generally in line with previous studies [3–5]. We suspect more studies are necessary during highly stratified periods to estimate the full impact of a stratified water column on acoustic detection efficiency, as stratification played only a minor role in detection efficiency for the VMT. Increased wind speeds decreased detection efficiency for the VMT and VR2c (Figs. 5b, 6b); however, the effect was more pronounced with the VMT. Wind stress has been shown to decrease detection efficiencies of VMTs [26]; however, we do not know why the VR2c appears to be less sensitive to wind in this study. Encouragingly, vehicle attitude and sensor orientation seemed to play a minor role in detection efficiency, indicating that Slocum gliders can play an important role in biotelemetry studies without major concerns of orientation affecting detection efficiency. The effect of target bearing is probably related to the orientation and position of the mounted receivers (Fig. 2). As a result, the VMT receiver had slightly higher detection efficiency when the bearing of transmitting glider was not near 180° (behind the receiving glider). The VMT was mounted slightly forward of the top integrated VR2c receiver, which may have caused some signal blocking from the transmitting glider. For example, the detection efficiency of the integrated VR2c receivers was slightly reduced when the bearing of the transmitting glider was near 0° (ahead of the receiving glider). We view these effects as conditional on the mounting relationship between the VMT and the integrated VR2c's, which could be changed.

The externally mounted VMT and integrated VR2c's had different effective detection ranges. The results of our study suggest the effective detection range to be ~0.4 and ~0.6 km for the VMT and integrated VR2c receivers, respectively, comparable to previous findings for detecting high-power tags (69 kHz, 161 dB) [25]. In addition, our range testing results are similar to estimates using a Slocum glider with integrated VR2c receivers passing by a moored test tag [11]. Studies using VMTs as receivers on AUVs and as animal-borne sensors are becoming more common and often have experimental designs that make range testing impractical [27–29]. Our study gives an upper bound on the scales of interaction that can be inferred between telemetered organisms and their environment as they move through the coastal ocean, outside of established fixed acoustic receiver arrays. Detection efficiency of the VMT and integrated VR2c's differed depending on the distance between the receiver and transmitter. At 0.1–0.2 km, the detection efficiencies of the VMT and VR2c receivers were near 30–40%, which is similar to the mean detection efficiency (33%) reported by fixed arrays in a shallow coastal ocean [3]. However, our detection efficiency was much lower than the 80–90% detection efficiency by high-power tags reported by arrays in an Arctic embayment, fresh water lake, and a subtropical marine reef [25]. A possible strategy to estimate detection efficiency using gliders throughout their mission would be to fly them in formation, one acting as a transmitter and the other as a receiver to estimate the detection efficiency distance decay curve. The detection efficiency "doughnut effect" we observed with the integrated VR2c receivers indicates that one system (VMT vs. integrated VR2c) might be preferable over the other depending on the science question. If the science question depends on localization, then the VMT might be preferred; however, if the science question depends on broader scale presence or absence, then the integrated VR2c receivers may be better suited as a result of their larger detection range.

Conclusion

Our analysis suggests that Slocum gliders can operate as effective and efficient acoustic telemetry sentinels outside fixed receiver arrays, whether they are using VMT or integrated VR2c receiver technology. The effective range for the VMT and VR2c receivers does not appear to be affected by vehicle attitude, but rather distance between transmitter and receiver, and environmental conditions. With the expectation that more Slocum gliders will be being used to map habitat associations of telemetered fishes during their migrations outside fixed receiver arrays, these estimates should provide valuable insights into study design and increase the precision of estimates.

This study outlines important length scales when considering the inferred relationships between telemetered organisms and their habitat.

Additional files

Additional file 1. GAMM model results for the VMT and VR2c Model in Table 1.

Additional file 2. VMT model response functions of the less important variables affecting VMT detections. Dashed lines indicate confidence intervals, and rug plots indicate observations. Of these predictors, only target bearing was statistically significant (Additional file 1: Table S1). Positive values indicate conditions that enhance detection efficiency and negative values indicate conditions that suppress detection efficiency.

Additional file 3. VR2c response functions of the less important variables affecting VR2c detections. Dashed lines indicate confidence intervals, and rug plots indicate observations. Of these predictors, density and pitch were not statistically significant (Additional file 1: Table S2). Positive values indicate conditions that enhance detection efficiency and negative values indicate conditions that suppress detection efficiency.

Abbreviations
AUV: autonomous underwater vehicle; VMT: VEMCO mobile transceiver; VR2c: VEMCO cabled receiver.

Authors' contributions
MO, MB, DH, and JK designed the experiment. MO, MB, DA, and JK collected the data for the experiment. MO, MB, and MC analyzed data for the experiment. MO, MB, DH, MC, JK, and DF wrote the manuscript. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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