UAS noise certification and measurements status report

Tigershark UAS measurements, tracking system development, and certification metrics status

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Final Report — September 2017

DOT-VNTSC-FAA-18-01
DOT/FAA/AEE/2018-01

Prepared for:
Federal Aviation Administration
Office of Environment and Energy
Washington, DC

U.S. Department of Transportation
John A. Volpe National Transportation Systems Center

Notice

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 2017	Final Report

4. TITLE AND SUBTITLE	5a. FUNDING NUMBERS
UAS noise measurement and certification status Tigershark UAS measurements, tracking system development, and certification metrics status	FA5JBA QC410
6. AUTHOR(S) David A. Senzig[1], Mehmet Marsan[2], Robert S. Downs[1], Aaron L. Hastings[1], Christopher J. Cutler[1], Robert W. Samiljan[1]	5b. CONTRACT NUMBER FA-14-01132-M03
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) [1]U.S. Department of Transportation John A Volpe National Transportation Systems Center 55 Broadway Cambridge, MA 02142-1093	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FAA-18-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) [2]US Department of Transportation Federal Aviation Administration Office of Environment and Energy 800 Independence Ave, SW Washington, DC 20591	10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FAA/AEE/2018-01

11. SUPPLEMENTARY NOTES
Program Manager: Mehmet Marsan

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
This document is available to the public on the DOT's National Transportation Library at: http://ntl.bts.gov/lib/62000/62500/62573/DOT-VNTSC-FAA-18-01.pdf	

13. ABSTRACT (Maximum 200 words)

This report documents work done by Volpe staff to support the FAA's development of Unmanned Aerial Systems (UAS) noise certification and noise measurement criteria. The primary elements were the development of a small, lightweight Global Navigation Satellite System-based tracking system, a noise certification test on a relatively large, fixed wing UAS, and continued testing and development of method of conducting satisfactory noise tests on UAS. Recommendations for future work includes continuing the development of the tracking system, expanding the database of UAS noise measurements, and working with other subject matter experts on the psychoacoustics of UAS noise.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Unmanned Aerial System, Noise, Unmanned Aerial System Noise, Acoustic Tests, Aircraft Noise, FAA, drone, drone noise	
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

Acknowledgments

We thank Jack Burton and the other members of the Crow Island Radio Control Club in Stowe, MA for allowing us to use their Airpark for our UAS testing. They were gracious and accommodating to all our requests.

We thank Ran Cabell of NASA's Structural Acoustics group for the spirit of comradery in allowing us to visit and kibitz during his group's UAS test flights.

We thank Bruce Conze for providing his insights into the world of aircraft noise certification.

We thank Bob Sgroi and Brian Brunelle of the Boston Air Traffic Control Tower for kindly allowing us to operate our drones in their airspace.

The work would not have been possible without the other members of the UAS team at Volpe: Jordan Cumper, Andrew Hansen, Dave Read, Chris Roof, and Chris Scarpone.

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List of Abbreviations

Abbreviation	Term
ADS-B	Automatic Dependent Surveillance - Broadcast
AMA	Academy of Model Aeronautics
ATC	Air Traffic Control
ATMP	Air Tour Management Plan
COA	Certificate of Authorization
CPA	Closest Point of Approach
CFR	Code of Federal Regulations
dB	decibel
dGPS	differential Global Positioning System
EAA	Experimental Aircraft Association
EMF	Electro-motive Force
EMI	Electro-Magnetic Interference
FAA	Federal Aviation Administration
GLONASS	Global Navigation Satellite System (Russian)
GNSS	Global Navigation Satellite System (generic)
GPS	Global Positioning System
HDMI	High Definition Multimedia Interface
Hz	Hertz (unit of frequency)
IGPM	Inverted Ground Plane Microphone
IGS	International GNSS Service
Lmax	Maximum A-weighted noise level
MOP	Microphone on Plate
MSU	Mississippi State University
MTOW	Maximum Takeoff Weight
NMEA	National Marine Electronics Association
NAF	NASA Auralization Framework
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NPS	National Park Service
OEM	Original Equipment Manufacturer
PPK	Post Processed Kinematics
PPP	Precise Point Positioning
PCB	Printed Circuit Board
PSD	Power Spectral Density
PVT	Position-Velocity-Time
RC	Radio Control
RF	Radio Frequency
RPM	Revolutions per Minute
RTH	Return to home
RTK	Real Time Kinematics
SBAS	Satellite based augmentation system

Abbreviation	Term
SEL	Sound exposure level
START	Survey and Tracking Apparatus for Research in Transportation
sUAS	Small unmanned aerial system
TBD	To be determined
TiSPI	Tiny Space Position Instrumentation
TSPI	Time-Space-Position Information
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
USB	Universal Serial Bus
VTS	Video Tracking System
WAAS	Wide Area Augmentation System

Executive Summary

This report documents work done by Volpe staff to support the FAA's development of Unmanned Aerial Systems (UAS) noise certification and noise measurement criteria. The primary elements were the development of a small, lightweight GNSS-based tracking system, a noise certification test on a relatively large, fixed wing UAS, and continued testing and development of method of conducting satisfactory noise tests on UAS.

Accurate position information of the UAS during noise testing is important for assuring the quality of the test results. The tracking system developed by Volpe allows for various levels of accuracy depending on the system configuration and latency/real-time data requirements. The system can achieve accuracy to the sub-foot level with post-processing. The system has been refined through in-house UAS vehicle tests but has not yet been optimized for field campaigns in a noise measurement environment.

A noise certification test was conducted on a Navmar TigerShark UAS according to CFR Title 14 Part 36 Appendix G regulations. Results of the noise tests are presented. The TigerShark did not meet the Appendix G standard, we believe primarily because the aircraft was not optimized for low noise operations.

Volpe staff witnessed several UAS tests conducted by NASA personnel. Experience from these tests and Volpe's own certification-quality tests were used to conduct a number of flight and noise tests on Volpe's in-house UAS vehicles. Testing has shown that the annoyance of the vehicle may be a function of their operational mode.

Recommendations for future work includes continuing the development of the tracking system, expanding the database of UAS noise measurements, and working with other subject matter experts on the psychoacoustics of UAS noise.

This work was supported by the FAA's Office of Environment and Energy.

1. Introduction

Unmanned Aerial Systems (UAS) are being considered by the Federal Aviation Administration for permission to operate in the National Airspace System (NAS). This permission would require consideration for the applicability of any environmental rules such as noise. These UAS may operate similarly to manned aircraft in that they take off and land at ground level. Unmanned Aerial Vehicles (UAV) may be powered by conventional or unconventional propulsion systems, i.e. piston engines, turbo shaft engines or electric motors driving a single or multiple propellers/rotors. Since there are no size, weight, use, or other configuration definitions that preclude these UAS from demonstrating compliance with the same noise regulations as other aircraft, they would be required to comply with CFR Title 14 Part 36. Note that is this document, “sUAS” particularly refers to vehicles under 55 lb (the CFR Title 14 Part 107 weight limit), and “UAS” is the more general term for all vehicles.

The report focuses on three items related to potential UAS noise certification under Part 36:

1) The development of the Time-Space-Position Information (TSPI) system for UAS vehicles (Section 2),
2) The Navmar TigerShark noise measurement program (Section 3), and
3) The UAS noise metric(s) issues which covers not only the tests conducted by NASA and Volpe but also the psychoacoustic aspects of UAS noise (Section 4).

The final section of the report (Section 5) contains conclusions and recommendations based on the work completed.

2. UAS Tracking System development

Knowledge of the four-dimensional position (X-Y-Z-T) of the UAS relative to the microphone(s) is a prerequisite to comparing noise levels of different UAS. Because UAS are generally smaller and quieter than manned aircraft, the practical requirements of the tracking system are affected in terms of payload (size and weight) and positional accuracy. To address these new concerns, Volpe staff have developed a lightweight, portable tracking system which can be installed on a sUAS aircraft. The tracking system allows for various levels of accuracy depending on the system configuration and latency/real-time data requirements. The Volpe system can achieve accuracy to the sub-foot level with post-processing. The system has been refined through in-house UAS vehicle tests but has not yet been optimized for field campaigns in a noise measurement environment.

2.1 Key Issues

2.1.1 Payload

The advent of small, unmanned aircraft systems (sUAS) brings new requirements in positional tracking systems. The size and weight of "rover" elements (i.e. the component on the moving vehicle) must be significantly reduced from conventional systems in order to avoid degrading the performance of the sUAS, which are defined in 14 CFR Part 107 as under 55 lbs. total weight. Additionally, there is a large market segment of sUAS under ten pounds. Such aircraft typically have no integral provisions for carrying a payload. Achieving very small size and weight parameters for the tracking system have thus become critical aspects of development.

2.1.2 Positional accuracy

Highly accurate positioning information is increasingly important, due to the shorter distances between microphones and aircraft resulting from smaller, quieter noise sources. Successful measurement and analysis of aircraft noise generally requires that the noise from the aircraft be at least 10 dB higher than the ambient background noise level. Since small UAS (sUAS) are generally quieter than conventional aircraft, the sUAS will need to be closer to the microphone than conventional aircraft to ensure "clean" noise measurements.

We can estimate a bound on the desired distance between the sUAS and the measurement microphone for an adequate signal to noise ratio. In this estimate we assume that spherical spreading of the aircraft noise is the dominant effect on acoustic propagation. Figure 1 below is a comparison for four notional sUAS which have varying reference (20 feet) noise levels from 40 to 70 dB. The horizontal axis represents the ambient noise levels and the vertical axis represents the maximum distance from the UAS to the microphone at the aircraft's closest point of approach (CPA) for the given UAS noise level and the ambient conditions. The distance is capped at 500 feet since that is similar to the limit for manned helicopter tests. As an example, a UAS with a reference noise level of 60 dB operating in an environment where the background level is 40 dB would require a maximum CPA distance to the microphone during the test of about 60 feet.

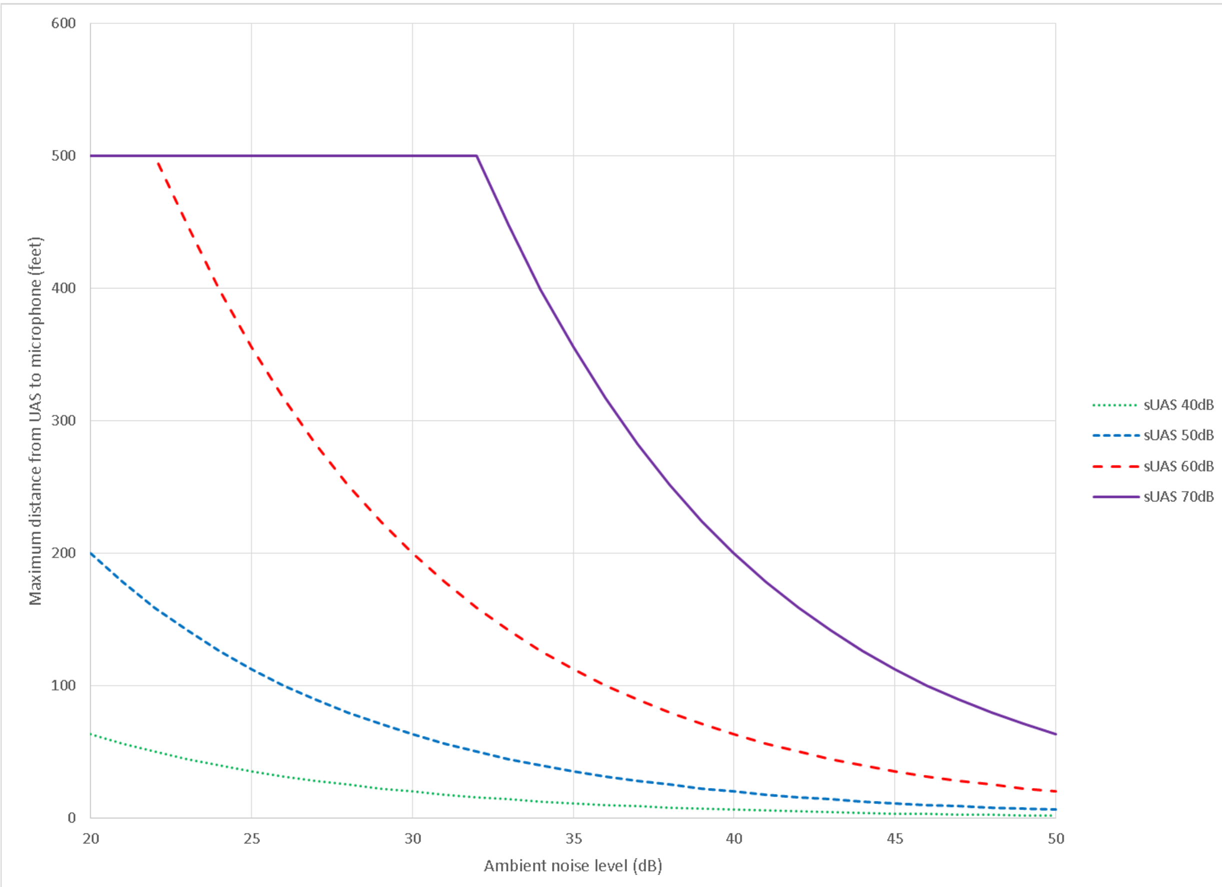

Figure 1, Maximum distance from UAS to microphone for an acceptable signal-to-noise ratio

Given that we can determine the distance from the vehicle to the microphone required for an acceptable signal-to-noise ratio during the test, we can also determine the required accuracy of the position information. If we take the Appendix G (U.S. Federal Government, 2017) position information as the standard required accuracy, we can determine that we need an accuracy of 1.5% of the distance between the vehicle and the microphone. The data above can be used to determine the accuracy requirements of the various sUAS noise levels and ambient levels. Figure 2 below shows the required range accuracy in feet for the various combinations of sUAS and ambient noise levels. Using the prior example of a 60 dB UAS operating in a 40 dB ambient environment requires a position accuracy of about one foot.

Note that the above analysis reveals a dependency between two competing constraints

- fly close to the microphone to maximize the signal-to-noise ratio
- fly farther from the microphone to minimize the relative error in the positioning to improve range accuracy.

Balancing these competing constraints is a new aspect of sUAS noise test and certification that has not generally been a concern in manned aircraft tests.

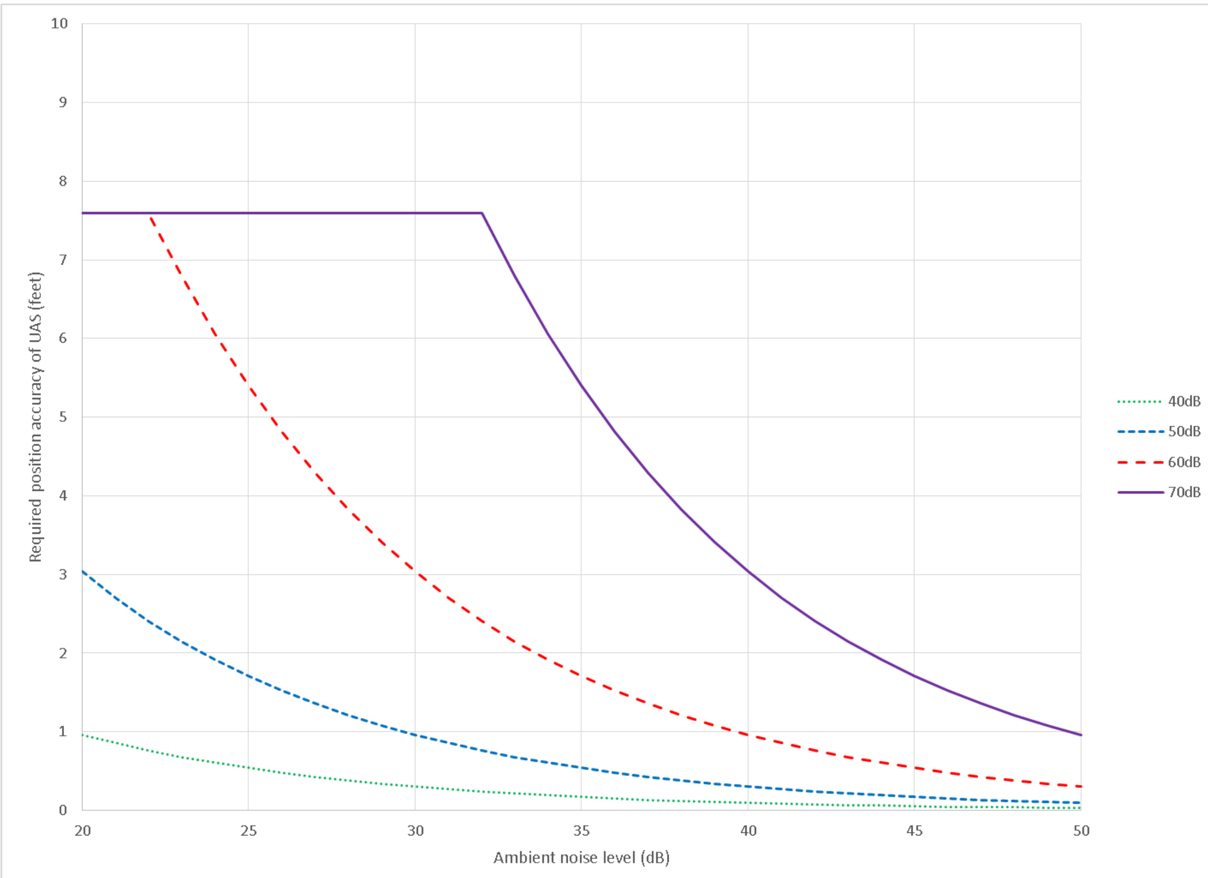

Figure 2, Accuracy bound required for UAS tracking

Note that the required ranging accuracy is needed when the microphone is nadir to the sUAS aircraft, that is, in the vertical direction. However, in practice GPS has the poorest positioning accuracy in the vertical dimension. Also note that the position accuracy being discussed is for the *measured* position of the UAS; the operator of the UAS is not required to fly the UAS to that level of accuracy. The derivation of the data presented in Figure 1 and Figure 2 is given in Appendix E.

2.2 Legacy Volpe tracking systems

In the early 2000s, Volpe staff developed a tracking system suitable for general aviation fixed-wing and rotary-wing aircraft. The system was based on using a differential GPS architecture (dGPS) (Volpe National Transportation Systems Center, 2003). It was used successfully in support of various source noise measurements conducted for the FAA/NPS Air Tour Management Plan (ATMP) program (Reherman, et al., 2005) (Lau, et al., 2010).

In addition, Volpe staff also developed a video tracking system. This system was used in measurement programs where the differential GPS system could not be mounted on the aircraft of interest (Senzig, Fleming, & Clarke, 2000) (Fleming, Senzig, McCurdy, Roof, & Rapoza, 2003). Both the dGPS system and the video tracking systems are discussed in more detail below.

2.2.1 TSPI

Volpe's dGPS system is a Time-Space-Position Information (TSPI) system. In a dGPS system, the standard GPS signal is augmented by a base reference station signal (the "Base") which provides the target aircraft (the rover) with additional information which improves the accuracy of the rover position information. In addition to the improved accuracy, the rover position is down-loaded in real time to the Base station. The real-time feedback of the rover position allows flight test personnel to determine the validity of the aircraft position with respect to the required test parameters.

2.2.1.1 Example projects

The TSPI system was developed to support the FAA/NPS ATMP aircraft noise data collection effort. Fixed-wing aircraft data collected as part of this effort ranged from single engine fixed-pitch propeller airplanes (e.g. Piper Cherokee) to a 30 seat turboprop (Dornier DO-328). Rotary-wing aircraft also ranged in size from the smallest piston-engine trainers (e.g. R-22) to middle-weight turboshaft helicopters (EC-130 and Bell 407).

2.2.1.2 TSPI advantages

The TSPI system provides real-time feedback to both the test personnel on the ground and to the pilots and test staff in the aircraft. The system provides feedback on the location of the aircraft relative to the desired location during the test. In addition, the system provides an indication of the accuracy of the system.

At maximum accuracy, the position error is on the order of 20 cm (0.7 feet). This is dependent on the accuracy with which the location of the Base station (i.e. the source of the differential signal) is determined. Errors in the location of the Base station directly affect the accuracy of the rover in absolute space (i.e. the world geodetic latitude-longitude system) but not in the relative coordinates used for these campaigns (the local coordinate system of the Base station and the microphones).

2.2.1.3 TSPI disadvantages

The TSPI system requires a significant amount of hardware. In particular, the hardware carried onboard the aircraft is substantial in terms of dimensions and weight: the major components are the GPS receiver, the datalink VHF radio, a laptop computer, and the batteries to support the electrical power requires of these components. The system also requires a dedicated GPS and VHF antenna. The need for the dedicated antennae has been problematic, since either new antenna mounts need to be installed on the aircraft or existing avionics need to be disconnected from their antennae (rendering those affected avionics inoperative for the test) so their antennae can be repurposed for the TSPI equipment.

The system also requires an operator in the aircraft. During a manned aircraft test, this is often helpful, since the rover operator can assist the pilot with coordinating test requirements while the pilot flies the aircraft. By definition, however, having an operator onboard a UAS is not an option.

2.2.2 Video tracking system

Volpe staff also developed a video system to passively track aircraft; "passive" in this sense means that the cooperation of the tracked aircraft is not required. The video tracking system (VTS) used two video cameras pointed in known directions to capture a common image of the tracked aircraft. The line-of-sight vector from each of the two cameras to the aircraft could be evaluated and the position of the aircraft estimated at the intersection of those two vectors. Note that this optical tracking system is different from the photo-scaling method of SAE 902A (A-21 Committe, 2017).

2.2.2.1 Example projects

The VTS was used to determine aircraft position information for a number of projects including a measurement program at the Grand Canyon in support of NPS and FAA model selection (Miller, Anderson, & Horonjeff, 2003), a research program looking at over-water acoustic propagation (Senzig, Fleming, & Clarke, 2000), and a research program to examine engine installation effects (Fleming, Senzig, McCurdy, Roof, & Rapoza, 2003).

2.2.2.2 Video tracking system advantages

The VTS is non-invasive, passive, and requires no cooperation from the target aircraft. With careful set-up and calibration of the equipment, the accuracy of the system is acceptable, although significantly lower than that of the dGPS system; VTS accuracy can be on the order of a few tens of feet.

2.2.2.3 Video tracking system disadvantages

The VTS is very labor-intensive, both during the equipment set-up prior to the test and during post-processing of the collected data. Calibration of the equipment in the field is complex and subject to errors; small errors in the system calibration can lead to large errors in the resultant position estimate.

The VTS has a relatively narrow field of view even with the use of 'fish-eye' lenses. If the target aircraft is not in the expected field of view of both cameras, the image is lost and no tracking can be done.

The current VTS relies on physical tape to record the image; these tapes must continuously record to maintain calibration. Aircraft tracking can't occur when the tapes are being changed so the possibility of missing aircraft of interest while switching tapes or during the calibration process is significant. The method of recording to tape is obsolete; the VTS's image storage technique could be upgraded to use computer memory, but the 2020 mandate for aircraft in the US fleet to broadcast their position via ADS-B, which has roughly equivalent accuracy, makes the entire VTS concept obsolete.

2.3 Requirements for the UAS tracking system

The following list presents, in no particular order, the key functionalities and challenges that are being addressed during the development process of the UAS tracking system.

1. System components, particularly the rover, must be ruggedized to the extent that they may withstand transport, highly dynamic movements, outdoor conditions and potential impacts resulting from accidents.
2. Low-mass components for the rover, including power supply. The system should weigh 1 pound or less, including the mounting hardware and transceiver.
3. Rover package to be mounted on aircraft should be low-profile and low-drag – should not generate or induce aerodynamic noise, nor affect the performance of the sUAS. Any components exposed to the airflow on a fixed-wing vehicle should be encased in an aerodynamic fairing or be designed for minimal extension into the airflow (e.g. a low profile or flush-mounted antennae).
4. Flexible mounting solutions must be developed as the Rover and accompanying antennae will be required to adapt to environments not explicitly designed for payload.
5. The telemetry system shall have a range commensurate with the Part 107 line-of-site requirements.
6. The rover must be able to operate continuously, in all operational modes, for at least 2 hours without a battery change.
7. Must capture and store raw GNSS observables at the Base Station (if used) and the rover.
8. Near real-time feedback to ground monitor. This capability is needed for high-level assessment of event quality.
9. X-Y-Z-T output at least twice per second, plus status or quality flag indicating reliability of solution.
10. Output in local coordinate system (primary microphone = 0,0,0) and in selectable units of feet or meters.
11. Data integrity insensitive to normal aircraft maneuvering (roll/pitch/yaw); i.e. the system maintains data integrity for all expected maneuvers. We expect the system to be insensitive to pitch angles of 10 degrees and roll angles of 20 degrees.

12. The second generation system is explicitly *not* intended to provide graphical feed-back to the UAS remote operator.

2.4 Development philosophy and history

Recent developments in Global Navigation Satellite System (GNSS) chipsets, microcontroller technology, and autonomous flight control systems developed for use in the consumer sUAS industry, paired with powerful open-source GNSS software tools, have created powerful, low-cost tools capable of meeting the challenges required for successful tracking of sUAS. Volpe has leveraged this technological innovation during development by focusing on currently available off-the-shelf hardware components in combination with manufacturer-developed software utilities, and publicly-available software libraries. With the current ability to collect and store raw satellite observables in a low cost, miniaturized package, there are multiple potential implementations for the development of a sUAS tracking system. The progression of the current development effort is outlined in the following sections.

2.4.1 First generation UAS tracking system

Volpe staff and contractors began to develop a Tiny Position Sensing Instrumentation (TiPSI) system in January of 2016. The first generation system was a proof-of-concept, with position accuracy and basic system functionality as the primary goal. The initial vision of TiPSI had dGPS-level tracking which could be carried on-board a sUAS aircraft. Position information could then be stored in the TiPSI system for downloading after the flight test.

The TiPSI system was developed into a ‘bread-board’ set of components in the spring of 2016. Initial testing was done with ground-based vehicles since Volpe did not have any in-house sUAS available and also did not have an area in which to conduct fight tests.

The TiPSI system was comprised of a GNSS chipset, an L-band antenna, a micro -computer (originally a Raspberry Pi but quickly substituted for an“HDMI stick” due to RF shielding concerns), and the batteries to power these units. A keyboard and display for interfacing with the system is included in all generations of the system but is not part of the rover as deployed during testing. Additionally, OEM software provided by GNSS chipset manufacturer is used to both configure the GNSS receiver and record/save data files. No modifications to the GNSS control software provided by the OEM were made.

After Volpe obtained sUAS vehicles and the authority to fly them, the TiPSI system was successfully tested in flight. These tests are discussed in more detail in Section 4.2 below.

While successfully demonstrating the concept that a high-accuracy position-tracking system could be carried on a sUAS, the limitations of a prototype system led to the recognition that a more user-friendly version of the system (both hardware and software) needed to be developed.

2.4.2 Second generation UAS tracking system

The second generation UAS tracking system, the Survey and Tracking Apparatus for Research in Transportation (START) system, is an evolutionary refinement of the TiPSI system discussed above. The most notable enhancements are the addition of an RF transceiver to enable telemetry to a ground monitor station, as well as the development of system operational modes which are functionality-based. A description of each operational mode is presented in Section 2.5 below. The detailed requirements of the system are given in Appendix A.

2.5 Current Status

START has multiple operational modes dependent on the particular hardware and software configurations chosen by the user. The system has three primary operational modes:

1) GNSS with WAAS ground monitor
2) dGPS with WAAS ground monitor
3) dGPS with RTK ground monitor

The raw GNSS data are stored on the HDMI stick computer in all operational modes to allow full post-processed (PPK or PPP) position determination. The ground monitor enables all three modes to have the capability of near real-time feed-back of the UAS position to the ground monitor. For campaigns such as flight tests, operational modes can be selected based on available resources, vehicle payload constraints and accuracy requirements.

2.5.1 GNSS with WAAS ground monitor (operational mode 1)

This operational mode is intended for easy deployment and can function as a stand-alone system, i.e. no reference surveys are required before operation. In this mode, the U-blox unit is using a Satellite-Based Augmentation System (SBAS), specifically, the Wide Area Augmentation System (WAAS) to enhance positional accuracy. Position accuracy can be expected to be on the order of the approximately ten foot standard WAAS-enabled GNSS systems accuracy. The usefulness of this operational mode is quick deployment, while the disadvantage is the lower accuracy of the position information, as compared to systems using a local reference (Base) station.

Note that in a minimum weight configuration, the RF transceivers can be eliminated so that the position history of the UAS would be stored on the HDMI computer. However, no feedback during testing would be available to the operator in this mode.

2.5.2 dGPS with WAAS ground monitor (operational mode 2)

Mode 2 is a differential configuration intended to deliver an increased level of accuracy and precision in the positioning function. This mode requires a Base reference station survey which significantly increases preparation time and resources required for operation, compared to mode 1.

In this mode, the raw GNSS data stored on the HDMI computer can be post-processed to enhance positional accuracy and precision using the open source RTKLIB software tools.

We see mode 2 as the default mode to use during UAS noise tests where position accuracy of the vehicle is the primary requirement. Note that this mode requires resources and personnel to locate the Base station, conduct a site survey, and post-process the data collected during the test.

As with mode 1, the RF transceivers can be eliminated, however no feedback to the operator during the test would be available.

2.5.3 dGPS with RTK ground monitor (operational mode 3)

Mode 3 is similar to Mode 2, with the difference that mode 3 uses an RF uplink from the Base to the rover to apply real time kinematic (RTK) correction to the on-board positioning. This leads to a better current positon status for the UAS, which, in turn, is downlinked back to the ground monitor so that the near real-time monitoring has a better accuracy than the WAAS-enabled positions of the modes 1 and 2.

Unlike modes 1 and 2, the RF transceivers are integral to the operation of mode 3 and so cannot be eliminated. Note that if the uplink is lost, the system would default to standard single-point GNSS position reporting as WAAS is unavailable in this operational mode. In all three modes, loss of the downlink means, of course, that the near real time position information is unavailable on the ground. It should be noted, however, that in the event of an uplink and/or downlink loss, the raw GNSS observables will continue to be collected at the Base and rover and thus will be available for subsequent post-processing.

2.6 System components

As with the prior TiPSI system, the primary components of START are the GNSS chipset and antenna, the HDMI stick computer, and the supporting battery and cables. A new component in this system is the RF transceiver. These three major components are discussed in more detail below.

2.6.1 GNSS chipset and antenna

The GNSS chipset (receiver) in the current START is a U-blox NEO M8T. The receiver is directly linked to the L-band antenna, the HDMI stick computer, and the battery which supplies power for all components. The GNSS chipset can also link to the RF transceiver via the HDMI stick computer when used in a real-time download mode.

The M8T unit is delivered as an exposed printed circuit board (PCB). Staff from Volpe have built various enclosures for the M8T for environmental and impact protection.

2.6.2 HDMI stick computer

The HDMI stick computer is a MeeGoPad T02 which contains an Intel Atom quad core processor running Windows 10. This computer runs the Ublox U-center software which controls, interfaces with, and stores data from the GNSS chipset. When START is used with the RF transceiver, the RTKLIB communications server software is also run.

2.6.3 RF transceiver

The RF transceiver provides a communication link between the UAS and the Base station. The primary purpose of the RF link is to provide feedback to the operator or test director on the near real time position of the UAS. The system will have enough latency that the UAS operator will not be able to fly the vehicle using the position feedback, but the success or failure of a particular pass (based on the test criteria) can be readily determined from the data.

2.6.4 Cost and weight specifications

The START components are intended to have a cost commensurate with the sUAS on which they will operate. As with the costs, the weight of the START must be less than the payload capability of the lightest sUAS envisioned for noise measurements.

Table 1, Weight and Cost of START components

Component	Function	Weight (g)	Volume (cm^3)	Cost ($)
5200 mAH Battery	Power	123	96	$40
MeeGoPad T02	Computer	50	138	$200
U-blox NEO M8T	GNSS receiver	9	16	$150
Tallysman 4721	GNSS antenna	72	21	$150
RFD900+	RF transceiver	15	120	$460
RF antenna	RF antenna	15	10	Included in RFD900+
Cables	Comm/power	100	-	$20
Installation kit	Attachment and protection	50	-	-
Totals		434 g	401 cm^3	$1020

Additional components of the system which are not on the flight vehicle are:

1) Laptop computer to display real-time position (when required)
2) HDMI monitor for interfacing with START and setting configurations prior to tests
3) Keyboard for setting configurations
4) Base station transceiver and antenna (when required)

2.7 Technical Challenges

2.7.1 Mounting

The mounting system currently used to attach START to Volpe's primary in-house sUAS (a DJI Phantom 3 advanced) is a combination of Velcro and zip-ties. The system is lightweight and works well: we have never experienced a failure in-flight due to component attachments. Additional mounting solutions will be required as more test vehicles with varying forms and performance considerations are introduced.

2.7.2 EMI interference

The earliest prototype of the TiPSI system incorporated a Raspberry Pi as the control computer. When operated in close proximity to the GNSS receiver, significant degradation of data was observed prompting a substitution to a micro-computer with better RF shielding. To our knowledge, we have not had an issue with EMI after switching to the HDMI stick computer, however the user should be aware that numerous components which transmit and receive RF signals are in close proximity. We have experimented with moving components outside the immediate vicinity of the sUAS body, but control problems with the sUAS indicated that keeping the majority of components close to the center of gravity of the vehicle was a better option for adequate flight performance.

2.7.3 Robustness and reliability

The ability of START to reliably operate in varying environmental conditions is an ongoing challenge. This includes factors such as heat, cold, and high humidity but also represents potential issues related to highly dynamic movement and possible effects on solution status via cycle slips or loss of satellites. This also includes basic resilience such as the ability of the system to withstand an impact-type accident. The system provides no environmental protection and no additional security for cable connection integrity. Initial feedback is promising in that the system has survived a few minor mishaps. The U-blox GNSS PCB itself has no OEM protection so a custom-fit foam enclosure, as well as a 3-D printed ABS enclosure was fabricated to provide some measure of protection for this component.

2.7.4 Ease of use

The OEM software provided by the GNSS chipset manufacturer is designed for multitude of purposes and diagnostics and thus does not provide a streamlined interface for operating a tracking system in the content of the Volpe use case. As such, it is not well suited for field use in terms of quick and efficient setup and safeguards against human error. It is recommended that custom software be developed to better suit the Volpe end-use. Hardware improvements already discussed, such as improved mounting options and system fortification may also serve to improve the systems “field-friendliness”.

2.8 Future Development

START is functional but relies on cumbersome OEM software which is not well suited for the Volpe end-use. As such, the primary focus of future development will be on improving ease of use and optimizing the system for reliable and efficient field use. The development of custom GNSS control, recording and display software is central to these objectives. The specific goal is to improve the way that system configurations are loaded and retained in the chip; the current method is labor intensive and subject to error, especially when working in the field conditions of an actual noise test.

To organize and potentially distribute the development effort across sequential phases, the flowing functional areas have been identified: machine interface, data processing, and data display.

2.8.1 Machine Interface

This functional area includes capabilities which provide the end user the ability to have strong visual feedback, in particular, the mapping of survey and tracking data for the purpose of evaluating conformance to predetermined flight path tolerances.

2.8.2 Data Processing

This includes capabilities which provide the end user the ability to have strong visual feedback, in particular, the mapping of survey and tracking data for the purpose of evaluating conformance to predetermined flight path tolerances.

2.8.3 Data Display

This functional area includes capabilities which provide the end user the ability to have strong visual feedback; in particular, the mapping of survey and tracking data for the purpose of evaluating conformance to predetermined flight path tolerances.

3. TigerShark UAS noise test

3.1 Purpose

In support of the FAA efforts to understand the noise certification issues regarding UAS, the Volpe Center's Environmental Measurement and Modeling division participated in a Navmar TigerShark UAS noise test at Griffiss Airport in Rome, New York on May 17, 2016.

The TigerShark is a fixed-wing, piston-engine UAS with a MTOW of about 450 pounds, with a 22 foot wingspan and up to eight hours of endurance. The TigerShark uses a 32 horsepower, 2-stroke engine; the engine has a red-line speed of 8000 RPM. The TigerShark uses a 31 inch diameter fixed pitch two blade propeller. The TigerShark was flown at a weight of 397 pounds for the noise test. The actual Tigershark flown in the noise test is presented in Figure 3 below. The yellow equipment case in the forward fuselage and the water bottle protecting the pitot tube on the right wing were both removed before the noise test.

We note that the TigerShark is currently operated by the U.S. military - military aircraft are not subject to noise certification requirements.

Figure 3, Tigershark flown in the noise test

3.2 Measurement program

The noise test was conducted on the southeast end of the primary runway at KRME, i.e. off the departure end of runway 33. The area is grass-covered, and was mowed by staff from KRME in the days prior to the test to a height of about 3 inches. There are no obstacles near this area of the runway other than runway navigation lights. The area of the test conformed to the noise test site requirements of Part 36 Appendix G, Section G36.101(a) for propeller-driven small airplanes. The view from the Volpe noise test site looking northwest along runway 33 is shown in Figure 4 below.

Figure 4, View from Volpe noise test site

Volpe staff set up a ground plate microphone at a site surveyed with a u-blox NEO-M8T GNSS receiver. The survey data were post-processed using precise point positioning (PPP) methods to increase the accuracy of the survey. PPP methods increase position accuracy over conventional GPS methods by post-processing the raw GNSS data to correct for the actual atmospheric properties and satellite clock biases that occurred at the time of the survey. The inverted ground plate microphone (IGPM) set-up is shown in Figure 5 below. The microphone used was a GRAS 40AD pressure response microphone. This microphone was connected to a Larson-Davis PRM831 pre-amplifier for the test. Prior to the test, system electrical-noise checks were made with a dummy microphone in place of the GRAS microphone. System calibration was conducted with a Brüel & Kjær 4231 calibrator.

The rest of the measurement system set-up is shown schematically in Figure 6 and in practice in Figure 7 below. The primary measurements were conducted with a Larson Davis 831 sound level meter. Backup measurements were recorded by a Sound Devices 744T audio recorder in parallel with the Larson Davis 831 through the use of an ADP015 signal splitter. Additional support equipment included the Vaisala

WXT-520 weather station, which fed wind, temperature, and humidity information directly into the 831 for concurrent recording of noise and atmospheric data, and a MasterClock GPS200A which provided time-synchronizing between the 744T audio recorder and the Larson Davis 831.

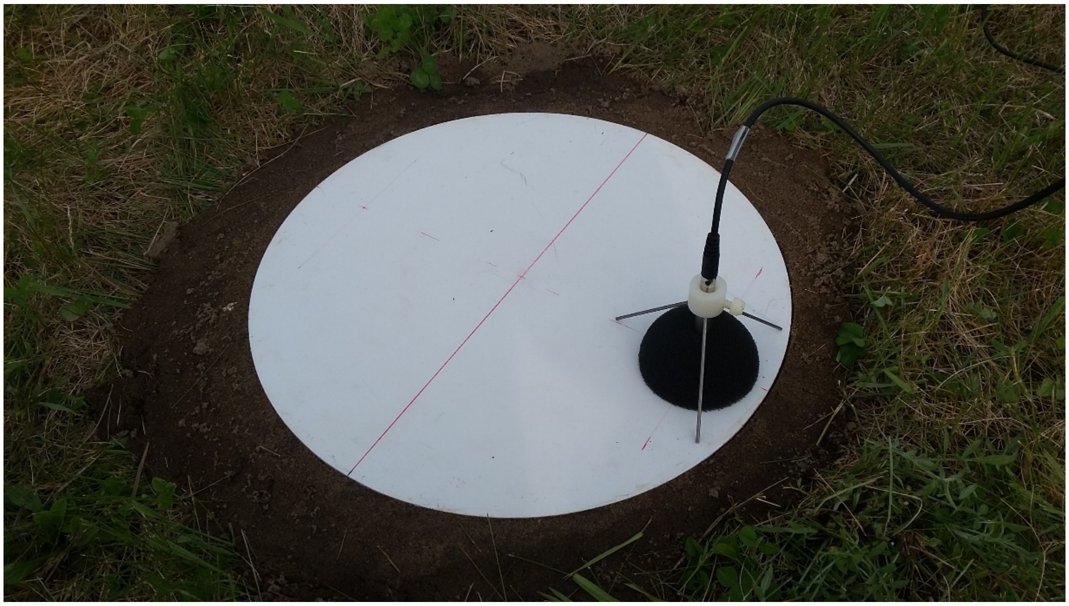

Figure 5, Inverted ground plane microphone (IGPM) set-up

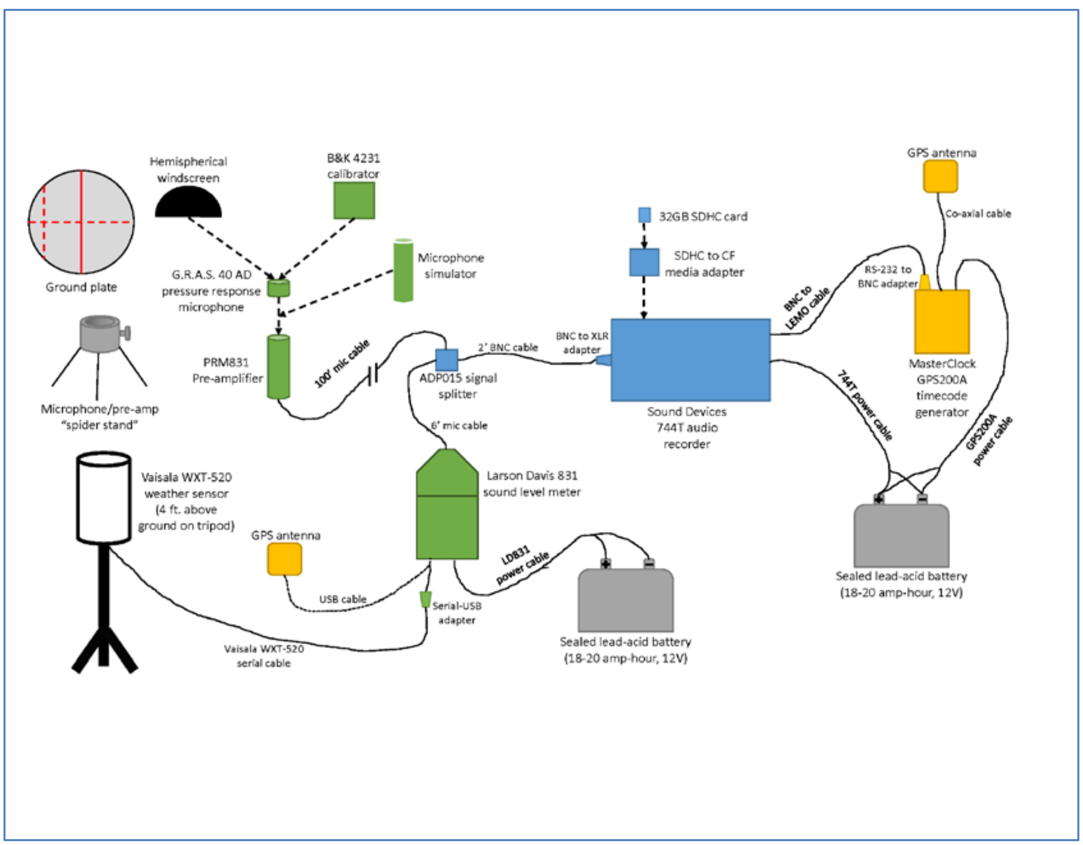

Figure 6, Schematic of TigerShark noise measurement set-up

In Figure 7, the practical set-up of the noise recording equipment is shown as used during the noise test. The Sound Devices 744T audio recorder is in the upper left. The MasterClock GPS200A is in the upper center. The ADP015 signal splitter is on the upper right corner of the table. The Larson Davis 831 is in the lower center, closest to where the operator sat during the test. A log sheet for the operator to note event noise levels and other test information is shown on the lower left. On the lower right of the table is an air-band radio used for monitoring and communicating with the Navmar flight test team.

Recordings from the 744T and the 831 are archived at Volpe, if further analysis is desired at a later date.

Figure 7, In practice TigerShark noise measurement set-up

3.3 Results from over-flight test

The first part of the TigerShark noise test consisted of level overflights at nominal altitudes of 200 and 400 feet AGL. The aircraft flew passes both in the direction of runway 33 (to the northwest) and runway 15 (to the southeast). Overflight noise measurements were recorded both by the Volpe team using the ground plate set up discussed above and the MSU team using two pole-mounted microphone set-ups.

Table 2 below shows the results of the Volpe team's noise measurements for the nominal 200 foot AGL series of passes. Aircraft state parameters of reported speed and engine/propeller RPM are also shown. The altitude of the TigerShark during pass 10 was not recorded. The Lmax noise metric is the maximum A-weight, slow response level recorded using the same methods as during the Appendix G takeoff flight test – these methods conform to G36.105(e). Table 3 below presents the same information for the nominal 400 foot AGL series of passes. As expected, the 400 foot series is notable quieter than the 200 foot series due to the greater propagation distance.

Table 2, TigerShark level overflight, 200 foot series

Pass	Altitude (AGL)	Speed (kts)	RPM	Lmax
6	296	75	6700	92.3
7	236	76	6700	96.6
8	226	70	6800	96.6
9	196	70	6800	96.0
10	-	70	6700	96.1
11	196	70	6700	95.4

Table 3, TigerShark level overflight, 400 foot series

Pass	Altitude (AGL)	Speed (kts)	RPM	Lmax
13	396	65	6600	88.4
14	476	70	6700	88.2
15	436	68	6600	90.2
16	436	73	6800	89.3
17	446	70	6800	90.0
18	466	74	6800	88.2

3.3.1 Ground plate and pole microphone measurement comparison

A comparison of the MSU pole-mounted microphones and the Volpe ground plate microphone measurements is given in Table 4 below. The same information is presented in graphical format in Figure 8 below. The data shown in the figure are the altitudes from Table 2 and Table 3, and the noise data from Table 4. Note that the MSU microphones were separated by 50 feet from each other, though which microphone was intended to be directly under the flightpath was not reported by MSU. The Volpe ground plate microphone recorded higher levels than the MSU microphones for all overflights. This is an expected result since the ground plate provides a pressure doubling surface for all frequencies which significantly contribute to the A-weighted levels, while the pole microphones are subject to some frequencies having cancelation of the direct and reflected sound waves. The data was not intended to show that one measurement technique is superior to the other, but rather that the two techniques will lead to different results.

Table 4, Volpe and MSU measurements

Volpe Pass number	MSU Event number	Volpe Lmax	MSU Mic #1 Lmax	MSU Mic #2 Lmax
6	2	92.3	87.7	88.9
8	3	96.6	92.4	91.4
9	4	96.0	90.6	91.9
10	5	96.1	91.3	90.8
11	6	95.4	90.2	91.0
13	7	88.4	83.3	85.2
14	8	88.2	82.2	85.1
15	9	90.2	84.8	85.8
16	10	89.3	84.1	86.2
17	11	90.0	84.3	85.6
18	12	88.2	82.9	83.8

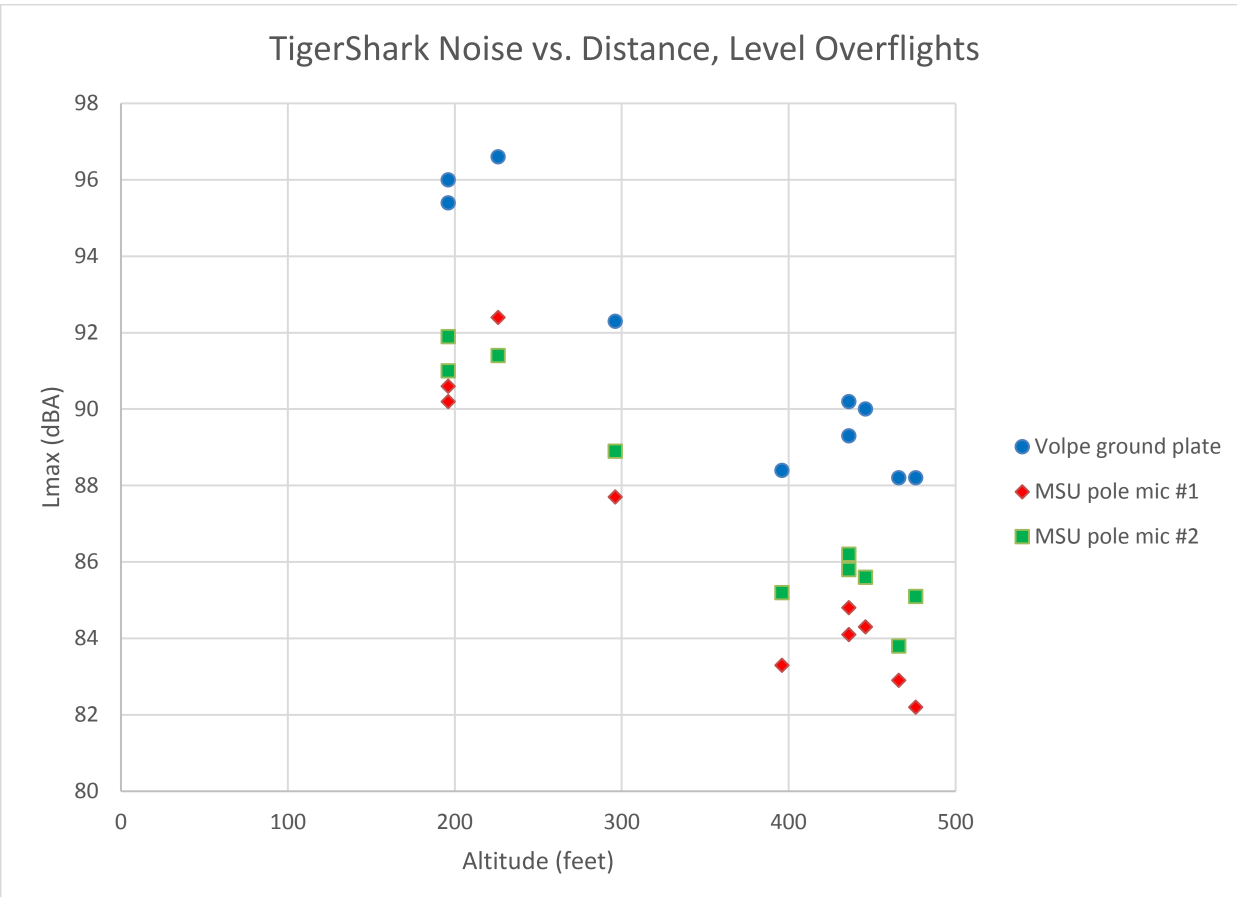

Figure 8, TigerShark measurement comparison

3.4 Results from Appendix G test

The results for the Appendix G noise test of the TigerShark are given in Table 5 below. One pass was removed from the analysis because the UAS airspeed at the overhead point was outside of the V_y ±5 knots criteria of G36.111(a). All of the Appendix G passes were within the atmospheric absorption window of G36.201. Only the distance correction of G36.201(d)(2) was used in these test; the other corrections did not apply.

Table 5, TigerShark Appendix G test

Pass	Altitude (AGL)	Speed (kts)	RPM	Lmax
19	781	59	6600	85.2
21	656	51	6540	86.1
22	726	55	6700	86.2
23	746	56	6600	86.3
24	768	58	6660	85.5
25	726	57	6600	84.9
26	756	63	6700	85.8
27	776	56	6620	85.4
28	696	58	6700	86.3

For the eight successful passes, the average of the Lmax noise levels was 82.8 dBA. The 90% confidence interval calculated for these eight passes is ±0.28 dBA, well within the Appendix g36.203 requirement of ±1.5 dBA. The consistency of the measurements is a credit to the Navmar flight team. The Appendix G36.301(c) noise limit for an airplane of this weight is 70 dBA, so the TigerShark could not be noise certificated via this test.

The original memo documenting the TigerShark noise test is given in Appendix C.

3.5 Results from Approach test

Two passes were also flown in an approach configuration. The results of the measurements of these two passes are shown in Table 6 below.

Table 6, TigerShark Approach

Pass	Altitude (AGL)	Speed (kts)	RPM	Lmax
29	166	55	5200	89.1
30	166	53	4200	84.6

3.6 Lessons Learned

We believe the TigerShark failed the Appendix G test for reasons that may point to further concerns with these types of UAS. The TigerShark has design features which optimize operational efficiency, not noise mitigation. These features are a pusher propeller, a direct drive system, and an un-muffled exhaust from an air-cooled 2-stroke internal combustion engine.

The pusher propeller design allows the entire forward section of the fuselage to serve as a cargo area. The propulsion system located at the back of the fuselage, behind the main wing, will introduce a tone at the propeller blade passage frequency where the blade interacts with the wake of the wing.

A direct drive propulsion system is structurally efficient and allows the propeller thrust to easily align with the center of mass of the aircraft. This in turn promotes controllability by minimizing pitch changes during thrust changes. The acoustic downside of a direct drive system is that the propeller turns faster than its optimal speed. The blade tip Mach number is the primary influence of the propeller noise; geared propulsion systems can slow the tip speed, resulting in less propeller noise, though the reduction gear itself will contribute some noise.

The TigerShark used no muffling on the exhaust. We only evaluated A-weighted levels for the Griffiss test, since that is the Appendix G requirement, so the effects of the propeller and the exhaust are difficult to distinguish. Adding a muffler to the airframe would increase cost and weight, and reduce payload, but would reduce the noise. A 2-stroke engine has an exhaust cycle at twice the frequency of a 4-strole engine, so the exhaust frequency of this engine is closer to the frequency range where the human auditory system is most sensitive, which leads to the perception of increased loudness.

3.7 Comparison with other UAS noise tests

Table 7 below shows a comparison of the UAS noise tests conducted to date known to the authors. The two columns on the left indicate the UAS and the type of vehicle. The third column is the weight of the vehicle in pounds. The fourth column indicates the operation type conducted during the particular noise test. “Takeoff” indicates that a Part 36 Appendix G test was used. “Level overflight” indicated a standard straight-and-level pass over the microphone was used. The fifth column indicates the type of microphone mounting used in the test. “IGMP” is an Inverted Ground Plane Microphone – this is the type of microphone mounting explicitly required in Appendix G. “MOP” indicates a microphone on a plate was used. Only the Navmar Tigershark had a test with more than a single operation and microphone type. The penultimate column represents the A-weighted maximum noise level normalized to a distance of 400 feet. Only spherical spreading was used in the normalization. The seventh and final column contains information on the quality of the test data. “Cert” indicates that the data were used in an actual noise certification. “Cert Quality” indicates that the procedures of Part 36 Appendix G were followed in the test. “Research” indicates that the data are useful for research purposes; the data were not collected with the intention of being certification quality.

Table 7, Comparison of UAS noise test data

UAS vehicle	UAS type	Weight (lb)	Operation	Microphone type	Lamax @ 400'	Data quality
AeroVironment PUMA	Fixed wing	13.4	Takeoff	IGMP	37.9	Cert
Insitu Scan Eagle	Fixed wing	46	Takeoff	IGMP	58.1	Cert
Navmar TigerShark	Fixed wing	397	Takeoff	IGMP	90.8	Cert Quality
Navmar TigerShark	Fixed wing	397	Level overflight	IGMP	88.2	Cert Quality
Edge 540	Fixed wing	25	Level overflight	MOP	53.4	Research
DJI Phantom 2	Quadcopter	3.5	Level overflight	MOP	44.9	Research
Prioria Hex	Hexcopter	5.5	Level overflight	MOP	45.9	Research

4. UAS measurement and metrics issues

Volpe staff have participated in a number of UAS measurement programs both as observers and as test leads. This section discusses five of those test campaigns and how they relate to the issue of determining which metrics are most suitable for correlating UAS noise with human response to that noise.

4.1 NASA sUAS test observations

Volpe staff observed NASA UAS noise measurements conducted on two occasions. The summary of the NASA measurements is given in a NASA report (Cabell, McSwain, & Grosveld, 2016). Summaries of the NASA tests are given below. Note that Volpe staff did not conduct noise measurements at these tests.

4.1.1 December 2014 test

NASA conducted a noise test with two fixed-wing and two rotorcraft sUAS at the Virginia Beach Airport, Virginia on December 17, 2014. Volpe staff participated in the test by using data collected during one vehicle's fly-bys in support of upgrading SAE-AIR 902 (A-21 Committe, 2017).

This first observed test was important for observing the state-of-the-art in sUAS tracking and for qualitative observations on the characteristics of the noise of the different vehicles during different flight observations. NASA's goals during a noise test can be dissimilar from FAA/Volpe's goals; a research project is not the same as a certification project. However, numerous observations made during this test were collected from the observers and sent to NASA. A copy of these forwarded observations are given in Appendix B.

4.1.2 August 2015 Test

Staff from NASA again invited Volpe to witness a follow-on test at the Finnegan Airfield at U.S. Army Fort A. P. Hill near Fredericksburg, Virginia in August, 2015. The NASA test involved evaluation of a new microphone array design. NASA flew a wider range of vehicles at this test compared to the Virginia Beach test. Additional vehicle types included a turbojet-powered UAS, and the GL-10 VTOL research aircraft.

Primary takeaways for the Volpe staff from witnessing this test included the need for pilots and test observers to have the same perspective on the location of the aircraft relative to the microphones during the test. The pilot and the test director, located at different spots during this test, did not agree on the location of the aircraft relative to the microphones during the individual passes. This highlights the need for feedback on the position of the vehicle in near real-time so the quality of the event can be quickly and objectively determined.

4.2 Crow Island Airpark tests

During early design and capability development the Volpe team identified a well situated, relatively nearby location for prototype testing and trial integration. The Crow Island Airpark in Stow, MA hosts both Experimental Aircraft Association (EAA) and Academy of Model Aeronautics (AMA) chapters. This provides both a collaborative environment and potential hosts of opportunity to gain knowledge of UAS and UAS-like operations.

4.2.1 June 2016 Site scoping

Volpe staff conducted a site scoping visit to Crow Island Airpark on June 17, 2016. Staff from the Crow Island AMA radio control (RC) aircraft club discussed the usability of the field. Figure 9 below shows a picture of the Crow Island air Park from the east end of the field (the departure end of runway 29) looking west. The ambient noise conditions are low except when the field is being used by RC pilots. The field is on the order of 1000 feet long, so space is available for maneuvering. Based on this scoping visit, we set up two following visits to conduct tests of the tracking and positioning systems discussed in section 2 above and to gain experience with sUAS noise measurements.

Figure 9, Crow Island Air Park

4.2.2 July 2016 test

The first Volpe sUAS tracking test was conducted at Crow Island Airpark on July 13, 2016. This was the first test of the first generation TiPSI system on an air vehicle. Post processing of the tracking information revealed that the TiPSI system was subject to data drop outs on the order of three seconds. This type of data drop out would be unacceptable during a maneuvering operation in an actual noise flight test. Note that no noise data were collected during this test; this was strictly a test of the tracking system.

During this test, the sUAS was inadvertently flown into a copse of trees bordering the runway. This crash was likely due to similar operator perception issues as at the NASA test at Hill AFB discussed in section 4.1.2 above. In the Crow Island case, the operator probably perceived the sUAS as farther from the trees than the vehicle actually was. We note that while the impact was severe enough to eject the battery from the vehicle, none of the tracking system components were damaged, but the RTK solution for the positioning appeared to have been scrambled. The propellers also sustained no visible damage; we had replaced the original plastic propellers with after-market carbon-fiber propellers prior to this flight test.

4.2.3 August 2016 test

After the July 13 test, Volpe staff corrected the data drop-out problem with the assistance of U-blox field support engineers: by disabling internal messaging (which is not associated with the tracking system data) all tracking data appears to be correctly sent to the on-board computer.

In the first sequence, the sUAS was flown in a straight line, level flyover above the measurement microphone and the binaural head. After the first set of flyovers where the binaural head was facing west, the head was re-oriented to face south. The level flyover pairs (E-W and W-E) were flown three times for three different altitudes (15 ft., 30 ft., and 50 ft.) above ground level. Altitudes were approximated by the operator during flight operations as no real-time feedback from the tracking system was provided.

In the second sequence, the UAS held a stable hover (no rotation), facing east, over the measurement microphone at heights of 15 ft., 30 ft., and 50 ft. above ground level.

In the third sequence, the sUAS was held in stable hovers facing East in the plane of the measurement microphone (4 ft. AGL), at 10 ft., 20 ft., and 50 ft. lateral distances from the microphone. After sufficient acoustic data was gathered from the Eastward orientation, the UAS was rotated on its yaw axis to face south, remaining in the plane of the measurement microphone at 4 ft. AGL.

Sequences 1, 2, and 3 are shown schematically in Figure 10 below.

In sequence four, the sUAS was hovered in the plane of the binaural head (4 ft. AGL), at varying lateral distances and angles relative to the head. The UAS was slowly flown between the two lateral points (100 ft. and 10 ft.) on the specific angle (0°, 45°, and 90°). Figure 11 below show a schematic of these flight tests using the binaural head as the receptor.

A the start of the test, GPS data was captured for approximately one hour at each microphone location, with the use of ground plates to mitigate the effect of multi-path on the GPS satellite signal. Static Base station GPS data were collected for the remainder of the test, approximately 4 hours, with the antenna placed on a ground plate.

Dynamic GPS data was gathered continuously on the UAS for the duration of the flight tests, approximately 3 hours. On review of the dynamic tracking data there were no apparent dropouts or large gaps in the data stream. A composite video from several perspectives of a single pass can be viewed at:
https://www.youtube.com/watch?v=8TMf_A_rpEk&feature=youtu.be

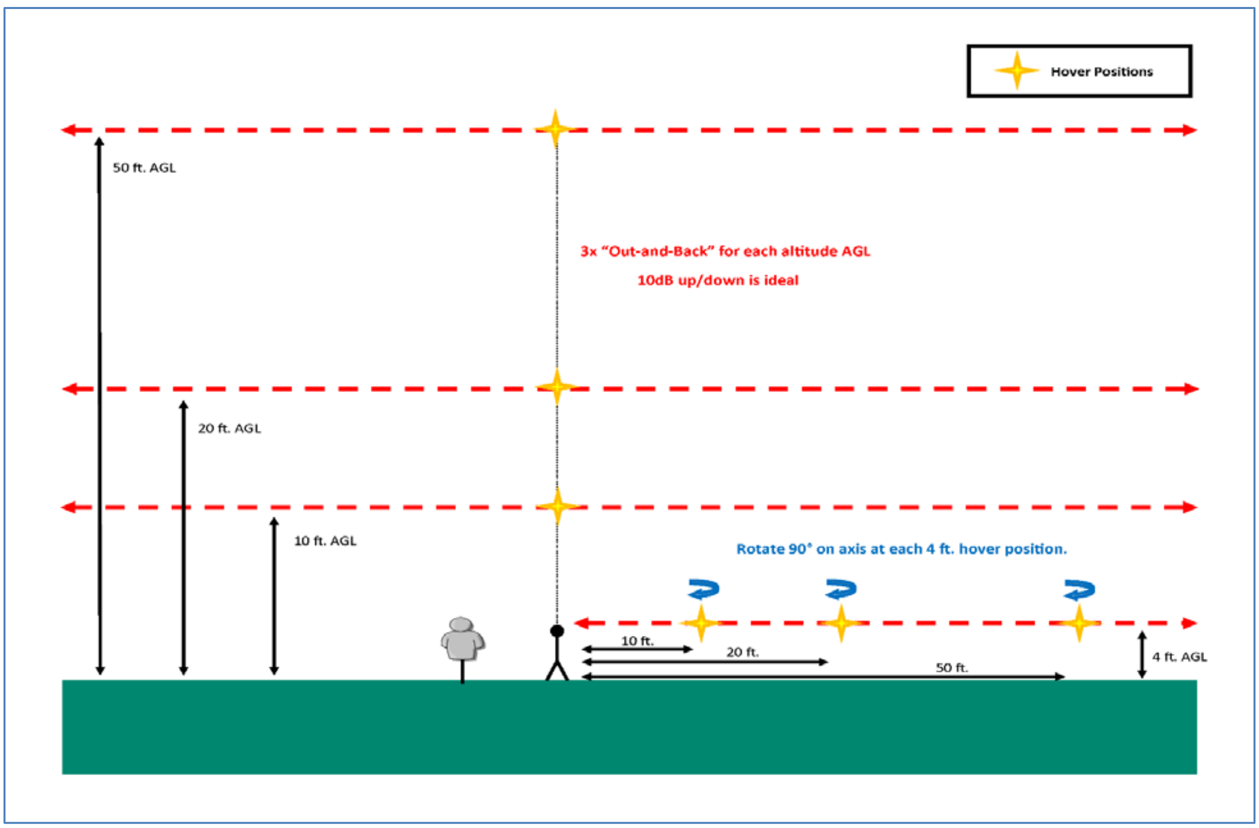

Figure 10, Crow Island overhead and hovering flight test schematic

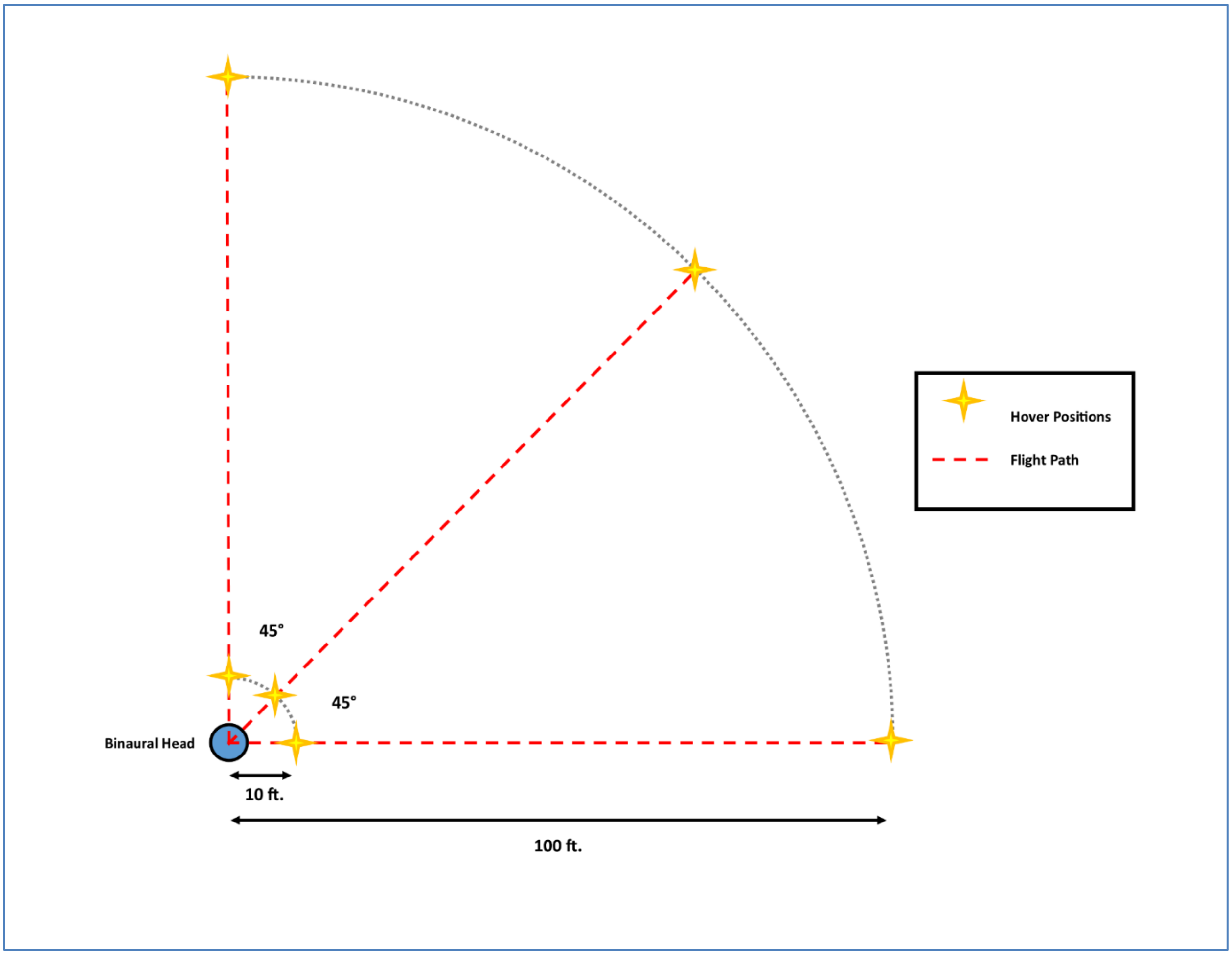

Figure 11, Crow Island binaural hovering and approach flight test schematic

4.3 Volpe Center on-site tests

In addition to the tests conducted at Crow Island Airpark, staff from Volpe have also conducted tests on the Volpe campus in Cambridge, Massachusetts. Conducting sUAS operations are Volpe allows for minimum overhead in conducting a test; the campus is a U.S. federal property, so despite being in the middle of a metropolitan area, access to the campus is restricted – testing can occur with minimal interference.

One of the downsides in testing at Volpe is that because the campus is in a metropolitan area, the acoustic environment is poor for conducting noise tests. The ambient noise levels on the Volpe campus are too high to conduct uncontaminated noise tests. In addition to the difficult acoustic environment, the GPS reception in the area is also poor due to a number of high-rise building in the area which can block satellite reception.

Despite these issues, Volpe staff have conducted a number of tests at the Volpe campus, particularly those where scoping-level results are needed. Note that this section only discusses outdoor tests; numerous indoor tests, used for system component analysis, are undocumented.

4.3.1 Part 107 issues

The Volpe Center campus lies within the Class B airspace of Boston's Logan International Airport. The FAA's Part 107 mandates that UAS operations within Class B airspace require Air Traffic Control (ATC) prior permission. On February 6, 2017, Volpe staff obtained permission from Boston ATC to conduct Part 107 operations at the Volpe campus. The FAA's Part 107 authorization for operations at the Volpe Center is given in Appendix D.

Note that Volpe staff originally pursued obtaining a Certificate of Authorization (COA) in the early part of 2016. A COA is a general authorization to operate UAS in the NAS. When the FAA released the Part 107 rule, Volpe's pursuit of the COA stopped; all of Volpe's envisioned sUAS operations were within the limits of the Part 107 rule and hence no need for conducting UAS operations under a more general COA.

4.3.2 March 2016 test

The first test conducted on Volpe property took place on March 30, 2016. Volpe staff conducted a tethered flight test of a sUAS aircraft; the vehicle was tethered so that any type of runaway operation would not leave Volpe property. The flight test was primarily intended to test the tethering system and to familiarize the sUAS operator with outdoor operations. No noise data were collected during this test.

As part of the testing to assess the usefulness and practicality of the drone system, dry ice was used to visualize the flow field of the sUAS aircraft. Figure 12 below shows one step in this process: water is being added to the dry ice to increase the amount of vapor given off. Once the bucket with the dry ice and water is ready, the bucket was lifted over the sUAS with the long pole (an apple picker). The sUAS is tied to a stool as shown in the lower middle of the figure. The test showed that the flow field of the sUAS was unlikely to pull the tether into the blades.

Figure 12, Dry Ice sUAS flow field test

4.3.3 April 2016 test

On April 13, 2016, Volpe staff conducted a tethered test of the Return To Home (RTH) capabilities of the sUAS. The RTH capability means that the sUAS will return to a pre-set location ('home") if the controller signal is lost. The RTH capability is an FAA requirement for operating under Volpe's Part 107 waiver. The RTH ability of the sUAS was successful: the vehicle was flown to the limits of the tether, the controller was physically shutdown, and the sUAS then returned and landed within 20 feet (the limits of the on-board GPS system's precision) of the designated home site.

In addition to the RTH test, staff also tested the ability to pre-set limits on AGL heights and radius from the home location. All tests confirmed that the sUAS would obey the pre-set limits.

As with the test on March 30, only flight operation tests were conducted and no noise data were collected.

4.3.4 June 2017 test

On June 1, 2017, Volpe staff conducted an un-tethered test of a sUAS. Unlike the two prior tests at Volpe, this test did involve an acoustic set-up. Three ground plane microphones were used; one in a standard Appendix G configuration (the microphone axis pointed straight down, which the Inverted

Ground Plane Microphone [IGPM] discussed in Section 3.7 above), one with the microphone lying flat on the plate (the microphone axis horizontal, this is the microphone on a plate {MOP} also discussed in Section 3.7 above), and one with the microphone mounted flush in the plate (the microphone embedded in the plate with the axis pointed straight up).

Figure 13 below shows the operator's view point on one aspect of this test: the three microphones used in the test are in the lower middle of the image, and the sUAS is just above the building 'horizon' in the middle of the image. For this set of passes, the sUAS was flown parallel to the three microphone ground plate, but at different altitudes for each pass. The sUAS operator is the person on the right; he is using the yellow flag past the microphones to judge the correct line-of-sight for keeping the sUAS over the microphones. Note that the operator has no way of judging the altitude over the microphones, nor the proximity of the sUAS to the building at the far end of the run. Methods of giving the sUAS operator useful visual cues on the required sUAS trajectory during tests are still a work in progress.

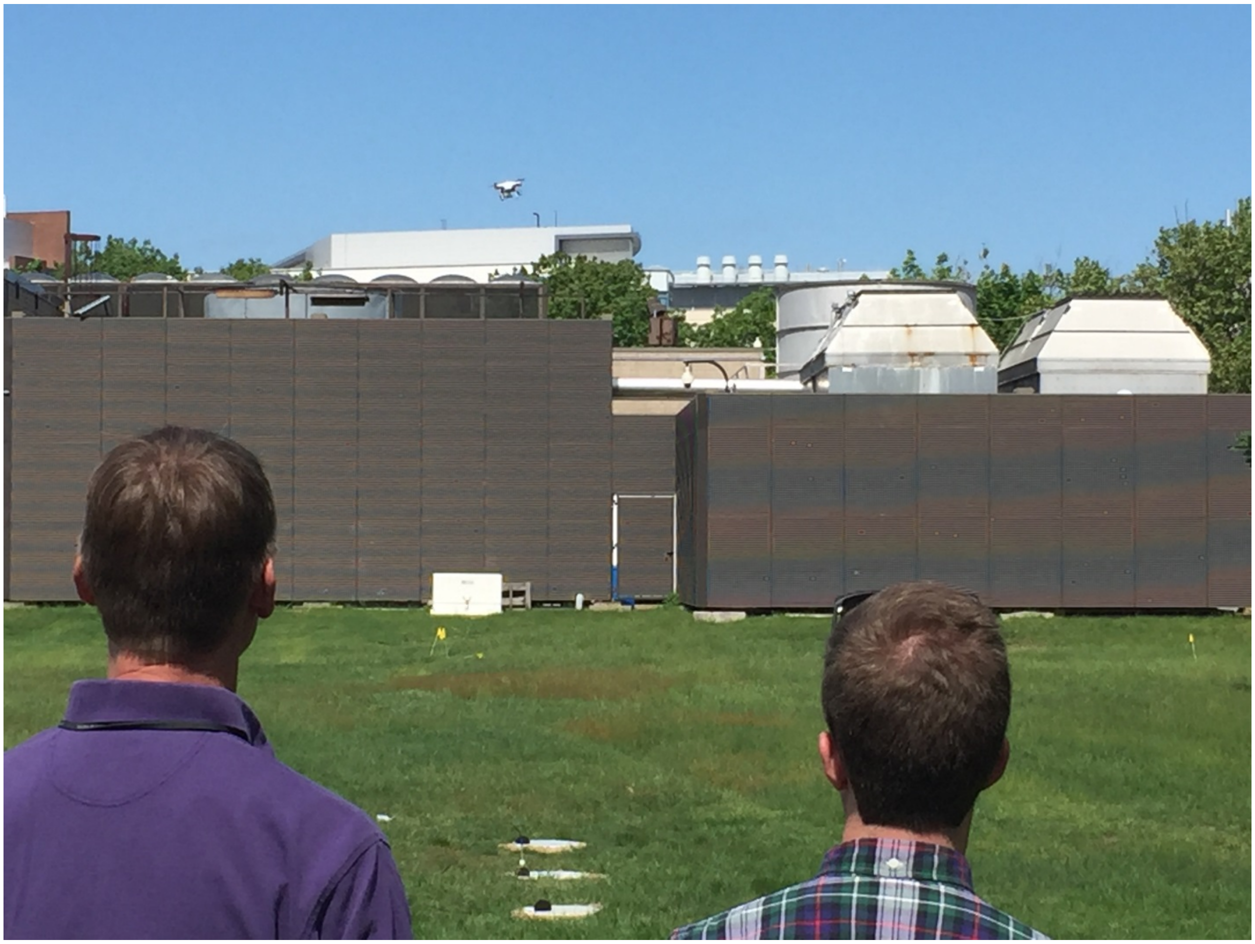

Figure 13, Operator's perspective on sUAS testing

An example of power spectral density (PSD) plots from hover and maneuvering data collected during this test is shown in Figure 14 below. The implication of the different PSD shown in the figure is discussed in more detail in Section 4.5 below. Note that the ambient levels at the lower frequencies are clearly setting the lower floor between the first (~200 Hz) and second (400 Hz) blade passage frequencies: the ambient noise levels at the Volpe campus environment is too high for certification-quality testing.

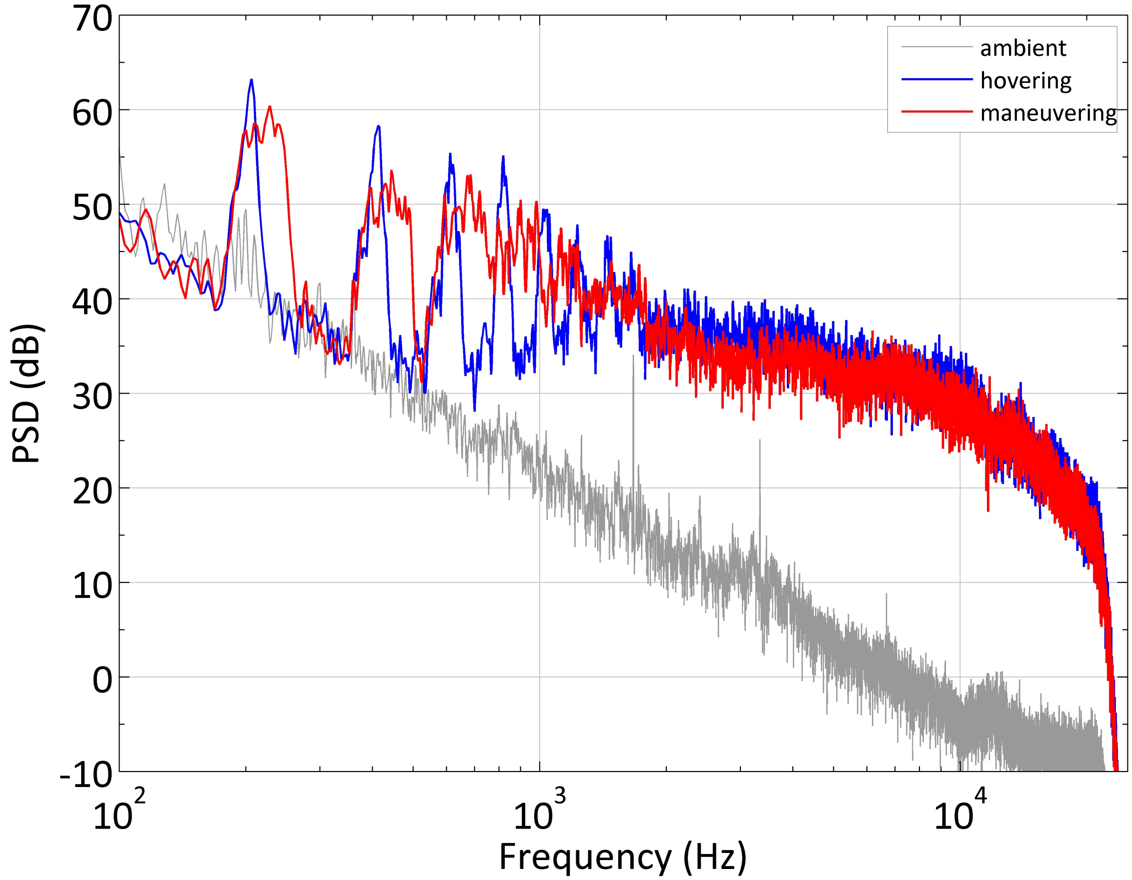

Figure 14, Power Spectral Density for an sUAS in hovering and maneuvering flight

4.4 X-57 test

While not directly related to the UAS noise certification program, NASA's X-57 noise tests have long term interest to the UAS community because of the possibility that the new electric propulsion system used on the vehicle may find application on future UAS vehicles.

4.4.1 May 2017 test

On May 16, 2017, staff from FAA and Volpe observed a noise test conducted by NASA at the Wallops Flight Facility on a Tecnam P2006T. The P2006T (Figure 15) is the baseline aircraft from which the X-57 is being developed. By conducting a baseline noise test on the 2006T, NASA will be able to determine how much the noise of the vehicle is reduced by the use of the new electric propulsion system and the advanced wing of the X-57.

Figure 15, Tecnam P2006T baseline aircraft at Wallops

A follow-up test of the actual X-57 is planned for early 2018.

4.5 Psychoacoustic issues

UAS vehicles have noise characteristics that are different from conventional manned aircraft. Some of the major differences we have identified are:

1) sUAS will potentially operate much closer to individuals than conventional aircraft so the rise and fall times of the noise may be much shorter. This may potentially lead to a 'startle' effect

exacerbating the annoyance of these vehicles. Even without the startle effect, quicker rise and fall times may increase general noticeability of the operations.

2) UAS have the potential to operate in a hover mode for an extended period of time. Extended exposure times relatively close to people may also increase annoyance.
3) The frequency distribution of sUAS noise is likely to have relatively more content at higher frequencies than conventional aircraft. High frequencies are typically not a concern with conventional aircraft because these frequencies are attenuated over the relatively long propagation distances associated with conventional aircraft. For sUAS, the noise propagation distance may be much less, so these high frequencies will comprise a greater portion of the total noise.
4) Existing multi-rotor sUAS use a different control method than conventional helicopters. Conventional helicopters are controlled by shifting the pitch and angle of the main rotor with little variation in the RPM of the main rotor; the noise produced by the helicopter is relatively constant (though that 'constant' noise may include repetitive impulsive noise such as "blade slap"). Multi-rotor sUAS are typically controlled by varying the RPM of each rotor individually: these RPM variations can induce aircraft pitch and roll changes due to the differential lift generated by each of the rotors, while yaw can be induced by differences in torque absorbed by the rotors. These RPM variations lead to noise fluctuations as the blade passage frequency of each rotor goes in and out of phase with those of the other rotors. These noise fluctuations can be perceived as roughness or beating of the sound, depending on the relative magnitude of the frequency differences.

Note that the A-weighted noise metrics used for certificating conventional small aircraft may not correlate well with the perception/annoyance of sUAS for the reasons discussed above (Christian & Cabell, 2017). In addition, the operations used in certification noise test of fixed wing aircraft are intended to replicate the noise generated in terminal operations (primarily takeoffs); small helicopter certification noise tests represent fly-over operations. The noise test of the sUAS should also replicate the expected operations of those vehicles and use metrics that correlate with the annoyance response of those operations.

Example data from sUAS noise measurements conducted for two different types of operations are shown in Figure 14 above. The blue line represents the Power Spectral Density (PSD) of an sUAS aircraft operating in a hovering mode. The red line represents the PSD of the same sUAS operating in a maneuvering mode. The gray line represents the ambient noise levels of the measurement site.

The spikes in the hover mode at about 200 Hz and the higher harmonics of this spike derive from the blade passage frequency at the sUAS's nominal rotor speed of about 6,000 RPM. The hover data are very tonal (large spikes in the PSD) because all the blades are operating at about the same RPM. In the maneuvering case, the spikes near the fundamental frequency are broader and slightly lower in amplitude, indicating that the rotors are turning at different speeds. In the mid-frequency range – around 1,000 Hz – the harmonic tones of the hover mode are replaced with broadband noise during maneuvering. The spectral differences represent what the human ear hears: the hover mode has sharp, steady tones; the maneuvering mode has an unsteady, warbling characteristic.

4.5.1 November 2016 visit to Langley

On November 18th staff from Volpe visited the NASA Langley Acoustics Branch to discuss their work on psychoacoustic analysis and how their efforts may align with FAA/Volpe's for UAS. Discussions centered on their work with sound auralization, psychoacoustic testing, and metric computations.

The NASA Auralization Framework (NAF) is a software environment that NASA staff have developed. NAF is reaching a level of maturity where it could be useful to third parties, such as Volpe and FAA. This tool allows the user to audition a sound source moving in three-dimensional space. The synthesis aspect of this tool can be as simple as a pre-recorded file to as sophisticated as a sound computed completely from first principles. This tool provides the ability to develop test sounds for psychoacoustic tests but could also be used to ask "what if" scenarios, such as what would happen if instead of one UAS flying overhead, there were several.

The NASA Acoustics Branch has developed a psychoacoustic testing room in the form of a small theater that can fit approximately 12 subjects. This room is not anechoic, but is reasonably well isolated (with the exception that HVAC noise can sometimes be heard if it is in operation). The room has a video projection screen that is capable of video play back that can be synchronized with audio playback so, for example, as the video of a UAS is passing overhead, so too is the audio representing that UAS passing overhead. The localization in the room is accomplished by using a number of speakers in the walls and provides the localization cues via changes in the relative amplitude of the speakers. The advantage of this method is that headphones are not needed and each subject is able to hear the sounds using their own personal head-related transfer function. Note that the localization cues include propagation issues such as frequency dependent absorption and ground reflections. The system also includes a touch screen pad whose input is also synchronized with the audio playback, so one can tell, for example, not only what rating a sound was given, but also when the rating was given.

In addition to their auralization tools and testing room, staff from Volpe and NASA discussed NASA's work with computing metrics and in particular psychoacoustic metrics. For the same reasons of control and refinement, NASA has been working on implementing various psychoacoustics metrics in a library that is compatible with their NAF. This library offers an alternative to FAA or Volpe developing a library from the ground up.

5. Conclusions and Recommendations

This section discusses the conclusion from the prior work and recommends actions by the FAA and Volpe in the future that will help mitigate UAS noise issues.

5.1 Tracking System

FAA should continue to fund the development of the Volpe tracking system so that the system can be utilized in future sUAS noise tests. In particular, the development focus should be on improving the software usability to work with our intended applications more efficiently and effectively in the field.

5.2 UAS noise testing

FAA should consider developing a set of recommendations to OEMs that will encourage them to include noise mitigation in their UAS design criteria. We have focused on the TigerShark in this document, but a similar effort should be undertaken for UAS in the consumer space.

Relatively few UAS vehicles have been subject to noise testing to date. FAA and Volpe should expand the number of vehicles tested, particularly those near the Part 107 55 pound cut-off, to determine if this weight limit is adequate to protect the public from undue UAS noise

5.3 Psychoacoustic issues

FAA should engage with psychoacoustic subject matter experts from Volpe, NASA, NPS, other Federal agencies, and possibly academia to determine which metrics adequately represent the human response to the noise characteristics of different UAS modes of operation.

For the additional testing discussed in section 5.2 above, the collected data should be used to inform decision-making on the acoustic metrics which best correlate with human annoyance to UAS noise.

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Appendix A: Tracking requirements

The Volpe Center Environmental Measurement and Modeling Division has an existing Time Space Position Information (TSPI) system that has been used for over a decade (Volpe National Transportation Systems Center, 2003). The Volpe TSPI system is a differential global positioning system (DGPS) designed to locate static or track dynamic points of interest in the field and record X-Y-Z-T coordinate position data electronically. TSPI's main purpose is to both survey field measurement sites such as microphone arrays for aircraft acoustic tests and to provide precise position, velocity, time information for the vehicle-under-test.

The advent of small, unmanned aircraft systems (sUAS) brings new requirements in positional tracking systems: the size and weight of rover elements must be significantly reduced from conventional systems in order to avoid degrading the performance of the sUAS which are defined in 14 CFR Part 107 as under 55 lbs total weight. Additionally, accuracy in positioning is increasingly critical, due to the shorter distances between microphones and aircraft resulting from smaller, quieter noise sources. Abrupt changes in vehicle position and trajectory are possible due to the high thrust relative to weight of the common quadcopter design and greater influence of wind turbulence on the vehicle's desired trajectory. These potential abrupt changes will require a fast response time from the tracking system. Recent developments in Global Navigation Satellite System (GNSS) chipsets, microcontroller technology, and autonomous flight control systems developed for use in the consumer sUAS industry, paired with powerful open-source GNSS software tools, may provide solutions to the challenges described for successful tracking of sUAS. Although current products are focused on navigation and flight control, the same technologies could be leveraged for use in sUAS tracking systems. Miniaturized packages are now able to collect and store raw satellite observables. There are multiple implementations possible for the development of a sUAS tracking system. The purpose of this document is to define requirements and criteria for evaluating various approaches with high likelihood of success while minimizing risk in development and operations. This is a continuation of the initial effort to explore the latest technology and prototype a system from available options.

1. Background

During the prototyping phase, Volpe investigated currently available off-the-shelf hardware components. These components were integrated with OEM software utilities, publicly-available software libraries, and customized in-house software. The first generation system was a major step toward the goal of meeting the acoustical measurement needs of sUAS including anticipated UAS noise certification applications.

The first generation system was a proof-of-concept with position accuracy and basic system functionality as the primary goal. In-situ functionality tests were conducted at Crow Island Airpark on July 13, 2016 and on August 29, 2016. The August flight test determined that the Base (ground reference) GNSS receiver and rover (on-board GNSS system) successfully collected GPS and GLONASS observables which proved adequate for post-processing corrections to the time-space-position data. Additionally, it was demonstrated that the miniature dimensions and weight of the rover were an acceptable payload for representative sUAS.

Given the success of the first generation system, we propose to advance a second phase of development. The goals of this phase will be to develop a multi-mode system with different trade-off objectives between simplicity and functionality. Further, the design will be modular so that the implementation can be configured to meet measurement-specific demands on a per-platform basis.

2. General System Requirements

The requirements in this section apply to all operational modes and are inclusive of hardware and software functionalities. Successful implementation of all requirements may necessitate additional manufacturing and/or software engineering beyond the proof-of-concept.

13. System components, particularly the rover, must be ruggedized to the extent that they can withstand transport, highly dynamic movements, outdoor conditions, and potential impacts resulting from accidents.
14. Low-mass components for the rover, including power supply. The system should weigh 1 pound or less, including the mounting hardware and transceiver.
15. Rover package to be mounted on aircraft should be low-profile and low-drag–should not generate or induce aerodynamic noise, nor affect the performance of the sUAS. Any components exposed to the airflow on a fixed-wing vehicle should be encased in an aerodynamic fairing or be designed for minimal extension into the airflow (e.g. a low profile or flush-mounted antennae).
16. Flexible mounting solutions must be developed as the rover and accompanying antennae will be required to adapt to environments not explicitly designed for payload.
17. The telemetry system shall have a range commensurate with the Part 107 line-of-site requirements.
18. Rover must be able to operate continuously, in all operational modes, for at least 2 hours without a battery change.
19. Must capture and store raw GNSS observables at Base Station (if used) and rover.
20. Near real-time feedback to ground monitor. This capability is needed for high-level assessment of event quality.
21. X-Y-Z-T output at least twice per second, plus status or quality flag indicating reliability of solution.
22. Output in local coordinate system (primary microphone = 0,0,0) and in selectable units of feet or meters.

23. Data integrity insensitive to normal aircraft maneuvering (roll/pitch/yaw); i.e. the system maintains data integrity for all expected maneuvers. We expect the system to be insensitive to pitch angles of 10 degrees and roll angles of 20 degrees.
24. The second generation system is explicitly *not* intended to provide graphical feed-back to the remote pilot.

3. Operational Mode-Specific Requirements

3.1 Rover-only GNSS with WAAS Ground Monitor: Mode 1

1. The Mode 1 configuration shall be a stand-alone solution which will mount directly to the exterior, or optionally the interior, of the vehicle-under-test. Note that interior mounting of the GNSS and telemetry antennae may negatively impact performance.
2. The Mode 1 configuration will collect and store GPS and GLONASS observables as well as NMEA format for position, velocity, time (PVT) data at 2 Hz. The observables may be subsequently post processed using PPP methods or, differentially, using the nearest (maximum 70 km baseline distance) Continuously Operating Reference Station (CORS) in lieu of a local Base station reference.
3. Mode 1 will provide near real-time PVT data back to a ground-based monitoring station, i.e., laptop, via an RF link. The PVT data will be enhanced using a Satellite Based Augmentation System (SBAS). The Wide Area Augmentation System (WAAS), operated by the FAA, will be used in North America. The ground monitor data may be optionally stored for play back.
4. In order to decrease the payload, Mode 1 may be operated without telemetry, however no NRT feedback will be available in this configuration option.

3.2 Differential GNSS with WAAS Ground Monitor: Mode 2

1. The Mode 2 configuration will consist of a local Base reference station, rover, and ground-based monitor station.
2. The Base station and rover will collect and store GPS and GLONASS observables and NMEA format position, velocity, time (PVT) data at 2 Hz. The observables will be subsequently post processed using PPP methods for static positions and differential post-process kinematic (PPK) methods, for dynamic operations, using the open source RTKLIB tools. Orbit, clock, and ionospheric corrections will be downloaded from the industry standard International GNSS Service (IGS) and NASA Jet Propulsion Lab servers.
3. The Mode 2 configuration is intended to provide the most accurate position information possible, given the size and power constraints of the sUAS environment. This necessarily means

that resources needed to operate the system will include personnel to locate the Base station, perform a site survey, if required, and post-process corrections for the GNSS observables.

4. Like Mode 1, Mode 2 will also provide near real-time PVT data back to a ground-based monitoring station. The PVT data will be enhanced using a Satellite Based Augmentation System (SBAS). The Wide Area Augmentation System (WAAS), operated by the FAA, will be used in North America. This data may be optionally stored for play back, however its primary purpose is to assess the quality of the intended flight path during noise tests.
5. In order to decrease the payload, Mode 2 may be operated without telemetry, however no NRT feedback will be available in this configuration option.

3.3 Differential GNSS with RTK Ground Monitor: Mode 3

1. The first three requirements of Mode 2 also apply to the Mode 3 configuration.
2. The primary difference between Mode 2 and 3 is that Mode 3 will implement an RF uplink from the Base station to the rover to apply real-time kinematic (RTK) processing of corrections to the data being stored on the rover. As a result, the telemetry link back to the ground station monitor will reflect the higher accuracy of the RTK solution. In the event that the uplink is lost, however, the rover solution and thus the ground station monitor, will revert to standard GNSS.
3. Since the RTK methodology is reliant on a robust RF link between the Base and rover, we will only rely on the RTK solution for positional feedback to the ground station monitor. To ensure data integrity, GNSS observables will be simultaneously collected and stored at the Base and Rover and subsequently post-processed, to provide the most reliable tracking data available.

4. Accuracy requirements

The system should provide position accuracy equal or better than currently required for Appendix G and Appendix J noise tests. Section G36.111(a) “Flight Procedures” gives the test limits as ±10 degrees offset from the vertical and ±20% of the reference height. The reference height limit is a function of the accuracy of the piloting of the aircraft and of the accuracy of the prediction of the performance of the aircraft. The Appendix provides methods to correct for differences in the reference height; no methods are given to correct for the offset of the aircraft from the vertical. Since an uncorrected error in the offset is allowed, we will use this as the basis for determining a limitation on the error of the position of the aircraft.

If we let the 10 degree offset of the Appendix G certification define the allowable distance error, then the limit of the error expressed as a ratio is 1/cos (10 degrees), where the numerator represents the actual distance of the aircraft to the microphone and the denominator represents the desired altitude of the aircraft directly over the microphone. The ratio of the error is about 1.015; so an error in the altitude of the aircraft equal to 1.5% of the actual altitude is the same as an error of 10 degree in the offset distance. What this potentially means for the development of the START system is that the limits on the accuracy of the position of the aircraft don't define whether or not a given accuracy is acceptable, but rather at what minimum altitude can the aircraft, with a known altitude and position error, overfly the microphones and still have an acceptable accuracy.

To make this concrete, consider a tracking system with an altitude accuracy of 2 feet. At a 500 foot flyover, this represents an error of 0.4%, which is within our tolerance. However, if we are testing a quiet sUAS and need to fly the vehicle at 50 feet to obtain an acceptable acoustic signal-to-noise ratio, then the position error is 4%, which is outside of our tolerance. Working backward for the 1.5% error, and the given 2 foot accuracy example, we find the resulting altitude is 133 feet for a minimum test altitude. So altitude of the vehicle over the microphones would need to be at or above this altitude, given the altitude reporting accuracy of this example. Curves representing these accuracy concepts are presented in Figure 1 and Figure 2 in the body of the report.

A full derivation of this method is given in Appendix E.

Appendix B: Lessons Learned from NASA UAS testing

Table 8, Lessons learned from NASA test

ISSUE	POTENTIAL CONSEQUENCE	MITIGATION STRATEGY
Consistent high level of noise contamination at 42VA test site	Unable to collect sufficient amount of quality data to characterize each aircraft. Difficulty isolating source noise and recording level/dB up/down	(1) Must research and perform reconnaissance on suitable, remote test locations. (2) Conduct flight test operations in a manner that maximizes use of quiet times between background noise intrusions 2a. Shorten go-around pattern to reduce times between measurements, and wave-off when too noisy.
Restrictions on UAS operations. Difficult to find suitable outdoor test locations	Compliance with Federal and local regulations. Safety of surrounding community.	Work with FAA and local authorities to obtain required permissions
PIKSI RTK dGPS hardware & software, as configured and operated by NASA, displayed limitations & instability	(1) Does not record absolute positioning in dGPS configuration, only local coordinates relative to each other; (2) GPS reception & GPS "RTK" solution is fragile - minor blockage of either GPS or downlink antennae can lead to failures requiring re-initialization; (3) positional shifts of track (both lateral and altitude) have been observed on numerous occasions - usually occurs at a consistent offset, however not clear when/if track "corrects" - cause TBD but believed to result during maneuvering when rover may lose or shift satellites leading to shift in carrier phase relative to Base receiver, e.g., when banking at turn-around ends	(1) PIKSI is product of Kickstarter campaign and development has not reached maturity. Work with vendor and/or open source code to address known "bugs". (2) Substitute GPS/telemetry antennae with higher gain options that may be available. (3) Always confirm rover and Base RTK lock by returning rover to pre-flight initialization position. If offset has developed during flight, it will now be apparent. (4) Explore additional dGPS RTK systems as well as alternative tracking solutions

ISSUE	POTENTIAL CONSEQUENCE	MITIGATION STRATEGY
Short time intervals between fly-over events due to relatively short flight paths	No time to actively manage data collection devices between events; UAS typically will not leave range of audibility	1. Continually collect data while test aircraft is in-flight 2. Alternatively, more actively control flight of UAS, and command to take holding pattern when time is needed for ground operations between measurements. Shortening loop for pattern would allow more fuel/battery time for this sort of operation.
sUAS have low wind tolerance	Although there was variability among the four sUAS, all experienced difficulty maintaining stability and accurate bearing in crosswinds as low as 5 -10 MPH. Noise profile may be erratic as pilot actively tries to maintain planned flight path	Need to establish acceptable tolerance limits for wind during noise testing. Consider indoor test options. (Additionally, instruct UAS pilot prioritize stable flight over precision in positioning. With good tracking data, can adjust for position if needed. May all be moot if recommendation is to exempt category of small UAS from traditional certification measurements.)
No redundancy built into acoustics data collection	If DAC, or more likely, laptop hard drive, hiccups or fails, there is no backup data being captured in parallel. This could result in small or large data loss scenarios	Design data collection system to simultaneously record and store a time synchronized, high resolution, audio signal through a shared mic system but stored to an independent data acquisition device. Consider a multi-channel audio recorder used in parallel with the laptop-based audio capture, in order to have backup recording of acoustic data... Explore configurations of instrumentation/software and develop optimized system.

ISSUE	POTENTIAL CONSEQUENCE	MITIGATION STRATEGY
Close proximity of data collection hardware relative to microphones	Data contamination from team members documenting events, e.g., camera "shutters" and team communication. Although not high level contamination, the close proximity of data collection hardware relative to microphones requires greater degree of silence from team.	Spread out data collection station from microphones. Manage trade-off between unnecessarily long cable runs (which could promote EMF/RF interference) and isolation from team noise
No mic simulator test or headphone “sanity check” was performed to check self-inherent system noise or EMF/RF interference	Data contamination via EMF/RF interference or faulty, unstable component would not be realized until it was too late to take corrective action	Perform dummy mic test to evaluate system noise at analyzer and use headphone test to "sanity check" integrity of audio signal
Piksi positional data time was +16 seconds relative to acoustics data, i.e., did not account for GPS "leap second" offset or perform time hack to check. Not sure of synchronization of other data sets , such as video or other GPS device (Pixahawk)	Unsynchronized or poorly synchronized data sets will have numerous negative implications for data analysis	Must perform time-base check prior to testing. Many devices can adjust for local time, UTC and GPS offsets within the settings, however knowing the offsets ahead of time is the most important part
Poor accuracy of pass-bys relative to microphone positions. Accuracy did, however, tend to improve over the course of repeated passes	May require too many passes for each event type in order to meet guidance requirements over microphones, or may not be able to meet acceptable tolerances at all	Relax guidance requirements based on class of UAS. This may be achieved, without compromising the data, by using a "line array" of microphones, e.g., mics could be spaced at distances equal to the lateral tolerance thus creating a much wider pass-by zone. This would require a change in the certification requirements and specifications - using such an array of microphones is not in conformance with current requirements.

ISSUE	POTENTIAL CONSEQUENCE	MITIGATION STRATEGY
Pilot was getting seemingly inaccurate verbal altitude readings from flight assistant. Unsure of sensor type being used, barometric?	Poor guidance feedback makes accurate flight nearly impossible at higher altitude flights. Lower altitude flights were more accurate due to the pilot's ability to use background (trees) as a reference.	May need to validate accuracy of sensors used for pilot feedback. Visual cues may be helpful in allowing pilot to attain desired altitude range. No guidance may be better than poor or inaccurate guidance. Real-time (or near real-time) feedback on positioning is crucial to obtaining accurate flights relative to microphone position. This whole area deserves substantial additional consideration.
Malfunction of automated navigation system ("Mission Planner" - free software) - designed for hobbyists, not maturely developed? Since this is a relatively new and growing market segment, the use of immature products may be rampant	If the state of auto-navigation for sUAS is not robust, or highly variable depending on system, this will compromise safety and accuracy of passes	Test personnel must have heightened safety awareness when auto navigation is employed. A test pass may also be recommended as part of a safety check. Must also have manual over-ride capability
Malfunction of motor on 3DRY6 "tricopter"	(1) Total loss of control (at worst) or inability to navigate with required level of accuracy (at best), (2) Spending too much time troubleshooting a single test UAS may limit opportunities with subsequent test vehicles - this was that case here, leaving very little time for the DJI Phantom 2 "Quadcopter"	(1) This type of failure may be difficult to assess, short of a pre-measurement test flight, since the motor still rotated the rotor, however, not at the intended RPMs. (2) Although circumstance will play a role, it may be wise to set a time limit on certain types of vehicle-specific troubleshooting, i.e., know when to cut your losses so you don't sacrifice subsequent measurement opportunities

ISSUE	POTENTIAL CONSEQUENCE	MITIGATION STRATEGY
Failure of Velcro-based GPS mounting solution on Edge 540 - did not hold properly during high speed events	Falling component could cause injury, cause UAV to lose control, or damage/lose equipment needed to perform measurements. Loss of GPS position information	Use custom-fitted hardware solutions where possible. Avoid reliance on tape/Velcro-based methods - use only as backup for redundancy The "Velcro" used was a newer design comprised of identical, stiff surfaces that interlock. The lack of flexibility to match rounded contours of some UAS may have been the main failure issue. This could have been avoided simply by test-mounting the instrumentation package on each of the test aircraft prior to measurement day.
Photo-scaling difficult due to small size of vehicles	When no GPS/on-board position information is available, we may need to rely on photo-scaling methods; the small size, low altitude passes have a high angular rate which makes accurately capturing the pass-by difficult	Multi-frame capture, enforce higher altitudes
Photo-scaling misses when altitude is off	Complete miss of aircraft if the altitude isn't 'as advertised' when shooting from the side (as opposed to under the vehicle)	Better altitude information so geometry of camera and flight path are known
No feedback of actual vehicle parameters. This is a modeling issue, not a certification or measurement issue	Little ability to model vehicle operations at non-test conditions	Full telemetry may be required – not trivial
No physical model or data for the vehicles. This is a modeling issue, not a certification or measurement issue	Little ability to model vehicle operations at non-test conditions	Include flight tests which will allow determination of physical parameters

Appendix C: TigerShark results memo

U.S. Department
of Transportation

Memorandum

Subject:	TigerShark noise flight test at Griffiss Airport	Date:	May 27, 2016
From:	David A. Senzig	Reply to Attn. of:	Volpe Center V-324 55 Broadway Cambridge, MA
To:	Dr. Mehmet Marsan Bruce Conze Gregg Fleming Christopher Roof		

Dear Dr. Marsan,

This memorandum documents preliminary results of the noise flight test conducted on the Navmar TigerShark UAS at Griffiss International Airport (KRME, http://www.ocgov.net/airport) in Rome, New York on May 17, 2016. This memorandum is intended to provide you with a preliminary summary of the data collected during the test; we intend to provide a full report after additional data processing.

Background

The TigerShark noise measurement was conducted with the support of Navmar (the manufacturer of the UAS), NUAIR (holder of the Certificate of Authorization for UAS operations at Griffiss), the Oneida County government (operator of KRME), and Mississippi State University (MSU).

The TigerShark is a fixed-wing, piston engine UAS with a MTOW of about 450 lb (https://nasc.com/Tigershark.php). For the noise test, the weight of the aircraft was reduced to 397 lb.

The noise test was conducted on the southeast end of the primary runway at KRME (runway 33). The area is grass covered, with no nearby obstacles. Staff from KRME mowed the grass before the test to a height of about three inches. The area conforms to the requirements of Title 14 CFR Part 36 Appendix G, Section G36.101(a). The noise test itself was conducted under conditions conforming to Section G36.101(b).

Acoustic Equipment

To conduct the acoustic measurements, Volpe staff used a system based on a Larson Davis 831 Sound Level Meter and a Sound Devices 744T digital audio recorder. All required instrumentation was calibrated before the test. The microphone was mounted on a ground plate in conformance with Section G36.107(a).

The location of the acoustic equipment was surveyed using a U-Blox NEO-M8T GNSS receiver; the data was post-processed using precise point position (PPP) methods of increasing the survey's accuracy. PPP methods increase accuracy by correcting for atmospheric properties and satellite clock biases observed during the survey.

Measurement Data

Navmar pilots conducted the flight test in conformance with Section G36.111 flight procedures. Nine simulated takeoffs flights were conducted for the Appendix G test; one flight was removed from the data set because its airspeeds at overhead was outside the V_Y ±5 knot criteria described in G36.111(a). All flights were conducted within the atmospheric absorption window of Section G36.201. The Appendix G measured and corrected maximum A-weight, slow response (Section G36.105(e)) sound levels for the seven acceptable passes are given in Table 1 below. The measured data were processed through a computer program which applies the corrections of Section G36.201. For this aircraft at the conditions of the test, only the distance correction (Section G36.201(d)(2)) was invoked.

Table 1, TigerShark Part 36 Appendix G noise test results

Pass	Altitude AGL (feet)	Measured L_{ASmx}	Corrected L_{ASmx}
19	781	85.2	82.8
21	656	86.1	82.6
22	726	86.2	83.1
23	746	86.3	83.5
24	768	85.5	82.9
25	726	84.9	81.8
27	776	85.4	82.9
28	696	86.3	82.8

The average of the noise levels for the eight passes is 82.8 dBA. The 90% confidence interval is ±0.28 dBA, within the limits of ±1.5 dBA required by Section G36.203. The noise level of the TigerShark is over the 70 dBA limit for aircraft of this weight as given in Section G36.301(c).

Please feel free to contact me if you have any questions or comments about the information contained in this memorandum. As mentioned above, a more detailed report containing additional analyses will be forthcoming.

Respectfully,

David A. Senzig, P.E.
USDOT-Volpe Center, V-324
617-494-3348
david.senzig@dot.gov

Appendix D: Part 107 Authorization

FAA FORM 7711-1 UAS PART 107 AUTHORIZATION Page 1 of 3
2017-ESA-224-P107 **Rev-1**

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

CERTIFICATE OF WAIVER OR AUTHORIZATION

ISSUED TO
David Senzig

POC PHONE NUMBER
617-494-3348

55 Broadway
Cambridge, MA 02142

This certificate is issued for the operations specifically described hereinafter. No person shall conduct any operation pursuant to the authority of this certificate except in accordance with the standard and special provisions contained in this certificate, and such other requirements of the Federal Aviation Regulations not specifically waived by this certificate.

OPERATIONS AUTHORIZED

Unmanned Aircraft Systems operations in accordance with Title 14 CFR Part 107.41, except "Operations for small unmanned aircraft" Part 107.51 b(2) are limited to the altitude listed below.
Class of Airspace: **B**
At or Below: **5**0 feet Above Ground Level (AGL)
With a radius of: **.91** Nautical Miles
Under the Jurisdiction of: **Boston ATCT**

LIST OF WAIVED REGULATIONS BY SECTION AND TITLE

NONE

STANDARD PROVISIONS

1. A copy of the application made for this certificate shall be attached and become a part hereof.
2. This certificate shall be presented for inspection upon the request of any authorized representative of the Federal Aviation Administration, or of any State or municipal official charged with the duty of enforcing local laws or regulations.
3. The holder of this certificate shall be responsible for the strict observance of the terms and provisions contained herein.
4. This certificate is nontransferable.

Note-This certificate constitutes a waiver of those Federal rules or regulations specifically referred to above. It does not constitute a waiver of any State law or local ordinance.

SPECIAL PROVISIONS

Special Provisions **1** thru **3**, inclusive, are set forth on page 2 of this authorization.

This certificate **2017-ESA-224-P107** is effective from **March 1, 2017** to **September 30, 2017**, and is subject to cancellation at any time upon notice by the Administrator or his/her authorized representative.

BY DIRECTION OF THE ADMINISTRATOR

FAA Headquarters, AJV-115
(Region)

Scott J. Gardner
(Signature)

February 6, 2017
(Date)

Acting Manager, UAS Tactical Operations Section
(Title)

FAA Form 7711-1 (7-74)

CIVIL PART 107 AUTHORIZATION, DECEMBER 1, 2016

SPECIAL PROVISIONS

1. **CONTACT INFORMATION:**

   David Senzig is the person designated as responsible for the overall safety of UAS operations under this Certificate of Waiver or Authorization. During UAS operations for on-site communication/recall, the Pilot shall be continuously available for direct contact at **617-494-3348** by **Boston ATCT** or designated representative

2. **SCHEDULE OF FLIGHT OPERATIONS:**

   a. This Certificate of Waiver or Authorization and the Special Provisions shall be in effect between civil **sunrise** and civil **sunset** local time.

   b. This airspace authorization does not relieve the remote pilots from the responsibility to check the airspace they are operating in and comply with all restrictions that may be present in accordance with see 14 CFR 107.45 and 107.49 (a)(2), such as restricted and Prohibited Airspace, Temporary Flight Restrictions, etc.

3. **EMERGENCY/CONTINGENCY PROCEDURES** - Lost Link/Lost Communications Procedures:

   a. If the UAS loses communications or loses its GPS signal, the UA must return to a pre-determined location within the operating area and land.

   b. The PIC must abort the flight in the event of unpredicted obstacles or emergencies.

ATTACHMENT 1

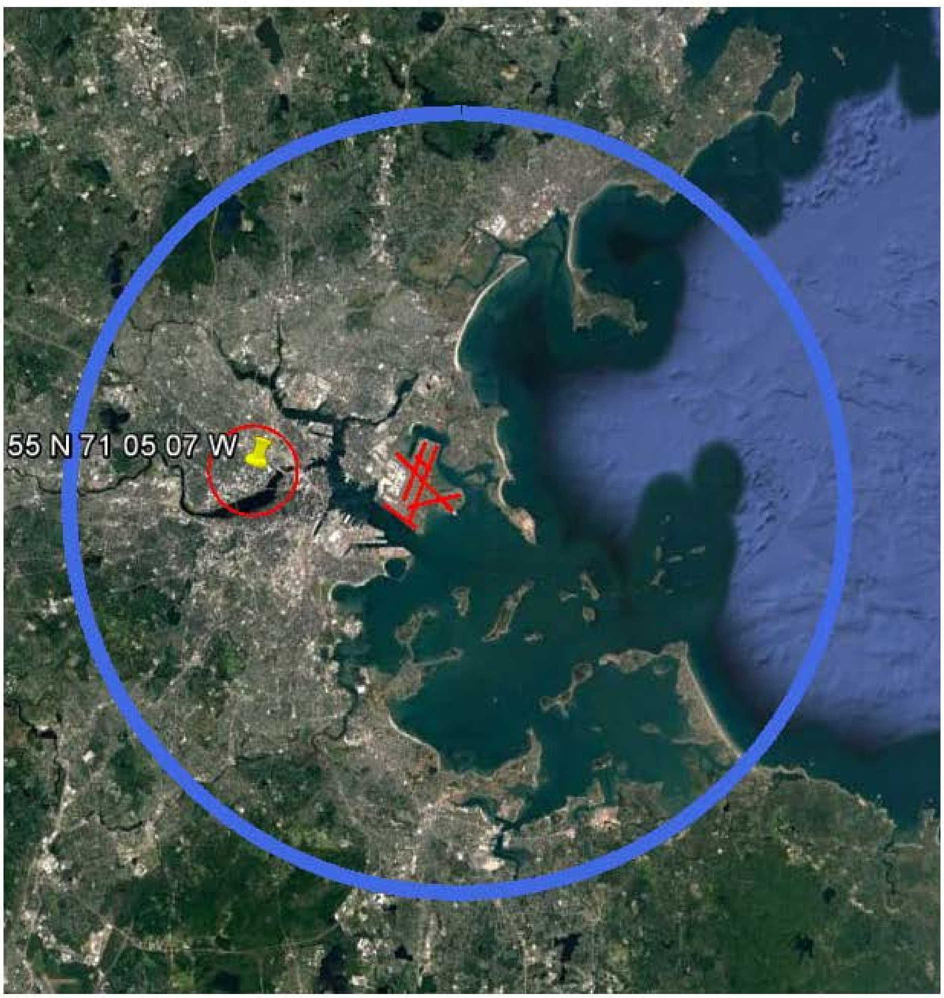
Operations Area

Class **B** Airspace

At or below **50** feet AGL

42 21 55 N, 71 05 07 W

.91 NM Radius



Appendix E: Minimum Distance and Position Accuracy Requirements

This appendix presents the derivation of the methods used to produce the minimum distance and required position accuracy graphics found in Section 2 in the body of the report.

The minimum distance methods use an assumption that the noise from the UAS must be greater than the ambient levels. A standard assumption in noise measurements is that the ambient levels are assumed to not contribute significantly to the total noise if the ambient level is 10 dB less than the maximum noise level. In this derivation, we will keep the ambient delta from the receiver noise as a general term: Δambient.

The minimum distance method starts with the standard acoustical spherical spreading equation:

$$\Delta dB = -10\log_{10}\left({}^{R}/_{R_0}\right)^2$$

R indicates the distance between the source and the receiver of the noise. R_0 indicates the reference distance. The squared term indicates that the sound energy changes as the square of the distance from the source – the energy per unit area drops as an inverse function of the surface area of the expanding sphere of sound: the surface area changes as a function of the radius squared.

The delta noise level is applied to a source at the reference distance, so the noise at the receptor microphone is:

$$dB\_UAS_{mic} = dB\_UAS_{ref} - 10\log_{10}\left({}^{R}/_{R_0}\right)^2$$

The dB_UAS_{ref} term indicates the UAS noise level at the reference distance. The dB_UAS_{mic} term indicates the UAS noise level at the receptor microphone.

Combining the ambient delta and the spherical spreading equation gives us an ambient level equation:

$$ambient\ level = dB\_UAS_{mic} - \Delta ambient$$

Or

$$ambient\ level = dB\_UAS_{ref} - 10\log_{10}\left({}^{R}/_{R_0}\right)^2 - \Delta ambient$$

A bit of algebra leads to an equation for R is terms of the other parameters:

$$R = R_0 10^{\left(\frac{dB\_UAS_{ref} - (ambient\ level + \Delta ambient)}{20}\right)}$$

This is the source of the curves in Figure 1: each curve represents a different dB_UAS_{ref} for a given reference distance R_0 (arbitrarily chosen as 20 feet) and the standard Δambient of 10 dB. The ambient levels are represented on the independent axis, and the dependent axis represents the resulting maximum distance from the UAS to the microphone for the given UAS noise levels. The upper curves are capped by the Appendix G limit of 500 feet.

Figure 2 is generated by using the Appendix G lateral offset limit of 10 degrees from a vertical plane passing through the microphone. This is discussed in more detail in Section 4 of Appendix A. We can quantify this angular limit as a function of the assumed distance and the actual distance between the UAS and the microphone – the actual distance is the same distance defined as R above:

$$\cos(App\_G\_angle\_limit) = \frac{Assumed\ Distance}{R}$$

The ratio of the difference between the actual and assumed distances to the actual distance is the accuracy ratio which is acceptable for a noise certification test.

$$Accuracy\ ratio = \frac{R - Assumed\ Distance}{R}$$

Using the distance R information already found, the equation for the acceptable accuracy in a UAS noise test as a function of the actual distance is:

$$Acceptable\ Accuracy = (1 - \cos(App\_G\_angle\_limit))R$$

In Figure 2 , the acceptable accuracy is referred to on the vertical axis as the required position accuracy of the UAS.

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DOT-VNTSC-FAA-18-01
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