Small UAV Noise Analysis

Raya Islam, Dr. Alexander Stimpson, Dr. Mary Cummings

Humans and Autonomy Laboratory, Duke University, Durham, NC, USA

April 26, 2017

Contents

Abstract

Amongst the myriad of new Unarmed Aerial Vehicle (UAV) applications, aerial monitoring of wildlife is one of the most disruptive given the ability of noninvasively track animals. However, species such as elephants have been observed to exhibit signs of discomfort around UAVs (even when unseen) thus decreasing the effectiveness of UAVs. These observations suggest that the elephants are alarmed by the noise of the UAVs, however little data exists detailing that noise. By comparing the sound profiles of UAVs to the sound profile of a known annoyance, honeybees, the following research develops a methodology to justify what UAV profiles are better than others for elephant conservation. The proposed methodology details how to capture the sound of UAVs and transform it into comparative measurements. Normalized spectrograms for different UAV profiles were compared to that of honeybees at the bees high frequency range resulting in a relative score per profile under the hypothesis: the higher the score, the less similar the UAV sound is to bees, hence the higher relative effectiveness of that UAV platform for elephant conservation, and in this case UAV 4 (DJI Phantom). By numerically characterizing the sound profiles of UAVs, the proposed data analysis techniques allow for growth of UAV applications.

1 Introduction

Due to increasing availability and decreased cost, the popularity of small Unarmed Aerial Vehicles (sUAVs)[1]has significantly increased. The use of UAVs for industrial and commercial applications is enticing due to the ability of UAVs to rapidly maneuver a payload without a pilot onboard, reducing operational costs. There are a wide range of payloads that can be carried by UAVs, including cameras and sensors for use in industries such as agriculture, real estate, and 3D mapping [1]-[2]. An important emerging field of UAV application is wildlife management and population ecology [3]-[4]. Research has shown that aerial surveys of wildlife in their natural environment provide easier tracking and management of both population and habitat [4]-[6]. Recent research and development efforts have investigated the applicability of UAV technologies with monitoring a variety of species. Thus far, UAVs have been used to track many types of species, including large terrestrial mammals, aquatic animals, and birds [7]-[10].

While there is the potential to provide aerial monitoring via UAV for a variety of species, the work presented here focuses on a study conducted using

[1]Note that the terms sUAV and UAV are used interchangeably here and is identical to the sUAS classification by the Federal Aviation Administration.

UAVs to track African elephants. Aerial surveys using light aircraft are one of the most effective ways to count large mammals like elephants, especially given that the alternative is to manually count the elephants, inevitably leading to estimation errors [9]. Additionally, in the remote African regions where many of these elephants reside, several years can pass between successive captures of aerial imagery due resource and transportation constraints [9]. When compared to light aircraft, UAVs have advantages due to their ability to provide data at high spatial and temporal resolution at low operational cost and risk [6]. The implementation of a reliable and noninvasive elephant tracking UAV system would not only allow wildlife rangers to monitor populations, but also would allow them to observe the animals behavior from above. It is also likely that a UAV system developed for elephant tracking could be useful in monitoring other large terrestrial animal populations. To this end, a UAV system was developed for the purposes of tracking elephants in Africa.

Researchers at the Duke Humans and Autonomy Lab were tasked with creating a fully integrated UAV system consisting of a thermal imagery device, and a flight planning app on a tablet with a live video feed of the payload on a robust and reliable platform, all for under 1500 USD. The proposed UAV system was designed for nighttime tracking due to the tendency of elephants to gather at night, as well as the easier identification of elephants in imagery produced by the UAV. A successful proof of concept of the system would ideally lead to a systematic way to implement UAVs for large scale wildlife monitoring. The final design of the UAV system was a 3D Robotics Iris+[2] drone integrated with a FLIR Lepton camera mounted on a Drone Thermal board [3] connected to a radio frequency system that allowed the thermal imagery to be viewed in real time. The UAVs flight path could be programmed onto the app and sent to the UAV. While the UAV was on its mission, the video feed could be viewed in real time on the tablet app. Once the final design of the UAV system was selected, the product was tested in realistic conditions at Wonga Wongue National Reserve in Gabon, Africa.

Upon testing the system with the park rangers, known as Ecoguards, and the researchers observed signs of disturbance amongst the elephants when using the UAV system. Interestingly, some elephants seemed unaware of the UAV, while others seemed distressed based on the presence of the UAV. Some signs of distress involved throwing dirt upon hearing the UAV and quickly retreating, as well as spraying dirt with their trunks, a behavior known as dusting [11]. In many of these cases the elephants would not have been able to visually perceive

[2]https://www.amazon.com/3DRobotics-3DR0171-3DR-IRIS-Quadcopter/dp/B00NWXY076

[3]http://www.flytron.com/thermal-cameras/303-dronethermal-micro-uav-thermal-camera.html

the UAV based on the terrain, which suggests that the elephants were exhibiting these behaviors upon only hearing the UAV. Additionally, the wildlife reserve in which these elephants live in is remote and utterly silent, therefore the sound of a UAV would have been unfamiliar, thus potentially disturbing to the elephants. The usefulness of UAVs applied to conservation is limited if the animals are distressed by the technology implemented to help them, however no public data exist characterizing the sounds from different UAV platforms. Thus, it represents an important research need to understand the nature of the sound emitted by UAVs and how the animals might react to the sound[4] of a UAV when used in conservation applications. This paper presents a methodology developed to measure the sound emitted by UAVs across a range of platforms that will systematically identify preferred platforms for elephant wildlife conservation.

2 Background

2.1 UAVs and Wildlife

When studying the effects of aircraft-type noises on wildlife, it is important to understand the potential psychological effects on the animals that can be observed. Repeated loud noises to which animals are not accustomed to can have a negative impact on the animals psychological health over time [12] . Some effects of these disturbances include behavioral changes, interference with mating, and missing important communication signals. Even if a behavioral response is not observed, that does not necessarily mean the animal was unaffected by the sound (such as from a UAV). For example, a study of bears tagged with cardiac biologgers that monitored their heart rate showed that while a UAV circled around them at 20 m altitude, changes in their physical behavior were minor, but there were magnitudes of heart rate spikes correlated with wind and proximity to the UAV [7]. Thus, there was a measureable stress response in the animals due to the presence of the UAV even without observable behavioral changes. Further identification of such stressors to wildlife is needed to ensure that the use of UAVs in such settings is not harmful to the animals.

To gauge the psychological disturbance UAVs might cause an elephant, this study focuses on the comparison of the sound of UAVs to a known source of annoyance to elephants: honeybees. Given their large nature, it is uncommon for elephants to have predators in their environment. However, in the presence of African honeybees, African elephants will move or run away from the bees, as the elephants are likely worried about the bees stinging sensitive areas, such as eyes, behind the ears, and trunk [11]. Research shows that playing a recording

[4]Note that both terms sound and noise are used here. Noise is a characterization of a sound as unwanted or unpleasant, as could be the case for UAVs interacting with wildlife.

of African honeybees *Apis meliffera scutellata* induced a myriad of stress signals from the African elephants *Loxodonta africana* such as retreating, engaging in head shaking and dusting, and even make a low-rumbling sound portraying alarm [13].

2.2 Understanding Sound

Sound is characterized in terms of frequencies and decibels and is typically represented in the form of spectrograms that plot frequency versus decibels or frequency versus time. The frequency of a sound represents the speed of the vibration that the sound creates in air. Recorded in Hertz (Hz, 1 vibration/second), frequency is considered the defining variable for sound profiles. Decibels are the pressure of sound in air, impacting the volume of sound that is heard. The relationship between frequency and decibels is unique since a sound can occur at a large range of frequencies, but what is actually heard by a machine or organism and at what its volume is depends upon both the sound and the listener. Frequencies are characteristic to a sound, whereas decibels are affected by different factors such as distance and the properties of the air in which it propagates. For example, humans can hear from around 10 Hz-10,000 Hz, therefore if a sound does not vibrate within that frequency range, no matter how high the decibel value, the human will not be able to perceive the sound [14].

Elephants can perceive a wide range of frequencies, from 16 Hz-12000 Hz [14]. Elephants have higher sensitivity to low-frequency sounds than that of most mammals. They also tend to communicate at low infrasound frequencies that are inaudible to the human ear (¡20 Hz), and are most sensitive to sounds around 1000 Hz [15]. However, they display a high perception threshold at higher frequencies (over 4000 Hz), based upon the relatively large functional distance between the two ears [14]. Essentially, elephants have adapted to detect low frequency sounds and are less capable of perceiving high frequency sounds.

The sounds produced by honeybees, not to be confused with the perception thresholds of honeybees, vary by species. Generally, frequency ranges of sound emanated by bees are most prominent in the 200-500 Hz and 2-5 kHz ranges, both of which are perceptible to elephants [14]. Similarity of UAV sound with bee sound across these frequency ranges is used as the basis for comparison of UAV sound to honeybee sound.

Currently, there exists little literature on systematic measurement techniques for UAV sound. Therefore, such a methodology to collect UAV sound data was created, along with analytical techniques to compare UAV noise with the reference bee noise. The procedures and analysis techniques in this report focused on the identification of key variables within the sound profiles that allow for the comparison between different UAV platforms and bee noise. This would allow wildlife experts to gauge what UAV platforms have superior noise qualities for elephant conservation purposes. Specifically, the greater similarity between a UAV's noise and bees noise, the more likely the UAV may be disturbing to elephants.

3 Methods

The experimental methods were designed with the goal of detecting and analyzing the unique sound signatures of different UAVs. Three different platforms, one of which was tested indoors and outdoors, were included in the sound data collection process (Table 1). The particular platforms selected were intended to represent some of the variability across commercially available platforms, including both rotorcraft and fixed wing drones, and based on the availability from the Humans and Autonomy Lab as well as the North Carolina State NextGen Air Transportation Center.Note that due to operational constraints, UAV 5 was only used to create a test procedure for fixed-wing UAVs. Because the fixed-wing UAVs from NGAT were on an autonomous mission, necessary adjustments to the flight path to allow the UAV to fly over the microphone could not be made. The little data that was collected from the fixed wing had too much environmental noise that prevented analyzing the platform, therefore its sound profile was not created.

UAV ID	Platform Name	Platform Type	Environment	Average Outdoor Ambient Sound
UAV 1	3DR Iris+	quadcopter	Indoor	33.0261 dB
UAV 2	3DR Iris+	quadcopter	Outdoor	39.4079 dB
UAV 3	DJI Inspire	quadcopter	Outdoor	39.4079 dB
UAV 4	DJI Phantom	quadcopter	Outdoor	39.4079 dB
UAV 5	Trimble UX 5	Fixed-wing	Outdoor	39.4079 dB

Table 1: UAV platforms tested and their respective environments

3.1 Testing Conditions

Testing in an environment with minimal ambient sound was crucial to ensure the quality of the results. While data was collected both indoors and outdoors for this experiment, pilot testing revealed that the data was most consistent indoors due to the relative lack of ambient sound (i.e. wind). However, outdoor tests were included for ecological validity, and were conducted in large open fields away from buildings to simulate the African environment. Before each platform was tested, multiple ambient sound measurements were recorded.

3.2 Experimental Procedure

Different methods were developed for the two different testing environments: indoors and outdoors, as well as for the main classes of UAVs: multirotor and fixed wing. To collect the data, the Signal Scope App [5] was used on a mobile device and connected to a Dayton Audio UMM-6 USB [6] unidirectional microphone [16] with a USB female to male connector. The app allows the user to simultaneously record sound data (frequency vs. time) while performing a Fast Fourier Transform that saved the data in the preferred spectrographic form (decibel vs. frequency). The data measurements were recorded at full throttle about 3 feet off the ground at 10 feet intervals away from the test stand (Figure 2), up to a maximum radial distance of 100 feet. The data collection at a range of distances generated a more comprehensive characterization of the sound profile of the UAV.

3.3 Methods for Multirotor UAVs

3.3.1 Indoors

For multirotor UAVs tested indoors, a wooden portable test stand was assembled (Figure 1a). The UAV is harnessed to the top part of the stand during testing with durable Velcro straps (Figure 1b). The setup was designed such that the UAV could be armed and throttled without physically lifting off, and lateral distance from the vehicle on the stand is used as a proxy for drone altitude above the sensor. By fixing the drone position in space, more accurate distance measurements could be made. After the UAV was tightly strapped down to the test stand, it was armed to full throttle. The microphone attached to the device was positioned at the first radial distance, and at the same vertical height of the UAV (about three ft). At this point, the Signal Scope App was used to record the sound for five seconds, and then the UAV was unarmed (Figure 1c, 1d). This procedure was repeated for each 10 feet interval (0-100 feet) as seen in Figure 2.

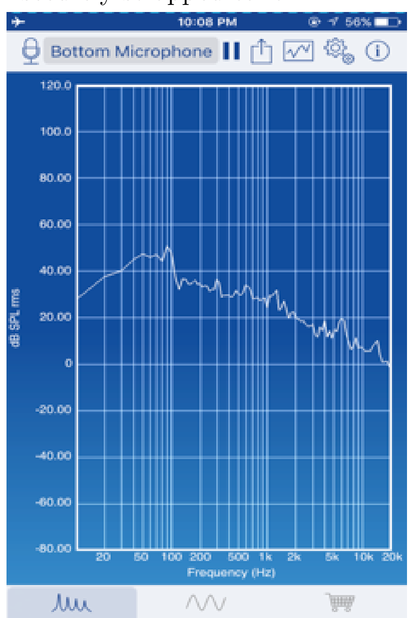
[5] http://www.faberacoustical.com/apps/ios/signalscope/

[6] http://www.daytonaudio.com/index.php/umm-6-usb-measurement-microphone.html

(a) Isometric view of test stand

(b) Test stand with IRIS + UAV securely strapped to it

(c) Experimental setup of microphone and Signal Scope App



(d) Screenshot of Signal Scope App

Figure 1: Sound collection equipment setup

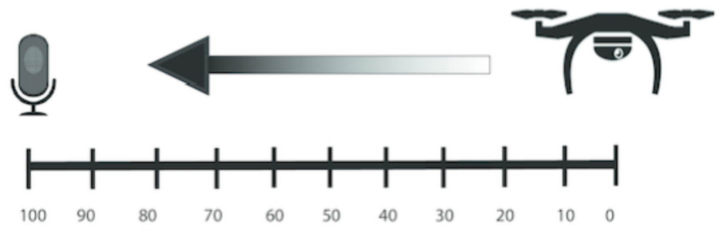


Figure 2: For indoor tests, the UAV is fixed to the test stand and the researcher handling the microphone moves away from UAV (Not to scale).

3.3.2 Outdoors

Outdoor testing was conducted with the assistance of the NC State University NextGen Air Transportation Center (NGAT). The procedures were adjusted due to being unable to fix the UAVs that belonged to other researchers to the test stand. Instead, the recording device was held at a fixed height of about 4 feet while the UAV was flown away from the microphone at specific distance intervals. To collect data proximal to the UAV (0 foot measurement), the microphone was placed as close to the UAV as possible while still adhering to safe procedures, and the UAV was armed without lifting off. For recording the rest of the distance intervals, the recording device was positioned approximately 4 feet above the ground and the UAV was hovered at 10 feet intervals away from the recording device (Figure 3).

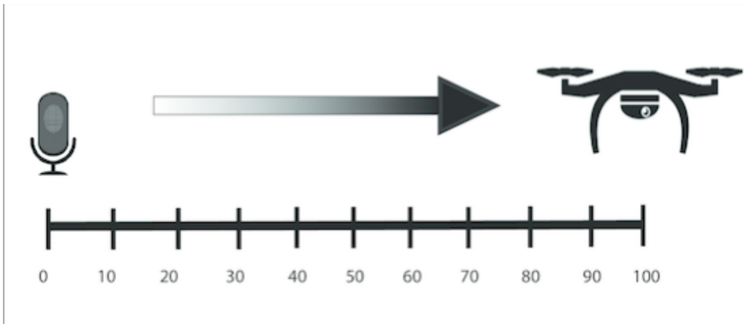


Figure 3: For outdoor tests, the UAV is flown away from the fixed position of the microphone (not to scale)

3.4 Methods for Fixed-Wing UAVs

For this experiment, only data from multirotor platforms were collected due to challenges obtaining flight time with fixed wing vehicles. However, pilot testing was conducted to create a procedure for fixed-wing platforms; observations of the flight paths of NGAT fixed-wing platforms allowed for a proposed systematic way to create sound profiles of these UAVs. Although some data was collected, it was not robust enough to convert into a sound profile, and the flights were unable to be repeated. The developed methodology relies heavily on the altitude sensing capabilities of the UAV system and requires a large, quiet open space due to the large volume required to fly fixed-wing UAVs.

The recording device was placed on the ground facing upward. After the UAV was armed and in stable flight so it could maintain a constant altitude, the measurements were recorded before and after the UAV flew directly over the microphone at approximately full speed. The UAV then stabilized at each altitude interval and flew over the microphone (Figure 4).

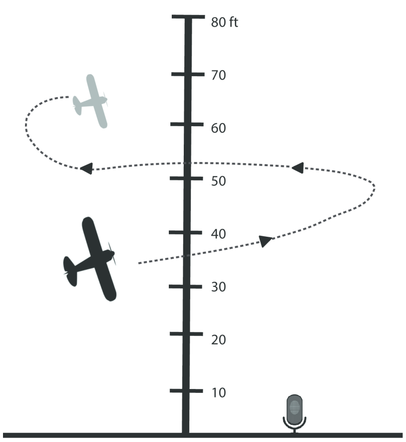


Figure 4: General flight path of fixed wing UAV during data collection with respect to microphone on the ground (not to scale)

3.5 Data Analytics

To acquire spectrograms for African honeybees, a recording from Dr. Lucy King [11], [13] (taken at an unknown distance) was analyzed in Praat Software[7]. The same honeybee recording was used in the comparison with all the UAV profiles in this experiment and all data was analyzed in Matlab. To quantify the similarity between honeybee noises and UAV noises, each spectrogram was smoothed with

[7]http://www.fon.hum.uva.nl/praat/

a moving average (10 Hz bandwidth) and normalized. Each spectrogram was normalized over the total area under the spectrogram from 0-198 kHz (based on the measurement ranges of the spectrograms). The normalization allows for the comparison of spectrograms between data samples under different ambient noise conditions (Equation 1). The individual sound profiles for each UAV and for African honeybees can be found in the Appendix. Similarity evaluation was conducted by numerically analyzing the difference in area between the normalized UAV spectrogram and normalized honeybee spectrogram over the two ranges of frequencies that honeybee sound is most prevalent (200-500 Hz) and (2000-5000 Hz) resulting in a low frequency and high frequency measurement (Table 2). By summing the differences between the normalized decibel values for each UAV platform and the bees within each frequency range, two types of measurements are created for each platform, one in the low frequency category, and one in the high frequency category (Equation 2-3). The hypothesized relationship is that within each frequency category, a lower relative value indicates greater similarity to African honeybees and therefore greater potential for disturbance to elephants.

$$normalized\ decibel_i(Hz_i) = \frac{decibel_i(Hz_i)}{\int_0^{198kHz} decibel(Hz)} \tag{1}$$

$$low\ frequency\ value = \sum_{i=200}^{500} (normalized\ bee\ decibel)_i - (normalized\ UAV\ decibel)_i \tag{2}$$

$$high\ frequency\ value = \sum_{i=2000}^{5000} (normalized\ bee\ decibel)_i - (normalized\ UAV\ decibel)_i \tag{3}$$

4 Results

The measurements in Table 2 demonstrate the degree of similarity between UAV and honeybee sound. The low frequency numbers suggest that either UAV sound is not prominent at the lower frequency ranges. They are almost two orders of magnitude larger than their high frequency counterparts, further supporting the dissimilarity between UAVs and honeybees in the low frequency range in general. Because of the large dissimilarity between UAVs at these low frequency ranges, although bee noises are known to disturb elephants, the low frequency values cannot quantify the relationship between UAVs and honeybees in this range. Therefore, the low frequency values are inconclusive in terms of identifying the usability of a certain UAV platform with respect to this experiment.

In contrast, greater similarity overall is observed at the higher prominent frequency range for honeybee noise. This result, combined with the knowledge that honeybee noise is disturbing to elephants coupled with their sensitivity to sounds in the high frequency range, suggests that disturbance of elephants by UAVs is likely resulting from this higher frequency range. This methodology suggests a metric to understand the relationship between each sound profile of the UAV to that of bees, hence providing a scoring system. The score generated for each platform at the higher frequency range can be used for the purposes of characterizing UAVs in terms of their propensity for disturbing elephants. Under this premise, the scores show that out of the four platforms tested, UAV 4 (DJI Phantom Quadcopter) would be least likely to agitate elephants with the highest score of 0.8902 in the high frequency category, the lowest score being UAV 1 (0.1764). Interestingly, UAV 1 (3DR Iris+) was the platform that had been previously brought into the field and was seen to disturb the elephants.

The quantitative data are further supported by the data plots. Figure 5 presents the normalized spectrograms of the UAVs compared with the honeybee spectrogram. The low frequency spikes in the honeybee sound in the 200-500 Hz range are clearly visible in the figure and much higher than all the UAV profiles. Figure 6 shows the profile shapes of each UAV compared to that of the honeybee for this frequency range. Qualitatively, all the UAV sound profiles are considerably lower in decibel values than the honeybee profile and do not show the same pronounced spikes, suggesting that any similarity between UAV noise and honeybee noise is not as a result of similarity across this lower frequency range. Figure 7 shows the comparison between sound profiles of the UAVs and honeybees at the high frequency range (2000-5000 Hz). It can be seen in this figure that the UAV sound profiles have greater similarity in shape to the honeybee profile for this frequency range.

4.1 Tables and Figures

	UAV 1	UAV 2	UAV 3	UAV 4
Low Frequencies (200-500 Hz)	12.1995	8.7761	9.9826	9.3856
High Frequencies (2000-5000 Hz)	**0.1764**	**0.7583**	**0.8155**	**0.8902**

Table 2: Relative similarity measurements comparing each UAV platform to honeybee noise.

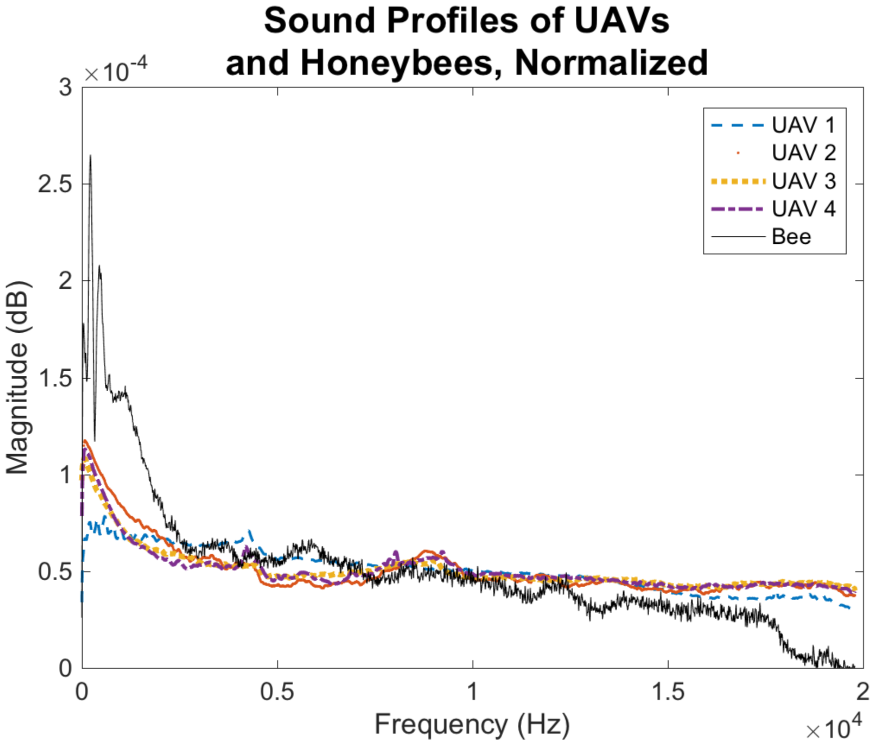


Figure 5: All UAV platforms tested compared to honeybee normalized sound profiles

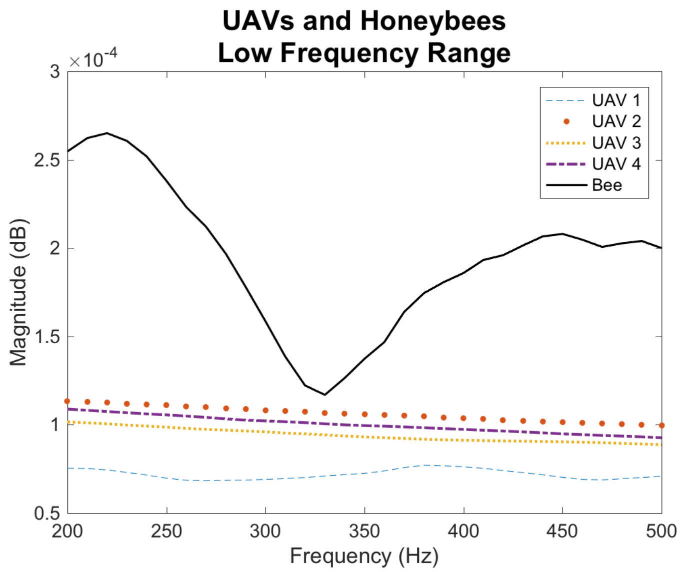


Figure 6: Subgraph of the normalized UAV and honeybee sound profiles shown in Figure 5 at the lower frequency ranges (200-500Hz).The shapes of these profiles differ drastically from the bee profile

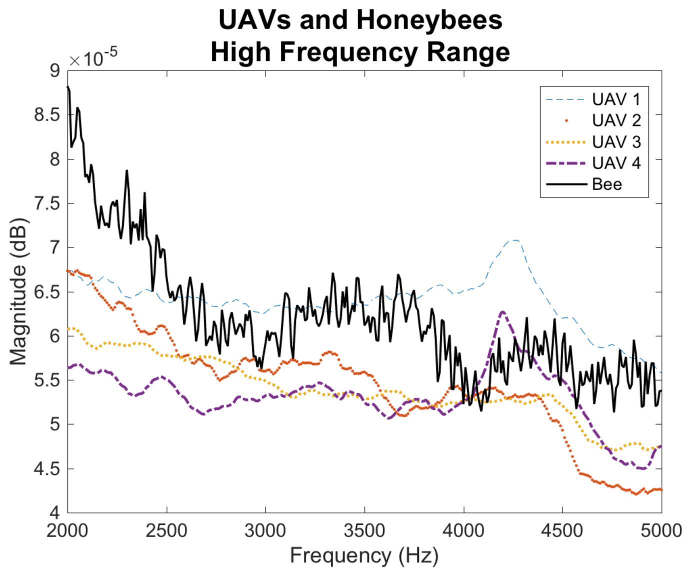


Figure 7: Subgraph of the normalized UAV and honeybee sound profiles shown in Figure 5 at the higher frequency range (2000-5000 Hz). The profile shapes in this range are significantly more similar than that of the lower frequency range.

5 Conclusion

Upon observing disturbances to the animals during field research implementing sUAVs for elephant wildlife conservation, researchers desired to understand why elephants reacted negatively to the UAVs. Given the novelty of sUAVs in wildlife conservation, systems and metrics must be created to properly understand how these novel technologies may impact the wildlife under study. One such system was conceived in this experiment by developing a methodology to measure and compare the potential annoyance an elephant might experience around different sUAVs.

In the experimental results, it was shown that through the comparison with a known source of annoyance to the elephants (honeybees), UAVs could be ranked in terms of the potential for auditory annoyance to the animals. Specifically, it was noted that UAVs showed similarity to honeybee sounds in higher frequency ranges, but not lower frequency ranges, and this was used to compare UAV platforms. Such a methodology (including both measurement and analytic techniques) could be utilized by other researchers in wildlife conservation to better understand how any UAVs they deploy might impact the animals they work with. In addition to using the methodology presented here, researchers investigating other species could mimic the strategies contained herein, specifically to utilize a known auditory source of animal disturbance as a baseline for the ranking of UAV platforms. Alternatively, the defined metric could possibly impact research efforts to understand what alterations to UAV sounds would not disturb wildlife. Researchers wishing to make UAVs more animal-friendly can integrate these physical and analytical procedures to monitor wildlife without disturbing them.

The results from proposed methodology for this experiment are limited based on the availability of different UAV platforms, as well as the permissions to fly them for the purposes of data collection. Additionally, it should be noted that this data analysis is based on the assumption that there is an aural source of discomfort displayed in a particular species, in this case elephants. Researchers wishing to implement this approach to justify what platforms are better than others for wildlife conservation must initially determine a potential auditory source of discomfort for a species of interest from which recordings could be obtained. As with all sound collection experiments, any form of ambient noise can alter results and while measures were taken in these data collection processes to prevent it, they are not completely eliminated.

While sUAVs have the potential to be a useful tool for the wildlife conservation field, the benefits are reduced if the animals are disturbed by the UAV in the process of data collection during flight. Greater understanding and characterization of UAV platforms in terms of their disturbance to animals is needed, and further research efforts such as the one presented here could help to construct more complete databases of UAV platforms, their sound profiles, and allow for the appropriate selection of platform not just on performance criteria, but also for their ecological suitability.

Appendix

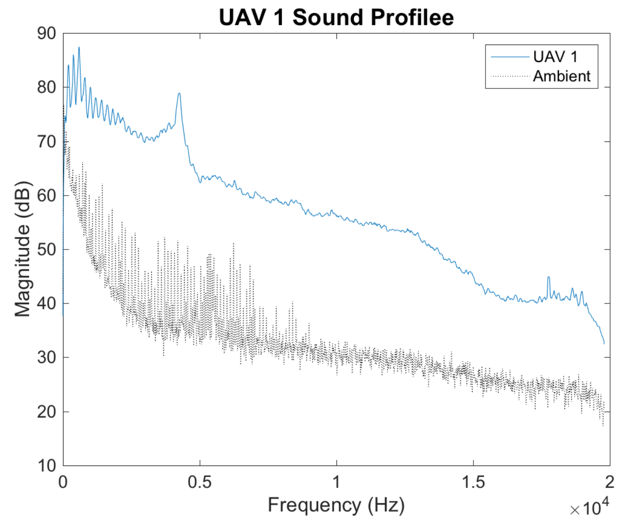


Figure 8: Raw data for the sound profile of UAV 1 collected indoors comparing the UAV sound to ambient sound.

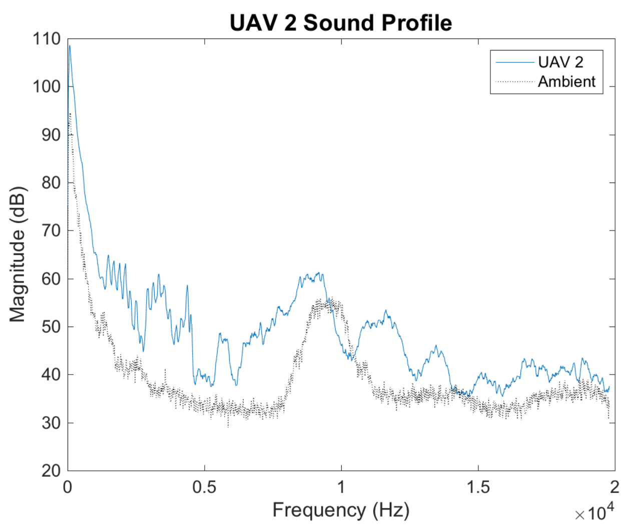


Figure 9: Sound profile for UAV 2 collected outdoors. The areas in which ambient sound has a higher magnitude than the sound profile is likely due to unavoidable sound interruptions of distant gunshots.

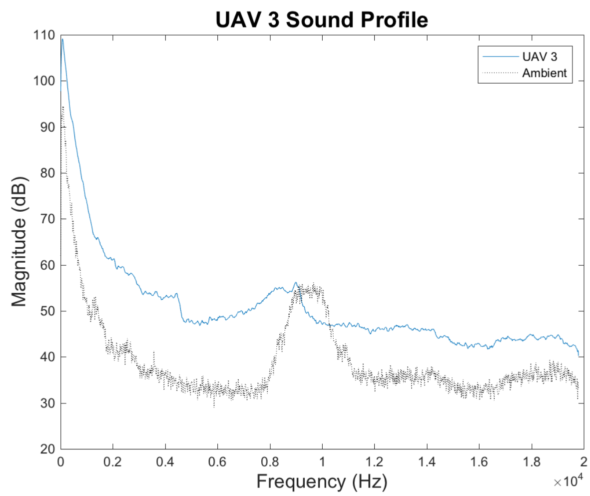


Figure 10: Sound profile for UAV 3 collected outdoors. The areas in which ambient sound has a higher magnitude than the sound profile is likely due to unavoidable sound interruptions of distant gunshots.

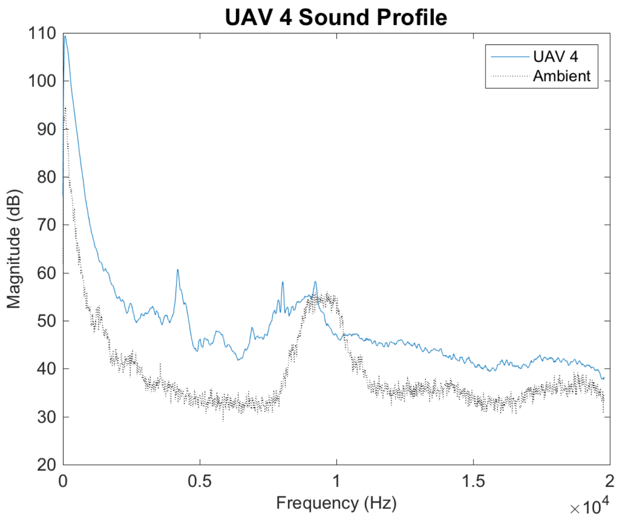


Figure 11: Sound profile for UAV 4 collected outdoors. The areas in which ambient sound has a higher magnitude than the sound profile is likely due to unavoidable sound interruptions of distant gunshots.

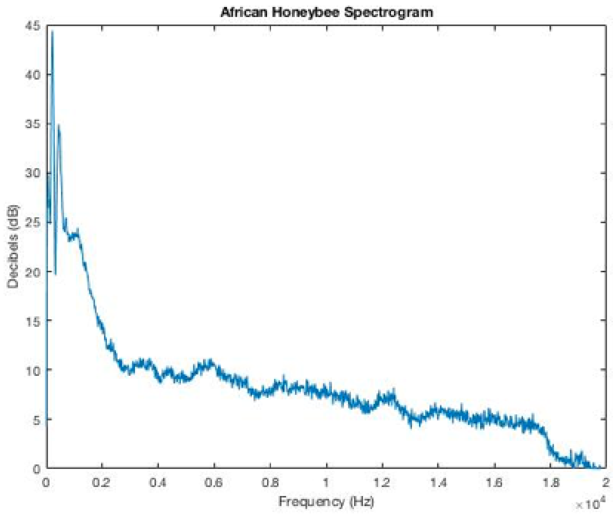


Figure 12: Honeybee spectrogram created from bee recording from Dr. Lucy King and analyzed in Praat Software.

References

[1] K. Anderson and K. J. Gaston, "Lightweight unmanned aerial vehicles will revolutionize spatial ecology," *Frontiers in Ecology and the Environment*, vol. 11, no. 3, pp. 138146, Apr. 2013.

[2] J. Brown, "What Is A Drone: Main Features and Applications of Todays Drones.".

[3] D. Chabot and D. M. Bird, "Wildlife research and management methods in the 21st century: Where do unmanned aircraft fit in?[1]," *Journal of Unmanned Vehicle Systems*, vol. 3, no. 4, pp. 137155, Dec. 2015.

[4] M. A. Ditmer et al., "Bears Show a Physiological but Limited Behavioral Response to Unmanned Aerial Vehicles," *Current Biology*, vol. 25, no. 17, pp. 22782283, Aug. 2015.

[5] R. S. Heffner and H. E. Heffner, "Hearing in the elephant (Elephas maximus): Absolute sensitivity, frequency discrimination, and sound localization.," *Journal of Comparative and Physiological Psychology*, vol. 96, no. 6, p. 926, 1982.

[6] G. P. Jones, L. G. Pearlstine, and H. F. Percival, “An Assessment of Small Unmanned Aerial Vehicles for Wildlife Research,” *Wildlife Society Bulletin*, vol. 34, no. 3, pp. 750758, Oct. 2006.

[7] L. E. King, I. Douglas-Hamilton, and F. Vollrath, “African elephants run from the sound of disturbed bees,” *Current Biology*, vol. 17, no. 19, pp. R832R833, 2007.

[8] L. E. King, J. Soltis, I. Douglas-Hamilton, A. Savage, and F. Vollrath, “Bee threat elicits alarm call in African elephants,” *PLoS One*, vol. 5, no. 4, p. e10346, 2010.

[9] S. Lhoest, J. Linchant, S. Quevauvillers, C. Vermeulen, and P. Lejeune, “HOW MANY HIPPOS (HOMHIP): ALGORITHM FOR AUTOMATIC COUNTS OF ANIMALS WITH INFRA-RED THERMAL IMAGERY FROM UAV,” ISPRS - International Archives of the Photogrammetry, *Remote Sensing and Spatial Information Sciences*, vol. XL-3/W3, pp. 355362, Aug. 2015.

[10] J. Linchant, J. Lisein, J. Semeki, P. Lejeune, and C. Vermeulen, “Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges: A review of UASs in wildlife monitoring,” *Mammal Review*, vol. 45, no. 4, pp. 239252, Oct. 2015.

[11] J. Malchaire, “Sound measuring instruments,” *Occupational exposure to noise: Evaluation, prevention and control*, pp. 125140, 2001.

[12] K. M. Manci, D. N. Gladwin, R. Villella, and M. G. Cavendish, “Effects of aircraft noise and sonic booms on domestic animals and wildlife: a literature synthesis,” *DTIC Document*, 1988.

[13] K. Massey and R. Gaeta, “Noise measurements of tactical UAVs,” in *16th AIAA/CEAS Aeroacoustics Conference, 2010*, p. 3911.

[14] T. Reuter, S. Nummela, and S. Hemil, “Elephant hearing,” *The Journal of the Acoustical Society of America*, vol. 104, no. 2, pp. 11221123, Aug. 1998.

[15] A. C. Uzialko, B. N. D. S. W. J. 27, and 2016 09:28 am EST, “7 Cool Commercial Drone Uses Coming to a Sky Near You,” *Business News Daily.* [Online]. Available: http://www.businessnewsdaily.com/9276-commercial-drones-business-uses.html. [Accessed: 13-Mar-2017].

[16]C. Vermeulen, P. Lejeune, J. Lisein, P. Sawadogo, and P. Bouch, "Unmanned aerial survey of elephants," *PloS One*, vol. 8, no. 2, p. e54700, 2013.

[17] J. Xu, G. Solmaz, R. Rahmatizadeh, D. Turgut, and L. Blni, "Animal monitoring with unmanned aerial vehicle-aided wireless sensor networks," in *Local Computer Networks (LCN), 2015 IEEE 40th Conference on, 201*5, pp. 125132.

[18] PRAAT_workshop_manual_v421.pdf.

Acknowledgements

The contents of this paper would not be possible without the opportunities and resources provided by the Duke University Humans and Autonomy Laboratory. Dr. Missy Cummings deserves superb recognition for her mentorship and patience with this project. I would particularly like to thank Dr. Alexander Stimpson for his attention to detail, intellect, and experience to guide me through the scientific writing process. The data collection in this report could not have been possible without Dr. Lucy Kings bee recordings and NC States NGAT UAV platforms. I would like to thank Dr. John Poulsen of the Duke Nicholas School of the Environment, the Duke Tropical Conservation Initiative (DTCI), the Information Initiative at Duke (IID), the Pratt School of Engineering, and the African Elephant Fund (AEF) for their support of this project. I would also like to thank The Elephant Sanctuary for their intellectual contributions and hospitability for testing the camera equipment. Finally, I thank the Agence Nationale des Parcs Nationaux (ANPN) and the Centre Nationale de la Recherche Scientifique et Technique for permission to conduct the research and for their administrative and logistical support. I also thank David Fine and the staff of the Rèserve Prèsidentielle de Wonga Wonguè for their collaboration and support while in the reserve.