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Acoustic Monitoring of Cetaceans in the Northern Gulf of Mexico using Wave Gliders equipped with High-Frequency Acoustic Recording Packages

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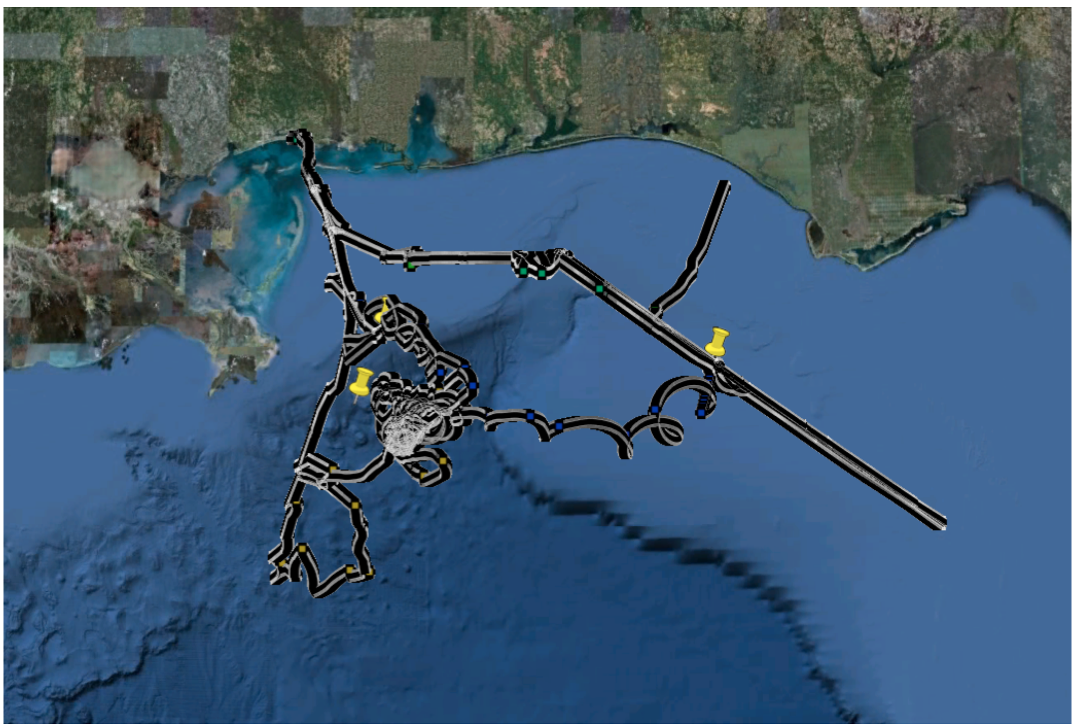

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Executive Summary

Two Wave Gliders equipped with High-frequency Acoustic Recording Packages (HARPs) were deployed to monitor cetacean sounds during three separate missions in the northern Gulf of Mexico (GOM) during 2011. Wave Glider HARP (WGH) based recordings contain delphinid and sperm whale (*Physeter macrocephalus*) vocalizations. Standard seafloor-mounted HARPs deployed in the GOM allow comparison of acoustic data when WGHs were in close proximity to the seafloor HARP sites.

Direct comparison of the WGH data to the seafloor HARP data revealed few clear instances of the same calls, or group of calls, being detected by both instruments. This is due to the limited time that the WGHs were positioned near the seafloor HARPs, as well as the directionality and finite detection range for calls from cetaceans present in this area.

Low frequency (< 400 Hz) WGH noise levels were sometimes, but not always, higher than seafloor HARP noise levels. This may be due to the shallow depth (~8 m) of the WGH hydrophone, and the need for it to be towed by the Wave Glider, suggesting that attention should be directed at decoupling the hydrophone from Wave Glider motion. High frequency (> 30 kHz) noise levels of the WGH hydrophone were also somewhat higher than those of the seafloor HARP. This could be remedied by using a more sensitive high frequency ceramic element than the one used in this study. The performance of the WGH hydrophones degraded over the period of this study, and both WGH hydrophones had intermittent electronic oscillations during their final deployment missions. The wear due to towing may be an explanation for degradation of WGH hydrophone electronics or wiring.

The seafloor HARPs had higher daily cetacean detection rates than the WGH for both delphinid and sperm whale calls, both on the continental shelf and in deep water. Since delphinids vocalizations are mostly near the surface, it was expected that their calls would be best recorded by the WGH. Acoustic propagation modeling may be helpful in understanding why the seafloor HARP had higher detection rates for delphinids on the continental shelf than did the WGHs.

Deep-diving animals such as sperm whales, which vocalize mostly at depth, are detected best by deep sensors, making them more likely to be recorded on a deep water seafloor HARP than on the WGH, however, the poor state of the WGH hydrophones during their final mission and the fact that little or no time was spent with the WGH positioned above a deep water seafloor HARP prevented an adequate test of the WGH deep water capabilities during this study.

It would be helpful to conduct another deployment with the WGHs that focuses on positioning them near the seafloor HARPs. In addition, modifications should be made to the WGH hydrophone design to diminish electronic noise and make them more robust for towing. Attention also should be paid to decoupling the WGH hydrophone from Wave Glider motion to improve low frequency noise performance.

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Introduction

The goal of this report is to compare cetacean sounds recorded by Wave Gliders near the sea surface and by stationary High-frequency Acoustic Recording Packages moored near the seafloor in the northern Gulf of Mexico (GOM). The Wave Glider, an autonomous surface vehicle, has a surface float connected by cable to a submerged glider, using wave action for propulsion. The Wave Glider surface float is equipped with real-time communications allowing its track to be controlled remotely. For this project, a High-frequency Acoustic Recording Package (HARP) was installed in the Wave Glider surface float and a hydrophone for sensing underwater sound was connected to the submerged glider, providing a mobile instrument for recording cetacean sounds that we will designate the Wave Glider HARP (WGH).

A broad range of cetacean species are known to inhabit the offshore northern GOM (Davis *et al.* 2002). Odontocete species (toothed whales) known to be present include: atlantic spotted dolphin (*Stenella frontalis*), pantropical spotted dolphin (*Stenella attenuata*), striped dolphin (*Stenella coeruleoalba*), spinner dolphin (*Stenella longirostris*), Clymene dophin (*Stenella clymene*), rough-toothed dolphin (*Steno bredanensis*), Fraser's dolphin (*Lagenodelphis hosei*), Risso's Dolphin (*Grampus griseus*), bottlenose dolphin (*Tursiops truncatus*), melon-headed whale (*Peponocephala electra*), false killer whale (*Pseudorca crassidens*), short-finned pilot whale (*Globicephala macrorhynchus*), pygmy killer whale (*Feresa attenuata*), killer whale (*Orcinus orca*), sperm whale (*Physeter macrocephalus),* pygmy and dwarf sperm whales (*Kogia breviceps* and *Kogia sima*), and beaked whales (*Mesoplodon europaeus*, *Ziphius cavirostris,* and an unknown species of *Mesoplodon sp.).* The only mysticete (baleen whale) known to regularly inhabit the northern GOM is the Bryde's whale *(Balaenoptera edeni)*.

The northern GOM has both shallow-water and deep-water environments. Although the water depth is but one parameter important to cetacean habitat, for purposes of this report, we will segregate the above species into those more likely to be encountered in deep water (sperm whale, pygmy and dwarf sperm whale, and beaked whale), and others that may be encountered predominantly in shallow or in both shallow and deep water (e.g. bottlenose dolphin).

Acoustic propagation is important to understanding at what range and depth sound produced by a cetacean may be detected, either near the sea surface, such as on the WGH, or near the seafloor, as on the bottom moored HARP. The GOM experiences seasonal variations in acoustic propagation between summer and winter. In the summer, a warm surface layer creates an acoustic waveguide near the sea surface. In the winter, the near surface waveguide may be less pronounced or lacking. When the near surface waveguide is present, sounds made within it, such as those of delphinids, tend to remain confined to the surface layer, limiting direct acoustic energy paths to the seafloor. This situation may be favorable to detection of cetacean sounds with a near surface sensor, such as on the WGH. For deep diving animals (e.g. sperm whales) or in the absence of near surface waveguide, a broad set of acoustic paths arrive at the seafloor, a situation more favorable to a seafloor sensor such as the moored HARP. These differences in propagation are important for understanding how sounds that are generated near the sea surface, such as those made by delphinids, may differ in detection from those generated near the sea bottom, such as those of sperm whales. Delphinids vocalize mostly near the sea surface, both over the continental shelf and over deep water, suggesting the WGH should detect many of their sounds. Whereas, sperm whales are deep-diving and will be found off the continental shelf and slope in deep waters and may be better suited for being detected on the seafloor HARPs.

The simultaneous WGH and seafloor HARP data analyzed in this report are considered in light of these differences in acoustic propagation and location of vocalizing animals, with the goal of identifying the capabilities of each approach for detecting cetacean sounds in the northern GOM.

Methods

Wave Glider HARPs

Wave Gliders are persistent, unmanned maritime vehicles that harness wave energy for platform propulsion and use solar panels to charge batteries used for powering control, navigation, communication and scientific instrumentation payloads (Manley & Willcox 2010). Wave Gliders consist of a surface float and a submerged glider. Wave Gliders have been configured with HARP data loggers and hydrophones for mobile acoustic recording of cetacean sounds near the ocean surface (Wiggins *et al.* 2010). The HARP acoustic recording electronics were installed in the Wave Glider surface float, and the hydrophone was towed behind the subsurface glider unit at a depth of about 8 meters.

The HARP recording package includes a 200 kSample/s data acquisition system capable of recording for 10 months. The hydrophone has a broad-band, high sensitivity, low self-noise response, and uses two sensors covering the band 10 Hz – 100 kHz (Wiggins & Hildebrand 2007). For seafloor HARPs, batteries are used for powering the autonomous instrument and the packaging contains buoyancy needed to recover the instrument from the seafloor after remote release of its ballast anchor. The hydrophone is tethered and buoyed about 10 m above the stationary seafloor package.

There are differences between the hydrophone sensors used for the seafloor HARPs and the WGH in the Gulf of Mexico. The seafloor HARP hydrophones were made to be more sensitive to sound because they were designed to operate on the quiet seafloor; whereas, the WGH hydrophones were designed for a moving, noisier environment near the sea surface.

The seafloor instruments used two sensors, one for the low frequency (10-3000 Hz) channel with six Benthos AQ-1 cylindrical PZT ceramic elements, and one for the high-frequency (3 – 100 kHz) channel with an International Transducer Corporation (ITC) 1042 spherical element. The AQ-1's have a relatively flat (+/- 1dB) sensitivity of -202.5 dB re V/µPa, and configured as six in series to give an additional 15.6 dB of gain prior to the preamplifier. The ITC-1042 has a sensitivity of about -202 dB re V/µPa and is relatively flat (+/- 2dB) over the sampled frequency range.

To reduce the potential for signal saturation from low-frequency sounds such as flow noise, hydrophone wire strum, and impulsive shocks between the surface float and sub wing unit, the WGH hydrophones used one AQ-1 instead of six. Fewer sensors coupled with a 5 dB lower gain preamplifier reduced the overall sensitivity of the WGH hydrophone by 20 dB for the low-frequency channel, compared to seafloor HARPs. To reduce hydrodynamic drag and keep the hydrophone package small, the WGH hydrophone used one Sonar Research HS-150 spherical ceramic sensor with a sensitivity of -205 dB re V/ µPa for the high frequency channel. The reduced sensitivity from this sensor coupled with a 10 dB lower gain preamplifier reduced the overall hydrophone sensitivity by around 13 dB for the high-frequency channel compared to the seafloor HARPs.

Two Wave Gliders with HARPs (WGHs), designated G4 and G5, were deployed for three sorties each for periods of one to two months per sortie in the northern GOM (Table 1). All operational dates were in the year 2011, so when a day is referenced in this report, only the day and month will be given, with an assumed reference to the year 2011.

Table 1: Deployment durations for each WGH sortie (dates in 2011).

WGH Sortie	Start	End	Duration Days:Hours	Duration Hours
G4 sortie 0	2/3 22:16	3/1 19:58	25 days 22 hours	622
G5 sortie 0	2/3 22:46	3/1 20:40	25 days 22 hours	622
G4 sortie 1	3/12 15:24	5/14 17:34	63 days 2 hours	1514
G5 sortie 1	3/7 15:34	4/24 0:00	46 days 9 hours	1113
G4 sortie 2	6/5 15:17	8/11 23:19	67 days 8 hours	1616
G5 sortie 2	6/5 15:18	7/20 21:52	45 days 6 hours	1086

Seafloor HARPs

One goal of this project was to compare the sounds recorded by the WGH with those recorded by seafloor-mounted stationary HARPs. For this purpose the WGHs transited near seafloor HARPs previously deployed in the northern GOM. The three seafloor HARPS previously deployed in the northern GOM and used for this study are designated: Main Pass (MP), Mississippi Canyon (MC) and DeSoto Canyon (DC) (Figure 1 and Table 2). MP HARP was located on the continental shelf, at 93 m depth, west of the Mississippi Delta. MC HARP was located in the offshore Mississippi Canyon, along the continental slope at 980m depth. DC HARP was on the continental shelf at about 260 m depth, south of Panama City, Florida.

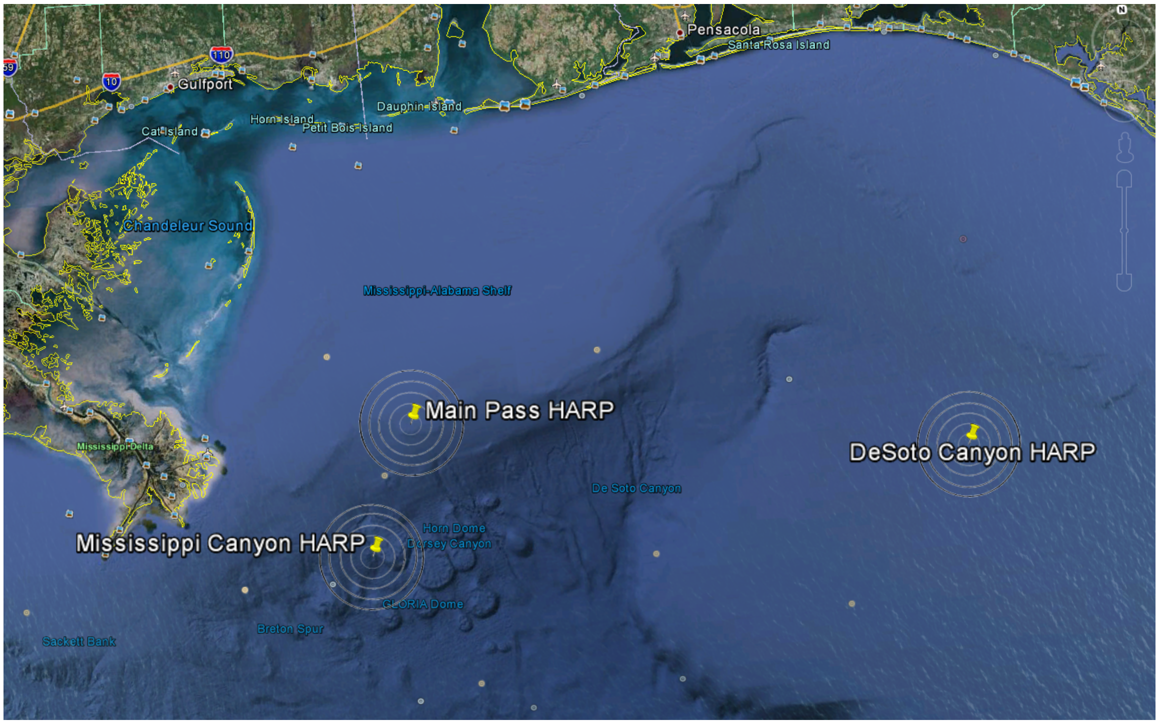


Figure 1: Site locations of seafloor-mounted HARPs in the GOM at Mississippi Canyon (MC), Main Pass (MP) and Desoto Canyon (DC). Concentric rings around each HARP are spaced 2 nm.

Table 2: Locations for seafloor HARPS used in this study.

Site	Longitude Deg-min N	Latitude Deg-min W	Depth (m)
Main Pass	88-17.808	29-15.318	93
Mississippi Canyon	88-27.946	28-50.775	980
DeSoto Canyon	86-05.800	29-03.210	260

The WGH and the seafloor HARP data were compared in several ways. The first was as power spectra for received sound pressure levels, which includes instrumentation noise, ocean ambient noise and the sounds of cetaceans. Next a direct comparison was attempted, in which individual sounds observed on the WGH were compared with the seafloor HARP data when the two sensors were close proximity of each other (< 2 nm). Finally, an indirect comparison was conducted, examining cetacean call detection rates for each instrument in respective habitats. The percentage of hours in which delphinid and sperm whale vocalizations were detected was categorized by sortie and species.

Estimated Maximum Detection Range for HARPs

Estimates of the maximum detection ranges for cetacean vocalizations were based on underwater acoustic propagation modeling using the parabolic equation RAMGEO software program (Collins 1993). Bathymetry and sound-speed profiles from the northern Gulf of Mexico used for the models were obtained from the National Ocean Data Center (http://www.nodc.noaa.gov/). The parameters used for the model assume shallow diving cetaceans (delphinids) will be in the first 30 meters from the sea surface, and deep diving cetaceans (sperm whales) will echolocate at depth (1000 m). Delphinids produce both whistles at about 15kHz, and echolocation clicks at 20 – 100 kHz. Sperm whales produce only echolocation clicks at 5-20 kHz. It is generally understood that delphinid whistles will be detected at greater ranges than echolocation clicks, owing to greater acoustic attenuation of the high-frequency clicks, however most northern Gulf of Mexico delphinids are known to predominantly produce clicks rather than whistles. Acoustic propagation in a warm water environment such as the GOM will make it easier to detect sounds produced at shallow depth on shallow receivers and likewise sounds produced at deep depths will be more easily detected on deep receivers. Table 3 gives detection range estimates for delphinids and sperm whales, by the WGH and by each seafloor HARP site.

Table 3: Cetacean detection range estimates (nautical miles).

	WGH	MP HARP	MC HARP	DC HARP
Delphinid Whistles	5	2.5	2	2.7
Delphinid Clicks	2	1	1	1
Sperm Whales	4	10	10	10

The number of hours of deployment time each WGH spent within a given range (in nautical miles) of each seafloor HARP is given in Table 4 and the closest-point-of-approach (CPA) between WGH and seafloor HARPs are given in Table 5. The Wave Gliders were outside the detection range for cetaceans by the seafloor HARPs for much of their deployment times. For direct comparison of WGH and seafloor HARP delphinid detection capabilities, they need to be separated by ranges of no more than 1 – 5 nm (Table 3). They were within less than 2 nm during sortie 0 for 192 and 191 hours, and during sortie 1 for 180 and 267 hours (G4 and G5 respectively). During sortie 2 they were never closer than 10 nm. This suggests that sorties 0 and 1 will be the primary data sets for direct comparison between WGH and seafloor HARP detections.

Table 4: Time WGH spent within a given range for each seafloor HARP (maximum range for calculation is 10 nautical miles).

Distance (nm)	Hours within Range
Sortie 0	
G4-MP HARP	
10 nm	197
8 nm	196
6 nm	195
4 nm	194
2 nm	192
G5-MP HARP	
10 nm	198
8 nm	196
6 nm	194
4 nm	192
2 nm	191

Sortie 1	
G4-DC HARP	
10 nm	193
8 nm	190
6 nm	187
4 nm	184
2 nm	180
G5-DC HARP	
10 nm	304
8 nm	296
6 nm	288
4 nm	280
2 nm	267
Sortie 2	
None	

Table 5: Date and time (hour:min), and distance for closest-point-of-approach between WGH and seafloor HARP.

	Date	Time	Distance (nm)
Sortie 0			
G4-MP	16-Feb	15:07	0.1
G5-MP	15-Feb	05:08	0.1
Sortie 1			
G4-DC	20-Apr	14:20	0.1
G5-DC	13-Apr	03:39	0.0
Sortie 2			
G4-MP	20-Jul	22:19	24.7
G5-MP	11-Jun	14:43	16.6
G4-MC	19-Jul	14:49	13.5
G5-MC	13-Jun	19:58	11.0

Results

Sortie 0

Sortie 0 was conducted from 3 February to 1 March; the two WGHs were deployed in the GOM starting and ending their mission near Horn Island, Mississippi (Figure 2).

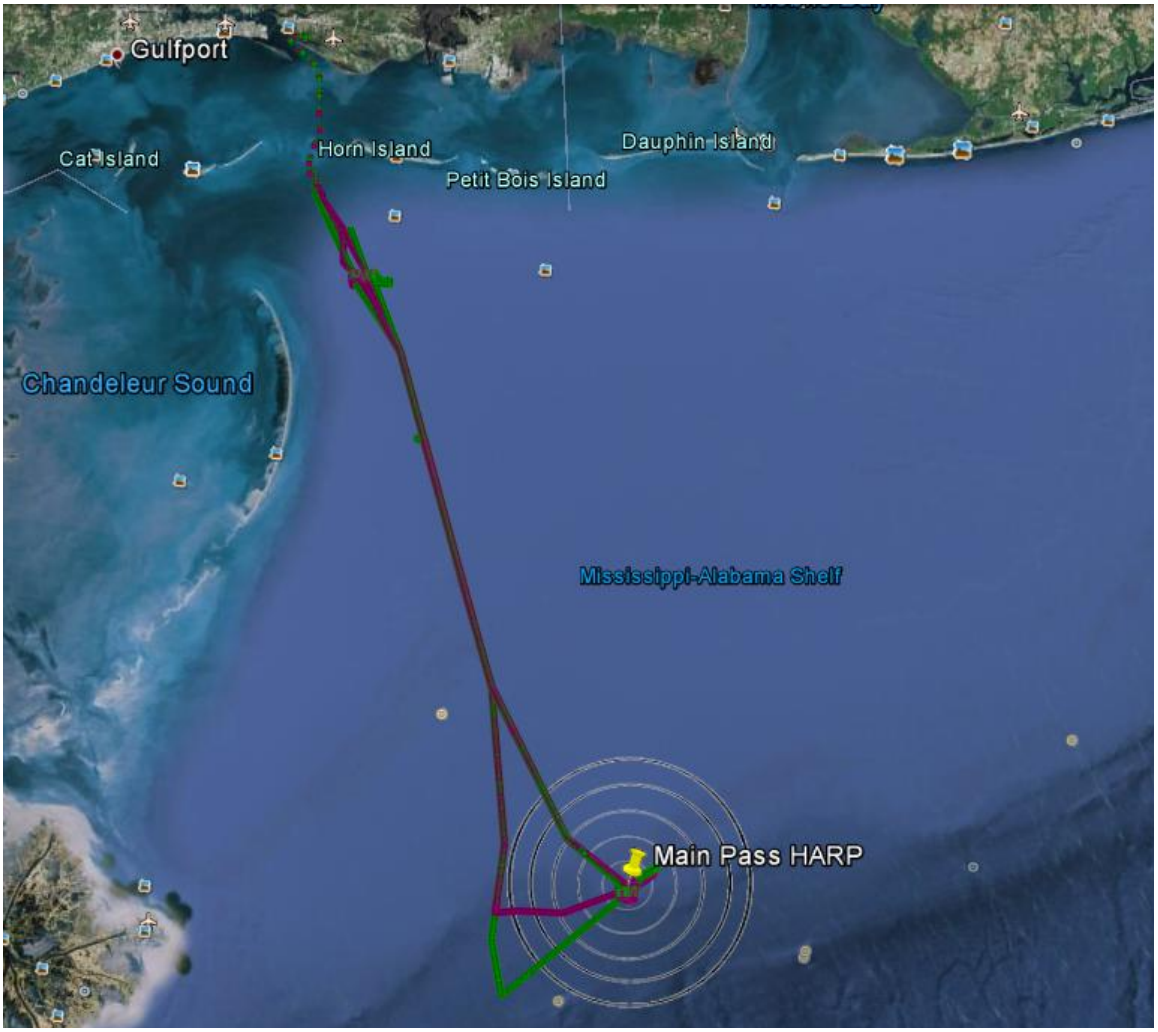


Figure 2: Sortie 0 Wave Glider tracks for the period 3 February to 1 March 2011. WGH G4 is green track and G5 is magenta track. Concentric circles show ranges of 2 – 10 nm in 2 nm increments. MP HARP location indicated by yellow pin.

Wave Gliders G4 and G5 transited to the MP HARP site and then remained on station at the MP site within 2 nm of the seafloor site (Figure 3) between 11 -20 February. G4 was launched with a known defective low frequency channel on the hydrophone, but had a working high frequency sensor, providing good recordings from 2 kHz – 100 kHz. The focus for this study is on delphinids and sperm whales, which both produce sounds in the high frequency range, so G4's defective low frequency channel should not interfere with detection of their signals.

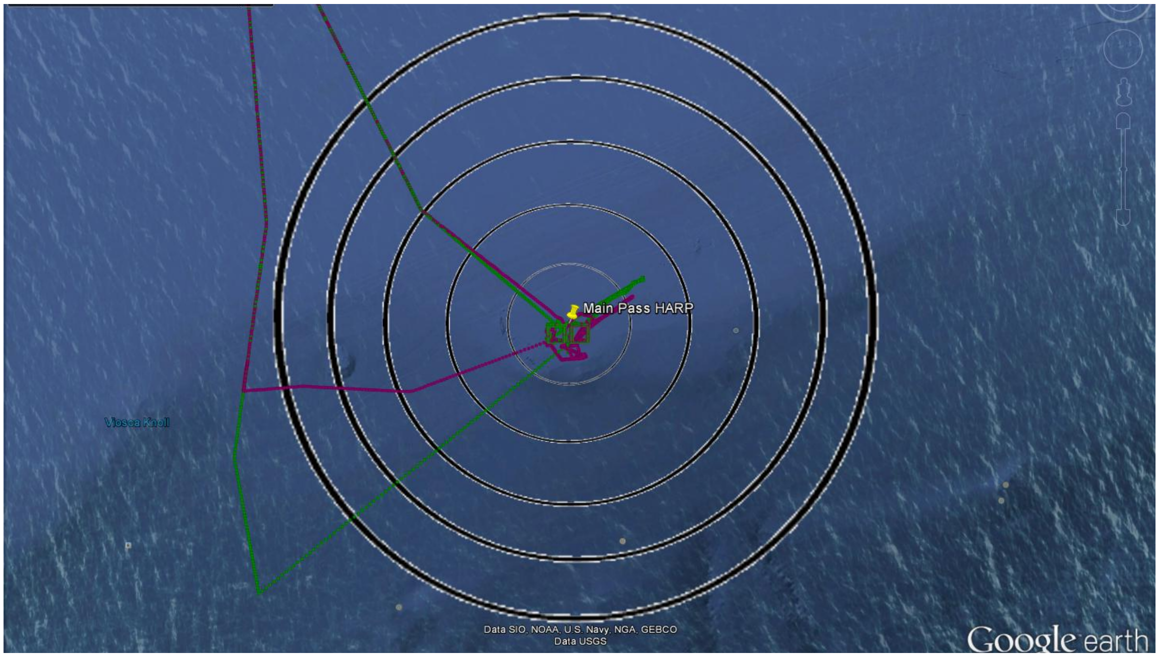


Figure 3: Sortie 0 Wave Glider tracks near MP HARP. WGH G4 is green track and G5 is magenta track. Concentric circles in 2 nm increments.

Sortie 0 WGH and MP HARP Comparison

Selected noise spectra for the WGH and the MP HARP during sortie 0 are shown in Figure 4 and Figure 5. When the WGHs were positioned within 2 nm of the seafloor MP HARP (February 11-20), comparable noise spectra are seen between WGH G5 and the MP HARP (Figure 4). However, both WGH G5 and MP HARP exhibit high noise levels at low frequency (> 130 dB at 10 Hz) at this time, probably from fluid flow at the hydrophones. At high frequencies (> 10 kHz) the WGH G5 has about 2-10 dB additional noise, although both systems are thought to be electronic noise limited at these frequencies. The WGH G4 low frequency noise levels are low in Figure 4 owing to the defective sensor.

Noise spectra for February 4-5 (Figure 5), show WGH G5 low frequency noise levels that are significantly higher than those of the MP HARP presumably during a period of slack tide when the seafloor currents are negligible and the HARP does not experience fluid flow at the hydrophone. The two sensors have similar noise levels for the frequency band 400 Hz – 30 kHz. The WGH has higher noise levels than the MP HARP for 30 – 100 kHz. Wave-motion induced noise is expected for the WGH, and this may explain the excess noise levels (e.g. ~60 dB at 10 Hz) below 400 Hz. Differences in the WGH and seafloor HARP hydrophone construction may partially explain the higher WGH noise levels at > 30 kHz (as discussed above).

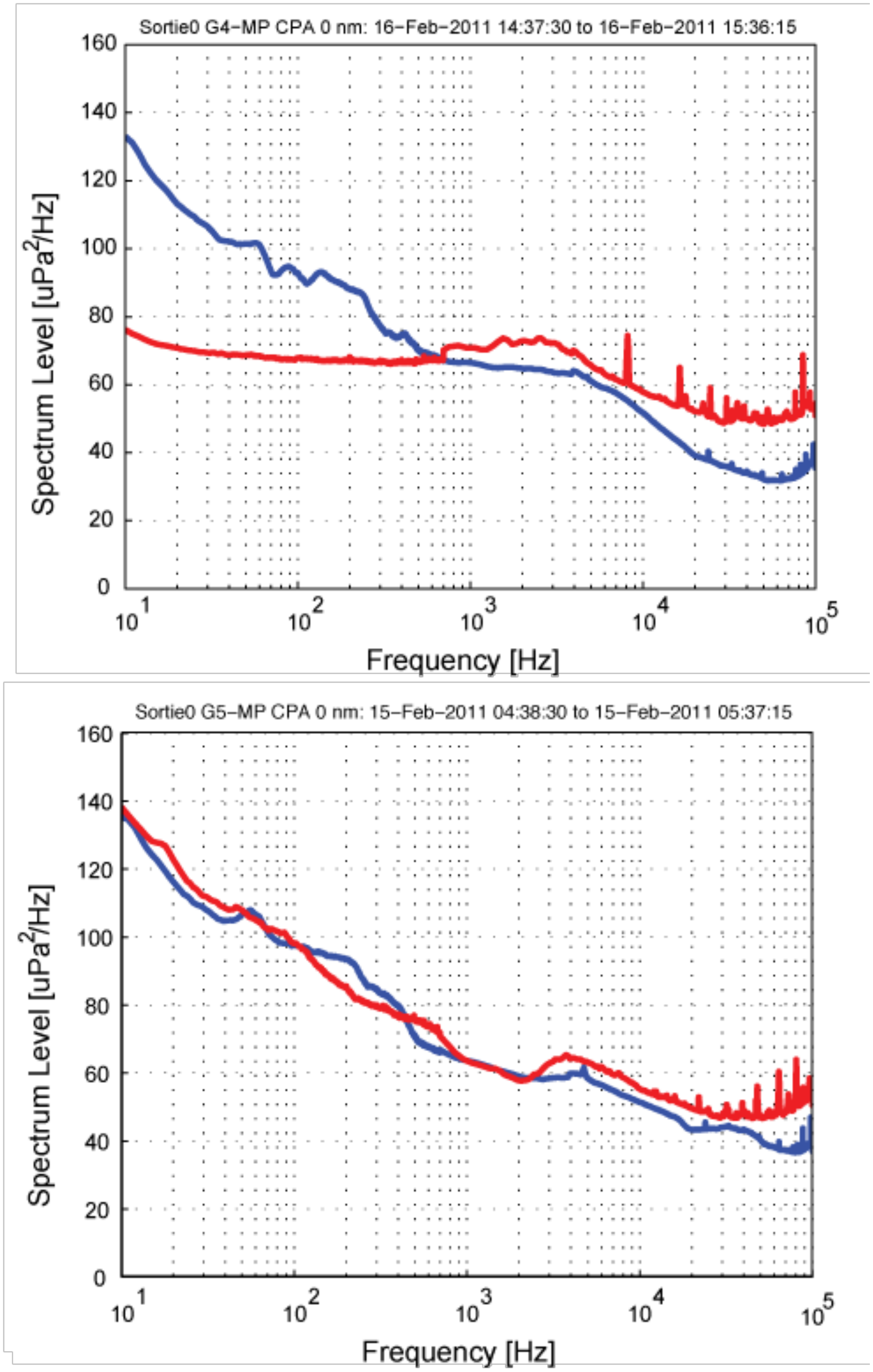


Figure 4: Noise spectra (in 1 Hz frequency bins) for (top) WGH G4 and (bottom) WGH G5 (red) compared to the seafloor MP HARP (blue) for 15-16 February.

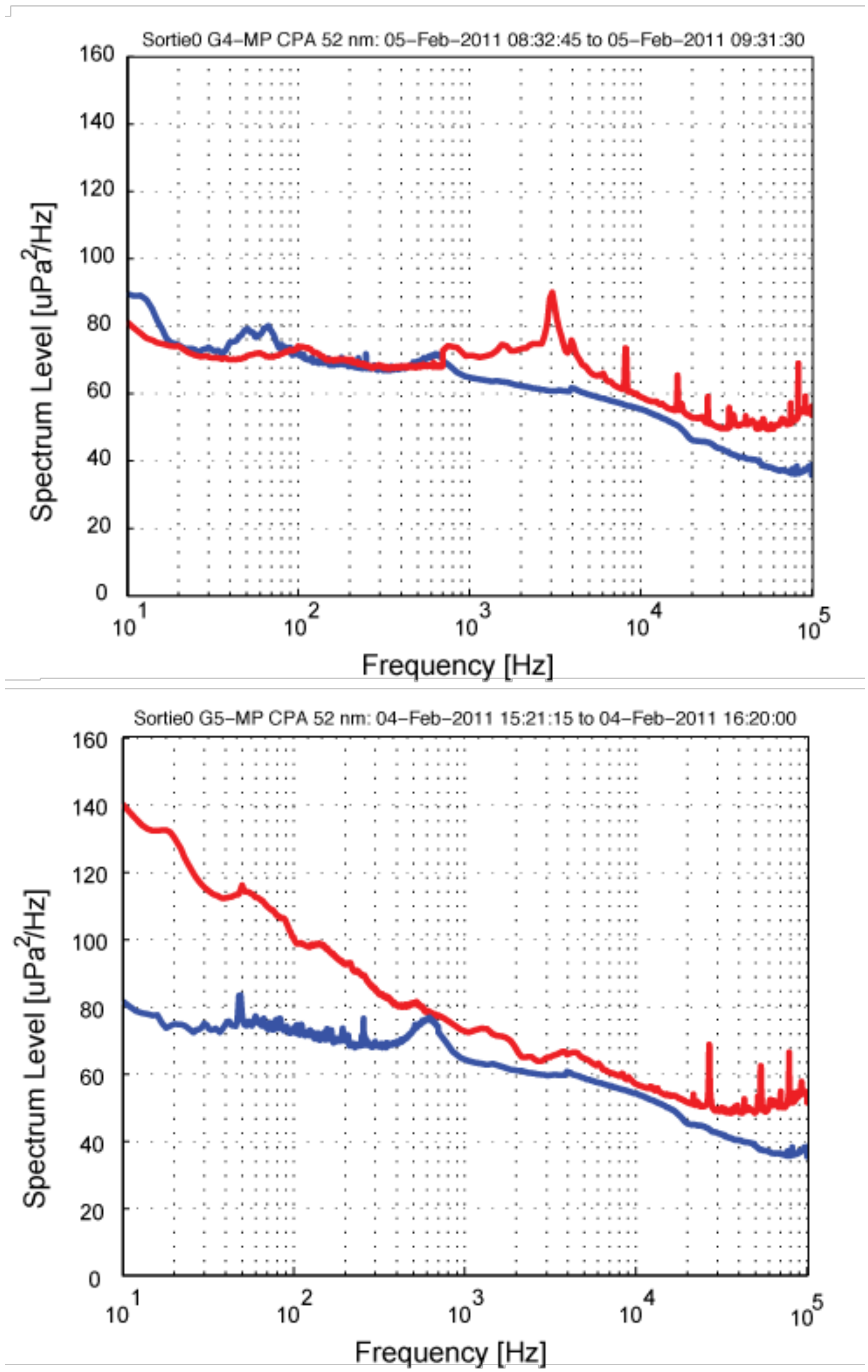


Figure 5: Noise spectra for (top) WGH G4 and (bottom) WGH G5 (red) compared to the seafloor MP HARP (blue) for 4-5 February.

A comparison of daily cetacean detection periods (percentage of one-minute detection windows with calls each day) for the two WGHs and the MP HARP during sortie 0 is shown in Figure 6. Delphinid sounds were detected at similar rates for the two WGHs, most likely because they traveled approximately the same path for much of the deployment (Figure 2). The WGHs show ample delphinid detections during the first week and last week of their deployment, while transiting across the continental shelf between Horn Island and the MP HARP site. Based on known cetacean distributions, these may be predominantly bottlenose dolphin detections. In contrast, during the time the WGHs were within 2 nm of the MP HARP site (pink period in Figure 6), they had relatively few delphinid detections on average (<40 min/day), and significantly fewer detections on average than for the seafloor HARP (6.5 hours/day). Only delphinids were detected on the WGHs during sortie 0. No deep diving cetaceans such as sperm whales were detected on the WGHs, though they were detected on the MP HARP, albeit for relatively short periods (Figure 6).

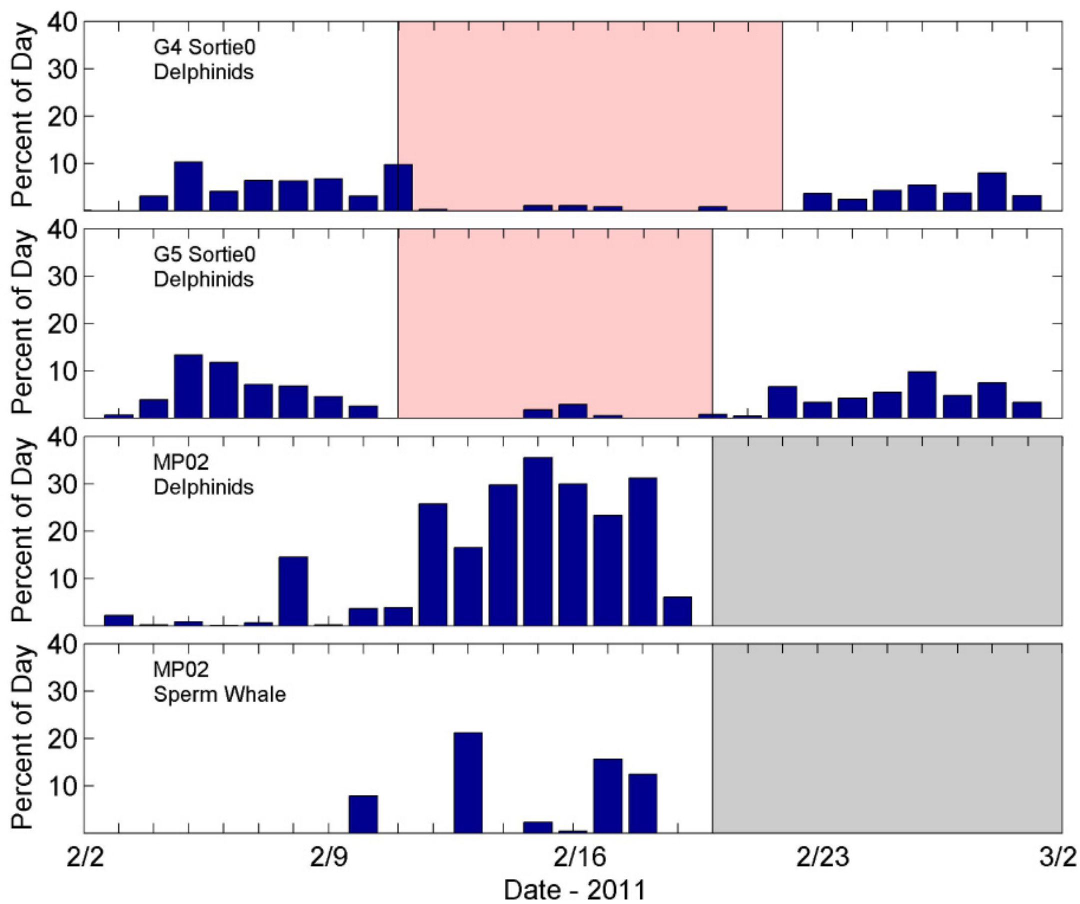


Figure 6: Percentage of one-minute windows with sounds detected each day during sortie 0: (top) WHG G4 delphinids; (2nd from top) WGH G5 delphinids; (3rd from top) MP HARP delphinids; (bottom) MP HARP sperm whales. G4 was within 2 nm of MP from 11-22 February (pink). G5 was within 2nm of MP site from 11-20 February (pink). No data available from MP HARP during February 20 – March 2 (gray).

On February 16, 2011, while both WGHs were located near the MP HARP, delphinid clicks were detected on both the WGHs and on the MP HARP. Clicks were recorded clearly on the G5 WGH at about 03:38 (Figure 7). They were not detected at this time on G4 WGH (Figure 8), although delphinid clicks were detected slightly earlier at 03:10. Clicks were detected only weakly on the MP HARP at 03:38, but later were recorded distinctly at 03:54 (Figure 9). The timing differences between the detections at the WGH and MP HARP may be because the narrow-beam dolphin echolocation clicks illuminated only a single sensor at any given time. Even though the G4 and G5 WGHs were within 2 nm of the MP HARP, we found no case where the same delphinid clicks or whistles were found on pairs of instruments allowing for direct comparison.

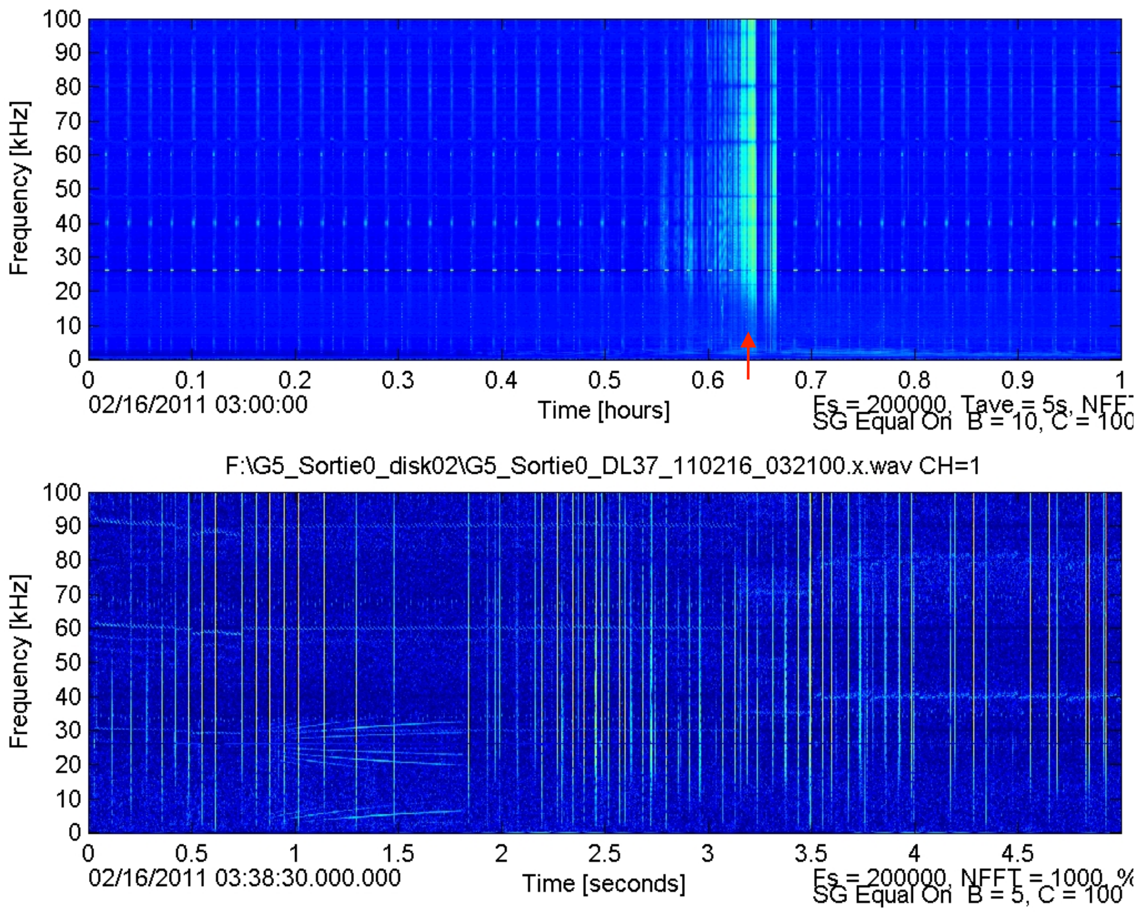


Figure 7: WGH G5 (top) long-term spectral average (1 hour duration) and (bottom) spectrogram (5 sec duration) from February 16, 2011. Clicks were clearly detected at 03:38 (red arrow in top and expanded in bottom spectrogram).

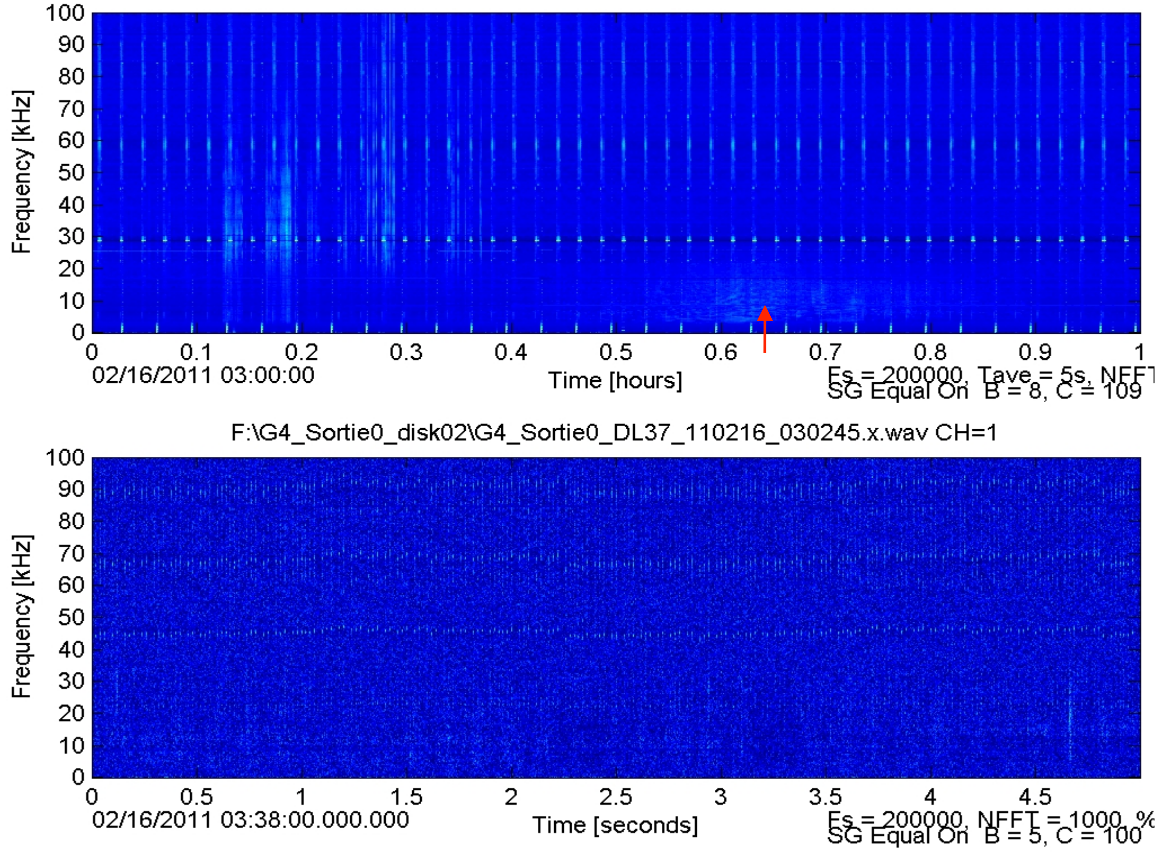


Figure 8: WGH G4 (top) long-term spectral average and spectrogram (bottom) from February 16, 2011. Red arrow same time as Figure 7.

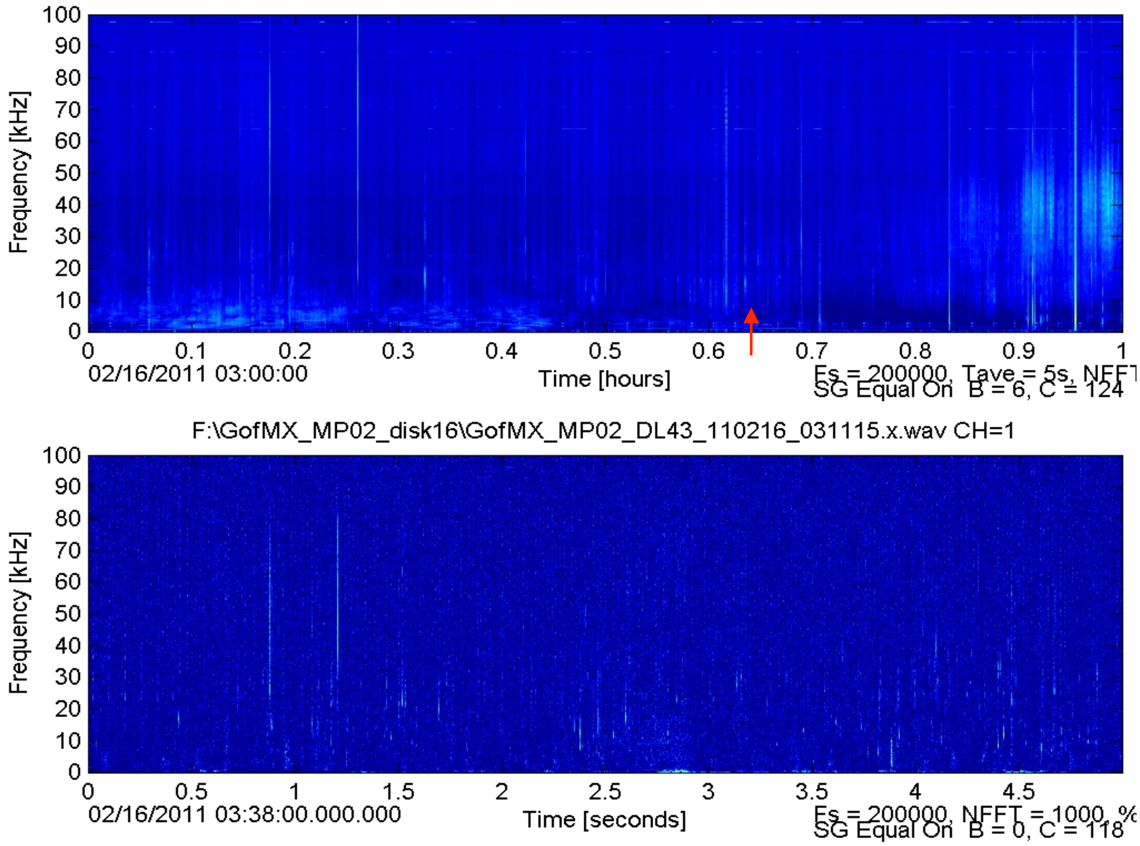


Figure 9: MP HARP (top) long-term spectral average and (bottom) spectrogram from February 16, 2011. Red arrow same time as Figure 7.

Sortie 1

Sortie 1 was conducted from 12 March to 14 May for G4, and 7 March to 24 April for G5. The two WGHs started their mission near Horn Island, Mississippi (Figure 10). G4 ended its mission near Horn Island, while G5 was recovered at a site farther east near Panama City, Florida. G4 and G5 held station near the DC HARP site for two separate periods 25-29 March and 13-20 April for 180 and 267 hours (respectively) within 2 nm of the seafloor site (Figure 11). The WGH held station by executing tracks around boxes with 1 km side length, just to the east and west of DC HARP (Figure 12). WGH G4 was inadvertently turned off between 23 March and 3 May. Upon recovery, the hydrophone from WGH G4 was found to have multiple punctures, suggestive of a shark bite.

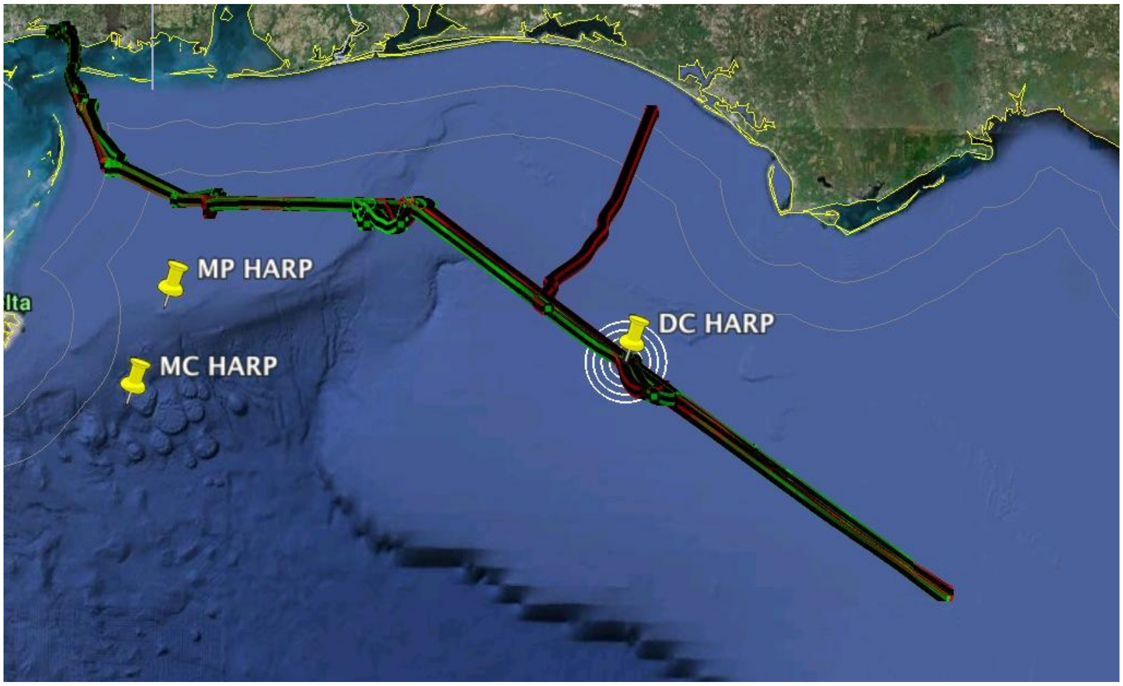


Figure 10: Complete track for sortie 1 Wave Gliders from 12 March to 14 May. WGH G4 is green track and G5 is magenta track. Concentric circles show ranges of 2 – 10 nm in 2 nm increments.

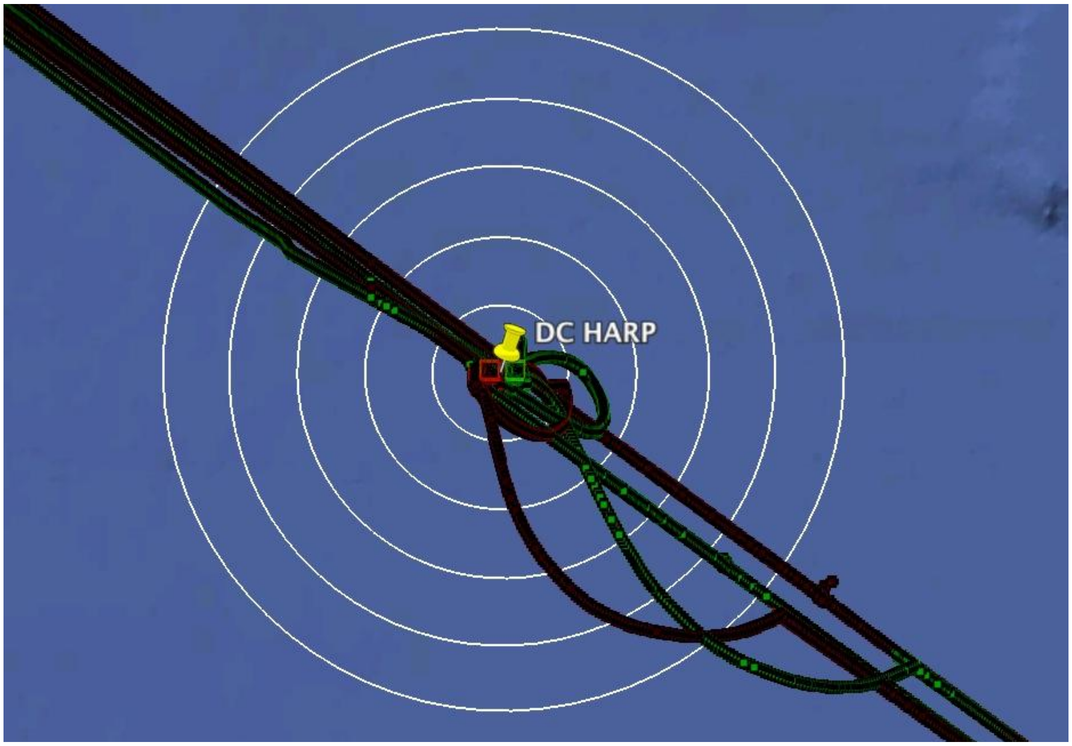


Figure 11: Sortie 1 Wave Glider tracks near DC HARP. WGH G4 is green track and G5 is magenta track. Concentric circles show ranges in 2 nm increments.

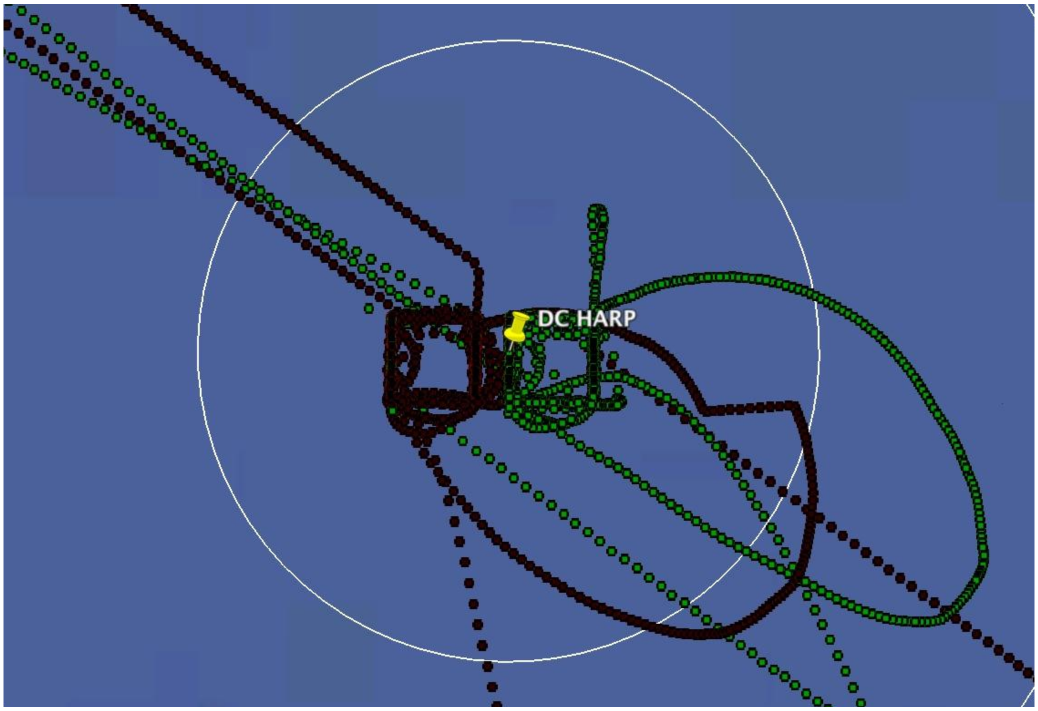


Figure 12: Sortie 1 Wave Glider tracks near DC HARP. WGH G4 is green track and G5 is magenta track. White circle shows range of 2 nm.

Sortie 1 WGH and DC HARP Comparison

Noise spectra for the WGH G4 and G5, and the DC HARP during sortie 1 are shown in Figure 13. These data show WGH low frequency noise levels that are 20-30 dB higher than those of the DC HARP. The two sensors have similar noise levels for the frequency band 400 Hz – 30 kHz, with the WGHs exhibiting 2-10 dB higher noise levels than the DC HARP. The WGH has > 10 dB higher noise levels than the DC HARP for 30 – 100 kHz.

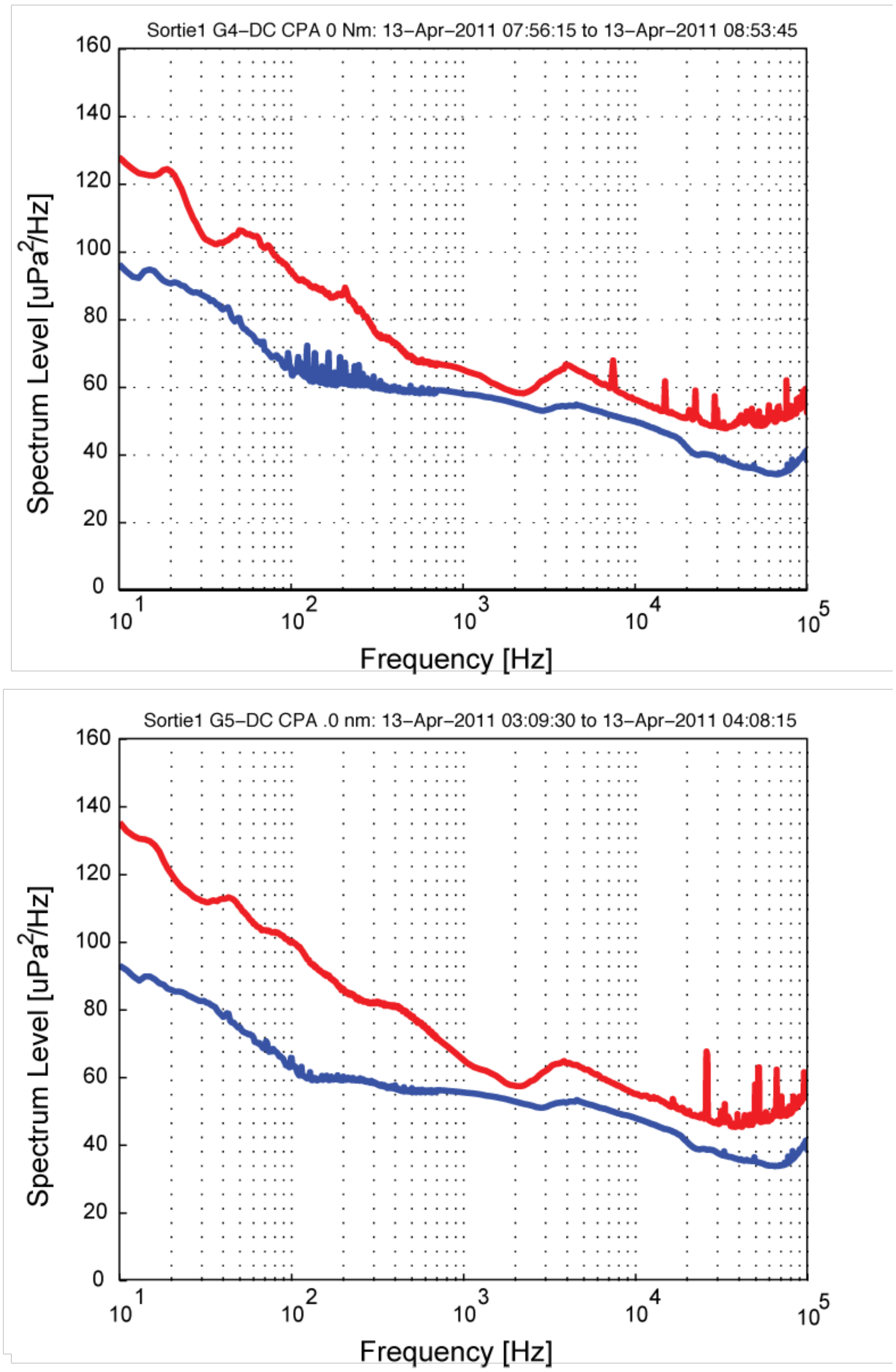


Figure 13: Noise spectrum comparison for (top) WGH (red) G4 and (bottom) G5 with seafloor DC HARP (blue) for 13 April.

There were higher numbers of delphinid detections on the DC HARP throughout Sortie 1 and also while the WGHs were positioned nearby the seafloor HARP (Figure 14). Between the two WGHs, G4 exhibited significantly lower call detection rates than seen for G5, despite their close proximity for much of sortie 1. One possibility is that the shark bite, noted earlier, may have partially disabled the G4 hydrophone. This could result in fewer call detections on G4, although the noise spectral levels of G4 and G5 in Figure 13 appear to be comparable. Sperm whales were not detected on either the WGH or the DC HARP, probably owing to the location of the Wave Glider tracks in shallow water on the continental shelf.

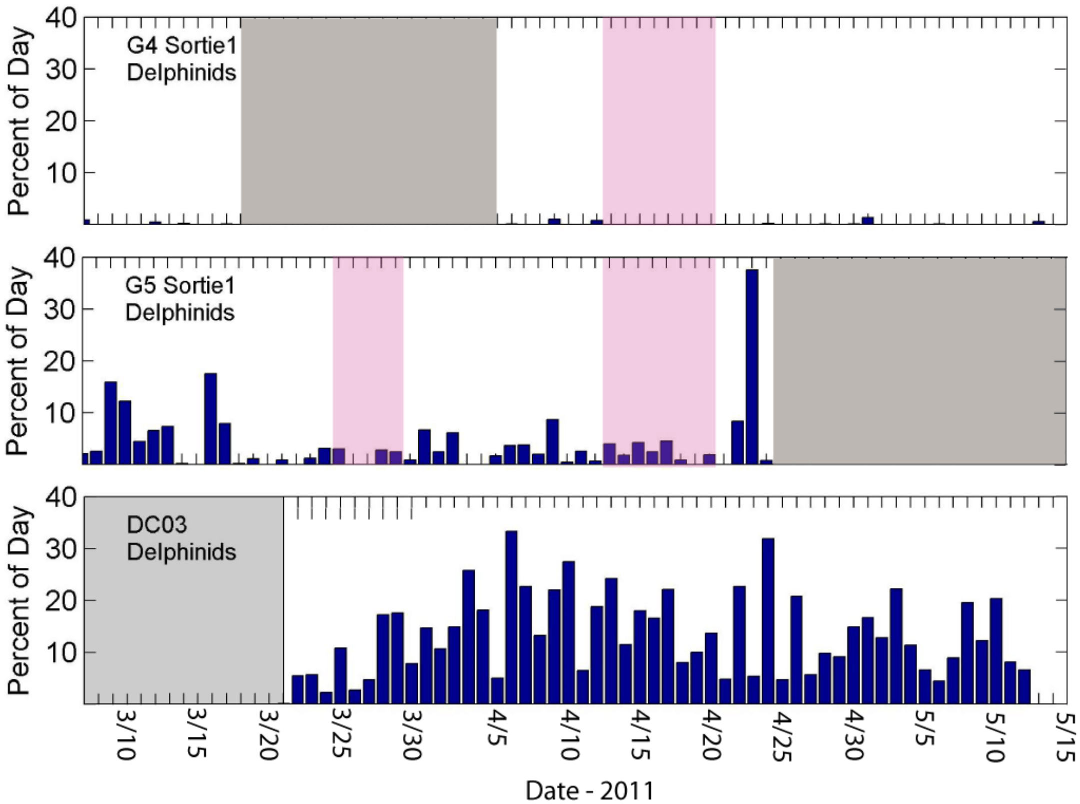


Figure 14: Delphinid sounds detected during sortie 1 on WGH G4 (top), G5 (middle), and on HARP DC (bottom). Pink shading indicates times when the WGH was near the DC HARP. Gray shading indicates no data.

Spectrograms of delphinid clicks are presented from the sortie 1 WGH G5 (Figure 15) and the DC HARP (Figure 16) as they were within close proximity on 28 March. The G5 WGH shows the passage of delphinids, but over a time period of about 10 minutes. The DC HARP shows the passage of presumably the same group of delphinids over an approximate 30 minute period.

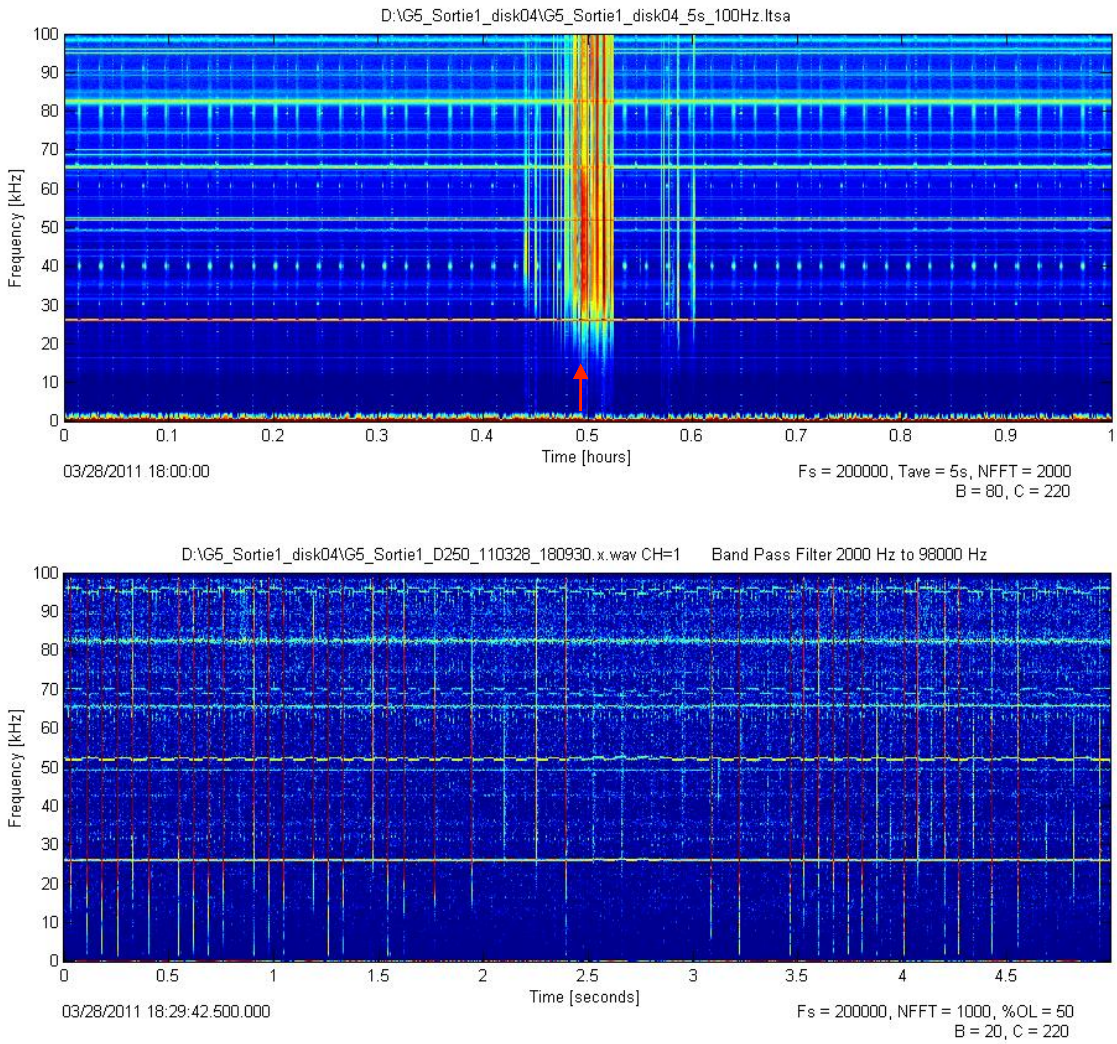
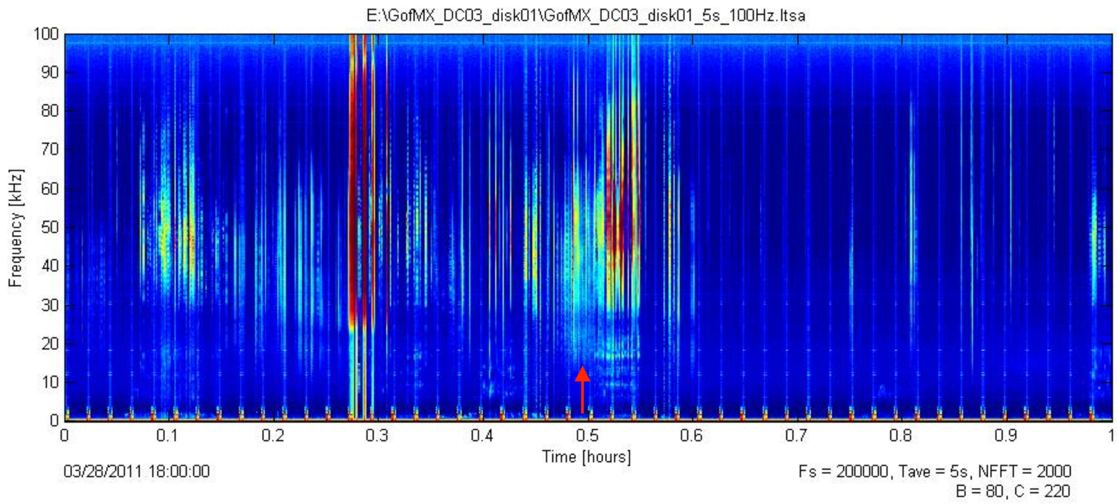


Figure 15: WGH G5 showing delphinid clicks detected on a long-term spectral average (top) and spectrogram (bottom) during 28 March. Data are coincident with passage of G5 near the DC HARP during sortie 1. Red arrow shows time of spectrogram (below).



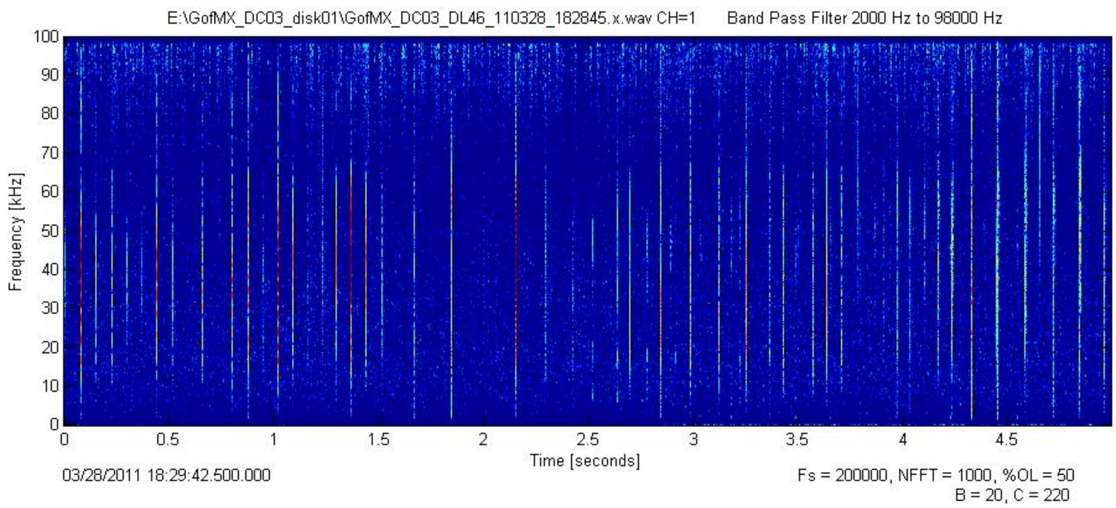


Figure 16: DC HARP showing delphinid clicks detected on a long-term spectral average (top) and spectrogram (bottom) during 28 March. Data are coincident with passage of G5 near the DC HARP during sortie 1. Red arrow as in Figure 15.

Sortie 2

Sortie 2 was conducted for WGH G4 from 5 June to 11 August and for G5 from 5 June to 20 July. The two WGHs were deployed in the GOM starting their mission near Horn Island, Mississippi (Figure 17). G4 ended its mission near the DC HARP site, while G5 was recovered closer to the MC HARP site. On 9 July both Wave Gliders were recovered, inspected and redeployed. During sortie 2 the Wave Gliders transited to multiple sites, including the Deepwater Horizon well site, and spent significant time in water depth of 1000 m or more along the continental slope (Figure 18).

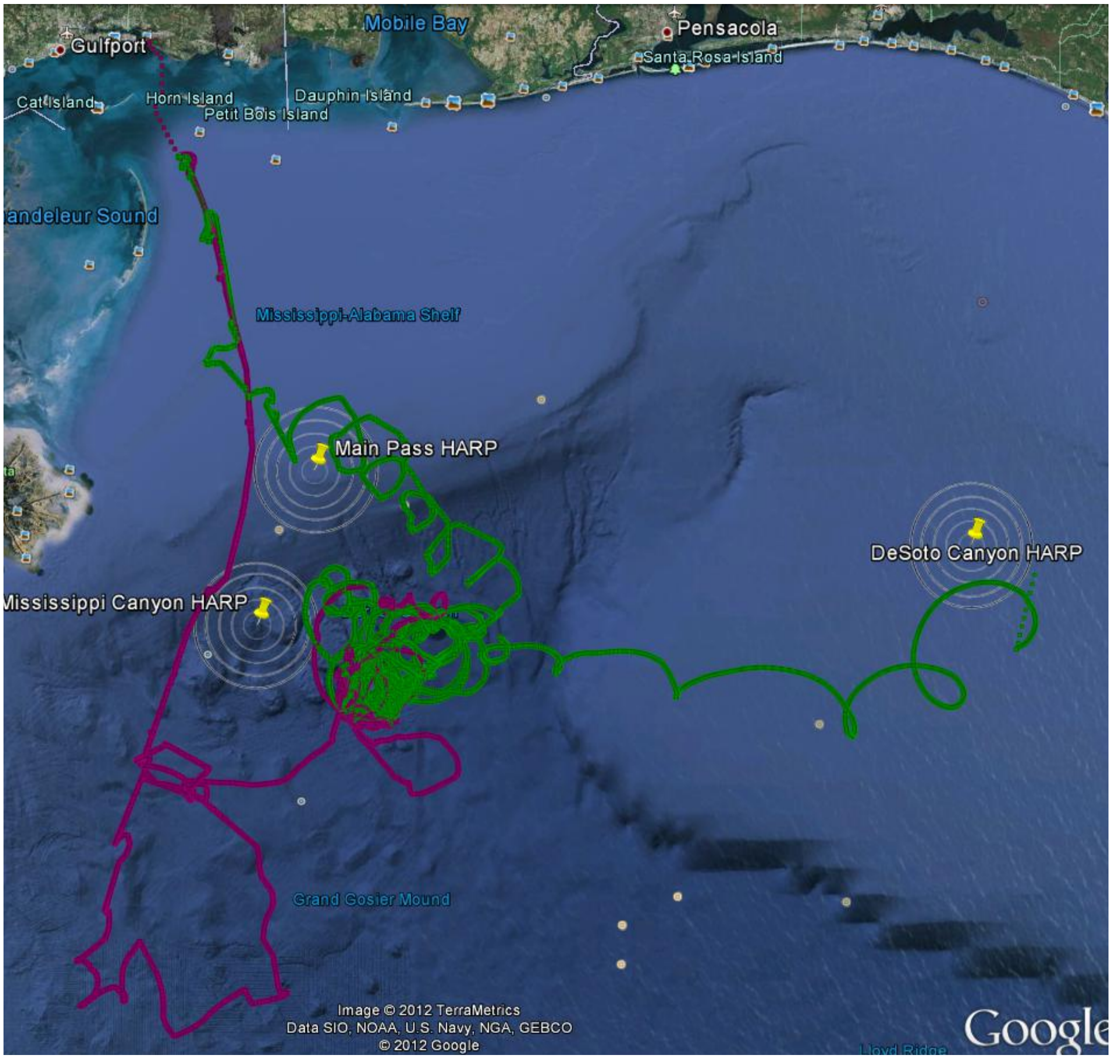


Figure 17: Complete tracks for Wave Gliders during sortie 2 from 5 June to 11 August. WGH G4 is green track and G5 is magenta track. Concentric circles around seafloor HARPs show 2 nm increments.

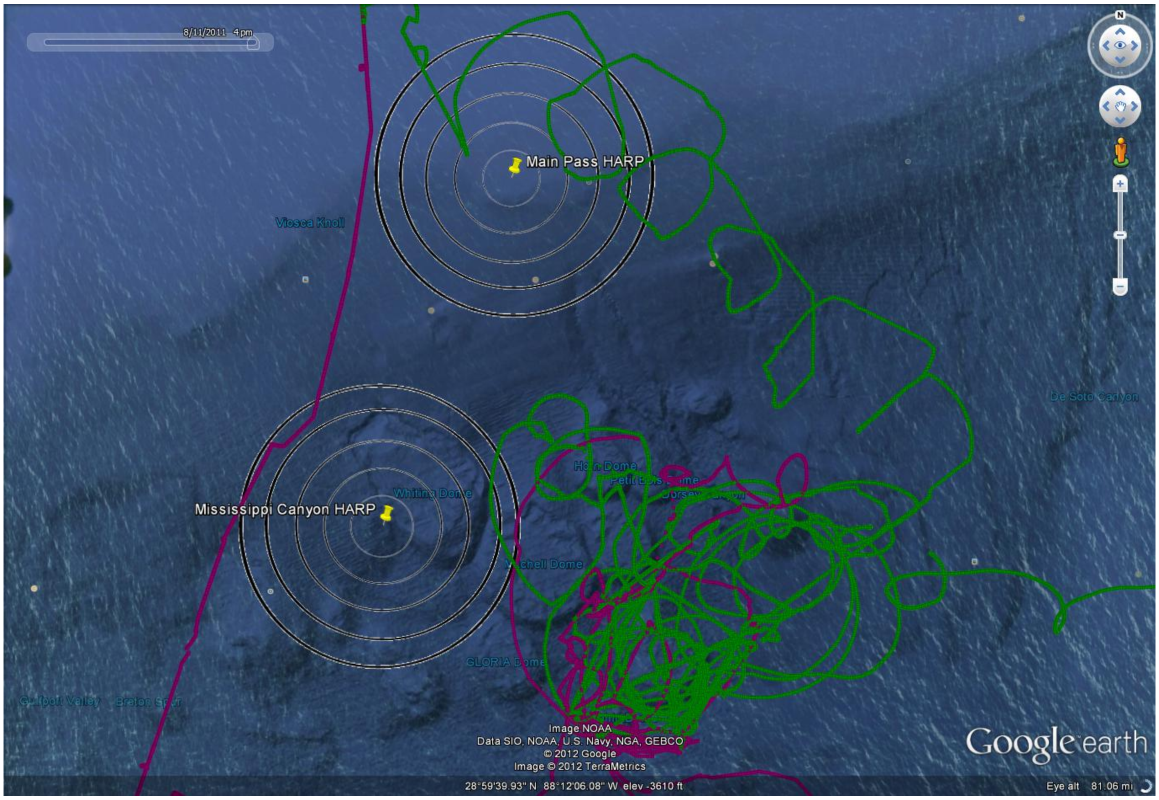


Figure 18: Wave Glider tracks during sortie 2 near MP and MC HARP. WGH G4 is green track and G5 is magenta track. Concentric circles in 2 nm increments.

The performance of both WGH hydrophones during sortie 2 was compromised by intermittent noise, potentially owing to breakdown of the hydrophone electronics owing to repetitive motion from towing. Figure 19 shows an example of degraded hydrophone data from WGH G5 during sortie 2. During the one-hour displayed in Figure 19 (upper panel), over 90% of the data have oscillations that would mask the presence of cetacean calls. A spectrogram with 5 sec of data (lower panel in Figure 19) includes 3 sec of oscillatory data and 2 sec that display sperm whale clicks.

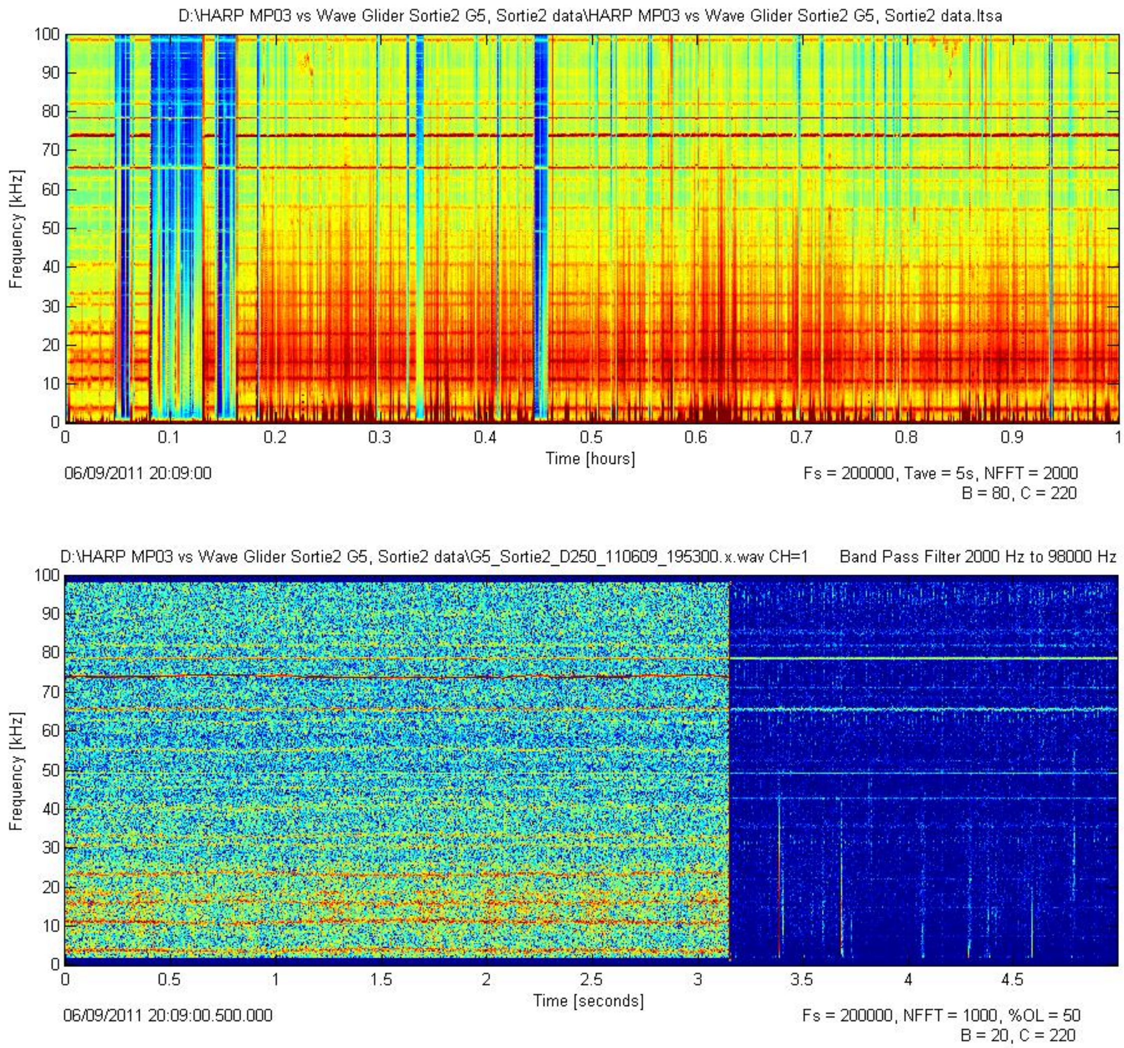


Figure 19: Intermittent hydrophone oscillations for sortie 2 WGH G5 as (top) long-term spectral average, and (bottom) spectrogram. Segments of good data have blue background, whereas those with red-yellow background display oscillations.

The performance of WGH hydrophones during sortie 2 is illustrated in Figure 20; time periods with intermittent electronic oscillations are designated by light red shading. In some cases it was possible to detect cetacean calls (blue bars) despite these oscillations, albeit with diminished detection probability. In addition to hydrophone problems, we could not find data for the period 5 June to 16 July for WGH G4 (Figure 20).

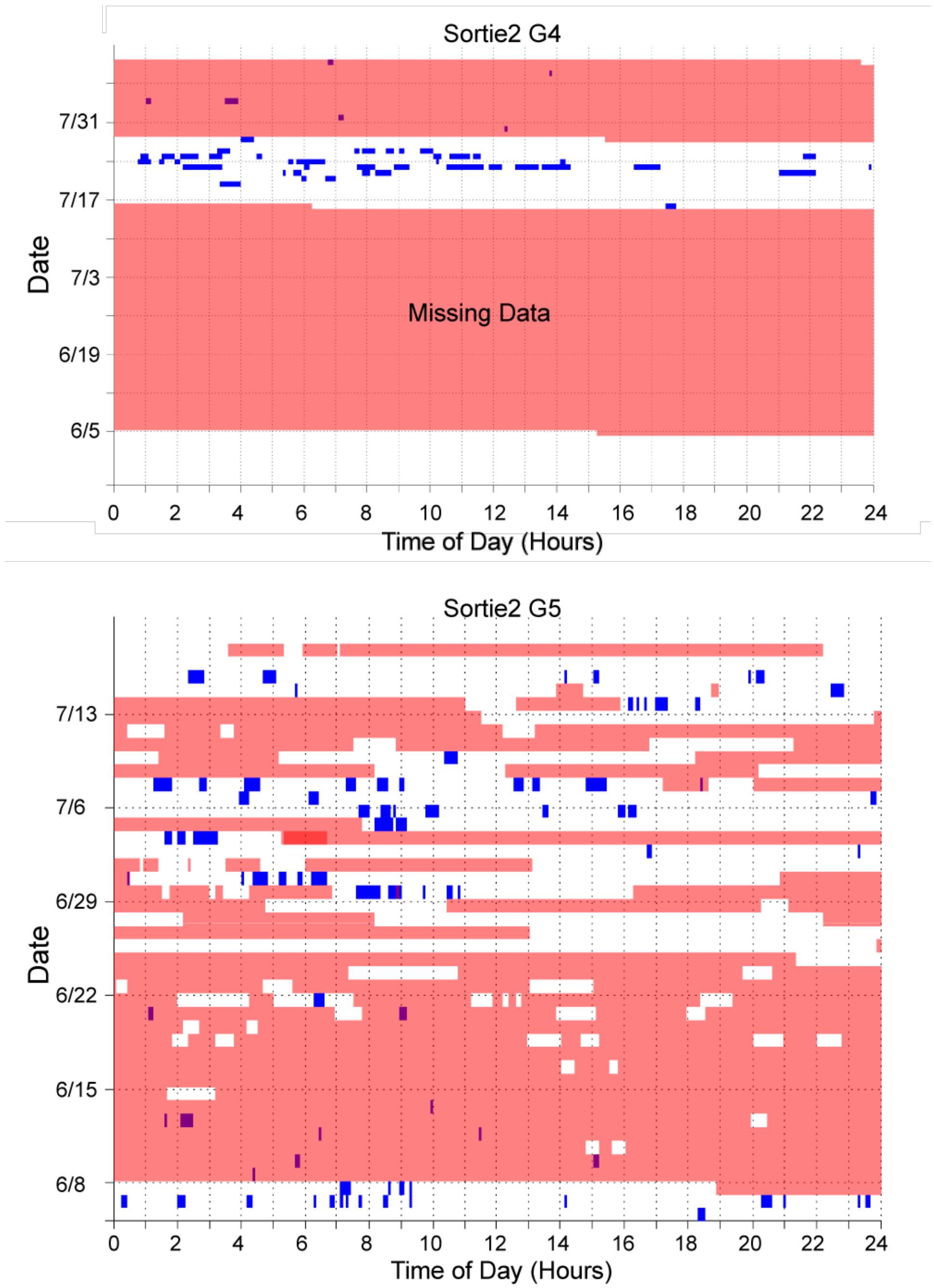
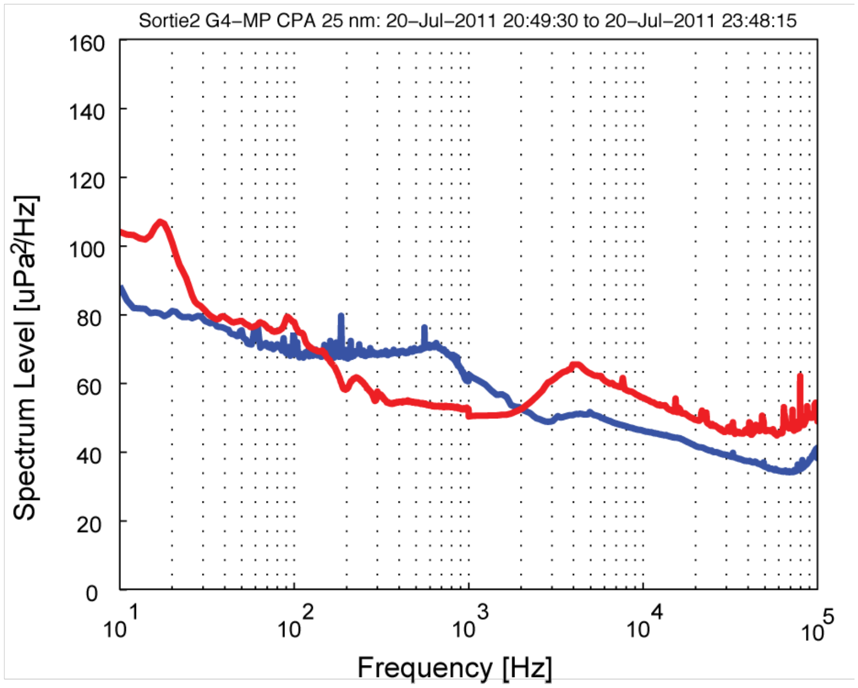


Figure 20: Periods of degraded hydrophone performance and missing data (light red) during sortie 2 for (top) WGH G4 and (bottom) G5. Cetacean detections designated (blue).

Sortie 2 WGH and Seafloor HARP Comparison

Noise spectra for the WGH G4, compared to the MP HARP, and WGH G5 compared to the MC HARP, are shown in Figure 21. These data show WGH G4 noise levels that are comparable to those of the seafloor HARPs below about 1 kHz, whereas WGH G5 low frequency noise levels are somewhat higher than the MC HARP. Above approximately 2 kHz the WGHs exhibit 5-20 dB higher noise levels than the seafloor HARPs.



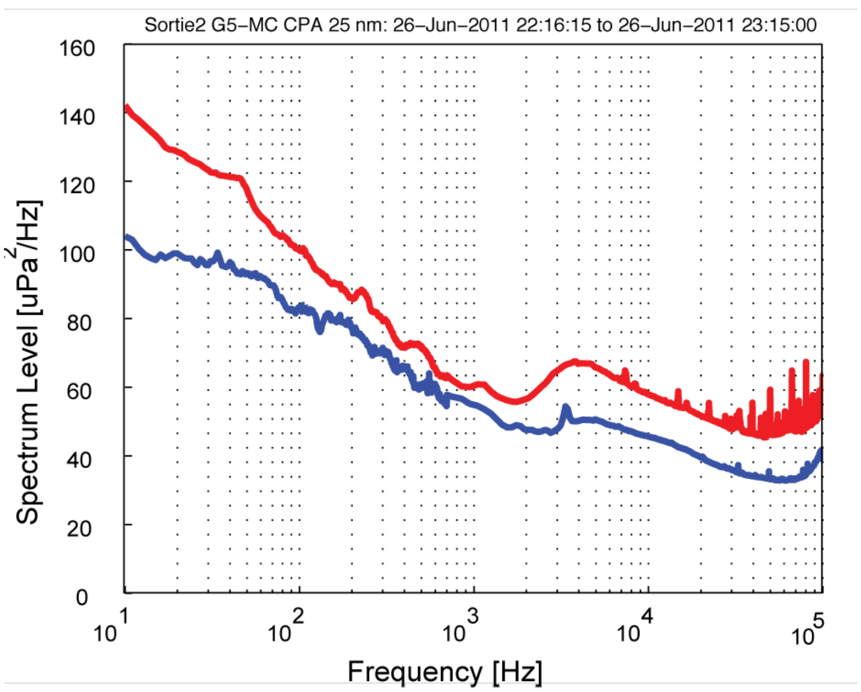


Figure 21: Noise spectrum comparison for (top) WGH G4 (red) with MP HARP (blue) and (bottom) WGH G5 (red) with MC HARP (blue) for 20 and 26 July.

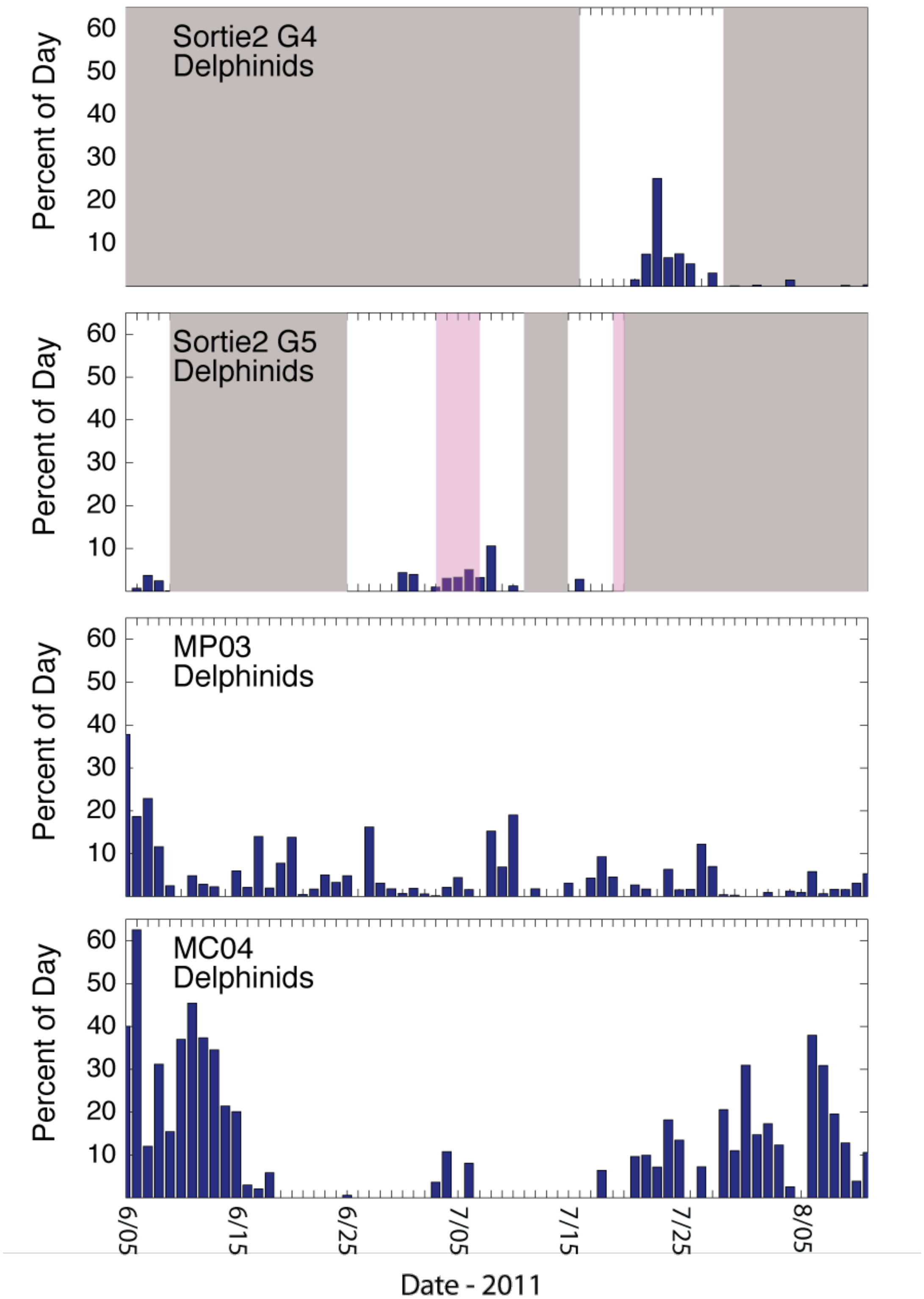


Figure 22: Delphinid detection rates during sortie 2 for (top) WGH G4, (2nd from top) G5, (3rd from top) MP HARP, and (bottom) MC HARP. Gray shading indicates missing or bad data, pink shading times of close proximity between the WGH and seafloor HARPs.

A comparison of daily delphinid detection rates for the WGHs and seafloor MP and MC HARP during Sortie 2 is shown in Figure 22 and sperm whale detection rates are shown in Figure 23. There were higher cetacean detection rates on the seafloor HARPs than on the WGHs, although intermittent WGH hydrophones may be a factor in explaining the differences.

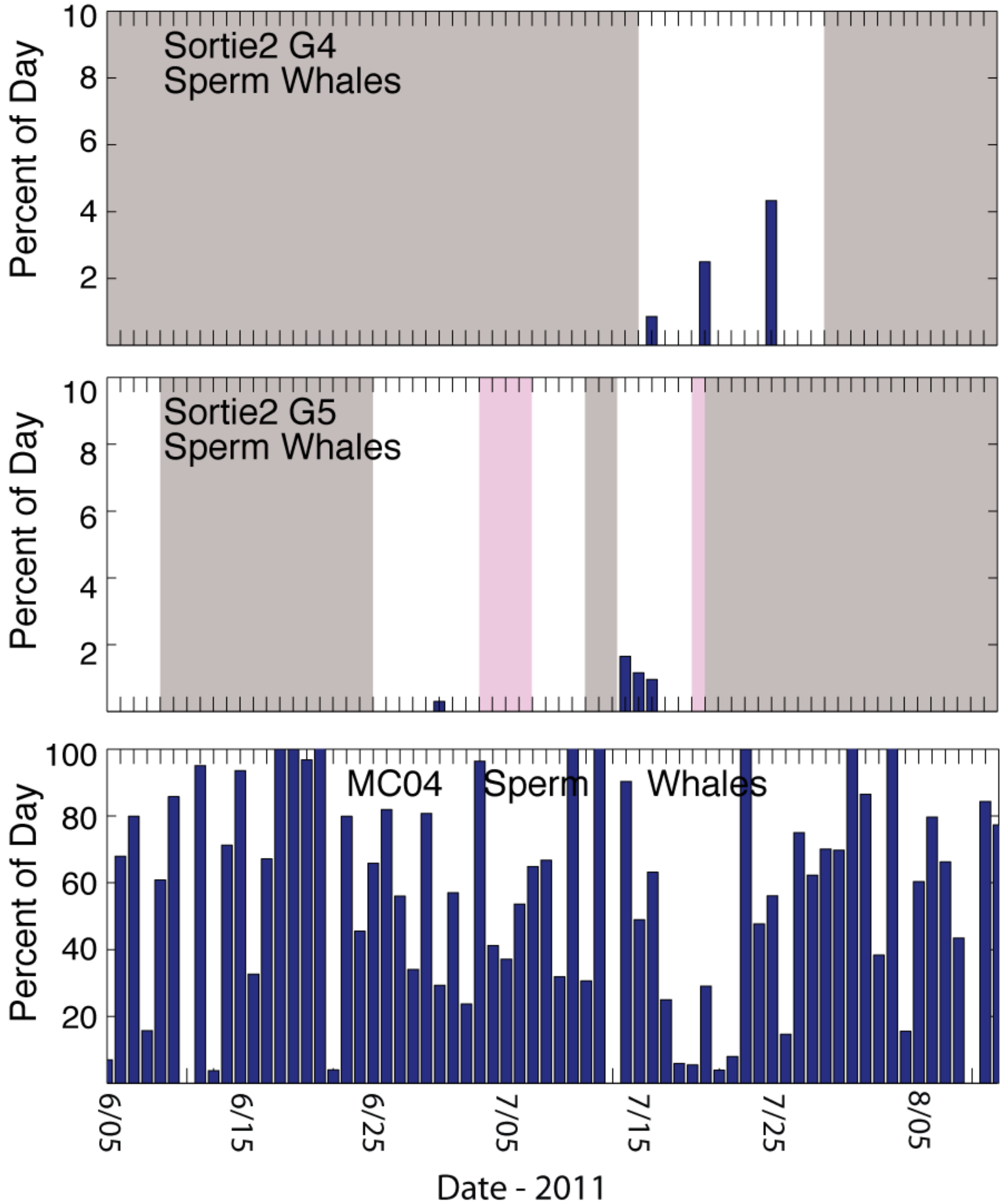


Figure 23: Sperm whale detections during sortie 2 on (top) WGH G4, (2nd from top) G5, and (bottom) MC HARP. Gray shading indicates missing or bad data, red shading times of close proximity between the WGH G5 and seafloor MC HARP. Note the vertical scale differences (10% for WGH and 10% for MC HARP).

On 16 July WGH G5 was about 20 nm from the MC HARP, and sperm whale clicks were detected both by the WGH (Figure 24) and by the MC HARP (Figure 25). The distance between these two sensors suggests that they do not have complete overlap in detection areas for sperm whales; however, it is possible that the same group of sperm whales may have been detected by both instruments.

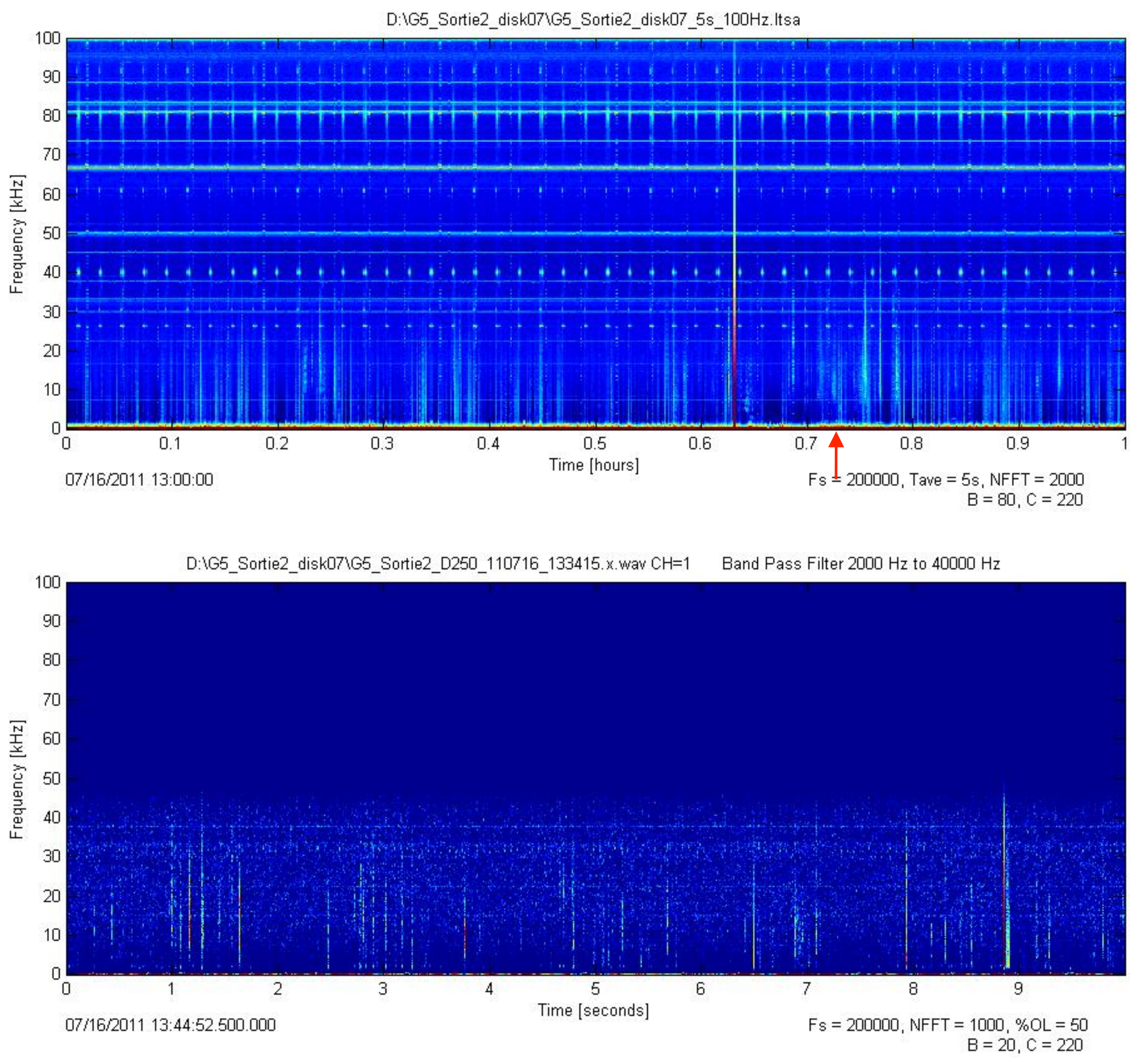


Figure 24: Sperm whale clicks detected during sortie 2 by WGH G5 from the (top) long-term spectral average (1 hour) and (bottom) spectrogram (10 sec). Red arrow shows time of spectrogram. Regularly spaced signals in long-term spectral plot (top) are times of disk writing.

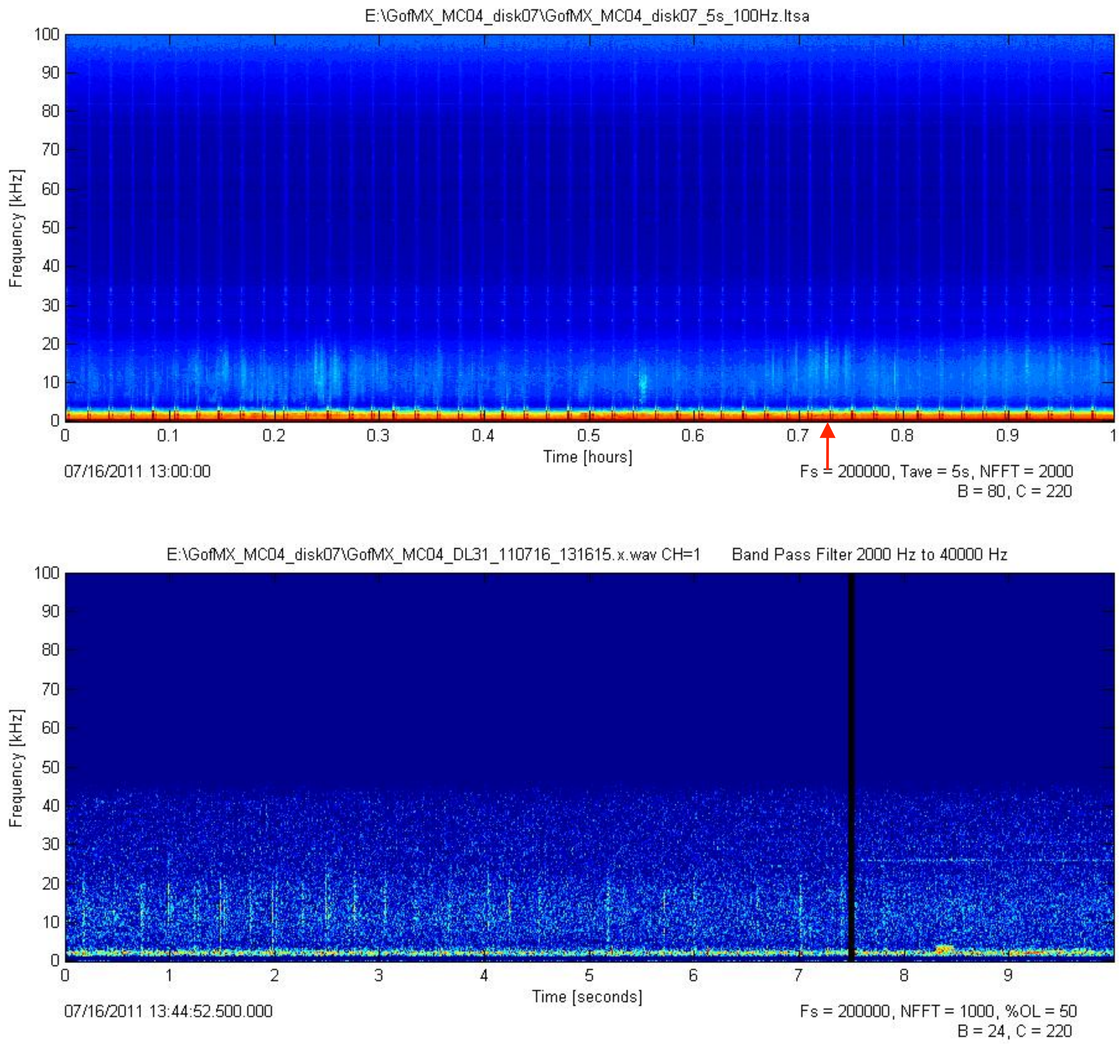


Figure 25: Sperm whale clicks detected during sortie 2 by MC HARP from the (top) long-term spectral average (1 hour) and (bottom) spectrogram (10 sec). Red arrow shows time of spectrogram.

Comparing Cetacean Detection Rates

We compared the daily encounter rates for each instrument in respective habitats to address the question of relative detection rates. To do this, we calculated the percent of total hours in which delphinid and sperm whale calls were detected, and categorized them by sortie and species (Table 6). We excluded from the analysis the WGH G4 during sortie 1 owing to its potentially damaged hydrophone, and time periods during sortie 2 with missing data or malfunctioning hydrophones (Figure 20).

For delphinids, the seafloor HARPs had slightly higher detection rates than the WGH (Table 6). This is particularly true for delphinids on the continental shelf detected by the WGH and MP HARP during Sortie 0, where the seafloor HARP detection rates were significantly higher. It is tempting to postulate that differences in acoustic propagation may be the cause of this discrepancy, although more detailed modeling would be required to test this idea.

For sperm whales, the MC HARP had higher levels of detection than the WGH during Sortie 2 when the WGH spent much of its deployment in deep water. It is possible that this difference is partially due to the damaged hydrophones used on the WGH; their performance during sortie 2 was severely degraded owing to intermittent oscillations (Figure 19).

Table 6. Average daily detection rates (%) and effort (days) for delphinids and sperm whales:

	Delphinids		Sperm whales	
	Detection Rate (%)	Effort (Days)	Detection Rate (%)	Effort (Days)
G4 Sortie 0	2.9	29	0	29
G5 Sortie 0	3.5	29	0	29
MP	11.8	19	3.1	19
G4 Sortie 1	0.1	53	0	53
G5 Sortie 1	4.0	49	0	49
DC	12.6	56	0	56
G4 Sortie 2	3.8	15	0.5	15
G5 Sortie 2	1.5	30	0.1	30
MP	4.7	68	NA	NA
MC	10.1	68	58.0	68

Discussion and Conclusion

During the three WGH sorties, a limited amount of time was spent with the Wave Gliders positioned near (< 2 nm) the seafloor HARPs and with both instruments in good operational condition. This limited the time periods during which direct comparisons could be made between WGH and seafloor HARP recordings. The limited detection ranges for cetaceans and the directionality of their sound sources further limited chances for direct comparison of WGH and seafloor HARP recorded signals. For these reasons, it appears that few sounds were recorded simultaneously by both WGH and seafloor HARPS during this study. In particular, at no time were the WGHs positioned < 2 nm of a deep water seafloor instrument (MC HARP) during this study. This limited our ability to test for simultaneous detection of deep water species such as sperm whales.

WGHs noise levels were sometimes, but not always, higher than seafloor HARP noise levels at low frequencies (< 400 Hz). This may be due to the shallow depth (~8 m) of the WGH hydrophone and the need for it to be towed by the Wave Glider. This suggests that attention should be paid to ensure that the hydrophone is well decoupled from the motions of the Wave Glider. Likewise, the high frequency noise levels of the WGH hydrophone were somewhat higher than those of the seafloor HARP. This could be remedied by using a more sensitive high frequency sensor in the WGH hydrophone. This may entail use of a larger sensing element (e.g. ITC 1042) relative to the one used in this study (HS150) and so hydrophone packaging for minimum drag and flow noise will be important considerations.

When comparing the WGHs and the seafloor HARPs using daily cetacean detection rates, the seafloor HARPs had somewhat higher detection rates for both delphinid and sperm whale calls, both on the continental shelf and in deep water (Table 6). Since delphinids tend to vocalizations near the surface, it was expected that their calls would be best recorded by the WGH, whose sensor is located near the sea surface. Propagation of sound varies with depth and seasonally with the ocean temperature profile. Acoustic propagation modeling may be helpful in understanding why the seafloor MP HARP had higher detection rates for delphinids on the continental shelf than did the WGHs during sortie 0.

Deep-diving animals, such as sperm whales, are detected best by deep sensors, making them more likely to be recorded on the deep water seafloor MC HARP than on the WGHs; however, the poor state of the WGH hydrophones during sortie 2 and the fact that little or no time was spent with the WGH positioned above a deep water seafloor HARP prevented an adequate test of the WGH deep water capabilities during this study.

Evaluation of WGH hydrophone function is a critical aspect of successful acoustic data collection. The hydrophone quality degraded during the course of this study, so that by sortie 2 both WGH hydrophones were only functioning intermittently. The wear due to towing may be an explanation for degradation of WGH hydrophone electronics or wiring.

It would be helpful to conduct another deployment with the WGHs that focuses on positioning them near the seafloor HARPs. In addition, modifications should be made to the WGH hydrophone design to diminish electronic noise and make them more robust for towing. Attention also should be paid to decoupling the WGH hydrophone from Wave Glider motion to improve low frequency noise performance.

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