Project 061 Noise Certification Streamlining

Georgia Institute of Technology

Project Lead Investigator

Prof. Dimitri N. Mavris
Director, Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Aerospace Systems Design Laboratory (ASDL)
Weber Space Science & Technology Building, Room 301A
275 Ferst Drive, NW, Atlanta, GA 30332
404-894-1557
dimitri.mavris@ae.gatech.edu

Dr. Michael Balchanos (co-P.I.)
Senior Research Engineer
Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Aerospace Systems Design Laboratory (ASDL)
Weber Space Science & Technology Building, Room 313B
275 Ferst Drive, NW, Atlanta, GA 30332
404-894-9799
michael.balchanos@asdl.gatech.edu

University Participants

Georgia Institute of Technology

- P.I.s: Dr. Dimitri Mavris and Dr. Michael Balchanos
- FAA Award Number: 13-C-AJFE-GIT-066
- Period of Performance: October 1, 2022, to September 30, 2023
- Tasks:
    1. Develop a traceable structure for unmanned aerial systems (UAS) noise certification requirements
    2. Formulate a library of UAS and testing procedures
    3. Document and model noise testing and certification procedures based on existing practices
    4. Develop alternative procedures and assess their performance with existing tools (proof-of-concept)

Project Funding Level

The total amount of current funding from the FAA for ASCENT Project 061 is $250,000 for a 12-month period of performance. The Georgia Institute of Technology has agreed to a total of $83,333 in matching funds.

Investigation Team

Georgia Institute of Technology

Prof. Dimitri Mavris, (P.I.), Tasks 1-4
Dr. Michael Balchanos, (co-P.I), Tasks 1-4
Dr. Jimmy Tai, (senior research engineer), Tasks 1-4
Dr. Evan Harrison, (research engineer II), Tasks 1-4
Balaji Ravikanti (graduate student), Tasks 1-4
Hussein Ali (graduate student), Tasks 1-4

Hajar Mali (graduate student), Tasks 1-4
Mika Xu (graduate student), Tasks 1-4
Nathnael Geneti (graduate student), Tasks 1-4

All team members are affiliated with the Aerospace Systems Design laboratory (ASDL), under the School of Aerospace Engineering at Georgia Tech. Please refer to Figure 1 for a breakdown of the Georgia Tech ASDL Team.

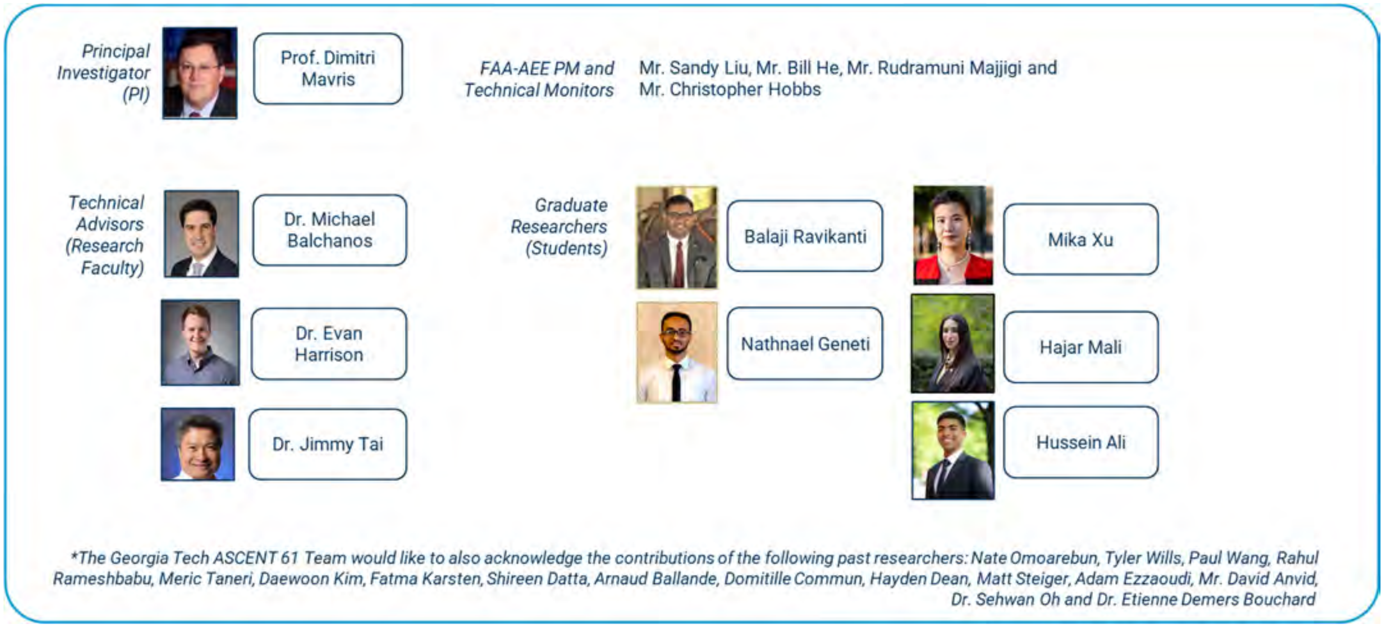


Figure 1. ASCENT Project 061 Georgia Tech Aerospace Systems Design Laboratory (ASDL) team.

Past technical advisors who contributed to the tasks:

- **Mr. David Anvid**, senior research engineer, provided guidance on best practices for noise certification testing, observed and articulated from an industry point of view.
- **Dr. Sehwan Oh**, postdoctoral researcher, focused on exploring current certification regulations, understanding their structure (hierarchy, associations, etc.) linked to Task 1, and providing input on the application of discrete event and agent-based methods as part of the efforts planned for Task 4.
- **Dr. Etienne Demers Bouchard,** postdoctoral researcher, focused on exploring process modeling methods from literature and formulating a canonical problem to assess the feasibility and applicability of various methods.

Former students who have contributed to the tasks:

- **Mr. Rahul Rameshbabu,** a third year PhD student, supporting activities in developing a parametric and interactive decision support tool.
- **Mr. Paul Wang,** a second-year PhD student, involved in the formulation of a model-based systems engineering (MBSE) verification model for UAS.
- **Mr. Daewoon Kim,** a second-year MSc student, is leading the team's MBSE efforts for representing the baseline certification process in systems modeling language (SySML).
- **Mr. Nathaniel Omoarebun,** a fifth-year PhD student, is supporting the team's MBSE efforts and SySML modeling activities.
- **Mr. Tyler Wills,** a second-year MSc student, is supporting the team's efforts in process improvement modeling (PIM) methods and process simulation.
- **Mr. Merc Taneri,** a second-year MSc student, is leading the team's efforts in PIM methods, stochastic process simulation (Markov chain Monte Carlo [MCMC]), and interactive visualization.
- **Ms. Shireen Datta,** an MSc student, supported efforts in documenting current procedures and exploring regulation-driven requirements, which are now included in the verification model.

- **Ms. Fatma Karsten,** a PhD student, worked on flight testing plan implementation and an effective perceived noise level (EPNL) calculation module within the MBSE verification model.
- **Mr. Arnaud Ballande**, an MSc student, worked on a process simulation capability for evaluating equivalent procedures under the PIM task.
- **Ms. Hayden Dean,** a PhD student, was instrumental in capturing and understanding current regulations and certification procedures, as dictated by the Title 14 Subchapter C, Part 21, and Part 36, as well as Part 36 Advisory Circulars (ACs), with a particular focus on AC 36-4D and an emphasis on guidance instructions regarding flight testing for noise certification.
- **Ms. Domitille Commun,** a PhD student, worked on implementing a discrete event simulation (DES) model-based process simulation capability for the certification baseline.

Project Overview

Noise certification procedures (with their inclusion of equivalent procedures) have served aviation stakeholders (original equipment manufacturers [OEMs], regulators, operators, airports, etc.) well since the 1960s (Metzger, 1970; Ollerhead, 1968; Senzig, 2018). With new vehicle types and new technologies (including new entrants, digital technologies for airframes, propulsion, and measurements, etc.), it is necessary to critically examine the existing certification processes. Key features of current certification practices include equivalent procedures and supporting technology, which many OEMs utilize (FAA, 2023). Equivalent procedures are anticipated for both existing and new standards to further accommodate innovation in the future.

The project objective is to examine current noise certification procedures and identify opportunities to streamline the noise certification process while recommending process updates for building the flexibility needed to accommodate all air vehicle types. Project 061 seeks to propose quantifiable process improvements and facilitate the application of traditional systems engineering for complex systems and MBSE, while leveraging these methods for the management of regulatory requirements. To perform the proposed research under this 3-year effort, Georgia Tech has teamed with several industrial partners with extensive experience in noise certification. Each industrial partner represents different types of vehicles, such as large subsonic transports, propeller-driven small aircraft, and rotorcraft.

The ASCENT Project 061 team is seeking to accomplish the following goals:

- Identify opportunities for increased efficiency (by expediting steps and simplifying processes) and flexibility in current noise certification processes to accommodate multiple vehicle categories.
- Formulate and evaluate revised noise certification processes for current vehicle types and offer recommendations to the FAA (Part 36, AC 36-4D, etc.) (FAA, 2017).
- Develop process modeling methods to enable quantitative assessments of noise certification.
- Facilitate the application of traditional systems engineering processes for complex systems and MBSE, leveraging these methods for the management of regulatory requirements.
- Leverage the technical expertise acquired in investigating and modeling noise regulatory frameworks and recommend procedures for certification testing and analysis to the FAA for small propeller-driven vehicles and UASs.

Overall ASCENT 061 roadmap and statement of work

An overview of the ASCENT 061 roadmap toward goals and milestones is shown in Figure 2.

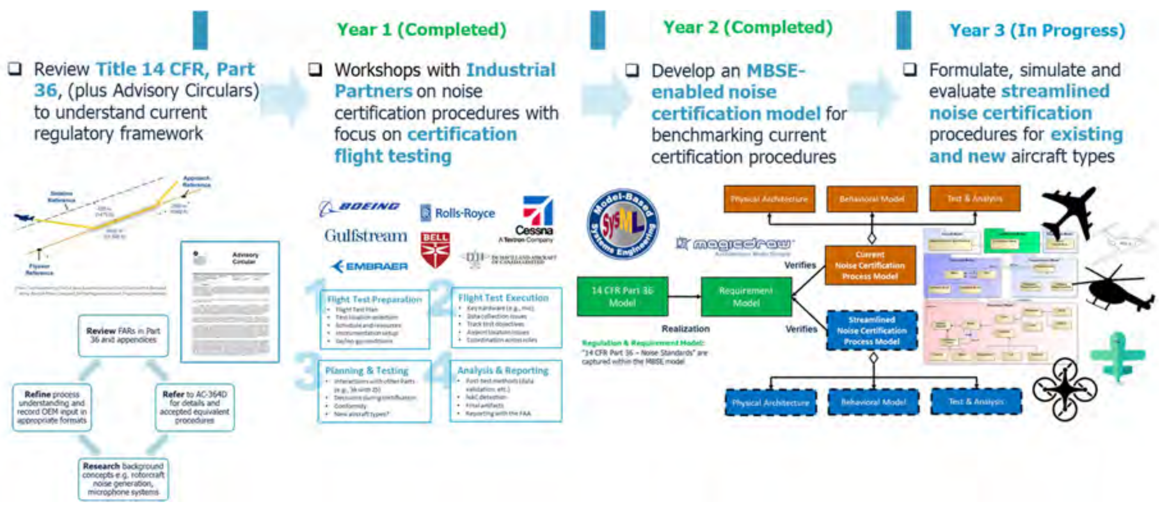


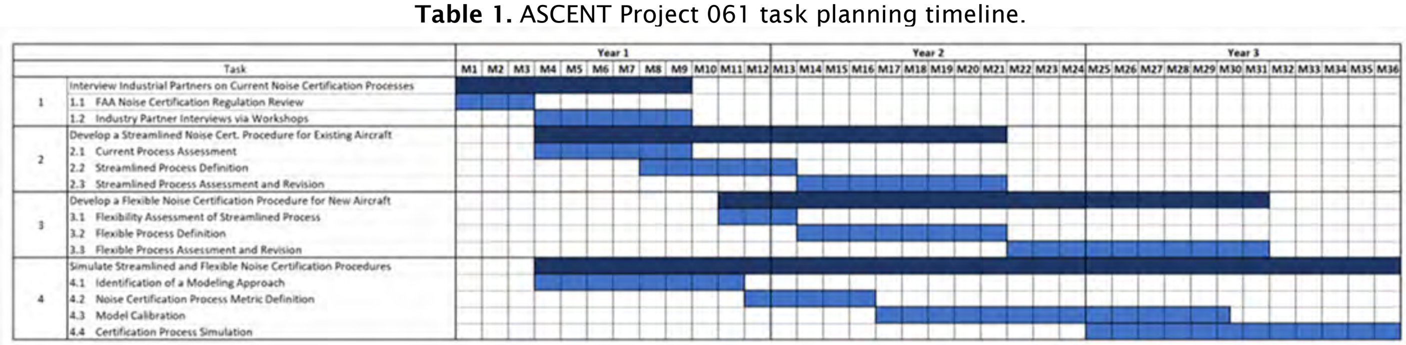
Figure 2. Roadmap toward a model-based framework for exploring current and streamlined noise certification. AC: advisory circular; CFR: Code of Federal Regulations; FAR: Federal Acquisition Regulation; MBSE: model-based systems engineering; NAC: non-acoustical change; OEM: original equipment manufacturer.

The main goal is to provide recommendations to the FAA in the form of feasible equivalent procedures, supported by the latest technologies/hardware, as well as analysis techniques to support the certification of future air vehicle types. These recommendations should be accompanied by evidence that the suggested equivalent procedures are fully in compliance with Part 36 (FAA, 2017) and use case examples for future air vehicles, e.g., small propeller-driven aircraft and UAS. To implement this roadmap and achieve the targeted outcomes, the team will engage in four main tasks, along with the subtasks that have been prioritized for Year 3 of ASCENT 061. These tasks are summarized below.

- Task 1: Develop a traceable structure for UAS noise certification requirements.
- Task 2: Formulate a library of UAS and testing procedures.
- Task 3: Document and model noise testing and certification procedures based on existing practices.
- Task 4: Develop alternative procedures and assess their performance with existing tools (proof-of-concept).

For the full three-year period of performance, the complete timeline for finalizing all Project 061 tasks is shown in Table 1.

Table 1. ASCENT Project 061 task planning timeline.



Pivoting to UAS category for ASCENT 061 Year 3

The FAA's Office of Environment and Energy (AEE) has suggested a timeframe for pivoting to UAS category certification. The main task for the Georgia Tech team is to investigate the feasibility and applicability of current ASCENT 061 models and analysis tools for exploring procedures and flight test planning to support noise certification of small propeller-driven UAS. The primary issue with UAS certification is that the spectrum of possible and available configurations covers a large class of aerial systems with completely different characteristics, as shown in Figure 3.

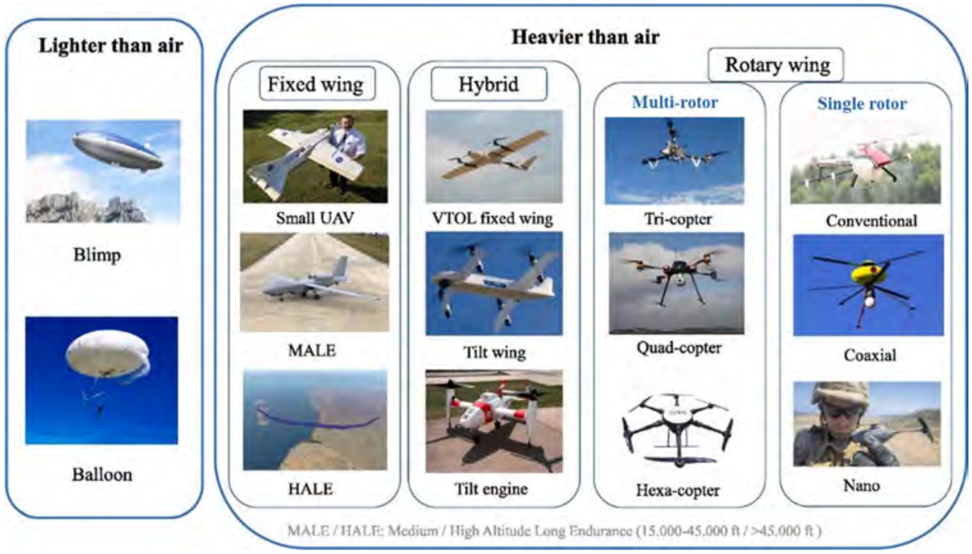


Figure 3. Overview of unmanned aerial system concepts. UAV: unmanned aerial vehicle; VTOL: vertical takeoff and landing.

It is assumed to be unlikely that UAS noise certification will be addressed as a "clean sheet of paper" process. Multiple efforts are underway to establish guidance for noise certification, similar to that for the transport category. The International Civil Aviation Organization (ICAO) is the recognized authority for developing and establishing a global baseline for noise standards and stringencies. Although rulemaking by the ICAO may lag behind the efforts of individual countries, ultimately, the harmonization of certification requirements among national airworthiness authorities is desirable. Several iterations of the regulatory framework may be required before this target is achieved.

Goals and technical challenges

The high-level goals for this direction are to (1) recommend testing procedures for UAS noise certification and, through the proposed methodology, (2) ensure traceability between regulations, testing requirements, and certification procedures. The key challenges that have been identified and will be addressed by the Georgia Tech team are as follows:

- There is currently a large spectrum of UAS designs and configurations under testing for production. As the FAA is preparing to release guidance for UAS noise certification, it is important to determine whether the MBSE-enabled method developed under ASCENT 061 is sufficiently flexible to accommodate UAS testing actions and to help establish a workflow that meets current and upcoming regulations.
- As there are currently no general regulations and the application of current certification procedures is on a case-by-case basis (e.g., recently completed certification framework for the Matternet UAS), it is important to assess whether current testing procedures are effective for UASs.
- We must determine how the ASCENT 061 team can use the established framework to demonstrate its effectiveness in assisting the FAA through the assessment of Notice of Proposed Rulemaking (NPRM) plans, as these are being iterated before they become approved as part of the UAS noise certification standards.

General direction for Year 3

Putting this plan forward, the suggested starting point is to perform an inventory of existing certification practices for low maximum takeoff weight (MTOW) general aviation and propeller/rotor-driven aircraft (i.e., fixed wing and rotorcraft). Currently, the priority is to focus on UASs before urban air mobility (UAM), as the anticipated risks are expected to be higher for the latter. In response to this pivot, the following guiding actions have been set:

- Study current certification practices for noise for small propeller-driven airplanes (Code of Federal Regulations (CFR) Title 14, Part 36, Appendix G) and light helicopters (CFR Title 14, Part 36, Appendix J).
- Perform a literature/technical review of noise source characteristics associated with propeller/rotor propulsion systems.

- Explore current practices for UAS flight testing for noise. The ASCENT 061 team has been encouraged to explore collaboration with ASCENT 077 researchers at Penn State regarding their research on "Measurements to Support Noise Certification For UAS/UAM Vehicles and Identify Noise Reduction Opportunities."
- Utilize the team's current MBSE-enabled certification framework to test current procedures for UASs and its overall flexibility to accommodate multiple aircraft categories.

As a starting point for the literature search, Appendices G and J are considered the only aircraft noise certification standards that might be applicable for noise certification of small unmanned aircraft systems (sUAS) in the United States, but a number of additional standards will be reviewed and included in formulating certification practices, including the following:

- ICAO Annex 16 Volume 1 Chapters 8, 10, 11, and 13
    - These are applicable to all fixed wing, rotorcraft, and tiltrotors below an MTOW of 3,175 kg.
- NASA Ref. Publication 1258, Aeroacoustics of Flight Vehicles: Theory and Practice Volume 1 & 2, August 1991.

Statement of work/task definitions for UAS noise certification research

Following the reassigned focus on UAS certification, the original task definitions that had guided the work on transport category aircraft noise certification required a review. An updated statement of work (SoW) has been formulated to guide the pivot toward the development of use cases that address the FAA's needs for UAS noise certification. This SoW is based on the concept that the original tasking is substantially complete; thus, a significantly revised SoW is necessary to reflect the integration of UAS certification goals with the previously developed MBSE and PIM modeling. This development will entail the generation of multiple libraries that enable flexibility of use across a broader range of UAS configurations and support traceability between regulations, requirements, and elements of the library.

The tasks under the revised SoW are defined as follows:

Task 1: Develop a traceable structure for UAS noise certification requirements

1.1 Document related regulations and current standards.
1.2 Generate noise certification requirements from currently known and established regulations.
1.3 Define a validation process for noise requirements.

Task 2: Develop a library of UASs and testing procedures

2.1 Complete technical documentation of UAS configurations.
2.2 Complete technical documentation of UAS noise testing equipment.
2.3 Define UAS noise test plans.
2.4 Define possible simulation techniques.

Task 3: Develop a noise certification procedure based on existing practices

3.1 Transfer noise testing plans to the MBSE model.
3.2 Transfer noise testing data to the MBSE model.
3.3 Develop a full noise test plan.
3.4 Implement a validation process.

Task 4: Develop alternative procedures and assess their performance with existing tools

4.1 Develop alternative testing procedures using the elements library.
4.2 Transfer alternative procedures to the PIM.
4.3 Report on the performance of the alternative procedures.

Matrixing of parallel ASCENT project efforts

Within the topic of UAS testing and certification for noise, there are currently three related but unique ASCENT research efforts:

- ASCENT 077: Measurements to Support Noise Certification for UAS/UAM Vehicles and Identify Noise Reduction (Penn State University)
- ASCENT 009/094: Geospatially Driven Noise Estimation Module (Georgia Tech ASDL)
- ASCENT 061: Noise Certification Streamlining (Georgia Tech ASDL)

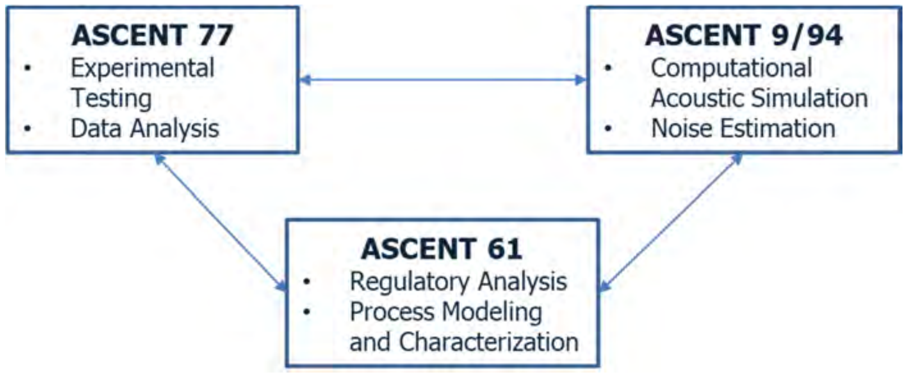


Figure 4. Coordination with parallel ASCENT work related to unmanned aerial system certification.

To preclude "mission creep" into other projects' remit and to leverage the work of the other ASCENT teams, the Project 061 team has been coordinating on a regular basis with Project 077 and Project 009/094 team members (as highlighted in Figure 4). The main collaboration areas are the following:

- ASCENT 77: Data sharing. Experimental test data provide real-world input for noise certification modeling. The results of the ASCENT 77 testing efforts provide a better understanding of the most significant parameters affecting UAS noise characteristics. The weighting of these parameters may influence modifications to the existing MBSE model.
    - Comparison of field geometry, test equipment, and basic flight profiles in addition to UAS configuration, weight, and vehicle performance
- ASCENT 009/094: Evaluation of possible vehicle operational environments and the practical impacts of noise profiles on the public. While the ASCENT 09/94efforts do not provide direct technical data for MBSE modeling, these efforts do provide context for how noise level outputs from the certification process may be applied to an operational environment.

Summary of major accomplishments to date

- Performed a literature search and documented regulations and current testing standards for small UAS (CFR Title 14 Part 36 Appendix G, J, and H, and recent NPRMs)
- Completed the **architecting of a noise certification modeling and assessment framework** for transport and UAS category aircraft.
    - Traceable structure for UAS noise certification requirements was created using the MBSE verification model developed for the transport category.
    - An implementation roadmap has been completed for the MBSE framework to accommodate multiple UAS types and to allow for process effectiveness and flexibility evaluation.
    - Scripts required to generate multiple noise metrics from raw frequency domain data were created.
- Completed **development of the PIM**, which has been applied to a typical plan for UAS noise testing demonstration example.
    - Metrics have been developed and the PIM has been integrated under a parametric interactive decision support environment.
    - Demonstrated the concept through a minimum viable project exercise; namely, a small-scale PIM using a DES approach through a deterministic modeling exercise.
    - Continued the development of a more comprehensive stochastic model using stochastic MCMC methods, formulated in a way that enables seamless integration into the verification thread within the MBSE framework.
    - Performed tuning of the existing PIM with automation and parametrization of user-defined input data to make the model representative of any desired process.
    - Applied the PIM as a demonstration example for a typical plan for UAS noise testing to better capture the process and properly estimate the cost, staff, and time implications.

- Formulated use cases that are aligned with needs and recommendations provided by OEM partners, with a focus on **exploring implications of alternative testing procedures on regulatory compliance** and highlighting the benefits of **process simplification** (e.g., lateral microphone placement or removal, if trusted analysis is used).
    - Preliminary analysis of noise measurement data was conducted, and resulting insights were utilized for requirement analysis.
    - Provided a demonstration by assessing a simplified noise collection/analysis process, with the Waco YMF-5 propeller aircraft as an example.
    - Documented options for equivalent procedures in a database/library compilation.
- Conceptualized and developed a **visualization environment** to aid as a use case demonstrator and decision support environment.
- Published articles with the American Institute of Aeronautics and Astronautics (AIAA) and for the SciTech 2023 and 2024 meetings.

In the following sections, key contributions are highlighted, along with detailed descriptions of technical progress, research approaches, key milestones, and accomplishments for each task.

Task 1 - Develop a Traceable Structure for UAS Noise Certification Requirements

Georgia Institute of Technology

Objectives

In support of the main research objective of Project 061, Task 1 focuses on examining current noise certification procedures (Task 1.1) and benchmarking against current industry practices in how these procedures are adopted and implemented (Tasks 1.2 and 1.3). In particular, the subtasks are organized as follows:

Task 1: Develop a traceable structure for UAS noise certification requirements

1.1. Document related regulations and current standards.
1.2. Generate noise certification requirements from currently known and established regulations.
1.3. Define a validation process for noise requirements.

Research Approach

Task 1.1

For Task 1.1, the main goal was to review and document current noise certification procedures. The task objective was to gain an understanding of the current regulatory framework for UAS noise certification, as required by FAA regulations and followed by OEMs to demonstrate compliance. In particular, the team conducted a thorough literature review of noise certification standards for multiple UAS that were issued by the FAA as Rules of Particular Applicability (RPAs), relevant 14 CFR parts (mainly Part 36), and associated documents where relevant. With recommendations from the team's partners, this task also considered other documentation from the European Union Aviation Safety Agency (EASA), the ICAO Environmental Technical Manual, and the Volpe website. Figure 5 illustrates some of the existing regulatory references that were explored during this process.

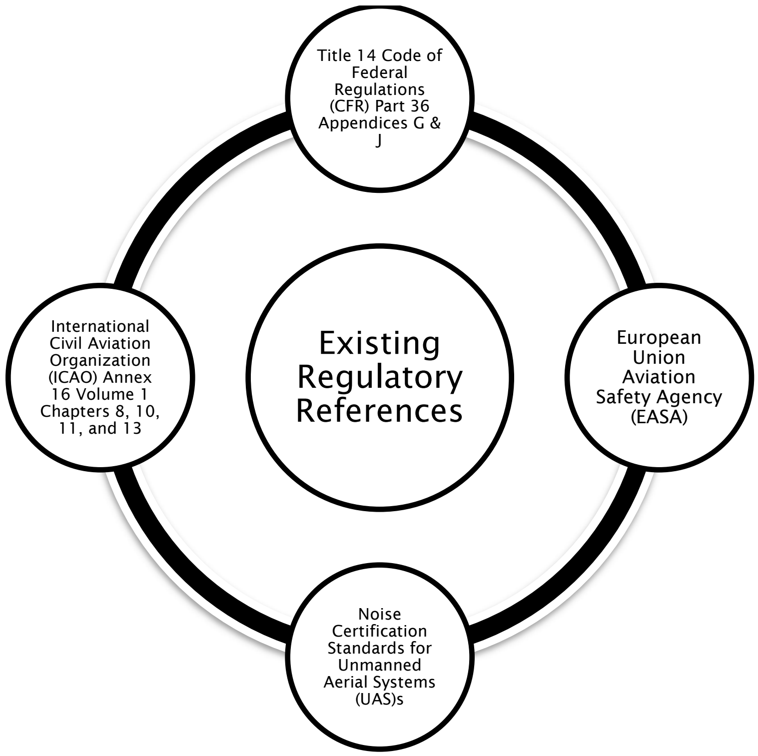


Figure 5. Existing regulatory references for noise certifications.

Along with the extensive review of Federal Acquisition Regulations (FAR) and literature on the regulatory framework, the team aimed to demonstrate the flow of procedures, associations, and dependencies across regulatory items. This was achieved by establishing a clear breakdown of regulations in a proper structural arrangement. Bendarkar et al. (2020) provided a structural hierarchy comprising four layers: part, subpart, grouping, and paragraph. The "part" layer is composed of the regulations provided by any of the sources presented in Figure 6. The "subpart" layer follows the "part" layer and pertains to the applicable body of regulations; therefore, it can be interpreted as the certification basis that constitutes the UAS noise certification standards RPAs. If a distinct group of regulatory statements is recognized, then it can be designated to a "grouping" layer. "Paragraph" is the lowest level in the hierarchy, and it contains regulatory statements.

Moreover, Fazal et al. (2022) constructed a regulatory framework identifying three main categories of regulatory statements: regulation requirement, regulation context, and regulation test. The categories are defined as follows:

- Regulatory requirements impose requirements on the applicant, aircraft, or specific systems/components. These statements often use the term "must" and provide specific standards or specifications.
- Regulation contexts include contextual statements that provide additional information within the regulatory framework, such as definitions or general specifications.
- Regulation tests consist of statements related to tests that must be undertaken by the applicant to demonstrate compliance with regulatory requirements.

Figure 6 illustrates the adapted structural hierarchy for the scope of this project.

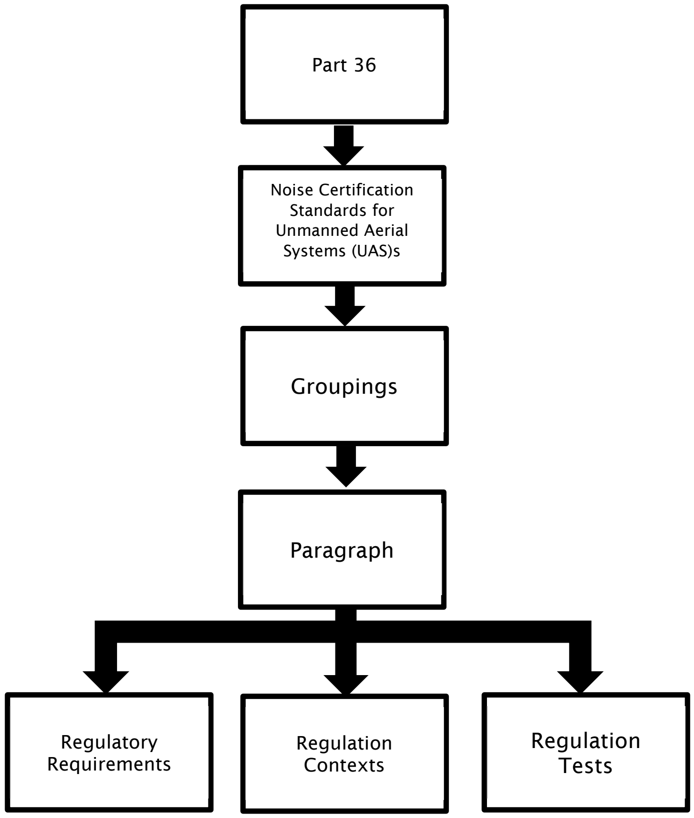


Figure 6. Structural hierarchy of noise regulations.

One of the benefits of this task's outcome is that team members quickly became more knowledgeable of the certification basics in preparation for Task 1.2 (defining requirements) and were able to build a comprehensive MBSE representation (in SysML) of the current framework (see Task 3.1).

Task 1.2

Defining and maintaining a good set of requirements is vital for the successful design, development, and operation of systems, products, and processes. It is also a crucial first step in creating the requirements model of the model-based certification framework (Kim, 2023). A requirement is defined as "a statement that identifies a system, product or process' characteristic or constraint, which is unambiguous, can be verified, and is deemed necessary for stakeholder acceptability" (INCOSE, 2006) . "Good" requirements are those having attributes such as necessary, unique, unambiguous, clear, concise, complete, consistent, technically feasible/achievable/obtainable, traceable, measurable/quantifiable, verifiable (e.g., testable), able to be validated, operationally effective, and survivable and singular as outlined by the Department of Defense (DoD) *Systems Engineering Guidebook* (2022). In addition, requirements can vary in their type, which encompasses functional, non-functional, design, performance, certification, etc. (Firesmith, 2005). For the purpose of the current work, the requirements are strictly regulatory "certification" requirements. Regulatory requirements are defined using the established certification basis, which constitutes the set of applicable regulations. The noise certification standards issued for the Matternet M2 Aircraft were selected as an initial starting point.

The FAA Writing Standards provide a useful guide for defining the requirements such that they will satisfy the desirable requirement attributes outlined by the DoD *Systems Engineering Guidebook* that are non-functional in nature (detailed in the next section). These standards include word choice such as using "must" instead of "shall," using short sentences and short paragraphs, limiting the use of abbreviations and acronyms, etc. (Federal Aviation Administration, 2003). While converting the regulations into requirements, the following considerations were considered (Kim, 2023):

- Not all regulations needed to be converted into requirements.
- A single regulation often needed to be broken down into multiple requirements. Conversely, multiple regulations were sometimes merged into a single requirement.
- The regulations do not always provide all the necessary information, so additional metrics and clarifying information were gathered from literature reviews and other regulatory documents.

Table 2 showcases five requirements that were extracted from regulation number 12 of the Matternet M2 noise certification standards.

Table 2. Regulation to requirements.

Regulation Section	Regulation Text	Requirements
12	(12) Level flight height and lateral path tolerances (Reference part 36, appendix J, section J36.105(b), as modified): A test series must consist of at least six flights. The number of level flights made with a headwind component must be equal to the number of level flights made with a tailwind component over the noise measurement station: (a) In level flight and in cruise configuration; (b) At the test height above the ground level over the noise measuring station as defined in paragraph (6) of this rule. For the selected height, the vertical tolerance of this height should be ± 10% value; and (c) Within ± 10 degrees from the zenith.	A test series must consist of at least six flights.
		The number of level flights made with a headwind component must be equal to the number of level flights made with a tailwind component over the noise measurement station.
		Each flight must be in level flight and in cruise configuration.
		At the test height over the noise measuring station, the vertical tolerance of this height should be ± 10% value.
		At the test height over the noise measuring station, the tolerance is within ± 10 degrees from the zenith.

Once the regulatory requirements are defined, regulation contexts and regulation tests will be used to refine the requirements by defining means of compliance and methods of compliance as demonstrated in Figure 7 for regulation 12(a). Means of compliance are defined as detailed design standards that ensure compliance with the regulations (Federal Aviation Administration Advisory Circular, 2017). Methods of compliance are more specific than means of compliance, and they describe how compliance will be demonstrated (e.g., ground test, flight test, analysis) (Federal Aviation Administration Advisory Circular, 2017). Once the methods of compliance are determined, all the required information for a certification plan can be consolidated, including the certification basis, requirements, means of compliance, and methods of compliance.

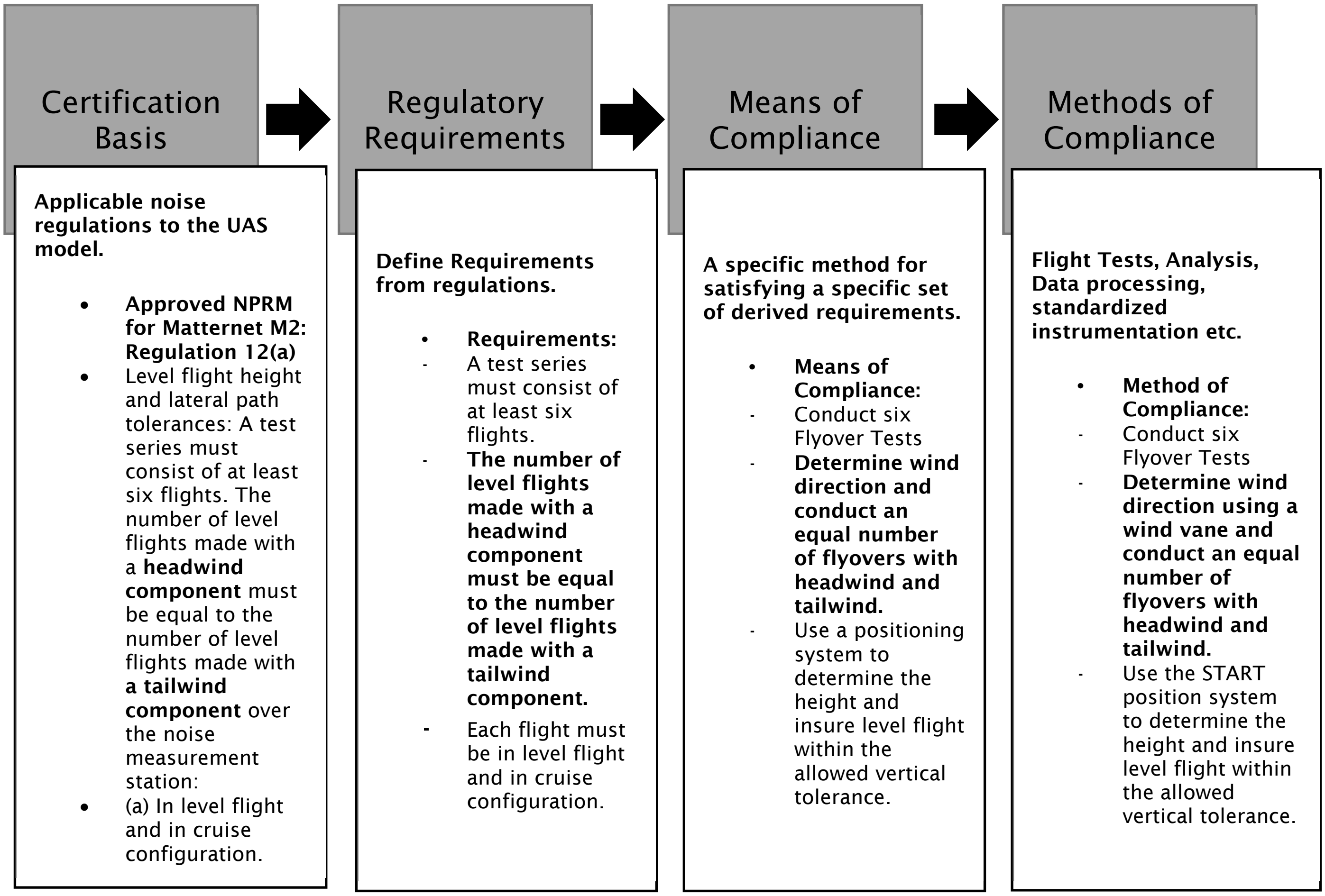


Figure 7. Certification basis to methods of compliance.

The complexity of this process becomes apparent by examining the intricate networks created between regulatory statements leading to the certification plan. MBSE can aid in nullifying this complexity by capturing the process of creating the certification plan in addition to other supplementary domain knowledge within one model that is the singular source of truth.

Task 1.3

Following the creation of the certification plan, it is imperative to check whether the regulatory requirements satisfy the desirable requirement attributes. The attributes can be classified into functional and non-functional categories, as illustrated in Figure 8. Functional attributes are concerned with the feasibility and technical adequacy of the requirements, whereas non-functional attributes are those concerned with language quality. Functional attributes require data for verification, unlike non-functional attributes. To this end, the regulatory requirements analysis process (outlined in Figure 9) provides a framework that allows for the verification of regulatory requirements' adherence to the desired requirement attributes. The outline indicates that once the requirements are defined, data need to be collected using the methods of compliance stated in the certification plan. Raw data are then processed by applying procedures such as correlating noise measurement data with position, calculating the required noise metrics such as sound exposure level (SEL), and applying the necessary data corrections (duration adjustments), etc. The processed data are then used to verify the requirements. Additionally, the requirements themselves can also be checked for functional attributes in the presence of available test data and experience. This is an iterative process, so there is a feedback element that allows for the refinement of the requirements such that it will satisfy the desired requirement features.

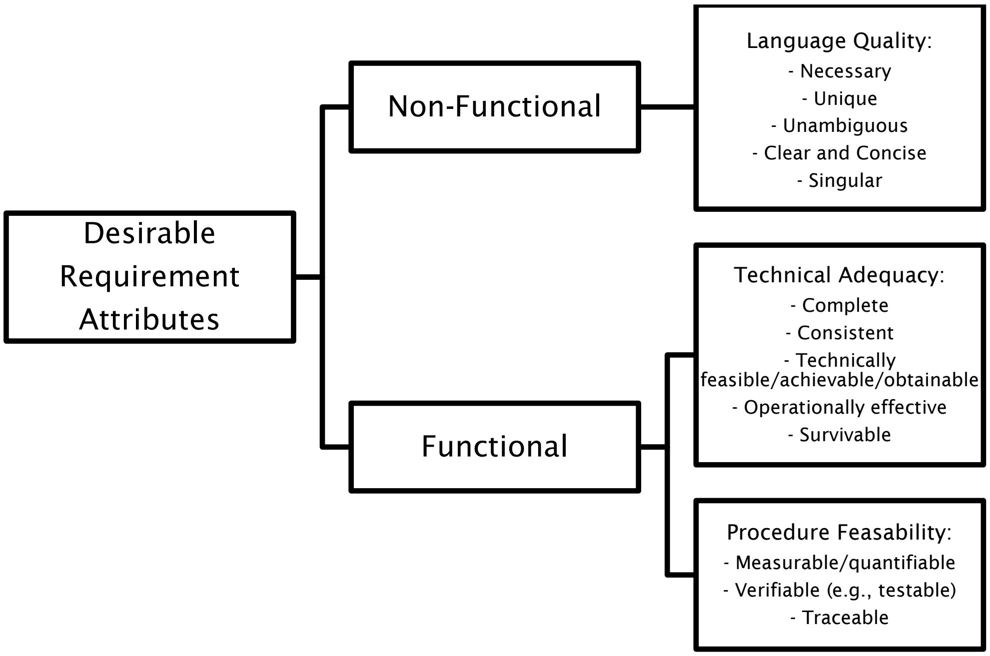


Figure 8. Attributes of desirable requirements.

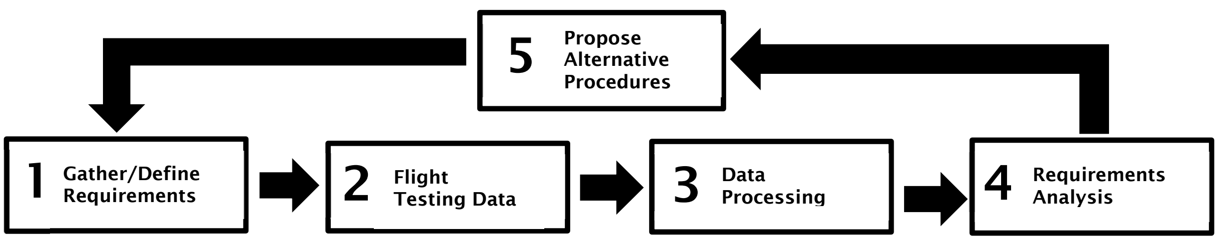


Figure 9. Regulatory requirements analysis process.

The iterative nature of the regulatory requirements analysis process dictates that if a requirement is deemed unsatisfactory or can be improved in terms of functional attributes, alternative testing procedures need to be proposed (as shown in Figure 9). These alternative procedures are meant to bridge the current gap that exists between current noise certification bases and UAS certification needs. Proposing alternative testing procedures will contribute to capturing the uniqueness of the UAS while also addressing the challenges associated with their certification (i.e., operational and noise metric limitations). The proposed procedures may include the use of different noise metrics, microphone setups, or additional flight tests that better capture the specific mission profile of the UAS. Such suggestions could convert to opportunities for potential process streamlining if recommended practices are out of sync with current procedures. The limitation in this exercise is that no recommendations should suggest or presume any change in the regulatory side; hence, the suggestions should be concentrated on equivalent procedures, with either simplified processes or connections to modern technologies that are expected to meet the same regulations.

The alternative procedures can be generated by identifying possible combinations in the morphological matrix shown in Table 3. The options provided by the matrix are surveyed from literature mainly FAA regulations such as the UAS Noise Certification Standards RPAs and Volpe UAS Testing Campaigns' noise measurement reports.

Table 3. Certification test procedure morphological matrix.

Morphological Matrix					
Flight Test Profile	**Flyover**	**Hover**	**Vertical Takeoff/Landing**	**Infrastructure Inspection**	**Maneuver**
Microphone Type	Ground microphone	Inverted ground microphone	Elevated microphone on a tripod	Elevated microphone on a crane (higher altitude)	-
Microphone Array Design	Linear (horizontal)	Circular	Vertical, elevated microphone array	-	-
Noise Measurement Metric	Sound exposure level (SEL)	A-Weighted maximum sound level (LAMAX)	Equivalent sound level (LAEQ)	Effective perceived noise level (EPNL)	-
…	…	…	…	…	…

The objective for generating alternative procedures is to explore options for formulating a streamlined certification process. The following target objectives for streamlining the certification process are currently being considered:

- Reduce the number of steps in the process, with anticipated savings in time and cost.
- Replace steps in analysis, data preparation, and post-processing with digital tools.
- Enhance automation on procedural tasks (e.g., data retrieval, queries, processing, and report generation).
- Simplify setup requirements to facilitate more test locations/weather windows.

Along with the selection of the equivalent procedures of interest, based on the above feedback, the outcome of this exercise is to present certain use cases for which a feasibility demonstration of an equivalent procedure would be possible. This effort would require data for calibrating the certification model against the system under test (SUT) configuration and for showcasing quantifiable improvements against the process criteria listed above, while meeting the same regulatory constraints and requirements as the benchmarked certification procedure. The quantitative assessment, which will be supported under the PIM module developed under Task 4, is the main enabler for allowing an iterative process until process alternatives can meet the expectations for process streamlining and simplification.

As mentioned above, the existing connections and synergies with other ASCENT projects are expected to provide the resources needed to support the demonstration of this framework as a platform for evaluating equivalent procedures.

Milestones

Between October 2022 and September 2023, the following milestones were achieved:

- Completion of exploration and assessment of NPRM (86 FR 48281) (FAA, 2022), which presents only the noise certification basis for one new model of UAS seeking type certification, the Matternet M2
- Review of the recently approved RPAs for noise certification of small UAS category vehicles

Major Accomplishments

- Performed a literature search and documented regulations and current testing standards for small UAS.
- Defined a traceable structure for UAS noise certification requirements, using the MBSE verification model developed for the transport category.
- Published articles with the American Institute of Aeronautics and Astronautics (AIAA) SciTech 2024.

Publications

Peer-reviewed journal publications

None.

Published conference proceedings

Ravikanti, B., Ali, H., Balchanos, M., Harrison, E. D., & Mavris, D. N. (2023). *MBSE-Enabled System Verification of Unmanned Aerial System Noise Certification.* Accepted and to be presented at the AIAA SciTech 2024 Forum, Orlando, FL, January 8-12, 2024.

Written reports

December 2022 ASCENT Quarterly Report, ASCENT Project 61. (2023, January 30). *Noise Certification Streamlining*. Award number 13-C-AJFE-GIT-066.

March 2023 ASCENT Quarterly Report, ASCENT Project 61. (2023, April 30) *Noise Certification Streamlining*. Award number 13-C-AJFE-GIT-066.

June 2023 ASCENT Quarterly Report, ASCENT Project 61. (2023, July 30). *Noise Certification Streamlining*. Award number 13-C-AJFE-GIT-066.

September 2023 ASCENT Quarterly Report, ASCENT Project 61. (2023, October 30). *Noise Certification Streamlinin*g. Award number 13-C-AJFE-GIT-066.

Annual Report (period ending September 2022), ASCENT Project 61. (2022, December 12). *Noise Certification Streamlining*.
Award number 13-C-AJFE-GIT-066.

Outreach Efforts

- Completed follow-up meetings with OEM partners for feedback on the certification model through spring 2022
- Completed a project overview and capability demonstration to Volpe and requested information for model finetuning
- Participated in conferences (ICAS and AIAA SciTech)

Awards

None.

Student Involvement

- All participating graduate students have supported Task 1 activities by contributing to the literature and background search and reviewing current regulations and FAA-instructed certification procedures.
- Recent efforts to document current regulations for UAS noise certification are currently led by Balaji Ravikanti.

Plans for Next Period

- Plan a series of workshops with partners and subject matter experts on small UAS category noise certification
- Demonstrate noise certification based on NPRM 86 FR 48281.
- Demonstrate an Equivalent Procedure (EP) assessment through certification modeling across different UAS configurations.
- Publish articles with *AIAA Journal* and AIAA SciTech.

References

Bendarkar, M. V., Harrison, E., Fields, T. M., Glinski, S., García, E., & Mavris, D. N. (2023). An Extended MBSE Framework for Regulatory Analysis of Aircraft Architectures. 2023 AIAA AVIATION. https://doi.org/10.2514/6.2023-3611

Fazal, B., Glinski, S., Harrison, E., Fields, T. M., Bendarkar, M. V., García, E., & Mavris, D. N. (2022). An MBSE Framework for Regulatory Modeling of Transport Category Airplanes. AIAA AVIATION 2022 Forum. https://doi.org/10.2514/6.2022-3256

Kim, D., Taneri, M., Omoarebun, E.N, Wills, T., Balchanos, M., & Mavris, D. (2023). MBSE-Enabled System Verification and Process Improvement of Transport Aircraft Certification. Accepted and to be presented In AIAA SciTech 2023 Forum, National Harbor, MD, January 23-27, 2023.

INCOSE (2006). SYSTEMS ENGINEERING HANDBOOK.

Department of Defense (2022). Systems Engineering Guidebook. https://ac.cto.mil/wpcontent/uploads/2022/02/Systems-Eng-Guidebook_Feb2022-Cleared-slp.pdf.
Firesmith, D. (2005). Are your requirements complete? The Journal of Object Technology, 4(1), 27. https://doi.org/10.5381/jot.2005.4.1.c3
Federal Aviation Administration (2003). FAA WRITING STANDARDS. https://www.faa.gov/documentlibrary/media/order/branding_writing/order1000_36.pdf.
Federal Aviation Administration Advisory Circular (2017). FAA Accepted Means of Compliance Process for 14 CFR Part 23. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_23_2010-1.pdf.

Task 2 - Formulate a Library of UAS and Testing Procedures

Georgia Institute of Technology

Objectives

Task 2: Develop a library of UASs and testing procedures

2.1. Complete technical documentation of UAS configurations.
2.2. Complete technical documentation of UAS noise testing equipment.
2.3. Define UAS noise test plans.
2.4. Define possible simulation techniques.

Research Approach

Task 2.1: Complete technical documentation of UAS configurations

Research tasks on investigating and archiving technical documentation of UASs, as well as recommended procedures for noise testing, started in July 2022. Due to the lack of historical data about the noise generated by most UAS models, the FAA is unable to provide generally applicable noise standards for UAS (Federal Aviation Administration, 2021). This insufficiency in data is caused primarily by the novelty and variety of UAS systems, such that no clear categorization of the systems is currently established. Figure 3 illustrates this problem by listing some of the different UAS configurations currently available.

The aforementioned problem is exacerbated by the various mission profiles of UAS systems and their different operating environments (Kim, 2022). As an alternative measure, the FAA issues RPAs for applicants who wish to certify their product for noise. To achieve this, the FAA assumes that the fundamental physics of UAS operation and noise are scalable if the UAS shares comparable characteristics with crewed aircraft. As a result, the current noise standards for crewed aircraft outlined in 14 CFR Part 36 can be applied to UAS or extrapolated for testing lower-weight UAS at lower altitudes. An example of this is the “Noise Certification Standards: Matternet Model M2 Aircraft,” which is the first RPA establishing a noise certification basis for a single model of aircraft described only for the Matternet Model M2 (Federal Aviation Administration, 2021). These RPAs alongside with the Volpe UAS Testing Campaigns’ noise measurement reports have been valuable for documenting the testing procedures and in identifying the most important technical challenges for UAS noise testing.

So far, depending on the availability of data, only multirotor UAS were encompassed within the scope of the provided analysis. This includes vehicles such as the Matternet Model M2, Tarot X8, and Flytrex FTX M600P. The three UAS are depicted in Figure 10. The Matternet Model M2 was issued the first RPA by the FAA in 2022; therefore, it was utilized for benchmarking efforts early on in the pivot toward UAS from the transport category. Tarot X8 is employed by the ASCENT 077 group for their noise measurement testing campaigns. Thus, in collaboration with ASCENT 077, a dataset was obtained from the testing campaign and was used to investigate the noise generated of Tarot X8 within the scope of the benchmarked regulations. Finally, the Flytrex FTX M600P is the SUT for the most recent case study under this project. Its noise certification standards were issued on July 3, 2023, and upon collaboration with the ASCENT 094 group, a dataset was obtained from the Causey Noise Measurement Testing Campaign that facilitated this case study. More details about the case study are provided in Task 4.

(a) Matternet M2

(b) Tarot X8

(c) Flytrex FTX M600P

Figure 10. Unmanned aerial systems (UASs) analyzed within this project

Task 2.2: Complete technical documentation of UAS noise testing equipment
Part of this grassroots effort in discovering the state of the art by looking at RPAs and Volpe UAS noise measurement campaigns' reports as well as collaborating with the ASCENT 077 group, is to generate technical documentation on UAS noise testing equipment. The equipment employed within a testing procedure includes everything from pressure sensors (i.e., microphones), to data recorders, weather data microstations, aircraft tracking systems, etc. This equipment will be supported by data measurement and collection software.

Microphones are the most critical element in noise testing. Figure 11 showcases three types of microphones that can be utilized during noise testing: ground microphones, inverted ground microphones, and elevated microphones. Ground microphones including the inverted ones, tend to minimize interference with directed or reflected sound, and reduce measurement uncertainty related to the microphone elevation; however, they tend to be relatively more complex to set up and more costly than the elevated microphones. In contrast, elevated microphones are simpler to set up and less expensive, but they suffer from interference with directed and reflected sound. All microphones utilized for noise measurement are outfitted with windscreens to ensure reliable acoustic measurements while minimizing noise due to weather variations (e.g., rain and wind) and birds.

The pressure fluctuations captured by the microphones are digitized via a data recorder. Data recorders are also used to power microphones, and they control the timing, synchronization, and data transfer between the input module and external host such as a computer. Moreover, meteorological conditions are continuously monitored during acoustic measurements. Weather data logging can be collected via weather microstations connected to anemometers and temperature/humidity sensors, as shown in Figure 12.

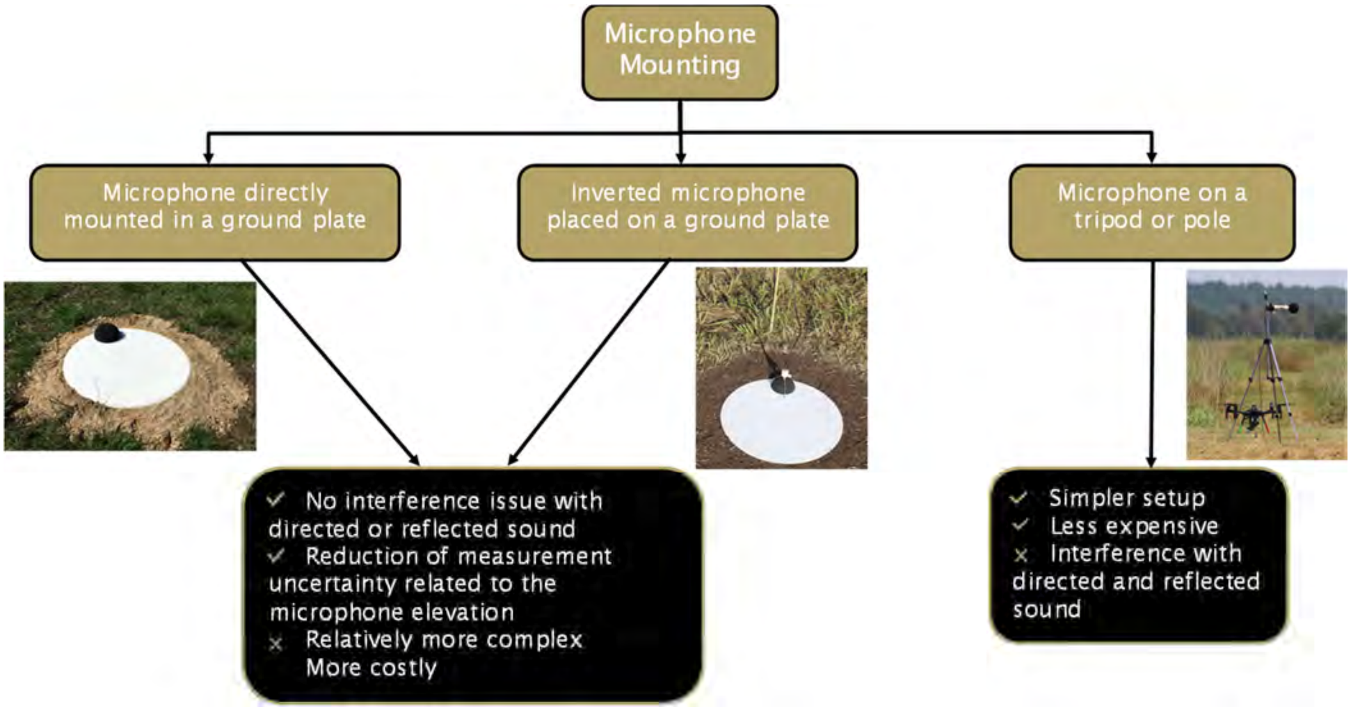


Figure 11. Microphone types and corresponding advantages and disadvantages.

Figure 12. Anemometers for Weather data acquisition equipment.

Time-space-position-information for the UAS within a noise testing procedure is captured by aircraft tracking systems such as the Survey and Tracking Apparatus for Research in Transportation (START) depicted in Figure 13. START is a tracking system developed by Volpe "for the purpose of deriving precise positioning and timing information from UAS and other automated platforms" (James, 2021).

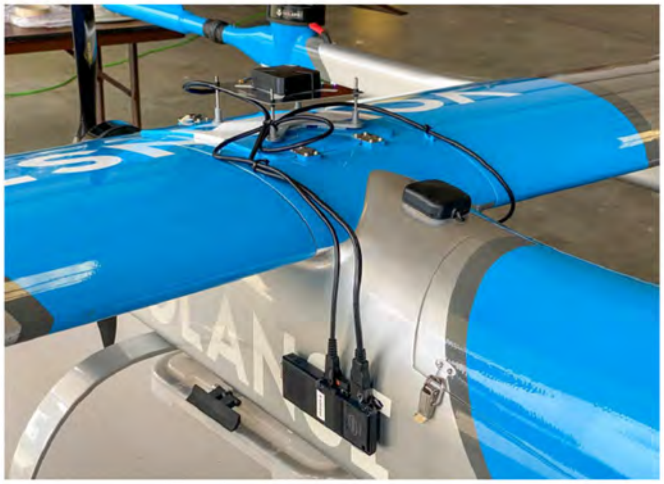


Figure 13. Survey and Tracking Apparatus for Research in Transportation (START) aircraft tracking system.

Task 2.3: Define UAS noise test plans
Research tasks on investigating and archiving technical documentation of UASs, as well as recommended procedures for noise testing, started in July 2022. One of the key studies that the ASCENT 061 team has started to document and that has been valuable in identifying the most important technical challenges for UAS noise testing is the document titled "Noise Measurement Report: Unconventional Aircraft" by the Choctaw Nation of Oklahoma (July 2019). The described practice for UAS noise testing took place on a grassland, which, taking the flight envelope into consideration, is not suitable due to the following reasons:

- Dense areas can have a different "perceived" noise.
- High altitudes and dense areas over buildings and hard surfaces can have different reflective behaviors.
- Within buildings, noise can be reflected, amplified, or attenuated.

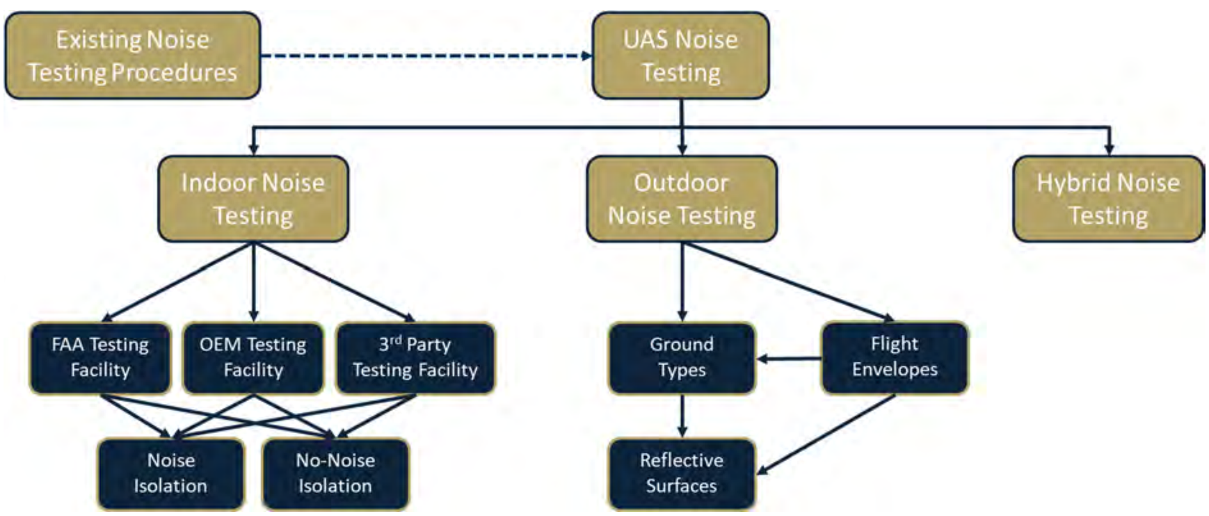


Figure 14. Alternative noise testing procedures for an unmanned aerial system (UAS). OEM: original equipment manufacturer.

Part of this grassroots effort in discovering the state of the art is the technical documentation on UAS noise testing equipment. By assessing testing procedures from a regulatory perspective, we can build some simple alternatives under the system verification model; examples are shown in Figure 14. Finally, the UAS noise test plans must be defined and executed. Physical testing will not cease to exist, but simulation techniques are needed for testing process alternatives.

A major part of the study for this cycle involved gathering available experimental test data to aid in understanding both the sensitivity of noise metrics to flight test parameters or test setup parameters and the times and costs associated with various sub-steps of a noise testing procedure. Note that the experimental noise testing campaign is more rigorous in many ways compared with the certification noise testing procedures. This enabled us to compare various microphone locations, flight conditions, and metrics, which is not possible when limited to the data typically available from certification-type noise testing procedures.

The experimental test campaign whose data was extensively utilized in this cycle of the study was the Causey test campaign. The objective of the testing campaign was "to gather data on UAS noise emissions in compliance with the UAS noise regulations specified in 14 CFR Part 135." Unlike other test campaigns, which may not be compliant with certification norms, the Causey campaign is explicitly meant to gather certification quality data. The report provides the acoustic measurements and resultant dataset. FAA, Volpe, and Blue Ridge Research and Consulting (BRRC) were the parties involved. Chris Hobbs (FAA) headed UAS flight operations, Robert Samiljan (Volpe) coordinated the vehicle tracking data collection, and Michael James (BRRC) managed the acoustic data collection.

Figure 15. Test vehicles of Causey testing campaign.From left to right, Flytrex FTX-M600P, Volansi VOLY C10 and DJI m210

Table 4 below lists the empty and maximum weights of the test vehicles shown in Figure 15 above. Vehicles performed flyover and hover operations for multiple flight conditions. The weight of the Flytrex FTX-M600P is comparable to that of the Matternet M2 (for which there is an existing recent noise regulation linked in references), which has a MTOW of 29 lbs, including a 4-lb payload. However, it is worth noting that the Flytrex is a hexacopter, whereas the Matternet is a quadcopter. An RPA for the noise certification of Flytrex FTX-M600P was approved recently, alongside six other vehicles of the same class. Flight conditions are derived based on various combinations of weight, speed, and altitude. Three groups of "test points" were conducted; namely, level flyover operations; hover operations; idle, takeoff, landing, or operational level flyover operations. The campaign took place from July 26 to July 29, 2021. Each day, a different vehicle underwent testing.

An additional day of Flytrex FTX-M600P measurements was conducted to capture new test points and repeat two flyover test points to account for day-to-day variations. The goal was to complete six repeated test flights of each condition; however, some test points were repeated more than six times, as will be discussed in later sections.

Table 4. Causey test campaign vehicle weights.

Weight	Flytrex FTX-M600P	Volansi VOLY C10	DJI m210
Empty	26.8 lbs	51.4 lbs	11.8 lbs
Max	33.4 lbs	55.0 lbs	--

Figure 16 below illustrates the Causey testing campaign layout. This view is later used in the visualization environment that is to host all the key details of a test procedure to enable effective decision-making.

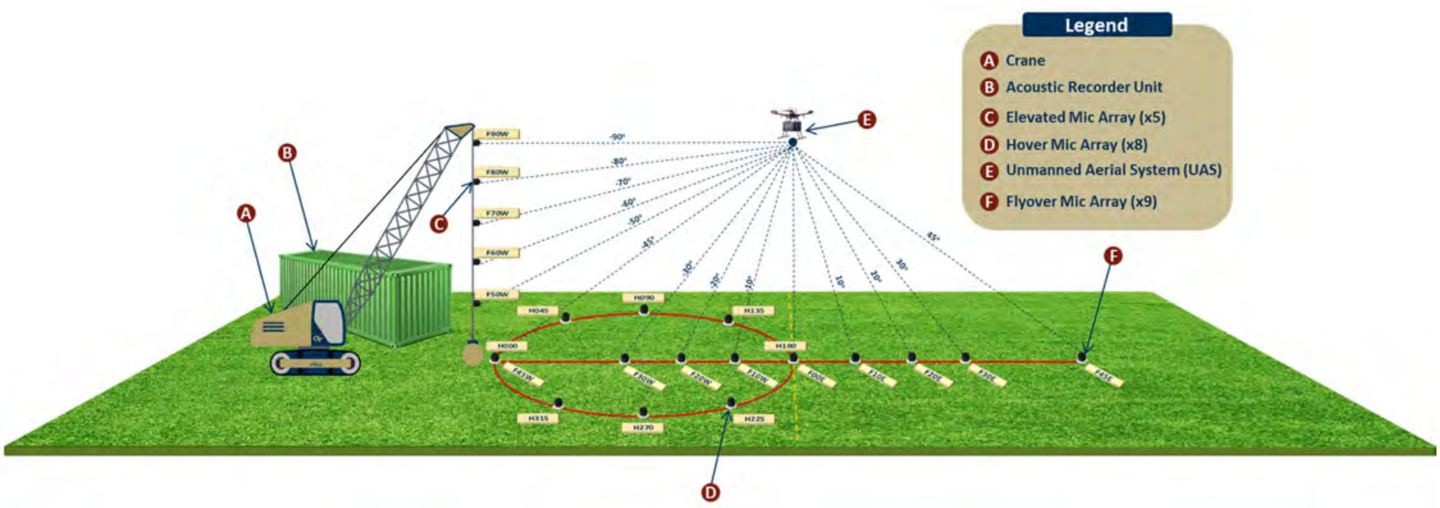


Figure 16. Causey test campaign concept of operations,

Task 2.4: Define possible simulation techniques

Within the scope of this project, MBSE was utilized to assess current noise certification procedures. Typically, MBSE methods are used to represent a vehicle's lifecycle and enable the use of data and information as an integrated systems engineering approach. In the case of Project 061, the product is a process architecture, within which current procedures will be assessed and equivalent procedures will be proposed, defined, implemented, and tested within this environment. The full MBSE model formulation for certification and implementation is showcased in Figure 17.

The validation process contains the steps needed to demonstrate that vehicle noise levels calculated from flight testing results are meeting requirements. Part of meeting the requirements is the instrumentation setup, which is implemented as a logical architecture within the model. A library of instrument model representations is also constructed, from which alternative instrumentation lineups can be modeled. The latter feature is key, as this framework should allow for the evaluation of equivalent procedures, e.g., ground microphone placement. Other components of the verification model are the test procedures and the test report checklist, which are prototyped as activity diagrams in SysML, as well as the vehicle configurations represented as a state machine.

Completing the verification model is any applicable regulation text in the form of a SysML verification thread. With the verification model in place, the user can import any UAS model, perform the certification equivalent process by executing the verification model, and then generate a final report, which would contain the instrument validation document and flight test plan. It is crucial that the overall framework be implemented in a highly modular fashion in order to obtain the needed flexibility for testing equivalent procedure alternatives and to accommodate a broader range of air vehicle designs and configurations. The SysML implementation currently comprises the following modules:

1. Requirement translation and constraints
2. Noise testing instrument architecture
3. Procedures, protocols, and behavior
4. SUT
5. System verification model overview
6. Auto-report generation and output to process evaluation model

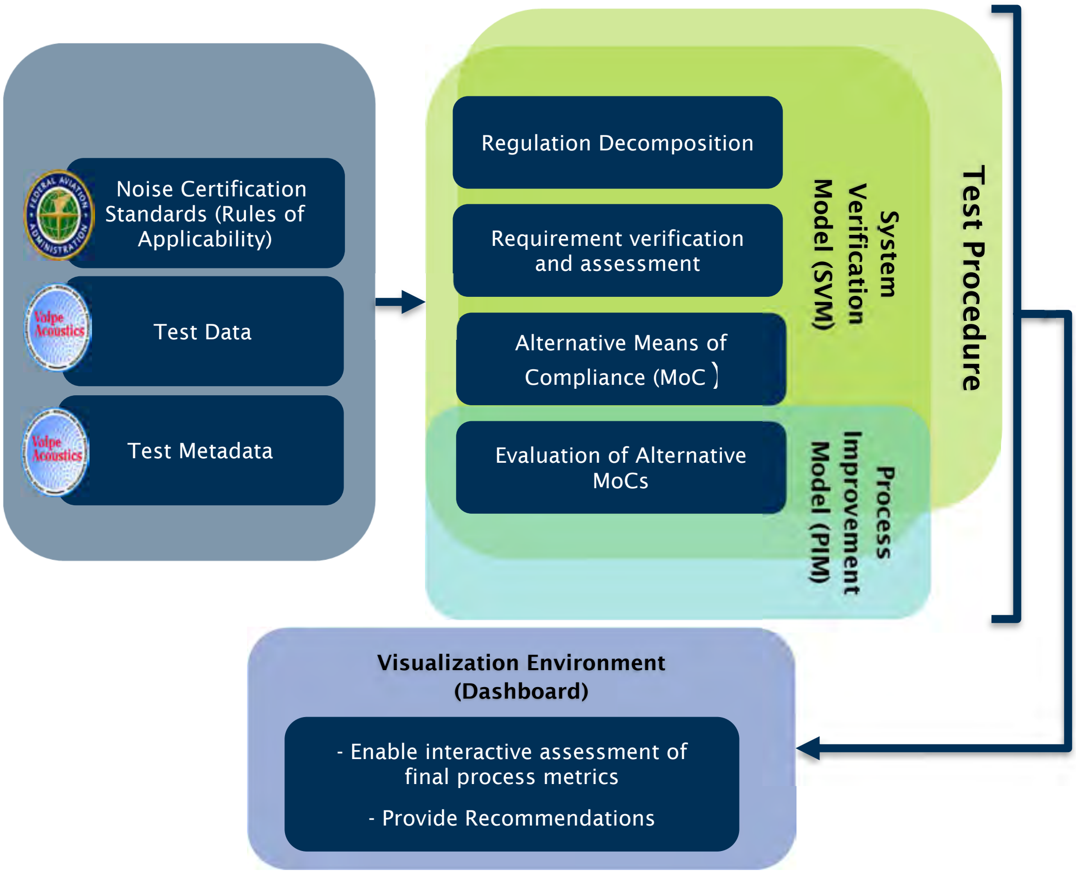


Figure 17. Model-based systems engineering (MBSE) verification model structure.

Event process modeling
With detailed guidance from the documents listed above, event-driven processes were defined and created within the certification model. Additions include modeling of the test-day acoustic collection process and test scenario event processes (flyover, hover).

Library creation
A new task was identified to command the creation of libraries within the certification model, to allow for added flexibility and modularity. Current libraries include the aircraft library, microphone library, and data amplifier library. The SUT representation has been modified to allow for adaptability to various UAS types and configurations.

Aircraft testing environment
Another finalized improvement on the certification model is the modeling of the UAS test environment, including the flight test setup configuration. With input from the documents such as RPAs and Volpe UAS noise measurement campaign reports, the model was updated and refined to include various instrumentation system architectures.

Noise calculation
UAS noise certification only requires a flyover test but also specifies a supplemental hover test to augment the process of collecting noise data that will inform the generation of generally applicable noise standards for UAS. The hover test, as described by the FAA in the Matternet M2 noise certification standards, is a voluntary test that “will not be used to inform the applicant’s airworthiness or type certification basis or be evaluated against any noise limits or regulatory criteria for noise certification purposes” (Federal Aviation Administration, 2021). So far, UAS RPAs have described two noise metrics

for noise measurements: SEL for the flyover test and equivalent sound level (L_{eq}) for the hover test (Federal Aviation Administration, 2021).

1. **Sound Exposure Level:**
SEL is energy averaged A-weighted sound level over a specified period of time or single event, with a reference duration of 1 second. SEL can be calculated using two methods defined as follows (Bennett & Pearsons, 1981):

1.1- Continuous time integration:

$$L_{AE} = 10\log_{10}[\frac{\int_{t_1}^{t_2} 10^{\frac{L_A(t)}{10}}dt}{1\ sec}]$$

where t_1 and t_2 define the time interval, and $L_A(t)$ is the time function of A-weighted sound level during the time for $t_1 - t_2$.

1.2- Temporal sampling:

$$L_{AE} = 10\log_{10}[\sum_{i=1}^{n} 10^{\frac{L_A(i)}{10}}\Delta t]$$

where $L_A(t)$ is the instantaneous A-weighted sound level for the n^{th} sample, n is the number of samples taken during the observational period, and Δt is the time interval between samples.

As mentioned previously, the UAS RPAs prescribe the use of SEL for the flyover test, in which they specify that the integration time $t_2 - t_1$ in practice must not be less than the time interval during which $L_A(t)$ first rises to within 10 dB(A) of its maximum value (L_{Amax}) and last falls below 10 dB(A) of its maximum value. In addition, the regulations allow for the use of an integrating sound level meter to obtain L_{AE} directly rather than manually calculating L_{AE} (Federal Aviation Administration, 2021).

2. **Equivalent Sound Level:**
L_{eq} is the level of the A-weighted sound energy averaged over a specified period of time. Similar to L_{AE}, it can be calculated by two methods defined as follows (Bennett & Pearsons, 1981):

2.1- Continuous time integration:

$$L_{eq} = 10\log_{10}[\frac{\int_{t_1}^{t_2} 10^{\frac{L_A(t)}{10}}dt}{t_2 - t_1}]$$

where t_1 and t_2 define the time interval, and $L_A(t)$ is the instantaneous A-weighted sound level.

2.2-Temporal sampling: $L_{eq} = 10\log_{10}[\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_A(i)}{10}}]$

where $L_A(t)$ is the instantaneous A-weighted sound level for the n^{th} sample and n is the number of samples taken.

UAS RPAs prescribe the use of L_{eq} for hover tests only. Similar to L_{AE}, the regulations allow for the use of an integrating sound level meter to obtain L_{eq} directly rather than calculating it manually (Federal Aviation Administration, 2021).

Before L_{AE} and L_{eq} are calculated, corrections must be applied to the measured data to account for uncertainties related to the measurement system, microphone and recording system used, background noise, actual flight path, and meteorological conditions present when the measurements were taken.

The use case described in Task 4 utilizes a python code to parse through the sound pressure time-history (audio) signals obtained from the Flytrex FTX M600P flyover and hover tests during the Causey UAS Acoustic Measurements campaign and calculate both L_{AE} and L_{eq} based on the equations above. Regarding the implementation of noise metric calculations, there is no option for directly performing such analyses within the SysML-based certification model. A possible solution is to create a function in Matlab and then incorporate the analysis in the verification thread.

Milestones

- UAS testing procedures from the literature were thoroughly reviewed.
- Useful test data were obtained from collaborators.
- Connections are established with OEMs and other research teams for further investigations.

Major Accomplishments

- Scripts required to generate multiple noise metrics from raw frequency domain data were created.
- UAS noise testing practices and processes have been documented.

Publications

None.

Outreach Efforts

- Full Year 2 performance review provided to the FAA AEE.
- Technical discussions and feedback provided by Volpe.
- Collaboration with ASCENT 077 and Dr. Eric Greenwood's research group and Flytrex Inc.

Awards

None.

Student Involvement

- All students participated in the collection and review of UAS noise testing practices and processes.
- Hussein Ali led the review of available noise testing data and the creation of scripts of noise metrics evaluation.

Plans for Next Period

- Identify use case examples to plan for demonstration, based on selected areas of improvement for alternative procedures and their evaluation

References

Federal Aviation Administration (2021). Noise Certification Standards: Matternet Model M2 Aircraft. https://www.federalregister.gov/documents/2021/08/27/2021-17769/noise-certification-standards- matternet-model-m2-aircraft.

James, M., Salton, A., Downing, M., & Calton, M. (2021). Blue Ridge Research and Consulting, Asheville, NC, tech.

Bennett, R., & Pearsons, K. (1981). HANDBOOK OF AIRCRFT NOISE METRICS (CR-3406). NASA.

"Noise Certification of UAS/AAM using Rules of Particular Applicability," Federal Aviation Administration, 2023. URL https://www.faa.gov/about/office_org/headquarters_offices/apl/aee/noise/uas_noise_certification

Task 3 - Document and Model Noise Testing and Certification Procedures Based on Existing Practices

Georgia Institute of Technology

Objectives

The focus of Task 3 is to develop an overall definition of a more flexible certification process and the evaluation criteria for determining that the procedure is more streamlined than the baseline. The pivot to a UAS focus is well aligned with the objectives of this task, where flexibility will be driven by the requirement for the MBSE model to accommodate a range of

UAS configurations and payloads. Task 3 will build upon the capabilities of the integrated MBSE platform and leverage contributions from all other tasks. The following subtasks will be conducted under Task 3:

Task 3: Develop a noise certification procedure based on existing practices

3.1. Transfer noise testing plans to the MBSE model.
3.2. Transfer noise testing data to the MBSE model.
3.3. Develop a full noise test plan.
3.4. Implement a validation process.

Research Approach

Tasks 3.1 and 3.2

Task 3.1 seeks to define what is meant by a "flexible" process. One way to develop this definition to determine whether the introduction of a different vehicle configuration leads to many incompatibilities with the streamlined process under evaluation. For instance, it is important to assess how the UAS configuration affects the microphone technology and quantity needed and the microphone placement in the testing facility. This subtask will involve testing procedures, and a mapping of compatibilities between vehicle configurations and testing procedures will be produced. A set of criteria and evaluation metrics is needed to assess the combinations of vehicle configuration, testing procedures, and uncertainty factors against regulatory-derived requirements, which will be implemented within the MBSE certification framework. Hence, a proposed set of flexibility criteria for the certification process could include the following:

- Compatibility and applicability of equivalent procedures
    - Alternatives in testing procedure should be accounted in the model so they can be verified; i.e., more microphones versus more flight test points.
- Complexity (e.g., if a switch to another configuration requires more steps to setup) and additional instrumentation if a vehicle is more sensitive to variations in certain factors during testing
- Sensitivity to weather, other aleatory uncertainties etc.

The defined criteria will be tested and applied in the following tasks; hence, this task is considered complete.

A regulation paragraph can contain both quantitative requirements and inspectional requirements. Quantitative requirements refer to those that contain numbers or a range of numbers to be met; inspectional requirements usually do not contain numbers but ask the test procedure to follow the instructions or guideline given in the paragraph. In the verification model, such paragraphs cannot be directly adopted but need functional breakdown. For quantifiable requirements, the subjects for which the quantified constraints are designed are identified and separated from each other for the convenience of validation. For an inspectional requirement, a straightforward number is not available to make constraint out of, but a simple yes or no test can be implemented to address the requirement. With the above modification logic, we use the function of the requirement diagram in MBSE to delineate each requirement within each regulation paragraph. The requirement diagram is constructed with two major components: requirement block and constraint block. A requirement block is a block that contains a regulation paragraph that contains a direct indication of requirements. A constraint block is a block that has quantified or yes/no constraints that actively test if the test data fulfill requirements.

Examples are given below to demonstrate both inspectional requirements and quantitative requirements. In MagicDraw, pink blocks are used for requirements and yellow blocks are used for constraint blocks. The requirement for mountings, as shown in Figure 18, specifies that to comply with the regulations, tripods or similar microphone mountings that minimize interference with the sound energy being measured should be used in the testing. There are no quantitative measurements about the microphones to be used; the comments are for its function. For this requirement, the constraint derived from it should stand for the testing of its qualification, thus the constraint block associated with it states that *Mountings_Test* must be 1, meaning it passes the test.

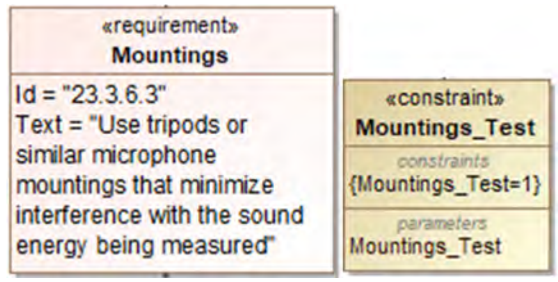


Figure 18. Example of inspectional requirements and constraints.

The requirement for audio signals recording specifics, as shown in Figure 19, details that sound pressure time-history (audio) signals obtained from aircraft flyovers under this paragraph must be recorded digitally at a minimum sample rate of 44 kHz for a minimum bandwidth of 20 Hz to 20 kHz, and encoded using a minimum of 16-bit linear pulse code modulation (or equivalent) during analog to digital conversion. This requirement paragraph mentioned three subjects to comply with the regulation, and for each, the specific quantitative requirements should be stated in the constraint block.

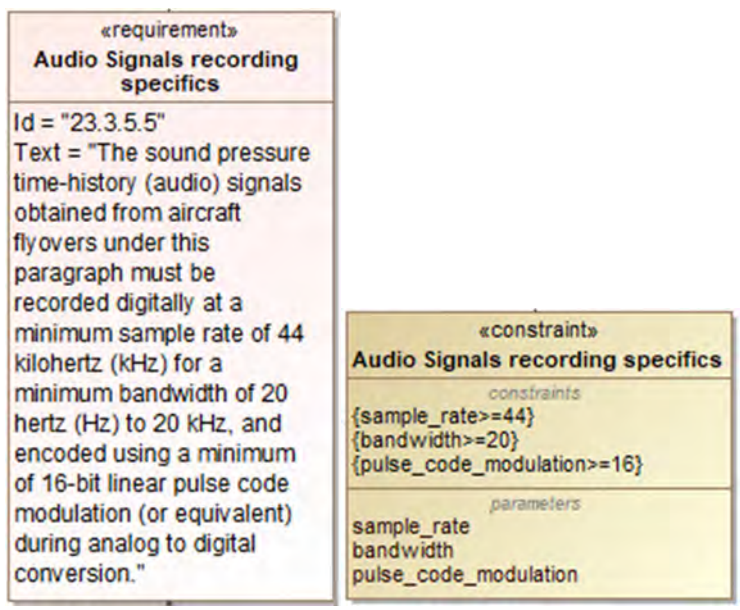


Figure 19. Example of quantitative requirements and constraints.

In the validation model, sections of the testing procedure are identified, and their chronological order is recorded. In the pre-test preparation phase, test site conditions, weather conditions, and multiple specifications on microphones (such as in calibration, how they are used in actual measurements, and what metrics should be embedded in the microphones) are to be confirmed to have met requirements. The testing part consists of two branches: flyover and hover, each having different sets of requirements. The constraint blocks will attach to the main sections of requirements like tree branches, each section will have several requirements blocks, and each requirement block will have several constraint blocks.

Based on the workflow proposed in Figure 20, the integrated framework for flexibility assessment of the certification process is expected to be reusable for a broader set of UAS configurations, as highlighted in Figure 21.

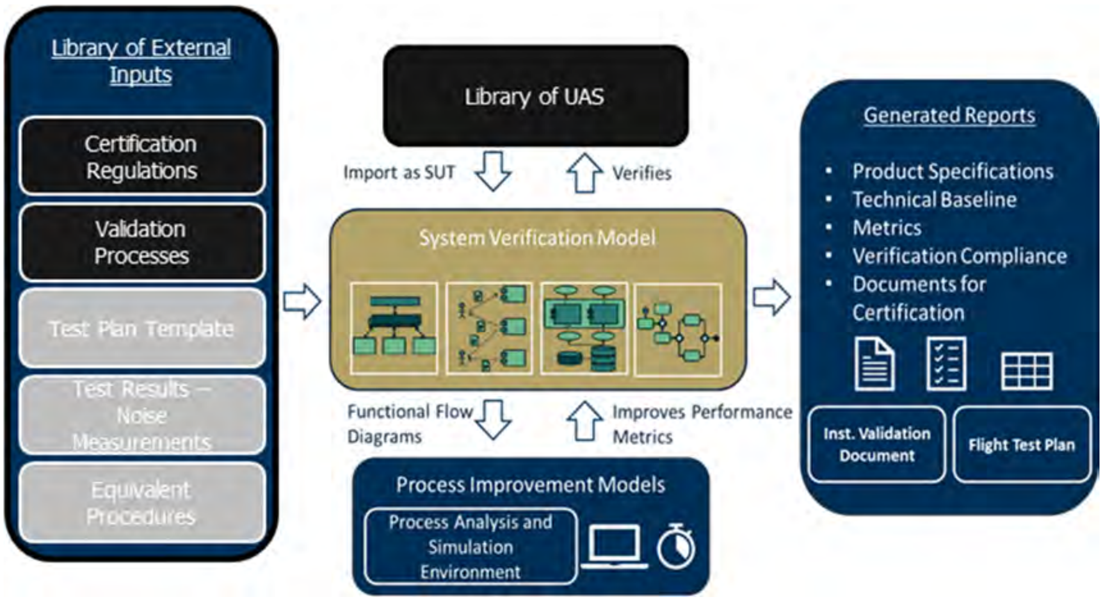


Figure 20. Model-based systems engineering certification framework version for unmanned aerial systems (UASs) to test category flexibility in equivalent certification procedures. SUT: system under test.

With the model, testing data can be validated against the requirements instantly after processing. For convenience of the users, data should be populated in the form of an instance table, aligning data to each corresponding constraint. The model validates data provided to each constraint instantly.

#	Name	lateral_distance	hover_height_0	lateral_distance	AGL_45	hover_height_9	radial_90
1	new_req_datapoint	3	4	1	2	7	2
2	new_req_datapoint1	3	3	1	1	2	1
3	new_req_datapoint2	2	3	3	4	4	4

Figure 21. Notional instance table.

Task 3.3

The certification framework for UASs developed under Task 3, as well as the use of the PIM completed under Task 4, will allow us to measure process flexibility, efficiency, complexity, and other figures of merit as part of comparing alternatives to the baseline. Framing this problem as a decision-making problem in this context, an "alternative" would be a version of the baseline certification process with a specific combination of a testing plan, instrumentation selection, and a setup for measurements and processing methods, as dictated by a possible equivalent procedure.

A typical flight test procedure can be divided into five major sections corresponding to 4 days of carrying out different activities or tasks (see Figure 22). These sections are not necessarily carried out over consecutive days as any two sequential sections can be separated by days, if not months, depending on the testing campaign and the scheduling and planning of the parties involved. These sections can be described in the following manner (see Figure 22 for the detailed steps for each day of the testing process):

1. **Test Site Inspection:** The team visits the potential test site to evaluate its suitability for conducting noise testing. This consists of assessing the site location and surroundings in terms of proximity to noise-sensitive areas, weather conditions, and levels of background noise, which could, for instance, include traffic, birds, construction noise, or sound reflections off nearby buildings. The type of ground surface is also important as it could influence the measurement results. Common ground surfaces considered can include grass, concrete, asphalt, and open terrain. Grass tends to be

the most preferred option due to its ability to absorb sound and reduce sound reflections compared to hard surfaces; however, this requires the grass to be well maintained and free from tall vegetation. The elevation and uniformity of the ground surface are also crucial to avoid measurement inconsistencies. The overall site area is also evaluated by checking whether it can properly accommodate the equipment installation and the distances and altitudes required for the flight tests. Following this inspection, the test site is either approved, if deemed appropriate for the testing requirements, or denied, if it does not meet certain criteria or would lead to test measurement complications or inconsistencies. The necessary permits for conducting UAS flights at the selected location and ensuring regulatory compliance are to be obtained.

2. **Test Site Preparation:** Once approved, a second visit to the test site is necessary to prepare for it before the actual flight test day. This consists of clearing the site of any obstacles or potential hazards, mowing the grass if needed, and marking the positions of microphones and other equipment, which requires having a clear flight plan for the specific flight paths, altitudes, and maneuvers to be performed by the UAS on the flight test day. The UAS to be flown is also inspected to ensure its proper functioning beforehand.

3. **Flight Test Day:** The flight test day can be further decomposed into three main action lists:

- Pre-test Procedure: All microphones, recording equipment, and other equipment are installed and deployed. Weather measurements are initiated, and microphones are calibrated and tested before the installation of windshields and the measurement of ambient noise. Throughout this procedure, multiple checks are conducted to ensure the proper functioning of all devices and adequate meteorological conditions for testing.
- Flight-test Procedure: Flight test profiles (flyover, hover, takeoff and landing, etc.) are initiated. Within each flight profile, multiple test points can be conducted under different conditions, including altitude, weight, and speed. To ensure the accuracy and reliability of measurements, each test point is repeated for a minimum of six test runs. After the completion of each test point, multiple checks are carried out to assess the need for microphone recalibration, maintenance, or battery change for the UAS, or a complete redo of the test point upon the detection of any anomalies or inconsistencies in the measurements.
- Post-test Procedure: Once all flight profiles are completed, the ambient sound is measured, the microphones are calibrated, all microphones and equipment are collected, and measurement data are saved.

4. **Data Analysis:** The data collected during the flight test day are post-processed and analyzed. Raw measurements are translated in terms of noise metrics of interest, and any sources of inconsistency or interference with the measurements can be revealed. Consequently, the need for replacement or additional measurements is decided at this step.

5. **Potential Additional Test Day:** Based on the results of data analysis, an additional flight test day might be necessary. This would either consist of a partial redo of some test measurement points or a full flight test redo if significant interference appears to have been present throughout the entire flight test day or throughout a major section of it.

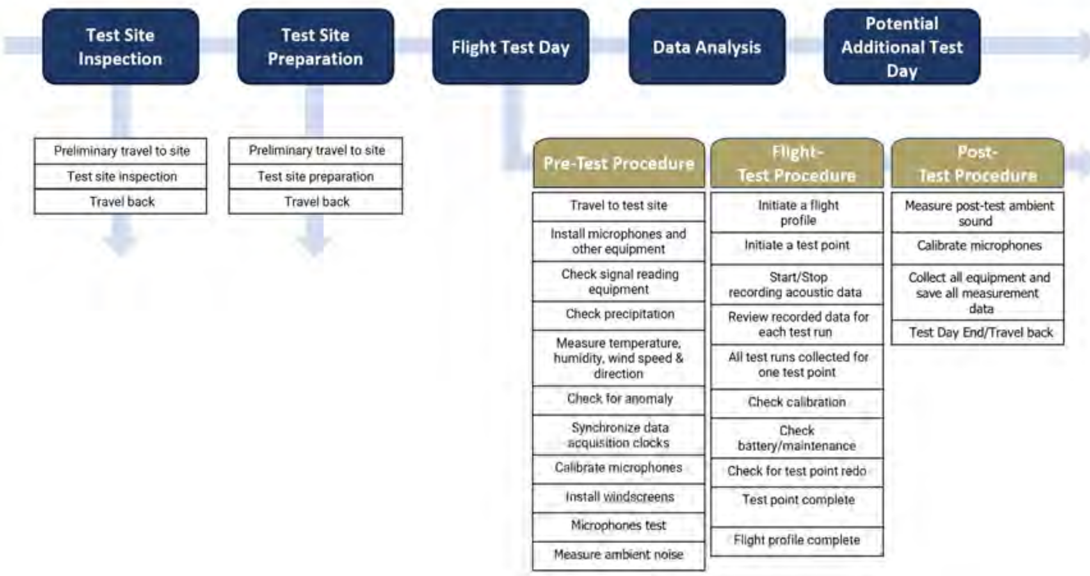


Figure 22. Flight test procedure layout for unmanned aerial systems (UAS) noise measurements.

After the model has been calibrated with inputs and parameter definitions that will be obtained from noise testing data resulting from ASCENT Projects 077 and 094, the model will rely on statistical analysis and an identification of process bottlenecks and showstoppers. Another set of metrics of interest will target the impact quantification of process complexities and will be used to indicate gaps and further drive certification process simplification through the use of technologies and estimation methods (e.g., virtual sensing and instrumentation), where process steps could be reduced or eliminated.

As a means of facilitating a scenario-based parametric decision-making capability, the ASCENT 061 team has been developing an interactive visualization environment. Through the use of visual representations of the process and key analysis outputs, this environment serves as a user-friendly interface for requirement validation, exploration of process alternatives and their impacts, detection of process shortcomings and gaps, and ranking for the selection of test plans, instrumentation, and noise measurement data analysis against user-set criteria. The ranked alternatives are validated through an assessment of the equivalency for a procedure to standard regulatory practices. A notional representation of the final version of this environment is shown in Figure 23.

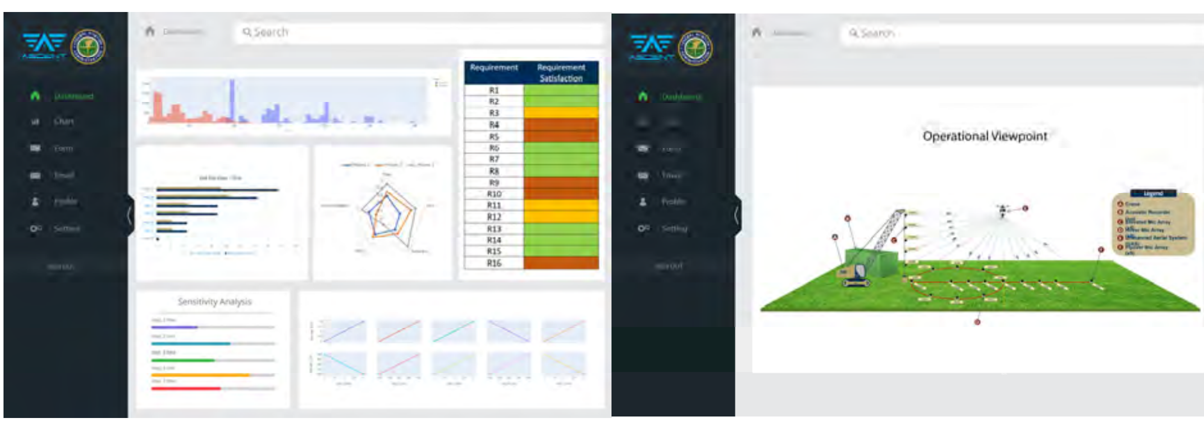


Figure 23. Graphical user interface for process specification.

As interactive dashboard development is often approached as a spiral development, the capabilities and features included in the current version are as follows:

- Histograms to visualize each metric of a given procedure. To compare procedures, it may be helpful to overlay the histograms for the respective procedures to visually compare time, cost, and so on.

- Sensitivity plots to help select from alternative procedures to improve upon the current baseline. These sensitivities can indicate how robust an alternative is to unforeseen variability in the procedure steps in terms of time or cost it takes to complete the step. For example, how sensitive the overall cost improvement (with respect to the baseline) of an alternative is to the cost it takes to complete the alternatives' first step. This information can be presented to the decision maker in the form of a matrix of plots like the prediction profiler plot in the JMP statistical software.

- For multivariate and multicriteria problems, a spider chart (radar plot) is used to compare process alternatives against multiple criteria. This chart can help to drive the evaluation of all tested process alternatives and map the strengths and weaknesses of each alternative against the prioritized evaluation criteria.

- The highest ranked process as a chain of events to rank order key steps identified by the PIM in the order of their importance for a given procedure.

- A requirements satisfaction section to present an assessment check on whether requirements are being met, which includes providing guidance toward the exploration of procedures and technologies that would help close any gaps and meet all requirements. In this part, the focus is on data analytics supported by Monte Carlo process simulations, using probabilistic inputs. Hence, the results are typically in the form of distributions for the metrics of interest and allow for exporting means, median values, and cumulative distribution functions to assess whether constraints and requirements are being met.

- A high-level concept graphic (OV-1) charts for physical representation of the test setup and easier communication with OEMs and decision makers as needed.

Using this visualization environment, decision makers can determine the feasibility of alternative procedures, compare alternatives relative to the baseline, and down-select between alternative procedures based on sensitivity to input values. On the actual model demonstrator, alternative procedures will be compared based on sensitivities. The sensitivity plots, along with the histograms and the complementary plots, will be used to select an alternative to the current baseline procedure that has the desired balance between mean performance, variability, and robustness in terms of relevant metrics such as overall time and cost of the procedures.

To enable the multicriteria, parametric, and interactive capability for rapid exploration of certification alternatives, the PIM, which executes a process simulation through Markov chains and graph analysis, can allow probabilistic Monte Carlo simulations for investigating the limitations of each process alternative. This capability is primarily the focus of Task 4 and is presented in the following section of this report.

Task 3.4

A particular instance to illustrate the analysis of alternatives proposed is regulatory paragraph J36.205(b) of CFR Title 14, Part 36, Appendix J, which prescribes the method of adjusting for test flight altitudes during flyover noise measurements that are off from the reference altitude prescribed in the regulatory paragraph J36.3(c). Figure 24 below (Figure 5 from Volpe test campaigns SEL Duration Adjustment Studies) shows that the higher the test flight altitude deviation from the reference altitude on which the correction curve is based, the higher the error that results from the adjustment. The test campaigns by Volpe evaluated these errors by means of the difference in adjusted noise measurement values and actual noise measurement values at various altitudes. So, possible alternative procedures to address this duration adjustment problem are as shown in Figure 25. Referring to the morphological matrix discussed earlier (Table 3; Task 1.3), an alternative procedure can emerge from any one of the procedural steps such as data processing methods, as in this particular use case. This again bolsters the need for a traceable platform that has the capability to conduct a holistic assessment of all potential certification bases.

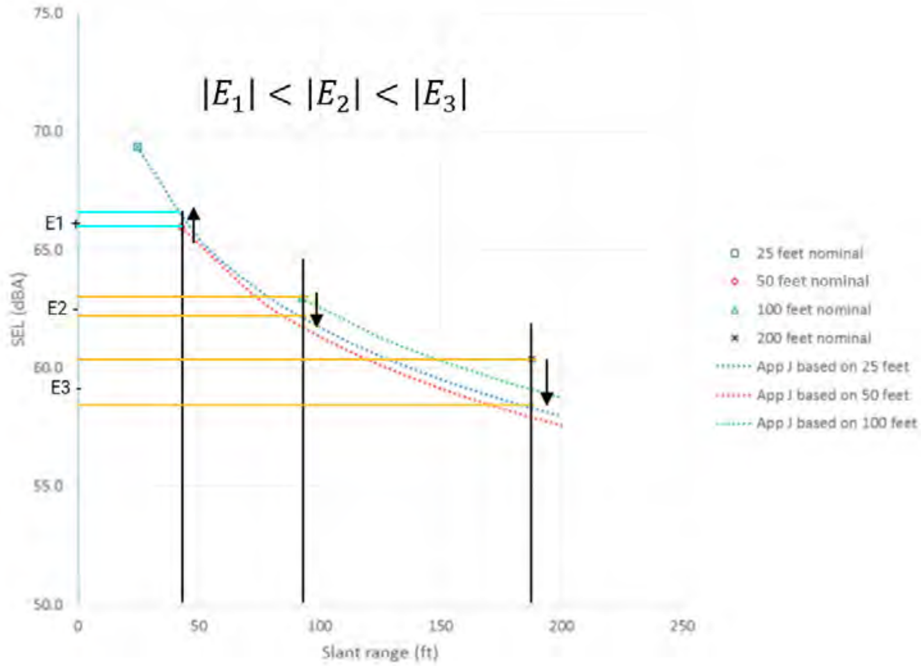


Figure 24. Appendix J duration adjustments applied to various altitudes (Figure 5 of SEL Duration Adjustment Studies).

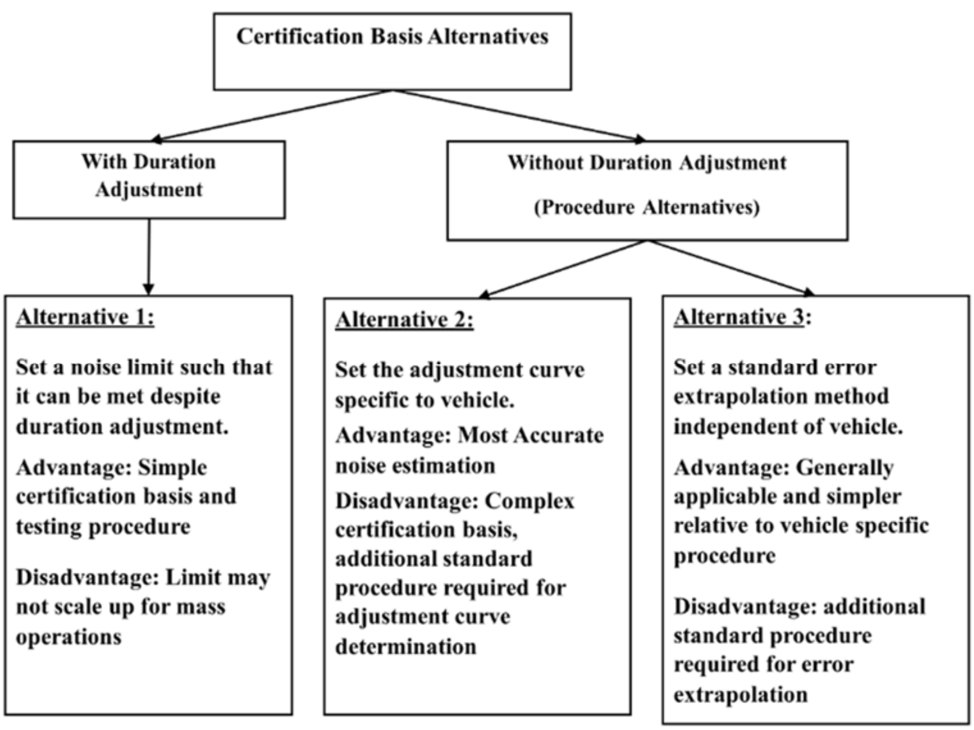


Figure 25. Alternative procedures to address the duration adjustment problem.

Each alternative procedure can have different ramifications on different paragraphs of a regulatory noise standard. Consider, for instance, the two alternatives illustrated in Figure 26 below for the hover test point. The variation of noise with respect to emission angles is represented using noise spheres in Cutler-Wood et al. (2022). Hence, noise standards such as those recently released by the FAA (UAS/UAM Rules of Particular Applicability) require applicants to measure and report noise levels in the test configuration shown on the left panel of Figure 26. The variability in the noise may necessitate several repeated runs to tighten the 90% confidence interval to ± 1.5 dBA (SEL) as required by the noise standards (UAS/UAM Rules of Particular Applicability). In the context of such requirements, the alternative on the right-side panel of Figure 26 may appear more efficient as one set of the necessary number of runs can potentially provide the noise measurement variation with respect to all emission angles. To determine the utility of the proposed alternative in the context of the measurement confidence requirement alone, it is necessary to know the effects of emission angle and flight profile parameters such as hover flight altitude and weight of the vehicle on the variability in the measurement.

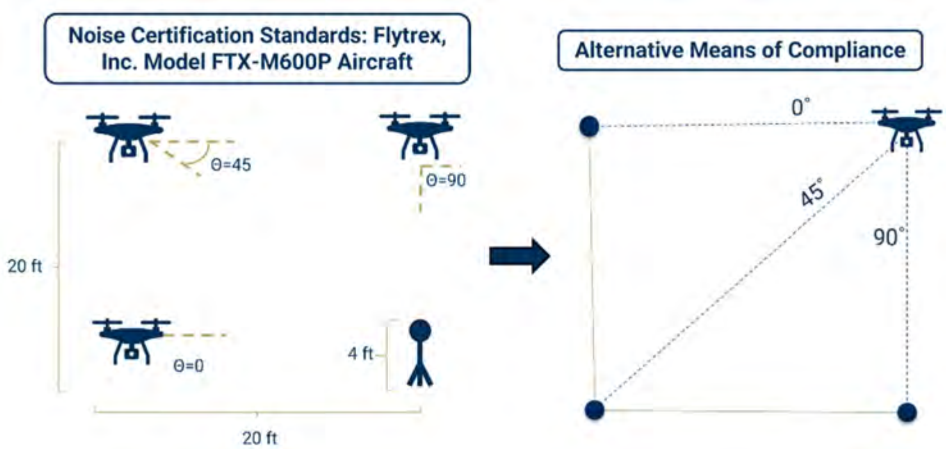


Figure 26. Alternative hover flight profiles (not to scale).

Figure 27 shows the microphone array configuration employed by the FAA and collaborating researchers to acquire noise data necessary to understand the effects. The vehicle deployed for the experimental campaign belongs to the small UAS category.

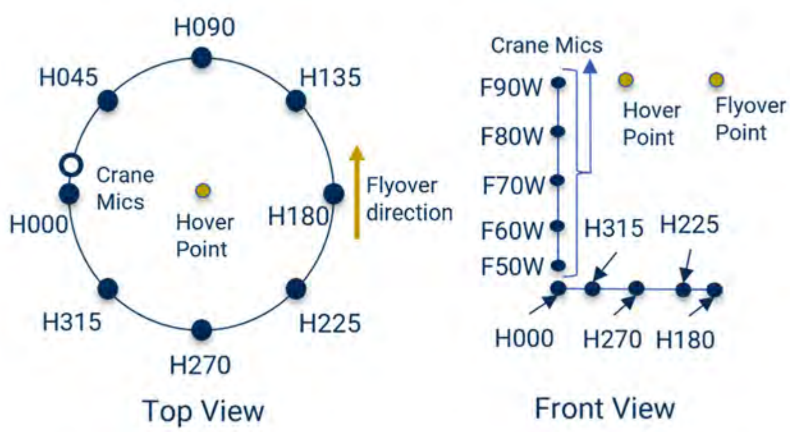


Figure 27. Experimental microphone array configuration (not to scale).

Experimental results consisted of higher-weight and lower-weight flights that were flown at 100 ft altitude and repeated five and six times, respectively. We evaluated the average confidence interval of SEL measurements of various subsets of a given number of repeats and plotted the results as shown in Figure 28. The figure highlights the effect that the weight of vehicle has on variability in noise measurement. We can observe that a higher weight configuration results in higher variability.

Figure 28, however, does not illustrate a strict relationship in emission angle and weight, and further investigation may highlight the same. We also observe that a greater number of runs is required to achieve a confidence interval limit of ± 1.5 dBA (SEL) at higher weight configuration.

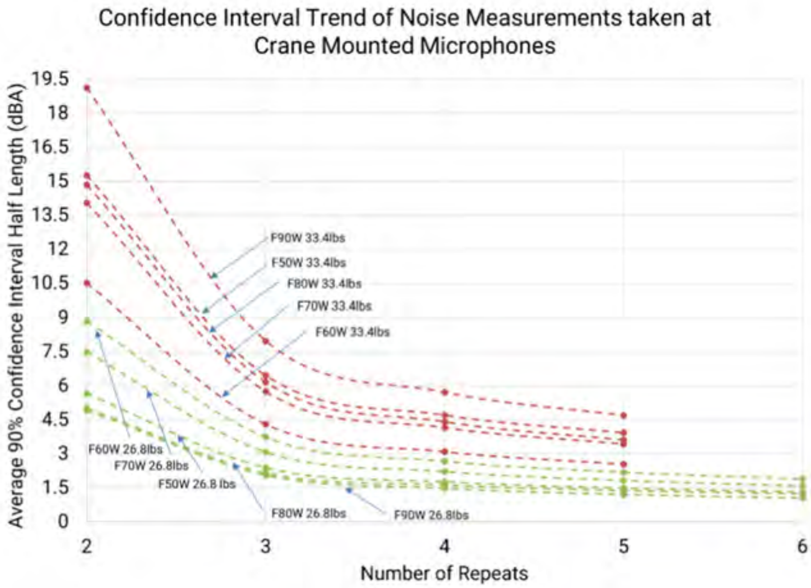


Figure 28. Effects of vehicle weight and emission angle on noise variability in hover flight.

Figure 29 shows the average confidence interval trends for a flyover flight condition that was repeated the highest number of times. Although this flight condition is different from the hover flight condition, it highlights the trend of the average confidence interval of SEL over a higher number of runs. Hence, we note that although fewer microphones are required for the alternative method in the left panel of Figure 26, the number of repeats required to achieve the confidence interval limit make the alternative method in the right panel of Figure 26 preferable. Ultimately, we need to compare the costs and times of additional microphones and their setup with those of additional flights to arrive at the right decision.

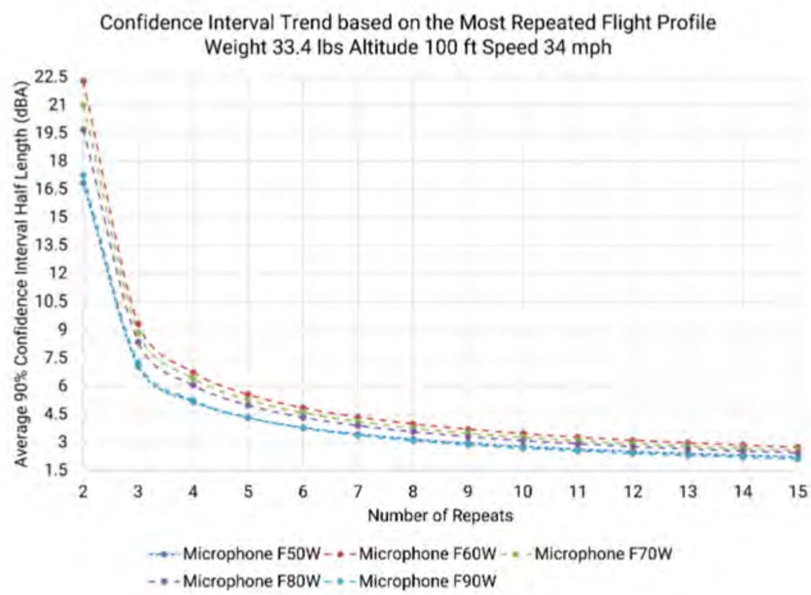


Figure 29. Effects of emission angle on noise variability in flyover flight.

Milestones
Please see the milestones under Task 1.

Major Accomplishments
- An initial concept formulation and implementation roadmap have been completed for the MBSE framework to accommodate multiple UAS types and to allow for process effectiveness and flexibility evaluation.
- Metrics have been developed and the PIM has been integrated under a parametric interactive decision support environment. The concept has been demonstrated through a minimum viable project exercise.
- The PIM is applied to a typical plan for UAS noise testing that has been formulated to better capture the process.
- Preliminary analysis of noise measurement data was conducted, and resulting insights were utilized for requirement analysis.

Publications
None.

Awards
None.

Student Involvement
- The full student team has participated in brainstorming sessions toward formulating the integrated certification process assessment framework for UASs.
- Mika Xu led the MBSE model building for the UAS noise certification.

Plans for Next Period
- Perform a morphological matrix exercise to explore and identify feasible certification process alternatives, based on permutations of UAS type, testing plan, testing and sensing technologies, data analysis methods, and map options for evaluation criteria.
- Finalize process evaluation metrics and incorporate them in the next iteration of the decision support tool.
- Demonstrate a simple use case, where a number of feasible alternatives lead to comparisons with the process baseline. The use case and the improvement propositions within the alternative options will be formulated with input from subject matter experts and current gaps in meeting certification targets.
- Conduct extensive analysis of the noise data available to inform regulatory rulemaking.

References
"PART 36—NOISE STANDARDS: AIRCRAFT TYPE AND AIRWORTHINESS CERTIFICATION," Federal Aviation Administration, 2023. URL https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-36.

Federal Register. (2022). *Noise Certification Standards: Matternet Model M2 Aircraft* (NPRM 86 FR 48281). https://www.federalregister.gov/documents/2022/09/12/2022-19639/noise-certification-standards-matternet-model-m2-aircraft.

FAA. (2022). *Noise Certification Standard: Matternet Model M2 Aircraft*. https://www.regulations.gov/document/FAA-2021-0710-0016.

Senzig, D. A., Marsan, M., Cutler, C. J., and Read, D. R., Sound Exposure Level Duration Adjustments in UAS Rotorcraft NoiseCertification Tests, 2018. URL https://rosap.ntl.bts.gov/view/dot/37057.

Cutler-Wood, C., Barzach, M., Hobbs, C. M., and Shirayama, S., "Estimating Unmanned Aircraft Takeoff Noise Using Hover Measurement Data," QUIET DRONES Second International e-Symposium, 2022. URL https://rosap.ntl.bts.gov/view/dot/64152.

"Noise Certification of UAS/AAM using Rules of Particular Applicability," Federal Aviation Administration, 2023. URL https://www.faa.gov/about/office_org/headquarters_offices/apl/aee/noise/uas_noise_certification.

Causey UAS Acoustic Measurements M. James, A. Salton, M. Downing, and M. Calton, Blue Ridge Research and Consulting, Asheville, NC, tech., 2021

Task 4 - Develop Alternative Procedures and Assess Their Performance with Existing Tools (Case Study)

Georgia Institute of Technology

Objectives

Task 4 seeks to explore options for evaluating noise certification within the MBSE certification framework. The purpose of this task is to allow a performance baseline to be established for current procedures and to allow for the evaluation and comparison of more flexible process alternatives as they are formulated within Tasks 2 and 3. The breakdown of tasks under Task 4 is as follows:

Task 4: Develop alternative procedures and assess their performance with existing tools

4.1. Develop alternative testing procedures using the elements library.
4.2. Transfer alternative procedures to the PIM.
4.3. Report on the performance of the alternative procedures.
4.4. Develop a proof-of-concept demonstration of the PIM capabilities

Research Approach

The goal of Task 4 is to identify process modeling approaches for the purpose of simulating and evaluating the performance of a noise certification procedure. Task 4 delivers a solution that, in a broader sense, is referred to as the PIM. Tasks 4.1 to 4.3. focus on PIM implementation, whereas Task 4.4 integrates the PIM into the current MBSE framework. The PIM must analyze the process performance and interface with the verification model for completing steps regarding requirements and compliance. The PIM must also be flexible and reusable within the verification thread and must accommodate UAS configurations. An overview of the integrated verification thread and the PIMs is shown in Figure 30.

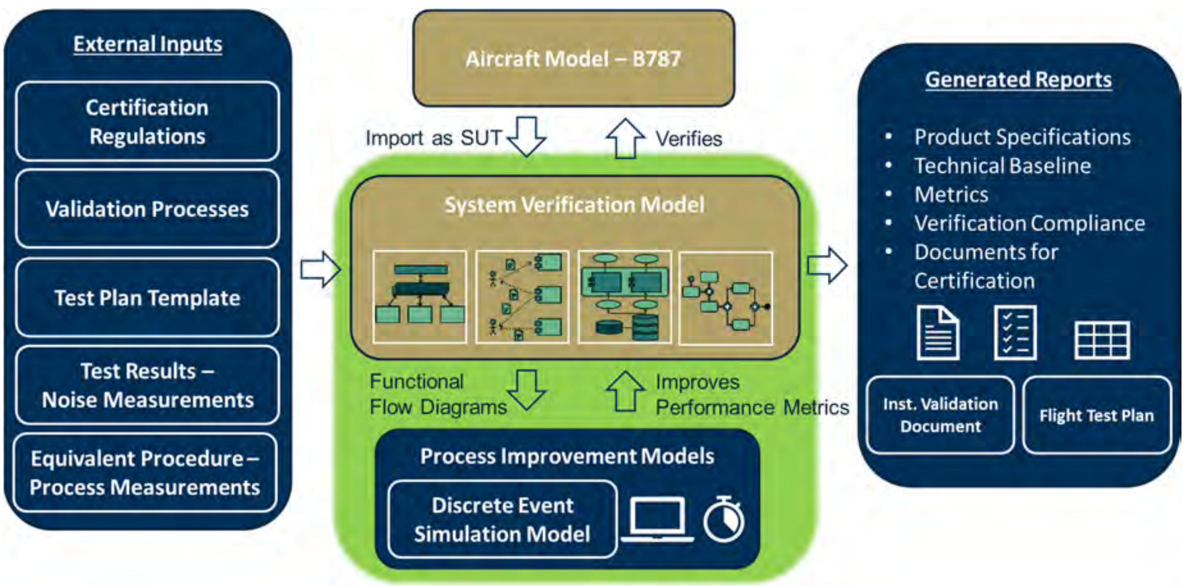


Figure 30. Integration of the process improvement model within the model-based systems engineering certification framework. SUT: system under test.

Task 4.1

The team has completed a literature review on process modeling methods to enable process simulation. These methods are listed below:

- DES, where a clock tracks the duration of the transition between model states
- Agent-based simulation methods
- System dynamics

- MCMC simulation methods

These techniques are evaluated on the basis of how well they can capture and simulate actual industry-applied procedures and their ability to interface with the verification thread. For simulating a simple process that is representative of transport category certification, the DES modeling approach appears to be the most effective. To demonstrate feasibility, a proof-of-concept version was developed using the DES method in a Python-based environment. The chosen example covered the testing process for a flyover approach, as shown in Figure 31. The objective was to demonstrate that a process model, as defined in the MBSE framework, can be simulated using DES. With the model states imported, DES can track the clock and return the time points at which each event is concluded. The DES results are then fed back as input and update the process diagram in the verification model, which then checks the process model against requirements and compliance.

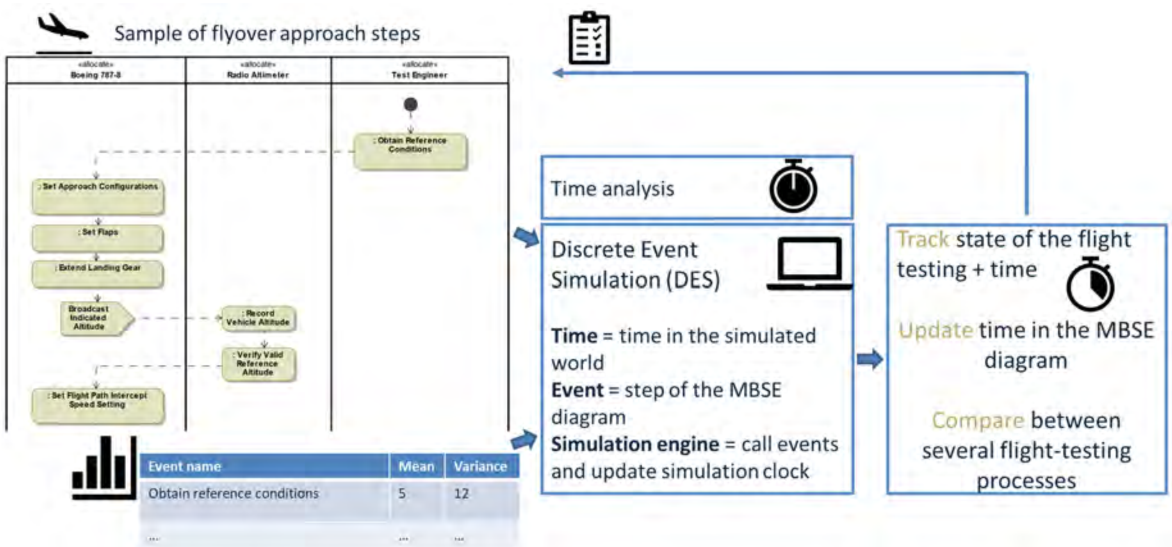


Figure 31. Discrete event simulation for a flyover approach. MBSE: model-based systems engineering.

However, because flight testing procedures are impacted by uncertainties, a different modeling approach is needed. To account for uncertainties, a probabilistic model using Markov chains has been developed to improve the accuracy of how interactions and emerging effects are captured. This approach is better suited to support use cases, with the objective of further process simplification, especially for flight testing portions, instrumentation setup, and measurement systems. This simplification could involve eliminating or replacing steps and possibly utilizing advanced data-driven or physics-based modeling approaches as a substitute.

Because of the extension of DES to Markov chain approaches and the need for large samples, the team adopted the MCMC approach, where a Markov chain model is used to run a Monte Carlo study to collect sample runs, given an input probability matrix and stakeholder value function. Each run is associated with an incurred time, cost, and accuracy penalty, and the output is provided in the form of activity diagrams and responses that are fed back to the verification model within the MBSE framework. Through the requirement model within the MBSE framework, the MCMC simulation data are imported to perform acceptance–rejection sampling, where each run (with its associated metric) is accepted or rejected by requirements/constraints within the verification model. The format of the MCMC simulation data follows the form of a step-by-step sequence (similar to a DES).

Summarizing the development of the PIM, the implementation path is shown in Figure 32, which illustrates the interface with the verification model. Using a similar flyover approach plan example as in Figure 31, the process model informs the PIM, which converts the flyover approach test into an executable simulation model. Based on the type of requirement test selected by the user, the appropriate response values, parametric settings for baseline values (time, cost, resources, disruption risks, accuracy penalty, etc.), and distributions for Monte Carlo simulations are chosen. The Monte Carlo simulation then generates the PIM metrics and prepares the dataset for verification.

For this task, the literature search, exploration of modeling options and selection, and proof-of-concept implementation are now completed.

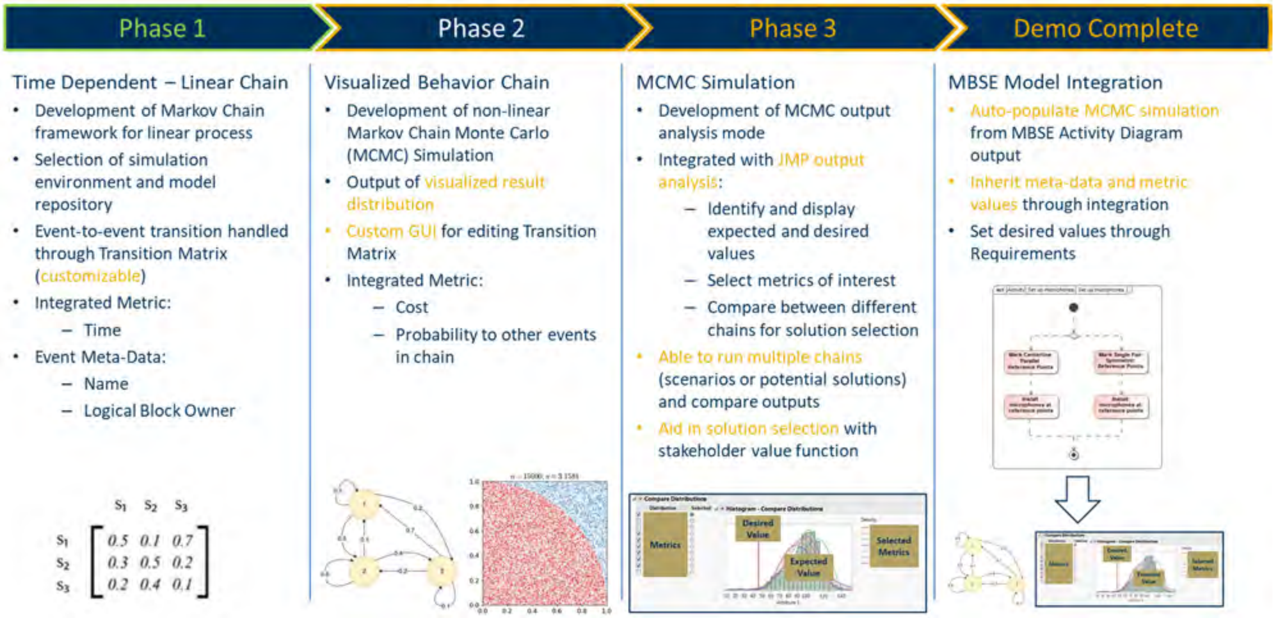


Figure 32. Functional development plan based on a process improvement model. GUI: graphical user interface; MBSE: model-based systems engineering.

Task 4.2
With the PIM model now available in a flexible and customizable format, in Task 4.2, we sought to expand the process simulation and analysis toward metrics that will link to use case objectives and process selection of improved alternatives.

The selected metrics should allow for a quantitative comparison of current and proposed streamlined noise certification process options. The current list of identified metrics is as follows:

- Time: schedule cost incurred to complete event
- Cost: budget cost incurred to complete event
- P(Failure): probability of repeating an event or reverting to a previous event (does incur time and cost [full or partial] in each occurrence)
- P(Success): probability of moving out of the current event
- Accuracy penalty: impact on overall accuracy value for executing the event (does not incur an additional cost in each occurrence)

The proposed integrated model uses a system verification model with external inputs such as current certification regulations, validation processes, and test plan templates. This results in an interconnected model for the unmanned aerial system, referred to as the SUT, which evaluates the validity of a certain certification procedure and generates alternative procedures suggesting one or a combination of modifications related to the utilized noise measurement metric, microphone type or array design, or flight profile (flyover, hover, vertical takeoff/landing, etc.). Figure 33 provides a general overview of the integrated structure of the system verification model, the PIM, and the visualization environment.

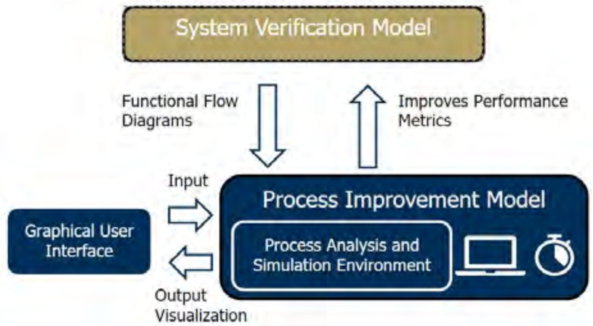


Figure 33. Integration of system verification model, process improvement modeling, and graphical interface.

Different detailed reports can be generated as outputs of the system verification model in addition to flight test procedure diagrams describing the sequence of events constituting the flight tests. The PIM assesses the performance of the baseline flight test procedure and other alternative procedures in terms of overall time and cost. The PIM captures a typical noise testing process (see Figure 22). Certain events within that process have feedback loops indicating that one or a set of events is to be repeated due to the detection of anomalies or calibration issues, for instance. Hence, some events can have different outcomes and, depending on the likelihood of each outcome, the overall flight test sequence would differ and lead to a different overall time and overall cost of the entire process. This steers the focus toward a probabilistic modeling approach, in which it is desirable that each event exclusively depends on the previous event. Moreover, to properly account for uncertainty and risks in predictions and decision-making, it is crucial for these flight tests to be simulated multiple times. With all these elements taken into consideration, a suitable approach for modeling a flight test procedure is using a Markov chain, also referred to as Markov process, which is a stochastic model describing a sequence of possible events in which the probability of each event depends only on the state of the previous one. To maintain a simplified terminology for the PIM, the flight test procedures extracted from the system verification model are to be considered flight test processes and the events are to be referred to as steps.

The PIM implements a Matlab script incorporating the mathematical representation of the flight test process to be analyzed using Monte Carlo simulations. Two Excel files are used as inputs to the script; the first includes all the steps of the flight test process and the probabilities of occurrence of each possible outcome, and the second contains the assigned time and cost values for each step.

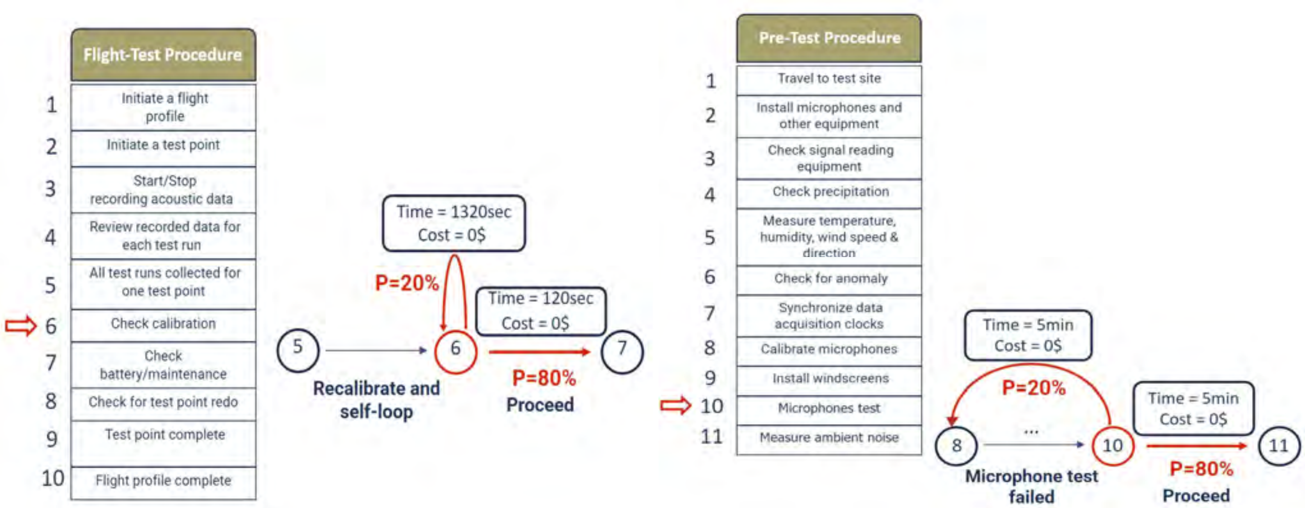


Figure 34. Example of self-loop (left figure) and feedback loop (right figure) within the noise testing process.

As noise testing is captured as a stochastic process, most of the steps can lead to different outcomes depending on many factors, including human error, unstable weather conditions, equipment malfunction, unsatisfactory measurements, and so on. These variations are modeled using feedback loops and self-loops in the Markov chain, in which the former represents the need to go back to a previous task in case an anomaly is detected, whereas the latter refers to the need to repeat the current task. Each potential outcome has a specific probability of occurrence assigned to it. Figure 34 portrays examples of a self-loop and a feedback loop within the process. In Figure 34, step 6 of the flight-test procedure consists of checking the calibration of the microphones after the completion of each test point. This step is crucial to avoid potential complications such as reducing confidence in the validity of noise test results, lacking a traceable chain of measurement standards, and impacting data comparability across multiple instruments. In this example, a probability of 20% is set for the need to recalibrate, which entails a longer time compared to the alternative outcome of not needing recalibration with 80% probability. Similarly, step 10 of the pre-test procedure consists of two potential outcomes for the microphone test; either the test fails, and the staff need to take the windscreens off, recalibrate the microphones, reinstall the windscreens and test again (probability of 20%), or the microphone test is successful (probability of 80%) and the following step is initiated.

Task 4.3

The objective of Task 4.3 is to produce a baseline of a noise certification procedure simulation and to propose a calibration step, as process data become available from ASCENT 061 partners. The analysis workflow for the PIM module is shown in Figure 35. The goal of the workflow within the PIM is to analyze the complexity of the process and to identify potential bottlenecks by assessing time, cost, and node/step criticalities. The workflow is completed in three basic steps:

1. *Definition of test data*: This step includes a test plan, setup, instrumentation and recording information, and sound pressure level measurement data.
2. *Process representation as an event chain through graph modeling*: In this step, the process is converted and represented as a weighted directed graph. Each node represents a step in the process, and the edges represent transitions between steps. The progression through the steps is represented by probabilities and parameters at each step.
3. *Execution of the MCMC algorithm*: The simulation starts from a node, and a “roll the dice” (generate a random number) function is performed. Depending on the outcome and the probability of each path, the algorithm selects the next node. A learning factor is utilized to update the probabilities of progressing through the steps (increased probability the second time).

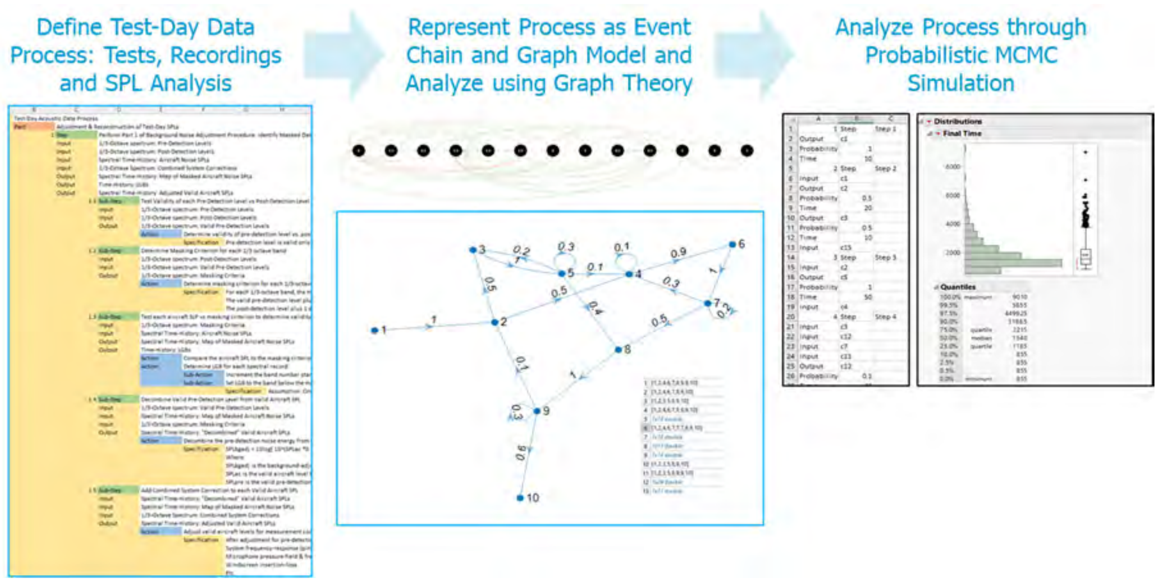


Figure 35. Analysis workflow based on the process improvement model. MCMC: Markov chain Monte Carlo; SPL: sound pressure level.

The analysis of different alternative procedures in noise flight testing relies on the evaluation of different performance criteria or metrics of interest to which the user may allocate different levels of importance. The outputs of this analysis heavily contribute to the decision-making alongside the regulatory adherence in which the requirements' satisfaction of each alternative procedure is evaluated. In the context of the suggested PIM, progression through the steps is associated with probabilities and parameters. Hence, tracking the propagation of these metrics of interest is enabled within the Monte Carlo simulations. Induced costs and time throughout the process are the main focus of the current efforts. When combined with the sequencing of events of each process simulation, these outputs can provide insight into process complexity and induced risks, and allow the anticipation of potential bottlenecks in the process as well.

Noise certification testing processes are represented using Markov chains within a probabilistic simulation environment. This approach relies on random variables, which are functions assigning real numbers to each potential outcome within the sample space of a random experiment. It also entails that every event solely depends on the previous event, thus preventing the propagation of uncertainties throughout the process. The entire process can be visualized using weighted directed graphs in which every node represents a step within the noise testing process, and the edges indicate the transitions between nodes. A valid representation of the certification testing process requires every node on the graph to be able to eventually reach the final step, thus ensuring process continuity by calculating the "connected components" in the graph. Figure 36 depicts the need to ensure continuity within the demonstrative process on the left side, in which step 7 cannot reach the final step, whereas the corrected Markov chain representation on the right implements process continuity for each step.

Figure 36. Illustration of process continuity in a sample flight test process.

Every edge of the Markov chain representation is assigned a probability characterizing the likelihood of moving from one node to another, thus mapping different potential paths to be taken. The Monte Carlo method is implemented to achieve repeated random sampling during the simulation. This method generates a random number that is compared to the cumulative sum of the row corresponding to the current step of the transition matrix, which contains all potential probabilities connecting any two nodes. The next step is chosen once the random number is less than or equal to the smallest cumulative sum. Each Monte Carlo simulation follows a specific path that is dictated by the aforementioned method. To achieve accurate estimates, the Monte Carlo simulation has to be repeated multiple times by increasing the number of runs set within the Matlab script. This underlines an important trade-off between the accuracy of the results and the script execution time. In this work, the analysis is exclusively targeting the most influential steps of the noise testing process as they will be the main sources of variation within the results. This approach allows the reduction of the computational time of the PIM execution while ensuring the accuracy and reliability of the results. This can be accomplished by implementing PageRank centrality, which is a metric providing the average time spent at each node during a random process simulation. The average for each node is weighted according to the probabilities of reaching a node and the value of the associated parameter. These key (i.e., most influential) steps, will be varied in each simulation using design of experiments (DOE). In addition to the identification of key steps, the code introduces the capability of detecting bottlenecks within the process giving enough insight about steps susceptible to causing delays or complications within the process workflow.

The baseline process for the PIM exclusively considers a hover flight profile with three test points with a minimum of six runs per test point. Each test point refers to a test condition with a specific combination of weight, speed, and altitude. With the use of only one microphone, the UAS will fly at three different locations relative to it (see Figure 37). The analysis can be turned into a parametric analysis capable of automatically changing some of the input values without having to manually modify the values in the input files. This will apply to parameters that would simultaneously affect multiple steps of the process in different ways, such as the number of staff members, number of microphones, and number of flight profiles and test points. Manually assessing and incorporating the changes due to variation in these parameters can be very tedious, as many steps can be directly or indirectly affected. Thus, all the impacted steps are identified beforehand and the effects are quantified and mathematically modeled in terms of time and cost consequences. Once the user identifies any combination of parameters, the code will automatically implement the corresponding changes to the time and cost values in the input file of the baseline process.

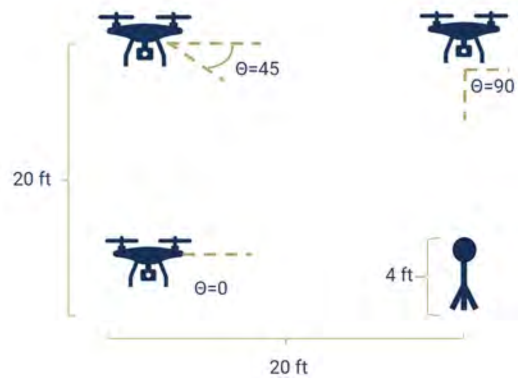


Figure 37. Baseline noise testing process (hover flight profile).

Calibration is an essential step for ensuring model accuracy and the validity of results and findings. This task requires a completed process simulation capability, which will be calibrated against a baseline that captures current certification testing plans and processing steps. The pivot to the UAS category has included plans to interface with ASCENT partners who can provide testing plans and noise datasets to be used as calibration data and overall process information. This task will be one of the key focus topics for the project's Year 3 activities. Scalability issues are bound to arise as this model is expanded to reflect the full verification thread; thus, the next step is to discuss options for data that ASCENT 061 partners could provide for further calibrating the model, according to the use cases of preference.

Task 4.4

In a proof-of-concept demonstration of the complete certification process simulation capability within the PIM, the team has been formulating use case examples based on scenarios provided by OEM partners. For these examples, simulation runs are being executed to test modifications and proposed improvements over the baseline process. Under this task, a first demonstration of the PIM has been completed. For this example, the goal is to assess the impact of a simplified noise collection/analysis process for the Waco YMF-5 propeller aircraft.

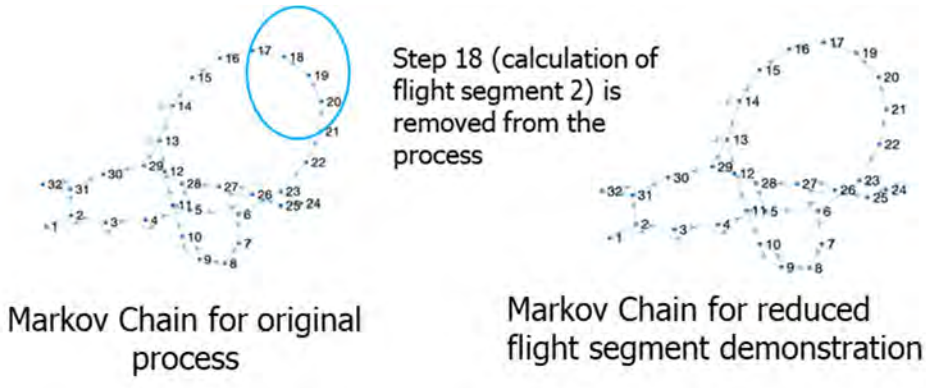


Figure 38. Process modification: Step 18 (calculation of the second flight segment) is removed from the flight-testing process.

The baseline (original) process was formulated within the PIM and executed using best estimates for time and cost. The term "best" implies that the team had to rely on rationalized assumptions that were initially formulated by input from OEM partners. As this information could be of a sensitive nature for most OEMs, the guidance was provided at a higher level, without any limitations on how the information would be distributed. Hence, for this example, a simplified process for flight segment testing is proposed, where a certain calculation is removed from the standard process. As shown in Figure 38, the simplified process removes step 18 (calculation of the second flight segment) while other steps were updated with new values to capture the updated process.

Table 5. Summary of cost ($) and time (hr) improvements.

		Mean
Original	Cost($)	166,770
	Time(hr)	155
Reduced Segments	Cost($)	140,430
	Time(hr)	151

A comparison of the two process alternatives is presented in Table 5. The results were obtained from an MCMC analysis and comparison between the baseline and simplified process. The PIM was able to quantify measurable savings in time and cost. In particular, the average process cost shows a reduction of 16%, and the average process time shows a decrease of 2%. The results are highlighted in Figure 39, where the Monte Carlo simulation data are plotted as distributions for the cost and time required for the process.

With this fundamental example showcased under this task, the groundwork is set for scaling up the PIM to more comprehensive modifications, which would also include technology impact forecasting functions. As this practice will now be exclusive to the UAS category, the team's priorities are to investigate current noise testing plans and procedures and to be in a position to propose promising equivalent procedures.

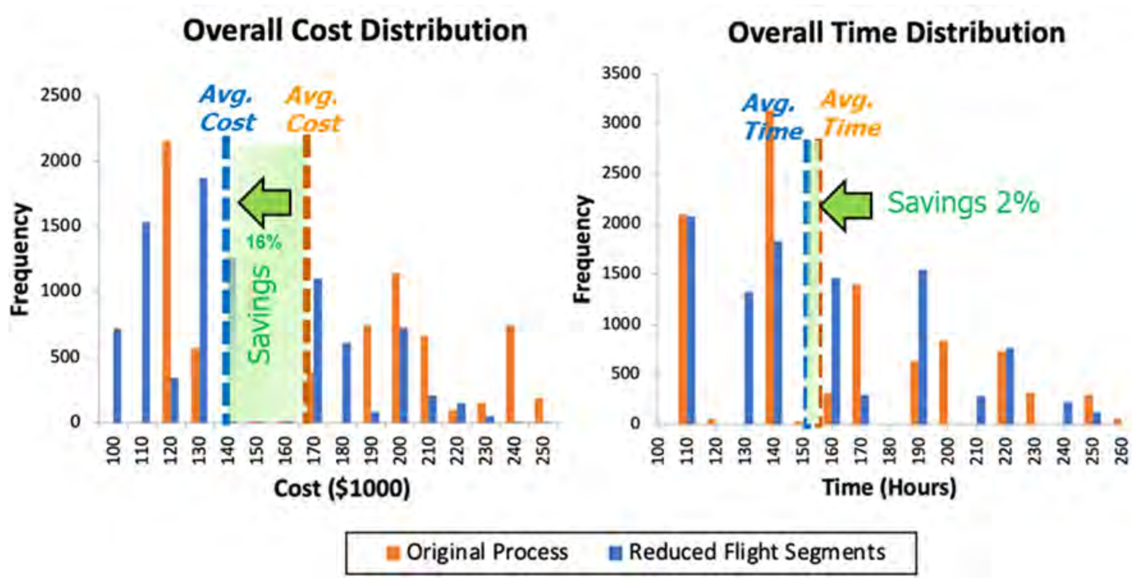


Figure 39. Execution of Markov-chain-based Monte Carlo analysis and comparison between the baseline and simplified process.

Milestones

Please refer to the milestones listed under Task 1.

Major Accomplishments

- Development of a small-scale PIM using DES, as a deterministic modeling exercise.
- Development of a more comprehensive stochastic model using stochastic MCMC methods, formulated in a way that enables seamless integration into the verification thread within the MBSE framework.
- Definition of a starting set of metrics, as a working solution with a focus on process efficiency improvements.
- Approach for integrating the PIM with the verification model within the MBSE framework.
- Finalized PIM analysis workflow with the use of Monte Carlo simulation for Markov chain models of the certification testing process.
- Workflow integrated with the MBSE verification model.
- Proof-of-concept use case for assessing the impact of process simplification through quantifiable outcomes, which has been supported by the current working version of the MCMC-enabled PIM module.
- Further improvement and tuning of the existing PIM with automation and parametrization of user-defined input data to make the model representative of any desired process.
- Application of the PIM to a typical plan for UAS noise testing to better capture the process and properly estimate the cost, staff, and time implications.

Publications

None.

Outreach Efforts

- Presentation of concepts to Volpe partners, who provided feedback on the tools and analysis methods.
- Collaboration with ASCENT 077 and 094 research groups.
- Discussions with experts in the field with similar applications, e.g., process simulations for industrial systems, manufacturing, supply chains, etc.

Awards

None.

Student Involvement

- Although a small portion of the team has been leading the technical approach of PIM development, this task has involved the full team, as PIM integration with the MBSE model is a key enabler to be addressed early in the process.
- Recent efforts to extend the PIM capabilities have been led by Hajar Mali, and the dashboard and visualization of results have been led by Nathnael Geneti.

Plans for Next Period

- Continuation with the PIM development steps, toward a full verification model scale capability for the UAS category.
    - Finalize the interface with the MBSE verification model.
    - Ensure flexibility with other UAS configurations (the Matternet M2 example is the current working baseline).
    - Iterate on noise measurement data to be used for PIM improvements.
    - Integrate sound pressure level conversion to EPNL for UASs.
    - Expand on metrics that can better track process complexity and vulnerability and test against varying contingency scenarios, with the goal of ensuring that the analysis is capable of driving robust decisions.
    - Calibrate the model with input from ASCENT 077 work.
- Expand on metric definitions at a level beyond process inefficiencies (e.g., directly addressing time and costs) and consider complexities that could affect the process with bottlenecks and unnecessary use of resources (e.g., duplicate testing, time-intensive procedures, etc.). The flight-testing part of the process will be the primary focus.
- Formulate a simple certification problem for each vehicle type and use it as a pilot for comparing and selecting the appropriate method.
- Integrate results and PIM analysis in the interactive decision support tool.

References

Metzger, F. B., & Foley, W. M. (1970). *Stol aircraft noise certification-a rational approach*. SAE Transactions. 700325. https://doi.org/10.4271/700325

U.S. Department of Transportation, Federal Aviation Administration. (1969). *Federal Aviation Regulation, Part 21, Certification Procedures for Products and Ports; Part 36, Noise Standards: Aircraft Type Certification*. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-36

Ollerhead, J. (1968). *Subjective Evaluation of General Aviation Aircraft Noise* (Technical Report NO-68-35).

Senzig, D.A. & Marsan, M. (2018). *UAS Noise Certification*.

FAA (2023). 14 CFR Part 36 – NOISE STANDARDS: AIRCRAFT TYPE AND AIRWORTHINESS CERTIFICATION. https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-36

FAA. (2017). *Advisory Circular 36-4D – Noise Standards: Aircraft Type and Airworthiness Certification*.

Federal Register. (2022). *Noise Certification Standards: Matternet Model M2 Aircraft* (NPRM 86 FR 48281). https://www.federalregister.gov/documents/2022/09/12/2022-19639/noise-certification-standards-matternet-model-m2-aircraft.

FAA. (2022). *Noise Certification Standard: Matternet Model M2 Aircraft*. https://www.regulations.gov/document/FAA-2021-0710-0016.

US Department of Defense. (2022). *Systems Engineering Guidebook Section 4.2.7*. Office of the Deputy Director for Engineering. Washington, D.C.

VOLPE Guides, "Validation Protocol for Digital Audio Recorders User in Aircraft-Noise Certification Testing" [2010].

VOLPE Guides, "Audio Recording & Analysis System Validation Checklist" [2018].

VOLPE Guides, "Test Data Acoustic Data Process" [2003].

VOLPE Guides, "Background Noise Adjustment Process" [2003].

FAA. (n.d.) *Details on FAA Noise Levels, Stages, and Phaseouts*. https://www.faa.gov/about/office_org/headquarters_offices/apl/noise_emissions/airport_aircraft_noise_issues/levels/.

Aleksandraviciene, A. (2018). *MagicGrid Book of Knowledge*. Kansas, 2018. NoMagic.

More, S. (2011). *Aircraft Noise Characteristics and Metrics* [Ph.D thesis Dissertation, Purdue University].

Konzel, N. (2022). *Ground based measurements and acoustic characterization of small multirotor aircraft* [Masters Thesis, Pennsylvania State University].

ASCENT 061 Year 3 Recap

The following key tasks and activities have been completed within the ASCENT 061 Year 3 performance period:

- Explored the applicability of the current ASCENT 061 framework for noise certification of rotor or small propeller-driven UAS.
- Performed a literature search and documented regulations and current testing standards for small UAS (CFR Title 14 Part 36 Appendix G, J, and H, and recent NPRMs).
- Completed the architecting of a noise certification modeling and assessment framework for transport and UAS category aircraft.
- Completed development of the PIM, which has been applied to a typical plan for UAS noise testing demonstration example.
- Formulated use cases that are aligned with needs and recommendations provided by OEM partners, with a focus on exploring implications of alternative testing procedures on regulatory compliance and highlighting the benefits of process simplification (e.g., lateral microphone placement or removal, if trusted analysis is used).
- Provided a demonstration by assessing a simplified noise collection/analysis process.
- Documented options for equivalent procedures in a database/library compilation.
- Conceptualized and developed a visualization environment to aid as a use case demonstrator and decision support environment.
- Engaged in a broader outreach of ASCENT 061 to the aviation community on noise certification:
    - ASCENT fall/spring meetings
    - Continued discussions with Volpe
    - UAS OEMs
    - Published articles with the American Institute of Aeronautics and Astronautics (AIAA) and for the SciTech 2023 and 2024 Meetings
- Exchanged noise measurements and knowledge with the ASCENT 77 team.
- Provided annual and quarterly reports, which are available on the ASCENT Knowledge Services Network database.
- Prepared contributions and new technical capabilities that will be published in conferences and peer-reviewed journal articles:
    - Kim, D., Taneri, M., Omoarebun, E.N, Wills, T., Balchanos, M., & Mavris, D. (2023). *MBSE-Enabled System Verification and Process Improvement of Transport Aircraft Certification.* Accepted and to be presented In AIAA SciTech 2023 Forum, National Harbor, MD, January 23-27, 2023.