Unmanned Aircraft Traffic Management Noise Characterization and Mitigation

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Abstract— **DriveOhio, the project sponsor, plans to utilize drones to monitor roadway conditions and seeks to characterize and mitigate drone noise. The O-H-Fly-O capstone team designed and carried out experiments to characterize the noise of a Phantom 3 and 4 during static testing, takeoff/landing, and horizontal "long-haul" flight. Also tested were various propeller blade materials and configurations. The optimal propeller type was determined to be a triple-blade glass fiber propeller. Takeoff was determined to be the loudest segment of the flight path, and the threshold for flyovers was determined to be 50 ft. Along with these results, the experimental methodology developed can be applied to larger drone platforms to continue to define noise inside the allowed flight envelope.**

I. Introduction and Background

DriveOhio, the project sponsor, wishes to safely integrate an Unmanned Aircraft Traffic Management (UTM) solution into the Columbus Smart City US Route 33 Smart Mobility Corridor to monitor traffic and roadway conditions more effectively. DriveOhio wants to take precautionary measures to make sure that the drones will not adversely affect people and livestock living along US Route 33, as recent studies have exposed the negative effects of drone noise. The drone noise does not necessarily have to be physically harmful to humans or livestock to be considered, as moderately loud sounds over long durations can still be detrimental. Regardless, if drones are to be deployed in a public setting, the sound that they produce must be characterized and considered in the design of DriveOhio's UTM initiative.

In order to understand the acoustic phenomena of a small unmanned aerial vehicles (sUAS) that might be used for future UTM and to mitigate drone noise to an acceptable level, it is crucial and necessary to characterize and analyze the drone noise at the anechoic chamber because the information available on the small drones' performance and characteristics of the drone noise for propellers or rotors is very little. Dr. Intaratep and his research team used DJI Phantom II quadcopter to study its aeroacoustics performance and the effects of multi-rotor interaction [1]. The quadcopter noise and thrust were measured with a single omnidirectional microphone that was placed 0.767 meters below the Phantom II and 1.295 meters away from the quadcopter while testing 4 different rotor configurations with a different type of propeller materials which are black carbon fiber, white carbon fiber, original 9450 plastic, and aftermarket 9443 plastic. According to the research work in [1], the results of 4-rotor operation illustrated that tones at the blade passing frequency, shaft rate and their harmonics dominate the quadcopter acoustic spectrum up to 6 kHz without much deterioration as compared to 1-rotor operation and 2-rotor operation. Furthermore, the broadband frequency hump present in the mid-frequency range which increased over 10 dB above the broadband level at low frequencies. Moreover, the work done in [1] shows that for a small-scaled rotor, different rotor configurations had greatly impacted the thrust performance of a drone, but its acoustic signature was only altered near mid and high range frequencies resulting in 102 dB change in the overall sound pressure level (OASPL) for the same thrusting setting. As a result, there was a significant increase in broadband noise when switching from 2 non-adjacent rotors to 4 rotors, but the multi-rotor interaction did not affect the acoustic signature. Furthermore, original props created more thrust at a certain speed as compared to other material props, and original props had lower OASPL as compared to other material props' OASPL as shown while the rotating motor speed and thrust increased. Although the work done in [1] studied DJI Phantom II's aeroacoustics performance in an anechoic chamber, DJI Phantom III and IV might have different aeroacoustics performance. Therefore, the team decided to characterize the noise of DJI Phantom III in the anechoic chamber, but the team expected to obtain similar results since the design of DJI Phantom II, III, and IV did not have any major changes. Besides that, O-H-Fly-O capstone team conducted two outdoor tests at Ohio Department of Transportation (ODOT), where it is located beside a highway, West Freeway and at the Ohio State University (OSU) ElectroScience Laboratory to study the noise characterization of an sUAS before determining whether sUAS noise is a concern for human communities and the environment and mitigating drone noise to a reasonable level.

Based on Schultz's research work on studying the synthesis of social surveys on noise annoyance, the annoyance response to a given level of aircraft noise is less in neighborhoods with heavy road traffic than where the road traffic is light [2]. Either the heavy road traffic helps to mask the aircraft; moreover, speech activities are more seriously disturbed by aircraft noise than is sleep and with respect to sleep interference, being awakened by aircraft noise, is more disturbing than being kept from falling asleep [2]. Even though results from [2] shows that noise from a large aircraft is a concern for human communities, further studies on the effects of an sUAS noise on human communities are still needed. Furthermore, work done in [3] by Pšenka and his research team presented that exceeding the limit of 85 dB during milking the cow given that the sensitivity of the hearing apparatus of cattle at 8 kHz, it induces the behavioral response of dairy cow. Since Pšenka's work shows that noise would affect the behavior of a cow, it is important for the team to determine what are the possible animals that live near Ohio's 33 Smart Mobility Corridor and to find out whether sUAS noise would be a concern for the wild lives around that area.

The geometry of a propeller is one of the crucial factors to characterize and mitigate the noise of a sUAS. For instance, according to Wright's work on researching the acoustic spectrum of the axial flow machine, a rotor blade with a suitable leading-edge trip would help to remove the laminar boundary layer noise [4]. Besides that, Braxton' work done in [5] presented that changing the wingtip of a baseline rotor could reduce the sound pressure level of the lower frequency range but not the mid-range frequency's sound pressure level; using twist, increasing angle of attack, chord length, and number of blades increase the ratio of thrust relative to overall sound pressure level. Therefore, the team would characterize drone noise with different propeller designs and shapes.

The main purpose of the unmanned aircraft traffic management (UTM) noise characterization and mitigation project is to determine the extent to which drone noise could be a concern to humans and livestock living in the area and to determine methods of reducing drone noise to an acceptable level for the UTM project and other future commercial applications.

II. Project Development

A. *Objectives*

The objective of the DriveOhio project is to characterize and mitigate small unmanned aerial system (sUAS) noise. In order to accomplish this, the team collected frequency spectrum and sound pressure amplitude data for multiple drone operation modes with various rotor props. The sound data will be used to make a propeller and operating conditions recommendations for DriveOhio's UTM use case. The team aims to have at least two formal, documented drone noise test plans, analyzed frequency/dB noise data for 2-3 trials with at least three different rotor props, and 2-3 confident recommendations about rotor props and drone operation for the UTM project.

B. *Scope*

The scope of the project includes the characterization of low-altitude (< 400 ft.), far-field drone noise for a small unmanned aerial system (sUAS), which is a drone weighing less than 50 lbs. Test environments will include indoor anechoic chamber flight and outdoor field testing. Test variables will include multiple off-the-shelf rotor props, takeoff/landing operation, and fly-by operation at multiple heights. UTM use case recommendations will be made based on the characterization data (flight modes, rotor props, etc.).

Work that is not part of the scope of this project is vortex/near-field noise characterization, custom rotor prop design, vertiport noise mitigation design, large UAS experimentation, livestock testing, high-altitude flight, and UTM technology integration or design. Near-field noise characterization was determined to be out of scope because far-field noise was assumed to be more relevant to the UTM use case. Custom rotor prop design fell out of the project scope because the team does not have a strong educational or practical background in applied fluid mechanics. Vertiport noise mitigation design and livestock testing fell out of the current project because of schedule changes and unexpected time constraints that encouraged the team to focus on noise characterization. Large UAS and high-altitude flight are not within the scope of this project because DriveOhio suggested that sUAS will most likely be applied for the UTM use case and because the team does not have FAA approval to fly above 400 ft. UTM technology integration and design are not within the scope of this project because there is a separate project through Ohio State that is dedicated to that topic.

C. *Assumptions and Constraints*

The first assumption made for the DriveOhio project is that near-field noise characterization is not as relevant to the UTM use case as far-field data. Near-field sound appears close to the sound source (approximately five times the dimension of the rotor) and does not decrease linearly with distance from the sound source. The team assumed that the drones would not be flying within approximately 5 feet of anyone, which is outside of the DJI Phantom 3's near-field vortex, so the team decided to neglect near-field noise measurements.

The second assumption made for the project was that the DJI Phantom 3 drone is a good representation of a typical sUAS that might be used in the UTM project or for other commercial applications. This assumption was made because the DJI Phantom 3 is one of the most popular off-the-shelf small drones available and because the Phantom 3 has a wide variety of props and add-ons available. Similarly, the Phantom 3 is a comparable size to other popular small drones on the market.

The first constraint for the project is that the Federal Aviation Administration (FAA) restricts "recreational" drone flight to low altitudes (less than 400 ft.) when in uncontrolled airspace. This limited the project's potential scope of work.

The second constraint is that the Phantom 3 is the only drone readily available to the team for testing. Due to a limited project budget, the team could not purchase a drone. Instead, an sUAS was borrowed from Ohio State's Aerospace Research Center, and the Phantom 3 is the drone the team was permitted to use. This removed drone body noise characterization from the team's potential work and limited the variety of tests the team can complete.

The final project constraint is that a certified drone pilot is needed for outdoor flight testing because this is a commercial project and because the team does not own the Phantom 3 drone. The Aerospace Research Center requested that one of their certified pilots fly the drone because they own the Phantom 3. This constrained the team to certain flight test times.

III. Technical Approach

A. Phase 1

Phase 1 testing was the first round of testing completed and was focused on the frequency response of the drone. The purpose of the Phase 1 test was to study the frequency response of the drone at the maximum thrust operating condition with different blade materials and blade configurations. Specifically, the propellers studied were 2-blade standard propellers, 2-blade carbon fiber propellers, 2-blade glass fiber propellers, and 3-blade standard propellers.

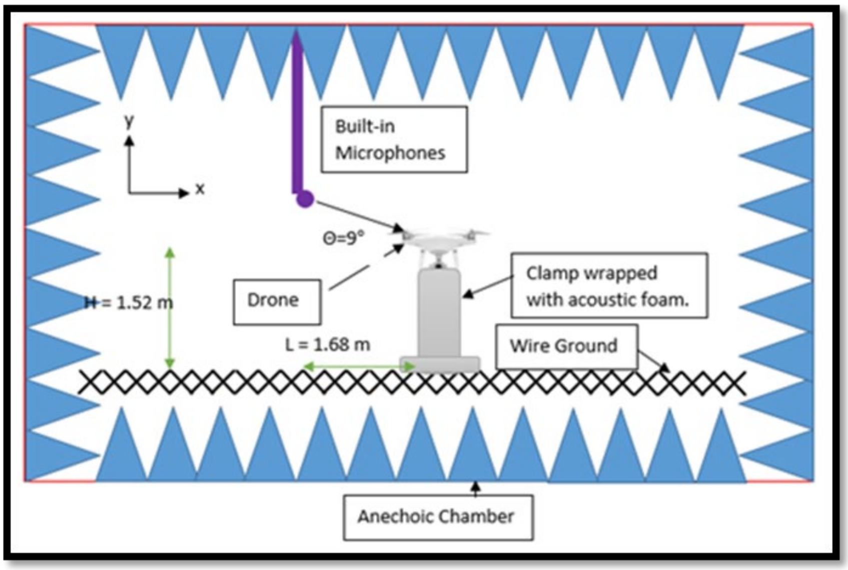

Figure 1: *Phase 1 Testing Setup.*

B. Phase 2

Phase 2 testing was the second round of testing completed and was focused on the drone noise during a typical use case. The purpose of phase 2 testing was to characterize drone noise through the two primary flight modes expected by the defined use case- takeoff/landing and long-haul horizontal flight. The results from this test can inform recommendations on drone operations conditions as well as for determining flight paths. Phase 2 testing was performed at multiple locations. The first round of testing was held at the Ohio State ElectroScience Lab field located at 1330 Kinnear Road, Columbus OH. The pilot was Ryan Thorpe, a graduate student who has Part 107 certification. Triple blades design was used throughout the test, since it was the least noise that produced among all other blades. This testing was repeated on two dates with two different data acquisition systems. The first round of ElectroScience testing utilized the built-in UMM-6 acquisition software whereas the second round of testing utilized a LabView based acquisition software. The reason for this shift to LabView was it enabled a larger degree of control over the sampling rate and allowed for longer recording windows which were necessary to perform analysis in the frequency domain as well as the time domain. During the second round of testing at ElectroScience testing, the pilot was Brandon Emshoff, a graduate student with ARC with a Part 107 certification.

The second test location was at the ODOT facility near US 33. The reason for this additional location was to more closely simulate use-case testing, as the near-highway test location is nearly identical to the defined use case. For this test, the Phantom 4 drone was used based on availability issues with the Phantom 3. While the body and frame of the Phantom 4 are comparable to that of the Phantom 3, the primary differences are improved camera function (which would not impact noise) and some different software functions for faster/more aggressive flight (which would impact noise). The pilot for this testing was Rich Granger, a professionally trained drone pilot.

Before beginning the actual tests, the team performed the safety pre-flight first to prepare for any circumstances that could happen in outdoor testing. The microphone was installed 1m above the ground on the mounting stand to avoid picking up reflected sound from the ground. Then the ambient noise was recorded to compare the data with drone noise in the result. Ambient noise recording consisted of 3 recordings of 30 seconds.

The first part of phase 2 testing will be focused on vertical takeoff/landing. The microphone recorded the sound and laptop acquired data beginning from launch from the ground at full throttle until reaching a maximum height of 60 ft. After reaching maximum height, the drone returned to the ground at which point the microphone stopped recording. A test schematic can be found in Figure 2.

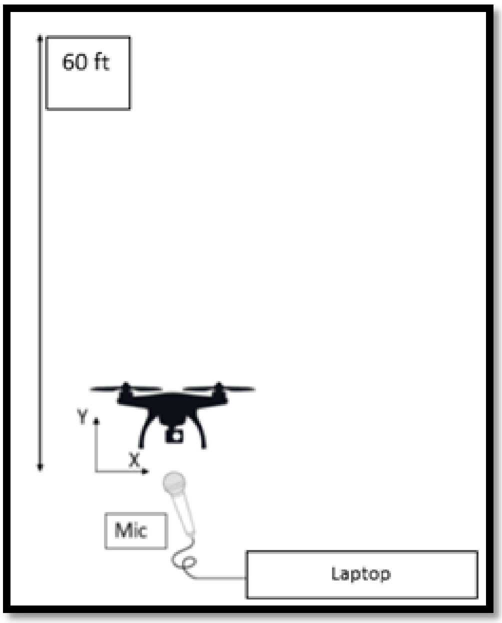

Figure 2: Takeoff/Landing Test Setup.

The second part of phase 2 testing was focused on the horizontal "long-haul" flight of the drone. A schematic of the test setup can be found below in Figure 3.

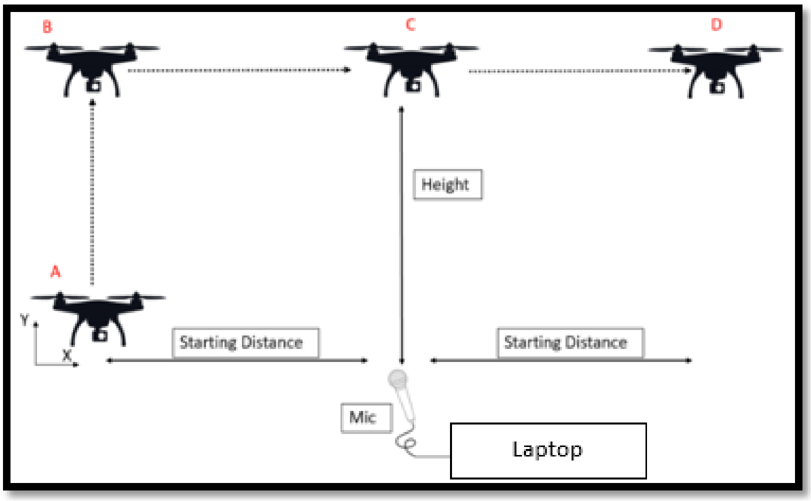

Figure 3: *Horizontal Flyover Test Setup.*

The drone was placed at a starting distance 50 ft from the microphone at position "A." The drone took off until reaching the height defined by the procedure at point "B" at which point the microphone began recording at maximum thrust overtop the microphone through point "C" until a distance of 50 ft on the opposite end of the microphone at point "D." The drone then returned to the starting point B and the microphone stopped acquiring. The microphone was the same used for vertical landing/takeoff.

The flyover heights were 25, 50, 75 and 100 ft. One trial was conducted for each height to account for limited battery power. The recorded data was the full noise/time file as well as a video of the test and a screen recording of the drone height over time. The weather conditions for the first round of outdoor testing at the ElectroScience Lab were 49 degrees °F, 90% humidity, and 1 MPH winds SSW. The weather conditions for the second round of testing at the ElectroScience lab were 50 degrees °F, 82% humidity, and 3.1 MPH winds NE. The weather conditions for the testing at the ODOT facility were 44 degrees °F, 49% humidity, and 9.1 MPH winds SW.

IV. Phase 1 and 2 Results

A. Phase 1

Phase 1 results from anechoic chamber testing were focused on an idealized frequency characterization. As shown in Figure 4, the relative amplitudes and frequencies are comparable for all three 2-blade configurations which the only differences between glass fiber blades having slightly lower fundamental frequencies.

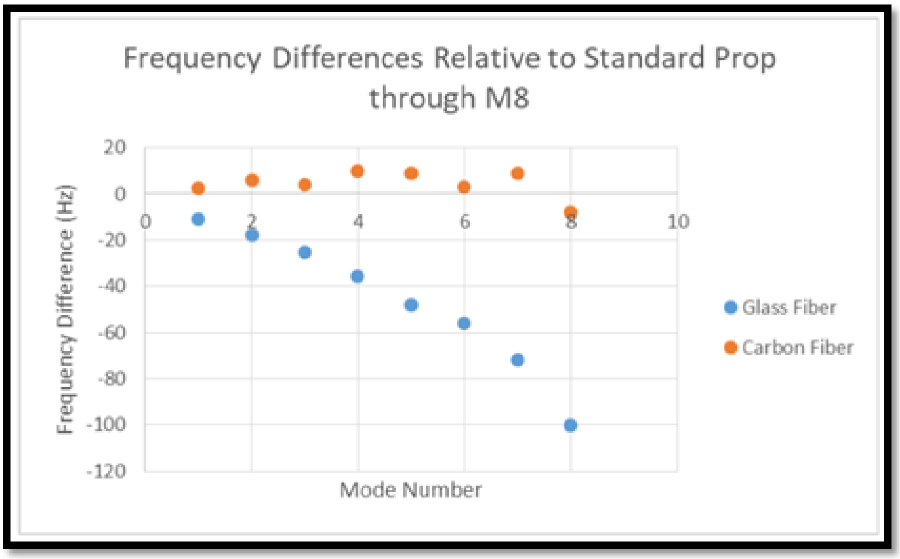

Figure 4: *Two-Blade Configurations Comparison*

However, the three-blade configuration is significantly different than the two-blade configurations. Because the three-blade configuration has 3 pulses per rotation compared to 2 pulses per rotation for a two-blade configuration, the three-blade will inherently have more fundamental frequencies. Because it has MORE frequencies, the result is that each frequency will have a lower amplitude compared to a comparable frequency amplitude for a two-blade configuration.

In order to capture the overall strength of each signal, the RMS of the signals was calculated within 2000 and 5000 Hz. The standard 2-blade was 30.50 dB, the standard 3-blade was 28.77 dB, the glass fiber 2-blade was 27.71 dB, and the carbon fiber 2-blade was 30.27 dB. Based on these results, the initial recommendation for reducing the overall drone noise level would be to use higher blade configurations. This is recommended because increasing from 2 to 3 blades for the standard propeller decreased the overall RMS by approximately 2 dB. Additionally, this result is confirmed by the conventional understandings of drone noise and a research review. In terms of material, among the 2-blade configurations, the lowest noise level was for the glass fiber, implying that the optimal blade combination would be a glass fiber blade with a triple-blade configuration. However, additional testing should be conducted to verify this conclusion.

B. Phase 2

After analyzing ambient noise before all three tests were completed, the overall ambient noise at ODOT was found to be 67.26 dB, 63.62 dB at ElectroScience round 2, and 57.1 dB for ElectroScience round 1. The reason for the difference between ElectroScience round 1 and 2 can be attributed to two different factors. The first is that for round 1, the calibration offset applied for the first set of testing was not correctly applied and the actual dB level is understated. However, the order of results and differences in magnitudes for various tests is correct. Additionally, the wind during the second round of testing was higher (3.1 MPH compared to 1.1 MPH). Therefore, the quantitative values from ElectroScience round 1 will not be considered and only ranking/ordering will be used.

The second two test dates at ODOT and ElectroScience 2 reflected expected ambient results with ODOT being louder due to less wind shielding and highway traffic present in the signal.

After studying ambient noise results, takeoff and landing results were analyzed and the noise levels from ElectroScience Round 1 can be found below in Table 1.

Table 1: *Takeoff/Landing Results*

Trial	Maximum Height [ft.]	Takeoff Noise [dB]	Landing Noise [dB]	Noise at Maximum Height [dB]
1	55.00	74.15	65.57	57.62
2	61.50	67.80	72.29	57.21
3	63.00	67.85	66.35	56.66
Average	59.83	69.93	68.07	57.16

As shown above, the max height varied from trial to trial ranging from 55 to 63 ft, introducing a large source of variables into the readings. However, the overall trends from ElectroScience 1 are supported by the more controlled testing at ODOT and ElectroScience 2.

For ElectroScience Round 2 and ODOT testing, the max height was hit exactly for all trials due to more careful test operation. For the second set of ElectroScience testing, the average takeoff noise was 99.6 dB and the average landing noise was 91.7 dB. For the ODOT testing, the average takeoff noise was 103.1 dB and the average landing noise was 95.4 dB. All three test tests lead to the same conclusion, that takeoff noise is louder than landing noise which can be explained by a more aggressive takeoff compared to a relatively conservative landing to adequately slow the drone before making contact with the ground. Also, the noise at the maximum height is near to ambient noise, especially at ODOT where the ambient noise level is louder. This is confirmed subjectively by ear during testing.

The results from phase 2 long haul flight at the ElectroScience lab can be found below in Table 2 with the results visualized in Figure 5 relative to the average ambient noise level.

Table 2: *Horizontal "Long-Haul" Flight Results at the ElectroScience Lab*

Flyover Height [ft.]	Peak Noise [dB]
25	78.61
50	73.98
75	71.46
100	69.74

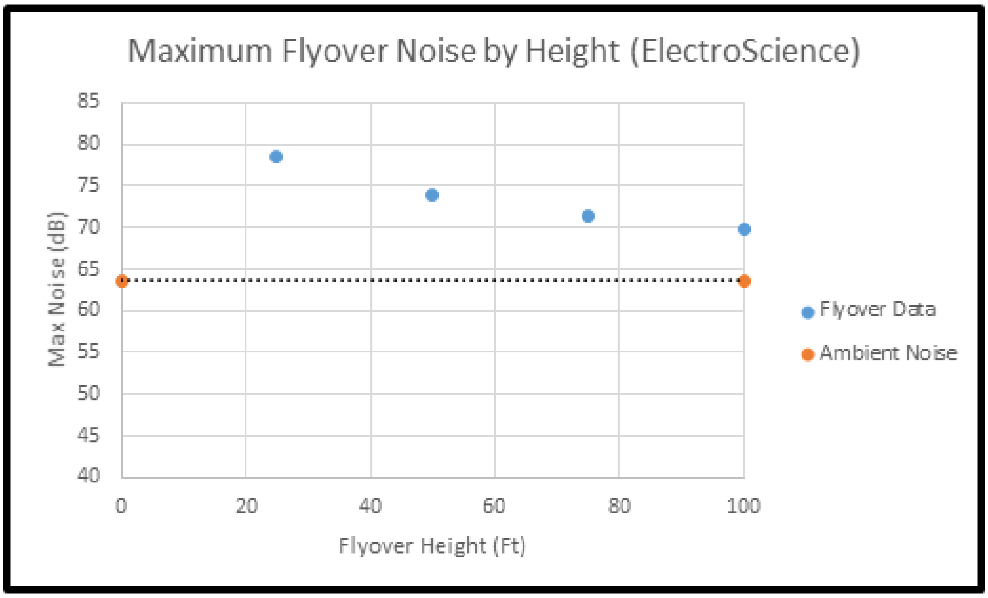

Figure 5: *Maximum Flyover Noise by Height at the ElectroScience Lab*

As expected, the noise level during flyover decreased as height increased. Some sources of variability in these results are due to not being able to completely control flyover speed and some drone "drift" due to momentum and wind speed. The results from ElectroScience can be compared to the results from ODOT testing. There are a few fundamental differences between the two tests. The first is the location being at ODOT where the ambient noise is significantly louder. Secondly, the pilot was more experienced and thus was better able to avoid drift, especially at higher flyover heights. Finally, the platform for ODOT was the Phantom 4 compared to Phantom 3 with the expectation being that the Phantom 4 would be marginally louder.

The results from ODOT testing flyover heights can be found below in Table 3 and can be visualized against ambient noise in Figure 6.

Table 3: *Horizontal "Long-Haul" Flight Results at the Ohio Department of Transportation (ODOT)*

Flyover Height [ft.]	Peak Noise [dB]
25	95.75
50	84.43
75	73.22
100	70.65

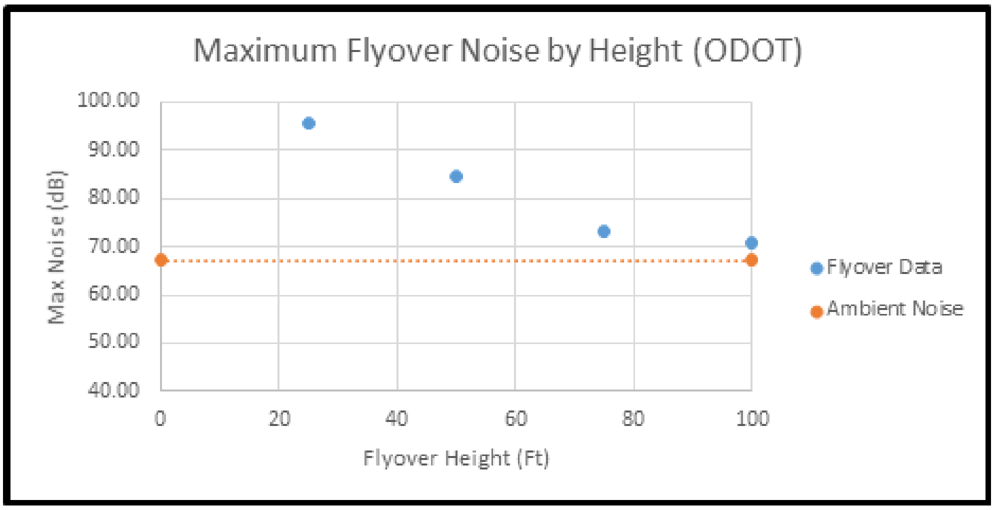

Figure 6: *Maximum Flyover Noise by Height at the Ohio Department of Transportation (ODOT)*

The trends reflected in this plot are comparable to the results from testing at ElectroScience. However, as noted in section 3.2.3, the peaks at 75 ft and 100 ft were almost indistinguishable compared to the louder ambient noise near the highways. Based on this observation, a recommendation for reducing drone noise would be to increase the height until reaching a minimum height of 50 ft before initiating long haul flight. The overall trends of both plots are as expected, with peak noise falling off non-linearly with respect to the height.

V. Conclusion and Recommendations

The overall project objective was to characterize and mitigate sUAS noise along US Smart corridor 33. Based on both Phase 1 and 2 testing, the noise and frequency response of an sUAS was characterized in both an idealized scenario (anechoic chamber), a non-idealized scenario (ElectroScience testing), and finally in a use-case scenario (ODOT testing). Based on the characterization activities, recommendations have been provided to assist with noise mitigation.

Phase 1 testing studied 4 propellers consisting of both 2 and 3-blade configurations as well as three different materials. The testing was conducted in an anechoic chamber and the frequency spectrum was generated for each propeller. The results from this test showed that among propellers with a 2-blade configuration, the quietest material was glass fiber at an average strength of 27.71 dB compared to 30.27 dB and 20.50 dB for Carbon Fiber and Plastic, respectively. When comparing plastic 2 and 3-blade configurations, the 3-blade has an average strength of 28.77 dB compared to 30.50 dB for 2-blade. Therefore, the overall blades configuration and material recommendation would be a glass fiber propeller with 3 blades.

Phase 2 testing studied the Phantom 3 and 4 in use-case operation with a focus on takeoff/landing and horizontal long-haul flight. The locations tested were the ElectroScience lab which was rural and the ODOT facility which was located adjacent to highways, closely simulating the use case environment. As expected, the ambient noise near the highway was greater (67.26 dB) compared to the rural ambient noise (63.62 dB).

The results from takeoff/landing showed that takeoff noise is louder (103.1dB for the Phantom 4, 99.6 dB for the Phantom 3) compared to landing noise (95.4 dB for the Phantom 4, 91.7 dB for the Phantom 3). At the peak takeoff height (60 ft), the drone noise was not significantly different than the overall variation in the ambient noise level.

The results from horizontal long-haul flight show a non-linear noise drop in noise compared to height. At heights above 50 feet in the use-case environment (ODOT), the sound peaks were not significantly different compared to the ambient noise level and fell below a typical "annoyance" threshold of 75 dB. Therefore, the recommendation for noise mitigation would be upon takeoff, immediately lift off until reaching 50 feet is reached before initiating horizontal flight.

VI. LIMITATIONS AND NEXT STEPS

There are several limitations and sources of error in this study. Because the tested UAS were only the Phantom 3 and 4, the results of this study should be considered relevant to only sUAS quadcopters. However, the overall experimental test method used could be utilized to larger quadcopters or even fixed-wing aircraft. The first is the inherent variability between test pilots, as three different pilots were used during the study which could have influenced both how fast the drone flew, as well as how much drift there was in the drone path. This risk was mitigated by carefully defining the test procedure and monitoring drift and redoing trials as needed. The second is the variability in wind level both between test dates as well as consecutive trials. This risk was mitigated by performing multiple trials, as well as by recording weather conditions from test to test to identify potential systematic shifts in noise level due to noise. Another limitation of the study was the relatively low sampling rate of the microphone. While the microphone was capable of sampling at 20 kHz, allowing for frequency reconstruction of most peaks within human hearing, the sampling was NOT adequate to reconstruct higher frequency noise that would impact animals and livestock.

Based on the results of the study, there are several recommendations the team has for future work. The first would be to acquire a microphone and DAQ system capable of sampling at 100 kHz. While this would represent a significant cost, the resulting improvement in resolution may lead to valuable insights with respect to any frequency domain analysis. Secondly, further studies could work with different aircraft systems such as UAS heavier than 50 pounds or fixed-wing aircrafts. Finally, this study was primarily focused on drone characterization and mitigation with respect to humans. However, when considered the context of the problem, interactions with livestock along the Smart Corridor may also be relevant. Therefore, studies focused on the impact of sUAS noise on animals/livestock would potentially be beneficial to reducing overall drone noise impact during use-case operation.

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