NASA/TM–20205011606

Best Practices Identified Through the Completion of UAS Flight Demonstrations

Jeffrey M. Maddalon and Kurt A. Swieringa
Langley Research Center, Hampton, Virginia

Israel Greenfeld
Glenn Research Center, Cleveland, Ohio

Summer L. Brandt, Peter I. Robinson, M. Gilbert Wu, and Seungman Lee
Ames Research Center, Moffett Field, California

Paul Volk
Adaptive Aerospace Group, Inc., Hampton, Virginia

John Del Frate
The Aerospace Corporation, Edwards, California

January 2021

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/
and select the "General" help request type.

NASA/TM–20205011606

Best Practices Identified Through the Completion of UAS Flight Demonstrations

Jeffrey M. Maddalon and Kurt A. Swieringa
Langley Research Center, Hampton, Virginia

Israel Greenfeld
Glenn Research Center, Cleveland, Ohio

Summer L. Brandt, Peter I. Robinson, M. Gilbert Wu, and Seungman Lee
Ames Research Center, Moffett Field, California

Paul Volk
Adaptive Aerospace Group, Inc., Hampton, Virginia

John Del Frate
The Aerospace Corporation, Edwards, California

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

January 2021

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

Acknowledgments

The authors would like to acknowledge that this report was greatly aided by helpful insights and comments from National Aeronautics and Space Administration’s (NASA) employees and contractors, Federal Aviation Administration’s (FAA) employees, and the Systems Integration and Operationalization (SIO) industry partners. In particular, the authors would like to thank Arya Abrego, Conrad Rorie, Bill Bishop, and Steve Bretmersky, from NASA; Wes Ryan, Richard Toth, Steve Van Trees, and Peter White from the FAA; David Yoel, Ali Etebari, Rosemarie Mooney and Tina Sicilia from American Aerospace Technology Inc. (AATI); Jennifer Andrews, Maurice Griffin, and Michael Smith from Bell Textron, Inc.; General Atomics Aeronautical Systems Inc. (GA-ASI); and many additional individuals from the FAA and SIO partners who worked diligently throughout the last two years to make the SIO effort a success.

Table of Contents

List of Abbreviations

AATI	American Aerospace Technologies, Inc.
AC	Advisory Circular
ACAS X	Airborne Collision Avoidance System
ACAS Xu	Airborne Collision Avoidance System for Unmanned Aircraft
ACAS sXu	Airborne Collision Avoidance System for Small Unmanned Aircraft
ADS-B	Automatic Dependent Surveillance - Broadcast
ADS-R	Automatic Dependent Surveillance - Rebroadcast
AGL	Above Ground Level
ANSI	American National Standards Institute
APT	Autonomous Pod Transport
ASTM International	International standards organization — formerly known as American Society for Testing and Materials
ATAR	Air-To-Air Radar
ATC	Air Traffic Control
ATO	Air Traffic Organization (FAA)
BVLOS	Beyond Visual Line of Sight
C2	Command and Control
CA	collision avoidance
CAS	collision avoidance system
CFR	Code of Federal Regulations
CNPC	Control and Non-Payload Communications
COA	Certificate of Waiver or Authorization
ConOps	Concept of Operations
CS	Control Station
D&R	durability and reliability
DAA	Detect and Avoid
DAIDALUS	Detect and AvoID Alerting Logic for Unmanned Systems
DAL	Design Assurance Level
DER	Designated Engineering Representative
DFW	Dallas Fort Worth
DWC	DAA Well Clear
EO/IR	Electro-Optical/Infra-Red
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FOR	Field of Regard
GA-ASI	General Atomics Aeronautical Systems, Inc.
GBSS	Ground-Based Surveillance System
GPS	Global Positioning System
GRC	Glenn Research Center
HMD	Horizontal Miss Distance
HSI	Human Systems Integration
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ITU	International Telecommunications Union
JARUS	Joint Authorities for Rule Making on Unmanned Systems
KTAS	Knots True Airspeed
LODA	Letter of Design Approval

LoWC	Loss of DAA Well Clear
LR	LoWC Ratio
LTE	Long-Term Evolution
MAAP	Mid-Atlantic Aviation Partnership
MASPS	Minimum Aviation System Performance Standards
METAR	METeorological Aerodrome Report
MGTOW	Maximum Gross Takeoff Weight
MHz	Megahertz
MIR	Maneuver Initiation Range
MIT-LL	Massachusetts Institute of Technology-Lincoln Labs
MOPS	Minimum Operational Performance Standards
mph	Miles per hour
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NM	Nautical Mile(s)
NMAC	Near Mid Air Collision
NOTAM	Notice to Airmen
NTIA	National Telecommunications and Information Administration
ORA	Operational Risk Assessment
RF	Radio Frequency
RFI	Radio Frequency Interference
RTCA	International standards organization – formerly known as Radio Technical Commission for Aeronautics, Inc.
RWC	Remain Well Clear
SATCOM	Satellite Communication
SC	Special Committee
SIO	Systems Integration and Operationalization
SMS	Safety Management System
SORA	Specific Operational Risk Assessment
STA	Special Temporary Authorization
sUAS	Small Unmanned Aircraft System
SWaP	Size, Weight and Power
TCAS	Traffic Alert and Collision Avoidance System
TPM	Technical Performance Metric
TSO	Technical Standard Order
TSOA	Technical Standard Order Authorization
UAS	Unmanned Aircraft System
UAS-NAS	Unmanned Aircraft Systems Integration into the National Airspace System
UAT	Universal Access Transceiver
VFR	Visual Flight Rules
VHF	Very High Frequency
VLOS	Visual Line of Sight
VTOL	Vertical Takeoff and Landing
WG	Working Group

Executive Summary

Over the course of the National Aeronautics and Space Administration's (NASA) Unmanned Aircraft Systems Integration into the National Airspace System (UAS-NAS) project, NASA has contributed to the development of standards, processes, and procedures necessary to allow Unmanned Aircraft Systems (UAS) routine access to the National Airspace System. The Systems Integration and Operationalization (SIO) effort advanced this goal by establishing partnerships with industry for a period of approximately two years to develop, integrate, and test the systems necessary to allow operations in non-segregated airspace. This document is a description of SIO and contains a compendium of best practices intended to be of value to any endeavor seeking to develop similar vehicles for commercial operations.

The three companies chosen as SIO partners proposed vehicles that varied in size, powerplant, and configuration according to their commercial missions. These missions ranged from long-endurance high-altitude surveys to short-hop urban deliveries. Vehicles ranged in wingspan from over 75 ft to under 10 ft, and in weight from over 12,500 pounds to under 300 pounds. Powerplants ranged from turboprop to piston to electric-powered. All vehicles weighed more than 55 pounds and were expected to conduct operations at altitudes greater than 400 ft above ground level, which required integration into the conventional air traffic management system.

The SIO partners were required to make initial progress toward type certification, to the extent that it could be done in such a compressed timeframe. This included creating foundational documents such as concepts of operations, operational risk assessments, and draft project specific certification plans. The document contains an overview of the Federal Aviation Administration's (FAA) type certification process and discussion on the detailed standards, regulations, advisory circulars, Certificates of Waiver or Authorization (COA) applications, and other references that provide direct guidance on design and operational requirements necessary to certify commercial UAS. Where appropriate, the document highlights the approvals sought for the SIO demonstration flights, but it also discusses differences related to the more stringent type certification approvals.

The SIO partners were also expected to integrate prototype Detect and Avoid (DAA) and Command and Control (C2) systems into their unmanned aircraft and conduct a flight demonstration that emulated commercial missions. In order to conduct the demonstrations, the SIO partners were required to obtain approvals from the FAA such as experimental airworthiness certificates, COAs, exemptions, and in one case a 91.113 waiver for beyond visual line of sight operations. Various best practices were identified by observing interactions between the FAA and the SIO partners and are summarized below with comprehensive descriptions included within the document.

The first set of best practices describes the relationship between business considerations to UAS design and describes several UAS development challenges:

- A well-defined business case will help an applicant make informed technological and procedural tradeoffs during the design of the UAS and throughout a type certification program.
- Increasing the size, weight, or operational risk of a UAS will increase the level of scrutiny and the number of required mitigations, which can have a significant impact on cost.
- Assuring proper operation of complex software or hardware used for safety-critical functions is difficult and induces both cost and schedule risk; therefore, it is advantageous to carefully align safety-critical systems to a well-defined business case.
- It is important to use conventional, thorough system engineering practices to evaluate and vet complex interactions between UAS components. In particular, the evaluation of these interactions by experts with different technical specialties allows for the identification of subtle unexpected interactions.
- A cause of many safety mishaps during UAS operations is poor human factors, which is often the result of rapid development of the machine while forgetting the operator in the design.

The second set of best practices is focused on navigating the UAS design and type certification process:

- Hiring personnel who have specialized experience with civil aviation certification and experience with UAS certification can help an applicant efficiently navigate the type certification process and understand specific elements that are unique to UAS.
- The type certification process should not begin until after the vehicle's research and development phase is complete.

- It is important for UAS manufactures and operators to develop strong aviation safety cultures where everyone in the organization from the top management to the person on the shop floor take ownership of the safety of the UAS.

The third set of best practices relates to the design of the DAA system. Deploying DAA systems in the SIO timeframe posed unique challenges. Commercial off-the-shelf DAA systems do not exist, necessitating custom development and, for two of the partners, the use of low-size, -weight, and -power (SWaP) sensors not completely specified for DAA. Among the related best practices discussed for these systems are:

- Adaptation of previously used or existing hardware and software not specifically designed for DAA, such as sensors or displays, may not prove effective because DAA will impose additional requirements on the hardware and software.
- Radars are the most mature sensor for detecting non-cooperative air traffic, followed by electro-optical/infra-red cameras. Both of those sensors have industry standards that are either published or being drafted.
- Currently available low-SWaP DAA sensors may not have the detection range that will be required to make an adequate safety case. Further analysis is needed to determine if current radars can meet key safety metrics or if the development of low-SWaP DAA sensors with greater range are needed.
- The use of modeling and simulation tools is a cost-effective and efficient means to determine that DAA systems meet key design requirements. Comprehensive evaluation of a DAA system requires a full suite of ground and flight testing.

A fourth set of best practices relates to lost-link contingency planning. The UAS demonstrated as part of SIO were piloted remotely, and for all aspects of flight safety, a C2 system was required to communicate DAA and other UAS subsystem data to the remote pilot and to allow the pilot to issue commands to the vehicle. Lost or degraded C2 link risk mitigations discussed are:

- Applicants with DAA systems that require a remote pilot to initiate avoidance maneuvers should carefully consider how the unmanned aircraft will remain well clear of all other aircraft if the C2 link is lost and the remote pilot no longer has control.
- Lost link procedures must be designed to mitigate hazards associated with the loss of command and control and accommodate other airspace users. Further work is needed to determine scalable lost link procedures for routine commercial operations in the NAS.

The final set of best practices relates to the design and testing of C2 systems and obtaining spectrum licenses. Because there are currently no certified C2 radios commercially available, the SIO partners either used prototype radios that were aligned with industry standards or commercial off-the-shelf radios using temporary authorizations on frequencies intended only for research and development and not viable for long-term commercial use. Nevertheless, a wealth of knowledge was gathered, which is reflected in the best practices that are summarized below and included in this document:

- The use of allocated C-band spectrum for safety-critical UAS C2 communications, 5030-5091 megahertz (MHz), is the most viable option for safety-critical C2 communications, since there are industry standards [DO-362], and an FAA Technical Standard Order [TSO-C213] that provides guidance on the use of that spectrum. Use of commercial infrastructure, such as satellite communication and cellular Long-Term Evolution (LTE), may be viable in the future if applicable standards are developed. Unlicensed spectrum is not viable for safety-critical C2 communications because protection from interference is not guaranteed.
- CNPC spectrum is both finite and valuable and is allocated for safety-critical UAS C2 communication. This observation motivates the need to scrutinize all information sent to verify its safety-critical role, the use of appropriate data compression techniques, and the need to follow applicable industry standards and FAA guidance.
- Spectrum licenses for C2, though issued by the Federal Communications Commission (FCC), require coordination with the FAA spectrum office for the use of spectrum either controlled by the FAA or used for purposes that impact the safety of flight. Coordination with the FAA can help identify issues early in the design process and maximize the probability of obtaining spectrum approvals. It should be noted that experimental licenses cannot be used for revenue operations.
- C2 analysis and testing are important due to the complex interactions between the C2 radio, antennas, and environment. NASA's testing, which provided data to help motivate industry standards, included testing over flat surfaces; hilly, dry areas; and over water.

- Spectrum licenses must be obtained for all UAS transmitters, including C2 radios, radios to transmit payload information, transponders, VHF radios, DAA radars, and applicable payload sensors. Legal protection against interference is desired for all transmitters that serve a safety-critical function (e.g., the DAA radar). If legal protection is not viable, the applicant will need to show that the risk of interference has been sufficiently mitigated.

Throughout the course of SIO, the partners integrated prototype DAA and C2 systems into unmanned aircraft, tested those systems, and laid the groundwork for type certification programs that are expected to continue to completion after SIO ends. Throughout SIO, the partners and NASA developed a better understanding of potential UAS markets and both programmatic and technical items that should be considered when designing, testing, and certifying a UAS. The information presented in this document can be used to learn from the efforts of the SIO partner companies and to enable new applicants to address the development, integration, and approval challenges related to ensuring UAS safety and NAS integration.

1. Introduction

Today, unmanned aircraft operate in the National Airspace System (NAS) at prescribed altitudes, largely below conventional aviation, providing commercial services that are suitable at these altitudes. However, the operation of UAS at higher altitudes are currently limited. When they are fully integrated into the NAS, unmanned aircraft have the potential to offer a variety of new commercial services that are expected to revolutionize the aviation industry. Examples of these services include, but are not limited to, infrastructure inspection, cargo transportation, search and rescue, transportation of life-saving medical supplies, and communication relay. In order to attain the benefits of commercial unmanned aircraft operations, these aircraft must be safely integrated into the NAS. The National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), industry, and other organizations have been working diligently for several years to address technical, procedural, and regulatory barriers that prevent robust and scalable commercial unmanned aircraft operations in the NAS.

NASA's Unmanned Aircraft Systems Integration into the National Airspace System (UAS-NAS) project was established with the goal of providing research to address barriers that currently prevent full integration of Unmanned Aircraft Systems (UAS). Throughout its lifespan, the UAS-NAS project has primarily focused on providing research to support the development of standards for two key technologies that are necessary for NAS integration: Detect and Avoid (DAA) and Command and Control (C2). DAA systems use sensors, alerts and guidance to detect surrounding air traffic and ensure that the unmanned aircraft remains well clear. C2 is the data link used to transmit information between the unmanned aircraft and the control station (CS) that is used to control the unmanned aircraft and manage the flight. Together, the work completed under the UAS-NAS project helped advance these technologies and facilitated significant progress toward UAS integration into the NAS; however, there is additional work required before routine commercial UAS operations can occur.

NASA's UAS-NAS project convened the Systems Integration and Operationalization (SIO) effort with the goal of working with industry to make strides toward routine commercial unmanned aircraft operations in the NAS. In order to achieve this goal, NASA partnered with three companies over an approximately two-year period beginning in October 2018. Each of these companies were expected to integrate prototype DAA and C2 systems into an unmanned aircraft, conduct a flight demonstration in the NAS that emulated a commercial mission, and make initial progress toward type certification. The primary objective of SIO was to incentivize the development, integration, and certification of UAS for commercially viable use cases.

This document is intended to serve as a "read-first" overview which shares best practices informed by working with the SIO partners and the FAA throughout SIO. It also highlights detailed standards, regulations, advisory circulars (ACs), and other documents that provide direct guidance on design and operational requirements. The information presented can be used to learn from the efforts of other companies and enable new applicants to better navigate the various approval processes necessary to ensure that UAS are safe and able to be integrated into the NAS.

After this introduction, the document provides an overview and background of SIO. Section 2 provides a high-level description of the SIO partners' concepts of operations, UAS, and flight demonstrations. Section 3 describes a general overview of safety and certification, which is intended for readers who are new to aviation and may not have experience in aircraft certification. Section 4 describes completed and ongoing industry standards development activities for UAS. Section 5 describes a general overview of the risk-based process that is being used for UAS certification. Section 6 describes best practices that should be considered during a UAS development program and gaps that must be addressed before fully integrated commercial UAS operations can be achieved. Lastly, Section 7 provides best practices related to obtaining flight tests and flight demonstration approvals.

2. Background

2.1. Document Scope and Limitations

The objective of this document is to convey best practices identified during SIO to the UAS industry and organizations that support UAS research. It is primarily intended for companies and organizations that wish to pursue civil UAS operations in the NAS at altitudes above 400 ft. Throughout SIO, NASA had the opportunity to watch three companies develop their UAS for commercial applications, interact with the FAA, and pursue operational approvals for the SIO demonstrations. The wealth of information gained through these interactions was used to develop the best practices presented in this document. In addition, SIO partners provided their observations regarding best practices. The information in this paper does not violate proprietary data restrictions intended to protect the intellectual property of the SIO partners, which were primarily developed using the partners' internal research and development financing. A note on terminology: what is referred to as "best practices" in some cases may be better called "lessons learned" or "technological gaps."

This document provides best practices for companies to consider as they develop concepts of operations (ConOps), operational risk assessments (ORAs), and airspace access approvals for future commercial unmanned aircraft operations. Readers should be aware that the information in this document is not intended to be comprehensive. There is no way it can be because the two-year timeframe of SIO did not allow the industry partners to complete their type certification programs or fully integrate their UAS into the NAS. Throughout the document, any unresolved issues are identified and presented as gaps. This document's limitations can be categorized in three ways. First, this document should not be viewed as a complete guide to unmanned aircraft certification or FAA policy. Type certification is the FAA's responsibility and it is expected that the FAA will release guidance material as UAS certification policy is refined. Furthermore, the SIO partners only began the initial steps of certification during this activity and the level of testing required for the SIO demonstrations was significantly lower than what will be required for a type certified UAS due to risk mitigations implemented for the demonstrations.

Next, this document is not intended to provide a comprehensive list of items that must be considered to achieve commercial UAS operations. There are three dimensions to this limitation. First, there are subjects that were not within scope of the SIO effort. Second, this document is intended to serve as a general overview of UAS approval and technical topics, not a comprehensive discussion of these topics. Technical topics that are addressed will require the reader to review other reference documents, such as FAA advisory circulars and industry standards, for a comprehensive understanding. Finally, readers should keep in mind that the best practices described are based on the experience of only three UAS manufacturers. Different best practices may have emerged from different manufacturers with different corporate knowledge, different markets, different use-cases, or different aircraft.

Lastly, as UAS policy is established and the path toward UAS type certification continues, some portions of this document are expected to become less relevant. Ideas expressed in this paper as novel may eventually become accepted practice. Other ideas may be eclipsed by new policy, regulations, or standards, or may be become outdated by continued technology research, development, and maturation.

2.2. State of the Art of UAS Operations

At the time of SIO, UAS operations above 400 ft typically require special approvals and operational risk mitigations, which are highlighted by the flight demonstrations conducted by the SIO industry partners. These special approvals and risk mitigations are expected to become less necessary as UAS are certified and standard methods of conducting lost link and other contingency procedures are established.

UAS operations that do not fall under Title 14 of the Code of Federal Regulations (CFR) Part 107, abbreviated 14 CFR 107, currently require different approvals. These approvals may include a Certificate of Waiver or Authorization (COA), a waiver for beyond visual line of sight (BVLOS) operations, spectrum approvals, and exemptions. The BVLOS waiver is a waiver for 14 CFR 91 Section 113, abbreviated 14 CFR 91.113 or sometimes simply 91.113. These approvals enable the FAA to assess the safety of operations and determine necessary special mitigations and accommodations. They also enable the FAA to coordinate lost link and other contingency procedures.

Approval for BVLOS operations without visual observers remain a challenge, particularly for operations at altitudes greater than 400 ft above ground level (AGL). BVLOS operations require a DAA system integrated with an unmanned aircraft in order to ensure that the hazard of collisions with other aircraft is sufficiently mitigated. As of the writing of this document, there are no known commercial off-the-shelf DAA systems that meet FAA certification requirements and industry standards for low size, weight, and power (SWaP). Though, there are low-SWaP DAA systems that are in the process of being created, refined, and tested.

Operational mitigations can be used to compensate for system limitations. One important class of operational mitigations are those used to compensate for risks associated with non-certified or non-proven systems. The operational mitigations implemented depend on the details of the operation and the information that an applicant provides to show that the operation will be safe. These operational mitigations may include visual observers on the ground or in a chase aircraft to see and avoid air traffic, avoiding operations above populated areas, flying in restricted or remote airspace, and special coordination with air traffic control (ATC) facilities through the COA process. As UAS are certified and data are collected to show that UAS operations are safe, these operational mitigations may no longer be required.

2.3. SIO Overview

SIO was a NASA and industry partnership with the goal of working toward commercial UAS operations in the NAS at altitudes above 400 ft AGL. SIO consists of three primary components: the integration of prototype DAA and C2 systems into an unmanned aircraft, conducting a flight demonstration in the NAS, and creating artifacts to form the foundation for type certification activities. SIO began in October 2018 after the completion of a partner selection process and ended in January 2021.

The first component of SIO was the integration of DAA and C2 systems into unmanned aircraft in order to motivate the development and maturation of DAA and C2 systems that had a path toward certification. Both DAA and C2 are key technologies for the integration of UAS into the NAS.

The second component of SIO was to conduct flight demonstrations in the NAS. The objectives of those demonstrations were to highlight potential commercial use cases and undergo the process of obtaining operational approvals for flight demonstrations in the NAS. The approvals and operational risk mitigations implemented for the flight demonstrations were also an indicator of the maturity of the UAS and their subsystems, since the ability to operate without operational mitigations indicates a more mature system than one that requires several operational risk mitigations.

The third component of SIO was to create some of the artifacts to begin a type certification program. These documents included a ConOps, ORA, and a draft project specific certification plan. While the original objective was to submit these artifacts to the FAA as part of industry-led type certification activities, one of the findings of SIO was that there was often a need to conduct additional research and development to finalize UAS configurations for certification. As such, in several instances these documents were provided as preliminary or draft documents. It should be noted that progress toward certification was an objective of SIO; however, there was an understanding that this two-year activity would be insufficient to complete a type certification activity and would only address the initial steps. The SIO partners also provided additional documentation to NASA, including a System Design Description focused on the DAA and C2 systems, a UAS User Manual, and a Test and Evaluation Report.

Together, these three components of SIO were used to advance the state-of-the-art toward commercial UAS operations. However, there are still gaps to address and a significant amount of work before full commercial UAS operations can be realized for operations above 400 ft AGL.

2.4. SIO Partners

NASA competitively selected three industry partners to participate in SIO under a cost sharing agreement: American Aerospace Technologies, Inc. (AATI), Bell Textron, Inc., and General Atomics Aeronautical Systems, Inc. (GA-ASI). One of the objectives of the selection process was to create a portfolio of partners that consisted of different types of operations and UAS with different sizes and weights. The operations and weights correspond to the risk-based process that the FAA plans to use for UAS certification, which considers both the kinetic energy of the unmanned aircraft and the risk associated with the operating environment (figure 1). Together, the three partners formed a portfolio of different commercial use cases, risk, and vehicle capabilities.

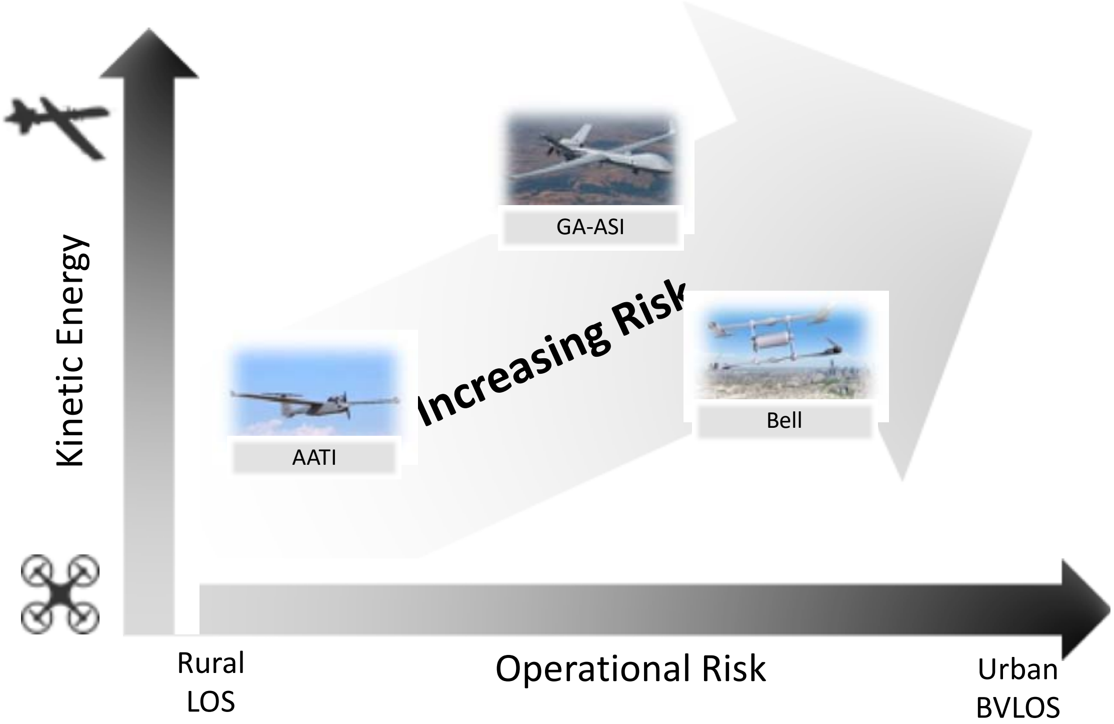

Figure 1: The SIO partners were selected to create a portfolio of different risk UAS and operations

2.4.1. *American Aerospace Technologies, Inc. (AATI)*

AATI will use their AiRanger™ unmanned aircraft to conduct an infrastructure inspection mission. The AiRanger is a derivative of the Resolute Eagle unmanned aircraft purchased by AATI in 2019. AATI's ConOps are focused on pipeline inspection in rural areas using a proprietary pipeline threat detection system. The AiRanger provides greater range, endurance, and payload capacity compared to a small UAS (sUAS) under 55 pounds, enabling the unmanned aircraft to cover more miles of pipeline for a given number of operators. Typical pipeline inspection flights are between 1,000 and 5,000 ft AGL. AATI's objective is for flight operations without the need for an instrument flight rules (IFR) flight plan, ATC separation services, or routine ATC interactions. This is similar to how conventional visual flight rules (VFR) aircraft with a human pilot onboard operate and is expected to provide operational flexibility required to conduct inspection operations.

The AiRanger is a fixed wing unmanned aircraft that weighs approximately 200 pounds. It is launched from a pneumatic launching system and lands on its belly using skid plates. As such, operations may be launched from non-traditional NAS access points and require only a relatively short flat surface for landing. Because of its relatively small size and weight, it is important for all required onboard systems to be low SWaP in order to maximize the range and payload capacity of the aircraft.

Figure 2: AATI AiRanger unmanned aircraft

The DAA system is expected to consist of low-SWaP radars for detection of non-cooperative intruders (aircraft not transmitting ownship state information), ADS-B In for detection of cooperative intruders, and a prototype version of airborne collision avoidance system (ACAS sXu) for generating alerting and guidance. The DAA display is also expected to be integrated into the CS to provide alerting and guidance for the remote pilot. Due to the assumption that flight will occur without an IFR flight plan, it is assumed that prior ATC coordination is not required to perform DAA maneuvers.

The C2 system will consist of a Collins Control and Non-Payload Communications (CNPC) 5000 prototype radio for CNPC communications and Long-Term Evolution (LTE) cell phone networks for transmission of data that was not safety critical, payload data, and to serve as a backup in case the primary C2 link was lost. Since the Collins CNPC 5000 prototype radio is aligned with an RTCA standard [DO-362] and an FAA TSO [TSO-C213], it allows temporary use of the C-Band spectrum allocated for safety-critical UAS CNPC communications.

Due to the transition of the AiRanger UAS assets from another company to AATI during SIO, the flight demonstration occurred at the beginning of 2021. The flight demonstration is expected to take place in sparsely populated areas of San Joaquin Valley in California and include the inspection of local pipelines utilizing the AATI-developed pipeline threat-detection payload. AATI's flight demonstration is expected to require certain operational risk mitigations to compensate for the fact that the aircraft is not certified, and testing is still being conducted to determine the performance of key subsystems, such as the DAA and C2 systems. Some of the safety risk mitigations being considered for the demonstration include visual observers to mitigate the risk of a new prototype DAA system and limiting their operations to sparsely populated areas.

2.4.2. Bell

Bell has been developing an electric-powered vertical takeoff and landing (VTOL) unmanned aircraft called the Autonomous Pod Transport (APT). This vehicle comes in different versions related to different payload capacities.

For SIO, Bell used the aircraft with an approximate 70-pound payload capability called the APT70. While there are several potential use cases for the vehicle, the one that motivated the SIO demonstration was the transportation of emergency medical supplies over urban areas. The APT70 is larger and more capable than sUAS that weigh less than 55 pounds, enabling greater range and payload capacity. The desired flight altitude range for the APT70 is between 500 and 1,000 ft AGL to remain above obstructions and hobbyist grade UAS and below most conventional aircraft flights. Since the objective is to conduct operations above an urban area, Bell's use case requires transit through the Mode-C veil and Class B terminal airspace that is often located above urban areas.

The APT70 weighs approximately 300 pounds. When the vehicle is on the ground it sits on its tail, takes off and lands vertically, and then transitions to horizontal flight during cruise. Because of its VTOL capability, the APT70 can operate from helipads and small aerodromes and does not rely on airport infrastructure. The APT70 is controlled via a CS utilizing a human-on-the-loop paradigm where the remote pilot provides a flight path and the vehicle automatically flies the programmed flight path. The APT70 is also capable of autonomously executing select contingency procedures in the event of lost link or other failures. Because of its relatively small size and weight, it is important for the systems and subsystems to be low SWaP in order to maximize the range and payload capacity of the aircraft.

Figure 3: Bell APT70 unmanned aircraft

The DAA system uses two low-SWaP radars, three HD cameras, and an Automatic Dependent Surveillance - Broadcast (ADS-B) transceiver. A remote pilot controls DAA maneuvers using CS displays based on the RTCA DO-365 Minimum Operational Performance Standards (MOPS) [DO-365], which provides alerting and guidance to the remote pilot. On a separate display, the pilot has access to a weather application with data sources from local weather radars and weather sources such as Meteorological Aerodrome Reports (METARs).

The C2 system consists of four different redundant links and a mechanism to merge the received data into a single stream to minimize the probability of lost link. The four links are two terrestrial radio systems operating on different frequencies and two LTE links utilizing different providers. The two terrestrial radio links did not use the C-Band spectrum allocated for safety-critical CNPC communications due to the lack of commercial-off-the-shelf radios that comply with standards, both RTCA's [DO-362] and the FAA's [TSO-C213], which contain C2 system requirements that must be followed to access the allocated CNPC spectrum. Instead, temporary spectrum licenses were obtained with the knowledge that the radios would need to be substituted for a compliant system for any future certification activities and commercial operations.

The flight demonstration took place in the Dallas Fort Worth (DFW) area and included flight at altitudes between 500 and 1,000 ft AGL in alignment with Bell's expected future commercial ConOps. For the flight demonstration, the APT70 flew an approximately 9.4 NM round-trip route that included segments in Class E and Class B airspace at a location that was deconflicted from instrument departure and arrival procedures used by commercial airliners arriving and departing from DFW airport. There were several safety risk mitigations implemented for the SIO demonstration due to the level of maturity of the UAS and its DAA, C2 and other key subsystems. Risk mitigations included visual observers to augment the DAA system and flying above unpopulated riverbeds, maintaining a one-to-one ratio between the aircraft's altitude and any populated areas, in keeping with recommendations provided by Joint Authorities for Rule Making on Unmanned Systems (JARUS) Specific Operations Risk Assessment [J18]. The flight was coordinated with DFW air traffic controllers. In the event of C2 lost link or other emergencies, there were several emergency landing sites specified along the path that were monitored by visual observers to ensure that they were free of people. If the aircraft lost its C2 link it would automatically land at one of these contingency landing areas before any air traffic could become a threat, since the prototype DAA system required a remote pilot to initiate avoidance maneuvers. There were other failsafe conditions, such as loss of global positioning system (GPS), that would trigger a similar, but not necessarily identical, automated response.

2.4.3. General Atomics Aeronautical Systems, Inc. (GA-ASI)

GA-ASI used their SkyGuardian UAS to conduct a long-endurance multi-modal infrastructure survey and inspection flight demonstration. The concept of operations was to fly a long endurance mission above 10,000 ft to survey multiple pieces of infrastructure in a single flight. In the future, data products from these types of flights may be sold to a variety of organizations to provide services such as public safety support, pipeline leak detection, powerline inspection, railroad inspection, precise mapping of terrain, and crop survey, among other services.

The SkyGuardian is a large, fixed-wing, unmanned aircraft that is a derivative of the military's MQ-9 Reaper platform and designed for civil use and certification. It weighs approximately 12,500 pounds when fully loaded, making it the largest unmanned aircraft that participated in SIO. The SkyGuardian resembles and operates as a traditional fixed wing aircraft does and it is expected to take off and land at traditional airports.

Figure 4: GA-ASI SkyGuardian unmanned aircraft during the SIO demonstration flight

The DAA system was a close derivative of the system used in another joint NASA and GA-ASI activity to perform the first flight of a large unmanned aircraft in Class E airspace without a chase aircraft [MVF18], utilizing the DAA system as an alternate means of compliance to the see and avoid requirements. This DAA system was directly aligned with the Phase 1 RTCA DAA MOPS [DO-365, DO-366]. The Class 2 DAA system used a suite of onboard sensors including an air-to-air radar (ATAR), ADS-B transceiver, and Traffic Alert and Collision Avoidance System II (TCAS II) to detect both cooperative and non-cooperative aircraft. DAA alerting and guidance information was displayed on the control station using DAA traffic displays aligned with RTCA's DO-365 standards, and the remote pilot controlled DAA maneuvers required to remain well clear of detected traffic. The DAA system on SkyGuardian also implemented automatic maneuvering in response to TCAS Resolution Advisories, with the ability for the remote pilot to override the automatic maneuver. These automatic collision avoidance maneuvers helped compensate for C2 latency when the vehicle was controlled through a satellite communication (SATCOM) link.

The C2 system used three different links: a legacy C-Band link, a Ku SATCOM link, and a CNPC link aligned with [DO-362] and [TSO-C213]. The legacy C-Band link is not intended for a future certified unmanned aircraft, but was employed for the SIO flight tests as a low latency line-of-sight link for takeoff, landing, and surface operations because the CNPC link integration did not support all required functions, and it was less risky to use a proven link during these critical phases of flight. The Ku SATCOM link was used for transmission of all ATC voice communications, DAA track data and payload imagery during en route operations. It was also used for transmission of C2 data to control the aircraft when out of range of the CNPC link, and as a safety backup during CNPC operation. The CNPC radio was a prototype Collins CNPC 5000 radio that was used in the vicinity of Gray Butte after takeoff. The Collins CNPC 5000 radio was only partially integrated into the UAS. This radio did not follow the data classes specified in DO-362 due to the need to implement data compression techniques in order to transmit all the necessary information through the limited available bandwidth. When the unmanned aircraft was in range of the antenna located at Gray Butte, the CNPC link was used to transmit C2 data and control the aircraft. However, ATC voice and DAA information, which CNPC Data Class 4 is intended to also carry, were transmitted only over the SATCOM link. In order to fully comply with DO-362, additional work is needed to compress C2, voice and DAA data and conform with the specified data classes.

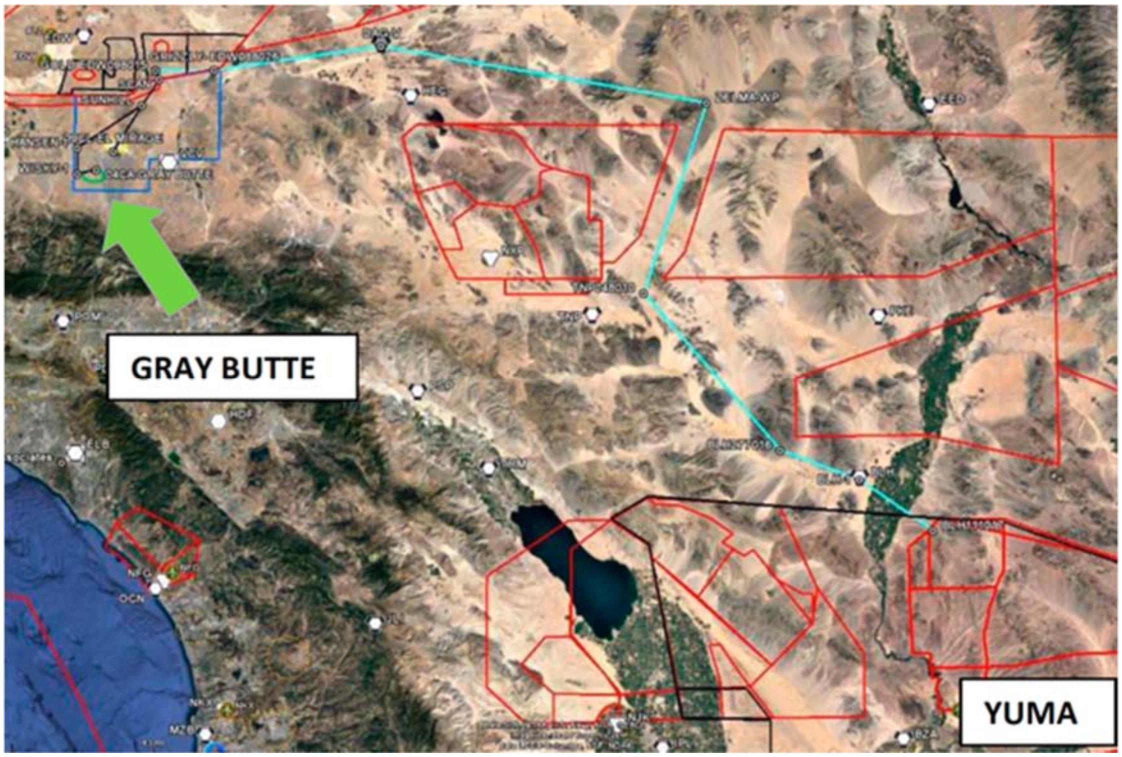

Figure 5: GA-ASI Flight Demonstration Route

The original flight demonstration was planned to occur on a route in the southern California area and included operations above densely populated Class B airspace, with portions of the flight in Class E airspace to be conducted without a chase aircraft. Initially, one of the risk mitigations explored by the FAA for the flight was supplemental ATC flight following services. The additional ATC services were intended to help mitigate the risk associated with a non-certified DAA system and provide extra staffing in case the C2 link was lost or there were other off nominal events. Due to ATC staffing shortages caused by the COVID-19 outbreak in 2020, the ATC facilities were not able provide additional staffing to support the flight following services and because there were areas where non-cooperative VFR traffic may not appear on their scopes. This resulted in a mitigated flight demonstration using an existing transit COA. In subsequent conversations with the FAA, it was clarified that the FAA's Air Traffic Organization (ATO) does not intend to provide any special flight following services to UAS as a mitigation for a non-certified DAA system. The lack of ATC flight following services motivated the need for additional scrutiny of the DAA system by FAA Aircraft Certification Service and the need for a new experimental airworthiness certificate that incorporated DAA system limitations based on the level of maturity of the DAA system. Later, GA-ASI received a new experimental airworthiness certificate and a COA that allowed BVLOS operations in Class E airspace without a chase aircraft. Operational mitigations currently require visual observers when below 3,000 ft AGL for takeoff and landing, and limit time below 10,000 ft MSL, but this approval represents significant progress towards the goal of unrestricted UAS flights within the NAS.

The mitigated flight demonstration used an existing transit COA between Gray Butte and the Yuma Proving Ground. Several pieces of infrastructure were identified along the route to emulate a multi-modal infrastructure inspection mission. The demonstration was a long-endurance mission that took place over an approximately nine-hour period. Since the COA did not authorize the use of the DAA system as the primary method of traffic avoidance, a chase aircraft was used in Class E airspace, standard ATC separation services were provided in Class A airspace, and other portions of the flight took place in restricted airspace. The SkyGuardian took off from Gray Butte and conducted operations in the local Gray Butte area to test the CNPC C2 link and survey local Gray Butte infrastructure. Next, the aircraft climbed up to Class A airspace and transited along the cyan route in figure 5, surveying land along the route. After conducting surveying operations in restricted airspace at the Yuma Proving Ground for approximately two hours, the SkyGuardian transited back to Gray Butte, where additional CNPC radio testing and local infrastructure inspection was conducted.

3. Overview of Safety and Certification

The aviation industry, overall, has an excellent safety record. UAS, as a relatively new part of the aviation industry, are expected to maintain that excellent safety record. However, the characteristics of a basic UAS operation, such as the pilot not being on board the aircraft, result in significantly different aircraft designs which, in turn, result in different hazards than conventionally piloted aircraft. (A conventionally piloted aircraft is an aircraft with an on-board pilot.) As such, how one shows that a UAS is safe is different than conventional aircraft. This section provides a very high-level overview. Readers who are already familiar with aviation safety and certification may skip this section.

Ensuring a system is safe is a complex problem. This problem spans the whole systems engineering process and involves an aircraft that is designed to be safe, manufactured to that design, maintained in conformance to the design, and is operated by a pilot with appropriate knowledge and skills. However, this problem also involves a foundation of clear and comprehensive airspace rules and an aviation system environment (for example, air traffic controllers, procedures, radars, and GPS) designed to support safe operations. In the United States, the FAA both provides this aviation infrastructure and acts as the regulator of aviation safety. As such, procedures and approaches have been developed to evaluate and improve the safety of each of these elements. As described above, the SIO effort was concerned with certification and operational approval. The FAA is also working in other areas to ensure the overall system is safe. Although safety is the primary purpose of the FAA's regulatory structure, the FAA also uses this structure to maintain other concerns of community acceptance such as noise minimization and efficient traffic flow management.

Ten years ago, the only existing regulations for civil type certification would have been a detailed set of requirements applicable to conventional aircraft. Applicants would have had to work entirely in a world of exemptions and special conditions to the regulations. Over the last ten years, the FAA has worked diligently to develop a series of safety and certification procedures to allow UAS to become full participants in the NAS. This aggressive campaign by the FAA has been geared at accomplishing two tasks: (1) to reshape the regulations around performance-based objectives that describe the safety goal instead of detailed design requirements that describe the means to achieve the safety goal and (2) to develop standard approaches for approving the safety of unique UAS characteristics. The FAA continues to work on integrating UAS into the NAS. If the regulations do not apply to a particular aircraft the FAA has many options including special conditions, equivalent level of safety determinations, waivers, and exemptions. An option that does not exist is for UAS developers or operators to ignore the nation's regulatory framework.

Certification is a particular legal process that the FAA uses to ensure certain regulatory requirements are satisfied. The expectation is that the regulatory requirements are established in a way to produce safe systems along with other Congressional objectives. The FAA certifies many entities, but for the purposes of SIO, the entity of study is the aircraft including systems that are part of the aircraft. With regard to aircraft, the FAA issues three primary types of certificates: type certificates, production certificates, and airworthiness certificates. For a readable introduction see [McC07]; for a more complete introduction see [GPC17]. The FAA issues a type certificate when they are satisfied that the regulatory requirements for a safe type of aircraft have been met. In essence, this is a certification of the design of the aircraft. The production certificate is a certificate that shows that a manufacturer can consistently produce aircraft in full accord with the type design. Finally, an airworthiness certificate is a certificate that says a particular aircraft has met the regulations required for safe flight, typically meaning that it was both manufactured and maintained in compliance with its type certificate. For various experimental or other one-off aircraft, the FAA will issue an experimental airworthiness certificate without an accompanying type certificate. Aircraft with a type certificate and manufactured under a production certificate have a much easier time getting an airworthiness certificate. For UAS, this basic structure is expected to be maintained, except for one key point, the aircraft will not simply be the part that flies but rather the whole system that includes the aircraft including all onboard systems, any ground support elements, and any approvals to use radio spectrum. One final notion is the condition of being airworthy, which is a separate concept from an airworthiness certificate. Being airworthy means being in a condition for safe flight. Pilots are required to ensure their aircraft is airworthy before each flight. An aircraft could have an airworthiness certificate and no longer be airworthy, perhaps due to a part breaking, maintenance personnel having disassembled the aircraft, or because of an incident during ground handling. Being airworthy is a concept that has been retained for UAS.

As discussed above, one can obtain an experimental airworthiness certificate for an aircraft without a type certificate. An experimental airworthiness certificate comes with some significant limitations on its operations. Since such an aircraft may have substantially less system integrity, its risk profile is higher and, therefore, the FAA limits where these aircraft can fly by both the types of airspace and the area being overflown. Perhaps even more significantly, an aircraft under an experimental certificate cannot be flown for "compensation or hire;" although, they can be used for other purposes related to the development, training, or marketing of an aircraft. The SIO partners used experimental airworthiness certificates to obtain operational approval to fly their aircraft for the SIO flight demonstrations. An operational approval is a different type of approval than an airworthiness certificate. Operational approvals, such as COAs and 91.113 waivers, are addressed briefly at the end of this section and more completely in the best practices (see section 7).

Next, we turn to how one shows that a type design complies with the regulations. As an example, listed below is one regulation, 14 CFR 23.2500:

(a) The equipment and systems required for an airplane to operate safely in the kinds of operations for which certification is requested (Day VFR, Night VFR, IFR) must be designed and installed to —
    (1) meet the level of safety applicable to the certification and performance level of the airplane; and
    (2) perform their intended function throughout the operating and environmental limits for which the airplane is certificated.

Certainly, this regulation is clear in its intent: systems must be safe. But, how, in practical terms does one achieve this and how does one show others that it has been achieved? The FAA approach relies on the discipline of system safety, which is sometimes called safety engineering, that has developed over the last 40 years. A good manual which describes many of the basic precepts of system safety is the FAA's System Safety Handbook [SS00]. Other references include [LT85, L95, B10, E11]. It would be impossible to give an overview of system safety in this section; instead a few important guiding principles are provided. One of the bedrock principles of a safety program is the elimination of harm; however, due to unavoidable personnel, technological, and economic limitations, this goal is rarely achieved. The FAA's role can be viewed as ensuring that all reasonable precautions have been taken to eliminate harm. For this discussion, harm means anything that we do not want to happen; it certainly includes events like the aircraft crashing, but it also includes events like disruption of air traffic. The next principle is that safety is different than damage mitigation. Damage mitigation techniques are ways that can reduce harm. Damage mitigation "makes an accident better," whereas safety eliminates the harm. There is a substantial difference between having a fire extinguisher (damage mitigation) versus using an inflammable material (safety). As important as damage mitigation is, it can never serve as a replacement for safety. Another principle is that reliability and safety are different concepts: a system can be very reliable but unsafe, or conversely, very safe and very unreliable. A car without brake lights is unsafe, and this fact is distinct from whether we can count on it starting in the morning (reliability). For many systems, the safety of the system depends on the reliability of some parts of the system, but simply making a system reliable does not make a system safe.

System safety is often assessed using a core analysis technique called hazard analysis. A hazard is a condition of the system that leads to harm when combined with environmental and other external conditions. The idea of a hazard analysis is if one knows all the hazards, then one can work to eliminate them and hence eliminate harm. Identifying hazards can get tricky, usually due to misunderstanding the nature of a hazard. A hazard is not the harm itself. One would not identify a near-miss as a hazard; rather, a near-miss is what we are trying to avoid. Another common confusion is that failures are not hazards. For instance, "loss of antenna" on a UAS is not a hazard, whereas "fly away" is a hazard. Loss of antenna is a potential cause for a fly away hazard that may cause harm to others if the UAS injures people or destroys property. Many mitigations can be put in place to ensure that a failure does not lead to a hazard.

Mitigations of hazards generally refer to either reducing the likelihood the system will enter the hazardous state or reduce the severity of the harm. Because of inherent personnel, technological, or economic limitations, one wants to ensure that the most important or most critical hazards are mitigated. This prioritization is accomplished through rating hazards by their severity and likelihood, or the metric which combines both: risk. Hazard mitigations often induce requirements on other parts of the system. Mitigations can take the form of design requirements such as adding redundant subsystems, development requirements such as integrity requirements on software, procedural requirements like pilot training, or operational mitigations such as limiting operations to regions of airspace that only have light air traffic. It is still an open problem if traditional aircraft mitigations are sufficient for UAS. One way to mitigate hazards related to design error is through Design Assurance Levels (DALs) [SAE4754A], which map to software development levels [DO-178C] and hardware development levels [DO-254]. These levels require more stringent, and hence more costly, engineering testing and verification practices for higher levels of assurance. The notion of integrity requirements is a common concern among UAS developers, especially for software. Software design error risk could also be addressed at the hazard analysis level. If the hazard is mitigated through an operational restriction, the software may no longer exhibit a safety-critical function and therefore no longer require high assurance of safe operation. There are multiple techniques to capture safety, hazard, risk, and other information. Draft AC21.17 proposes guidance on hazard analysis standards that may be used: aircraft greater than 55 pounds may use the hazard analysis process described in [SAE4761] and sUAS less than 55 pounds may use the process described in [ASTM-F3178-16]. [GNW00] describes a comparison of two approaches. FAA personnel are experts in reviewing this type of material, so an applicant can expect probing questions on any safety, hazard, or risk information they present to the FAA.

It is reasonable to consider that if the FAA must approve a UAS's safety through the certification process, then an applicant should collect the preferred safety information and present it in the FAA's preferred format. This reasonable observation leads to the extensive and detailed process related to aviation certification [McC07]. Although conceptually the process is straightforward, many important details remain. These details are best handled by people with experience dealing with the different FAA offices and certification. Due to the massive detail on this subject, only a few topics will be brought up in this section that are directly relevant to topics brought up in the rest of this paper. One term of art that is used in this document is a Technical Standard Order (TSO). A TSO is a document that lists a set of requirements for some aircraft material, part, component, process, or appliance. It could be a simple part like a bolt, or a complex part like a flight control system including both hardware and software. When a TSO is approved it indicates that this piece of equipment can be used to satisfy some of the regulatory airworthiness requirements. A manufacturer must obtain a Technical Standard Order Authorization (TSOA) to say that parts coming from their manufacturing process comply with the associated TSO. However, just because a part complies with a TSO does not mean that a part can be installed on an aircraft. Either the aircraft's Type Certificate or a Supplemental Type Certificate must be issued to allow such a part to be installed on an aircraft. (A Supplemental Type Certificate is a certification of the design of an existing aircraft.)

As described above, the Type Certificate is reviewed by the FAA to ensure the design of the aircraft is safe. Another common issue is how to show evidence indicating the aircraft complies with a regulation. The FAA uses two more terms of art: *means of compliance* and *methods of compliance*. The means of compliance are typically detailed documents from industry consensus standards organizations such as the ASTM or RTCA. These documents describe what evidence is to be collected, but not how the evidence is to be collected. There are an extensive set of documents that can be used for the means of compliance and many of them have been specialized for UAS. The methods of compliance are the methods proposed by the applicant to collect the evidence in support of a means of compliance and these include analysis, ground testing, flight testing, and similarity. It should be noted that some applicants find some methods easier to conduct than others, so the FAA typically gives some leeway with regard to the methods of compliance. The last term of art is a Designated Engineering Representative (DER). DERs are people, approved by the FAA but paid by the manufacturer, who can oversee and approve the collection of engineering evidence to ensure that it was collected in a suitable, uncorrupted manner. Essentially, they are attempting to ensure that the evidence shows what it was intended to show. DERs are used extensively when certifying conventional aircraft. The DER structure has not been adopted by the FAA for UAS; only the FAA can approve UAS evidence. Due to the sheer volume of UAS designs and operations, it seems reasonable to expect that in the future the FAA will use some structure to ensure that certification evidence is collected in a consistent manner. DERs also serve another role due to their expertise in FAA policy and procedures: they often act as consultants to developers regarding the most effective approach to solving engineering and certification problems. In the SIO project, DER's offered valuable insights to system developers regarding how the FAA "typically" approaches certain types of problems.

An aspect of safety that became significant during the SIO effort was the notion of operational approval. Type and experimental certification address whether the UAS is airworthy, not whether the aircraft operates safely and as a well-behaved member of the NAS. Officially, operational approval is not aircraft certification, but many of the same concepts apply; hazards must still be mitigated. The main difference are the organizations in the FAA involved and the hazards of concern. Operational approvals ensure that one does not place an unnecessary burden on other NAS users or consume a disproportionate amount of attention from ATC.

4. Current State of UAS Standards

As described in the previous section, the FAA relies on documents to show a *means of compliance* to specific certification and operational approval regulations. Although applicants are not required to use standards documents from industry consensus organizations as means of compliance, for consistency, this is the FAA's preferred path. In fact, a regulation could be satisfied through different means of compliance, representing different industry consensus standards. An applicant uses these documents as part of their safety case, essentially stating that they are going to meet the regulatory requirements by complying with the detailed technical requirements that are captured in these standards. Some of these standards cover rigorous engineering development and others cover the specific performance requirements of an aircraft system. A number of these documents have been developed for UAS in recent years that cover key technologies such as DAA systems, C2 communications, and control stations. Several of these are formulated through the RTCA; others are formulated through ASTM, SAE, and other standards bodies. A number of world-wide standards organizations address portions of the UAS function. The American National

Standards Institute (ANSI) Unmanned Aircraft Systems Standardization Collective (UASSC) 20-001 Standardization Roadmap for Unmanned Aircraft Systems [ANSI2020] provides an organization and direction of the various standards for UAS. This section does not provide all the detail in each standard, rather it attempts to provide a general overview of several key documents.

4.1. RTCA Standards

The RTCA is an organization with a long history in developing standards for the aviation industry. RTCA produces Minimum Aviation System Performance Standards (MASPS) which define global behavior and MOPS which define system-level behavior. Three RTCA MOPS are directly relevant to UAS including C2 [DO-362], DAA [DO-365], and ATAR for Traffic Surveillance [DO-366]. Additionally, RTCA developed a C2 Link System MASPS [DO-377] which articulates a series of requirements for a C2 system. RTCA also produces development standards for software [DO-178C], for complex computer hardware [DO-254], and for environmental testing [DO-160G]. Other relevant standards and organizations include the TCAS II MOPS [DO-185], NEXCOM [DO-285], ACAS-X [DO-386], and Approval of Air Traffic Services [DO-264].

4.1.1. RTCA-DO-362 Command and Control Data Link MOPS

RTCA-DO-362 MOPS [DO-362] describes a UAS-specific communications link system called CNPC. The CNPC link system is responsible for performing the control and communication functions of the UAS in order to allow the remote pilot to safely control, monitor, and manage the UAS. The main focus of DO-362 is the compatibility requirements to share the spectrum that has been allocated for their use and remain waveform agnostic (L-Band or C-Band). Link security standards are also critical.

“Control” (the C of CNPC) is defined with respect to the bi-directional information exchanges that allow the remote pilot to perform closed-loop control of the UAS in order to safely maneuver the aircraft on the ground and in the air. Examples of commands to UAS from the remote pilot include executing turns, changes in engine operation, changes in radio frequencies. Examples of information to the remote pilot from UAS include confirmation of receipts and actions taken in response to commands. “Non-payload communication” (the NPC of CNPC) is defined with respect to the capability to support remote pilot to/from ATC voice communications. CNPC is specifically not payload data; this communication includes target data (DAA), video, navigation data, weather data, and ATC voice relay.

The frequency allocation for CNPC in the L-Band, C-Band, cellular, and satellite (Phase 2) pose challenges due to over-subscription in some bands and undersubscription in other bands. Two frequency bands have been identified as potentially available for terrestrial CNPC use L-Band 960-1164 megahertz (MHz) and C-Band 5030-5091 MHz. The L-Band, though potentially more desirable for its substantially longer communication ranges than C-Band, is much more congested than the C-Band. On the other hand, the C-Band is much less congested, and it is anticipated the full band is available for UAS use. Appendix C of DO-362 addresses methods to integrate L- and C-Band operation in order to (1) reduce certification costs, (2) improve system performance due to simultaneous operation, and (3) evaluate SWaP approach with physical integration into a common L/C-Band radio. Note that ongoing discussions with the FAA have left the use of L-band uncertain. Further studies are needed to ensure that L-band can be used for C2 without interference to other L-band systems.

Equipment test procedures are defined to demonstrate compliance with the performance requirements. Test classes are Environmental Tests, Bench Tests, Installed Equipment Tests, Operational Tests, and Equipment Test Procedures. The validation and verification of the DO-362 requirements focus on sharing spectrum, remaining waveform agnostic, baseline waveform performance standards, and manufacturer performance standards. The validation of the normative requirements was accomplished through a combination of analysis and test for the nine operational capabilities defined in Appendix F of DO-362. The safety design assurances are touched upon briefly, noting that software must follow DO-178C and DO-254. Environmental tests and performance requirements provide a laboratory means of testing UAS performance under conditions which would be encountered in actual operations. These tests leverage DO-160 and define over 25 different environmental conditions.

4.1.2. RTCA-DO-377 Command and Control Link Systems MASPS

RTCA recognizes that different C2 links, or combinations of links, will be necessary to support different UAS missions, SC-228 WG2 sought to develop a common set of requirements applicable to any C2 link that supports UAS operations described in the MASPS ConOps. The DO-377 MASPS, which was issued after the DO-362 MOPS, contains a series of operational, functional, performance, safety, and security requirements for C2 link systems.

The C2 Link MASPS currently contains ConOps for two UAS missions (local linear sensing and local aerial survey) with an expectation that additional missions will be included in future revisions. Operational Services and Environmental Descriptions are then developed based on these ConOps, followed by the Operational Safety Assessment and Operational Performance Assessment that were used to develop the minimum performance requirements for C2 link systems supporting the missions described in the ConOps and Operational Services and Environmental Descriptions.

4.1.3. RTCA-DO-365 MOPS for Detect and Avoid Systems

Routine access to the NAS will require compliance with the existing “see-and-avoid” requirement for separation maintenance as defined by the regulations in 14 CFR 91. The DAA MOPS was developed to provide a means for UAS operators to comply with the regulations by generating and displaying predictive alerting and guidance to assist the remote pilot in maintaining safe separation from surrounding aircraft. In conjunction with RTCA Special Committee 228 (SC-228), NASA has been working closely with the UAS community to develop the DO-365 MOPS for DAA equipment [DO-365].

Phase 1 of the DAA MOPS includes the transition to and from Class A or special use airspace (SUA), and the traversal through Class D, E, and G airspace above 400 ft AGL. Phase 2 Rev A of the MOPS, scheduled for publication in 2021, expands the operational environment to support extended operations in Class D, E, and G airspace; take-off and landing from Class C, D, E, and G airspace; and transit through Class B airspace. Phase 2 Rev B of the MOPS, scheduled for publication later in 2021, incorporates Rev A of the Airborne Radar MOPS (DO-366A) and ACAS Xu (from DO-386). Phase 3 of the DAA MOPS will address use cases applicable to smaller UAS, including platforms with limited performance and operations closer to terrain/obstacles.

The MOPS require that UAS be operated in accordance with IFR, that they be equipped with communication, surveillance and navigation instruments and an anti-collision lighting system appropriate for IFR operation, and that they sufficiently support all the necessary DAA functions. Since requirements for autonomous DAA maneuvers have not been developed except for specific mitigations such as lost link or automatic responses to Resolution Advisories (RAs), a remote pilot is considered to be in the loop at all times.

DO-365 contains DAA open- and closed-loop performance metrics and includes details for consistent metrics collection. The Technical Performance Metrics (TPMs) defined herein serve as an objective and implementation-independent basis to determine the open-loop alerting performance and closed-loop performance of a specific alerting system implementation. The open-loop TPMs measure unmitigated open-loop alerting system performance. The fundamental task of an alerting system is to determine whether a particular hazard is present during an operation, given limited information about the environment. The closed-loop TPMs measure how well a system performs when maneuvering (mitigating) after an alert. Closed-loop TPMs enable the quantification of nominal DAA system performance in the airspace environment.

DAA systems rely upon the ability to create tracks for the aircraft in their vicinity. From these tracks, a variety of DAA alerts can be generated by a dedicated DAA algorithm. For DO-365 the baseline algorithm is Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) [MNHUDCC15]. However other algorithms are also being developed, including ACAS-Xu, which adds DAA alerting and guidance to the collision avoidance (CA) alerting and guidance it inherited through its ACAS-X and TCAS II lineage.

Most of time these tracks are created from the data of Mode-S and/or ADS-B transponders. However, in the event aircraft do not have these transponders or the systems have failed, DAA systems still require tracks for these aircraft if they are to be effective. One method is the use of radar through ATAR [DO-366 ATAR]. In principle, additional non-cooperative onboard methods could also be used including vision processing methods as well as auditory methods.

4.1.4. RTCA-DO-366 Air-to-Air Radar

RTCA SC-228 is responsible for developing the MOPS for traffic surveillance radar on UAS. ATAR is required to detect non-cooperative intruders and/or validate surveillance of cooperative intruders. The RTCA-DO-366 MOPS [DO-366] is a companion document to DO-365; as such, the scope mirrors that of DO-365 for vehicle, airspace, level of vehicle automation and core assumptions. Accordingly, the initial release of the DO-366 MOPS in 2017 pertained to Phase 1 DAA MOPS requirements. DO-366A, approved by RTCA in September 2020, contains additional requirements for Phase 2 DAA, which includes requirements for low-SWaP radar.

DO-366A revises the required surveillance volume using the non-cooperative DAA Well Clear (DWC) definition, and expanded to three categories, named A1, A2 and A3, supporting Class 1 and 2 DAA equipment for UAS operations with varying speed ranges:

1. High-speed unmanned aircraft (Radar Class A1) between 100 and 291 KTAS
2. Medium-speed unmanned aircraft (Radar Class A2) between 40 and 200 KTAS
3. Low-speed unmanned aircraft (Radar Class A3) between 40 and 110 KTAS. This is the assumed speed range for low-SWaP operations

DO-366A also contains a B1 class for Class 3 DAA equipment, for which ACAS-Xu is required. The B1 class is intended for supporting unmanned aircraft between 40 and 200 KTAS.

The intended airspace operation is the same as DAA Phase 1: transitioning to/from Class A airspace, traversing Class D, E, and G airspace. It does not apply to smaller UAS flying below 400 ft AGL. DO-366A requires that the minimum altitude for radar operation be defined by the manufacturer, but recommends a minimum altitude of 1,000 ft AGL, below which ground cluttering issues can be challenging.

The ATAR provides tracks for aircraft within the radar declaration volume and is the primary source of surveillance for non-cooperative aircraft. Aircraft can be non-cooperative for a variety of reasons including (1) older aircraft that do not have baseline technology, (2) current aircraft which have lost their ability to communicate with baseline technology, (3) aircraft that are currently exempted from transponder requirements (for example, ultralights and some light sport aircraft), and (4) adversarial aircraft with respect to security.

4.1.5. RTCA-DO-386 ACAS Xu MOPS

The RTCA-DO-386 ACAS Xu MOPS [DO-386] specifies minimum requirements for a collision avoidance system (CAS) including surveillance, tracking, and threat resolution functionalities. It includes optimized logic methodologies used by the collision avoidance logic and its performance, as well as providing testing of all requirements. The ACAS Xu MOPS will be used by the regulators as a basis for new or revised TSO(s) and guidance material as appropriate. These MOPS will be used by the SC-228 Phase 2 DAA standards development effort. ACAS Xu will provide collision avoidance protection for UAS that is interoperable with TCAS II and ACAS X systems.

DO-386 will be released in two volumes as follows:

- Volume 1: Covers the minimum performance standards for relevant equipment (scheduled 2021).
- Volume 2: ACAS Xu algorithm description document (scheduled 2021). It should be noted that the ACAS Xu DAA algorithm is independent of the Phase 1 RTCA-DO-365 reference algorithm known as DAIDALUS.

As required by all DAA collision avoidance algorithms, ACAS Xu requires that UAS will be operated in accordance with IFR, will be equipped with communication, surveillance and navigation instruments, an anti-collision lighting system appropriate for IFR operation and that all the necessary DAA functions are supported. DO-386 pertains to UAS with cruise speeds between 40-200 KTAS, with maneuverability assumptions such as 500 fpm climb/descent and 3 deg/sec turn rate. There are no vehicle size limitations.

ACAS Xu will be authorized for use in the same airspace as Phase 1 RTCA-DO-365, which includes operations transiting into, out of, or through Class D, E (up to 18,000 ft or flight level 180), and G airspace to/from Class A or SUA higher than 400 ft AGL. It does not apply to UAS operating in low-level environments (below 400 ft AGL) or other segmented areas. Operations between 400 ft and 1000 ft AGL are considered part of the takeoff or landing phase and separation will be handled by other means. Class E airspace above flight level 600 is out of scope for Phase 1 DAA equipment. No terminal operations are authorized.

ACAS Xu is currently intended for remotely piloted operations; autonomous DAA maneuvers are not authorized for specific mitigations such as lost link; however, automatic responses to resolution advisories are allowed. DO-365B will include the optional automatic collision alert requirements that ACAS Xu implementers may choose to follow.

SC-228 and SC-147 have drafted an Inter-Special Committee Requirements Agreement which recognizes that “DAA will need to coordinate and be fully interoperable with TCAS and future CAS, such as ACAS X.” SC-147 and SC-228 will develop an interoperability standard for collision avoidance systems to support the development of the DAA MOPS. It delegates to SC-147 the task of producing “Interoperability and Coordination Requirements to ensure that any new collision avoidance, self-separation, or integrated DAA system … will not adversely affect the performance of TCAS or other CAS.” SC-228 is responsible for coordinating the relationship between the scopes of the Phase 2 DAA MOPS and the initial ACAS Xu system. Existing standards such as ACAS Xu MOPS can be evaluated for consistency and compliance with the SC-228 DAA MOPS. The draft version of DO-365B contains an appendix to aid in this effort.

4.2. ASTM Standards Documents

When the UAS standards process began in earnest in 2012, the RTCA standards were targeted to UAS above 55 pounds, while ASTM standards (specifically, the F38 subcommittee) were targeted to UAS below 55 pounds and operations under 1,200 ft AGL. As time has gone on, the ASTM standards continue to be targeted at the lower end of the UAS size range, but the scope of some of the standards are applicable to vehicles above 55 pounds.

The FAA Modernization and Reform Act of 2012 brought about a number of large changes still in effect today, including the approval of 14 CFR 107 concise requirements for sUAS with no COA required for visual line of sight (VLOS) operations. This type of operation, commonly referred to as “Part 107,” specifically prohibits autonomous operation. Much of the motivation of Part 107 was to streamline the approval process required to fly in the NAS for UAS under 55 pounds. With the advent of Part 107, the extension of sUAS operations to higher risk categories such as operations over people and BVLOS have resulted in an increased number of Part 107 waivers. ASTM standards have sought to address the absence of a COA requirement for Part 107 for extended operation through the development of ASTM systems engineering foundation and baseline standards certified through operation risk methods [ASTM-F3178-16]. The standards include design and construction standards, operations over people, and BVLOS operations [K18, R17].

The F38 subcommittee of ASTM produces standards for UAS in three areas: airworthiness, flight operations, and flight training. F38.01 Airworthiness is currently developing work item 62668 entitled “DAA Performance” [ASTMWK62668] and work item 62669 entitled “DAA Test Methods” [ASTMWK62669]. The rationale for these proposed standards is to reduce the number of waivers sought for sUAS BVLOS operations due to significant interest from industry (BVLOS operators and manufacturers of DAA systems).

The “DAA Performance” work item [ASTMWK62668] is in draft form and under development by the ASTM committee. It defines the minimum performance standards for DAA systems applicable to smaller UAS BVLOS operations for the protection of manned aircraft in lower altitude airspace and applies to unmanned aircraft with a wingspan or rotor diameter less than 25 ft and assumes no ATC separation services. The standard is applicable to the avoidance of manned aircraft by unmanned aircraft, not unmanned aircraft-to-unmanned aircraft terrain/obstacle/airspace avoidance (to be addressed in future efforts). Although designed to enable BVLOS, such systems may also support operations within the remote pilot's VLOS. The system is DAA architecture agnostic and is expected to be used by a wide range of applicants including DAA system designers/integrators, sensor suppliers, unmanned aircraft developers, CS designers, and flight control designers. The standard assumes DAA systems share a common set of attributes, including intruder level of cooperation, DAA level of autonomy, location of DAA systems and functionality, and sensor type. The sUAS System Description is divided into a set of subsections: system verification, safety, sUAS DAA performance requirements, sUAS DAA robustness requirements, reliability and maintenance, security, and environment. Additional sUAS sections identify system timing for detection, alert, and avoid.

The Test Methods for Detect and Avoid Systems work item [ASTMWK62669] is in draft form and under the development by the ASTM committee. The scope of this work item is to define test methods for DAA systems and sensors applicable to smaller UAS BVLOS operations for the protection of manned aircraft in lower altitude airspace.

In addition, the F38 subcommittee has produced guidance documents to aid in the FAA certification for smaller UAS. The FAA has been working with industry and ASTM to develop a durability and reliability means of compliance for smaller UAS. Several industry standards are invoked by the durability and reliability process including the following ASTM standards:

- F2908-18 – Standard Specification for Unmanned Aircraft Flight Manual for UAS,
- F3153-15 – Standard Specification for Verification of Avionics Systems, and
- F3322-18 – Standard Specification for sUAS Parachutes [F19].

ASTM proposed a means of compliance to satisfy 14 CFR 23 based on the ASTM consensus standards spreadsheet for larger UAS. This gives industry applicants a jumpstart on what standards they can look at to provide a means of compliance for type certification.

5. UAS Through the Process

As described in the "Overview of Safety and Certification" section (section 3), safety is an emergent property of the whole system, and the whole system has many aspects to it. These dimensions include the vehicle being designed and built safely, the operators being trained to operate the aircraft safely, and a set of airspace rules that ensure safety for all types of airspace users, including conventional air traffic, unmanned aircraft, weather balloons, and many others. Sometimes this collection of information is called a "safety case." The term comes from a legal metaphor, the case is being made that the system is safe. This section addresses a primary focus of SIO: ensuring the UAS is designed and built to be airworthy. When documentation about a UAS shows, to the satisfaction of the FAA, that the aircraft is airworthy, the FAA will grant that aircraft an airworthiness certificate. This section describes the current FAA approach to UAS certification. An important step before the airworthiness certificate is a Type Certificate. A Type Certificate, by current FAA regulations, can be issued in two ways. 14 CFR 21.17(a) states that a Type Certificate can be based on the specific regulations for a class of aircraft. Unfortunately, the FAA does not currently have the specific regulations for UAS as an aircraft class. Therefore, the most promising avenue is 14 CFR 21.17(b) which says that an applicant to the FAA can assemble a set of design standards appropriate for their aircraft, perhaps from existing conventional aircraft regulations, aviation industry standards, or other sources, in order to get FAA approval, then proceed to obtaining type certification. This is the path that the FAA assumes with a draft advisory circular "Type Certification – Unmanned Aircraft Systems (UAS)" [DraftAC21.17].

The FAA has offered an alternate approach to show the safety of a UAS system where the foundation of this approach is based on using durability and reliability (D&R) testing as a means of compliance to the regulations [F19]. The D&R approach is intended for smaller UAS than the SIO partners' vehicles. This approach requires functional testing of the UAS with the number of hours of flight testing based on the risk of the operation, where risk can be determined through factors like kinetic energy, overflown area, and airspace. For larger sizes or faster aircraft speeds, the hours of testing required may become cost prohibitive or impractical. Due to the higher kinetic energy involved, no SIO partner followed this approach. This is an active area of regulatory development; maximum aircraft weight limits have not been established yet.

There are three aspects to D&R testing. First, is the testing itself to show safe and effective overall system functionality. Next, the FAA requires specific failure modes to be demonstrated to ensure the system response is what was expected given that such modes may not appear during testing, for example, lost link. Finally, there are some hazards that cannot be effectively mitigated through testing alone, so the FAA requires specific design items to be present. A key aspect of this approach is that "where and how" one tests their aircraft is the definition of the operation. For example, if one demonstrates that they can fly over a hill, then that does not mean that they will be approved to fly over a building. It will be challenging to use the D&R approach until there is a DAA solution with a TSO. This may be a no-win situation since one cannot fly without an FAA-approved DAA, but they cannot get certified until they fly. It may be the case that the first certified DAA solution will require a traditional certification.

5.1. Concept of Operations (ConOps)

One key document for a UAS type certification process is the Concept of Operations or ConOps. This document presents a description of the vehicle, the mission that the vehicle is intended to perform, the proposed area of operation (including airspace), and the actions of the relevant personnel regarding how the vehicle will be operated to accomplish the mission [DraftAC21.17]. Sometimes the ConOps document itself does not contain all this information; rather it contains references to other documents which contain this information. The ConOps serves as the foundational document describing the UAS aircraft and mission, and under [Order8110.4C], its approval by the FAA is a necessary precondition to proceed to the type certification board. The primary safety analysis tool used for UAS is the ORA, and the ConOps serves as a basis for the development of the ORA [DraftAC21.17]. Every risk mitigation in the ORA should be tracible to the ConOps.

In engineering system development, ConOps documents are used by different groups for different purposes. The purpose of the ConOps will often determine the information that is included and the depth at which it is covered. In some contexts, the purpose of a ConOps is primarily to describe the mission. In these situations, the people reading these ConOps are attempting to determine if the system will help them accomplish their goals. This might be thought of as a customer focused ConOps. In other contexts, the purpose of a ConOps is to evaluate the benefits and costs of the system, perhaps to determine if ConOps captures an operation that is economically viable. This might be thought of as an investor-focused ConOps. Answering the questions of key stakeholders like customers or investors is critical to the success of any UAS project; however, the questions that these groups want answered are not of primary importance to the FAA.

By both law and custom, the FAA's primary focus is on safety. Interpreting this general statement for a ConOps, the FAA is primarily interested in how the operation will be performed in a safe manner. The FAA is interested in a description of the vehicle, like in any ConOps, but the FAA is primarily interested in the vehicle description to answer safety questions. The FAA is interested in how the aircraft will detect and avoid other traffic (see section 6.3 for more details). The FAA is interested in how the remote pilot will maintain control of the aircraft; therefore, the number of C2 links and the characteristics of these links (see section 6.4 for more information) are the areas where the FAA is most interested. However, one should not view this document narrowly and only talk about safety. The FAA asks for a description of the entire operation. Part of the reason for this is that safety issues may arise in slight incompatibilities between system elements. For instance, as one SIO partner discovered, if the DAA system takes autonomous action, this enhances safety from the standpoint of a fast response time. However, it introduces a potential uncertainty about what happens if the remote pilot issues a command while the DAA system is commanding the aircraft. The FAA is interested in system descriptions to ensure that all such interactions are handled in a predictable and safe manner.

The FAA is interested in the purpose of the operation, but not its value. Value is fundamentally a business decision and not of the FAA's concern. However, purpose can be helpful in the FAA's analysis. If the FAA understands the purpose of the operation, they may be able to suggest another way to accomplish an operation, presumably with lower risk. Although the FAA may perform this role, they are not required to. Ultimately, the FAA is only required to evaluate the safety information presented to them. The FAA offered this type of solution to one SIO partner with regard to the class of airspace; although the partner chose a different way to lower risk.

In more practical terms, the ConOps should be written recognizing that someone outside the development team is reading it. All acronyms should be defined, and simple document hints like a table of contents can greatly help the reader. One partner initially didn't include these simple things and the FAA noted a lack of certain information within the application. The partner had included the information, but there was no obvious way for the FAA to find the answer in the document given the absence of a table of contents. The objective of this document should be to make the operation clear, so that the FAA will make a judgement based on the clearest possible understanding of what is being proposed. The ConOps is evaluated by different groups within the FAA that have different specialties. Each of these groups may be seeing the document for the first time, so a table of contents and other standard formatting techniques can help the reader quickly find pertinent information. As another partner found out, the FAA will not approve an operation until all questions are answered; confusing language causes unnecessary delays.

From [DraftAC21.17], the FAA provides a detailed description for the contents of a ConOps document. The reader is cautioned that this document is in draft form, so it is not FAA policy. The draft advisory circular certainly contains some topics of importance to the FAA, but it does not represent a means to meet the requirements of a regulation and, at this point, there are no better sources for official information on UAS certification. The main sections that the FAA expects to see in a UAS ConOps include an introduction to provide a brief overview description of the proposed operations and a concise explanation of the intended mission, a description of the unmanned aircraft, a description of the DAA system (if requesting BVLOS operations) including limitations, any flight limitations, information about crew and other personnel, CS and supporting equipment, command and control information, and information about the operation of the aircraft. Each of these topics will be covered in the paragraphs below.

5.1.1. Unmanned Aircraft Specifications

For the unmanned aircraft specification, the unmanned aircraft is to be described in a conventional sense. A three-view diagram, providing front, top, and side views with dimensions should be provided along with basic statistics like length, diameter, wingspan, weight, and payload. Other important information including how the aircraft generates lift (wings, rotors, other) and the type of the aircraft's powerplant (electric, piston, or turbine), must be provided along with fuel and battery information. Key flight characteristics such as maximum and minimum operating altitude, maximum cruise speed, endurance, and range should also be provided. Furthermore, any relevant information about UAS subsystems, the payload, and any other special features of the UAS should be provided.

5.1.2. Flight Limitations

The FAA also requests any flight limitations. Flight limitations refers to the required environmental and airspace conditions that must be met for the aircraft to fly. Some UAS require visual meteorological conditions (VMC) and some can fly in instrument meteorological conditions. Maximum wind speeds are another example. Any limitations on flying through visible moisture, icing conditions, or snow must be noted. The requested flight rules that this aircraft will fly under (VFR or IFR) are also provided in this flight limitations section. In addition, any line of visual sight limitations between the vehicle and ground personnel are noted; this may include day or night limitations.

5.1.3. Crew and Personnel

True to the notion of a ConOps, this document is not merely a description of hardware and software, but it is also a description of the roles of the people involved; for instance, remote pilot, visual observer, payload operator, ground crew, etc. The obvious place to start is to describe the minimum number of people involved in the operation. From an FAA perspective, they will assume that the operation will be conducted with this number of people. This is the conservative, safe assumption. Sometimes more people may be involved, but the FAA is really only concerned with the minimum number of people involved. Then, for each of these people, their roles must be described. An assumption is that a pilot will be in command of the flight operation and retain responsibly for the safety of flight. In addition to a description of the role, a description of any training or licensing requirements (for example, pilot license) for the people in these roles must be provided. The FAA is going to ask safety questions about these roles, and the FAA is interested in how these roles contribute to overall system safety. However, the FAA does not want the description of the roles to be limited only to their safety actions. Instead, the FAA is interested in the total role; this is partly due to many safety issues arising from the gaps between or slight incompatibilities between two roles. For instance, the FAA will likely ask about any payload responsibilities the remote pilot has; since those responsibilities could impact workload. Communication is needed between people involved in the operation to enable them to work together. As one partner discovered, the FAA is interested in the means of this communication (visual, radio, in person, etc.) and the content of the communication. The means of communication are important due to the need to assess failure modes and the content is important to ensure that all the personnel involved in the operation have the information they need in a timely manner. If there are multiple operators, this section should provide the procedure to hand-off from one operator to another or perhaps one CS to another. Finally, any training that the crew receives should be noted.

5.1.4. Control Station and Support Equipment

One significant difference between UAS and conventional aircraft is the existence of and reliance upon CS and ground support equipment. The FAA would like the ConOps to describe the CS and any additional ground support equipment such as radars, launch/recovery equipment, communication equipment, etc. In addition, the FAA would like to know the physical location of the ground support equipment relative to the operation.

5.1.5. Command and Control (C2)

Another significant distinction between UAS and conventional aircraft is the C2 link. In a conventional aircraft the C2 link consists of cables or wires between the on-board flight deck and the aircraft systems. On a UAS, this link is replaced with radio communication for command and control of the aircraft. In addition to the physical media changing, the information conveyed over the C2 link changes. For most UAS, inner loop control is handled by an on-board autopilot so this information would not need to be conveyed over the link. On the other hand, the C2 link in a UAS typically must contain information regarding DAA. Due to these differences and the assumed criticality of the C2 link, the FAA is interested in detailed information about the C2 system. First, the FAA is interested in how the C2 functions are allocated between people and systems, whether on the ground or in the air, including the UAS operator and any observers. The FAA is also interested in the C2 link itself, including security protocols, situational awareness, lost link procedures, emergency procedures, and information communicated (up/down). Finally, a description should be provided about any other communication links (for example, secondary C2, video or payload) and any information about the software used in the C2 system should be defined.

5.1.6. Unmanned Aircraft Operations

The final part of the ConOps document is a description of operational procedures. The information requested by the FAA may seem similar to the information in other parts of the ConOps document. However, regardless of the apparent duplication, appreciate that different organizations within the FAA will evaluate different parts of this document. To increase the chances of approval by aiding the reader, it is better to duplicate information rather than pointing to a different section of the document. The FAA is interested in limitations on the operational environment, whether those be geographical or airspace limits. These include geographical boundaries, classes of airspace, altitudes, and flight conditions that may affect C2 or DAA performance. Furthermore, whether or not these boundaries are physically contiguous is important. Next the FAA is interested in how launch and recovery operations are conducted. This includes a clear and concise description of where launch and recovery will be conducted (e.g., conventional airports or non-conventional launch and recovery locations). Of particular interest is if the operation is completely over a private property owner’s land (with permission), whether people will be overflown, and a description of the unmanned aircraft’s proximity to people, infrastructure, and surface vehicles. The FAA is also interested in any potential airspace congestion, proximity to other users of the NAS, and requests to block-off airspace for exclusive use. Since the airspace has many aviation users it is best to develop a ConOps that does not limit or impact other users. In addition, the FAA would like to know how separation assurance is accomplished, any automated control functions, and the operator to aircraft ratio (e.g., 1:1). Due to the vagueness of the terminology of these technologies, instead of using labels, such as “pilot over-the-loop” or “fully autonomous,” a description of what the system can and cannot do is more helpful. The final information required is a description of the communication between the UAS remote pilot and ATC. This information includes a description of coordination and communication regarding flight plans, liaison information, mishap reporting, and notice to airmen (NOTAM) information.

5.2. Operational Risk Assessment (ORA)

The primary safety analysis technique requested by the FAA is an ORA. The specifics of this assessment are described in the [DraftAC21.17]. Another relevant document is FAA Order 8040.6, the Unmanned Aircraft Systems Safety Risk Management Policy [Order8040.6] and the SORA [J18] from JARUS. The ORA is based on the ConOps and used to motivate the certification requirements.

The FAA does not specify a methodology to arrive at risk assessment data, instead it specifies the information which must emerge from this process. The basic format is envisioned as a table, where each risk is represented as a row of this table. For each risk, the hazard is identified. Recall a hazard is a condition of the system that, when combined with environmental conditions, leads to some harm. The FAA requests two types of hazards: the main hazard related to this risk and any lower level hazards that contribute to that hazard. Next, any information about the phase of flight related to this hazard should be included, because the relevance and severity of hazards often depend on the phase of flight. The FAA also requests information about the causes of factors that cause hazards and the exposure (time, location, etc.) to hazards. Next, the list of all mitigations to the hazard are presented along with the methods of compliance that will be used to show that the mitigations are effective.

Experience from SIO indicates that risk mitigations come in three forms: training mitigations, operational mitigations where the operation of the UAS is restricted to lower the likelihood or severity of the associated hazard, or technological mitigations where design features of the UAS eliminate or reduce the likelihood of the hazard. If the hazard is addressing a failure, it must address both loss of function and malfunction. Typically, a malfunction is harder to address than loss of function because distinguishing between correct behavior and malfunctioning behavior is not obvious. Any newly identified mitigations must then become part of the ConOps. Finally, an assessment must be performed again after all mitigations have been applied to determine the final severity and likelihood for each hazard. One well-accepted type of mitigation is to use a relevant section from an existing regulation for a conventionally piloted aircraft, such as 14 CFR 23, 25, 27, 29, 33, 34, or 35. In fact, reviewing each rule in a relevant section for the appropriate class and category of aircraft, typically normal category either rotorcraft or fixed wing, is required by [DraftAC21.17]. This activity is helpful in the risk analysis process. The set of mitigations forms the foundation of the type certification basis. The ORA may also provide information related to the means and methods of compliance to the required behavior.

5.3. Safety Case

Once the ORA has been completed, one must demonstrate to the FAA that the claims made in the ORA are valid. The means of compliance should have been approved as part of the ORA; now the methods of compliance can come under scrutiny. The methods of compliance relate to how the applicant will collect data to show compliance. The data may come from analysis, ground tests, or flight tests. Unfortunately, none of the SIO partners got to this point within the timeframe of the SIO effort (approximately 18 months).

Helpful observations described here come from a presentation given about a joint project by the insurance company State Farm and the Mid-Atlantic Aviation Partnership (MAAP) [BB19]. State Farm was interested in using UAS to assess damage and engaged the MAAP to help them build a safety case. Their presentation describes the FAA’s active engagement approach to regulatory compliance. This approach is not one where companies comply with the rules to their own satisfaction. Instead, this presentation describes how the FAA is actively involved in each step of regulatory compliance. The MAAP developed a process to develop a safety case. This involves a planning effort that includes test requirements and the data to be collected, along with a description of how the data will be collected, including test setup, collection procedures, the schedule, and resources. This process is coupled with an engagement cycle with the FAA to ensure that if the data are collected it will be sufficient to satisfy the claimed efficacy of the mitigation; that the plan to collect the data will ensure that the data are not corrupted; and finally, that the actual data collection was performed in accordance to the plan. All of this information is collected together into a *safety case* that is presented to the FAA.

A contrived example of this would be if visual observers are being used in a new role during the UAS's operation to detect if the aircraft has undergone a mechanical failure. If detecting this behavior is critical to the safety of the operation, then the FAA would want a clear rationale for what the visual observer is supposed to do, how this information will be communicated to the operator, and the actions that the operator will take to move the UAS into a safe state. Although the rationale may seem obvious to the system developers, the FAA will want this provided. In addition, a test program will need to be established to show that the visual observers will be able to accomplish their tasks in an effective manner.

6. Best Practices

The section includes a collection of best practices that were identified throughout the SIO effort. The topics of these best practices range from technical insights to organizational items that may help future applicants begin UAS design and certification activities be better prepared. The best practices are categorized as general, certification, DAA, C2 and spectrum, and lost link best practices.

6.1. General Best Practices

6.1.1. Criticality of a Well-Defined Business Case

A well-defined business case is critical to the success of a UAS certification program. In conversations with (non-SIO) UAS industry players and the FAA, the idea of an "aerial truck" often arises. The idea is to build a UAS with an empty payload bay and then offer the aircraft based on the aircraft's performance characteristics (range, altitude, speed, etc.). This aircraft is claimed to be able to perform a variety of commercial missions. Advice from the FAA and other international regulatory bodies has focused on a defined ConOps (see section 5.1) which, in turn, can be scoped by a well-defined business case. The business case will define not only unmanned aircraft sensors but the payload for a specific use. Therefore, this defines important operational limits like speed, altitude, and airspace allowing the FAA to give permission to operate within these limits.

The advocates for an aerial truck counter that the certification of a conventional aircraft does not require the elaboration of a business case, so why should UAS? This comment is based on a misunderstanding of how the FAA assesses and ultimately accepts risk of aircraft integrated into the NAS. Without a detailed operational scope defined in the ConOps, which is defined by a business case, the FAA will assume that the aircraft will be used in the most congested, most complex, and most integrated parts of the NAS. This will push the risk of the operation to levels on par with transport category aircraft (that is, the most-risky category), and very stringent requirements for certification and operational approval will result. The applicant with their aerial truck may respond that this risky operational environment wasn't intended. However, a well-defined business case will help the applicant determine an operation that will be valuable to paying customers, enabling them to make intelligent tradeoffs with the FAA regarding operational mitigations, equipment, certification requirements, and their business considerations.

The SIO partners bore out this hypothesis. One partner used the SIO demonstration flights to clarify their business case. They found with much more clarity the payload sensors and altitude requirements that would provide real value to their potential customers. In addition, this partner found that some potential customers were only mildly interested in the data, and others were very interested. With this knowledge the partner will be able to shape their many design choices. For instance, if they originally intended to carry three payload sensors, but found that their real customers were only interested in one, then not only can they remove the sensors, but potentially they can choose a vehicle that is the right size and capability for the business case (section 6.1.2). It is notable that performing this type of market research is part of the FAA's intent of an experimental airworthiness certificate (14 CFR 21.191).

6.1.2. The Intersection of UAS Regulations and Business Opportunity

One important dimension to having a business case (see section 6.1.1), is that it can be used to design the vehicle appropriate for the business case. Effective design of a UAS for a particular business case requires expert knowledge of the tradeoffs between aircraft design elements, the current state of UAS regulations and certification policy, and the business opportunities. Carefully minimizing the weight, speed, complexity, or operational risk may result in significant reductions in the cost and time required to certify the UAS and bring it to market. There are a number of trade-offs, but as the FAA moves to complete UAS certification policy, kinetic energy and operational risk categories are expected to be significant drivers. Understanding how the business opportunity is impacted by vehicle kinetic energy and operational risk early in the design process will help an applicant converge on optimal vehicle parameters, design, and ConOps.

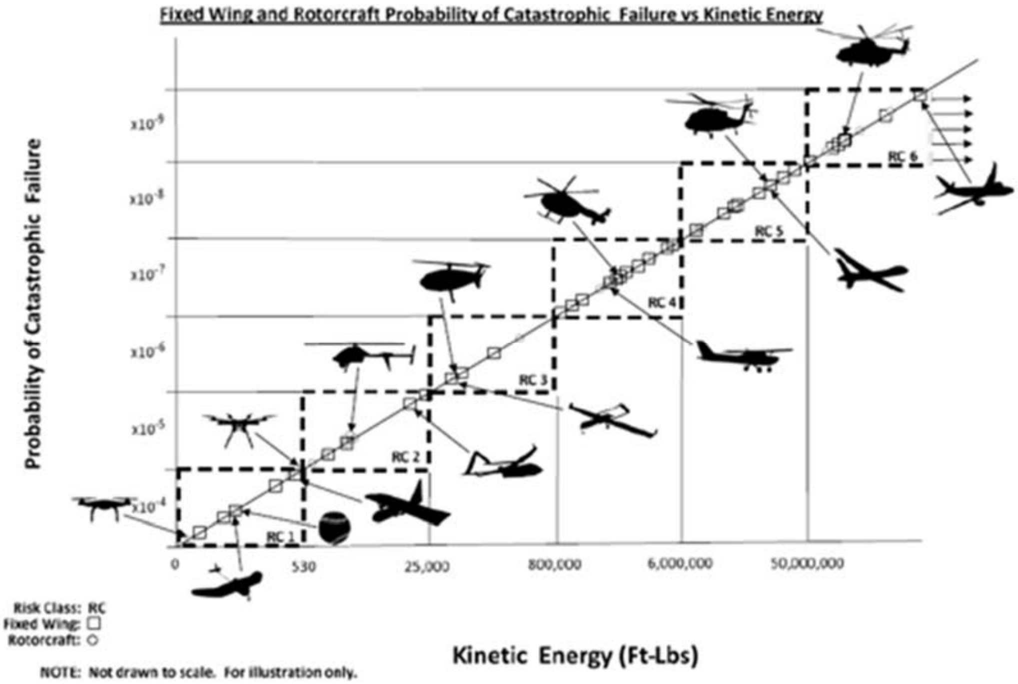

Figure 6: Proposed Risk Categories for Type Certification [DraftAC21.17]

The FAA uses a risk-based approach to provide airworthiness certification and operational approval for unmanned aircraft. In one reference [DraftAC21.17], risk is based on a combination of the kinetic energy (e.g., a function of weight and speed) of the unmanned aircraft and the operational environment. **Error! Reference source not found.** depicts a relationship between kinetic energy and the likelihood of harm to people on the ground. Using tools like this one can roughly define six proposed risk classes (RC1–RC6), which are represented by rectangles. A risk class corresponds to a required set of design or operational mitigations. A higher risk class will result in risk mitigations in the form of more stringent requirements for safety assurance, which is expected to increase the cost of the unmanned aircraft and its subsystems. For a particular vehicle a small increase in kinetic energy may result in a higher risk class and therefore incurs potentially significant additional safety assurance requirements. Conversely, reducing kinetic energy of a UAS into a lower risk category may simplify the certification process. Risk classes should be considered in the design and business tradeoff phase. There are similar categories for operational areas. Choosing the correct vehicle risk categories should be paramount. It is, however, important to understand the risk classes don't always reflect the potential impact.

For example, a low-risk class UAS could be sucked into the engine of a transport aircraft if flying in high-risk airspace. There are additional factors, such as operational risk, that must also be evaluated using the ORA.

Part 107 represents the lower end of the risk class, where the size of the unmanned aircraft must be below 55 pounds, with a 100 mph speed limit a 400 ft AGL ceiling, and operations within VLOS, among other restrictions. For UAS exceeding these boundaries, the FAA is pioneering a durability and reliability approach to type certification that requires a certain number of hours of test data in a representative environment, testing certain corner cases, and meeting other criteria to obtain type certification [F19]. While the FAA is exploring extending the durability and reliability approach to vehicles above 55 pounds, one of the SIO partners found that as the size and weight of the unmanned aircraft is increased, eventually the amount of testing becomes unachievable. Another operational parameter that can impact risk is operational altitude. One of the SIO partners learned that there was increased scrutiny on operations above 400 ft AGL due to the increased likelihood of encounters with other aircraft. Keeping the business case in mind, an applicant should consider if it is possible to reduce the weight and speed of the unmanned aircraft and the risk associated with its operations.

Automation is another major trade off category where a minimalistic approach will likely result in lower cost and quicker time to market. With advances in electronic systems, complex logic can be embedded in small packages; thus, allowing complex decisions for safety risk mitigations to be performed by machines instead of humans. It may be tempting to address these risks with increasing levels of automation. However, as the DAL of the unmanned aircraft increases, which often increases with increasing risk class, the cost to certify safety-critical software increases significantly. The safety assurance of electronic systems does not end with the software. The platform the software operates on must also be assured to operate properly, which may result in the need for redundant systems and aviation grade parts. To make matters more difficult, safety assurance for complex or non-deterministic autonomy is a field in its infancy, and the FAA offers no clear guidance about how certification of these systems should be accomplished. Therefore, this is a source of significant uncertainty in the certification process, which can have a significant impact on cost and time to market. Applicants should make sure that any complex software that is used for safety-critical functions are necessary and have a solid evidence that their system exhibits the correct behavior and does not exhibit unexpected behavior [H19].

Described below is general list of considerations affecting design, certification, manufacturing, maintenance, training, and operations. All can have a significant impact to both the risk and cost of a UAS and operation:

- An unmanned aircraft’s weight and speed will impact the risk posed to people on the ground. As the kinetic energy of an unmanned aircraft increases, shelter provided by automobiles and buildings may no longer provide sufficient protection to prevent serious injury and fatalities.
- The operational risk caused by an unmanned aircraft will depend on factors such as the population density of the overflown area and its proximity to high-population areas, the intended airspace and air traffic density, speed, altitude, time of day, and whether the operations are BVLOS or within VLOS.
- As the risk level increases, the design assurance of the UAS must also increase, potentially resulting in the need for redundant avionics or parts, higher levels of software assurance, increased design scrutiny, and the need for aviation grade parts. All of those items may have a large impact on cost. Redundant avionics or parts may require additional software to fuse information or determine the correct information source and increase the weight that the unmanned aircraft must carry, impacting the structural and propulsion requirements.
- Certain UAS architecture and design decisions may impact risk and cost. Examples include the DAA system architecture and sensors, C2 system, any safety-critical autonomous system, and the design of the control station(s) and flight control system.
- The need for external infrastructure may impact cost. For example, the need for a nationwide terrestrial C2 network or a networked ground-based surveillance system may be costly to build and maintain.
- Operating cost will be impacted by the number of ground crew and pilots required to support operations and maintenance. These crew members may be needed to support various functions such as a preflight inspection, maintenance, visual observers (if used), and piloting the unmanned aircraft. Operators should also consider if any staffing is required at contingency airports to provide support in case a diversion is needed due to lost link procedures or emergency operations.

In summary, the best way to control cost and manage a schedule is for companies planning new UAS enterprises to minimize an unmanned aircraft’s kinetic energy, operational risk, and complex autonomy while still performing the operation in the well-defined business case. UAS certification policy, standards, and procedures are still in the process of being established, which can add uncertainty to the certification process.

6.1.3. The Use of Conventional Systems Engineering Practices

UAS are complex systems with critical interactions between various hardware and software components. Changes to one subsystem may impact other subsystems in nuanced ways. It is important to use system engineering practices such as hazard analysis, code reviews, configuration management, and testing to capture these interactions. Implementing and following these types of systems engineering practices is one component of creating a safety culture (see section 6.2.3).

The purpose of configuration management is to prevent incorrect, ineffective, and/or unsafe products being released. By following a rigorous configuration management process, controlled items can be analyzed and discussed by experts with different technical specialties before they are accepted and incorporated into the official configuration. A healthy configuration management process will demonstrate that the “as built” configuration matches the latest approved design, thus preventing delays in the certification approval process.

Configuration management aids the concept of conformity used in type certification. For a type-certified aircraft, each component on an aircraft must conform to its type design, which is approved based on data and evidence collected to comply with airworthiness requirements. A safe and vetted configuration must be maintained throughout the development and operation of the aircraft. Key configuration information may be captured in the maintenance and operation manuals that are developed and approved during the type certification process. Maintenance personnel and operators, along with system designers, have the responsibility of maintaining the system configuration.

6.1.4. Application of Human Factors Design Principles to UAS

Human factors (i.e., designing systems with human capabilities in mind) is a cornerstone of safe operations in a variety of fields, including aviation. A cause of many safety mishaps is poor human factors design, and as it relates to UAS, is often the result of rapid development of the machine while forgetting the operator in the design. By using the term “operator,” we mean to include the remote pilot, but also any other personnel involved in the aircraft operation including roles such as ground observers, payload operators, and launch and recovery personnel. The application of human factors guidelines to UAS is crucial to rectifying these issues. Specific to SIO, a number of best practices for human factors emerged while working with our partners. Please note this is not an exhaustive list of UAS human factors, rather a sampling of principles that were discussed during the SIO project. For a more comprehensive review of human factors guidelines for UAS, please review Hobbs and Lyall [HL16a, HL16b].

- C2 link latencies and interruptions can lead to difficulties in maintaining safe operations (see section 6.4). A loss or interruption of C2 link not only impacts the operator’s ability to maneuver the unmanned aircraft quickly in response to conflicts, but also impacts interactions with local ATC, as radio communications are often relayed through the C2 link.
- Alerts are intended to capture one’s attention to a potential hazard. However, if one must devote time and attention to determine if the alert is valid and action is required, this is known as a nuisance alert and poses human factors problems. Unfiltered surveillance noise (e.g., during low-altitude operations due to birds, ground clutter, or non-aircraft targets) can cause nuisance alerts that distract the remote pilot and can lead to slower responses to real threats. Careful consideration must be made when dealing with surveillance noise such as how to filter and how to display the information to the remote pilot. Additional human factors evaluations are often required.
- The physical characteristics of the control room vary drastically and often look more like an office than a cockpit. There is more space which can result in information overload from additional displays and poor ergonomics when controls are placed out of reach. Maintaining a sterile cockpit at critical phases of flight may also be more challenging.

- Inadequate or poor interfaces can lead to operator input errors and unintended aircraft responses (e.g., safety-critical controls placed in areas where they can be accidentally activated). The interface design is often placed later in project planning which can result in poor overall system design and integration. The display of information should be considered alongside the design of the system.
- Widespread use of commercial off-the-shelf consumer products (e.g., laptop, trackball, keyboard) can result in integration issues and lack of consistency. Related to the best practice of adapting existing tools to develop a DAA system (see section 6.3), integration and consistency considerations of products and tools is key to supporting the system and operator.

There is a large number of human factors related standards and guidance material available for conventional aviation cockpits. These documents may be referenced and incorporated into the UAS design requirements as applicable; however, as mentioned above, UAS pose different human factors challenges that must also be addressed early in the design phase.

6.2. Certification

During SIO the three partners touched on various aspects of certification and operational approval. One of the main goals of the original vision of SIO was a focus on a flight demonstration to further type certification goals. Unfortunately, flight testing as part of SIO was ineffective for certification. The time scales of type certification are very long and do not align with the near-term needs to accomplish a flight demonstration in non-segregated airspace. However, significant progress was made. Through the emphasis on flight demonstrations, the SIO partners acquired valuable expertise in conducting flight demonstrations for system development and obtaining experimental airworthiness certificates and COAs.

6.2.1. Criticality of Specialized Certification Expertise

Aviation has the reputation as being one of the safest and most regulated industries in the United States. The safety problems associated with aviation are complex and detailed. As a result, the certification activities associated with providing evidence and analysis to establish the safety of a product and adherence to the process requires specialized knowledge and attention to many details. For this reason, successful interactions with the FAA require personnel who have specialized experience with civil aviation certification with knowledge of UAS certification. Many consultants can provide safety analysis expertise while others can provide expertise with high-quality UAS design and operations—perhaps with a military heritage. However, the SIO partners that successfully communicated to the FAA were the ones that brought in experts with civil aviation certification experience, augmented with UAS expertise where necessary.

The approach the FAA has taken in civil certification for conventional aircraft is to delegate some aspects of the process to others. For example, the DER program is one where a company employee can be delegated certain FAA roles, such as approving a test or other engineering data. This program is critical to successful completion of many civil certification projects. However, at this point, the FAA has not approved anyone to act as a DER for delegation of UAS-related tasks. As one SIO partner discovered, DERs can offer valuable insights to a system developer regarding how the FAA typically approaches certain types of problems; however, they cannot act in their delegated authority. For another SIO partner, their DERs acted more as consultants than as FAA delegates.

Another dimension to the Certification Expertise best practice is that the UAS industry's experience with UAS certification is limited, unlike the conventional aviation industry that has decades of experience with certification requirements. In the name of accommodating many different approaches to meeting safety objectives, the FAA has pursued a performance-based approach to regulation. The idea is that instead of the older approach of providing detailed design requirements, the FAA provides overall safety performance objectives which can be met through multiple approaches. One SIO partner preferred the more specific guidance of earlier safety requirements. This older approach had the advantage of a more well-defined path to approval.

Another SIO partner considered using their payload camera as a mitigation for certain detect and avoid situations where the primary DAA system would be ineffective. Using the expertise of team members who came from a civil certification background, the partner realized that this would require the payload camera to be designed and maintained to certification standards. This was unacceptable for several reasons and other options were pursued.

6.2.2. Timing of Type Certification

The type certification process should not begin until after the vehicle's research and development phase is complete. This includes having a strong business justification with an understanding of why this business case is valuable to the customer (section 6.1.1). In addition, a well-defined concept of operations should be developed including location, airspace, time of day, allowable atmospheric conditions, and roles of the human operator(s) (section 6.1.4). Regarding the vehicle, all system tradeoff analyses, and major design decisions should be complete. This is not to say that the design is complete or that the aircraft is ready to be manufactured, since the type certification process will induce its own set of changes to the concept of operations or the aircraft. One standard could be that the design of the entire aircraft is complete such that it is under configuration control, meaning that any changes to the design are only allowed once all members of the design team can weigh in regarding impact of the change. Significantly, the design team must be readily available to respond to questions and actively solve issues brought up by the FAA during the certification process. While still in the design phase, FAA involvement should be coordinated to understand FAA requirements and to build a staffing plan, certification plan, schedule, and risk assessment plan [GPC17].

This best practice was born from the experience of several partners trying to use the certification process to clarify their designs, which confused the FAA. One partner offered two different means to perform DAA with the partners' intent that they would try one to see how it worked, and if it didn't, then they would use the other approach. The FAA's interpretation was that both systems would always be used. This misunderstanding caused needless delay. The certification process is not a time to be actively making design decisions. Substantial design changes while the FAA is evaluating the design will result in a reset of the FAA's evaluation process that ultimately results in delays.

6.2.3. Safety Culture

Successfully completing the ORA involves thinking about the system as the FAA will, or as a safety engineer will. This can be thought of as thinking about the worst-case behavior of the system instead of the typical or normal behavior. The typical behavior of the system is important for assessing the system's behavior most of the time, especially when the aircraft is operating for its intended purpose. However, safety behavior is based on thinking about what can go wrong. As an example, one partner was developing an innovative C2 system and an innovative DAA system. This partner attempted to use the DAA system to mitigate the hazards of the C2. However, the FAA pointed out that since the DAA system is an unproven system it cannot be used as a backup to another unproven system. The FAA assumed the worst case where both systems would misbehave at the same time, either due to coincidence or some common cause.

Creating an effective safety culture in an organization is, unfortunately, not as simple as thinking about a few key failure modes. These activities are important, but more important is to develop a safety culture in the organization [L95]. A safety culture is where everyone in the organization from the top management to the person on the shop floor take ownership of the safety of the UAS. A good set of guidelines for setting up a safety culture is ICAO's Safety Management Manual [SMM13, section 2.6]. One word of warning, the FAA requires some operators to follow a particular safety management system to comply with certain regulations that UAS operators are not subject to. Instead, reference [SMM13] is only offered for background information about understanding and building a safety culture. One mistake an organization may make when they implement a formal document like [SMM13] is that the organization may believe that establishing a safety culture only involves satisfying a few requirements, instead of the "safety ownership" notion described above. In an organization with a well-functioning safety culture, the FAA should need to perform very few enforcement actions, since the organization will address safety shortcomings on its own.

6.3. DAA Best Practices

Routine access to the NAS will require compliance with the existing "see-and-avoid" requirement for separation maintenance as defined by 14 CFR 91. DAA systems provide a means for UAS compliance by integrating sensors, displays and UAS communication links to provide the remote pilot with surveillance information about aircraft near the unmanned aircraft, alert the pilot to potential threats and enable the pilot to execute approved procedures for maintaining safe separation ("well clear") from other aircraft with or without controller coordination.

In conjunction with RTCA SC-228, NASA has been working closely with the UAS community to develop MOPS for DAA equipment. A few key assumptions made by SC-228 regarding the UAS operations enabled by the DAA MOPS are:

1. UAS flights follow IFR. Therefore, UAS operators or remote pilots must coordinate with ATC if possible.
2. Pilots are involved in all decisions (pilot in the loop).
3. The operations can go beyond the visual line of sight.

In order to accurately frame a best practices discussion for DAA, the state of the art must be captured for the time the recommendations were written. Standards governing DAA for large UAS were only recently finalized, and DAA requirements for smaller UAS are still being developed. Consequently, turnkey solutions are not available for UAS manufacturers, integrators, or operators. Even for large UAS, airborne or ground-based DAA systems are developed in a "horizontal" fashion by integrating standardized components of hardware and software that are typically from different vendors. Commercially available components already exist that are suitable for integration into a DAA system, such as sensors, processors, displays, as well as public domain software that implements DAA alerting and guidance. However, because specifications are lagging, manufacturers of candidate sensors, such as low-SWaP radars, have adopted a "wait and see" posture regarding development of sensors to support DAA. Low-SWaP sensor alternatives to radar for the detection of non-cooperative targets are progressing, with promising results being seen for electro-optical/infra-red (EO/IR) and acoustic sensors. Nonetheless, these technologies currently lack the readiness to be integrated into a compliant, certifiable DAA system.

6.3.1. Adapting Components Not Specifically Designed for DAA

An initial approach to DAA development may be to apply tools, sensors, displays, and other components that are commercially available and adapt them for use as a DAA system. While this may be a worthwhile approach, there are risks to applicability and scope. For instance, it is not unusual for UAS to include on-board cameras for situational awareness during ground operations, takeoffs, and landings, but this does not guarantee the same sensor is suitable for DAA purposes. Likewise, any adaptation of a commercial CS displays for DAA use must be done with MOPS compliance in mind, lest it controvert the considerable efforts of human factors research that went into the DAA display requirements.

In some cases, the effort required to adapt existing components to DAA may not prove cost-effective. For example, one SIO partner explored an "in house" solution to adapt an existing CS to support DAA traffic display requirements but encountered cost and scheduling challenges. Instead, it was decided to use an open-source software implementation of a CS and make customizations. The SIO partner was able to adapt the NASA-developed and open-source DAIDALUS algorithm to provide DAA alerting and guidance algorithm, resulting in a cost-effective DAA traffic display solution. Although the implementation met the needs of the SIO demonstration, this did not constitute a certified DAA system. To certify this system would entail additional design and safety and testing requirements (see section 6.3.5).

Two SIO partners developed entirely new DAA systems for their vehicles, and given the compressed timeframe, had to select from commercially available components such as processors, sensors, and displays. The selection of suitable low-SWaP non-cooperative sensors was one of the most difficult tasks as existing sensors were not built to meet DAA specifications since those specifications did not yet exist.

Newer airborne non-cooperative sensor technologies other than ATAR exist, such as EO/IR and acoustic sensors, but they currently suffer from the same lack of DAA standards guidance and technology maturity. Generally, these sensors were not technically ready for use in a DAA system for the SIO demonstrations. Manufacturers of these sensors with an interest in this market would be wise to monitor and/or participate in ongoing standards development to ensure their products will meet future DAA requirements.

6.3.2. Non-Cooperative DAA Sensors

DAA systems require the use of sensors to detect air traffic that are not transponder-equipped (non-cooperative) and to validate ADS-B tracks. This section describes non-cooperative sensors and their technical readiness during the SIO activity.

6.3.2.1. Air-to-Air Radar

Radar is the best understood non-cooperative sensor for DAA. The main advantages of ATAR as a non-cooperative sensor is that it provides superior penetration capability through most weather conditions, and it is also equally effective during day or night. Several radar-specific lessons from the SIO activity follow.

The detection range of radars depends on many factors, but for SIO DAA systems, the governing factors were radar SWaP, which is discussed in section 6.3.3. The specified detection range is typically valid for straight-ahead detection; actual detection range can drop off significantly (as much as 50-65%) for small intruders at the edges of the radar field of regard (FOR). Generally, two to three overlapping radars are required for the total horizontal FOR of ± 110 degrees and the vertical FOR of ± 15 degrees specified in the RTCA MOPS; however, multiple radars can cause frequency interference. This can be mitigated by using different frequencies for each radar (the best practice), or by time-sharing scans on the same frequency, which lowers the effective scan rate for the entire FOR.

Mechanical integration of flat, rectangular low-SWaP radar antennas can be problematic for some smaller UAS configurations. For fixed-wing configurations without a provision for antenna fairings or radomes, considerable drag can result from the external attachment of the radar antenna. If radomes are used, the performance of the radar should be evaluated with the radome in place.

Radar has an effective altitude that is dependent on the radar system’s ability to discriminate airborne targets from ground clutter returns commonly encountered at lower altitudes. For DO-365, effective radar altitude is a minimum of 1,000 ft AGL. This limitation can be problematic for UAS operations at lower altitudes and the use of radar filtering to block ground clutter returns may be required. RTCA SC-228 Phase 1 DAA work does not intend the DAA system to be enabled during airport traffic pattern operations, only during en route flight, and assumes other means for traffic avoidance are needed, such as visual observers or ground-based surveillance. Radar performance for low-altitude (below 1,000 ft AGL) operations will be addressed in future DAA and radar MOPS.

6.3.2.2. Electro-optical/Infra-red (EO/IR) Sensors

EO/IR sensor systems for DAA produce imagery of the area around UAS and process the imagery to detect local air traffic. Some basic characteristics EO/IR sensors are:

- Sensors operate at a much faster rate (20 to 60 Hz) than radar (0.25 to 4 Hz).
- Sensors are completely passive and provide accurate angular tracking on aircraft; typical errors are less than 0.12 degrees.
- EO/IR systems do not measure range directly. Range must be provided by another system or estimated using a passive ranging algorithm (or some other technique).
- Depending on the engagement geometry and ownship motion, the passive ranging algorithm may require ownship maneuvers to resolve range.
- The range estimate accuracy varies greatly with the size of the intruder (and the intruder’s orientation). It can be reasonably accurate (<10% error) for a King Air at 3.5 NM, but not so until down to 2 NM for small intruders such as a glider.

EO/IR sensor's advantages are that they are very low SWaP compared to equivalent radar systems, with comparable or better angular tracking accuracies. Among the disadvantage of EO/IR is that its effectiveness can be diminished by conditions that affect visibility—sun angle, scattering, humidity/moisture, temperature, or time of day/night. Also, target discrimination is a more complex process, because unlike radar, EO/IR sensors must respond to a variety of signatures dependent on the local background, color, or brightness of the target, or night lights to name a few.

One SIO partner included an EO/IR camera as part of their DAA sensor package. Requirements of EO/IR sensors for DAA have not been published and RTCA SC-228 is currently reviewing a draft EO/IR MOPS that is planned to be published in January 2021. For the SIO partner, this was a technology demonstration using a custom implementation of commercial off-the-shelf components. The camera system was co-located with other forward-facing DAA sensors in the radome of the aircraft. While actual performance of the EO/IR sensor in detecting and tracking targets is not available currently, it was thought that its main contribution to DAA would be to improve the accuracy of radar-detected targets.

6.3.2.3. Acoustic Sensors

Acoustic sensing for DAA is a promising low-SWaP technology but is currently at a low technical readiness level. Acoustic sensor systems consist of arrays of UAS-mounted microphones to listen for aircraft sounds, with on-board processing to detect and declare potential intruders.

Acoustic sensor technology has the principal advantage of being very low SWaP and does not depend on whether operations are conducted during the day or night. It also has good detection range (claims of more than 10 km, although usable range may be lower), a 360-degree FOR, an easily integrated form factor (small microphones and processor), and less sensitivity degradation due to adverse weather than sensors such as EO/IR.

Acoustic sensors likely require additional research, development, and testing before they can be incorporated into certifiable DAA systems for large UAS that fly above 400 ft AGL. Current challenges include poor-to-nonexistent altitude discrimination without complicated microphone configurations, means to address silent aircraft such as gliders and balloons, and background noise interference with intruder detection.

6.3.2.4. Ground-based Surveillance System

A ground-based surveillance system (GBSS) is not an airborne sensor, but the surveillance data may be supplied to airborne DAA processing via the UAS C2 links. A GBSS operates independently of the FAA's radar surveillance system and may track aircraft not tracked by FAA systems. The [DO-381] MOPS provides standards for GBSS implemented with UAS transiting and performing extended operations in Class D, E, and G airspace, along with transiting Class B and C airspace. The DO-365A MOPS provides guidance for using GBSS in a DAA system as a non-cooperative sensor.

GBSS overcomes several disadvantages of current airborne low-SWaP sensors:

- Alleviates payload and power requirements
- Target detection not subject to limitations of low-SWaP technology
- Mechanical integration of sensor is unnecessary
- Can help provide surveillance for takeoff and landing zones, which may be particularly important if non-traditional NAS access points are used
- Provide full 360 coverage (with the correct setup) for VTOL takeoffs and landings.
- Facilitate low-altitude takeoff and landing (or low-altitude operations in general) without being hampered by ground clutter.

The major disadvantage of relying on GBSS as a non-cooperative sensor is that C2 failure could cripple DAA functionality, a tradeoff which may increase C2 complexity, size, and/or weight to enhance its reliability. This might especially be a disadvantage for autonomous DAA operations.

One of the SIO partners originally considered a ground-based radar system as a backup contingency to their airborne sensors. As COA approvals were sought from the FAA, it became apparent that ground-based surveillance was a viable enhancement to ground observers for their SIO ConOps.

6.3.3. Range Limitations of Existing Low-SWaP Sensors

Currently available DAA sensors for low-SWaP UAS may not have the range that will be required to make an adequate safety case. DAA systems defined by DO-365 use ATAR as the sole surveillance sensor to detect non-cooperative aircraft that do not carry transponders or ADS-B equipment. The function of the radar is twofold: to track all aircraft within its surveillance volume, and to provide validation for ADS-B data received from cooperative aircraft. The major disadvantage of ATAR for UAS is that its effectiveness, particularly the detection range and FOR, is directly proportional to the radar's size, weight, and power consumed.

Existing DAA standards do not yet adequately address low-SWaP requirements, but there are several standards being developed that address this gap. For instance, RTCA's SC-228 anticipated that airborne sensor systems for Phase 1 DAA equipment classes could weigh 200 pounds or more, with the radar being the most significant contributor to sensor weight. For smaller UAS, with maximum gross takeoff weights (MGTOW) generally under 300 pounds and maximum payloads of approximately 75 pounds, sensor systems must by necessity be of low SWaP. The compromise for low-SWaP radar is lower detection range and FOR. As a result, there are alternate requirements for DAA radar being developed for DO-365B. Additionally, ASTM is developing standards for "smaller" unmanned aircraft with wingspans less than 25 ft flying at low altitudes in less risky environments.

Because SC-228 assumes both flights under IFR and a pilot in the loop for DAA decisions, radar declaration range must support the DAA alerts for conflicting traffic specified in the MOPS. The requirements for these alerts are based on human-in-the-loop research that examined the time necessary for a remote pilot to respond to an alert and the UAS to perform the avoidance maneuver. Simplified, for a UAS with a remote pilot, the required declaration range to remain DWC combines the minimum maneuver initiation range (MIR), which is based on vehicle performance parameters, with the additional alerting time (converted to range) necessary to allow the remote pilot to interpret DAA alerting and guidance, coordinate, if possible, any necessary avoidance maneuver(s) with ATC, and execute the maneuver(s). Declaration range that complies with the MIR does not also necessarily comply with the DAA alerting requirement. In the ATAR MOPS, DO-366, the radar declaration range was defined as the range that provides 25 seconds alerting time (ATC and remote pilot response time combined) before reaching the MIR for non-accelerating encounters.

In the Phase 2 RTCA DO-366A MOPS, a new ATAR class for slower unmanned aircraft speeds between 40 and 110 kts is added to support the low-SWaP sensor DAA equipment class. The required declaration range for the head-on intruders is between 3.4 and 2.6 NM. Similar to the Phase 1 ATAR classes' declaration range, a time window of 25 seconds was added to MIR to arrive at these numbers. The required ranges are difficult to achieve by current low-SWaP radar technologies but can be met by EO/IR sensors.

SIO partners with vehicles requiring low-SWaP sensors considered several candidate radars that were available within the SIO timeframe. Candidate radars were generally rectangular in shape, with a comparable size range between that of a small tablet and a large laptop computer. Power consumption ranged from 35 W to 100 W. The advertised detection ranges varied from about 1.5 km to 6 km (1–4 miles). The candidate radars were evaluated for their ability to provide radar track data to the DAA system. Of particular interest was the declaration range of the radars, as it relates directly to the alerting requirements found in DO-365. While other potential DAA standards for sUAS and smaller UAS are being developed, DO-365 and DO-366 were still considered the most well-understood standards to provide performance benchmarks. None of the radars evaluated met the DO-366A requirements for radar declaration range, which were reduced from DO-366 to accommodate the smaller DWC definition for non-cooperative targets found in DO-365A.

In performing trade studies on sensor range requirements for SIO demonstration flights, the DAA team assisted one SIO partner in running several simulations to estimate the minimum maneuver initiation range for a head-on encounter. The simulations were run using the non-cooperative DWC definition adopted by SC-228 for their vehicle and ConOps, with appropriate maneuvering parameters for the vehicle supplied by the SIO partner. (It should be noted that the simulation assumed no latency between remote pilot input and maneuver initiation, and that any latency would tend to increase the required maneuver initiation range.) The non-cooperative DWC definition was horizontal miss distance (HMD)* = 2200 ft, h* = 450 ft, $\tau^{*}mod$ = 0 seconds. Intruder speeds for the simulations ranged from the MOPS-recommended 170 knots true airspeed (KTAS) down to 130 KTAS, because the SIO partner thought that slower intruder speeds would be more representative of the traffic to be encountered, based on its ConOps of 1,000-foot altitude operation in and near Class B airspace.

The results of one such MIR simulation can be seen in figure 7. They indicate that the detection ranges of some candidate radars could indeed satisfy the MIR requirement at UAS speeds between 50–110 KTAS and turn rates between 3–20 degrees per second. However, even for the largest turn rates, the remaining detection margin was not sufficient to support the full DAA alerting requirements.

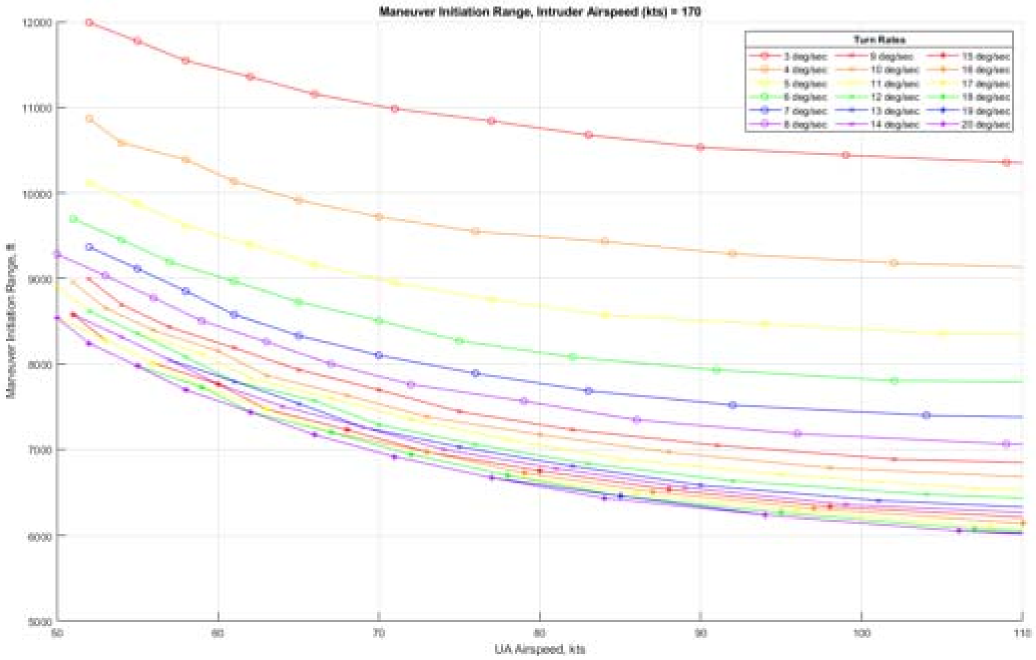

Figure 7: MIR Simulation, Intruder Airspeed (KTAS) = 170

6.3.4. DAA System and Spectrum Interactions

DAA systems have a number of components that require radio frequency (RF) spectrum licenses and serve a safety-critical purpose. Examples include transponders, radars, and C2 links. The possibility of RF interference with any of these components must be carefully considered when developing risk mitigations for the safety case. This is especially true when using components whose RF spectrum is not specifically allocated by regulation. Examples of this include:

1. The possibility of RF interference with a DAA radar must be carefully considered if the spectrum used by the radar does not have statutory protection. Interference from other transmitters may degrade DAA radar performance, preventing the radar from detecting non-cooperative aircraft and being used to validate ADS-B tracks. DAA system designers should consider using a spectrum that provides statutory protection or methods of detecting and mitigating the impact of interference.
2. Intentional or unintentional RF interference with the C2 link. This condition may invoke automated flight modes of the UAS. However, if a DAA system depends on the C2 link for correct operation, then a loss of

the C2 link will also result in the loss of DAA functionality. A similar loss of DAA functionality can occur if a degraded C2 link does not have sufficient bandwidth to relay all necessary DAA information to/from the UAS. In either of those cases, an applicant will need to show how the UAS will remain well clear of other aircraft after the loss of DAA functionality occurs (see **Error! Reference source not found.**).

6.3.5. Use of Modeling and Simulation Tools for DAA Validation

The use of modeling and simulation tools is a cost-effective and efficient means to verify that a DAA system design will meet some key requirements. Compared to the use of modeling and simulation techniques, actual flight testing will realistically only be able to validate a subset of the required DO-365 Appendix P test vectors. However, flight testing is a necessary part of DAA validation. While not specifically called out in the MOPS, the FAA may reserve the right to examine underlying simulation results that may be part of developer design and verification.

Risk ratios (RRs) are the key metrics for evaluating the relative safety benefit for equipping with DAA, and determination of these ratios requires simulations using a baseline set of traffic encounters. The FAA will want to see these as part of the safety case presented for certification. In MITRE's Study 5 that supported the FAA's safety risk management document for the Phase 1 MOPS, MITRE utilized a large number of encounters sampled from Massachusetts Institute of Technology-Lincoln Laboratory's (MIT-LL's) encounter models.

By way of explanation, the near midair collision (NMAC) RR is defined by the ratio of the probability of an NMAC during an encounter if the UAS pilot follows the DAA system's guidance to mitigate the conflict to the probability of an NMAC during an encounter if the UAS pilot does nothing to mitigate the conflict. The NMAC RR indicates the DAA system's effectiveness in reducing the occurrence of NMAC hazards when presented with a set of statistically significant encounter scenarios representative of NAS observations of manned aircraft behavior.

Similarly, the loss of well clear (LoWC) ratio (LR) is defined by the ratio of the probability of an LoWC during an encounter if the UAS pilot follows the DAA system's guidance to mitigate the LoWC to the probability of an LoWC during an encounter if the UAS pilot does nothing to mitigate the LoWC. The LR indicates the DAA system's effectiveness in reducing the risk of LoWC when presented with a set of statistically significant encounter scenarios representative of NAS observations of manned aircraft behavior.

Modeling and simulation techniques will reveal most nominal and some off-nominal characteristics of the DAA system; however, sensor reliability and uncertainty must be demonstrated in flight under both nominal and stressing "real world" conditions. Some stressing conditions include:

1. DAA system susceptibility to false tracks. For DAA systems using radar as a non-cooperative sensor, low-altitude operations will probably require flight testing down to the minimum altitude as defined by the manufacturer (section 4.1.4) to reveal the effects of ground clutter, birds or other non-aircraft targets (such as cars) until modeling and simulation techniques can adequately duplicate these effects.
2. DAA system performance in various environmental conditions. For example, atmospheric conditions such as low visibility, precipitation, or clouds, variations in lighting conditions (especially for EO/IR sensors), day/night operations (EO/IR sensors again), or possibly even variations in temperature may affect DAA sensor effectiveness. Flight testing guided by the established environmental flight limitations for the UAS will probably be more effective than simulations.
3. DAA system performance while maneuvering. UAS maneuvering may introduce temporary sensor blind spots, and depending on the time to recover, could interrupt the tracking process of other aircraft. Maneuvering could cause temporary degradation of the C2 link, and if the DAA system is transferring DAA data over the C2 link, then critical safety-related information could be lost. Again, flight testing is probably the best way to test for these effects.

Modeling and simulation methods for DAA vary according to the performance metrics under evaluation, and generally fall into the categories outlined in Table 1. [WCL19, WLSGESAC20]

Table 1: Modeling and Simulation Methods and Metrics

Modeling & Simulation Method	Associated DAA Evaluation Metrics
Open-Loop: Unmitigated encounters (no unmanned aircraft remain well clear (RWC) maneuvers); typically, batch mode, often employ Monte Carlo techniques for traffic generation	• Baseline for unmitigated NMAC encounters for RR • Baseline for unmitigated LoWC encounters for LR • Compliance with DAA alert generation and timing requirements • Compliance with DAA guidance requirements
Closed-loop simulations: Mitigated encounters (unmanned aircraft RWC maneuvers follow DAA alerting and guidance). Pilot model used in batch mode to evaluate human systems integration (HSI) effects on DAA system performance. [DO-365B, Appendix C].	• Determination of mitigated NMAC encounters for RR • Determination of mitigated LoWC encounters for LR • Determination of Probability of mitigated NMAC and LoWC safety metrics • Determination of severity of LoWC (SLoWC) safety metric • Compliance with DAA alerting requirements during mitigated encounter • Compliance with DAA guidance requirements during mitigated encounter
MIR simulations [DO-365, Appendix D]	• Tool for determining required sensor detection range. • Shows effects of varying unmanned aircraft speed and unmanned aircraft avoidance maneuver turn rate, while holding intruder speed constant, for a head-on encounter.
Special Case	• Evaluate specific DAA worst-case or corner-case scenarios. • Perform trade studies based on sensor characteristics, unmanned aircraft maneuvering parameters, exceptions to MOPS requirements, etc.

Sensor uncertainty mitigation algorithms should be modeled and tested in a manner that will assess the effectiveness of these algorithms. Baseline closed-loop simulations using ideal surveillance ("truth") data and no tracker errors should be compared with simulations which include sensor models that accurately reflect the candidate system's sensor and tracker performance under actual flight conditions. Note that sensor uncertainty also applies to equipment used to determine UAS position and orientation, i.e., GPS, inertial guidance, etc.

6.3.6. Massachusetts Institute of Technology – Lincoln Labs (MIT-LL) Open Source DAA Analysis Tools

One of the lessons learned during SIO was that many companies lack robust modeling and simulation capabilities that are needed to derive and verify DAA system requirements. In order to address this gap, NASA sponsored MIT-LL to enhance and open source DAA analysis tools that they have been developing for the past several years. The DAA tool suite will consist of three separate software components: Airspace Unmitigated Collision Rate Tool, Detect and Avoid Encounter Generation Tool, and Detect and Avoid Performance Simulation Tool. When complete, these tools will facilitate several of the simulation analyses described previously.

The *Airspace Unmitigated Collision Rate Tool* can be used to establish a baseline for the RR safety metric that is based on one year of recent NAS-wide radar data. Airspace density and its effect on the probability of NMAC or LoWC is a key factor in planning UAS ConOps.

The *Detect and Avoid Encounter Generation Tool* provides an alternative means of generating sets of test vectors than those described in DO-365. Some of these are dynamic cases that require the alternative late alert criteria to be used. DAA systems are not required to pass these test vectors for certification, but the DAA safety benefit may be enhanced for doing so.

The *Detect and Avoid Performance Simulation Tool* implements closed-loop batch study methods for DAA system evaluation described in this document. It is based on the RTCA SC-228 sensor models and the NASA DAIDALUS DAA alerting and guidance algorithm.

One resource that may help DAA system developers is the DAIDALUS software library, which is released under the NASA Open Source Agreement and is available in Java and C++ at https://github.com/nasa/daidalus. DAIDALUS is a software reference implementation intended to satisfy the DAA functional requirements detailed in [DO-365]. Appendix H of DO-365 describes the logic and assumptions of this software implementation. Use of the DAIDALUS code does not provide any evidence towards the certification of a DAA system.

6.3.7. General DAA Best Practices

The following are not fully formed best practices, but rather a collection of observations and answers to frequently asked questions. They are derived from observing the common experiences that the SIO partners went through during DAA system development and test and are included to provide additional insight to DAA requirements.

1) DAA systems implement alerting and guidance, but are not considered auto-guidance, because they lack the following information:
   - Intruder intent
   - Terrain/obstacle awareness
   - Airspace restrictions
   - Awareness of the aviation operations regulations, such as right-of-way rules, etc.
2) The following are questions concerning DAA surveillance requirements that came up more than once during SIO:
   - Postern surveillance is not required by DO-365. However, there may be cases where, in the FAA's judgement, manned aircraft cannot effectively see the UAS. In these cases, 360-degree non-cooperative surveillance may be required in order to give right-of-way to all manned aircraft.

- Bird detection is not required by DO-365. However, there may be cases where, in the FAA’s judgement, bird track filtering may be needed for DAA systems operating at lower altitudes or in terminal airspace where nuisance alerts should be avoided.

3) Generally, ADS-B will be the most accurate DAA sensor for cooperative aircraft. ADS-B dual-link receivers should be considered mandatory for UAS, until it is known whether the UAS will be allowed to transmit on ADS-B frequencies. (At this writing, the FAA is considering not allowing some UAS to transmit ADS-B in order to mitigate frequency congestion that would adversely affect the entire ADS-B system.) A dual-link receiver will allow direct reception of all ADS-B transmissions from either Mode S or Universal Access Transceiver (UAT). Even if the UAS is allowed to transmit ADS-B, dual-link receivers are important for ConOps that spend significant amounts of time out of ADS-B ground station coverage. For instance, low-altitude operations in terminal areas or VFR traffic patterns may preclude receiving Automatic Dependent Surveillance – Rebroadcast (ADS-R) transmissions.

4) Sensor fusion by the DAA tracker should not be mistaken for target data from independent sensors that happens to closely agree. Tracker fusion occurs when the tracker makes a best-source selection from multiple sensor inputs. Sensor outputs for traffic targets may be used in a complimentary fashion. For example, a sensor with good azimuth accuracy may be used to enhance the accuracy of a target detected by another sensor with good range accuracy.

   Care should be taken with sensor fusion so that neither the overall probability of a track is negatively impacted, nor that non-aircraft tracks are introduced. For example, requiring multiple non-cooperative sensors to track an aircraft can help to reduce nuisance alerts and enhance track accuracy, but may reduce the overall system probability of tracking an intruder. Likewise, if non-cooperative sensor(s) can independently produce a track with best source selection, there is the risk that more non-aircraft tracks can be generated than a single sensor generates.

6.4. Command and Control (C2) Best Practices

6.4.1. Overview

One difference between conventional and unmanned aircraft is the use of a C2 link to send information between the CS and the unmanned aircraft. The information transmitted over the C2 link is safety critical and may include elements other than command and control information, such as voice communications between ATC and the remote pilot, DAA tracks, and weather radar information. Due to the safety-criticality of this information, the C2 system must be designed to meet a set of link performance requirements. Additionally, contingency procedures must be developed to ensure safety when the link is degraded or lost.

Reminders of the importance of the C2 link and the challenges of obtaining spectrum licenses were experienced throughout SIO. All of the SIO partners encountered challenges obtaining spectrum licenses; one reason being that there are currently no FAA or FCC certified C2 radios commercially available. The SIO partners either used prototype radios that were aligned with standards developed by RTCA SC-228 Working Group 2 (WG2) or commercial off-the-shelf radios using temporary authorizations on frequencies that are not viable for long term commercial use. It is imperative for UAS C2 radio manufacturers and system operators to understand the landscape of C2 standards and policies early in the design process in order to ensure their UAS plans are consistent with the performance and limitations of certifiable and interoperable C2 systems.

6.4.2. Frequency Spectrum

Conventional aeronautical radios must use a specific RF spectrum that has been assigned for their operation type. The assignments are based on international agreements and are designed to enhance safety by restricting interference between users. C2 communications for a UAS flight demonstration is limited to approved UAS spectrum, and not using a radio that operates in that band may be denied by the FAA.

6.4.3. Spectrum Agencies

UAS spectrum policy decisions have been motivated by the fact that spectrum is a limited resource that is highly sought after by all wireless communications entities. In order to make sure that radios can operate without interference, RF transmissions in the United States are closely regulated by the FCC and National Telecommunications and Information Administration (NTIA). The FAA Spectrum Assignment and Engineering Office provides frequency management and deconfliction of the aviation bands used for communications, navigation, and radar facilities in the United States.

6.4.4. FAA Spectrum

In the case of aeronautical communications, where safety of life is at stake, additional considerations are required to determine how a proposed frequency allocation can operate in a free-space environment without interfering with incumbent and new users.

By Federal regulations, air operations communications must be conducted in designated aeronautical mobile services radio frequencies. Those allocated frequencies are reserved for communications relating to safety and regulation of flight. Although temporary frequencies (not unlicensed) could be proposed to the FAA for temporary non-revenue missions in non-populated areas, the frequencies ultimately need to be sanctioned and regulated for restricted aeronautical use by the International Telecommunications Union (ITU). The process of international competition between expanding radio services, which takes place in the ITU, obliges all existing spectrum users, aeronautical and non-aeronautical alike, to continually defend and justify the retention of frequency bands or the addition of new bands to those already allocated to their service. Unlicensed spectrum is not viable for safety-critical communications, since unlicensed spectrum does not have protections against interference from other users.

While spectrum licenses are issued by the FCC, coordination with the FAA spectrum office is necessary for the use of any aviation-designated spectrum or used for purposes that may impact the safety of flight. Early coordination with the FAA can help identify issues before they can cause delays in the UAS aircraft and mission design process and subsequently maximize the probability of obtaining spectrum approvals. Based on our observations, in addition to early engagement, periodic follow-up with both the FAA and the FCC is key to keeping the application moving forward.

6.4.5. FAA Spectrum Request Process

The FAA has a broad view of the frequency bands and users assigned for the many aeronautical operations that can occur daily. To affect safety in the air, the FAA frequency management office's most important day-to-day duty is to the quick resolution of RF interference (RFI). Whether the RFI is intentional or unintentional, it can quickly become a hazard to NAS operations.

Also, any flight in the airspace that uses a non-allocated band of frequencies poses a danger. The non-conforming aircraft cannot announce its intentions, cannot hear the announcements of other aircraft in their vicinity, cannot receive control commands from ATC, and cannot request assistance from ATC if needed. As such, the safety of air operations is integrally tied to the use of sanctioned frequencies.

To obtain spectrum from the FAA, the aircraft operator must submit a detailed request for the spectrum allocation and follow the prescribed process. Various documentation requirements are included in the request package so that the FAA can ascertain the communications system's adherence to safety regulations and applicable standards. The specific proposed transmit and receive frequencies are listed along with the respective bandwidth of each channel being proposed. Once approved, the user must not deviate in any way from the approved allocation or intended mission while using these frequencies.

Because of the large number of air operations and COA applications, the FAA must obtain specific mission and channel use data from the requester and look for conflicts with current spectrum assignments operating in similar geographic areas and in the same and adjacent frequency bands. Additionally, because the FCC has jurisdiction over civilian communications, they too must assess any request to determine its legality and appropriateness. The combined mandatory evaluations that both the FAA and the FCC must make and the large number of requests in the queue mean that the requestor must provide the needed information well ahead of the planned scheduled use.

Although the SIO partners were aware of the need to obtain RF assignments from the FAA Spectrum Office, there were often detailed C2 requirements and interactions with other spectrum users that they were not fully aware of. Additionally, there were various analyses required by the FAA to evaluate the spectrum request.

During the FAA meet-and greet sessions with the partners, it was realized that the amount of documentation the FAA was looking for was substantial. Early documents and presentations that were given to the FAA never seemed to check all the boxes. Based on this experience, it was decided that very early contact with the FAA should be made with an understanding of what is needed, in addition to developing a schedule of deliverables for a successful demonstration. Specific points of contact on each side for every deliverable should be established to be time efficient. Regular status meetings should be scheduled accordingly.

This early engagement and regular communication with the FAA will enhance the applicant's ability to obtain the required spectrum assignment in a timely manner.

6.4.6. C2 Radio Standards and Requirements

RTCA's SC-228 WG2 has been developing standards for CNPC radios that are designed to carry the wireless safety-critical information between the CS and unmanned aircraft. In 2016, they developed and issued the C2 Data Link MOPS (Terrestrial) [DO-362]. Subsequently, in 2018, the FAA issued TSO for a UAS CNPC terrestrial link system radio [TSO-C213] for manufacturers applying for a TSOA or letter of design approval. In this TSO, based in part on RTCA DO-362, the FAA identifies the minimum performance standards that UAS terrestrial non-networked CNPC link system radios operating in C-Band, 5040-5050 MHz, must meet for approval and identification with the applicable TSO marking.

The benefit of adhering to established standards, such at the C2 MOPS and its associated TSO, is that a COA request approval process time frame is likely to be reduced. An additional advantage is that the applicant is not attempting to incorporate a non-compliant UAS radio into their unmanned aircraft or CS.

The C2 MOPS details are predominantly technical in nature and require close study to be fully understood so that meeting the standards can be demonstrated to the FAA. At one point, the FAA posed a question to one of the SIO partners concerning latency (delay) in certain elements of the C2 system. The C2 MASPS provides guidance on these durations that should be carefully considered during the UAS design phase.

The C2 MOPS contains a description of four basic classes and describes both the information and relevant service parameter characteristics for each of the data classes. One note that was relevant to all of the SIO partners is that the data classes in the C2 MOPS result in data rate limitations designed to support communication of safety-critical information while conserving spectrum so that as many UAS as possible can be supported within a given geographical area. In order to meet the data rate constraints, it is necessary for the information to be compressed. The C2 MOPS contains other valuable information pertaining to the aircraft and CS radios such as equipment performance requirements and test procedures, installed equipment performance, and equipment operational performance characteristics.

6.4.7. C2 Radio Certification

Aircraft systems are complex, and new applications need careful scrutiny. A newly introduced system may lack precedence which obligates the FAA to perform a more rigorous examination in consideration of a

COA/certification application. Additionally, the FCC will have to certify the spectral emissions for the radio system in question.

Obtaining an FAA certification is necessarily a long and involved process consisting of numerous studies and flight tests needed to generate data by which the C2 system’s safety can be validated. The process requires in-depth studies followed by tests that examine the results of the studies. The steps and data required by the FAA are involved and costly, but their aim is to assure the necessary safety of the C2 system, so they’re necessary. When an applicant delivers all the required studies, tests and data, the FAA is in a better position to fully evaluate the system and determine whether the UAS can be certified.

When the radio in question is C2 MOPS-compliant based on RTCA standards, the FAA Spectrum Office knows that the radio meets well thought-out and researched requirements and meets or exceeds safety goals. The FAA has a strong presence in SC-228 WG2 and consistently provides much support in its studies and recommendations, including sharing authorship of the C2 MOPS itself. Naturally, the burden to demonstrate that the radio, its spectrum, power, and waveform meet FAA requirements, is lessened when the radio being considered for approval is designed using an established set of standards.

A central goal in SIO was to help the SIO partners to move closer to FAA certification. As such, the SIO requirements recommended using a radio that has an RTCA MOPS. However, not all of the SIO partners were able to follow this recommendation since DO-362 compliant radios are currently not commercially available. However, NASA and the SIO partners were able to learn about various aspects that the FAA considers when determining if spectrum is viable for safety-critical applications. Those insights are discussed in section 7.4, which focuses on obtaining temporary spectrum approvals for flight tests and demonstrations. SIO also provided valuable insight into the considerations and documentation necessary for certification, the FAA and FCC offices that need to be engaged, and the processes those offices expect the applicant to follow.

6.4.8. C2 Radio Testing

Radio systems are very complex, and comprehensive testing must be completed to verify that a radio system works reliably and meets the intended functionality. They are a combination of hardware and software that are intricate and involve numerous subsystems. When those subsystems are combined, the level of complexity grows non-linearly, which can lend itself to unintentionally overlooked issues. The only proven approach of bringing hidden problems to the fore is the creation and execution of a test plan that includes subsystem tests followed by integration and flight tests.

C2 radio testing, both in the lab and in the air, is a long, iterative, and involved process that needs to be accomplished. Understanding the certification requirements, both reports and test data, allows the applicant to plan resources and schedule so that these deliverables are not delayed. For the sake of knowing, in the first place, that a particular radio works as intended and for demonstrating to the FAA what its characteristics are, a successful applicant must perform rigorous ground and flight tests. Testing assures the applicant that the radio can perform as expected, and test results are often required by the FAA to approve a flight demonstration. In the longer run, the results of extensive tests are needed in some form for certification.

6.4.9. NASA C2 Radio Testing

NASA experience with C2 radio development and testing fully demonstrated the indispensable need for rigorous testing, both in the lab and flight testing. Radios that had been designed and tested by the manufacturer were found to have problems that were only detected when a comprehensive set of tests were run in the lab. Additional issues were encountered during flight testing. Only that kind of exercising of full range of functionality revealed where problems developed. The same is true about later testing in flight. Each encountered environment involves situations that can reveal problems only obvious when the radio is run in the particulars of that environment.

The C2 radio testing environments included flat surfaces; hilly, dry areas; as well as over water. The degree of roughness of the terrain underlying a flight test area can have significant impact on the communications RF signal. While the “direct path” signal between the ground antenna and the aircraft antenna is the “good” signal, involving only free-space path loss, systems can also experience a “reflected” signal that leaves the ground antenna at a slight angle, bounces off of the land or water surface, then travels to the aircraft antenna. When the two signals (direct and reflected) arrive at the aircraft out of phase, they can cancel one another and produce a “fade” or temporary loss of signal. Water with surface waves or hilly terrain causes dispersion, which degrades the reflected signals, whereas smooth water or flat wet land cleanly reflects signals. The UAS-NAS executed flight tests over different environments to measure best and worst-case signal quality situations. The results of those tests determine how RF power, antenna gain, and radio receive sensitivity affect the system.

NASA’s first UAS flight campaign dedicated to spectrum testing consisted of L-Band and C-Band channel sounding tests in support of International Civil Aviation Organization (ICAO) for their use. Subsequent radio flight tests were dedicated to RTCA support. These tests were conducted at the NASA Glenn Research Center in Cleveland, Ohio.

The SIO partners found that applying for FAA COAs was tied to proof of testing; having validation data to show the FAA. This is a part of the COA approval process and not planning for it up front invariably slows the process.

6.5. Lost Link

Unmanned aircraft use a C2 data link to transmit command and control information from a CS to an unmanned aircraft. When that C2 link and all other redundant links are lost, the unmanned aircraft is unable to receive inputs from the remote pilot and thus the pilot and aircraft are unable to comply with ATC instructions. These lost link events may be of a short duration if caused by a temporary antenna blockage or interference, or much longer if caused by equipment failure. Well-designed lost link procedures are required to ensure safe operations and minimal impact to other airspace users.

6.5.1. Lost or Degraded Link Risk Mitigation

Lost link or degraded link procedures should be designed to mitigate risk to other air traffic and people on the ground. The first mitigation to prevent lost link can occur during flight planning. An analysis of the flight path and C2 infrastructure can reveal areas where antenna placement, terrain, or other obstructions may result in degradation or loss of the C2 link. During flight, lost link can often be predicted by degraded C2 link performance. Monitoring the C2 link for degraded performance and executing a degraded link procedure when performance has degraded past a threshold would likely reduce the number of times that the C2 link is lost, which may also reduce disruptions to the mission. A degraded C2 link may also reduce the information that can be transmitted, potentially resulting in the loss of functionality of certain systems (e.g., the DAA system or weather radar). Pilot alerting and mitigations for the loss of those functions should be considered.

When the primary C2 link is lost, the unmanned aircraft may switch to a redundant link if one is available. The performance of that redundant link may impact the safety of an operation. For example, the redundant link may have higher latency than the primary link, which may impact the response time to ATC commands, DAA alerts, and/or TCAS resolution advisories. Since redundant links are often used for payload information, care should be taken to prioritize any safety-critical C2 information over payload information. While the use of a redundant link is preferable to losing C2 entirely, the safety implications of redundant link with lower performance than the primary C2 link should be carefully considered.

If the unmanned aircraft loses C2 link and a redundant link is not available, the remote pilot will be unable to control the unmanned aircraft and respond to ATC commands. Instead, on-board automation or lost link procedures must be used to ensure that the flight remains safe and that, if necessary, the unmanned aircraft can land safely. When designing lost link automation or procedures, the applicant should carefully consider how safety-critical functions typically done by the remote pilot will be performed, including responding to ATC instructions. For example, if the DAA system requires a remote pilot in the loop, the risk of losing well clear with other air traffic will need to be mitigated. This can be accomplished through an autonomous DAA system, extended ATC services (if agreed to by the FAA), or another method of remaining well clear of other aircraft such as landing immediately at a location free of people (likely only applicable to smaller UAS). The applicant should also consider how TCAS resolution advisories will be implemented, how hazardous weather will be avoided, and how the aircraft will land and remove itself from an active runway if the C2 link is not reestablished.

Integration of automation for lost link operations can mitigate a particular risk but may also create new risks. For example, implementing an automated DAA system requires that DAA system to have functionality to prevent automated flight into terrain and hazardous weather, and to return to course in a manner that is predictable to ATC after the DAA maneuver is complete. Careful design of data-filtering methods to minimize false tracks, validated through flight testing, would be required to minimize unnecessary and potentially hazardous DAA maneuvers. Additionally, any automated DAA maneuvers would need to conform with traffic routes, local terminal airspace procedures, and ATC directives, which is a particular challenge for terminal airspace operations. Any new hazards introduced by automation should be carefully considered during the design phase of the UAS and when creating the ORA.

6.5.2. Lost Link Procedures Should Minimize Impact on Other NAS Users

In addition to safety, the FAA is responsible for maintaining efficient traffic flow. When developing lost link procedures, applicants should consider the impact of those procedures on other airspace users and on ATC workload. This was highlighted during SIO when the FAA identified the need for unmanned aircraft to fly routes and contingency procedures that did not impact commercial airline travel and further reinforced by a decision to avoid providing unmanned aircraft with special accommodations.

Currently, lost link procedures are typically agreed to between the applicant and the FAA ATO as part of the COA process. In the future, standardized procedures are expected to be developed and implemented. When proposing lost link procedures to the FAA, the applicant should consider the traffic density along the lost link contingency route, at the destination airport, and near any loiter points. The applicant should also consider all phases of flight and surface operations to make sure that the lost link procedures can be safely executed without significantly inconveniencing other airspace users. For example, if the unmanned aircraft is required to land while in a lost link state, there should be a method of promptly removing the aircraft from an active runway. This may require a trained ground crew at the airport or complex automation for UAS surface operations.

6.5.3. Need for Standardized Lost Link Procedures

There is a need to develop consistent lost link procedures for UAS that fly in controlled airspace to enable scalable commercial UAS operations in the NAS. During today's operations, lost link procedures are often proposed by the UAS operator and agreed to by the FAA as part of the process for obtaining a 91.113 waiver and COA. Smaller unmanned aircraft that do not require an airport for takeoff and landing may choose to identify contingency landing areas along their route and immediately land or fly a preprogrammed trajectory and then land if communications are not reestablished within a specified amount of time. The lost link procedures for large UAS often involve continuing along a predetermined contingency route and landing at either the departure or destination airport or a contingency airport. The lost link route may contain a hold point with time thresholds to provide an opportunity to reestablish a communications link with the unmanned aircraft. When the unmanned aircraft enters a lost link state, the unmanned aircraft's transponder is set to squawk 7400 and the remote pilot is expected to contact ATC to notify them of any deviations from the unmanned aircraft's lost link procedure described in the COA.

The lost link procedures typically assume that the unmanned aircraft will follow the filed IFR flight plan. However, conventional aircraft are often vectored by ATC for traffic flow management and aircraft may be offered shortcuts or alternative routes. In order to fully integrate unmanned aircraft into the airspace, lost link procedures should be designed to accommodate common ATC actions. Additionally, lost link procedures must be flexible enough to take into consideration the unmanned aircraft and operating environment. For example, an operator may include a hold point in an unpopulated area near a C2 transmitter on the ground to maximize the probability of reestablishing a link.

While there is the need for some flexibility, too many permutations of lost link procedures may strain ATC resources as the number and diversity of UAS operations in the NAS increase. Air traffic controllers may need a more general set of procedures than those outlined in COAs submitted by individual operators. One option may be to develop a general framework for lost link procedures. RTCA is currently expected to create industry standards for lost link operations as part of its planned SC-228 Phase 3 working groups.

7. Best Practices for Demonstration Approval

Obtaining approvals for flight demonstrations in the NAS was a significant portion of SIO. Demonstration flights are useful for purposes such as testing technologies, evaluating system integration approaches, and performing market research. Because the UAS have not been certified and technologies may be at various levels of maturity, it is common for restrictions to be placed on the operation that are commensurate with the level of risk. The approach used by all the SIO partners was to obtain an experimental airworthiness certificate, COA, spectrum licenses, and other necessary approvals for experimental operations in the NAS. In this section, we describe the approvals that the SIO partners needed to obtain and provide some pointers to best practices related to each approval.

Depending on the risk of the operation and weight of the vehicle, there are other paths to obtaining approval to operate in the NAS that may be considered. Applicants may use different sets of rules to fly a UAS in the airspace including Part 107 and Title 49 of the United States Code Section 44807 (referred to as “Section 44807”). However, using either of these approaches places severe limits on the operational envelope and they were not used by the SIO partners for the flight demonstrations. Developers interested in pursuing these paths should consider whether the quicker path to operations will achieve the project’s ultimate goals. Making use of people with certification expertise (see section 6.2.1) can help with this decision.

7.1. Experimental Airworthiness Certification

The requirements for experimental certificates are described in various sections of 14 CFR 21, including sections 21.173, 21.191, and 21.193. The requirements revolve around establishing the identity of the aircraft and providing basic airworthiness information. The requirements in 21.193 are deliberately vague to capture the large range of experimental aircraft. Some experimental aircraft are developed by hobbyists. Other experimental aircraft are attempting radical new concepts in aircraft design. For a UAS manufacturer that intends to develop and sell their aircraft for commercial benefit—the focus of the SIO activity—an experimental certificate is a step towards eventual type certification. In this way, the UAS manufacturer, in their experimental certificate application, can provide preliminary versions of their safety case (see section 5.3) justifying the safety of their UAS. The safety case for an experimental certificate will include special hazard mitigations that will not exist in the final system. For instance, a UAS without an approved DAA solution could use a chase aircraft to provide “see and avoid” capability. If this safety case is well developed, then once the special hazard mitigation is removed, it becomes clear where the regular system must compensate. In this way, the best practice in obtaining an experimental certificate is to have a well-developed safety culture (see section 6.2.3). In addition, for elements of the UAS with a strong human/interaction component, the best practice related to human/automation interaction is relevant (see section 6.1.4).

Additionally, there are various restrictions associated with the use of aircraft with experimental certificates. While an experimental airworthiness certificate may be used for research and development or operations related to certification, it can only be operated within the limits defined by the certificate and is specifically not allowed to be used for “compensation or hire” per the operational restrictions specified in 14 CFR 91.319. Furthermore, 14 CFR 91.319 specifies that aircraft with an experimental certificate may not be operated over densely populated areas or in congested airways. One of the SIO partners had to modify their originally planned flight demonstration route to comply with those restrictions.

Over the course of SIO, the FAA also determined that adding a DAA system to a UAS to fulfill see-and-avid requirements constituted a major change to the aircraft, even if the DAA system was previously carried onboard the unmanned aircraft as a payload. This required one partner to obtain a new experimental airworthiness certificate, enabling the FAA's Aircraft Certification Service to evaluate the DAA system and determine operating limitations based on the maturity and design assurance of the DAA system. These operating limitations were then used by FAA's Air Traffic Organization to incorporate those limitations into the 91.113 waiver process and COA.

7.2. Certificate of Waiver or Authorization (COA)

Whereas the experimental certificate establishes that the aircraft has basic airworthiness, a COA establishes that the aircraft behaves as a good citizen in the airspace. The COA is an authorization granted by the FAA's ATO and includes provisions and limitations to make sure that the unmanned aircraft operates safely, does not interfere with other airspace users, and can be managed by ATC. The content of the COA includes basic information related to system and operational description (see section 7.2), equipage considerations like avionics and lighting, spectrum analysis (treated separately below), ATC communications, surveillance (treated separately below), flight crew qualifications, and lost link and emergency procedures.

The main objective of a COA application is to provide a way to safely accommodate all the 14 CFR 91 airspace regulations, including ones that are particularly hard to meet for UAS like the 14 CFR 91.113 "see and avoid" requirements. Meeting this objective involves an approval to perform operations in a specific region of airspace; though, there are cases where nationwide COAs have been granted for operations in Class G airspace. The SIO partners performed an assessment of their respective operational areas by assessing the population, roads, and structures below and the airspace environment and by assessing the number of IFR and VFR operations in the region.

One observation made during this time was that the FAA was very vigilant with regard to risk, both to people on the ground and to people in the air. The FAA would question if there were any people being flown over. Since these systems were not certified, the FAA appeared to assume that the aircraft would misbehave. Furthermore, the FAA was very skeptical regarding mitigations. If the aircraft was assumed to stay within some boundary, the mitigation that the FAA would accept was some direct means to (1) observe the aircraft and (2) bring it to a safe state. Mitigations that involved sophisticated computer or communication systems were rejected, unless the applicant had significant data that this equipment worked as intended.

A second observation was that it was necessary to ensure that the unmanned aircraft had a mechanism to remain well clear from other aircraft at all times. One partner originally proposed lost link procedure where the unmanned aircraft returned to base when the C2 link was lost. However, the DAA system relied on the C2 link and therefore the DAA system was not functional during lost link, which required this partner to develop an alternate solution. Instead of returning to base, they identified emergency landing locations along the route and implemented automation into the vehicle to enable it to land at one of those emergency landing locations if the C2 link was lost or if some other emergency occurred. This solution forced them to have observers to verify that the emergency landing sites were clear of people. In the future, automation or new procedures will be required to enable scalable commercial operations without these types of mitigations.

7.3. Aircraft Registration

Essentially all UAS are required to have a registration number. The process of obtaining a number involves providing identifying information about the UAS and the owner of the UAS. No SIO partner indicated that this process was burdensome or required any specific considerations. The FAA has helpful information at the website faadronezone.faa.gov.

7.4. Spectrum Approval

Spectrum licenses are vital for flight demonstrations and type certification and were one of the most difficult approvals for the SIO partners to obtain. Spectrum licenses are needed for every system associated with the UAS that radiates RF signals. These systems may include, but are not limited to, C2 radios, radios to transmit payload information, transponders, VHF radios, DAA radars, and applicable payload sensors. While FCC licenses for these systems should be the ultimate goal and is the advisable method of obtaining approval, there were cases when temporary experimental spectrum licenses and Special Temporary Authorizations (STAs) were used for the SIO demonstrations because fully licensed equipment was not commercially available.

If temporary experimental spectrum licenses and STAs are used, there are various restrictions that must be adhered to that may impact the operational limitations placed on the UAS. One restriction is that the transmitters utilizing these Temporary Licenses must not cause interference to other transmitters or receivers. If they do cause interference, the applicant is required to immediately discontinue operation of the transmitter. Additionally, there is no guarantee that other licensed transmitters will not cause interference with the experimental system. Obviously, this will be problematic if the transmitter is fulfilling a safety-critical function, such as the C2 link or a DAA radar. This was one of the barriers that a SIO partner encountered when pursuing a 14 CFR 91.113 waiver for BVLOS operations. If these temporary or experimental spectrum licenses are used for safety-critical functions, the applicant will need to have acceptable safety mitigations in place. There are other restrictions to experimental licenses, such as restrictions that prevent use for revenue flight.

As described in section 6.4.5, when obtaining spectrum licenses for any frequency managed by the FAA, the applicant must coordinate with the FAA spectrum office to obtain a formal coordination letter. Failure to do so may result in project delays and possibly the need to change frequencies that are used if the requested are not acceptable. Even if the FAA does not manage the spectrum being requested, the FAA Spectrum Office will provide expertise as part of the other approval processes to make sure that any spectrum-related risk is understood and appropriately mitigated.

The availability of various frequencies may depend on geographical location and other complex factors. One of the partners was required to either reroute their flight or turn off a payload sensor to avoid conflicts with transmitters on the ground. Multiple partners conducted a RF survey of the operational area to understand frequencies that were commonly used in the demonstration area. One of the other SIO partners used cellular LTE to transmit payload information and serve as a backup C2 link. They learned that coordination with the cellular network administrators was required to make sure that certain cellular bands that are not approved for airborne operations were not used. Even though the LTE link was used as a payload and backup link, the FAA recommended that the SIO partner request high network priority on any commercial LTE networks used to transmit safety-critical information in order to reduce the probability of a lost or degraded link due to network congestion. It should be noted that additional standards development is needed before cellular LTE is viable for the primary C2 link.

One item addressed in section 6.4.4, but worth reiterating here, is the use of unlicensed spectrum for safety-critical C2 communications. Two of the SIO partners investigated the use of unlicensed spectrum for their C2 links. One of those partners had a C2 system that could switch between four different redundant datalinks. In all cases, the FAA stated that unlicensed spectrum is not viable for the transmission of safety-critical information during flight above 400 ft AGL because this violates radio frequency regulations (47 CFR 300.1 subsections 7.8 and 7.9), in addition it is not possible to guarantee protection from interference with other transmitters.

7.5. 91.113 Waiver

A 91.113 waiver is currently required for any BVLOS flights without visual observers and is one of the most difficult waivers to obtain. This is a waiver of an airspace regulation that is separate from the COA process described above. 14 CFR 91.113 provides the requirements to see and avoid other air traffic. For aircraft that require BVLOS operations, a DAA system will provide this capability. The problem from a flight demonstration standpoint, is that currently there are no FAA-approved commercial off-the-shelf DAA systems. Therefore, applicants must provide information as part of the 91.113 waiver process to show that the DAA system and any other risk mitigations provide an acceptable level of safety without the need for special accommodations that may burden ATC or other airspace users. This was highlighted when special ATC flight-following services were considered as a risk mitigation for one of the partner's flight demonstrations. However, the FAA decided that providing special services as a risk mitigation was not a scalable approach as the number of UAS operations increase. Instead, the applicant must be able to provide design and test information to show that the DAA system will operate safely in the existing NAS without flight-following services.

One question many applicants have is what the requirements are to prove that their DAA system meets a satisfactory level of performance. The most effective method is to obtain a TSO for the DAA system using [TSO-C211, TSO-C212] and the RTCA standards that these TSOs are based on [DO-365, DO-366]; however, this approach is currently only applicable to large UAS and does not account for BVLOS approvals that may be needed to conduct testing for a TSO. Another avenue that may be considered is showing compliance with industry standards. One of the SIO partners created a requirements matrix that showed all the requirements and tests for applicable standards, which requirements were met, and risk mitigations for any requirements that were not met. While that approach has not resulted in a successful BVLOS flight as part of SIO yet, it is an approach that may be considered by companies that are on a path toward a TSO or certified DAA system. If applicable standards do not exist, applicants may also create their own DAA performance requirements derived from a comprehensive safety assessment. This will likely be the most challenging approach and the applicant will need to provide information and test data to substantiate their performance requirements. One applicable best practice is related to using modeling and simulation (see section 6.3.5) which allows the flight demonstration test conditions to be established, making the test operations more effective.

When seeking approval for BVLOS operations, it is important to implement safety mitigations that are commensurate with maturity of the DAA system. This is often referred to as a "crawl, walk, run" approach. One of the SIO partners conducted a series of ground tests followed by tests onboard a conventional rotorcraft prior to integrating the DAA system into the unmanned aircraft. The tests onboard the conventional rotorcraft included functional tests followed by encounter tests with an intruder. Testing onboard a manned rotorcraft allowed the partner to solve engineering problems, characterize the DAA system, and collect data without the need for visual observers or a 91.113 waiver. These tests were followed by tests with the DAA system integrated into the unmanned aircraft. Additionally, the SIO partners conducted surveys of the air traffic in the demonstration area to assess the unmitigated collision risk (i.e., the collision risk without a DAA system). Databases created and maintained by MIT-LL, which plan to be open sourced, may help future applicants conduct similar analyses (see section 6.3.6). One SIO partner pursued a 91.113 waiver but did not obtain it in time for their demonstration. The other two partners identified the need for additional DAA testing and safety assessments for BVLOS flight at their demonstration locations and did not pursue a 91.113 waiver. This type of self-policing is an example of a safety culture (see section 6.2.3).

There are interactions between the 91.113 waiver and other approvals that must be considered. First, the FAA requires a method to make sure that the DAA system meets its intended function. During SIO, the FAA identified the need to evaluate the airworthiness of the DAA system, to make sure that it meets its intended function, and describe any DAA limitations within the experimental airworthiness certificate. Those DAA limitations were then used during the evaluation of the 91.113 waiver, which is approved by a different organization within the FAA. A second interaction was with the spectrum licenses for a partner's DAA air-to-air radar. Since a STA was used for spectrum approval, there was no guarantee against interference. This meant that the partner needed to implement various mitigations to reduce the likelihood or consequence of interference resulting in harm.

7.6. Exemptions

If a flight cannot be completed under existing FAA regulations, in some cases a petition for exemption may be submitted to request relief from the regulation. It should be noted that exemptions can be granted from rules but not statutes. The applicant should have clear rationale regarding how the regulation is a burden, what the alternative is and how the alternative will not degrade safety, and how the request is in the public's interest. 14 CFR 11.81 provides instruction on how to prepare and submit a petition for exemption. An exemptions petitions summary may be posted for public knowledge and comment in the federal register for the legally specified period. The FAA must address the public comments in granting or denying the exemption request. Per FAA policy, petitions for exemptions take 120 days. However, that time can increase based on the complexity of the project and the regulations from which the applicant is seeking an exemption. In SIO, one partner required an exemption that took over nine months to obtain, suggesting that early planning is beneficial if any exemptions are needed.

8. Concluding Remarks

NASA's SIO effort was created with the goal of motivating progress toward commercial UAS operations in the NAS NASA partnered with AATI, Bell, and GA-ASI to, (1) integrate prototype DAA and C2 systems into unmanned aircraft, (2) conduct flight demonstration in the NAS, and (3) develop key documentation relevant to type certification. Along the way, NASA provided expertise to industry partners on both technical and approval issues as they arose. Ultimately, these flight demonstrations were driven by the SIO partners and the success of these demonstrations is a testament to the capabilities of those organizations. NASA was also able to work with the FAA to understand the struggles they have approving the safety case of the SIO flight demonstrations when there is almost no objective data or history about what has been shown to be safe or unsafe for these categories of UAS.

NASA's interest does not lie solely in helping the three partners perform their integrations and flight demonstration or to begin their certification activities. Rather, NASA is interested in helping the entire UAS industry develop, test, and certify their systems. This report endeavors to serve that purpose. As NASA watched and helped the SIO partners, best practices where captured that, hopefully, will be of value to others in the UAS industry, including UAS manufacturers, UAS operators, and component suppliers. In addition, technology gaps were captured, which indicate areas where industry focus is needed to fill those gaps.

The gaps themselves are very far ranging. They cover high-level issues such as business case and tradeoffs between vehicle design choices and meeting business needs. Other best practices address high-level design considerations such as special issues associated with effective UAS design for human operator use. Certification best practices address issues around timing of certification, developing a culture to make building safe systems natural, and use to people with specialized expertise in certification. DAA best practices cover specific information about sensors, including considerations for ground-based sensors and limitations of low-SWaP sensors. Other DAA best practices address the need and means to generate validation information for DAA performance metrics. Best practices about spectrum and C2 address issues such as conserving valuable C2 spectrum, avoiding use of unlicensed spectrum bands, understanding of C2 performance standards, and finally coordinating effectively with the FAA.

Initial feedback is that the SIO effort was enlightening to the SIO partners and to the FAA. The SIO partners developed a better understanding of potential UAS markets and how to realize a UAS platform to serve that market. The FAA developed an understanding of the issues that industry is facing. NASA has served both as a source of technical expertise and an agent of change for this exciting new field of aviation.

9. References

[ANSI2020] ANSI Unmanned Aircraft Systems Standardization Collaborative. *Standardization Roadmap for Unmanned Aircraft Systems*, American National Standards Institute (ANSI). June 2020.

[ASTMWK62668] ASTM F38.01. "ASTM WK62668 New Specification for Detect and Avoid Performance Requirement." (In development). https://www.astm.org/DATABASE.CART/WORKITEMS/WK62668.htm

[ASTMWK62669] ASTM F38.01. "ASTM WK62669 New Test Method for Detect and Avoid." (in development). https://www.astm.org/DATABASE.CART/WORKITEMS/WK62669.htm

[ASTM-F3178-16] ASTM F3178-16 (Nov 2016), *Standard Practice for Operational Risk Assessment of Small Unmanned Aircraft Systems, (sUAS)*, ASTM, http://www.astm.org/cgi-bin/resolver.cgi?F3178-16

[BB19] Binion, T. and Blanks, M. "Is Your UAS Safety Case Ready for Flight – Leveraging Research and Operations to Get to Yes." FAA UAS Symposium. June 2019.

[B10] Bozzano, M. and Villafiorita, A. *Design and Safety Assessment of Critical Systems*. Auerbach Publications. 2010.

[E11] Ericson II, C. *System Safety Primer*. CreateSpace Independent Publishing Platform. 2011.

[GPC17] Federal Aviation Administration. “The FAA and Industry Guide to Product Certification, Third Edition.” May 2017. https://www.faa.gov/aircraft/air_cert/design_approvals/media/cpi_guide.pdf

[SS00] Federal Aviation Administration. “The System Safety Handbook.” December 2000. http://www.faa.gov/library/manuals/ aviation/risk_management/ss_handbook/.

[TSO-C211] Federal Aviation Administration. “Technical Standard Order: Detect and Avoid (DAA) Systems.” TSO-C211. September 25, 2017.

[TSO-C212] Federal Aviation Administration. “Technical Standard Order: Air-to-Air Radar (ATAR) for Traffic Surveillance.” TSO-C212. September 22, 2017.

[TSO-C213] Federal Aviation Administration. “Technical Standard Order: Unmanned Aircraft Systems Control and Non-Payload Communications Terrestrial Link System Radios.” TSO-C213. March 9, 2018.

[DraftAC21.17] Federal Aviation Administration. “Type Certification – Unmanned Aircraft Systems (UAS).” FAA, AC21.17-XX. May 14, 2018 (draft).

[Order8040.6] Federal Aviation Administration. “Unmanned Aircraft Systems Safety Risk Management Policy.” October 4, 2019. https://www.faa.gov/regulations_policies/orders_notices/index.cfm/go/document.information/documentID/1036752

[F19] Foltz, J. “UAS Type Certification: Durability and Reliability Means of Compliance.” Presentation to ASTM F38. November 2019. https://www.astm.org/COMMIT/Nov2019.pdf

[GNW00] Graydon, Mallory S., Neogi, Natasha A., Wasson, Kimberly S. “Guidance for Designing Safety into Urban Air Mobility: Hazard Analysis Techniques.” AIAA SciTech 2020 Forum. January 2020. https://arc.aiaa.org/doi/abs/10.2514/6.2020-2099

[HL16a] Hobbs, A., and Lyall, B. “Human factors guidelines for unmanned aircraft systems. Ergonomics in Design.” *Ergonomics in Design.* 24, 23-28. 2016. DOI:10.1177/1064804616640632

[HL16b] Hobbs, A., and Lyall, B. “Human factors guidelines for remotely piloted aircraft system (RPAS) remote pilot stations (RPS).” NASA Contractor report. ARC-E-DAA-TN34128. 2016.

[H19] Holloway, C. Michael (2019), “Understanding the Overarching Properties.” NASA Langley Technical Report. NASA/TM-2019-220292. 2019.

[SMM13] International Civil Aviation Organization. “Safety Management Manual.” Third Edition. Doc 9859. 2013.

[J18] Joint Authorities for Rulemaking of Unmanned Systems. “JARUS guidelines on Specific Operations Risk Assessment (SORA).” Version 1.2. JAR-DEL-WG6-D.04. May 31, 2018.

[K18] Kenul, Philip. The Key Role of Standards in Support of Safe, Efficient and Economical Future UAS Airspace Integration, AUVSI Xponential. May 2018.

[L95] Leveson, Nancy G. *Safeware: System Safety and Computers*, Addison Wesley. 1995.

[LT85] Lloyd, E. and Tye, W. *Systematic Safety: Safety Assessment of Aircraft Systems*. Civil Aviation Authority, London, England, 1982. reprinted 1992 edition.

[MVF18] Marston, M., Valkov, S. and Flock, A. “UAS-NAS NASA 870 Ikhana UAS No Chase COA (NCC) Flights.” AFRC-E-DAA-TN60378. 2018.

[MNHUDCC15] Munoz, C., Narkawicz, A., Hagen, G., Upchurch, J., Dutle, A. Consiglio, M., and Chamberlain, J. “DAIDALUS - Detect & Avoid Alerting Logic for Unmanned Systems.” NASA Langley. September 13, 2015. https://ntrs.nasa.gov/citations/20160007498

[McC07] McCormick, F. “Certification of Civil Avionics.” In Cary Spitzer (Ed). *Avionics: Development and Implementation, 2nd Edition*, CRC Press. 2007.

[DO-160G] RTCA, Inc. “Environmental Conditions and Test Procedures for Airborne Equipment.” RTCA DO-160G. December 8, 2014.

[DO-178C] RTCA, Inc. “Software Considerations in Airborne Systems and Equipment Certification.” RTCA DO-178C. December 2011.

[DO-185] RTCA, Inc. “Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II).” RTCA DO-185. June 19, 2008.

[DO-254] RTCA, Inc. “Design Assurance Guidance for Airborne Electronic Hardware,” RTCA DO-254. April 19, 2000.

[DO-264] RTCA, Inc. “Guidelines for Approval of the Prevision and Use of Air Traffic Services Supported by Data Communications.” RTCA DO-264. December 14, 2000.

[DO-285B] RTCA, Inc. “Next Generation Air/Ground Communications (NEXCOM) VDL Mode 3 Interoperability.” RTCA DO-285. April 10, 2003.

[DO-362] RTCA, Inc. “Command and Control (C2) Data Link Minimum Operational Performance Standards (MOPS) (Terrestrial).” RTCA DO-362. September 20, 2016.

[DO-365] RTCA, Inc. “Minimum Operational Performance Standards MOPS for Detect and Avoid (DAA) Systems.” RTCA DO-365. May 31, 2017

[DO-365A] RTCA, Inc. “Minimum Operational Performance Standards MOPS for Detect and Avoid (DAA) Systems.” RTCA DO-365A. March 20, 2020.

[DO-365B] RTCA, Inc. “Minimum Operational Performance Standards MOPS for Detect and Avoid (DAA) Systems.” RTCA DO-365B. In progress.

[DO-366] RTCA, Inc. “Minimum Operational Performance Standards (MOPS) for Air-to-Air Radar for Traffic Surveillance.” RTCA DO-366. May 31, 2017.

[DO-377] RTCA, Inc. “Minimum Aviation System Performance Standards for C2 Link Systems Supporting Operations of Unmanned Aircraft Systems in U.S. Airspace.” RTCA DO-377. March 21, 2019.

[DO-381] RTCA, Inc. “Minimum Operational Performance Standards (MOPS) for Ground Based Surveillance Systems (GBSS) for Traffic Surveillance.” RTCA DO-381. March 26, 2020.

[DO-386] RTCA, Inc., “Minimum Operational Performance Standards for Airborne Collision Avoidance System X (ACAS X) (ACAS Xa and ACAS Xo).” Volume I and II, RTCA DO-386. In development.

[R17] Ryan, Wes. “FAA Update – Standards Overview and UAS Update.” Presented to ASTM F38. May 2017.

[SAE4754A] SAE, International. “Guidelines for Development of Civil Aircraft and Systems.” ARP-4754A. December 21, 2010.

[SAE4761] SAE, International. “Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment.” ARP-4761. December 1, 1996.

[WCL19] Wu, M.G., Cone, A.C., Lee, S. “Detect and Avoid Alerting Performance with Limited Surveillance Volume for Non-Cooperative Aircraft.” *AIAA SciTech Forum*, AIAA-2019-2073, 2019. https://arc.aiaa.org/doi/pdf/10.2514/6.2019-2073

[WLSGESAC20] Wu, M. G., Lee, S., Serres, C. C., Gill, B., Edwards, M. W. M., Smearcheck, S., Adami, T. and Calhoun, S. “Detect-and-Avoid Closed-Loop Evaluation of Non-Cooperative Well Clear Definitions.” *The Journal of Air Transportation*, 2020. https://arc.aiaa.org/doi/full/10.2514/1.D0199

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01/01/2021

2. REPORT TYPE
TECHNICAL MEMORANDUM

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Best Practices Identified Through the Completion of UAS Flight Demonstrations

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jeffrey Madalon, Kurt Swieringa, Israel Greenfeld, Summer L. Brandt, Peter Robinson, M. Gilbert Wu, Seungman Lee, Paul Volk, John Del Frate

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
629660.04.41.07.20

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

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-001

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

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-20205011606

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

After several years of research into Detect and Avoid (DAA) and Command and Control (C2) systems for Unmanned Aircraft Systems (UAS), the National Aeronautics and Space Administration’s (NASA) UAS Integration into the National Airspace System project initiated a focused two-year effort along with the Federal Aviation Administration (FAA) and three industry partners to investigate remaining issues in the specification, test, certification and airspace integration to allow UAS operations in non-segregated airspace. The approach taken had the industry partners propose a flight demonstration approximating a commercial operation, while NASA helped, as needed, the partners through design and test phases and N

15. SUBJECT TERMS
NASA, FAA, unmanned, aircraft, system, UAS, certification, type, operational, operations, approval, DAA, detect and avoid, command and control, C2, spectrum, radio, lost link, best practice, design, flight test

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
U	U	U	UU	61	HQ - STI-infodesk@mail.nasa.gov
					19b. TELEPHONE NUMBER *(Include area code)* 757-864-9658