Exploration of sound disturbance from unmanned aircraft systems in a coastal marine environment

Jackson Floum

Under the supervision of Dr. Douglas Nowacek,
Division of Marine Science and Conservation, Duke University

May 2017

Research Supervisor

Faculty Reader

Director of Undergraduate Studies

Honors thesis submitted in partial fulfillment of the requirements for graduation with Distinction in Biology in Trinity College of Duke University

Abstract

Unmanned Aircraft Systems (UAS) provide a safer, cheaper and more efficient means of collecting and, with accompanying software, processing scientific data compared to conventional survey techniques. Marine Scientists are quickly discovering new applications for UAS that can not only allow them to replace survey tools such as manned aircraft and boats, but also to continue to open new avenues of research, providing the capabilities to answer previously challenging questions. Though assumed to be less intrusive than manned aircraft, there is extremely limited information on the potential for UAS acoustic and visual disruption caused by aircraft hovering or simply passing over animals and habitat.

Anthropogenic sound in the marine environment can be highly disruptive and can alter animal behavior and vital life functions. In shallow coastal zones, boat noise has been shown to influence both vocalization rates and sound intensity of fish calls. No literature exists that has investigated UAS sound in any marine environment. The aim of this study was to provide preliminary data on UAS sound penetration characteristics into the water, as well as data on the effects of UAS engine sound on marine biophony.

Using five separate UAS of various sizes and remote sensing capabilities, I flew at various heights over an autonomous acoustic recording system deployed in a coastal marine environment to learn how UAS sound penetrated the water and if it influenced vocalization rates of all nearby animals or call intensities of oyster toadfish. As hypothesized, lower altitudes and larger UAS had higher sound intensities, and the presence of UAS had no measurable impact on vocal production rate or intensity. I measured no acoustically-mediated disturbance from UAS missions in this developed coastal area. The observations of this study provide robust initial data and preliminary information on UAS acoustics in water and insight into their potential impacts on marine life.

Introduction

Unmanned Aircraft Systems (UAS), or drones, are rapidly becoming ubiquitous tools for data collection in marine science (Jones et al. 2006, Fritz 2012, Hodgeson *et al.* 2013 Ditmer *et al* 2015, and Smith *et al.* 2016), with their growing popularity stemming from the ease with which data can be collected. Aerial surveys have long been critical tools for data collection and the management of wildlife, providing crucial data on habitat conditions, migration routes, and population demographics (Smith *et al* 2016). However, manned aircraft pose safety risks to those flying and are often too expensive to be feasible for most projects. Satellites can provide aerial imaging as well, but low image resolution, image timing, cloud cover and limited coverage all can drastically slow down data collection and limit research opportunity. UAS offer a much cheaper and safer alternative to manned aircraft and allow scientists to quickly collect data at their whim with very high image resolution. Not only are UAS effective at replacing sampling techniques such as manned air and water craft, but they are also rapidly breaking ground in new areas of research, allowing scientists to research in ways never before possible (Duke University Marine UAS Facility).

In addition to their extremely high performance as data collection tools, UAS are much smaller and quieter than manned aircraft, indicating that they are likely less intrusive than conventional means of data collection. UAS cause minimal behavioral disturbance in many animals such as bears and cetaceans (Jones et al. 2006, Fritz 2012, Hodgeson *et al.* 2013 and Ditmer *et al.* 2015), and cause significantly less acoustic disturbance than manned aircraft flying at similar heights (Moreland *et al.* 2015). However, because UAS research is still relatively new, few studies have formally examined their disturbance impacts. While many studies have flown UAS to conduct biological sampling and testing, the disturbance effects of research operations are vastly underreported in the literature (Smith *et al.* 2016).

Though not anecdotally observed, UAS do have high potential to severely disrupt wildlife if used recklessly. The ease with which both hobbyists and commercial pilots can fly poses issues of higher frequency of disturbance. Acute or chronic disturbance can significantly affect individuals, population and species health, and fitness by disrupting normal behaviors such as breeding, feeding and sheltering (Fair and Becker 2000 and Smith *et al.* 2016). UAS have two main forms of disturbance, disturbance from noise and from visual cues from the aircraft. Though there is no conclusive information yet distinguishing disturbance between noise and visual cues as a function of altitude, and that drones are quieter than conventional aircraft (Smith *et al.* 2016), there is still serious potential for noise disturbance by UAS, particularly in marine environments.

Many marine organisms make and rely on sound for communication and as a source of environmental cues (McWilliam and Hawkins 2013). For many species, sounds play a role in vital behaviors such as navigation, foraging, predator detection, and communication (Simpson *et al.* 2004, Slabbekoorn and Bouton 2008, and Janik and Sayigh 2013). The physical combination of all the environmental and biological sound at a certain place and time is called a soundscape (Krause *et al.* 2011). Recently, researchers began to emphasize the impacts of anthrophony on marine soundscapes (McWilliam and Hawkins 2013) due to the likely harmful effects of anthropogenic noise in the water column. Like other forms of anthropogenic disturbance, manmade sound can disrupt travel, rest, calling patterns, foraging, vigilance, and habitat use (for examples see dos Santos *et al.* 2005, Nowacek *et al.* 2007, Heenahan 2016, Shannon 2016). Ocean noise level has been increasing for decades (Frisk 2012) and anthrophony is an increasingly prominent component of marine soundscapes (Gage and Axel 2014), therefore it is crucial to understand the effects of anthropogenic sound in the water column (Heenahan 2016).

The sound scape of the benthic zone is a mixture of snaps, grunts, squeaks, hums and rasps produced by various crustaceans and fishes. Vocal communication in this environment plays many important roles, including: attracting mates, repelling rivals, deterring predators or maintaining territories (Staaterman *et al.* 2011). Fish produce an array of sounds using mechanisms ranging from muscle contractions in the swim bladder to fin movements (Lobel 1992). Anthropogenic noise, mostly from boat engines, has been shown to affect vocalization in benthic environments (Picciulin *et al* 2012, Johansson *et al.* 2016, Luczkovich *et al.* 2016$_a$ and Luczkovich *et al.* 2016$_b$). For example, boat noise has been shown to increase calling rates in brown meagre (Picciulin *et al* 2012), while oyster toad fish have been shown to exhibit the Lombard effect (Luczkovich *et al.* 2016$_a$), increasing both intensity of frequency of vocalizations to overcome background noise, when exposed to boat engine noise.

Although UAS are quieter than other forms of manned aircraft (Moreland *et al.* 2015), their motors and propellers still generate noise that can potentially propagate into the water column and disturb wildlife, particularly when hovering at low altitudes. UAS also pose a unique risk given the lack of certification requirements and vague guidelines for use. It’s not unlikely that a single individual or group could be targeted by multiple UAS, greatly enhancing the probability of disturbance (Smith *et al.* 2016).

Almost all the information on UAS disturbance, particularly Vertical Take Off and Landing (VTOL) drones, is largely anecdotal, with observations mentioned in the context of other research without any empirical data (Smith *et al.* 2016). I was unable to find any published literature on how drone noise penetrates the water column and how it can potentially impact the soundscape. I conducted two experiments that aimed to collect the some of the first empirical data on potential UAS disturbance. The first preliminary experiment explored if UAS sound from realistic mission altitudes can be heard underwater, and how deep the sound can penetrate in a shallow environment. I also examined the relative intensity differences at distinctive depths and altitudes to compare the sound intensities of my experimental flights to each other and to the ambient soundscape. I hypothesized that both flight altitude and hydrophone depth would relate to sound intensity in the water, and that sound intensities would be low, especially at greater altitudes and depths. In the second study, which was influenced by the results of the first study, I examined sound intensities and frequencies of five separate VTOL UAS of various sizes and remote sensing capabilities to investigate potential acoustic disturbance effects of VTOL drones flying over water on biological vocalization rates and intensities. I hypothesized that larger UAS would produce the highest sound intensities in the water column but that no aircraft would induce observable alteration of biological vocalization rates or intensities due to the relatively quiet nature of all UAS. Any extra sound in the water column has the potential to mask vocalizations and disturb, this study is one of the first to provide empirical data on potential UAS disturbance and the first attempt at understanding their acoustic signature underwater.

Methods

Study site

I performed the entirety of this study off of the Social Sciences Dock (34°43’00.21” N 74°40’24.82” W) (Figure 1) on the Western side of Pivers Island at the Duke Marine Lab in Beaufort, North Carolina. The dock extends out into a narrow, dredged channel between Pivers Island and an adjacent sand bar, an area frequented by boats. The area has a steep shoreline with sandy and rocky substrate. Oyster beds are present in the intertidal zone and water level varies greatly with the tidal cycle, fluctuating about five feet between tides during the time of this experiment. Missions for experiment 1 were performed during the slack tide periods just after the high and low tide, when the current moves slower through the channel. Flood tides generally have higher visibility than ebb tides due to the particulate matter flowing out from the Newport River Estuary.

UAS

I flew five separate VTOL UAS from the Duke Marine UAS Facility over the three study days (Table 1). UAS have various remote sensing capabilities with the larger drones capable of carrying heavier, more complex sensors. Due to individual UAS characteristics such as portability, sensor capability, flight time, and ease of operation, the preferred aircraft for scientific data collection is highly mission specific.

Table 1: Aircraft type, weight, maximum flight time and maximum payload weight of VTOL UAS missions flown on 8/2/16, 8/3/16, and 9/17/16.

UAS	VTOL Type	Weight (lbs)	Max Flight Time (min	Maximum Payload (lbs)
3D Robotics IRIS	Quadrocopter	2.8	20	0.88
3D Robotics Solo	Quadrocopter	3.3	25	0.93
MikroKopter XL	Hexacopter	4.9	40	3.5
FreeFly Cinestar	Hexacopter	5.8	30	4.4
FreeFly Alta	Hexacopter	30	45	15

Experimental design and Protocol

Experiment 1:

I collected data during the afternoon low tide on August 2, 2016 and the morning high tide on August 3, 2016. Audio recordings were taken using a sound trap hydrophone set with a sampling rate of 96 kHz on high gain. I then attached the hydrophone to a 10ft piece of rebar and a Secchi disk was attached directly under it in order to obtain water visibility. I deployed the hydrophone, with Secchi disk attached, at .5m, 1m, and 1.5m each day. Once deployed at the specified depth, the hydrophone recorded continuously for at least ten minutes before flights started in order to record a short, instantaneous signature of the ambient soundscape. I flew a 3D Robotics Iris+ UAS over the sound trap, stopping for one minute at 20m, 10m and 3m above the surface of the water. I flew the drone semi-manually in loiter mode, which holds stability and a GPS waypoint without human correction on the transmitter. Using the right and left sticks on the transmitter, the pilot effectively moves the GPS position that the IRIS+ is locked to, causing it to move in the desired direction. I mounted a Go Pro Hero 3 to the UAS on a downward facing gimbal and recorded 4k video during all the flights in an effort to obtain visual sight on the Secchi disk under the sound trap, as well as any potential movement from disturbed animals. The three flights on August 2, 2016 occurred between 14:13 and 15:28, just after the low tide of -1.4 feet at 14:02. The three flights on August 3, 2016 occurred between 9:14 and 10:35, just after the high tide of 3.36 feet. In between the flight at 1m sound trap depth and 1.5m sound trap depth on 8/3, it started to rain, so operations paused for the weather to subside before flying, adding an extra 30 minutes to the sound trap deployment time.

Experiment 2:

I collected data during nine flight missions occurring during the morning high and afternoon low tides on September 17, 2016. Audio recordings were sampled using identical calibrations as in experiment 1, and I attached the hydrophone to a ring stand and deployed it from the edge of the dock. The hydrophone remained at a fixed distance from the seafloor at ~.5m. I deployed the hydrophone at 8:32 with the experiment starting at 8:37. The hydrophone recorded continuously for the duration of the experiment with 10 minute intervals between each flight. The five UAS flown were the IRIS+, 3DR SOLO, MikroKopter XL, Cinestar and Alta (Table 1). Each aircraft flew a mission during the morning high tide with a maximum flood of 4.16 feet and afternoon low tide with minimum of 0.0 feet, except for the Alta which only flew one mission starting at 11:20, two hours and twenty-five minutes after the high tide. UAS were operated by Julian Dale, lead engineer of the Duke Marine UAS facility. Each UAS was flown over the deployed sound trap stopping at 3m, 10m and 20m for one minute each before ascending slowly to 30m and returning to launch. Each flight lasted between six and seven minutes. Morning flights occurred between 8:47 and 9:50 and high tide flights occurred between 14:28 and 15:21. The hydrophone remained deployed and recorded continuously throughout the duration of the experiment and was retrieved ten minutes after the final flight ended at 15:22.

Figure 1: A sound trap hydrophone was deployed off the Western side of Pivers Island at the Duke Marine Lab in Beaufort, NC, (34°43’00.21” N 74°40’24.82” W).

Data analysis

I analyzed audio files using the audio analyzing software Raven Pro 1.5. I used Raven Pro 1.5 to listen to each audio file and generate a spectrogram of the sound waveform for the duration of each deployment. For experiment 1, I set discrete Fourier transform (DFT) size to 9502 samples and zoomed the viewing window to 1.4kHz to effectively visualize the drone engine signature in the spectrogram. For experiment 2, I set DFT size to 7033 samples and zoomed the viewing window to 2.8kHz to best visualize both engine signature and biological sound. I analyzed audio files both visually and aurally to manually inspect for UAS engine noise at each height and depth in experiment 1.

In addition to UAS engine noise at each altitude, in experiment 2 I manually selected all anthropogenic (i.e. boat engine noise and pile driving) and biological sound (except for the constant snaps of snapping shrimp) ten minutes before, during, and ten minutes after each flight. With the assistance of Dr. Douglas Nowacek, I identified and categorized known calls by species. Using Raven Pro 1.5, I selected segments of the drone signature in the frequency spectrum to obtain average relative power and maximum relative power. Of the harmonic bands in the drone signature, I selected and sampled the darkest in color (indication of being loudest). Sound levels were similar in the fundamental frequency band and first two harmonic bands. Due to logarithmic scale of the decibel, sampling only one band caused the difference between the sampled and overall intensities to be negligible. I selected and averaged at least three 10-20 second segments per altitude to obtain both an accurate and precise representation. However, in many cases, harmonic bands occurred at the same frequency of snapping shrimp snaps or other biological or anthropogenic sounds. To avoid sampling shrimp snaps, which can occur more than twice per second, I sampled and averaged numerous very short segments in between snaps to obtain overall intensity levels and minimize contamination from other sound sources. For every instance of boat engine noise observed, I selected the entire duration of the engine signature to obtain both the total time that the area was affected by boats and their relative sound intensities. Additionally, I sampled broad spectrum background noise in experiment 1. Background noise was randomly selected in at least 4 long (minimum 1 min) segments before the flights started, and one time after mission completion to compare sound intensity of the IRIS+ to ambient sound levels in the water. Average and max power for broad spectrum background noise was calculated by finding the average and maximum intensity measurement within each background noise selection, and then averaging those values for in between each mission to create a mean average and mean max power for each hydrophone deployment.

For the final two flights on 8/3/16, at 1m and 1.5m depth respectively as well as for at least some of every flight on 9/17/16 except for the morning IRIS+ flight, boat noise masked the lower, louder harmonics of the UAS signature. Boat noise was present for the entire duration of the Alta flight.

I estimated vocalization rates by counting vocalizations for every minute and averaging to obtain rate per minute estimations during flights (FB), in the presence of boat noise (B), with UAS noise but no boat noise present (F), and a control without boat or UAS noise (C). Estimations were likely lower than actual vocalization rates due to both manual selection techniques and the likely presence of chorusing, multiple animals calling in unison, which has been shown in benthic fishes and crustaceans (Staaterman *et al.* 2011 and Picciulin *et al.* 2012). I ran a one-way ANOVA in Microsoft Excel to compare means between C, B, FB, and F to determine if and which anthropogenic noises affected vocalization rates. I also ran two t tests to compare mean average sound intensities between boat and UAS engine noise and mean maximum sound intensities between boat and UAS engine noise. I also ran two simple linear regressions comparing average vocalization rates during the entire flight (all altitudes) of each aircraft to its weight for both high and low tide. Because the Alta was flown only once at mid tide, it is included in both regressions. I calculated vocalization rates for the entire sampling period using Microsoft Excel by counting all vocalizations in five minute segments and averaging them to obtain per minute estimations. To test the presence of the Lombard effect, I compared average call intensities of oyster toad fish calls using t tests in Microsoft excel. T tests involving C were done using a one tailed t test because calls necessarily get louder from background noise while the other t tests were two tailed to see if any difference existed.

I manually inspected Go Pro footage from experiment 1 for visual sighting of the Secchi disk and for potential biological movement. I did all statistics using Microsoft Excel with a confidence level of 95% and created figures using Google Earth, Raven Pro 1.5 and Microsoft Excel.

Results

Experiment 1

I performed a total of six flight missions over two days, three taking place at high tide and three at low tide. For every flight on both days (.5m, 1m, and 1.5m hydrophone depths), I detected IRIS+ motor noise at all three altitudes flown. IRIS+ motors emitted frequency signatures leaving four harmonic bands, 225Hz, 450Hz, 650Hz, and one faint harmonic band at 1025Hz.

I detected the sound at all depths and altitudes, however relative sound levels emitted from the drone neither exceeded nor matched the maximum, or even the average, sound intensity in the ambient soundscape at any point (Table 2).

Table 2: Average relative sound power measurements (in relative dB) for each depth of the hydrophone (rows) and altitude of the aircraft (left columns), as well as the average and maximum relative broad band background sound power for each recorder deployment (right columns). The loudest powers are highlighted in green, the quietest in blue, UAS noise never reached levels of background noise. Low tide missions were flown on 8/2/16 and high tide missions were flown on 8/3/16.

		UAS		Broad Spectrum Background Noise	
Low Tide	Power 20m (re dB)	Power 10m (re dB)	Power 3m (re dB)	Avg Background Power (re dB)	Max Background Power (re dB)
0.5m	33.83	39.9	42.767	44.767	88.4
1m	35.067	36.6	39.6	44.65	82.6
1.5m	38.267	40.2	40.467	44.25	80.8
High Tide	Power 20m (re dB)	Power 10m (re dB)	Power 3m (re dB)	Avg Background Power (re dB)	Max Background Noise Power (re dB)
0.5m	32.25	32.333	37.9	48.3	83.4
1m	33.367	39.225	40.96	48.675	80.5
1.5m	33.433	33.7	37.947	48.575	84.3

Within five of the six flights, UAS sound intensity increased as the drone altitude decreased, indicating the likely inverse relationship between altitude and sound intensity in the water. Drone noise was louder at low tide than high tide during hydrophone deployment depths of .5m and 1.5m, while the hydrophone deployed at 1m recorded higher intensities at high tide (Figure 2).

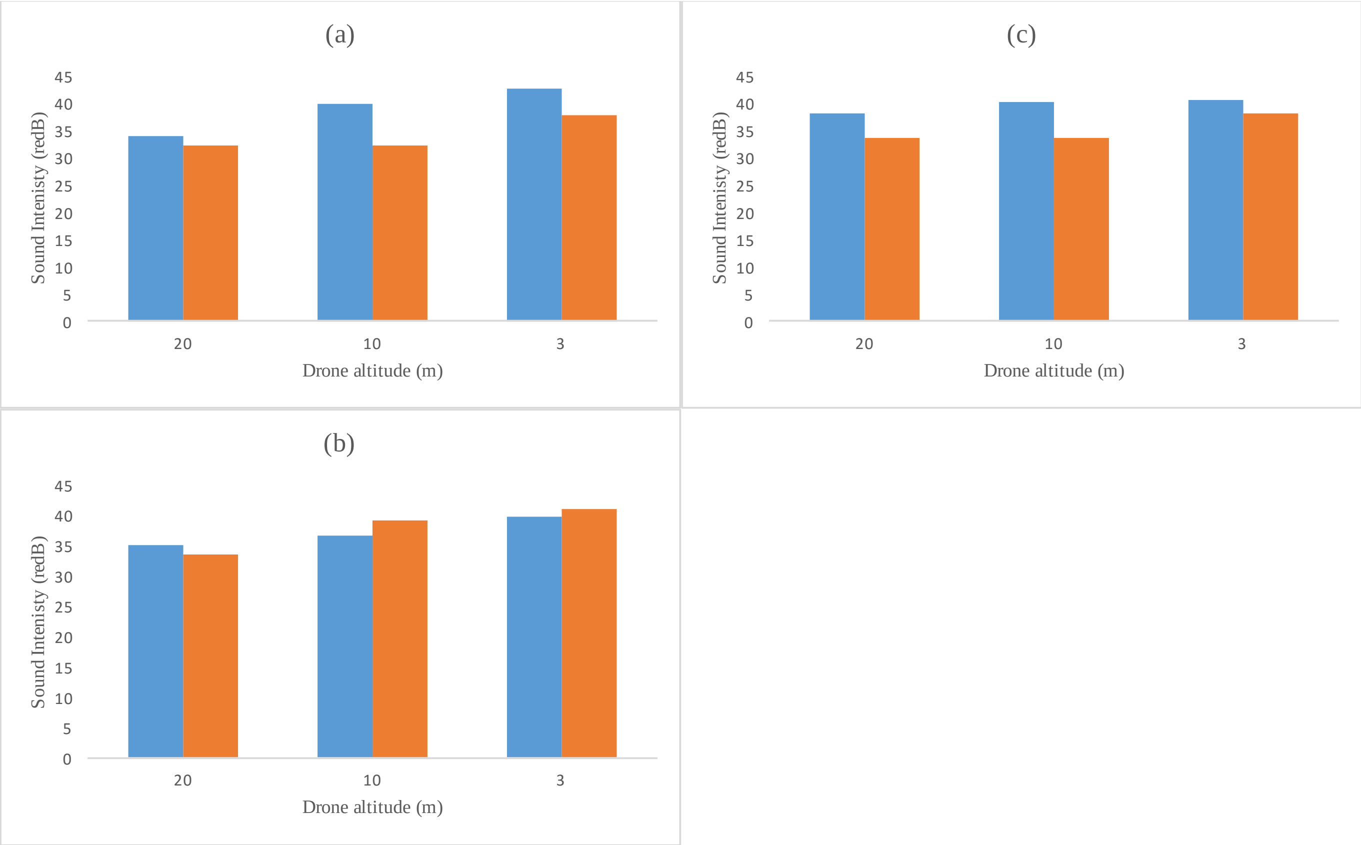

Figure 2: Representation of relative sound intensities of IRIS+ at hydrophone deployment depths of .5m (a), 1m (b), and 1.5m (c). Blue bars represent flights flown at low tide on 8/2/16 and orange bars represent flights flown at high tide on 8/3/16.

While altitude appeared to correlate with sound propagation in the water, depth of the recorder did not, with no clear pattern emerging, deeper hydrophone deployments did not record lower sound intensities than more shallow ones (Figure 3).

Weather conditions were not optimal on either day, with wind speed reaching 20mph (the limit of the IRIS+) on 8/2, and rain on 8/3. The Secchi disk was detected via video footage for every flight except for 1m and 1.5m deployments at low tide on 8/2 and no movement from any organism was seen during any flight.

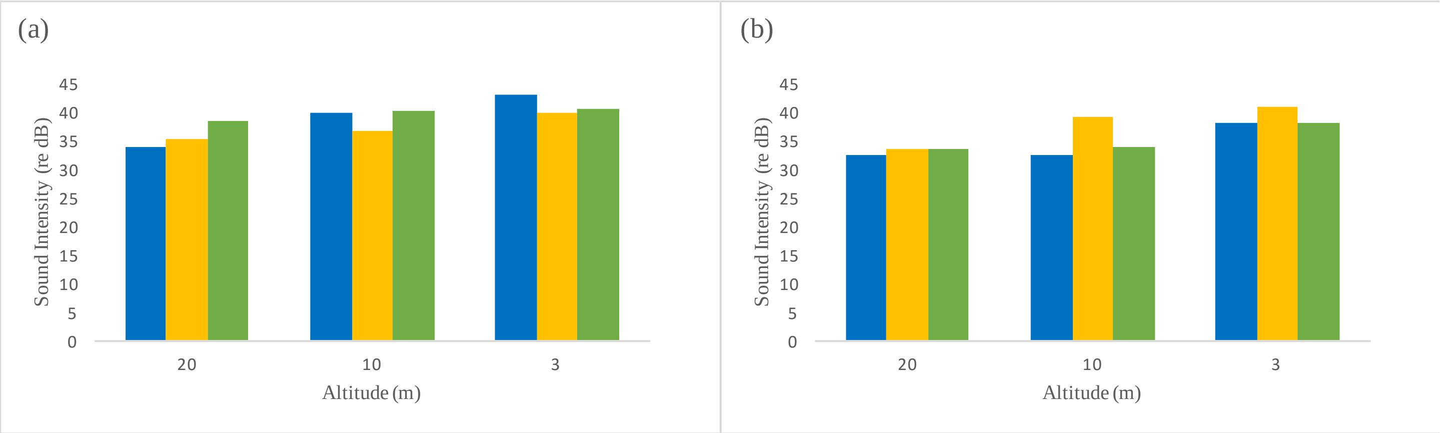

Figure 3: Representation of relative sound intensities by altitude at low (a) and high tide (b). Blue bars represent .5m hydrophone deployments, orange bars represent 1m and grey bars represent 1.5m.

Experiment 2

A total of nine flights took place on 9/17/16, four flights during the morning high tide, four flights during the afternoon low tide and one flight at the mid-level ebb tide. I detected each UAS at every altitude and they all had a unique frequency signature. The Solo emitted a frequency signature with a fundamental frequency at 225Hz, and harmonic bands at 450Hz, 675Hz and 900Hz, the MikroKopter XL emitted a fundamental frequency at 300Hz, and harmonic bands at 425Hz, 550Hz, 700Hz, 850Hz, and 1000Hz, the Cine Star emitted a fundamental frequency at 150Hz, and harmonic bands at 325Hz, 475Hz, 600Hz, and 725Hz, and the Alta emitted a fundamental frequency of 200Hz and seven harmonic bands up to 500Hz. The largest UAS, the Alta, had the highest average and maximum relative sound intensities while the smallest UAS, the IRIS+, had the lowest (Figure 4).

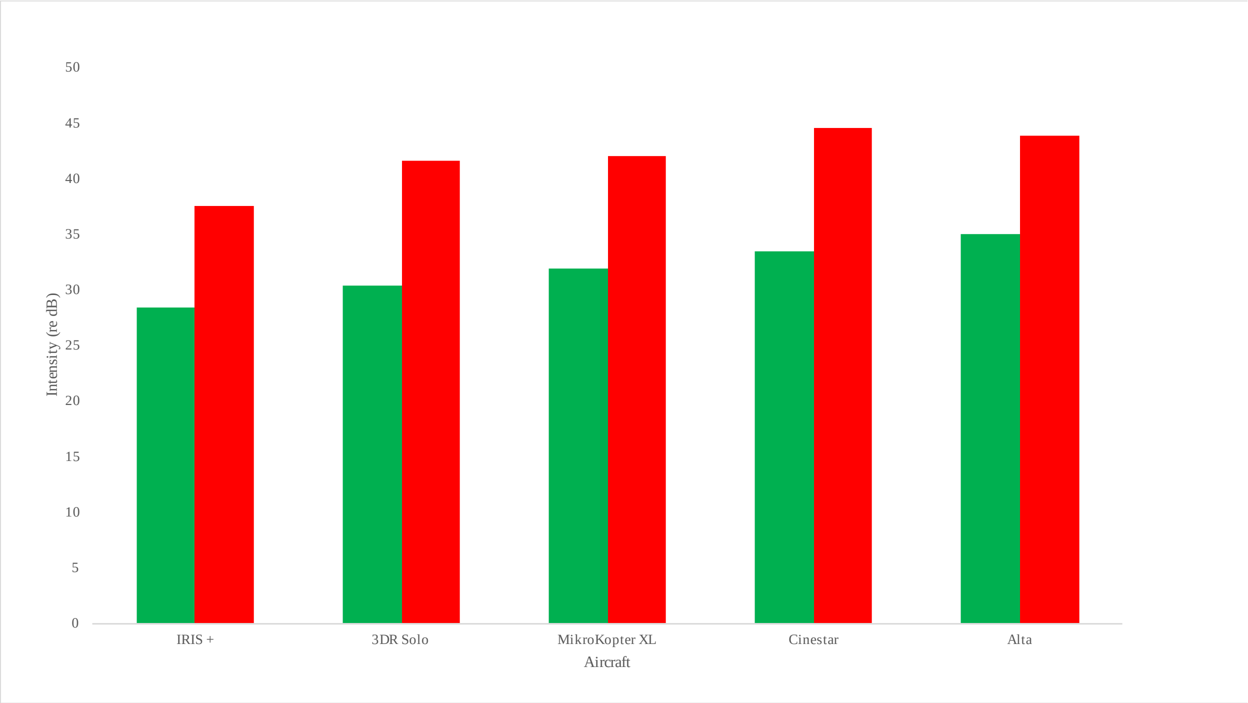

Figure 4: Relative sound intensities of the five UAS in experiment 2. UAS weight increases from left to right on the X axis, red bars represent average max intensity of selections and green bars represent mean average intensity.

UAS had lower average relative sound intensities (mean = 31.72) and maximum intensities (41.75) than boats (mean = 43.85, 67.61) with the maximum intensity for a drone falling well below the max intensity for a boat (Table 3). T tests showed differences between average intensities ($t_{(39,\ 2)}$ = 6.16, p = 3.14794E-07) and average max intensities ($t_{(42,\ 2)}$ = 15.54, p = 5.04871E-19). In total, of the 3 hours 8 minutes sampled and processed, boat engine noise was present for 1 hour 49 minutes, UAS engine noise was present for 53 minutes and there was neither boat nor UAS noise was present for 45 minutes.

Table 3: Average, average maximum and maximum sound intensity levels for boat and average of all 5 UAS engine noise (relative dB).

	Average Intensity (re dB)	Average Max Intensity (re dB)	Max Intensity (re dB)
UAS	31.72206573	41.74553991	60.3
Boat	43.85945946	67.61081081	87.6

During the first sampling interval, vocalization rates rapidly fell and leveled off around five calls per minute, during the second and third sampling intervals vocalization rates fluctuated between about 5 and 12 per minute (Figure 5).

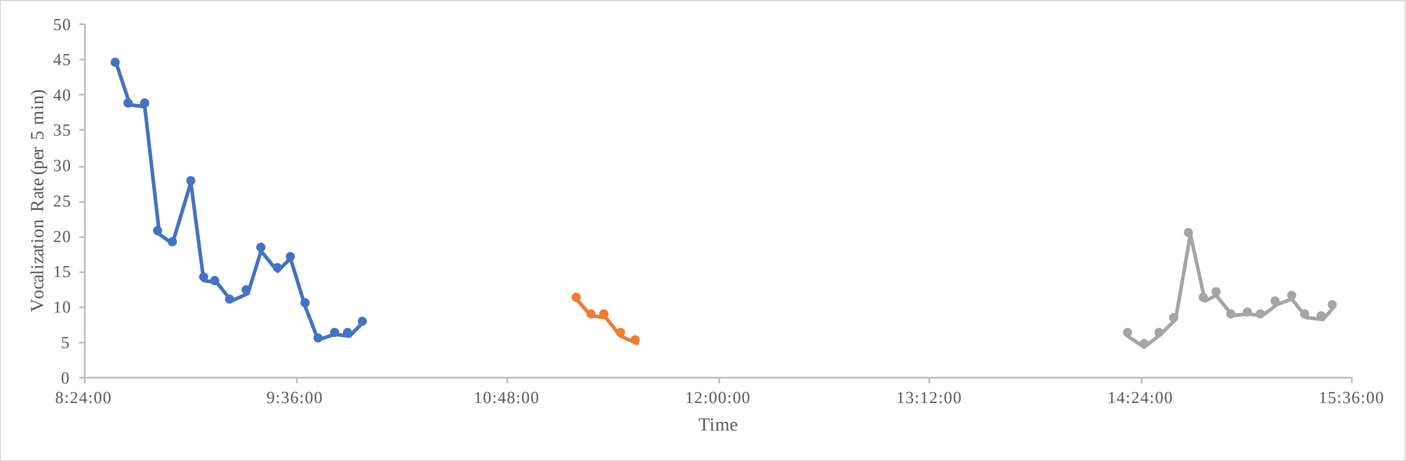

Figure 5: Total biological vocalization rates per minute over the three sampling intervals on 9/17/15 with a continuously recording hydrophone with a fixed distance from the seafloor. The blue indicates the sampling interval for the morning high tide flights, the grey indicates the sampling interval for the afternoon low tide flights and the orange indicates the sampling interval for the one Alta flight. Blank space indicates non-processed time intervals.

I observed 10 distinctive call types, including vocalizations from oyster toadfish, sand and spotted sea trout, silver perch, cusk eel and five unknowns. Sand sea trout calls vastly outnumbered the calls of any other species. I ran a one-way ANOVA to determine if total vocalization rates were affected by either UAS or boat engine noise. Average per minute vocalization rates of C (mean = 16.04), B (mean = 12.48), FB (mean = 11.95), and F (mean = 11.68) showed no statistical difference (df = 265, f = 1.75, p = .158), indicating that neither boats nor UAS influenced vocalization rates during the experiment.

Flight altitudes also showed no apparent influence on vocalization rate, but generally vocalization rates were higher in the morning during high tide (Figure 6). Aircraft weight also did not correlate to average vocalization rate at either high or low tide (r^2 = .26, t = -1.02, p = .38), (r^2

= .0024 t = -.08 p = .93), indicating that the size of the aircraft did not affect the level of behavioral response in the study site.

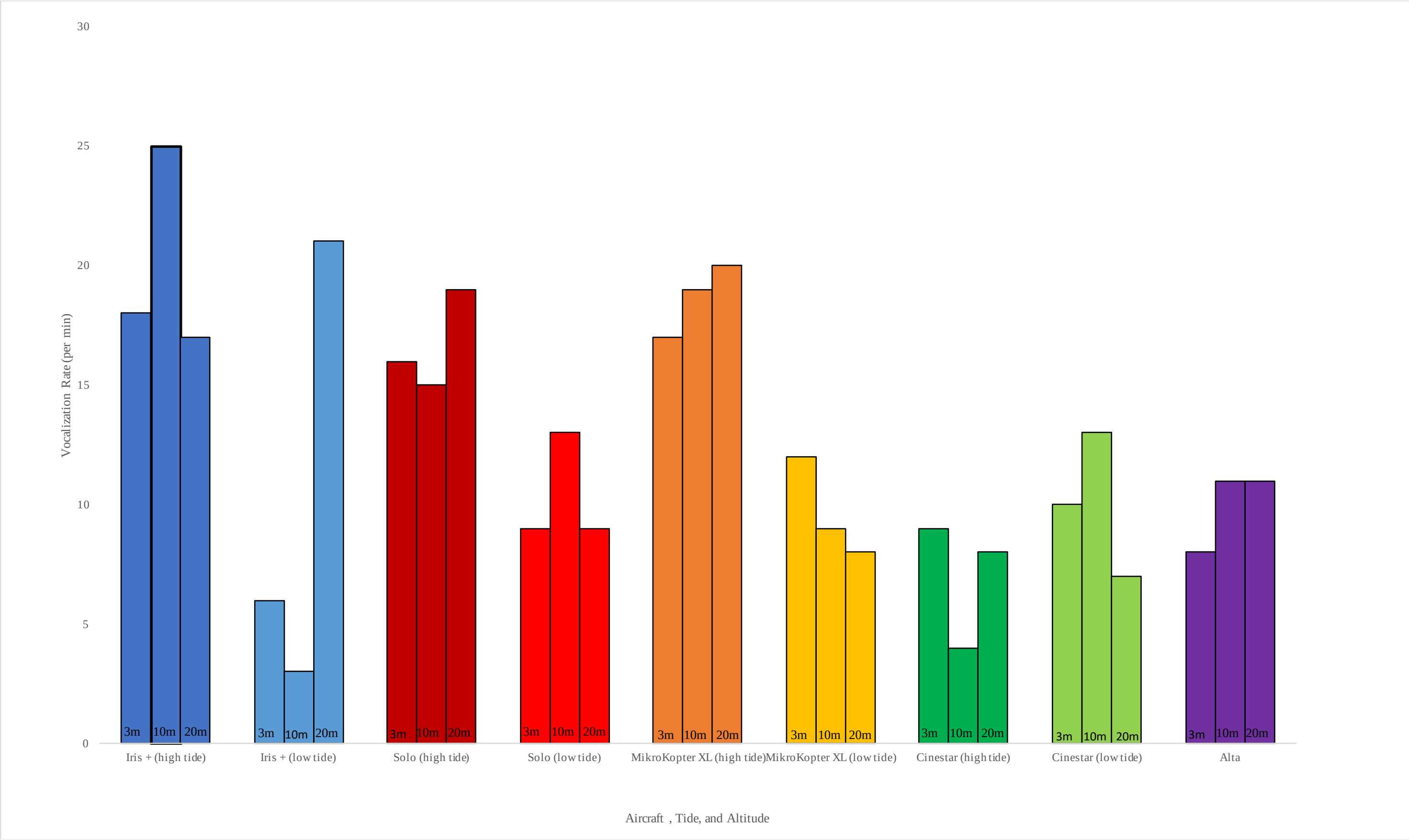

Figure 6: Vocalization rates of all flights and altitudes. UAS listed in order of increasing weight from left to right on the X axis. Blue bars = IRIS+ flights, red bars = Solo, orange bars = MikroKopter XL, green bars = Cinestar and purple = Alta.

To determine if UAS induced the Lombard effect, I compared mean intensities of oyster toadfish calls. I selected oyster toadfish because they have been observed to exhibit the Lombard effect in the presence of boats (Luczkovich 2016_a). I compared average intensities of C (mean = 32.5 re dB), B (mean = 35.73 re dB), FB (mean = 35.24 re dB) and F (mean = 34.74 re dB) for oyster toadfish using five t tests, C vs. B ($t_{(63, 1)}$ = -1.61, p = .056), C vs. F ($t_{(34, 1)}$ = .77 p = .22), C vs. FB ($t_{(56, 1)}$ = 1.41, p = .13), B vs. FB ($t_{(49, 2)}$ = -.23, p = .82), and B vs. F ($t_{(27, 2)}$ = -.34, p = .71).

No average intensities of toadfish calls differed, indicating that neither boats nor UAS caused toadfish to increase the intensity of their calls.

Discussion

Characteristics of UAS sound

As hypothesized, UAS altitude appeared to correlate with sound intensity levels in the water. Higher altitudes generally yielded lower sound intensities. This is to be expected due to the sound intensity inverse square law, $I=P/4\pi r^2$ where I = sound intensity P = source power and r = distance from source. Sound intensity emitted from the UAS increased exponentially as the drone descended and moved closer to the hydrophone, and due to the extreme density change at the surface, the loss of intensity at the air-water interface was greatly reduced (Zhang and Peng 2014).

Though I hypothesized that hydrophone depth would relate to sound intensity, I failed to consider the complicated nature of sound reflections from the seabed and surface. Every depth in this study was relatively shallow, with a max of 1.5m. The seabed of the study site was scattered with hard surfaces, excellent for reflecting sound waves, and the extreme density difference at the water-air interface is almost a perfectly reflective surface, only allowing very low frequencies to pass through via anomalous transparency (Godin 2006 and Glushkov *et al. 2013)*. Due to the shallow study site and the highly complex nature of sound propagation in shallow water, in which intensity can be higher at increased depths (Chapman 1989), the lack of correlation between hydrophone depth and intensity is likely consistent with current shallow water sound propagation models.

During the low tide missions on 8/3/16, the wind was relatively strong, up to 20mph, slightly disturbing the surface of the water. Although wind speeds were much slower during the high tide flights, it lightly rained during flights, also disturbing the surface of the water. Zhang and Peng (2014) found that disturbance at the surface of the water scatters the sound waves entering the water by changing the angle of refraction entering the water, thus more disturbed water can lower sound intensity at the surface. However, the study site is well protected by the barrier islands of the Rachel Carson Reserve so water disturbance remained at a minimum. Additionally, while flying at low during many of the missions, wind from UAS props disturbed the surface of the water likely increasing scattering.

Although sound entering the water likely didn't lose much power from the air, sound intensities in the water were still very low, never even reaching ambient sound intensities. This is likely due to low source intensity, scatter from the non-smooth water surface, and a vibrant soundscape of biophony and anthrophony. The study area is frequented by boat traffic and all the maximum sound intensities measured in the ambient soundscape, which dwarfed that of the UAS, came from boats well outside the study channel (see Figure 1, Table 2). Also, as expected, larger heavier UAS with more and larger rotors were louder than the smaller UAS, but even the largest drone, the Alta, had an average max intensity more than 24dB lower than average max intensity of boats. Interestingly, all UAS frequency signatures were very similar to those of boats not visually detected during surveying, likely losing their high-energy frequency wave bands over a long distance to absorption. With boat noise present for almost two of the three hours sampled in experiment 2 compared to only 45 minutes of UAS noise, it is far likelier that boats have larger disturbance potential than UAS in this area.

Water visibility did not remain consistent across the two days in experiment 1. In this area, visibility is generally better during flood tides than ebb tides due to the presence of murkier estuarine water during ebb tides. The opposite was observed here, but a variety of highly variable environmental factors determine water visibility each day, causing the prediction of water visibility to be nearly impossible. Low water visibility in this area potentially could have prevented the camera from detecting any animal response if present. Low tide recordings of UAS being louder than high tide recordings was likely dependent on a variety of environmental factors and human error, such as wind speed, current speed, salinity, temperature and operator imprecision.

Effect on biophony

With the continual rise of sound intensity and anthropogenic noise in the water column (Frisk 2012 and Gage and Axel 2014), UAS offers a much quieter, and likely less intrusive alternative to boats and manned aircraft (Moreland *et al.* 2015) for data collection that doesn't match ambient sound levels even when flown directly above the surface of the water. One of the major risks from anthropogenic noise is masking, which can disrupt communication and cause confusion (dos Santos *et al.* 2005), but in this study, engine noise intensity was so low that I had to actively select sections of frequency bands with as little ambient noise as possible to avoid snapping shrimp or fish masking the UAS sound signature. But even though UAS's are quieter than other forms of anthropogenic noise, it's still important to understand any possible impact on wildlife, because even sound levels significantly lower than boats or manned aircraft may still be harmful given the sensitivity to and reliance on sound in these marine animals.

UAS engine noise yielded no change in vocalization rates or intensities relative to the control or presence of boat engine noise. Surprisingly, the presence of boat engine noise also yielded no change in vocalization characteristics when compared with the control. Studies have shown physiological stress responses in fish from boats, but that repeated and prolonged exposure can cause them to habituate, decreasing the response (Johansson *et al.* 2016). Additionally, this study was performed on a small time scale. Due to extremely short flight times of VTOL UAS, less than one hour, disturbance was only considered over a very short time, but boats may be having an impact at a larger time scale. Because it is ubiquitous in this area in warm months, boat noise may not influence behavior instantly, but rather over greater time periods. Sound disturbance and behavior alteration of fish species can be gradual and require longer exposure periods (Whitfield and Becker 2014), it is likely that a larger data set over a more prolonged period (i.e. an entire season, or multiple years) may yield sound disturbance trends in the Beaufort area. Therefore, vocalization rate fluctuations, outliers like at 14:40 (Figure 5), and differences between low and high tide, are likely due to individuals leaving or entering the study area. Additionally, the sharp decrease in vocalization rate at the start of experiment 2 (Figure 5) could indicate the end of a large chorusing event of sand sea trout, whose calls were essentially constant when sampling began ~1.5 hours after sunrise.

Deep channeled areas such as this are the documented habitat of sand sea trout, which can reach large chorusing group sizes in such areas. Sand sea trout chorusing events, a high temporal overlap of calls, have been shown to last over six hours and are far more common at night where darkness acts as an environmental cue for spawning aggregations (Locascio and Mann 2008), therefore a chorusing event that began in darkness may have lasted until the start of sampling. Furthermore, since boat noise has previously been shown to decrease vocalization rates in fish (Luczkovich *et al.* 2016$_b$), it is possible that it may have an effect over a 24-hour period. If boats are in fact having an impact on a larger time scale, then call rates may also have dropped at the start of sampling in the morning as recreational boats became active in the Beaufort Inlet. Though not formally analyzed, altitude of UAS did not appear to affect vocalization rates either, likely indicating that UAS at any altitude would not influence the behavior of species in the study area. Larger, louder aircraft didn't correlate to higher disturbance when compared with smaller UAS either. Although the Alta is more than ten times heavier than the IRIS+, on average it was only ~7 dB louder, indicating that the size of aircraft also likely doesn't influence behavior in an area frequented by boats. Vocal compensation depends on the benefits of successful communication versus the costs of changing vocalization patterns. In this case, the benefits are clear. Fishes, including oyster toadfish (Luczkovich *et al.* 2016$_a$ and Luczkovich *et al.* 2016$_b$) and sand sea trout (Locascio and Mann 2008), use vocalization primarily for mating purposes. Costs of call emission changes are harder to describe, but one possibility is fatigue of sonic muscles, or higher detection rate from predators if the compensation is an increase in emissions (Picciulin *et al.* 2012). In this case, the benefits of effective communication likely outweighed the costs due to almost constant daytime boat activity and the absence of predators such as *T. truncatus* during sampling.

In addition to habituation to boats and the benefits of steady vocalization emissions outweighing costs, a potential lack of behavioral response to UAS can likely be attributed to the low sound intensities they emitted. However, UAS sound can induce strong physiological responses without a change in behavior. Ditmer *et al.* (2015) found that flying over bears with the same IRIS+ quadcopter flown in this study could increase their heart rate by as much as 123bmp with no behavioral response. A similar lack of behavioral response to UAS has been observed in many cetacean studies (Jones et al. 2006, Fritz 2012 and Hodgeson *et al.* 2013), however based on the results from Ditmer *et al.* (2015), UAS could elicit a similarly substantial physiological response in marine animals as well as other species sensitive to acoustic anthropogenic disturbance.

Conclusions

This study provides valuable insight and the first empirical data on UAS noise propagation into the water column and their effects on vocalization traits of coastal marine species. The results indicate that UAS engine noise likely does not alter biological vocalization rates or induce the Lombard effect in oyster toad fish in coastal environments with heavy boat traffic. In an area such as the Newport River Estuary/Beaufort Inlet, acoustic disturbances from boats and pile driving (Pavia *et al.* 2015) pose a much larger risk to benthic species, fishes and marine mammals. This study may help focus conservation efforts seeking to limit anthropogenic disturbance in coastal environments and encourage marine scientists to continue to utilize UAS as a minimally intrusive data collection tool.

As the use of UAS in marine science continues to grow, future studies should test for UAS disturbance in coastal areas less frequented by boats to determine if missions affect vocalization patterns in all areas where marine research is likely to occur. Researchers using UAS for marine mammal studies should also collect empirical data on behavioral and physiological responses to their potential visual and aural disturbance, as flying directly over cetaceans may cause stress (Ditmer *et al.* 2015). More data from all marine UAS missions will provide a better understanding of their potential disturbance impacts on marine ecosystems. This study provides evidence that UAS may provide a less invasive means of marine data collection and a good starting point to UAS disturbance research.

Acknowledgments

I would like to thank my research supervisor, Dr. Douglas Nowacek, for helping and supporting me throughout the process. I would also like to thank Dr. Dave Johnston, Everett Newton, and Julian Dale for their crucial help in mission operations and UAS education.

References

Chapman, D. and Ward, P. 1990. The normal mode theory of air-to-water sound transmission in the ocean. *J. Acoust. Soc. Am.* 87(2): 601-618.

Ditmer, M.A., Vincent, J.B., Werden, L.K., Tanner, J.C., Laske, T.G., Iaizzo, P.A., Garshelis, D.L., and Fieberg, J.R. 2015. Bears show a physiological but limited behavioral response to unmanned aerial vehicles. Curr. Biol. 25(17): 2278–2283. doi: 10.1016/j.cub. 2015.07.024.

dos Santos, M. Louro, S. Couchinho, M. Brito, C. (2005). Whistles of bottlenose dolphins (*Tursiops truncatus)* in the Sado Estuary, Portugal: characteristics, production rates, and Long- Term contour stability. *Aquatic Mammals.* 31(4): 452-461.

Fair, P.A., and Becker, P.R. 2000. Review of stress in marine mammals. J. Aquat. Ecosyst. Stress Recovery. 7(4): 335–354. doi: 10.1023/ A:1009968113079.

Frisk, G. V. 2012. Noiseonomics: The relationship between ambient noise levels in the sea and global economic trends. *Scientific Reports* 2:437

Gage, S. H., and A. C. Axel. 2014. Visualization of temporal change in soundscape power of a Michigan lake habitat over a 4-year period. *Ecological Informatics* 21:100-109

Glushkov, E. Glushkova, N. and Godin, O. 2013. The effect of anomalous transparency of the water-air interface for a volumetric sound source. *Akusticheskii Zhurnal*, 2013, Vol. 59(1): 8–18

Godin, O. 2006. Anomalous transparency of water-air interface for low-frequency sound. *The American Physical Society.* 97 (164301): 1-4

Heenehan, H. 2016. Soundscape ecology of Hawaiian spinner dolphin resting bays (dissertation). Duke University, Durham, NC. *ProQuest.*

Hodgson, A.J., Kelly, N., and Peel, D. 2013. Unmanned aerial vehicles (UAVs) for surveying marine fauna: A dugong case study. PLoS One. 8(11): e79556, PMID: 24223967.

Janik, V. and Sayigh, L. (2013). Communication in bottlenose dolphins: 50 years of signature whistle research. *Journal of Comparative Physiology A.* 199(6): 479-489.

Johansson, K., Sigray, P., Backstrom, T., Magnhagen, C. 2016. "Stress Response and Habituation to Motorboat Noise in Two Coastal Fish Species in the Bothnian Sea" in *The Effects of Noise on Aquatic Life II. Springer New York. 513-521*

Jones, G.P. IV., Pearlstine, L.G., and Percival, H.F. 2006. An assessment of small unmanned aerial vehicles for wildlife research. *Wildl. Soc. Bull.* 34(3): 750–758.

Krause, B., Gage, S.H., Joo, W., 2011. Measuring and interpreting the temporal variability in the soundscape at four places in Sequoia National Park. *Landscape Ecol*. 26 (9), 1247–1256.

Lobel, P.S. 1992. Sounds produced by spawning fishes. *Experimental Biology of Fishes*. 33: 351-358.

Locascio, J.V., and Mann, D.A. 2008. Diel Periodicity of Fish Sound Production in Charlotte Harbor, Florida. *Transactions of the American Fishers Society* 137: 606-615.

Luczkovich, J.J., Krahforst, C.S., Kelly, K.E., Sprague, M.W. 2016. The Lombard effect in fishes: How boat noise impacts oyster toadfish vocalization amplitudes in natural experiments. *Proceedings of Meetings on Acoustics*. 27: 1-14.

Luczkovich, J.J., Krahforst, C.S., Hoppe, H., Sprague, M.W. 2016. "Does Vessel Noise Affect Oyster Toadfish Calling Rates?" in *The Effects of Noise on Aquatic Life II. Springer New York. 647-653.*

McWilliam, J. N., and A. D. Hawkins. 2013. A comparison of inshore marine soundscapes. *Journal of Experimental Marine Biology and Ecology* 446:166-176.

Moreland, E.E., Cameron, M.F., Angliss, R.P., and Boveng, P.L. 2015. Evaluation of a ship-based unoccupied aircraft system for surveys of spotted and ribbon seals in the Bering Sea pack ice. *J. Unmanned Veh. Syst*. 3(3): 114–122.

Nowacek, D. P., L. H. Thorne, D. W. Johnston, and P. L. Tyack. 2007. Responses of cetaceans to anthropogenic noise. *Mammal Review* 37:81-115

Patek, S.N., Shipp, L.E., Staaterman, E.R. 2009. The acoustics and acoustic behavior of the California spiny lobster (*Panulirus interruptus*). *The Journal of the Acoustical Society of America.* 125(5): 3434-3443.

Pavia, E. Salgado Kent, C. Monique Gagnon, M. McCauly, R. Finn, H. (2015). Reduced detection of Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) in an Inner Harbour Channel during pile driving activities. *Aquatic Mammals.* 41(4): 455-468.

Picciulin, M., Sebastianutto, L., Codarin, A., Calcagno, G., Ferrero, E.A. 2012. Brown meagre vocalization rate increases during repetitive boat noise exposures: A possible case of vocal compensation. *The Journal of the Acoustical Society of America.* 132(5): 3118-3124.

Shannon, G., McKenna, M. F., Angeloni, L. M., Crooks, K. R., Fristrup, K. M., Brown, E., Nelson, M.D., White, C., Briggs, J., McFarland, S., Wittemyer, G. 2016. A synthesis of two decades of research documenting the effects of noise on wildlife. *Biological Reviews*, 91(4), 982-1005.

Simpson, S.D., Meekan, M.G., McCauley, R.D., Jeffs, A., 2004. Attraction of settlement-stage coral reef fishes to reef noise. Mar. Ecol. Prog. Ser. 276, 263–268.

Slabbekoorn, H., Bouton, N., 2008. Soundscape orientation: a new field in need of sound investigation. Anim. Behav. 76 (4), e5–e8.

Smith, C. Sykora-Bodie, S. Bloodworth, B. Pack, S. Spradlin, T. Lebeuf, N. 2016. Assessment of known impacts of unmanned aerial systems (UAS) on marine mammals: data gaps and recommendations for researchers in the United States. *J. Unmanned Veh. Syst*. 4: 1–14.

Staaterman, E.R., Clark, C.W., Gallagher, A.J., deVries, M.S., Claverie T., Patek, S.N. 2011. Rumbling in the benthos: acoustic ecology of the California mantis shrimp *Hemisquilla californiensis. Aquatic Biology*. 13: 97-105.

Whitfield, A. K., and Becker, A. 2014. Impacts of recreational motorboats on fishes: A review. *Marine Pollution Bulletin.* 83: 24-31

Zhang, L. and Peng, Z. 2014. Effect of sources height on air-to-water sound transmission with a small-scale rough sea surface. *Chin. Phys. Lett. Vol. 31, No. 9 (2014) 094302*