A Summary of NASA Research Exploring the Acoustics of Small Unmanned Aerial Systems

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ABSTRACT

Proposed uses of small unmanned aerial systems (sUAS) have the potential to expose large portions of communities to a new noise source. In order to understand the potential noise impact of sUAS, NASA initiated acoustics research as one component of the 3-year DELIVER project, with the goal of documenting the feasibility of using existing aircraft design tools and methods on this class of vehicles. This paper summarizes the acoustics research conducted within the DELIVER project. The research described here represents an initial study, and subsequent research building on the findings of this work has been proposed for other NASA projects. The paper summarizes acoustics research in four areas: measurements of noise generated by flyovers of small unmanned aerial vehicles, measurements in controlled test facilities to understand the noise generated by components of these vehicles, computational predictions of component and full vehicle noise, and psychoacoustic tests including auralizations conducted to assess human annoyance to the noise generated by these vehicles.

INTRODUCTION

The proliferation of small unmanned aerial systems (sUAS) and potential missions for small propeller- and rotor-driven air vehicles have motivated research to better understand the potential noise impact of these vehicles operating in communities. Initial research to explore the noise impact of sUAS was conducted as part of the Design Environment for Novel Vertical Lift Vehicles (DELIVER) project at NASA. (Ref. 1) The DELIVER project assumed a definition of sUAS consistent with FAA guidelines, which specify *small* UAS as weighing less than 55 lbs. (Ref. 2). The overall goal of DELIVER was to determine the feasibility of producing a conceptual design tool for sUAS that encapsulates NASA's capabilities in full-scale rotorcraft and fixed-wing aircraft design. Such a tool would incorporate performance considerations such as speed, range, payload, and efficiency, as well as environmental impact in terms of noise and annoyance. The result would be a capability to optimize a vehicle configuration for multiple performance aspects as well as predicted annoyance due to noise.

Although the relationship between noise and annoyance has been extensively studied for larger aircraft (see, for example, (Refs. 3, 4)), the applicablity of annoyance metrics developed for larger vehicles to sUAS has not been established. In addition, the suitability of applying existing noise prediction tools developed for full-scale rotorcraft and propeller airplanes to noise-generating components of sUAS has not been established. Within the DELIVER project, a multifaceted approach was implemented to improve the understanding of sUAS noise and progress toward a goal of specifying a noise metric that could be incorporated into a conceptual design tool to quantify annoyance due to noise. This approach consisted of coupled research endeavors in the following areas:

- Acquisition of sUAS vehicle data while flying outdoors, including vehicle state data and the corresponding noise on the ground
- Testing of representative sUAS components and subsystems in a controlled indoor acoustic environment
- Application of existing numerical tools to predict sUAS component and full vehicle noise
- Psychoacoustic testing to explore the relationship between human annoyance to sUAS noise and existing noise metrics

As this is an overview paper, references are provided for the reader to obtain more detailed information from publications generated as part of the DELIVER project.

OUTDOOR FLIGHT NOISE

Acoustic measurements of flyover noise generated by sUAS were made in a series of flight tests conducted between December 2014 and December 2016. Some of the tests were dedicted to acoustic measurements while other tests involved non-acoustic test goals, such as vehicle performance, that presented an opportunity to collect acoustic data. This section describes the recording hardware and methods used during the tests, as well as details of the vehicles, flight conditions, and recording locations.

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Instrumentation

For the tests discussed here, the noise generated by the sUAS was recorded using three microphones with two placed directly beneath the flyover path of the vehicle and the third placed 10 m to the sideline of the flight path. One of the two microphones under the flight path was on a tripod 1.2 m above ground level with the second microphone directly beneath this microphone on a 0.4 m diameter rigid plastic ground board. The sideline microphone was also on a rigid ground board. The microphones for these tests were 1/2" (12.7 mm) pre-polarized, random-incidence microphones covered with a hemispherical foam windscreen (for the ground board microphones) or a spherical windscreen (for the tripod microphone).

The microphone responses for the first three flight tests discussed here were digitized using a portable USB data acquisition system with a sampling rate of 20 kHz connected to a laptop computer. Microphone responses for the fourth test in San Diego were digitized using a 6-track field recorder in uncompressed PCM format.

For all tests, an external GPS receiver with a time code generator provided a UTC time signal that was acquired simultaneously with the acoustic data for post-flight synchronization with vehicle state data recorded by a flight data acquisition system. GPS coordinates of the microphones were also measured so they could be referenced to the vehicle location in post-processing. Meteorological measurements were not made during all of the flights, but recordings were only deemed acceptable when winds were below 10 knots and interfering background noises were minimal.

Vehicle state information, including roll, pitch, yaw, and GPS position, was recorded with either a detachable flight data acquisition system or using data storage capabilities of the vehicle's flight control system.

Virginia Beach Airport

Measurements of flyover noise of three sUAS were made in December 2014 at the Virginia Beach Airport, a privately owned airfield with a 1477 m long, 58 m wide grass runway. The vehicles included a fixed-wing, internal combustion powered airplane, a quadcopter, and a hexcopter with 3 sets of co-axial rotors. All vehicles had fixed-pitch propellers/rotors. Vehicle weights ranged from 2.5 kg to 11.3 kg. Specifics of the tested vehicles are described in Ref. 5.

The attitude control mechanism for the multicopters can play an important role in the vehicle noise signature. Whereas airplane attitude (roll, pitch and yaw) is controlled using relatively quiet control surfaces such as ailerons, elevators, and a rudder, control of multicopter attitude is often accomplished by varying the rotation speed of the propellers. Changes in rotation speed produce thrust variations about a desired axis of the vehicle. The specific rotor speed changes are determined by the flight control system in response to pilot commands or external perturbations such as wind gusts. Modifications to rotor speed result in unique, time varying blade passage frequencies (and harmonics) for each rotor that create an unsteady noise signature very different from the noise of conventional propeller aircraft or helicopters.

The vehicles were manually piloted in level trajectories at target altitudes and speeds. For the multicopters, the target altitude range was 3-30 m above ground level (AGL), with a target speed range of 0 m/s (hover) to 15 m/s. For the fixed wing vehicle, altitudes ranged from 20-100 m AGL and speeds ranged from 20-40 m/s. The human pilot introduced unsteadiness in the vehicle flight path and resulting acoustic signature that may not have been present in an autopiloted flyover.

Finnegan Airfield

Noise measurements were made of a hexcopter with non-coaxial rotors in August 2015 at Finnegan Airfield at Fort AP Hill, Virginia. Finnegan Airfield is dedicated to sUAS and has a 365 m long, 30 m wide paved runway. The hexcopter weighed 7.3 kg, including the weight of an instrument payload.

Examples of spectrograms from the ground microphone of the quadcopter flyover, recorded at Virginia Beach, and a hexcopter flyover, recorded at AP Hill, are shown in Fig. 1. (Ref. 5) Harmonics of multiple blade passage frequencies, one for each rotor, are visible as time-varying horizontal traces in the figures. The figures illustrate the multi-tonal, time varying nature of the acoustic signatures of these vehicles.

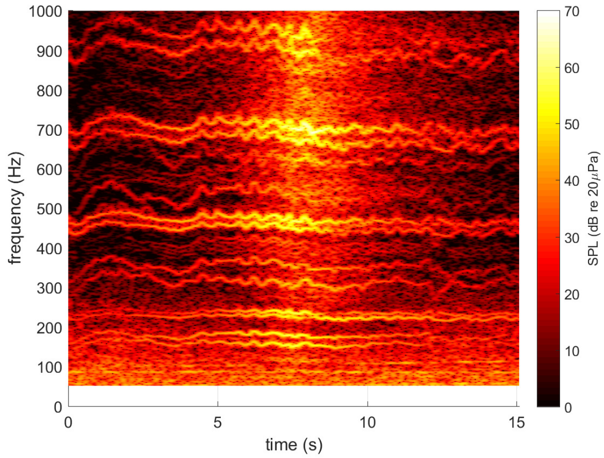
Oliver Farms

Flyover noise generated by two quadcopters and an octocopter was recorded during flights that took place on a small grass strip, referred to as Oliver Farms, in September, 2016. One of the quadcopters and the octocopter used the common attitude control method of varying rotor rotation speed, but the other quadcopter drove its four rotors with a single motor so they all spun at the same speed. Attitude was controlled by varying the pitch of individual rotors. The result was a vehicle that sounded more like a single-propeller airplane than a typical multicopter with time-varying rotor speeds.

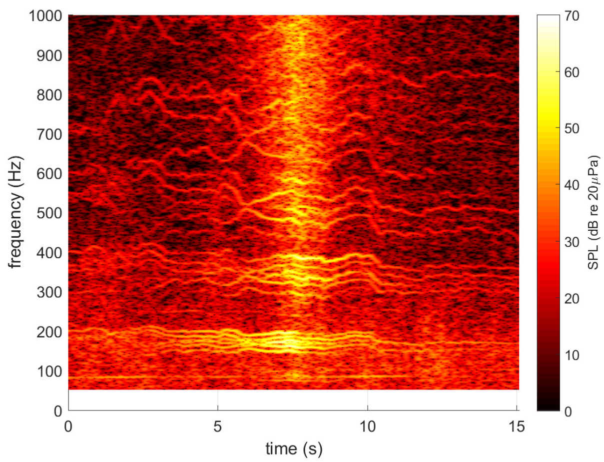
Nominal flight trajectories for the vehicles consisted of straight and level flyovers at 5 and 10 m/s forward flight speed at various altitudes AGL. Actual speeds and altitudes obtained during the recordings varied depending on the vehicle and the capabilities of the pilot or autopilot.

Wind conditions were generally calm for these flights, with winds less than 10 knots. A large number of cicadas and birds were present in the woods that bordered the field. This was an unfortunate noise source that required consideration when the recordings were subsequently used for human subject testing.

Shortly after the Oliver Farms measurements, the same recording equipment was used to record drive-by noise of various ground vehicles at NASA Langley. Noise from a small passenger hatchback, utility van, box truck, and step van was



(a) Quadcopter flyover (∼6 m AGL, 6 m/s).



(b) Hexcopter flyover (∼5 m AGL, 13 m/s).

Fig. 1. Spectrograms of multicopter flyovers.

recorded while the vehicles were driving on a stretch of flat and straight road. The target test condition was a 10 m/s (≈25 mph) drive-by of the tripod mounted microphone, which was approximately 10 m from the centerline of the vehicle's path. The drivers were instructed to maintain a constant speed while passing the microphones to minimize engine noise associated with acceleration. All vehicles were in good mechanical condition. The recordings were dominated by tire noise, as well as some low frequency engine noise for the larger vehicles. As it was winter in Virginia, there was considerably less background noise from local fauna than at Oliver Farms. (Ref. 6)

San Diego

The final set of sUAS recordings discussed here was taken in December 2016, in the Cleveland National Forest, about 35 miles northeast of San Diego, CA. These flights were conducted with help from Straight Up Imaging (SUI), a San Diego-based firm that builds and operates sUAS for imaging and surveying purposes. During these flights, noise produced by SUI's Endurance vehicle was recorded along with vehicle state information including position, attitude, and flight speed. This vehicle weighs approximately 3.2 kg unloaded. (Ref. 6) The Endurance performed autopiloted straight and level flyovers at 5 and 10 m/s, and at 20, 30, 50, and 100 m AGL. These flyovers were much more tightly controlled than flyovers made in any of the three previous flight tests. Winds were calm on the day of the test, and ambient noise was significantly lower than at Oliver Farms.

sUAS COMPONENT TESTS

Although measurements of flyover noise from flight testing provided valuable insight into the noise characteristics of sUAS, testing under more controlled conditions enhanced understanding of the noise generation mechanisms of these vehicles. Measurements made in these controlled tests were then compared with predictions from propeller or rotor noise prediction codes of varying fidelity.

Hover Source Noise Measurements

Two test campaigns have been performed to study components of rotary wing sUAS in static hover conditions. These tests were conducted in an anechoic chamber within the Structural Acoustic Loads and Transmission (SALT) facility at the NASA Langley Research Center. (Ref. 7) The goal of the first campaign was to assess the accuracy of existing noise prediction techniques for rotors and rotor speeds typical of sUAS. (Ref. 8) More information on these prediction techniques is provided in the next section. The sUAS components tested in this first campaign consisted of an isolated rotor powered by a brushless motor in a vertical tower arrangement to allow clean wake development.

The second test campaign was conducted to study the noise generating mechanisms of more realistic rotor-vehicle configurations. (Ref. 9) The tested configurations consisted of a single rotor-motor system, similar to the first campaign, with simplified airframe geometries intended to represent a generic multi-copter support arm. An image of the rotor and airframe test stands is shown in Fig. 2.

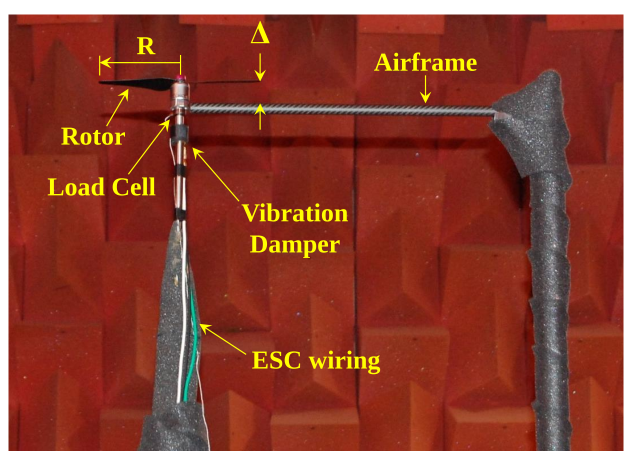


Fig. 2. Components and geometric parameters of source noise measurement test setups.

Figure 3 provides experimental acoustic spectra, in the form of narrowband sound pressure levels (SPLs), for a range of separation distances between the rotor and the support arm, where the vertical separation between the two is denoted by the nondimensional parameter Δ/R (as illustrated in Fig. 2). The rotor rotation rate was 5400 RPM, corresponding to a blade passage frequency (BPF) of 180 Hz. The noise was measured with a microphone positioned 45° below the plane of the rotor and 90° from the centerline axis of the support arm $(\theta, \phi) = (-45°, +90°)$.

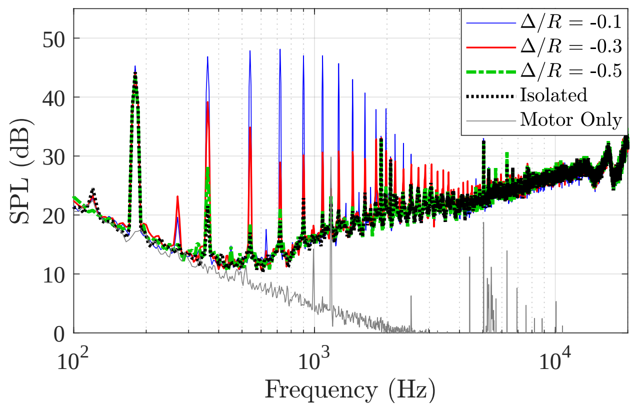
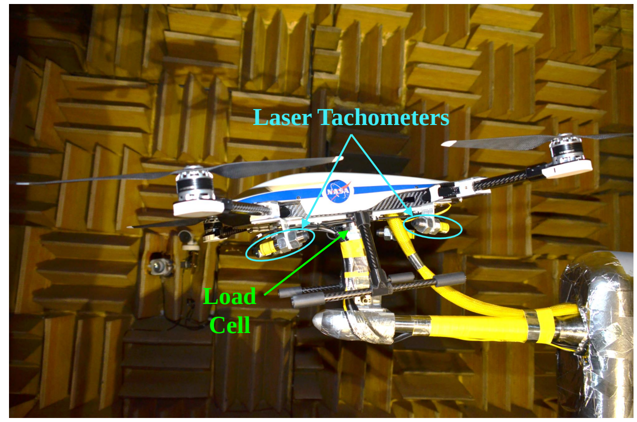


Fig. 3. SPL versus rotor-arm vertical separation. (Ref. 9)

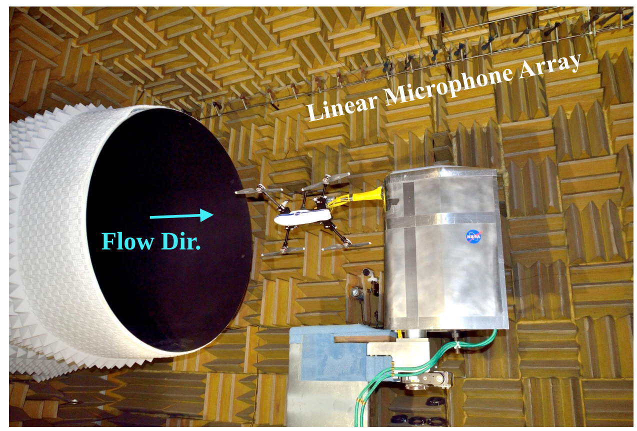
As the data show, noise generated by an isolated rotor (no airframe) is dominated by a tone at the BPF, with much lower levels at higher harmonics of the BPF. Broadband noise out to 20 kHz is evident in all cases. Reducing the vertical separation between the rotor and the support arm dramatically increases SPLs of higher harmonics of the BPF. The case of least vertical separation, $\Delta/R = -0.1$, corresponds to highest harmonic levels of the BPF, while the case of maximum vertical separation, $\Delta/R = -0.5$, yields only a slight increase in acoustic energy at the 2nd and 3rd BPF harmonics of 360 and 540 Hz, respectively, relative to the isolated rotor configuration. These results demonstrate the acoustic impact of airframe components located close to the plane of the rotors, a characteristic of some sUAS.

Full Vehicle Noise Measurements

An additional test campaign explored the noise generated by a full quadcopter airframe in both hover and forward flight conditions. The tests were conducted in the NASA Langley Low Speed Aeroacoustic Wind Tunnel (LSAWT), an open-circuit free jet wind tunnel. The facility has recently undergone a capability enhancement to enable the acquisition of aerodynamic performance and acoustic data of sUAS and small electric propeller/rotor platforms. (Ref. 10) The test article for this campaign was an SUI Endurance airframe with motor and rotor hardware representative of the actual vehicle. This vehicle was tested to provide controlled wind tunnel data to complement data collected in earlier flight tests. (Ref. 6) Photographs of the vehicle installed in the LSAWT test section are provided in Fig. 4.



(a) Upright Orientation



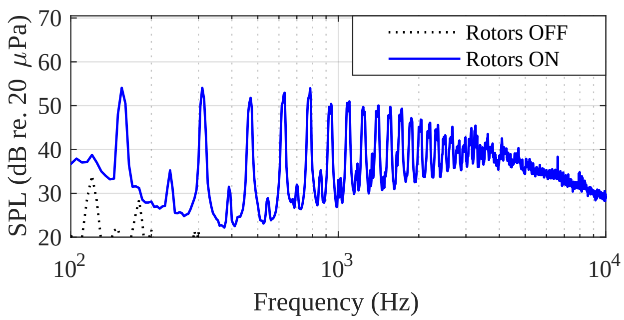
(b) Flyover Orientation

Fig. 4. SUI Endurance quadcopter vehicle test configurations in the LSAWT.

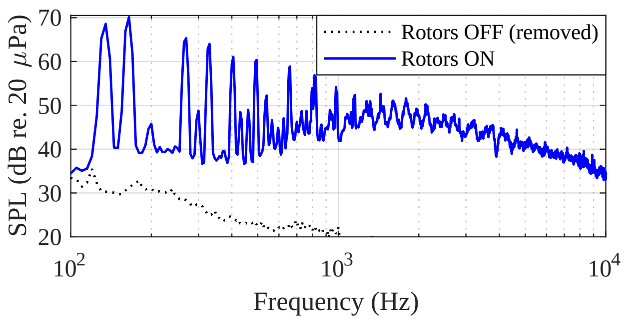
The vehicle airframe was positioned within the tunnel open-jet core flow via a vertical strut and sting arm extending upstream from an airfoil fairing. Motor rotation rates and approximate relative rotor positions were monitored using vehicle-mounted laser sensor tachometers. Two vehicle orientations were tested: one with the vehicle in an upright orientation (Fig. 4(a)), and one with the vehicle in a flyover orientation (Fig. 4(b)) relative to a ceiling corner-mounted linear microphone array. The upright orientation utilized a multi-axis load cell to determine motor rotation rates needed to trim the vehicle for different desired thrust conditions. The flyover orientation was used to provide an acoustic survey of the vehicle flying overhead.

Sample acoustic results for a 4.5-kg net vehicle thrust in both hover and forward flight conditions are provided in Fig. 5. The hover data shown in Fig. 5(a) indicates a BPF of approximately 155 Hz that is common to all four of the vehicle rotors. The high SPLs of higher BPF harmonics may be indicative of prominent rotor-airframe interaction noise.

Forward flight data in Fig. 5(b) shows BPFs at 135 and 165 Hz, corresponding to the forward and aft rotor rotation rates, respectively. These rotation rates were set manually to achieve a trimmed forward flight condition at the load cell beneath the vehicle. A similar splitting of forward and aft rotor rotation rates was observed in the quadcopter flyover spectrogram measured outdoors in Fig. 1(a). While the front and aft rotor BPFs for the forward flight condition are between 13 and 15 dB higher in amplitude than that of the hover condition, the following harmonics are seen to roll-off at a much faster rate. Further analysis of these results will be reported in a future publication, including comparisons to flight test data of this vehicle.



(a) Hover Condition (No Tunnel Flow)



(b) Forward Flight Condition (U_∞ =15.2 m/s)

Fig. 5. SPL of the SUI Endurance in a flyover orientation in LSAWT. ***Note: Spectra are for an observer located at*** 70° ***below flight path.***

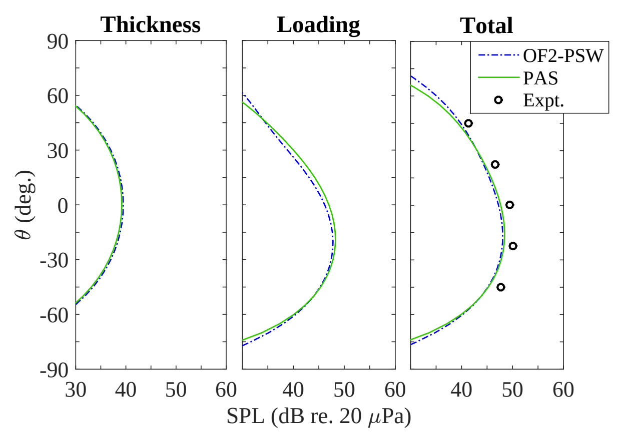
COMPUTATIONAL PREDICTIONS

Multiple computational techniques were used to predict hover noise corresponding to the component measurements discussed in the previous section. These include a high-fidelity computational fluid dynamics (CFD) technique coupled with a Ffowcs Williams-Hawkings (FW-H) solver, a low-fidelity blade element analysis method for predicting tonal acoustics, and a semianalytical frequency domain tool for predicting broadband rotor self noise.

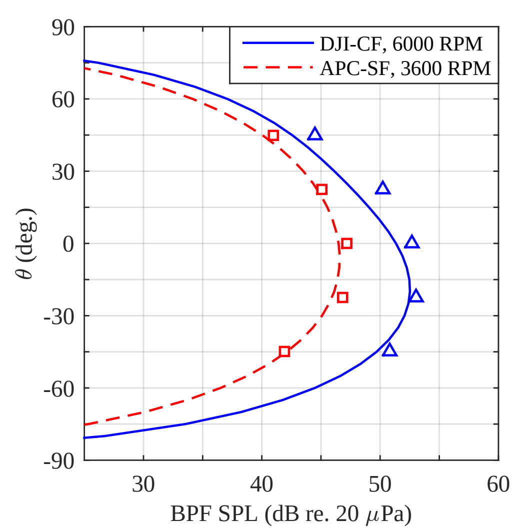
Isolated Rotor Noise Predictions

As mentioned previously, the goal of the first component test campaign was to assess the accuracy of existing noise prediction techniques for rotors and rotor speeds typical of sUAS. High-fidelity CFD predictions were used to generate periodic impermeable surface pressure loading data that were then input into a FW-H solver. The respective CFD and FW-H codes utilized in this study are OVERFLOW2, (Refs. 11, 12) an unsteady Reynolds-averaged Navier Stokes (URANS) code, and the PSU-WOPWOP code. (Ref. 13) The overall noise prediction technique is referred to here and elsewhere as OF2-PSW. (Ref. 8) Low-fidelity tonal acoustic predictions were also implemented using the Propeller Analysis System (PAS) part of the NASA Aircraft NOise Prediction Program (ANOPP). (Ref. 14) Finally, broadband noise predictions were performed using the Broadband Acoustic Rotor Codes (BARC) suite, which was originally developed for modeling broadband self noise of full-scale helicopter rotors. (Ref. 15)

The OF2-PSW and PAS methods predicted tonal noise generated by the rotor measured in Fig. 3. The data in that figure indicate that the tonal content for the isolated rotor is dominated by the BPF. Figure 6(a) provides a directivity comparison for the isolated rotor case of Fig. 3 among OF2-PSW predictions, PAS predictions, and experimental data.



(a) BPF Predictions using OF2-PSW and PAS



(b) PAS Predictions for Similar Thrust Conditions

Fig. 6. BPF directivity predictions using OF2-PSW and PAS with comparisons to experimental data. (Ref. 8)

These results demonstrate excellent agreement between the two prediction techniques in terms of both thickness and loading noise contributions, as well as excellent agreement between the total predicted noise of these and the experimental data. To further assess the prediction capability of a low-fidelity tool such as PAS, it was tested against two rotors of considerably different geometries for similar thrust conditions. Figure 6(b) shows the PAS BPF directivities for these two rotors with comparisons to the experimental data (symbols). These results demonstrate that a computationally efficient prediction method such as PAS may be suitable for tonal acoustic characterization of isolated sUAS rotors in static hover conditions.

As is shown in Fig. 3, high-frequency broadband noise could potentially play an important role in sUAS rotor noise. Being able to predict this noise is also important for the purposes of auralization (see next section). Therefore, the BARC was implemented on the small rotors tested in Ref. 8, a sample result of which is shown in Fig. 7. This figure demonstrates the ability of the BARC to predict the broadband trends of the rotor, with additional insight into contributions from difference source mechanisms. These mechanisms are further explained in Ref. 8.

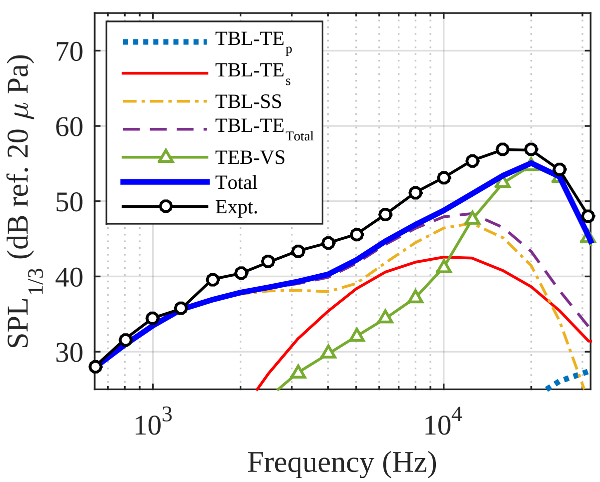
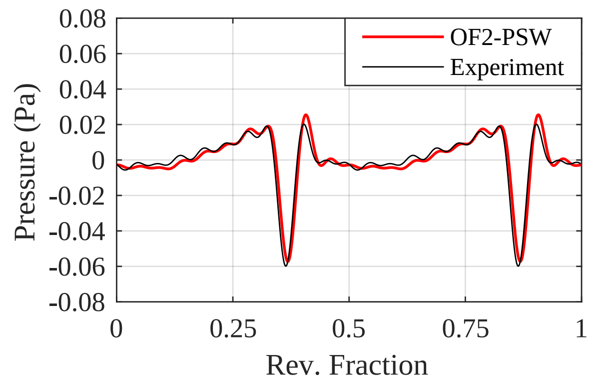


Fig. 7. Component noise source breakdown for broadband predictions for the isolated rotor case of Fig. 3. ($\theta = -45^{\circ}$)

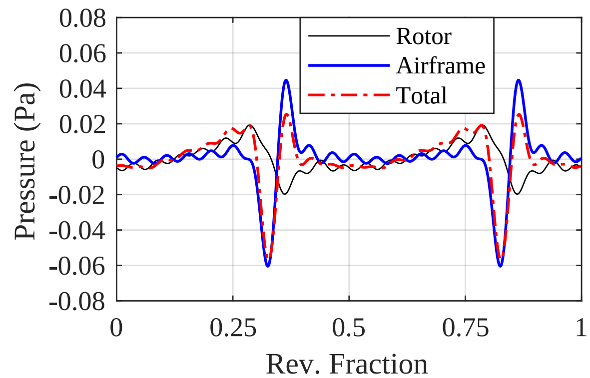
Rotor-Airframe Interaction Noise Predictions

The high-fidelity OF2-PSW prediction technique was applied to the rotor-horizontal arm configuration depicted in Fig. 2. Figure 8(a) presents a comparison of time histories of acoustic pressure between prediction and experiment for the case of least vertical separation between rotor and horizontal arm ($\Delta/R = -0.1$). As the results show, excellent agreement is obtained between prediction and experiment, thus providing confidence in the acoustic predictions for identifying the roles of the rotor and airframe surfaces in noise generation.

Figure 8(b) shows the same acoustic prediction time history shown in Fig. 8(a) broken into the noise contributions of the rotor and airframe geometries. The sum of these contributions yields the total predicted noise. These predictions indicate that airframe surfaces close to the rotor are the primary acoustic contributor, being responsible for the largest amplitude negative pressure events. These results are useful for exploring the complexity of rotary-wing sUAS noise source mechanisms, which can be heavily dependent on parameters such as rotor-airframe proximity.



(a) Prediction comparison with experiment



(b) Predicted source contributions

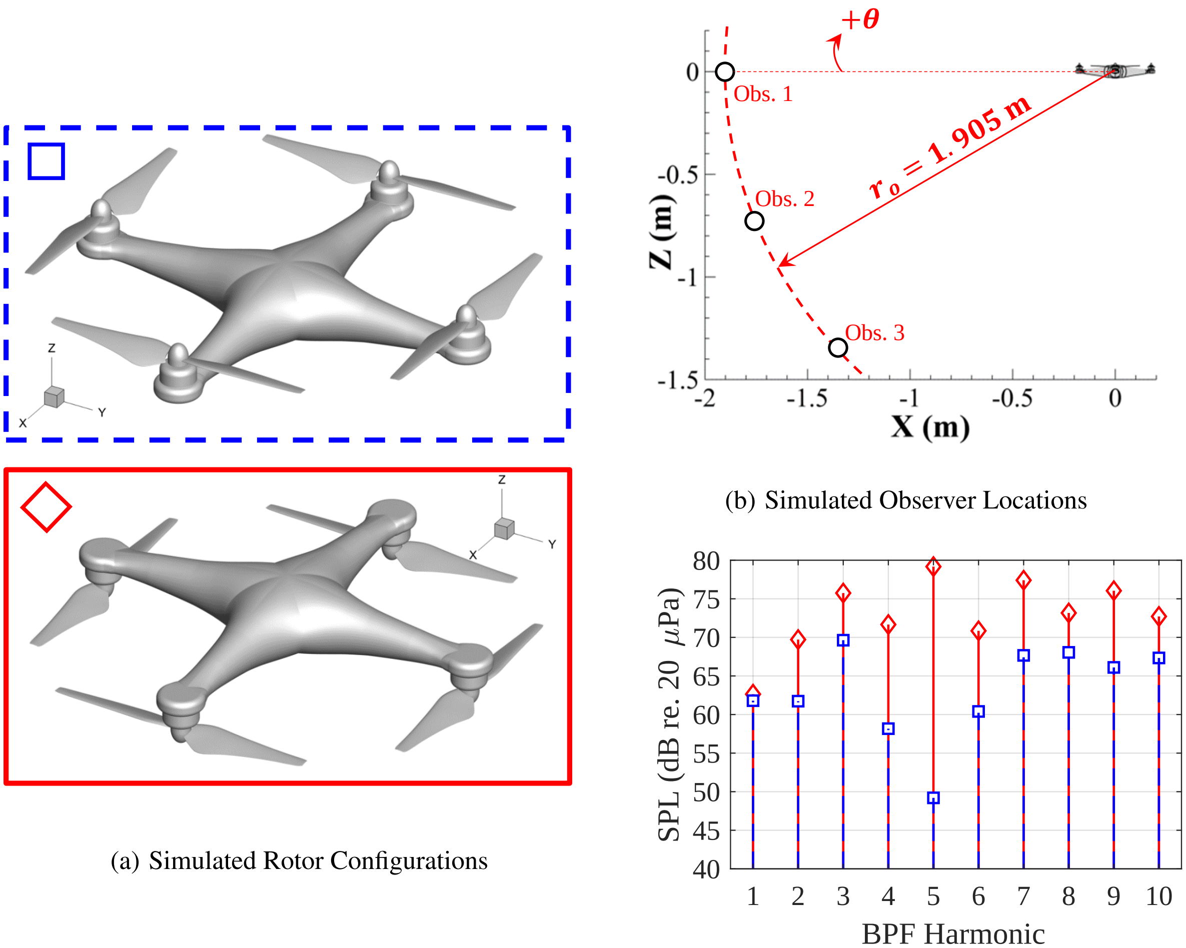
Fig. 8. Rotor-airframe noise. ***Note: Case of*** **$\Delta/R = -0.1$, $\Omega = 5400$** ***RPM,*** **$(\theta, \phi) = (-45^{\circ}, +90)$. (Ref. 9)**

Full Vehicle Noise Predictions

To better assess the tonal noise associated with a realistic sUAS vehicle, the OF2-PSW prediction technique was applied to simulations of a DJI Phantom-like vehicle. Details of the aerodynamic CFD simulation results are provided in Ref. 16. Figure 9(a) provides images of the two simulated cases on which acoustic predictions are done, corresponding to an airframe with rotors located a common distance either above or below the vehicle arms. All rotors are rotating at a common rate of $\Omega = 5400$ RPM under static (hover) conditions for both simulation cases, and are spatially in phase with one another.

Acoustic predictions for the two rotor configurations for an observer 45° degrees below the plane of the rotor are provided in Fig. 9(c) in the form of BPF harmonic spectra.

The results show that the vehicle configuration with undermounted rotors exhibits considerably higher tonal content



(a) Simulated Rotor Configurations

(b) Simulated Observer Locations

(c) Obs. 3 Tonal Spectra ($\theta = -45°$)

Fig. 9. Discrete observer acoustic predictions for two different quadcopter rotor configurations in hover.

than the over-mounted rotor configuration. This is consistent with the findings reported in Ref. 9, which documented a very similar increase in noise associated with a comparable change in rotor-airframe configurations. These higher noise levels are attributed to the larger potential field disturbance caused by the quadcopter airframe on the inflow to the rotor disks when the rotors are mounted below the airframe. The resulting higher rates of change of induced velocity on the rotor blade upper surface as it passes under the airframe then results in high-amplitude pressure fluctuations on the lower surfaces of the airframe. A comparison of overall sound pressure level (OASPL), defined here as the summation of energy at the first ten BPF harmonics, is provided in Table 1. These results show the under-mounted rotors are on average 8.1 dB louder in terms of OASPL, and indicate the utility of computational studies for acoustic trade-offs associated with different rotor-airframe vehicle configurations. However, it is important to note that these high-fidelity simulations come at a considerable simulation time cost (between 48-72 hours for a single configuration). (Ref. 16) This may not be ideal for the conceptual design stage when many configurations are considered.

Table 1. Tonal OASPLs (dB) of quadcopter simulations.

Rotor Config.	Obs. 1	Obs. 2	Obs. 3
Above Airframe (□)	70.0	73.3	75.5
Under Airframe (◊)	78.3	80.0	84.7

PSYCHOACOUSTICS AND sUAS

An important component of a conceptual design tool with acoustic considerations is a readily computable metric that correlates with human annoyance. Within the DELIVER project, work was conducted to explore an appropriate metric and to develop a tool that could be used to elucidate specific aspects of sUAS noise that drive annoyance. This section describes the tool development as well as research to specify an acoustic metric that correlates with annoyance due to the unique noise signature of these vehicles.

Auralization

Acoustic noise predictions, such as those discussed in the previous section, do not usually take a form that is amenable to direct listening. This can be because the prediction is generated for a limited range of frequencies, averaged over time, or is only valid for a small range of operational states of an aircraft, as with many of the preceding computational predictions. The process of creating a sound from such predictions in a way that preserves the objective parameters of the noise while attempting to capture any subjective qualities of the device being modeled is called "auralization." (Ref. 17)

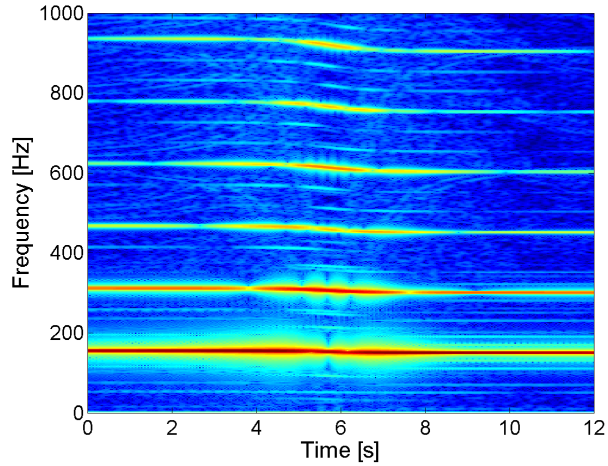
This process is akin to the visualization process used by, for instance, an architect who has designed a structure on a computer and wishes to communicate their work to stakeholders and the public. In a similar way, auralization can be used to communicate with stakeholders and those who are impacted by aircraft noise. Further, auralizations can be presented to human listeners for subjective evaluation of the noise of aircraft that do not necessarily yet exist. This usage, within the loop of a "perception–influenced design" process, has been explored for novel aircraft configurations within the recent past (see, e.g., the examples noted by Rizzi (Ref. 18)). One goal of NASA's work on sUAS noise is to explore the generation of auralizations of these systems suitable for communication and subjective evaluation.

Hemisphere Synthesis Previous auralization efforts at NASA have focused on full–scale commercial aircraft (e.g., Rizzi et al. (Ref. 19)). In contrast to these vehicles, sUAS present a challenge for auralization, as they are, in general, not able to be 'trimmed,' or set to a nominal operational state that will result in a functionally steady flight path. Rather, their operational state is dynamically tied to their orientation due to their payload, mission, and local atmospheric conditions (i.e., turbulence). These factors cause the vehicle to constantly adjust in order to maintain stability and control in the air. Therefore, auralization of these vehicles requires a method to interpolate the source noise of the vehicle at arbitrary time, emission angle, and operational state.

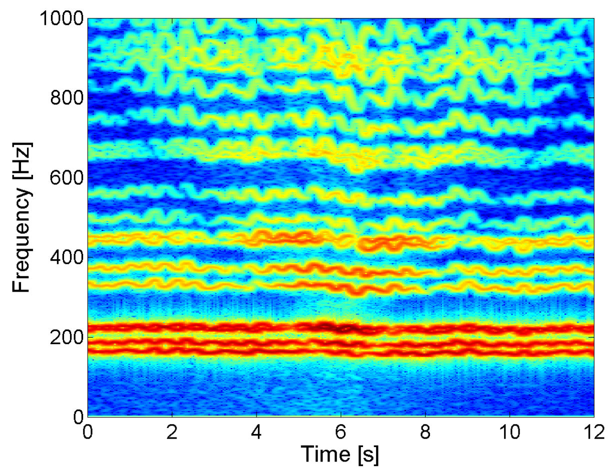
The source data that was used to develop the interpolation scheme came from the isolated rotor noise predictions described in the preceding section. CFD–generated acoustic pressure time histories for a single rotor revolution blade passage were provided in a rectilinear lattice that was distributed over a hemisphere located a sufficient distance below the simulated rotor. A frequency domain interpolation scheme was designed to interpolate within this data format (Ref. 20) to yield source noise data at desired emission angles and operational states. Pressures on the hemisphere were combined with existing NASA capabilities to simulate propagation (Ref. 21) to produce auralizations at a receiver located above a rigid ground plane for a notional flyover operation resembling those recorded at the Virginia Beach Airport.

A spectrogram of this auralization is shown in Fig. 10(a). It can be seen that the output of this early effort lacked the fluctuations of the rotor blade passage harmonics that were clearly present in the recordings of Fig. 1.

Dynamics Modeling Due to the patent lack of fluctuation in the early auralizations, and the resulting paucity of qualitative similarity to the recordings, an effort was made to create a computer simulation of the dynamics of a flying quadcopter. (Ref. 22) The outputs of this simulation were time histories of position, attitude, and motor state (in terms of rotational speed) that could be used as inputs to the auralization program.



(a) Without simulated dynamics.



(b) With simulated dynamics.

Fig. 10. Spectrograms of auralizations. ***Note: Contour levels represent a common dynamic range of 60 dB, with decreasing intensity represented by a color scale from red to blue.***

The dynamics simulation environment was made to be modular so that dynamical effects could be individually controlled in order to observe the effect on the resultant auralizations. These effects included not only drag on the body of the quadcopter, but also multiple sources of drag generated on the fixed-pitch rotors (e.g., induced, flapping). Also included was a model of near-ground atmospheric turbulence, and a simple model of the effect that manufacturing tolerance may have on the parts of the notional aircraft. Figure 10(b) shows a spectrogram of an auralization made with all of these effects included. It is clear that this sound has many more of the characteristics present in the recordings of Fig. 1.

Using this capability, it was possible to explore the level of detail needed in a simulation in order to produce an auralization that compares favorably with a recording. It was found that all of the dynamical effects included in the study had a significant role to play in the generation of a high–fidelity auralization, and that, in some cases, the interaction between multiple effects was the driver of perceptually important features. (Ref. 22) This is somewhat unfortunate, as it indicates that if, for example, the nature of the fluctuations of these sounds plays a large part in the annoyance generated by sUAS, it will be necessary to produce a high–fidelity dynamics model of a novel system if one would like to employ a perception–influenced design approach.

Psychoacoustic Testing

Acoustic emissions from sUAS are not necessarily detrimental in and of themselves. In order to understand the possible impact that sUAS noise might have on the communities they may serve in the future, it is necessary to understand how humans will subjectively evaluate the noise of sUAS in terms of perceived annoyance.[1] In early 2017, NASA performed an initial psychoacoustic test using human subjects in order to start to understand the relationship between noise and annoyance for sUAS. (Ref. 6)

The concept of the test was to explore whether or not future sUAS package delivery operators should expect their devices to be judged on an equal scale of annoyance due to noise relative to contemporary delivery trucks. The test was comprised of sounds of sUAS recorded from the Oliver Farms and San Diego locations detailed earlier. The sounds used were mostly of straight–and–level flyovers with microphones placed on tripods 1.2 m above a grassy surface. In addition, the ground vehicle recordings made after the Oliver Farms tests were used. The test took place in the Exterior Effects Room at NASA Langley Research Center. This room is an acoustically treated small auditorium equipped with 31 speakers that can be used to reproduce a sound so that it appears to travel across the listener's auditory stage. This capability was used along with the GPS time histories that were recorded in synchrony with the microphones in order to play the recordings back with their original motion. Thus, sUAS recordings appeared to fly overhead and ground vehicles appeared to pass in front of the subjects. In all, 38 normal–hearing subjects recruited from the local community listened to 103 sounds. For each sound, each subject recorded a level of perceived annoyance on a scale demarcated by the words "Not at All," "Slightly," "Moderately," "Very," and "Extremely."

Figure 11 shows an example of results from the test. Each point represents a sound presented to the subjects: black circles are sUAS recordings and blue triangles are road vehicles (labeled *Cars* in the figure). The abscissa indicates the A-weighted sound exposure level of the flyover, and the ordinate is the scale of annoyance on which the subjects responded. Each point is the mean of the 38 subject responses and the whiskers indicate the 95% confidence interval of the mean. Linear regression has been performed on this data such that the two groups are fit with separate lines. The lines are constrained to have the same slope, but their intercepts can differ. The result of this analysis is that the line linking sound exposure to annoyance for cars is offset significantly (lower or shifted to the left) than that for sUAS. In other words, at an equal sound exposure level, test subjects rated the sUAS as more annoying than the road vehicles. This trend held for all noise metrics explored, a set that included several other metrics commonly used for community noise regulation. The implication of this result is that future sUAS package delivery operators might not be well served by an assumption that an amount of noise due to road vehicles will have the same impact on a community as an equal amount of sUAS noise.

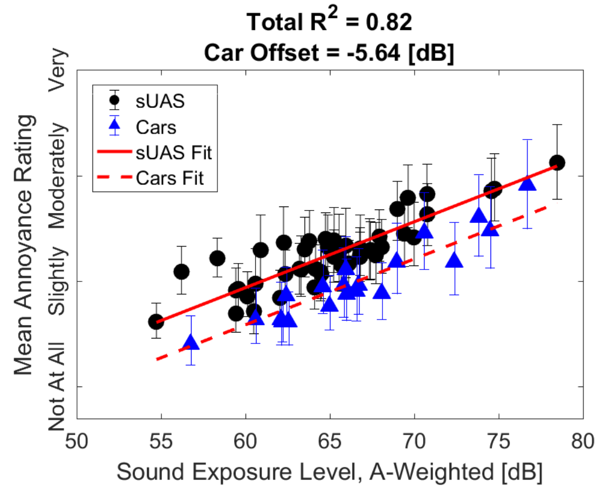


Fig. 11. Results from initial sUAS psychoacoustic testing.

The idea that noise from various sources, presented at nominally equal physical levels, may produce differential annoyance responses in humans is not new. This has been demonstrated through *in situ* surveys of communities, where psychological "non-acoustic" factors are known to play a significant role in the annoyance response. Early results are well summarized in a NASA reference publication (Ref. 24), as well as in laboratory environments (for instance, Kim et al. (Ref. 25)) where the effects of non-acoustic factors are as yet unresolved. One of the significant aspects of the current work is that most subjects were not able to identify the source of the sUAS noise as coming from a 'drone,' as the sound of these devices are novel to large parts of the population. Therefore, this study represents a situation in which recorded sounds that the subjects had no predisposition to were shown to cause a differential annoyance response.

[1] There are multiple ways that aircraft noise can psychologically and physiologically impact a community. A recent review of these paths is given by an ICAO workgroup. (Ref. 23) NASA's efforts regarding sUAS noise thus far have concerned themselves only with the issue of annoyance.

CONCLUSIONS

Research was conducted within NASA's DELIVER project to assess the feasibility of incorporating sUAS acoustics into a conceptual vehicle design tool. The research included measurement and analysis of sUAS acoustics in realistic outdoor flight conditions, controlled indoor acoustic and performance testing of representative sUAS vehicle components, application of acoustic prediction tools, development of an auralization process from predicted noise data, and psychoacoustic testing.

Outdoor flight testing was conducted over a two year period to collect flyover and hover noise of a variety of sUAS. Ground microphone data and vehicle position and state data were synchronously collected in order to relate acoustic emissions to vehicle speed, orientation, and distance.

Testing of isolated sUAS vehicle components and vehicle sub-systems in a controlled acoustic environment was performed to characterize the primary noise generation mechanisms of these components. These data were also used to assess the validity of existing noise prediction capabilities. Results of testing of isolated rotors in static hover conditions revealed that lower fidelity blade element-based noise prediction codes, such as ANOPP-PAS, performed well at predicting the BPF acoustic amplitudes for these hover conditions. Additional testing demonstrated the significant impact of closely spaced rotor and airframe components on tonal noise generated by the vehicle. This testing also demonstrated the capability of a high-fidelity CFD-based acoustic prediction method to capture the resulting acoustic behavior. Such a high-fidelity computational approach is warranted for this type of configuration since the considerable added complexity of the flow field and resulting acoustic field of a rotor-airframe configuration in which the airframe is itself a prominent noise contributor is outside of the scope of a blade element-based predictive code such as ANOPP-PAS. The CFD-based method was also applied to a quadcopter geometry to demonstrate the increased noise created by placing the rotors under the airframe, compared to placing the rotors above the airframe. The under-airframe configuration results in greater variation in periodic blade and airframe surface loading, with a resulting increase in tonal noise.

Research to explore psychoacoustic aspects of sUAS noise included the extension of NASA's auralization capabilities to sUAS and an initial human subject test to quantify annoyance due to sUAS noise. Within auralization, a hemisphere interpolation method was developed in order to synthesize the noise of vehicles with continuously changing emission angles during a flyover. A vehicle dynamics simulation, including a flight control system reacting to external disturbances, was also developed in order to produce realistic flight data for input to multicopter auralizations. NASAs psychoacoustic testing facilities were used to perform an initial test to assess possible disparities in perceived annoyance between common sUAS platforms and road vehicles typically encountered in a residential environment.

This initial study of sUAS acoustics highlights the need for continued research into the noise due to small rotor and propeller powered vehicles. Although a CFD-based method was shown to be able to capture some of the more complex noise generation mechanisms due to rotor-airframe interactions that could not be captured by a simpler blade-element prediction method, the computational complexity of the CFD method presents a barrier to its easy adoption in the conceptual design stage. Results of initial psychoacoustic testing quantified the inability of existing loudness metrics to capture increased annoyance generated by sUAS relative to ground vehicles. Work remains to improve our understanding of the acoustic characteristics that drive this annoyance difference, and possible ways to incorporate those characteristics into a computable annoyance metric.

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