NASA/TM–20240011587

UAM Source Noise Hemisphere Flight Test Measurement Protocol

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October 2024

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October 2024

Acknowledgments

There were many members of the Urban Air Mobility Noise Working Group, Subgroup 2: Ground and Flight Testing who contributed to this document. This paper is a culmination of monthly discussions amongst the group. We would like to acknowledge contributions of the following people: Jose Alonso (Collins Aerospace), Jeremy Bain (Joby Aviation), Durand Begault (NASA Ames), Benjamin Bernard (Porsche Engineering), Nathan Burnside (NASA Ames), Jordan Cluts (NASA Glenn), Chris Debusschere (Siemens), Michael Doty (NASA Langley), Robert Dougherty (OptiNav, Inc.), Robert Downs (Volpe National Transportation Systems Center), Eric Greenwood (Pennsylvania State University), Ben Goldman (Archer Aviation), Hua (Bill) He (FAA), Clif Horne (NASA Ames), Mary Houston (NASA Langley), David Josephson (Joby Aviation), Samuel Kantor (NASA Armstrong), Siddhartha Krishnamurthy (NASA Langley), Andrew Lind (NASA Langley), Philip McCarthy (National Research Council Canada), Roberto Merino Martinez (TU Delft), Ed Okorn (Scantek, Inc.), Per Rasmussen (G.R.A.S.), Dave Read (Volpe National Transportation Systems Center), Natasha Schatzman (NASA Ames), Parthiv Shah (ATA Engineering), Royce Snider (Bell Helicopter), James Stephenson (US Army), Austin Thai (Joby Aviation), and Alan Wall (Air Force Research Laboratory).

We would also like to thank the other UNWG subgroups, SG1: Tools and Technologies, SG3: Human Response and Metrics, and SG4: Regulation and Policy, for their contributions and review of this document. Finally, we would like to thank the UNWG Executive Committee Leadership, Stephen Rizzi (NASA Langley), and Brenda Henderson (NASA Glenn) for their continual planning and service to this working group.

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Abstract

The overall goal of the NASA Urban Air Mobility Noise Working Group (UNWG) Ground and Flight Test Subgroup (SG2) is to develop a research measurement protocol, or set of guidelines, which can be used to adequately quantify the Urban Air Mobility (UAM) community noise impact via the creation of acoustic profiles that describe the vehicle source emission characteristics. This document lays out a measurement protocol for acquiring data suitable for the development of compact noise hemispheres that characterize the source acoustic emissions from full-scale UAM or Advanced Air Mobility (AAM) vehicles in outdoor flight. It also provides a narrative describing the numerous aspects of outdoor flight test design and execution that will hopefully prove useful to flight test engineers and practitioners.

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1 Introduction and Goals

The overall goal of the NASA Urban Air Mobility Noise Working Group (UNWG) Ground and Flight Test Subgroup (SG2) is to develop a research measurement protocol, or set of guidelines, which can be used to adequately quantify the Urban Air Mobility (UAM) community noise impact via the creation of acoustic profiles that describe the vehicle source emission characteristics. This document lays out a measurement protocol for acquiring data suitable for the development of compact noise source hemispheres that characterize the acoustic emissions from full-scale UAM or Advanced Air Mobility (AAM) vehicles in outdoor flight.

The development of a measurement standard for a hemisphere is complicated by the numerous unknowns surrounding the problem. The lack of existing public measurement data makes it difficult to fully define best-practice measurement requirements. Unknowns include source directivity, source levels and their dependence on the vehicle design and its operational envelope, acoustic variation due to flight control laws, and the sensitivity of acoustic emissions to atmospheric effects (e.g., wind or atmospheric turbulence).

The subgroup has, thus far, discussed these types of questions to collectively brainstorm, summarize, and build upon existing measurement methods. The intent of the group is to guide flight test engineers to make the best decisions with the information known at this time.

Acquisition of a noise sphere is preferable to a hemisphere due to the potential urban operational environments of UAM aircraft. However, practical limitations for microphone placement often restrict the measurements to points that can only be used to reconstruct a hemisphere, i.e., below the vehicle. To this end, this document will focus on measuring hemispheres with the understanding that novel measurement techniques, symmetry assumptions, or supplementation of measured datasets with numerical simulations are needed for a full sphere definition.

The information required on a hemisphere is that which, when propagated to a point of interest, adequately reproduces the relevant attributes of a listener's experience at that location. The subgroup cannot yet project which attributes will be required. It is expected the measurement protocols will evolve alongside parallel research on metrics and human subjective response to UAM operations. These procedures are thus representative of possible measurements that could be performed, and as vehicles and datasets become available that would fully define the acoustic emission, propagation, and response, the appropriate measurement protocols may become more apparent. The subgroup recognizes it may not be possible to execute some types of measurements discussed in this document, so the rationale and associated advantages, limitations, and dependencies are provided so that users of these protocols can appropriately prioritize.

The initial datasets will be used to support research and development of tools and noise metric studies, including the determination of the minimum datasets needed to adequately quantify the community experience. Over time, the datasets and the measurement protocols may be used to inform future efforts to develop a technical measurement standard. Herein, an entity that will acquire the data or the vehicle that will be used for the exercise is not defined. UAM designs are very diverse, as evidenced by the World eVTOL Aircraft Directory hosted by the Vertical Flight Society, listing over 1,000 aircraft concepts, prototypes, technology demonstrators, and production designs as of April 2024 [1]. The NASA Revolutionary Vertical Lift Technology Project conceptual vehicles in Figure 1 are representative of this diversity [2, 3]. Many configurations can be categorized as multirotors (e.g., quadcopter, hexcopter), Lift + Cruise which have dedicated propulsors during Vertical Takeoff and Landing (VTOL) operations and cruise, and those with tilting propulsors that can vary the thrust line (e.g., tiltwing, tiltrotor). The protocols described here are intended to be general and not restricted to a particular vehicle design.

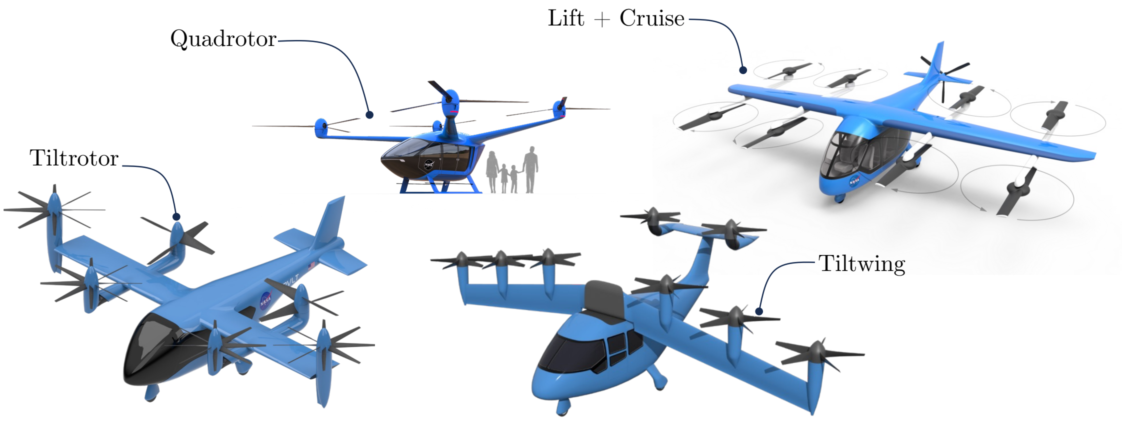


Figure 1. The NASA Revolutionary Vertical Lift Technology Project's UAM concept vehicles (Refs. 2, 3).

The starting point for this protocol is reviewing current best practices by leveraging noise measurement procedures described in, for example, existing Standards and Recommended Practices (SARPs) from the International Civil Aviation Organization (ICAO) [4], or noise certification standards (e.g., the Federal Aviation Administration (FAA) 14 CFR Part 36 [5]). Practices used in other standards and measurement guidelines such as the rules of particular applicability for Unmanned Aircraft Systems (UAS) that are published by the FAA [6], technical specifications for VTOL-capable aircraft by European Union Aviation Safety Agency (EASA) [7], the noise measurement for UAS ISO standard [8], and the noise measurement standard for military jet aircraft (ANSI/ASA S12.75 – 2012 [9]) will also be utilized.

It should be noted that efforts of the UNWG Ground and Flight Testing Subgroup aim to develop a noise measurement protocol to be used for research purposes. The subgroup does not seek to develop noise measurement standards. It is intended that this noise measurement protocol will be updated periodically. The ground and flight test procedures developed by, and the efforts of, SG2 are intended to support the efforts of the Tools and Technologies, Human Response and Metrics, and Regulation and Policy subgroups of the NASA UNWG and the UAM community at large. We welcome your input and contributions to advancing UAM measurement best practices.

2 Hemisphere Overview

A source noise hemisphere is a useful tool to both visualize and quantitatively store the angular and spectral dependence (or, less often, pressure time series) of vehicle noise for a given condition. With synchronized source position, microphone data, and knowledge of the sound speed from environmental conditions, the noise metric of interest (e.g., overall sound pressure level, band-limited sound pressure level) and associated emission angles are computed from multiple ground-based microphone measurements. Levels are adjusted for spherical spreading and atmospheric attenuation given the difference between the propagation distance and the vehicle-centered virtual hemisphere surface.

Note that these geometric considerations imply the source is compact, i.e., the characteristic length scale of the aircraft is much smaller than the distance between the aircraft and any microphone. Because the process relies heavily on synchronized vehicle tracking and acoustic data, one must consider the quality, accuracy, and precision of the vehicle data streams (e.g., position, attitude, propulsor states, control interceptor behavior, etc.) with respect to the acoustic processing and eventual noise hemisphere use.

Figure 2 is an example of a virtual data surface that is fixed to the vehicle frame of reference. Note that this surface is drawn with a realistic circumstance in mind; that is, data are only gathered below the horizon line of the vehicle. Ground-based microphones cannot typically acquire data at the horizon (assuming straight-ray propagation and that the vehicle attitude is level relative to the ground) because those propagation paths are parallel to and never intersect the ground. Using this hemispherical reference surface enables quick interpretation of the overall vehicle noise directivity. Hemispheres can also be generated and visualized at specific frequencies as each data node would have its own independent spectrum.

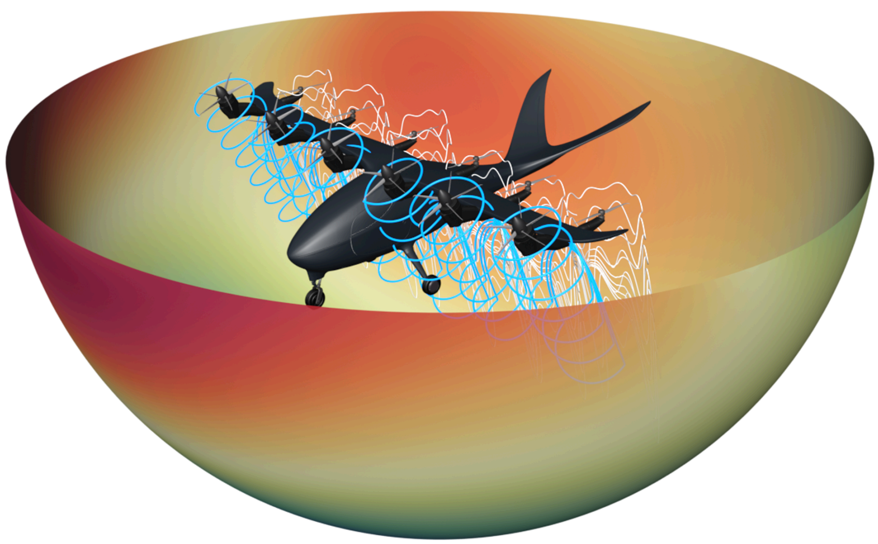


Figure 2. Example of source noise hemisphere surface centered on the vehicle. Source: Blue Ridge Research and Consulting, LLC

While each hemisphere represents a steady state flight condition, a database of hemispheres can be defined if multiple flyovers are performed during the flight test. If enough hemispheres are available, or suitable interpolation methods/semiempirical models [10] are used, arbitrary flight trajectories or full missions can be modeled by segmenting the flight based on operational state and repropagating the set of hemispheres to ground observers. This has already been accomplished for conventional rotorcraft [11–13] for operational or mission planning. Similar tools are also being developed for UAM vehicles and have been exercised using simulated hemispheres [14, 15].

A great deal of overlap exists in measurement methods used for conventional rotorcraft and what is recommended for UAM vehicles herein. This parallel is obvious throughout this document as many recommendations mirror those relied upon by the rotorcraft acoustic community. That said, UAM vehicles offer more complex flight controls and much higher degrees of freedom (i.e., multiple independently controlled propulsors) relative to conventional platforms. With a finite amount of flight time to gather acoustic data, the flight test engineer will have to devise a test matrix which best parameterizes the vehicle under test. Parameterization considerations are likely to be configuration dependent and are out of the scope of this group's current efforts. However, it is likely a subset of hemispheres can still be useful to approximate the community impact of future operations.

2.1 Angle Definitions

A spherical coordinate system is currently in use for depropagating measurement data into noise spheres using the publicly available Advanced Acoustic Model [16] and for noise source modeling in ANOPP2 [17] as shown in Figure 3. The spherical coordinates use sideline (ϕ) and longitudinal (θ) angles. The origin of this coordinate system should be located at the center of the noise source and aligned with the body-fixed coordinate system. The direction angle θ points from the center toward the nose (bow) of the vehicle where $\theta = 0°$, and from the center toward the tail (stern) where $\theta = 180°$. $\phi = 0°$ is directly underneath the vehicle, 90° on the horizon of the starboard (right) side, and $-90°$ on horizon of the port (left) side. For an idealized level flight flyover, the acoustic measurements will lie along lines of constant ϕ when an appropriately designed array of microphones is used to collect the data. This convention has the benefit that the measured data (for a dense array) will be fairly close to the grid points when depropagated, which reduces the error introduced when applying conventional structured interpolation algorithms to the spherical grid. Different UAM vehicles may necessitate the selection of different noise source centers (spherical coordinate origins), depending upon their exact configurations. The point of origin should be explicitly defined when reporting any results.

An alternative hemisphere angle convention uses spherical coordinates in azimuth and elevation relative to the horizon plane (with the poles aligned vertically instead of nose to tail). Referring to Figure 4, -90° elevation is directly under the vehicle while 0° elevation represents noise radiated in the horizon plane. Azimuth angles start at 0° behind the vehicle and progress counterclockwise such that 90° is vehicle starboard, 180° is out the nose, and 270° is the vehicle port side. This coordinate system is perhaps easier to interpret but does not follow the angular microphone traces. Instead, data are stored as unstructured points and mesh-free geodesic interpolation methods are needed to get uniform angular resolution.

2.2 Visualization

Properly representing a sphere or hemisphere is important to disseminate results in an easily interpretable manner. Two-dimensional projections enable the surface of a hemisphere to be mapped to a flat plane. Due to the long history of cartography, there are many types of projections to choose from. Only the most common forms found

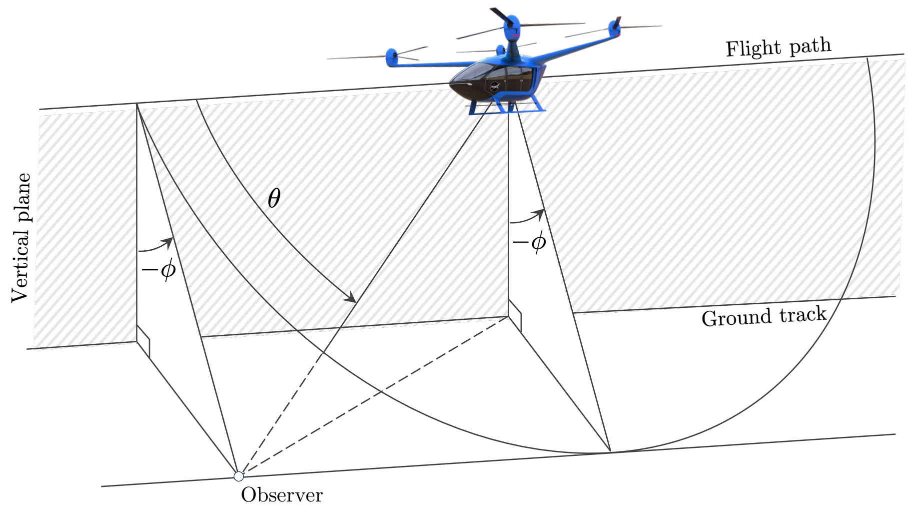


Figure 3. Spherical angle convention commonly used in measurements and modeling. Adapted from Ref. 16.

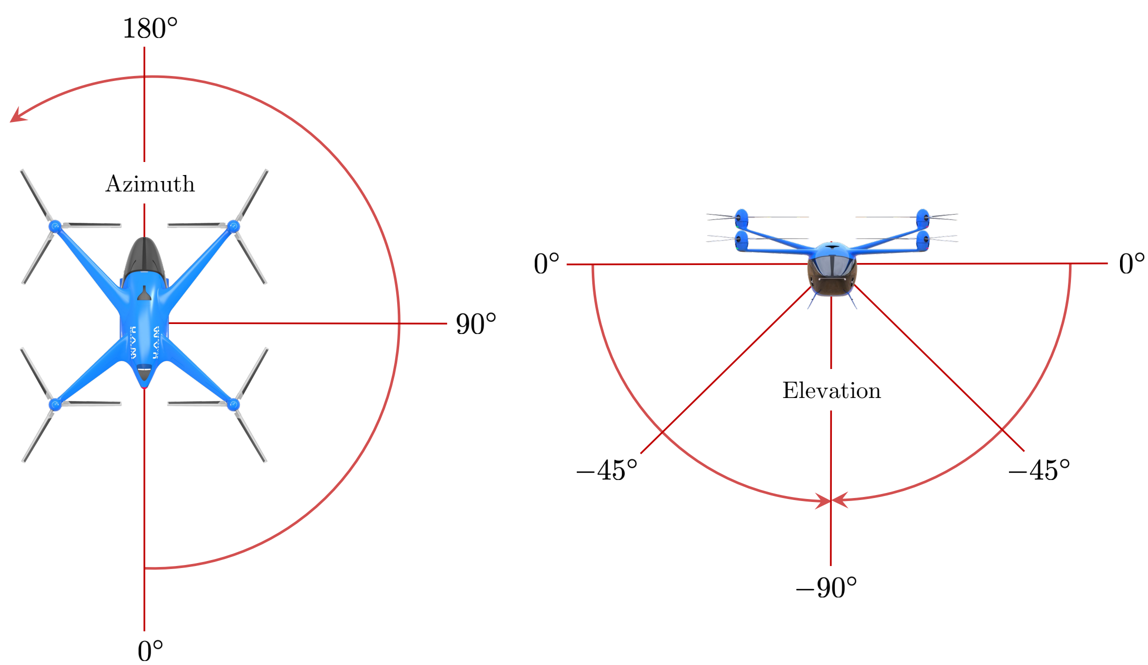


Figure 4. Alternative spherical angle convention using azimuth and elevation.

in flight vehicle acoustic research will be discussed here. Note that the azimuth and elevation angle convention (Fig. 4) will be used in the following examples.

Azimuthal projections are commonplace as they are arguably the most intuitive. Figures 5b-c provide two examples for the same data given as a three-dimensional hemisphere in Figure 5a. The first, an orthographic projection, is if the hemisphere was viewed along the axis of its pole from a large distance away, i.e., a distance much greater than the hemisphere radius. The main issue with an orthographic projection is the significant visual bias for angles directly underneath the vehicle. Data close to the horizon are squeezed and only account for a very small area on the map. A stereographic projection is more impartial to near-horizon angles and is a reasonable choice for plotting hemispheres. It is conformal (angle-preserving), although distortion of both area and distance increases away from the center point of the projection [18]. In either case, the documentation should either clearly specify what type of projection is being presented or include obvious reference angle annotations.

To minimize distortion beyond the stereographic projection, a Lambert Conformal Conic projection can be utilized [19], as shown in Figure 5d. In this example, a single standard parallel of $-45°$ is chosen. The Lambert projection is a balanced approach to obtain minimal angle and area distortion. Thus, it is neither conformal nor equal area, but a balance between both projection extremes. The Lambert projection is conceptually formed by projecting the hemisphere onto a cone that surrounds the hemisphere. The cone can then be unrolled and shown in 2-D space, resulting in a projection that is locally conformal with minimal area distortions.

3 Microphone Array Layouts

A single microphone could be useful to confirm the similarity of noise characteristics between multiple flyovers, for comparison to prior measurements or analytical predictions, or to provide a useful baseline of the emitted noise levels. However, it cannot yield a noise hemisphere for a single flyover. Rather, a collection of microphones is needed to capture a range of emission angles. The arrangement and number of microphones relative to the orientation and flight direction of the vehicle is chosen based on several considerations, including the desired data outcomes, equipment and resource availability, and operational considerations such as vehicle characteristics, available flight time, and the testing environment.

The overall size of an array on the ground is dependent on the physical constraints of the test site including topography and site restrictions. Flight altitude and the desired range of elevation angles also play a role. Assuming the physical site is large enough, the microphone locations are governed by the trigonometric relations computed from the three-dimensional vehicle position. For example, flying twice as high will result in approximately twice the ground footprint. Lower altitude flight (and thus a smaller array) is more prone to data loss due to inaccuracies of the flown flight path. Slight lateral offset of the flight path relative to the array center can result in a loss of coverage on one side of the vehicle. If GPS is not available to the pilot for accurate path planning, visible landmarks such as high-visibility banners or azimuthal guidance lights should be considered to mitigate this issue.

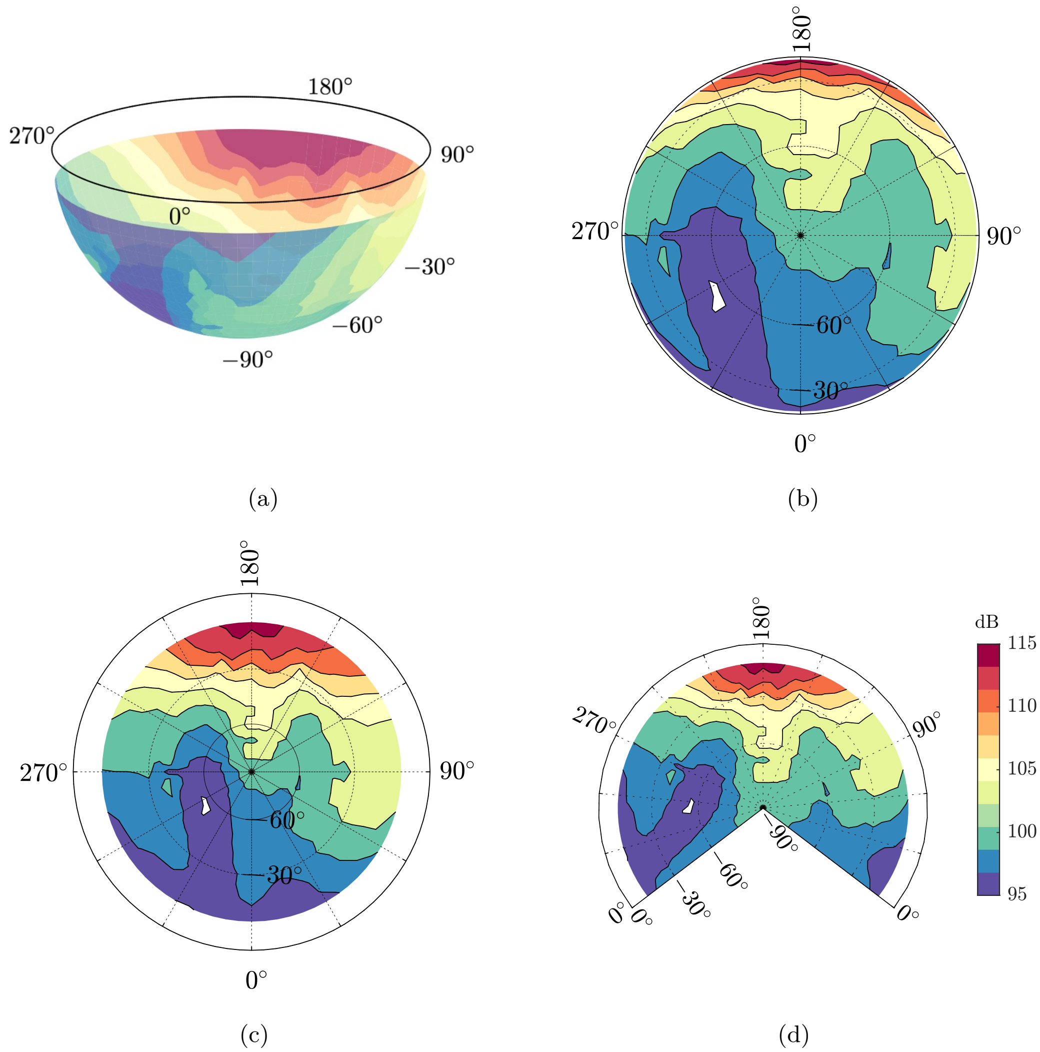


Figure 5. Overall sound pressure level hemisphere projections of a Bell 205 helicopter flyover using a (a) 3D hemisphere, (b) orthographic, (c) stereographic, and (d) Lambert conformal conic projection.

A number of array layouts are well represented in acoustic testing literature. The most relevant to UAM testing will be covered in this section. To start, linear arrays are typically positioned perpendicular to and on either side of the flight path [20, 21]. They are used for quasisteady source characterization for relatively straight (level, climbing or descending) flight paths. Snapshot arrays are designed to capture simultaneous source characteristics in multiple directions to "freeze" the vehicle state and can be used to mitigate temporal acoustic variation or maneuvering flight [22]. Distributed arrays usually cover an area of interest and can be a collection of linear arrays to assess source variability during a flyover. Other objectives unrelated to source noise hemispheres include capturing ground noise contours of unsteady conditions (e.g., departures, approaches, maneuvers) [23, 24]. Asymmetric arrays can be utilized when space or microphone resource limitations exist allowing for offset flight to capture more acoustic density in a targeted side or location of the vehicle. Assuming acoustic symmetry about the longitudinal axis may enable higher spatial resolution for a given array channel count by only acquiring data on one side of the flight path. Phased arrays have also been used for source characterization but are not covered in detail in this document given their lack of emission angle coverage (unless a set of phased arrays is used). In all cases, microphone positioning precision should be commensurate with the intended eventual source hemisphere granularity considering the angular resolution, acoustic data processing, and the geometric relationship between the source and receiver (see Section 4.1).

3.1 Linear Arrays

A linear array consists of a line of microphones oriented nominally perpendicular to the flight track. As shown in Figure 6, the aircraft sweeps through a range of emission angles as it performs a flyover. Straight rays can be used to calculate propagation paths at various source-time segments (e.g., $\tau_1 - \tau_3$) in both the observer frame and body-fixed frame. The time segment lengths can be chosen based on the desired angular hemisphere resolution.

The advantage of a linear array is that it is geometrically and analytically simple, and typically uses fewer microphones than other array layouts. The linear array arrangement for creating quasisteady noise hemispheres has been in use for tiltrotors, conventional helicopters and fixed wing aircraft for many decades and is a well understood and accepted procedure for compact source characterization [25–29].

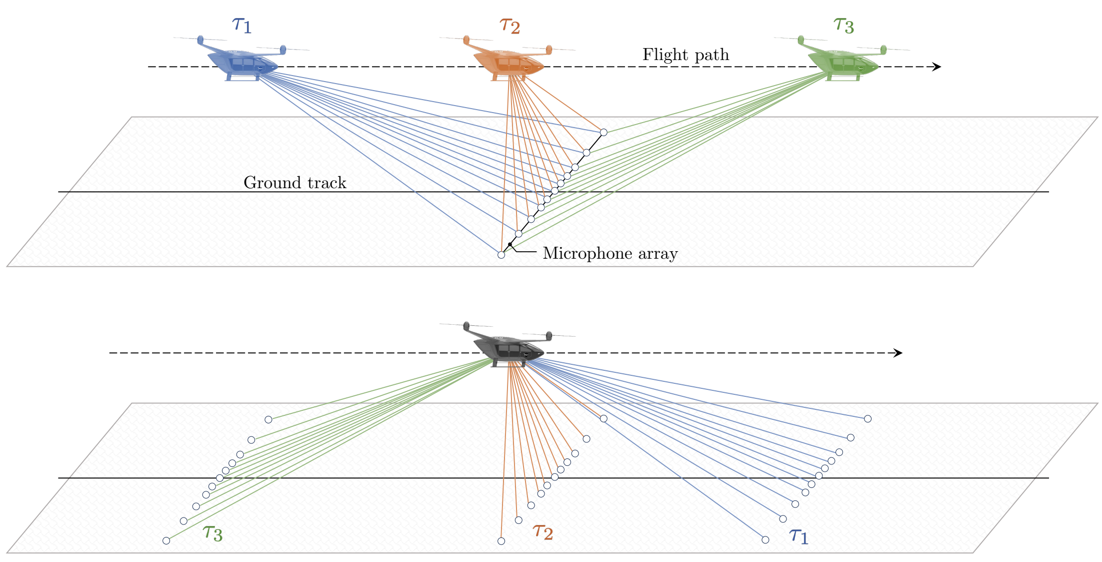


Figure 6. Straight rays emanated from the vehicle to the linear microphone array in a ground-based frame of reference at three source-time instances (top). Depropagated rays from the microphones in a vehicle frame of reference (bottom).

The validity of the quasistatic assumption must be considered carefully for UAM vehicles, their flight operations, and the eventual use of the noise hemisphere data. The duration and length of the quasisteady condition flight – relative to the linear array position – will affect the valid, steady flight region of acoustic geometric coverage. This process could require a large test matrix or careful prioritization of flight conditions within resource constraints.

When utilizing linear arrays, the furthest lateral microphones dictate the degree of lateral coverage on the noise hemispheres, while the earliest and latest trajectory points dictate the fore and aft extent of noise hemisphere coverage[1]. These considerations are subject to signal-to-noise ratio (SNR) and atmospheric absorption effects, discussed more in Sections 4.2 and 6.4, respectively. Military high thrust fighter jet protocols (ANSI/ASA S12.75 – 2012) recommend the use of elevated microphones in the array to capture acoustic characteristics at lateral angles up the sides of the flight vehicle; however, these elevated microphones are subject to complexities due to ground interference effects. They also introduce a number of additional flight test safety considerations. Vertical arrays are not covered in detail in this protocol document.

The array lateral spacing distance to obtain a given angular resolution is a function of the flight altitude. The microphone positions on the ground are calculated to give a constant angular resolution when projected back on a unit circle for the given vehicle height. Without prior knowledge of the source directivity, it is recommended to have at least 15° resolution, which necessitates a linear array consisting of 11 microphones as shown in Figure 7. Increasing resolution may be beneficial if sharp gradients in directivity are known to exist. If symmetry can be assumed, then only six positions are necessary. If vehicle directivity characteristics are known a priori, the resolution can be adapted accordingly, commensurate with the source emission gradients over the flight operating conditions of interest.

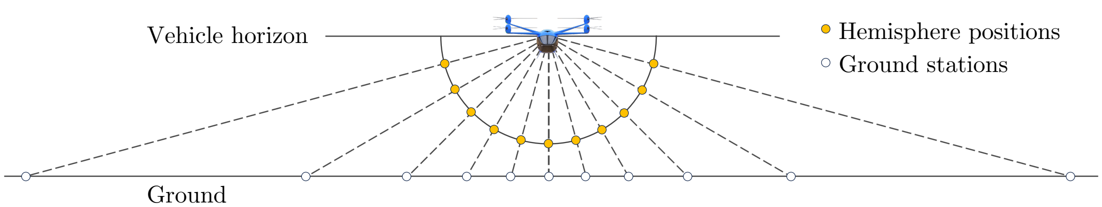


Figure 7. Microphone positions for a constant angular hemisphere resolution. This example illustrates 15° elevation spacing.

As described in Section 4.1, the aircraft flight altitude above the array impacts the slew rate, i.e., the fore/aft sweep angle per unit time. Low altitude operations can result in high slew rates, causing smearing and loss of resolution, especially directly underneath the vehicle. Increasing altitude is advantageous to avoid smearing but can result in reduced SNR, particularly at the most lateral microphones. Figure 8 exemplifies this for various ground speed and flight altitudes for constant time-segmenting of the data records. An alternative approach can be used to segment the data records to hold angular resolution constant by allowing time segments to have variable lengths.

[1]For steady level flight over microphones on flat ground. Variations in vehicle orientation or position can affect the lateral and fore/aft coverage.

However, caution should be taken when interpreting spectral representations of short-interval segments as they inherently have higher uncertainty.

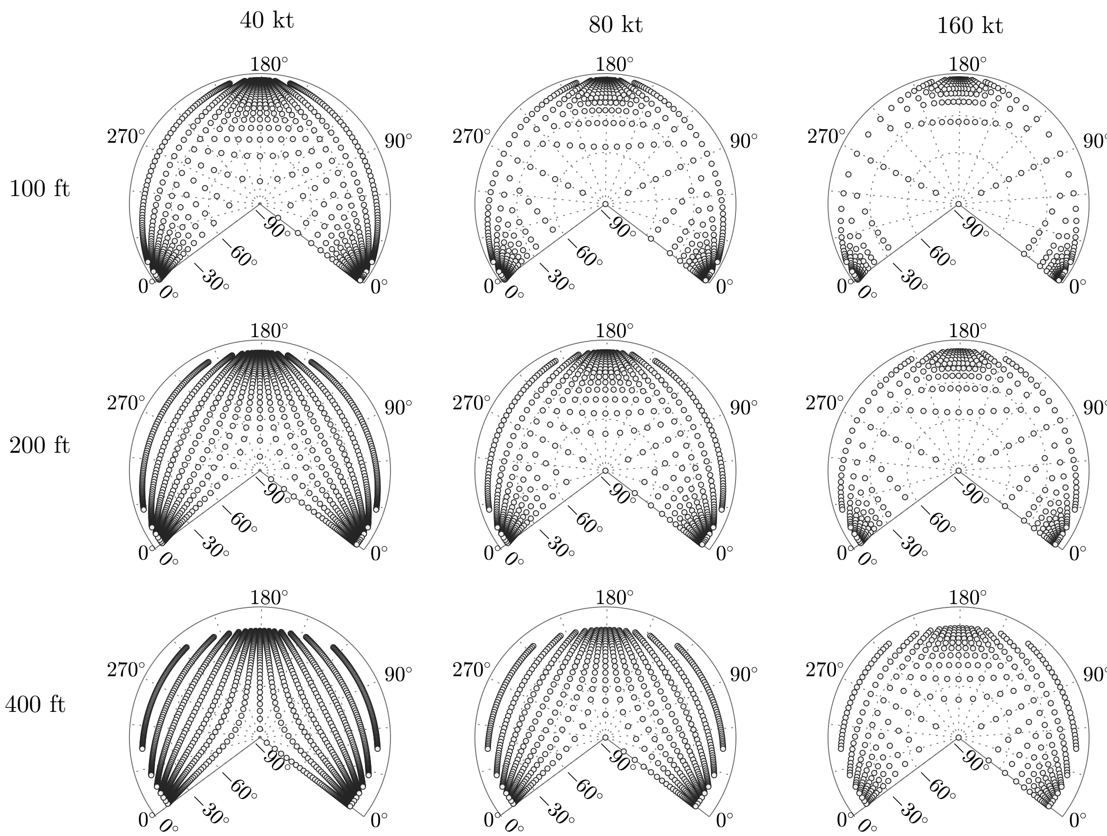


Figure 8. Hemisphere geometric coverage of a 15 microphone linear array for a vehicle flying at various constant airspeeds and altitudes. The total width of the microphone arrays are ten times the flight altitude. Each marker denotes a 0.5 second time segment.

This perpendicular linear microphone arrangement is not the only layout that can be used. The hemispheres rely on the independence of the acoustic emission from one source angle to the next. Creative microphone layouts with varied lateral spacing and augmented with additional lateral arrays up track and down track can potentially provide additional information for source regions expected to have high acoustic gradients. Additional lateral arrays can also be used to augment analysis for quasisteady conditions whereby the combination of linear arrays provides acoustic emission over an area on the hemisphere, rather than a line. This idea led to the development of snapshot and distributed arrays, covered in Sections 3.2 and 3.3, respectively.

The linear array protocol is applicable to quasisteady flights that are operating at near constant aerodynamic and acoustic states. The flight tracks can be for level, climbing or descending flight in a nominally straight line. To the extent possible, microphones should be positioned to ensure sufficient SNR (Section 4.2), in the acoustic far field (see Section 4.3), and at acceptable grazing angles (Section 4.4). This geometric arrangement might be challenging for trajectory points at the initiation and near the end of steep angle descents and ascents. A simple linear array is not necessarily suitable for transition conditions and maneuvering flight where the vehicle emission is changing as it traverses the microphone array. For obtaining noise spheres for turning and accelerating operations, a snapshot array or a distributed array might be more suitable.

3.2 Snapshot Arrays

An alternative microphone layout to the linear array configuration to acquire data suitable for acoustic hemispheres is the snapshot array. Rather than relying on the time-varying relative position between the vehicle and microphones to sweep through emission angles, all observer angles are acquired simultaneously in a near instant in time, producing a "snapshot." Figure 9 illustrates full emission angle coverage when the vehicle is over a snapshot array. This method has been utilized previously to characterize steady flight and has been compared to hemispheres derived from linear arrays [22, 30]. Unsteady flight conditions such as maneuvers [23, 24], departures, and approaches can also be investigated, but the hemispheres will only represent an instant in time of those procedures.

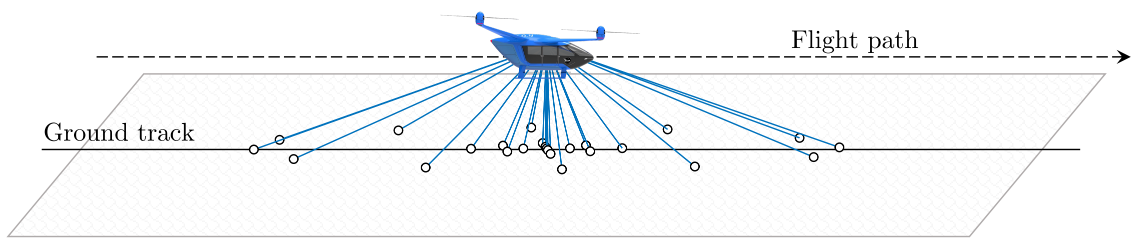


Figure 9. Full emission angle coverage of a snapshot array.

One of the major benefits of this technique, particularly for UAM configurations, is that the acoustic data are acquired over a period of time that is often small compared to the time-varying nature of the vehicle aerodynamic state. Even if a UAM vehicle is flying level at a constant airspeed, the flight controller or pilot is often continuously manipulating the propulsors and control surfaces. Holding a constant state, i.e., maintaining all propulsor rotation rates, propulsor angles, blade pitch, etc., over a 4,000 ft (1219 m) segment (as typically required for a linear array) may not be possible. Thus, the snapshot array is well-suited to characterize most types of flight involving state variation by "freezing" the vehicle in time. These types of arrays may also benefit comparative studies with numerical predictions by avoiding acoustic variability over the course of a flyover event.

Similar to other array types, if information about the acoustic directivity of the vehicle under test is known a priori, the microphone positions can be clustered to increase resolution at angular regions of interest (e.g., clustering underneath the vehicle for investigating near-vertiport operations) or regions with sharp directivity gradients. Often, little is known about the nature of the directivity pattern and how it varies over the range of the selected flight conditions. To this end, a constant emission angle resolution over the hemisphere surface may be preferred. Figure 10 contains examples of near-equal emission angle spacing for three different channel counts. The ground-based microphone layouts are also provided, which are computed by tracing rays through each emission angle node emanating from the hemisphere center to the ground plane. Unfortunately, a much higher channel count is needed to obtain similar angular resolution produced by a linear array.

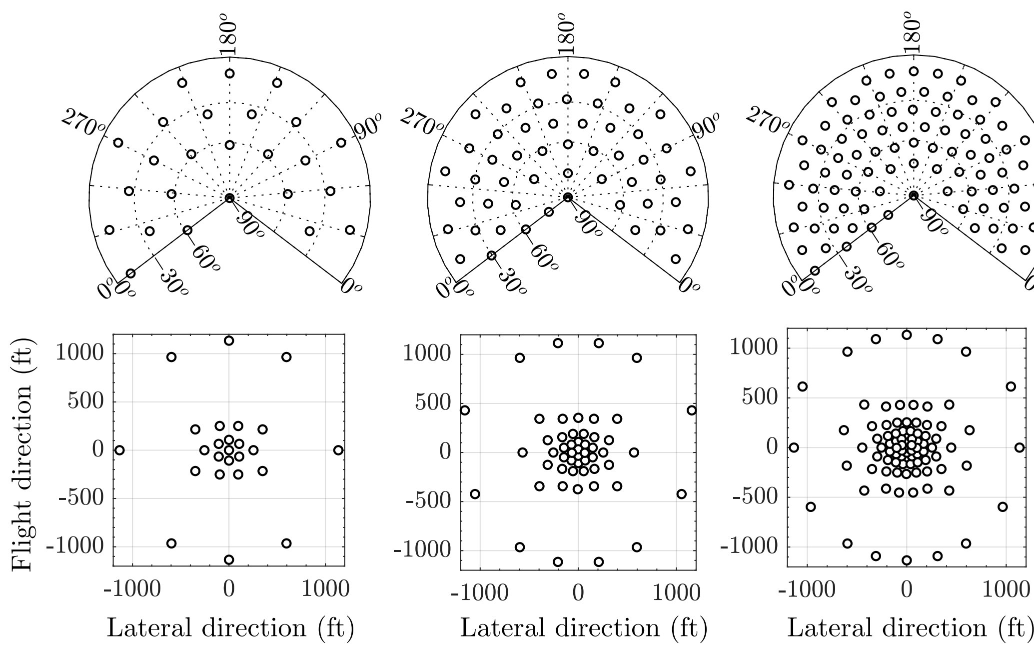


Figure 10. Snapshot array layouts on the ground for 25 (left), 53 (middle), and 89 (right) microphones. Vehicle altitude is 200 ft (61 m), and the outermost microphone stations are defined to be 10° below the vehicle horizon.

To the extent possible, the number of channels, and thus angular resolution, should be considered relative to the anticipated character of the source. Mathematical tools such as Lebedev quadrature of a hemisphere or geodesic relations can aid in determining optimal spacing as a function of channel count. Slight advantages may be found between the choice of the discretization scheme, but they depend on many factors such as the chosen spatial interpolation scheme of the processed data.

With the potential for high acoustic variability between flyovers as well as over the duration of a single flyover, multiple snapshot arrays can be deployed along the flight path. Figure 11 provides an example from a recent rotorcraft acoustic test [22]. Multiple independent snapshot hemispheres can then be acquired for a single flyover for averaging. Strategically overlapping neighboring snapshot arrays can reduce channel count. Nonetheless, multiple arrays come at the cost of increasing the overall number of deployed channels.

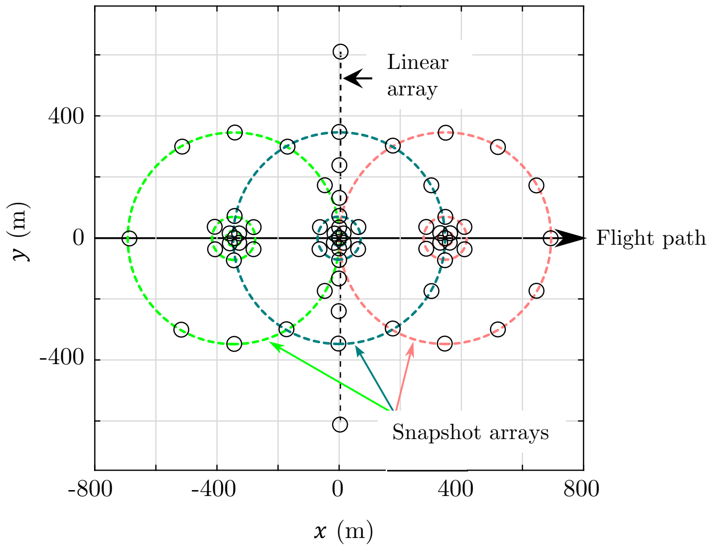


Figure 11. Multiple snapshot arrays which are overlapped along the flight path to reduce channel count. Used with permission from Ref. 22.

3.3 Distributed Arrays

Distributed arrays are not typically intended to gather data for source noise hemispheres. Rather, the intent is to capture vehicle acoustic emission over a broader geographic area to characterize unsteady flight, e.g., departures, approaches, and maneuvers, in the form of ground noise footprints. These footprints are contours which enable assessments of ground noise in proximity to the flight path and can provide maps of any metric of interest, for example, maximum levels over the duration of the flyover, or integrated metrics which evaluate the unsteady event as a whole. Thus, they provide a complementary type of result for unsteady flight to aforementioned arrays acquiring steady flight data for source noise hemispheres.

With this in mind, distributed arrays can be efficiently designed (with regards to channel count) to be dual-use if a linear array is nested into the two-dimensional layout. For example, Figure 12 is a distributed array used during a helicopter acoustic flight test [20]. The test matrix involved a set of approaches in which ground noise contours were generated. Steady flyovers were also included in the test matrix. Source noise hemispheres were computed for the steady flight conditions using a subset of microphones, specifically, the main linear array as annotated in the image. Generally speaking, there is commonality in the lateral extent needed for ground noise footprints and source hemispheres. Thus, only a small number of additional channels are required underneath the flight path to maintain reasonable angular resolution for source hemispheres. The same dual-use design practice could also be implemented with a snapshot array.

There is anticipation that many UAM vehicles may have high acoustic variation, even during steady flight. With that in mind, distributed arrays can also be designed with nested snapshot or multiple linear-arrays. In the example of Figure 12, five additional lines of microphones perpendicular to the flight path could be used to provide

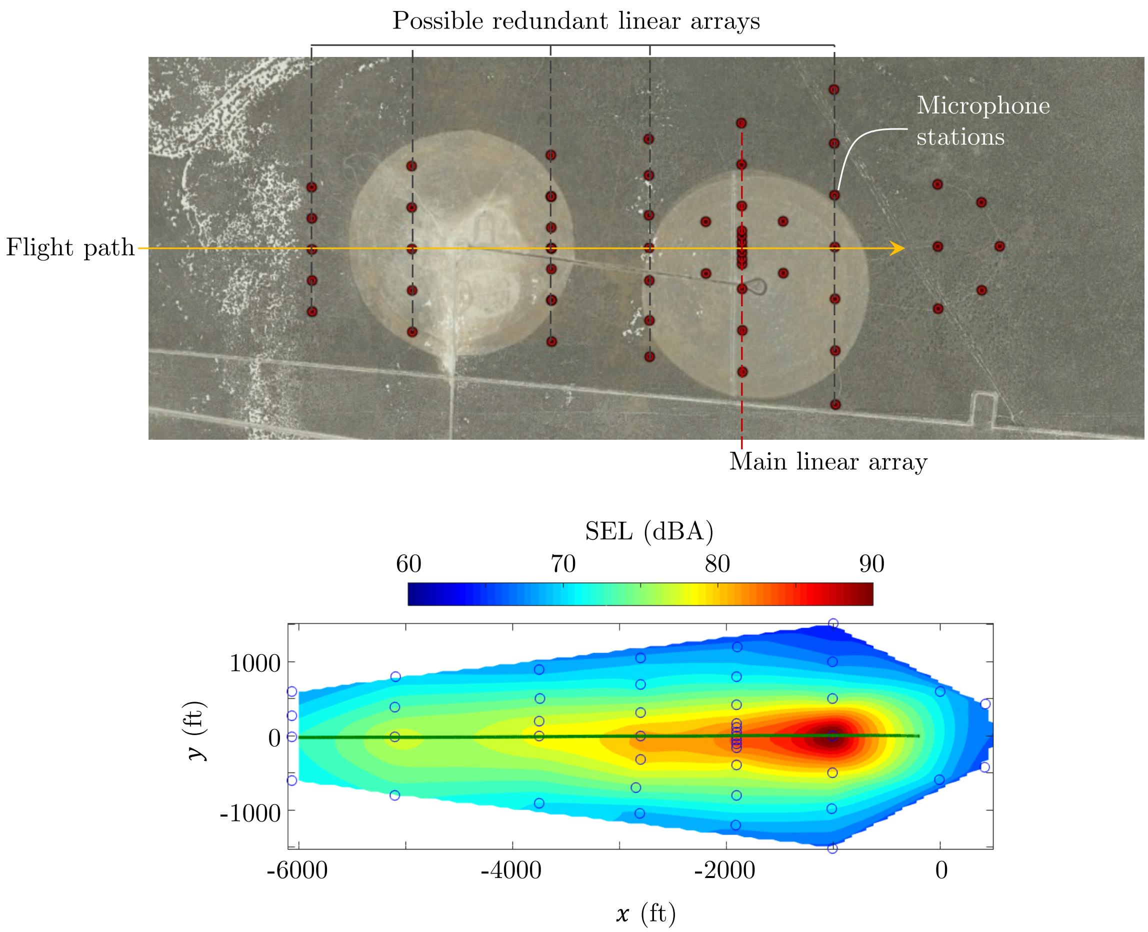


Figure 12. Example of a (top) dual-use distributed microphone array layout and a (bottom) processed ground noise footprint of a Robinson R-44 helicopter decelerating approach [20]. The microphone layout has a nested linear array to be utilized for source hemispheres under steady flight conditions. Additional linear arrays along the flight path could be employed to characterize acoustic variation of steady flight.

additional independent measurements of the same (or similar) emission angles. Averaging microphone signals at similar emission angles could reduce uncertainty of the source hemispheres and potentially reduce the number of repeated flyovers required for statistical confidence. Redundancy can also assist in gathering additional data at emission angles prone to smearing due to high slew rates as described in Section 4.1.

3.4 Asymmetric Arrays

Asymmetric arrays can be useful when there are flight path limitations or test site constraints (size, topography, accessibility, etc.). If such an issue arises, the microphone layout can be biased to one side of the flight path to measure one side of the vehicle for one flight pass, then altering the flight track to obtain data for the other side of the vehicle. Considerations should be given to the time proximity between passes and the direction of the passes relative to any atmospheric winds present between the source and the receivers. If this approach is to be used, at least one microphone on the sparsely populated side could be used to assess repeatability.

Depending on the distributed propulsion configuration and flight control laws, acoustic symmetry about the longitudinal axis of the vehicle could be an appropriate assumption. This avoids the need for two flyovers at the same condition, effectively halving flight time and the number of passes. Due to the limited space of the test site, NASA employed this postprocessing technique using data acquired on the Joby Aviation preproduction prototype [31]. Figure 13 demonstrates this for a 62 kt constant true airspeed level flyover. Microphone traces from a linear array are plotted illustrating a biased number of microphones on the vehicle port side. Two microphones were spaced evenly

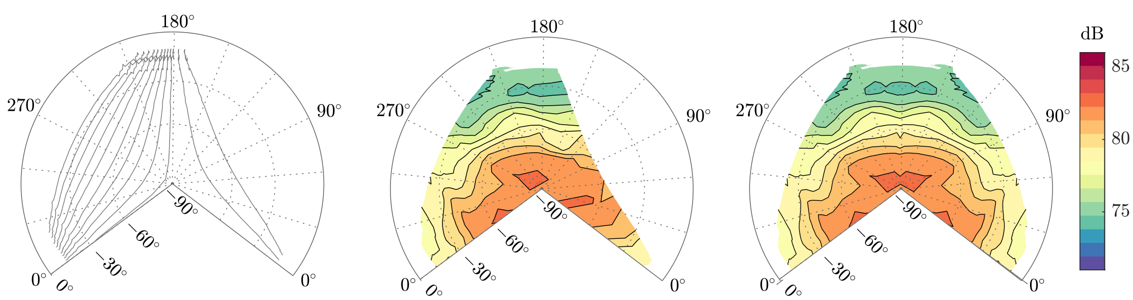


Figure 13. Example overall sound pressure level source hemisphere of the Joby preproduction prototype from a linear array. The microphone traces (left) show the limited coverage on the vehicle starboard side (right side of hemisphere). Levels are scaled to a radius of 100 ft (30.5 m) and are plotted over the available microphones (middle) and with expanded coverage assuming longitudinal symmetry.

over the largest lateral extent available on the starboard side. Plotting the overall levels over all acquired microphones yields a partial source hemisphere, as shown. However, applying acoustic symmetry enables a full source hemisphere to be estimated.

The vehicle state data were first assessed to ensure acoustic symmetry was valid for this flyover event. Figure 14 plots the average of two propulsor state parameters,

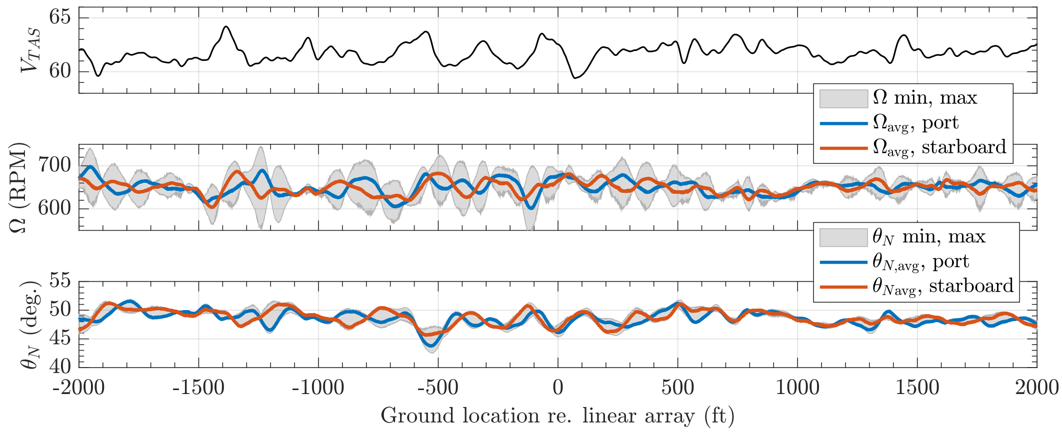


Figure 14. Variation of true airspeed (top) over a flyover of the Joby preproduction prototype (same event as Figure 13), and comparison between averaged propeller rotation rates, Ω, and tilt angles, θ_N, of the port and starboard side of the vehicle. The small differences between vehicle sides validate longitudinal symmetry.

rotation rate and propeller tilt angle, for each side of the vehicle. Comparing the port and starboard side, the averaged rotation rates are often within 50 RPM of each other. Similarly, the average tilt angles (and blade pitch which is not shown) are often within 2° of each other. These small aerodynamic state differences are assumed to minimally influence the source noise. It is recommended to take appropriate precautions to understand the sensitivity of the vehicle state with respect to the radiated acoustics to fully validate the symmetry assumption. This approach should be utilized with additional care and only be done in cases of necessity.

3.5 Phased Arrays

Phased arrays are typically used to provide relative acoustic contributions of various sources on a vehicle through the use of beamforming algorithms (for more detailed information, see Ref. 32). It is common to produce source maps, or "acoustic images," of the vehicle to visualize relative source strength. Directivity information, however, is typically not acquired as these images pertain to a single location (or line) on the source hemisphere. The number of channels required to handle the geometric scales and lower frequencies of full-scale flight testing is typically large (on the order of 100) to obtain reasonable spatial resolution of the source maps with low sidelobe (false sources) levels. Although a single phased array cannot produce a source hemisphere like the other types of arrays previously mentioned, it can be a useful tool to supplement a linear or snapshot array. One approach may be to replace some microphones on the ground, or on towers, with small, self-contained arrays. A specially defined beamforming method, e.g., Selective Orthogonal Beamforming (SOB) [33], can be applied so that each array measures the sound radiated by the UAM vehicle to the exclusion of interference from non-UAM vehicle sources and, in the case of elevated arrays, ground reflections. The benefits of the phased arrays in this case are improvement of the SNR, increasing the dynamic range of the hemisphere data, and, in the case of elevated microphones (i.e., a tower), widening the results to cover more of the hemisphere.

As innovation continues to enhance technological capabilities and reduce hardware cost, it may soon become feasible to deploy many phased arrays in a pattern covered in Sections 3.1-3.3. This would further increase the hemisphere quality by increasing SNR throughout a range of angles and may alleviate the (often uncontrollable) requirement of low background noise at the test site. The viewing angle limitation may prohibit the use of beamforming algorithms at emission angles close to the hemisphere horizon.

4 Measurement Proximity and Angle Considerations

4.1 Flight Altitude Tradeoff

The selection of flight altitude has numerous implications on data quality. With altitude defined, the atmospheric absorption, which scales with the square of frequency, should be assessed to ensure predicted signal-to-noise ratios are desirable (see Section 4.2). This should be most scrutinized for long propagation distances, e.g., for near-horizon angles. Combined with flight speed, these parameters will also drive the tradeoff between angular discretization, spectral resolution, and spectral uncertainty. It has been previously shown [9, 16] that higher speeds and lower altitudes result in a larger sweep of observer angles per unit time. For an observer along the flight path (the worst case), the spherical angle θ as defined in Figure 3 and its time rate of change are given by the equations below.

$$\theta = \tan^{-1} \frac{h}{x}, \tag{1}$$

$$\left| \frac{\mathrm{d}\theta}{\mathrm{d}t} \right| = \frac{\sin^2 \theta}{h} \frac{\mathrm{d}x}{\mathrm{d}t}. \tag{2}$$

This slew rate in Equation 2 is dependent on altitude, h, and ground speed, $V = \mathrm{d}x/\mathrm{d}t$. Figure 4.1 illustrates these trends for microphones along the flight path. If a constant time segment is used to represent the levels at that emission angle, the vehicle will sweep through a larger range of emission angles for microphones underneath (90°) relative to microphones far ahead (10°) or behind the vehicle (170°). For example, if a time segment of 1 second is chosen for segmenting emission angles, flying at 80 kt and 200 ft (60 m) altitude results in a maximum emission angle sweep of approximately 35° in that time segment. This results in relatively poor angular resolution directly under the vehicle ($\phi = 90°$). Conversely, if the time segment is chosen to result in constant emission angle resolution, the random component of the spectral uncertainty (with a fixed frequency resolution) at these positions under the vehicle will be relatively high. Thus, it may be beneficial to add additional microphones where high slew rates are found to acquire additional data and average over a smaller range of emission angles. Note that deterministic source component measurements may be relieved by these temporal/frequency resolution tradeoffs if time-varying state information is acquired and synchronized with the acoustic signals by applying order tracking filters (e.g., Vold-Kalman filter [34]). However, current methods are only useful for harmonic noise components and cannot aid with nondeterministic (i.e., random) noise sources.

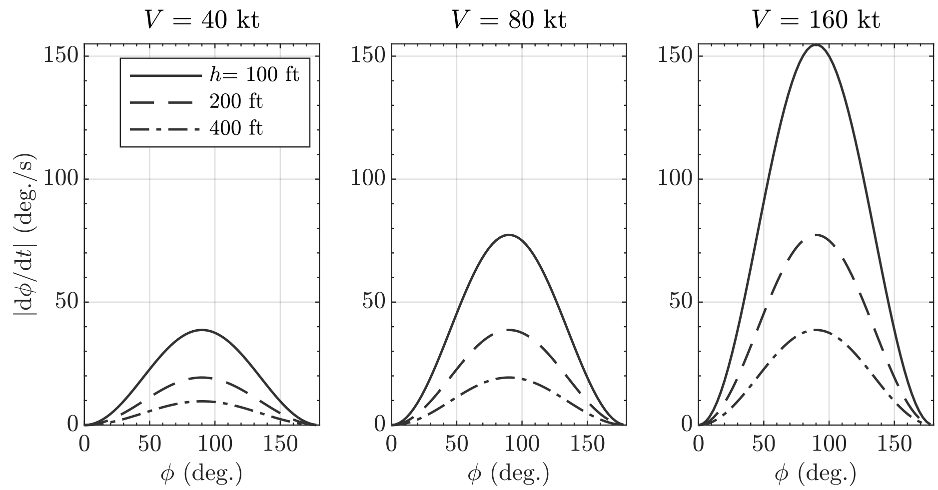


Figure 15. Rate of change of elevation angle for an observer directly under the flight path for various flight speeds and altitudes.

4.2 Signal-to-Noise Ratio

At each frequency, the measurement noise floor is defined by the highest level of the measured background noise, the data acquisition noise floor, and the microphone noise floor. In this discussion, the background noise is assumed to dominate the measurement noise floor, but that may not always be the case. The ratio between the spectral estimate of the source and the measurement noise floor represents the signal-to-noise ratio (SNR) at each frequency. SNR should be assessed to ensure the acoustic content pertains to the noise produced by the vehicle and not the ambient environment. It is recommended that a strict minimum of 3 dB SNR is appropriate for a single microphone measurement (consistent with 14 CFR Appendix H, Part 36), although 6-10 dB is recommended.

As an example, there may be an upper frequency, f_h, in which the measurement noise floor + 3 dB crosses the source spectra, as illustrated in Figure 16. Additionally, a subset of spectral amplitudes at frequencies lower than f_h may also not exceed 3 dB of the background noise. These data should be treated as unusable and potentially corrupt. Note that this analysis should be performed as a function of time over the course of a flyover event. It is likely f_h will shift to lower frequencies when the vehicle is far from the observing microphone. There may be instances where only a portion of the spectrum is above the background. When applying frequency integrated metrics (e.g., band-limited overall sound pressure level), the uncertainty of the metric calculation should be quantified to determine the effect of having insufficient signal-to-noise in the spectra over specific frequencies of interest.

If a phased array is leveraged, beamforming algorithms allow a separation of source and background noise for certain types of monopole and dipole noise sources. Hence, the source noise could be as much as 10 dB below background levels and still enable extraction of reasonable estimates of the source noise itself [32].

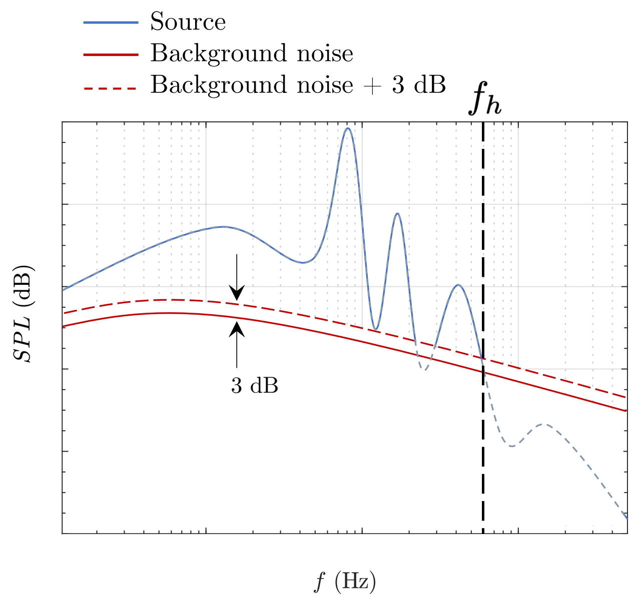


Figure 16. Illustration of the relative levels between the source (vehicle) signal and estimate of the background noise. The dashed blue line indicates source noise levels at unacceptable SNR.

4.3 Compact Source and the Far Field

The depropagation process that is often used for evaluation of three-dimensional vehicle noise emissions relies on the assumption that the source can be considered acoustically compact. Compactness depends on factors such as the characteristic length scale of the vehicle, the distribution of sources on the vehicle, and the distance from the sources to the measurement instrumentation. ISO 3745-1977 definition 3.10 for far field states "That portion of the radiation field of a noise source in which the sound pressure level decreases by 3 dB for each doubling of the area of the measurement surface. This is equivalent to a decrease of 6 dB for each doubling of the distance from a point source." The far field is therefore the distance from the source where the sound pressure level reduction is 6 dB per doubling of distance. The minimum distance for a valid far field assumption for any given UAM vehicle is likely to be configuration dependent and may vary with directivity angle, operating condition (via shift of the lowest frequency of interest), and the characteristic length scale of the vehicle (geometric compactness).

Recent efforts have provided some initial insight in determining the far field distance. In particular, computational efforts found a lack of consistency in far field distance scaling with rotor or vehicle characteristic lengths across several multirotor configurations [35]. Another example of a far field assessment was conducted by NASA for a static ground test of the Moog Surefly, now known as the S-250 [36]. The rotors are 92 inches (2.3 m) in diameter and are ± 5.3 ft (1.6 m) offset from the nose to tail centerline. Figure 17 provides the 6 dB per doubling of distance slope compared to the acoustic measurement data slope, providing an initial look at where the far field begins for a full-scale vehicle. Follow-on hover measurements enabled further assessment of the S-250, illustrating the far field is reached at 8.1 rotor diameters (equivalent to 2.7 vehicle characteristic length scales, defined by the tip-to-tip length between a diagonal rotor pair) [37].

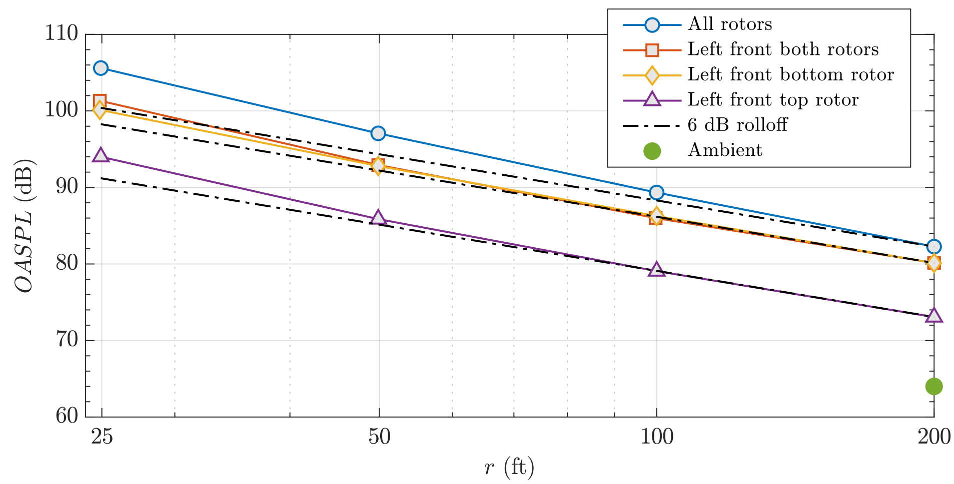


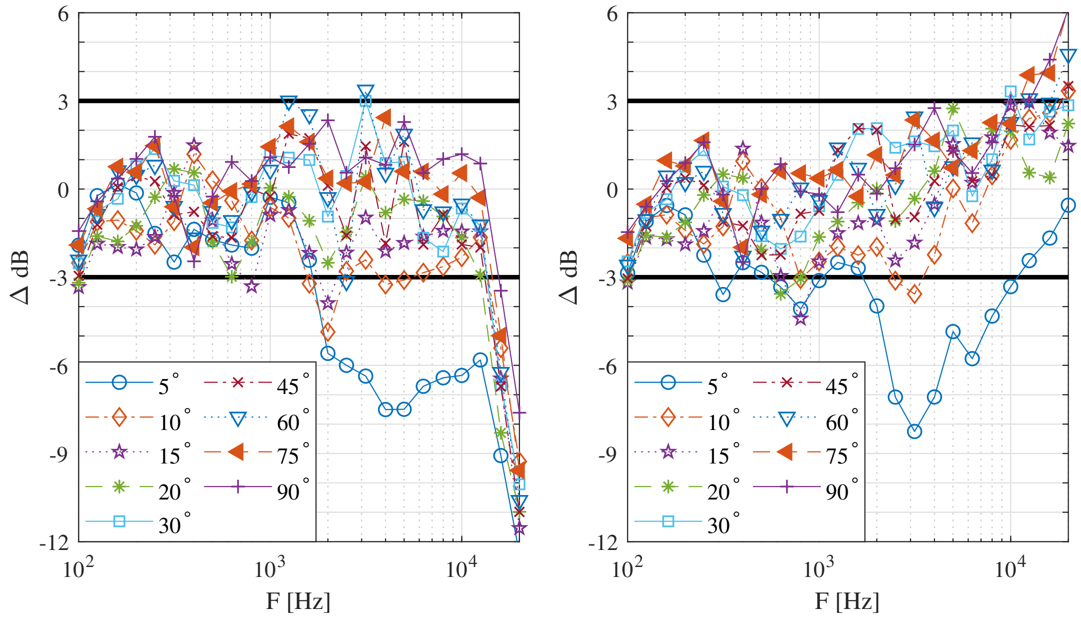
Figure 17. Example overall sound pressure level versus microphone distance and 6 dB falloff for the full-scale Moog Surefly, now known as the S-250 [36]. Vehicle was at 55% motor speed (grounded) and data are from microphones stationed in front of the vehicle.

4.4 Low Grazing Angle Concerns

Microphones located at low grazing angles, below 10°, should be avoided. Although all microphone measurements are influenced by the interaction with propagating sound waves and the surrounding ground, the microphones located at emission angles closest to the horizon are more susceptible to a range of adverse interactions. These adverse interactions may result from one or a combination of the following phenomena: ground waves, surface waves, ground impedance associated with porosity and roughness, elasticity effects, wind and temperature gradient effects, shadow zones and incoherence due to atmospheric turbulence and effects from test areas that are not perfectly flat. Research by Anderson et al. [38] examined propagation in an anechoic chamber over a sand pit using inverted and ground board flush-mounted microphones. As illustrated in Figure 18, differences for propagation over sand versus free field data are within 3 dB for grazing angles greater than or equal to 20° below 10 kHz. The most prominent disparities are clearly seen at 5° incidence angle.

5 Microphone Station Details

The preferred method for microphones is flush mounted in or inverted over a ground board. These setups best imitate a free field measurement as they best avoid ground reflection interference and dependence of local ground impedance [39]. Supplemental elevated microphones consistent with 14 CFR Part 36 Appendix H or K are suggested



(a) (b)

Figure 18. Differences (re: free-field) for (a) inverted and (b) embedded microphones over three inch thick sand substrate at various elevation angles [38]. 90 degrees is directly over the microphone, and the long edge of the ground board is facing the source for oblique angles.

to obtain comparative data that may be useful to inform and enable a future UAM noise standard (Section 5.3). To support psychoacoustic experiments or for analysis, it is recommended that elevated or binaural measurements also be obtained (Section 5.4).

5.1 Microphone Installation

The microphones shall be either flush mounted (embedded) in a ground board plate or mounted inverted over the ground board (Figure 19). Laying the microphone on the ground board is not recommended as it yields results that vary with the direction of the sound incidence. An acoustically reflecting hard surface, (e.g., a high-density plastic, 3/4” plywood) is the recommended ground board material. To achieve full pressure-doubling at normal incidence, the surface must be acoustically hard over a radius corresponding to a few wavelengths over the frequency range of interest, resulting in the measured sound pressure level 6.0 dB greater than the free field sound pressure level. Placing such a ground board on acoustically soft material such as sand or loose dirt can cause response anomalies. The ground board material cited in SAE ARP 4055A calls for an extensively hard smooth and flat surface (e.g., concrete, or well-sealed asphalt) or a white-painted circular metal plate, 0.4 m diameter and at least 2.5 mm thick [40]. However, this technique was intended only for use with light propeller driven aircraft using A-weighted sound pressure measurement such that the response anomalies at low frequencies could be neglected. Other recent research characterizes the use of high-density plastic ground boards, that reduce the effects of ‘ringing’, a behavior that can sometimes be seen from metal ground boards.

Using the example of a circular ground board, the microphone should be mounted off-center at 3/4 radius from the center of the plate to minimize edge-diffraction effects at a single frequency related to the plate radius. While a circular ground board is recommended at this time due to its simplicity and overall good performance[2], other ground board geometries have been utilized with varying success (e.g., larger round or square boards, the exponential flush dish [43, 44] and further developments of “flower petal” geometry [45]). Further converging to a free field response often requires a larger ground board, becoming impractical at the lower frequencies of interest for UAM vehicles. In all cases, the ground board should be embedded as flush as possible with the surrounding area minimizing physical discontinuity effects on diffraction but noting that acoustic impedance will change between the surface types.

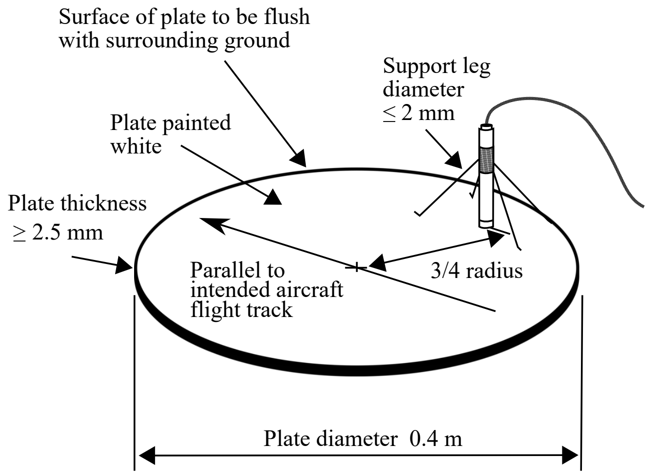
Frequency limits of embedded ground board microphones are mostly a function of the sensor limitations, while inverted microphones are dependent on both the sensor and installation geometry. As noted in SAE ARP 4055A, an inverted microphone is a practical arrangement that minimizes interference effects for frequencies of interest up to 10 kHz. In this case, the diaphragm should be parallel to and at a small, but precise, distance above a hard ground surface. If the separation between the diaphragm and hard ground surface is sufficiently small, the upper frequency limit will typically be above the maximum frequency range of interest for the measurements. The inverted microphones should be mounted so that the microphone diaphragm is one half of the microphone diaphragm diameter from the ground board surface (see Willshire et al. [39] for inverted microphone height considerations). For example, the distance between the board and a half-inch diameter pressure microphone diaphragm (not between the board and grid cap) should be a quarter inch (7 mm +/- 1 mm). This separation noted avoids high frequency amplification for smaller gaps and ground reflections that affect high frequencies for larger gaps [40]. The microphone mounting apparatus should not be bulky to minimize acoustic impact.

Contrary to SAE ARP 4055 [40], a wind screen is recommended to avoid a reduction in signal-to-noise ratio at low frequencies. Measurements have indicated [46] that there is not much difference between different configurations with a comparable thickness of an appropriate open-cell foam, e.g., conventional wind screens or offset cylindrical windscreens. An open-cell windscreen enables the acoustic pressure fluctuations to pass while simultaneously reducing the airflow prior to reaching the microphone diaphragm [47].

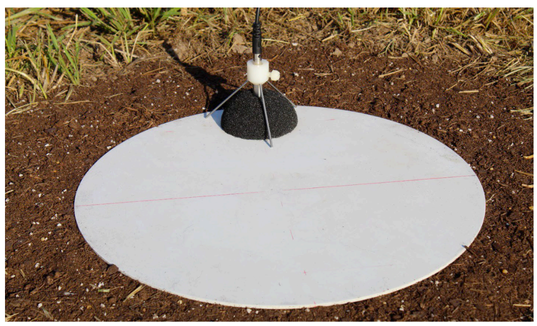
5.2 Ground Board Orientation

For a given microphone station, the ground board shall be oriented so that the off-center embedded (or inverted) microphone is on the far side of the ground board relative to the direction of received acoustic waves (see Fig. 19(a)). For a linear array, the

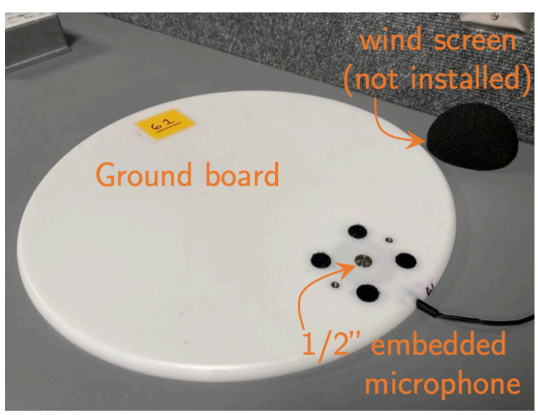
[2]The SAE circular ground board is found to have a relatively flat response over at least 100 Hz to 4 kHz, with experimental measurements displaying a divergence from free field no more than 2 dB from ideal pressure doubling [42]. These trends, albeit slightly different, are similar to what is shown in Figure 18.



(a)



(b)



(c)

Figure 19. Example of ground boards with an (a) inverted microphone as defined by SAE ARP 4055A [40], (b) an example of an inverted microphone in use with a wind screen [41], and (c) a ground board with an embedded microphone (GRAS 67AX).

microphones should be on the far side of the ground board relative to the flight path, as shown in Figure 20. Mircophones located along the flight path can be oriented at the discretion of the engineer to minimize edge scattering effects at emission angles deemed most important (see Ref. 48 for an in depth discussion on emission-angle-dependent scattering patterns). The ground boards for snapshot arrays should be oriented such that the microphones are farthest away from the array center.

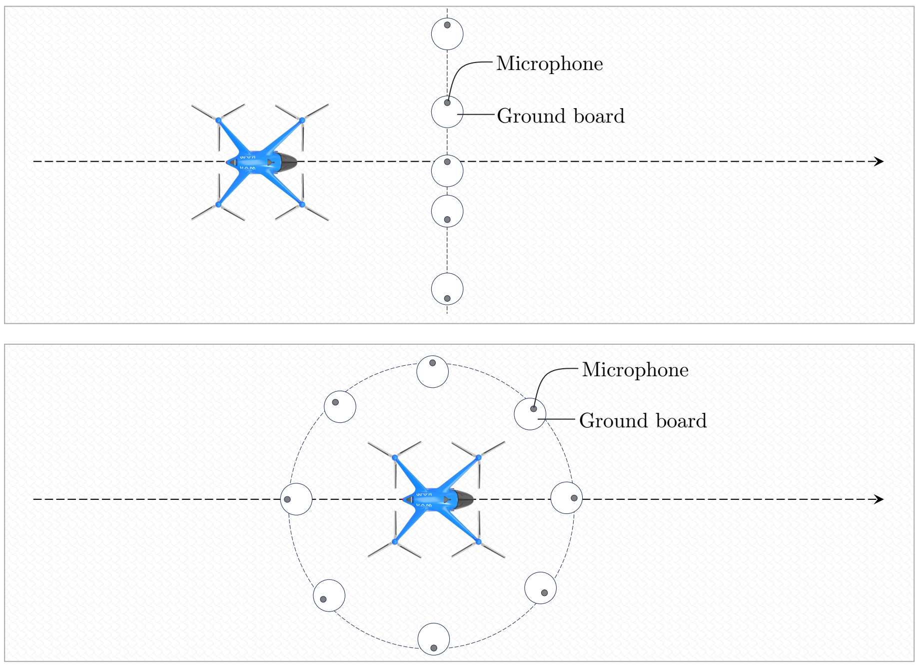


Figure 20. Ground board orientation for use in a (top) linear array and a (bottom) snapshot array.

5.3 Elevated Microphones

Consideration should be made to add at least one and preferably three microphones elevated 4 ft (1.2 m) above ground if human response data are desired to capture ground reflections in addition to the direct source. If one microphone is to be deployed, it should be placed at the flight track centerline. Additional microphones should be placed at lateral locations at a sideline distance from the flight track equal to the aircraft level flyover height above the ground track. The microphone should be oriented for grazing incidence with the sensing element substantially in the plane defined by the predicted reference flight path of the vehicle with the measuring station. All 4-ft microphones should be semi-collocated (close enough to measure the same acoustic information but far enough to avoid interference due to the presence of the instrumentation) with surface microphone ground locations to provide geometrically comparative data. Local ground impedance estimates (see Ref. 42) can also be performed to supplement the comparison and assist in removing site-dependent ground characteristics.

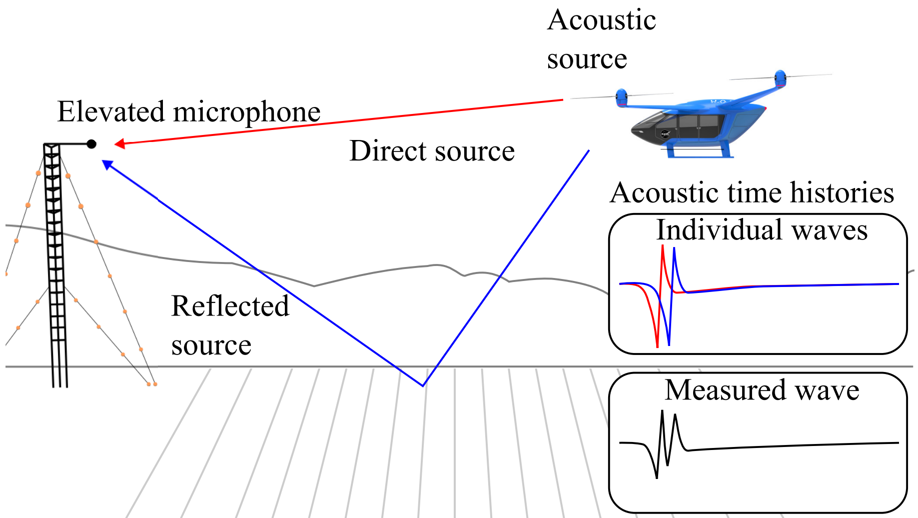


Figure 21. Diagram of a conceptual ground reflection problem. Adapted from Ref. 50.

The addition of these supplemental microphone positions is intended to permit comparison between microphones within a single dataset and provide commonality to facilitate comparison to other acoustic datasets. As noted in Rizzi et al. [49], there exists a lack of data to support development of UAM noise certification. Data are needed to understand the noise emissions from UAM aircraft and provide a comparative context between existing certification procedures employing 4-ft and ground-based microphone measurements as recommended in this document. UAM operating modes are likely to affect spectral content and time-varying characteristics which could present differently between ground-based and 4-ft microphone positions due to differences in direct and reflected interference effects. Such data could be utilized to understand the influence of microphone heights on noise limits for UAM operations; however, elevated microphones are less than ideal for quantifying noise source emissions as described elsewhere in this document. The test designer is therefore guided, in the event of microphone resource limitations, to assess prioritized outcomes, uses, and needs for the eventual dataset.

Sickenberger et al. [50] illustrate the elevated microphone ground reflection problem with a conventional helicopter waveform (Figure 21). In an effort to circumvent this, a novel approach was suggested and tested on a rotorcraft using suspended microphones from a hot air balloon [50]. A key advantage is the ability to obtain data above the rotor plane. They note that the microphone moving with the air mass is subjected to minimal wind noise. Geometrically flying at larger separation distances can help to minimize acoustic blurring where directivity angles and Doppler frequencies are rapidly changing. While flying at high altitudes can reduce ground reflections and ground-based background noise contamination, instances in which the aircraft noise is louder along the reflected path relative to the direct path can still be problematic. This scheme may necessitate local GPS receivers at each microphone (or other localization methods), as well as wireless recording or transmission capabilities. These systems exist but may not be commonly available.

The Department of Defense acoustic data gathering process for high performance military jet aircraft [9] describes procedures for source characterization utilizing microphones ranging from ground level to 300 – 1200 ft (91-366 m) above the ground suspended from towers or cranes to obtain vehicle source directivity data of an upper hemisphere above the vehicle horizon. Due to the potential for a greater amount of tonal, or deterministic, noise sources (e.g., harmonic loading of propellers) for UAM vehicles as compared to jet aircraft, a vertical array may make it too difficult to separate partially coherent reflections for removal. Thus, elevated arrays are not recommended for source noise measurements.

5.4 Binaural Measurements

During a test campaign to acquire data for source hemispheres, supplemental information in the form of binaural recordings may benefit human response studies without a significant amount of additional effort. Thus, some introductory information on the topic will be given here. Note that data from such measurement setups would not augment or be included in the source hemisphere process. It would, however, introduce additional paths of bridging the gaps between aircraft source noise and the subjective nature of human reaction.

Binaural recordings are recommended to be from standing head height and capture both the ambient and flight operations. Such data can be used for creating psychoacoustic test stimuli, for certain calibrations of stimuli from multiple ground-level microphones, and for use in psychoacoustic experiments and analysis. Recordings from one or more head and torso simulators should capture accurately the experience of a listener in terms of level, envelope, and spectra versus time with the inclusion of ground reflections that will be part of a typical experience. The inclusion of ground reflections can be a significant sound quality component for simulating the experience of persons in a community.

Binaural testing should utilize blocked meatus microphones and include wind screens or reasonable substitutes (e.g., foam wrapping). The mannequin head, pinnae and torso of the recording device should conform to ASA/ANSI S3.36-2012 [51]. The International Telecommunications Union's recommendation [52] and the International Electrotechnical Commission's standard [53] are also applicable. These procedures are applicable to testing with "blocked meatus" devices for measuring sound quality in listening tests, where the microphone is located at the ear entrance, and do not include an ear canal simulator. There could be useful analysis information from alternative mannequin head recording devices that include an ear canal simulator; however, these are typically not useful for listening tests.

All binaural measurements should include documentation of all components used for the microphone, ear canal simulator, orientation and height of the mannequin, type of pinna used, etc. See Section 6.3 for additional guidance regarding ambient noise recording protocols.

6 Test Range Properties

6.1 Ground Characteristics

The ground impedance over the test area should be uniform. Acoustic propagation over various natural and man-made ground surfaces has been shown to present frequency-dependent losses, particularly at propagation paths near parallel to the ground [54]. Such effects should be accounted for when attempting to derive free field levels. The ground impedance and flow resistivity become important at grazing incidence and may dominate within 10° of the horizon even if ground boards are employed in the measurements. It is advisable to avoid using data that have these strong effects unless they can be confidently corrected. Ground loss models vary in fidelity; a single-parameter model based on flow resistivity [55] or an effective flow resistivity [56] has proven to be reasonably accurate over various surfaces for elevated microphones. Arguments have been made that two-parameter models provide superior overall accuracy and are physically admissible [57]. Typically, these models will fail if ground properties vary widely over the propagation path. It is recommended that a ground impedance test be conducted at the measurement site to quantify the ground characteristics commensurate with the impedance model being used for elevated microphones [58]. Alternatively, a method to infer the ground impedance [42, 59] could be useful to better understand the ground interference effects and potentially normalize measurements over various ground types.

6.2 Terrain and Obstructions

Local changes in ground elevation, as well as terrain within and surrounding the measurement field should be minimized to avoid additional sources of measurement uncertainty. Additionally, line of sight between each microphone and the vehicle for the full duration of the test point is required. The test site should be clear of reflective objects and local vegetation that may introduce unwanted interference. A crude approximation based on acoustic reflection and scattering of a cylindrical surface to quantify this statement is that an object should be at least $10L$ away from the measurement location, in which L is the characteristic length scale of that object. Engineering judgment should be used for the specific circumstances of any given test.

6.3 Background Noise

It is important to ensure the acquired signal is above background noise levels at all frequencies of interest. In rural areas, ambient noise has been shown to change on an hourly scale as winds and animal activity pick up or die off [60, 61]. Background noise measurements should capture that change. Nontransient background noise tends to change slowly; so measuring background noise for every test point is unnecessarily restrictive. It is recommended to acquire 30-60 s of background noise during every 60-90 minutes of flight time due to possible changes in environmental effects and other external noise sources that may be present, including wildlife, ground and air traffic, etc. Care should be taken to ensure the aircraft is completely shut off or far enough from the measurement site to avoid contaminating ambient levels.

To estimate signal-to-noise ratio, an accurate measurement of the ambient environment is needed. Fractional octave spectra or narrowband spectra are often used to estimate frequency-dependent background levels. In general, a smaller spectral bin width requires a longer acquisition time to capture enough data to obtain a given spectral uncertainty. This also gives the chance for transients (e.g., wildlife, a nearby ground vehicle) to average out, which is beneficial. If low signal-to-noise ratios are observed, it is best practice to acquire background levels as close in time to the test points, given the likelihood of the ambient levels changing over the course of a day.

If time constraints exist, a moving bandwidth filter could be applied to the frequency spectra computed from a short-duration recording. The moving bandwidth filter smooths out the spectra similar to that produced from a longer time series. Care should be taken to preserve persistent tonal content if such extraneous noise sources exist. The moving bandwidth filter will smooth out spectral uncertainty, the extent of which is dependent on the band percentage chosen (e.g., 5%). In other words, autospectral estimates averaged over N_d adjacent frequency components will produce results with the same random error as averaging over an ensemble of autospectral estimates from N_d different records [62].

6.4 Ambient State Parameters

The temperature and humidity environment for testing is an important consideration as it affects the acoustic propagation, source characteristics, and the aircraft flight performance. Existing standards such as FAA Certification (CFR Part 36 Appendix H / AC 36D) and Military High Performance Jet Aircraft (ANSI / ASA 12.75-2012) both include a range of temperature requirements. With those in mind, it is also recommended that the temperature and humidity range at all measurement points should fall within 36 – 95° F and 20-95%, respectively, during the data acquisition test period.

An additional constraint is to limit the temperature and humidity combinations that yield excessive atmospheric attenuation. An example of appropriate atmospheric conditions is given in Figure 22 for two different frequencies, with the recommended conditions falling within the black outlined region [63]. The lower curved portion of the outlined region demarcates conditions that produce greater than 10 dB attenuation at 6 kHz, and for this example, over 100 m propagation. These ranges enable reasonable accuracy for calculation of atmospheric absorption [64, 65] and avoid envelopes of high sensitivity of attenuation levels to ambient conditions. If operating in such adverse envelopes, small changes in humidity or temperature could have a large impact on the level of attenuation, implying questionable back-propagated levels to the source hemisphere. FAA 14 CFR Part 36 Appendix H states that the attenuation in the 8 kHz 1/3-octave band be no greater than 12 dB per 100 meters. This limit may not be suitable for all tests and desired frequency ranges. Thus, the predicted impact on the acoustic measurement should consider the expected attenuation in the bands of interest for the vehicle under test to ensure measured signals at all frequencies of interest meet the recommended signal-to-noise ratio above background levels.

Atmospheric parameters should be monitored throughout the data acquisition test period, more frequently in response to varying environmental conditions, to ensure these recommendations are met over the noise path between the aircraft and the microphones.

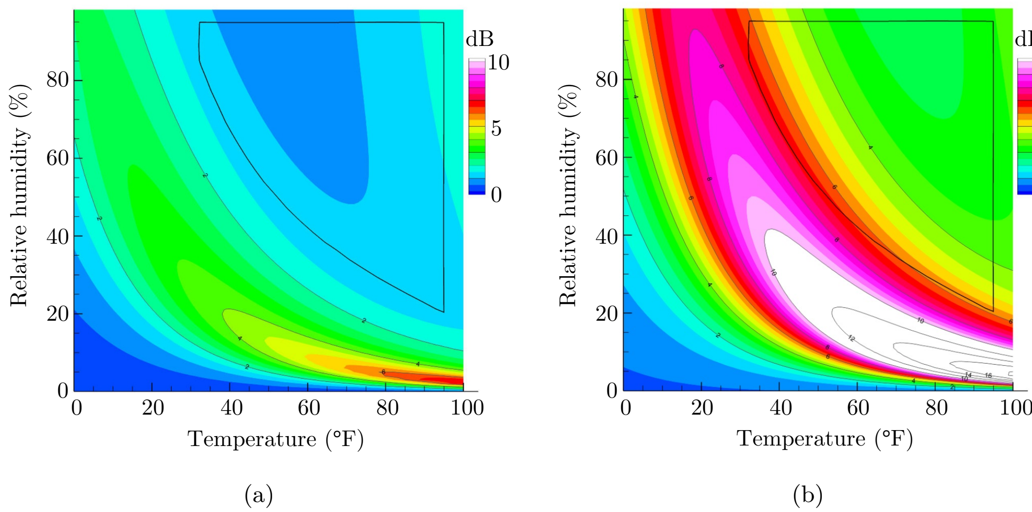


Figure 22. Example atmospheric attenuation over 328 ft (100 m) at (a) 2 and (b) 5 kHz. The black outlined region is the recommended window to avoid conditions which cause high acoustic attenuation. Used with permission from Ref 63.

Temperature inversions should be avoided as they can significantly alter the noise level through propagation path distortion. In addition to temperature and humidity, atmospheric pressure should also be documented during acoustic data acquisition. This enables estimation of the sound speed [66] and density of humid air [67], which can be useful to compute propagation time and nondimensional parameters (acoustic pressure, vehicle state information such as propulsor tip Mach number, etc.). Nondimensionalization provides an accurate way to compare measurements under different environmental conditions.

6.5 Wind

The presence and direction of wind will change the vehicle operating state, the resulting aeroacoustic source mechanisms, and acoustic propagation. It will be necessary to know the wind speed and direction at the ground measurement location, and it is recommended to also record these parameters at the flight altitude, where possible. 14 CFR Part 36 Appendix H stipulates a wind speed no greater than 10 kt with the crosswind component no greater than 5 kt. ANSI/ASA S1.26-2014 stipulates a recommended wind speed of less than 8 kt and termination of the test above 12 kt. The crosswind component should be less than 5 kt sustained.

With many UAM vehicles expected to be in the 2000-6000 lb (900-2700 kg) range and use differential thrust for stability and control, the effects of wind are likely to result in high variability in ground noise levels. Furthermore, propulsors operating at low tip Mach numbers are expected to be dominated by unsteady loading noise [68]. This can be further exacerbated by atmospheric turbulence and wind gradients, both likely to be present in urban environments [69]. Without more measurements on these vehicles at this time, the allowable wind speed or direction (e.g., headwind or tailwind vs. crosswinds) cannot be clearly defined. Measurements should be acquired during the lowest possible wind speeds, and an attempt should be made to document the sensitivity of wind speed on the measurements. There could be considerations made for capturing acoustic data in higher wind states to characterize vehicle noise emission under these conditions. In this case, it is plausible that more meteorological measurements will be required.

6.6 Meteorological Equipment Placement

At a minimum, atmospheric conditions should be measured at the ground, e.g., using a ground weather station. However, it is preferable to measure conditions at the flight altitude or at several incremental altitudes up to the maximum flight altitude. Proximity to the flight path should be such that measurements are indicative of conditions along the flight path, or acoustic propagation paths, but far enough from the flight path to be considered a safe distance.

The placement of meteorological equipment should ensure that atmospheric measurements provide a representative sample of the conditions that exist over the entire acoustic measurement area. Ideally, this equipment should be near the measurement microphones, while ensuring that the obstruction criteria specified in section 6.2 are maintained. For sparsely distributed microphone arrays, it is recommended that more than one ground weather station be used, situated at multiple locations across the measurement area.

Noise certification procedures only require meteorological measurements to be taken by ground-based equipment situated between 5 ft (1.5 m) and 33 ft (10 m) above ground level. Improved noise propagation modeling and a greater appreciation for the acoustic impact of wind conditions on the UAM vehicle can be gained if additional measurements are taken at various altitudes up to the maximum flight altitude. Traditionally, these measurements have been recorded using weather balloons. There has recently been a growth in alternative techniques. Ground-based, vertically oriented Light Detection and Ranging (LiDAR) systems have proven successful at measuring wind speed and direction for multiple vertical heights [31] and Small Unmanned Aerial Systems (UAS) have also demonstrated their versatility as flying weather stations capable of measuring wind conditions as well as temperature, humidity, and pressure [70].

7 Data Acquisition

7.1 Acoustic

Requirements for signal processing will depend on the specific analysis to be performed. There are many types of signal processing techniques, but for this purpose only signal conditioning will be discussed. To reduce the constraints on options for post-measurement signal processing, it is important to ensure that acoustic measurement data include microphone pressure time history sampled at a sufficient rate, with no frequency-weighting filters or time averaging applied. It is required to use a sampling rate which is at a minimum two times the highest frequency of interest. This is to comply with the Nyquist sampling theorem.

For full-scale UAM vehicles, the highest frequency of interest is typically around 10 kHz, but could be higher for certain configurations. For measurements with fast moving sources, where de-Dopplerization by re-sampling the original signal through linear interpolation is usually required, guidelines usually recommend limiting the maximum frequency of analysis to 10% of the sampling frequency for phased arrays [32], and to 40% for other array types. Digital decimation in delta-sigma type analog-to-digital converters (ADCs) reduces the need to rely on antialiasing filters. Some COTS devices, however, use built-in analog prefiltering before delta-sigma ADC. It is recommended to set the sampling rate such that the alias-free bandwidth of the signal acquisition hardware to be used includes the highest frequency of interest. The upper edges of the highest frequency band of interest should be used in sampling rate determination.

The objective of the signal processing is often the evaluation of a noise metric for the aircraft given the tested environmental conditions, vehicle state parameters, and acoustic sensor locations. More ambitious signal processing may aim to estimate the noise metric for virtual observation locations and/or environmental conditions different from those tested. In either case, the signal processing methodology should be selected, tuned, and evaluated such that statistical error estimates for the resulting metric values can be minimized and, ideally, quantified. These errors depend on other topics in the document, especially the signal-to-noise ratio and microphone installation details.

7.2 Vehicle Operating State Conditions

Testing procedures dictate adequate recording of the vehicle operating state parameters not only to appropriately document testing conditions, but also to provide information for eventual users of the noise spheres. It is suggested that the static, dynamic and optional parameters (Tables 1-3) are captured and recorded during the test operations. The sampling frequency should be commensurate with the expected variations in vehicle dynamics and maximum flight speed, and sufficient fidelity to support requisite posttest analysis. Additional parameters (such as individual propulsor rotation rates, orientation, tilt angle, and controller data) should also be considered depending on the eventual data use.

7.3 Time Synchronization

Recorded digital data, including acoustic pressure, vehicle state parameters, and environmental conditions, are typically sampled periodically. It is critical that all recording devices are time synchronized. Given the ubiquity and precision of GPS systems, it is reasonable to expect that the recording is done in such a way that the timestamp for each acoustic data sample can be determined in postprocessing to single sample accuracy. This assures that synchronization errors will not be the limiting factor for coherent acoustic processing, extracting acoustic trends as a function of vehicle state, or studies of acoustic source and propagation effects. The test engineer should take care when synchronizing data from different timestamp systems (GPS, UTC, TAI, 'local' time, etc.). The engineer should account for any time offsets, including leap seconds, and should report out all data in a common time format. The total number of leap seconds is maintained by the International Earth Rotation Service (IERS).

Table 1. Recommended known aircraft static parameters during test operations.

Static parameters	Units
Gross weight	lb (kg)
Propulsor(s) diameters	ft (m)
Onboard inertial navigation system location (x, y, z)	ft (m)
Aircraft range	nm
Lift mode transition speed	kt
Best endurance speed, V_{BE}	kt
Design cruise speed, V_C	kt
Never exceed speed, V_{NE}	kt
Best angle of climb speed, V_x	kt
Best rate of climb speed, V_y	kt

Table 2. Recommended aircraft dynamic parameters to be recorded at the prescribed accuracy during test operations. Acronyms: UTC - Coordinated Universal Time, GPS - Global Positioning System, TAI - International Atomic Time.

Dynamic parameters	Units	Accuracy
UTC, GPS, or TAI time	s	μs
Vehicle latitude	decimal degrees	10 μdeg. (≈3 ft, 1 m)
Vehicle longitude	decimal degrees	10 μdeg. (≈3 ft, 1 m)
Vehicle altitude	ft (m)	3 ft (1 m)
True airspeed (TAS)	kt (m/s)	2 kt (1 m/s)
Vehicle pitch	degrees	1 degree
Vehicle roll	degrees	1 degree
Vehicle heading	degrees	1 degree

Table 3. Recommended optional aircraft dynamic parameters to be recorded at the prescribed accuracy during test operations.

Optional dynamic parameters	Units	Accuracy
Propulsor(s) rotation rate(s)	RPM	20 RPM
Propulsor(s) tilt angle(s)	degrees	1 degree
Propulsor(s) blade pitch	degrees	1 degree
Vehicle angle of attack	degrees	1 degree

8 Concluding Remarks

Measurement methods intended to support the creation of noise source hemispheres for Urban Air Mobility aircraft have been described. The guidance herein is a collection of the Urban Air Mobility Noise Working Group, Subgroup 2: Ground and Flight Testing discussions over the last several years to obtain research quality data. It is not intended for certification by regulators. No strict protocol to acquire source noise hemisphere data is given. Rather, to encompass disparate levels of resources, flight test objectives, and the fact that UAM covers a broad class of air vehicles, options selected by the subgroup as most suitable are provided. As measurement and modeling techniques improve, these suggestions will require updating.

Various microphone array patterns are described, each having advantages over the other. For example, the linear array is a low channel count solution, but may introduce acoustic uncertainty if there is aircraft state or acoustic unsteadiness. The snapshot or distributed arrays are higher channel count but provide a means to manage acoustic variability. Phased arrays may be used to supplement the other microphone array patterns, but are not recommended to be solely used to gather full hemisphere data. Asymmetric arrays (biasing the number of microphones to one side of the flight path) may prove useful if there are test range size limitations. However, care should be taken if acoustic symmetry is assumed. Vertical arrays are not recommended to avoid ground reflections corrupting the direct signals.

Dependencies on flight altitude include angular resolution, spectral uncertainty, and signal-to-noise ratio (SNR). Increasing flight altitude is beneficial from an angular resolution perspective, but will reduce SNR, particularly at the most lateral microphones due to increased propagation distance. Too low of a flight altitude may result in near field measurements, which can cause errors when using far field decay rates for backpropagation to the hemisphere surface. Additionally, care should be taken when handling shallow emission angles (near the hemisphere horizon) due to grazing angle concerns and lack of confidence in correction methods.

Microphones embedded in or inverted over a ground board are recommended. The ground board geometry commonly used (and documented in SAE ARP 4055A) is acceptable, although more exotic geometries (flower petal designs) can minimize edge diffraction effects to further decrease errors when applying free field corrections. Elevated (i.e., at a height of 4 ft (1.2 m)) or binaural setups can be helpful to supplement hemisphere data for human response studies.

The test range should be quiet, flat, and to the extent possible have uniform ground impedance. Terrain and obstructions should be avoided to prevent extraneous reflections, local scattering, or shielding. Background noise should be broadband in nature, and if it dominates the measurement noise floor, should allow for at a minimum 3 dB SNR. Preliminary acoustic measurements of the test aircraft can prove extremely useful to ensure signal levels are sufficient for the planned instrumentation layout. Ambient state parameters including temperature, relative humidity, and wind should be measured at least near the ground, but ideally as a function of altitude. Several stations across the microphone array should be deployed to assess environmental differences.

To enable accurate backpropagation to the hemisphere surface, vehicle position should be recorded at a rate that captures its variation. If possible, additional parameters (e.g., propulsor states) should also be recorded and time-synchronized with the acoustic measurements to gain greater physical insight of the source noise mechanisms.

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704–0188

1. REPORT DATE (DD-MM-YYYY): 01-10-2024

2. REPORT TYPE: Technical Memorandum

3. DATES COVERED (From - To):

4. TITLE AND SUBTITLE: UAM Source Noise Hemisphere Flight Test Measurement Protocol

5a. CONTRACT NUMBER:

5b. GRANT NUMBER:

5c. PROGRAM ELEMENT NUMBER:

5d. PROJECT NUMBER:

5e. TASK NUMBER:

5f. WORK UNIT NUMBER:

6. AUTHOR(S):
Kyle A. Pascioni
Juliet A. Page
Devin K. Boyle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES):
NASA Langley Research Center
Hampton, Virginia 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER: L–xxxx

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES):
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S): NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S): NASA/TM–20240011587

12. DISTRIBUTION/AVAILABILITY STATEMENT:
Unclassified-Unlimited
Subject Category 64
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES:
An electronic version can be found at http://ntrs.nasa.gov.

14. ABSTRACT:

15. SUBJECT TERMS:
Urban Air Mobility, Acoustics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU		STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER (Include area code): (443) 757-5802

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18