NASA/TM—2020—20205004052

UAS Integration in the NAS Project: Overview of Flight Test Series 6

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July 2020

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July 2020

This report is available in electronic form at

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1. Abstract

The National Aeronautics and Space Administration (NASA) Unmanned Aircraft Systems Integration in the National Airspace System (UAS-NAS) Project has conducted a series of flight test campaigns intended to support the reduction of barriers that prevent unmanned aircraft from flying without the required waivers from the Federal Aviation Administration (FAA). The 2019 Flight Test Series 6 (FT6) campaign furthered this path and supported three test configurations: 1) Radar Characterization, 2) Scripted Encounters and 3) Full Mission. Radar Characterization assessed the performance of Honeywell's low size, weight, and power (low SWaP) radar system; Scripted Encounters investigated the timing of Detect and Avoid (DAA) alerting thresholds using a Department of Defense (DoD) Group 3 unmanned aircraft system (UAS) equipped with low SWaP sensors and three different live intruder aircraft flown at varying encounter geometries; and Full Mission validated human-in-the-loop simulations by collecting pilot performance data from a ground control station while controlling a live unmanned aircraft on a mission in both virtual and live air traffic controlled airspace. The subject pilot observed a research display that presented DAA advisories to maintain separation from live and virtual aircraft. The test was conducted over a twenty-week period within the R-2508 special use airspace located near Edwards Air Force Base (EAFB), CA. Over 240 encounters were flown during the test series and FT6 proved to be invaluable for the purposes of planning, managing, and executing this type of integrated flight test in both live and virtual environments. Data collected from FT6 was provided to the RTCA Special Committee 228 (SC-228) to help inform the Phase 2 Minimum Operational Performance Standards (MOPS). FT6 was the final test series for the UAS-NAS project that began in 2012. This paper provides an overview of FT6 and its success can be directly attributed to the diligent work of the men and women who supported this effort.

2. Acronyms

ACAS	Airborne Collision Avoidance System
ACON	ADS-B Console
ADRS	Aeronautical Datalink and Radar Simulator
ADS-B	Automatic Dependent Surveillance-Broadcast
AFRC	Armstrong Flight Research Center
ARC	Ames Research Center
ATAR	Air-to-Air Radar
ATC	Air Traffic Control
ATM	Air Traffic Management
ATOL	Automatic Takeoff and Landing
AVP	Air Vehicle Pilot
BITS	Business Information Tracking System
BRLOS	Beyond Radio Line of Sight
C2	Command and Control
CCB	Configuration Control Board
CCT	Cloud Cap Technology
CDR	Critical Design Review
CDTI	Cockpit Display of Traffic Information
CFR	Code of Federal Regulations
COA	Certificate of Authorization
COMEX	Commence Exercise
CONOPS	Concept of Operations
COTS	Commercial off the Shelf
CPA	Closest Point of Approach
CSE	Center Scheduling Enterprise

CST	Combined Systems Test
DAA	Detect and Avoid
DAAP	Detect and Avoid Processor
DAIDALUS	Detect and AvoID Alerting Logic for Unmanned Systems
DAPA	Digital Active Phased Array
DATR	Dryden Aeronautical Test Range
DD	Decimal Degrees
DGPS	Differential Global Positioning Systems
DICES	Digital Integrated Communications Electronic System
DMP	Data management Plan
DoD	Department of Defense
DROID	Dryden Remotely Operated Integrated Drone
DSRL	Distributed Simulation Research Lab
DWC	DAA Well Clear
EAFB	Edwards Air Force Base
EGI	Embedded GPS/INS
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FCC	Federal Communications Commission
FCF	Functional Check Flight
FM	Full Mission
FOM	Fiber Optic Multiplexer
FOR	Field of Regard
FTD	Flight Test Director
FTRD	Flight Test Requirements Document
FT1	Flight Test Series 1
FT2	Flight Test Series 2
FT3	Flight Test Series 3
FT4	Flight Test Series 4
FT5	Flight Test Series 5
FT6	Flight Test Series 6
GCO	Ground Control Operator
GCS	Ground Control Station
GDT	Ground Data Terminal
GPS	Global Positioning System
GS	Groundspeed
GW	Gateway
H&S	Health and Status
HDG	Heading
HiDAN	High Reliability Data Acquisition Node
HITL	Human in the Loop
HQ	Headquarters
HSI	Human Systems Integration
HUD	Heads-Up Display
IASP	Integrated Aviation Systems Program
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IFE	In-flight Emergency
IFF	Identification Friend-or-Foe

IFR	Instrument Flight Rules
IGT	Integrated Ground Test
INS	Inertial Navigation System
IP	Initial Point
IT&E	Integrated Test & Evaluation
JOG	Joint Operation Graphics
KA	King Air
KEDW	Airport Code for Edwards AFB
KRME	Airport Code for Griffiss International Airport
LaRC	Langley Research Center
LL	Lost Link
LMR	Land Mobile Radio
LOS	Line of Sight
LoDWC	Loss of DAA Well Clear
LRE	Launch and Recovery Element
LRO	Long Range Optics
LVC	Live Virtual Constructive
LVC-DE	LVC Distributed Environment
MACS	Multi Aircraft Control Simulation
Mag	Magnetic Course
MC	Magnetic Course
MCC3	Mission Control Center 3
MEL	Minimum Equipment List
MOA	Military Operating Area
MOC	Mobile Operations Center
MOF	Mobile Operations Facility
MOPS	Minimum Operational Performance Standards
MP	Maneuver Point
MSL	Mean Sea Level
MTBF	Mean Time Between Failure
MUX	Multiplexer
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASC	Navmar Applied Sciences Corporation
NAV	Navigation
NMAC	Near Mid Air Collision
NOTAM	Notices to Airmen
NTIA	National Telecommunications and Information Administration
O/S	Ownship
OML	Outer Mold Line
OWG	Operations Working Group
PCC	Piccolo Command Center
PE	Project Engineer
PI	Principal Investigator
PIC	Pilot in Command
PIRA	Precision Impact Range Area
PM	Project Manager
PT	Point
PUT	Pilot Under Test
RAIF	Research Aircraft Integration Facility
RCO	Range Control Officer

RCON	Remote Console
RCS	Radar Cross Section
REQ	Required
RF	Radio Frequency
RFSMO	Radio Frequency Spectrum Management Office
RFSO	Radiation Frequency Safety Officer
RGCS	Research Ground Control Station
RNG	Range
RTB	Return to Base
SA	Situational Awareness
SAA	Sense and Avoid
SAAP	Sense and Avoid Processor
SC	Special Committee
SCO	System Checkout
SDK	Software Development Kit
SDL	Software Development Lab
SME	Subject Matter Expert
SOR	Senior Operations Representative
SPD	Speed
SPORT	Space Positioning Optical Radar Tracking
SPUT	Subject Pilot Under Test
SRD	Systems Requirements Document
SSA	System Safety Assessment
SSWG	System Safety Working Group
SUA	Special Use Airspace
SUM	Sensor Uncertainty Mitigation
SWaP	Size, Weight, and Power
TC	Test Conductor
TCAS	Traffic Alert and Collision Avoidance System
TCOR	Test Coordinator
TD	Test Director
TFR	Temporary Flight Restriction
TRACON	Terminal Radar Approach Control Facilities
TREC	Test Recorder
TRK	Track
TSD	Tactical Situation Display
TSO	Technical Standard Order
UA	Unmanned Aircraft
UAP	Unmanned Aircraft Processor
UAS	Unmanned Aircraft System
UAS-NAS	Unmanned Aircraft Systems Integration in the National Airspace System
VFR	Visual Flight Rules
VHF	Very High Frequency
VID	Visual Identification
VMC	Visual Meteorological Conditions
VoIP	Voice over Internet Protocol
VSCS	Vigilant Spirit Control Station
VSI	Vertical Speed Indicator
VSM	Vehicle Specific Module
WG	Working Group
WP	Waypoint

WPT	Waypoint
ZLA	Los Angeles Air Route Traffic Control Center
ZOA	Oakland Air Route Traffic Control Center

3. Definition of Terms

Circuit	One complete lap around the Full Mission racetrack flight plan.
Cooperative	Aircraft equipped with an electronic means of replying to interrogations or reporting aircraft state information.
Corrective Alert	DAA caution level alert that advises the pilot to coordinate with ATC before maneuvering in order to maintain DWC.
Encounter	A preplanned condition between the ownship and an intruder aircraft designed to collect surveillance data and DAA alerting and guidance data. For FT6, all encounters contain at least two geographic points (initial point (IP) and closest point of approach (CPA)) for each aircraft.
Full Mission	Human research evaluation using a subject pilot under test who operates an ownship aircraft from a prototype DAA display interface to test human performance against both live and virtual traffic in a combined live and virtual test environment.
Geometry	Encounter angular offset between ownship and intruder aircraft.
Group 3 UAS	Department of Defense definition of a UAS that has a maximum takeoff weight under 1320 lbs, a normal operating altitude under 18,000 ft, and speed (KIAS) below 250 kt.
Intruder	Manned aircraft interacting (horizontally and / or vertically) with the ownship to excite DAA system responses.
Maneuver	A planned vertical and / or horizontal geospatial change performed by the intruder, ownship or both aircraft that occurred at some point during the encounter.
Mitigated	An encounter where the ownship makes some maneuver, either manually or automatically, to avoid a loss of DAA Well Clear (DWC) with an intruder aircraft.
Non-Cooperative	Aircraft that are not equipped with an electronic means of replying to interrogations or reporting aircraft state information.
Ownship	Unmanned aircraft equipped with surveillance systems used for testing airborne geospatial encounters with intruder aircraft. For FT6 the ownship was the TigerShark XP UAS.
Preventative Alert	DAA alert that advises the pilot of proximate traffic to be monitored but not acted upon.
Radar Characterization	Flight test configuration using specific encounters designed to collect radar performance data to determine the surveillance system capability against a variety of manned intruder aircraft of varying size and configuration.
Scripted Encounters	Flight test configuration using preplanned, intercept encounters between ownship and intruder aircraft designed to collect surveillance and DAA alerting and guidance data.

System Checkout	System performance/readiness investigation and operational risk reduction flights used to prepare the FT6 system for test configuration flights.
Unmitigated	Non-maneuvering or fly through-type encounter.
Warning Alert	DAA alert that requires immediate action from the pilot to start maneuvering to maintain DWC.

4. Introduction

The use of unmanned aircraft (UA) to perform national security, defense, science, and emergency management are driving the critical need for routine access into the NAS. UAS represent an emerging capability which will provide a variety of services in the government (public) and commercial (civil) aviation sectors. The growth of this potential industry has not yet been realized due to the lack of a common understanding of what is required to safely operate UAS in the NAS.

Detect-And-Avoid systems are a critical component to the successful integration of UAS operations in the NAS. A DAA system provides surveillance, alerts, and maneuver guidance to keep a UAS "well clear" of other aircraft (refs. 27and 28). In the United States, simulation tests as well as flight tests, have provided supporting information for defining a DAA Well Clear (refs. 27 and 29) (DWC) envelope and requirements for the alerting and maneuver guidance performance (refs. 30, 31, 32, 33, and 34). Prototype DAA algorithms have also been developed for alerting and maneuver guidance research (refs. 35, 36, 37, and 50). These developments enabled the RTCA SC-228 to publish the Phase 1 MOPS for DAA systems (ref. 9) and air-to-air radar (ref. 10) in May 2017. The corresponding Technical Standard Orders (TSOs), TSO-C211 (ref. 11) and TSO-C212 (ref. 12), were published by the FAA in September 2017. These standards, referred to as the Phase 1 MOPS, target UAS operations in non-terminal areas. A DAA system, according to the Phase 1 MOPS, contains surveillance components of Automatic Dependent Surveillance-Broadcast (ADS-B) In, airborne active surveillance, and air-to-air radar that can detect aircraft with or without transponders. Traffic Alert and Collision Avoidance System (TCAS) II is an optional component.

While Phase 1 operational environment focused on UAS operations transitioning from Class A or special use airspace and traversing Class D, E and G airspace, SC-228 Phase 2 operational environment expands the MOPS to include extended operations in Class D, E and G airspace, plus take-off and landing operations in Class D, E and G airspace (ref. 49). Phase 2 MOPS includes language to address technologies enabling UAS with less available payload capability, such as low SWaP non-cooperative sensors. While low SWaP sensors are desirable, they must provide sufficient surveillance volume and accuracy to ensure the DAA system's capability of maintaining safety. FT6 supported this area of focus.

The Integrated, Test and Evaluation (IT&E) Subproject for NASA's UAS-NAS project was responsible for the planning, integration and execution of FT6. Specific FT6 flight activity and design coordination began in early 2018, although high-level discussions on low SWaP requirements started as early as late 2016. A tiger team was established to determine UAS requirements and to conduct a market study of available platforms. The UAS was selected in early 2017 and later a Cooperative Agreement Notice was released (May 2017) for the non-cooperative detect and avoid sensor. The team encountered some issues with the initial UAS selection and with the maturity of the low SWaP non-cooperative sensor that will be described in more detail in this paper. Refer to table 1 for a description of the chronological sequence of significant events for FT6.

The top-level objectives of FT6 are described in section 4.2 of this paper, were focused on informing the Phase 2 DAA System MOPS featuring low SWaP non-cooperative sensors integrated on a Group 3 UAS (ref. 51). Three configurations were tested during FT6 as a method for collecting data required to meet the test objectives: Radar Characterization, Scripted Encounters and Full Mission. Specific test objectives for each configuration are also described in the section 4.2.

The project followed a typical system engineering approach to aeronautical flight test (refs. 15, 16, 17, and 18). The project followed the AFRC airworthiness and flight safety review process to obtain authorization to conduct the flights. A system test workflow was mapped out and followed during the campaign. Leading up to the flight test were software tests, lab tests, core system and connectivity tests, various subsystem tests, followed by multiple ground tests of the various subsystems as installed on the aircraft, and a combined system test.

Conducting flight test within R-2515 restricted airspace required coordination with various offices within the 412th Test Wing (412TW) such as, the Airspace Management office. The FT6 CONOPS information presented to that office who would, in turn, advocate on the project's behalf through the 412TW Operations Group (OG) Commander office. The 412TW/OG is the authority for permitting flight operations in R-2515. Other offices such as, Airfield Manager, Real Property, Safety, Emerging Technologies Combined Task Force (ET-CTF), and Spectrum all required some level of coordination in order to comply with local and federal regulatory requirements for operating from a military reservation prior to receiving approval to operate.

Early engagement with these various offices was key to preparing the project to schedule and use the airspace within R-2515. This was especially true for FT6 since the project was employing a Group 3 UAS as testbed to host the DAA sensors. Group 3 UAS operations had no precedence at Edwards prior to the preparatory work that the UAS-NAS project had completed. This early coordination with the 412TW paved the way for the Navmar Applied Sciences Corporation (NASC) to use the TigerShark XP, the eventual ownship for FT6, for a brief test mission that supported ET-CTF and Sandia National Laboratories just prior to FT6 flight activities.

FT6 concept of operations was similar to previous project campaigns in that the test involved an ownship UAS and manned intruder aircraft flying intercept-type encounters within R-2515 airspace (figure 1). The mission was managed by a team located at NASA Armstrong. The project's LVC environment enabled the test to be distributed to other NASA centers. For FT6, NASA Ames was connected via the LVC. Multiple ground control stations (GCS) supported the test. A control room used during past campaigns supported FT6. A series of test configurations: Radar Characterization, Scripted Encounters, and Full Mission were performed and the data collected during each configuration helped to inform NASA research and the RTCA SC-228 Phase 2 MOPS.

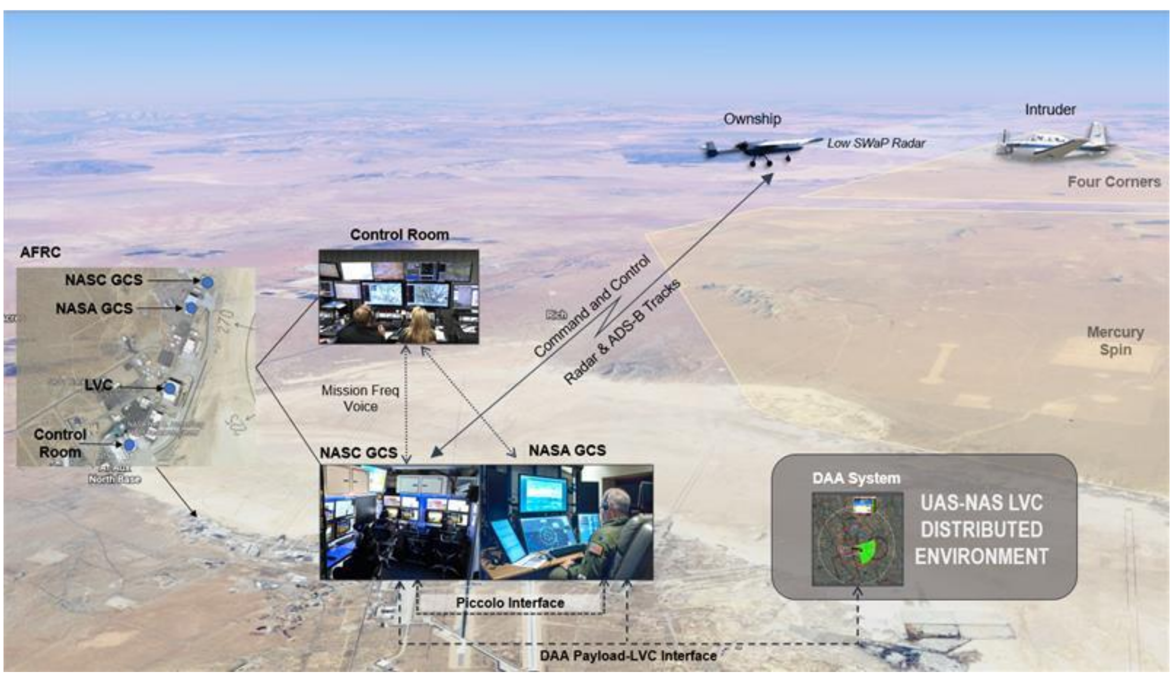


Figure 1. FT6 Concept of Operations.

System Checkout (SCO) flights preceded the aforementioned confirmations to not only ensure the aircraft and sensors were operating properly, but to run through the planned flight operations and procedures. SCO had three main elements: 1) familiarization flights, 2) basic payload checks, and 3)

Research Ground Control Station (RGCS) checks. Specific test objectives for each flight check element are described in section 4.2. During SCO, project participants analyzed aircraft performance and DAA system operations in flight. Certain flight test scenarios, called encounters, were flown to assess initial DAA alerting and guidance, plus the flights provided an early look at sensor performance. Finally, SCO provided the team with an opportunity to exercise the flight test procedures developed during the planning phase of the project life cycle.

During Radar Characterization and Scripted Encounters, the TigerShark ownship flew specific encounters against manned intruder aircraft of various equipage and performance. Once DAA system data was collected and verified, the project moved on to the Full Mission flight configuration. This final flight configuration incorporated a subject pilot and a Live Virtual Constructive (LVC) environment to achieve specific objectives.

Originally 165 unique flight test encounters were designed based on the test objectives provided by the Principal Investigator (PI). A total of 245 encounters were performed by the TigerShark during the series; of those runs, many were repeats or reattempts of a specific encounter set as was needed to obtain the necessary data or to remedy poor encounter setups. Beyond the original encounter set, due to changing requirements stemming primarily from radar performance, several additional encounters were designed and executed in order to meet specific test objectives that were not originally envisioned by the PI. These encounters are described in this report.

FT6 required a large team geographically distributed team both at NASA Armstrong Flight Research Center (AFRC) located at Edwards, CA and at NASA Ames Research Center (ARC) located at Mountain View, CA. Other participants included NASA Langley Research Center (LaRC), NASC, and Honeywell International, Inc. The process of integrating a diverse and dispersed team into an effective flight test team is notable. The project met its test goals through the successful execution of 23 test sorties, totaling nearly 68 hours of flight test activity. Ultimately, the UAS-NAS Level 1 project milestone for FT6 (flight test completion) was fully achieved as the project completed FT6 prior to the December 20, 2019 deadline.

Table 1. Significant Events for FT6, with Major Milestones Highlighted in Green.

Flight Test 6 Summary		
Date	**Event**	**Description**
9/1/2016	FT5-6 'Medium Size UAS' UAS Tiger Team Formulation	Formulated tiger team to conduct trade study to determine suitable UAS to support low SWaP testing
12/19/2016	Tiger Team Decision	Outbrief on trade study results
1/13/2017	Medium Size UAS Decision	IT&E recommends ARC SIERRA as ownship platform to project office
2/2/2017	Technical Interchange Meeting	TIM with SIERRA team to begin test planning
10/2/2017	SIERRA AFSR	ARC airworthiness and flight safety review
1/23/2018	FT5 Preliminary Design Review	PDR for FT5 flights using SIERRA-B as the UAS platform
8/3/2018	First FT6 OWG	First Operations Working Group to present & discuss FT6 objectives and success criteria
8/7/2018	FT6 Phase 1 CDR	Phase 1 Payload Subsystem CDR
8/2018	Abandonment of SIERRA-B UAS	UAS-NAS project abandoned ARC SIERRA-B UAS due to development delays and Project Office decision to contract out the airborne platform to NASC
9/14/2018	NASC Contract Award	The contract was awarded to NASC to provide a TigerShark UAS with the integrated DAPA Lite radar.

10/3/2018	FT6 Kickoff Meeting/SRR	The Flight Test 6 IT&E team and project partners gathered for a kickoff meeting to start the System Requirements Review.
10/16/2018	FT6 Full Mission SRR	System Requirements review for the Full Mission Phase of Flight Test 6
10/2018	FT5 data buy contract with Honeywell	Honeywell contracted to fly limited flight tests using prototype DAPA Lite radar system.
1/15/2019	UAS-NAS Risk Reduction Tabletop Training	Initial team training to brief entire UAS-NAS team of the Risk Reduction Flights using the µCub as the UAS.
2/21/2019	FT6 Phase 2 Full System CDR	Phase 2 Full System CDR to include Aircraft/Payload Integration and Flight Test Plan.
3/12/2019	First TigerShark Envelope Expansion Flight	Navmar completed the first envelope expansion flight of the TigerShark in Rome NY.
4/25/2019	Risk Reduction CONOPS approved by EAFB 412th TW	Risk Reduction CONOPS document approved by EAFB 412th OG/CC & Airspace Management
5/6/2019	NASC MOC & TigerShark Delivery	NASC Delivered the Mobile Operations Center (MOC) & TigerShark. AFRC PAO captured assembly of the UAS.
5/13/2019	Abandonment of µCub Risk Reduction	Project moved Risk Reduction Flights to FT6 with the TigerShark UAS.
6/26/2019	FT6 Tabletop Training	UAS-NAS Team gathered for Tabletop training event over FT6 CONOPS, Objectives & Procedures.
6/28/2019	FT6 CONOPS approved by EAFB 412th TW	FT6 CONOPS document approved by EAFB 412th OG/CC & Airspace Management
7/1/2019	FT6 System Checkout Tech Brief	Tech Brief for the first flight phase of FT6, System Checkout.
7/9/2019	First System Checkout Flight	First SCO flight in R2515
8/8/2019	FT6 Radar Characterization/Scripted Encounters Tech Brief	Tech Brief for the second & third flight phases of FT6, Radar Characterization & Scripted Encounters
8/22/2019	First Radar Characterization Flight	First Radar flight using the DAPA Lite radar
10/1/2019	First Scripted Encounters Flight	First Scripted Encounters flight with DAA Guidance/Maneuvers
10/28/2019	FT6 Full Mission Tech Brief	Tech brief for the final flight phase of FT6, Full Mission
10/31/2019	First Full Mission Flight	First Full Mission Flight using Subject Pilot
11/21/2019	Last Full Mission Flight	Last Full Mission Flight using Subject Pilot, Test Complete

The successful completion of FT6 is largely attributed to the experience acquired from previous flight test campaigns performed by the UAS-NAS project. These campaigns included: Airborne Collision Avoidance System (ACAS) Xu and Self Separation (SS) Initial flight test flown in December 2014, Flight Test Series 3 (FT3) flown in the summer of 2015, Flight Test Series 4 (FT4) flown in the summer of 2016, and ACAS Xu Flight Test 2 (FT2) flown in the summer of 2017, Flight Test Series 5 (FT5), and the No Chase COA (NCC) flight demonstration performed in 2018. Table 2 shows several metrics for the major flight test campaigns completed.

Table 2. UAS-NAS Flight Test Campaigns.

Campaign	ACAS Xu Flight Test 1	Flight Test 3		Flight Test 4	ACAS Xu Flight Test 2	Flight Test 6
		Config 1	Config 2			
Sorties	9	11	15	21	12	23
Flight Hours	41.3	56.2	36.4	98.1	56	67.6
Encounters	170	212	38	321	241	245

4.1. Responsible Organizations

The NASA Integrated Aviation Systems Program (IASP) provided direction for the UAS-NAS project as the parent program office. The UAS-NAS project office had the overall responsibility for flight test activity. NASA Ames, NASA Armstrong, NASA Langley, NASC, and Honeywell were participants. The following is a brief description of responsibilities:

- **NASA Ames Research Center (ARC):** NASA Ames IT&E subproject coordinated the research content and provided the flight simulation team who supported the preparatory integrated hardware in-the-loop simulations required to validate the DAA algorithm. ARC also provided the virtual environment and staff Human Systems Integration (HSI) and Modeling & Simulation (M&S) researchers needed to accomplish the Full Mission phase of the flight test. The NASA Ames DAA subproject provided support for the development of the DAA algorithm and GCS interfaces.
- **NASA Armstrong Flight Research Center (AFRC)**: NASA Armstrong IT&E subproject was the responsible test organization for conducting FT6 test missions. IT&E was responsible for planning, coordinating, executing and reporting on the flight test. AFRC provided facility and logistical support for the TigerShark UAS and was the source of intruder aircraft for the test. AFRC designed, tested, and supported the integration of the low SWaP surveillance system payload onto TigerShark. AFRC also provided qualified and current aircrew through the Pilot's Office and Dale Reed Subscale Flight Research Laboratory to support flight test. AFRC provided the Mobile Operations Facility (MOF) /GCS for conducting test operations, provided range coordination, and provided technical and airworthiness reviews responsibility.
- **NASA Langley Research Center (LaRC)**: NASA Langley was responsible for providing technical content and the Principal Investigator, along with a flight simulation team, who supported the preparatory simulations required to develop the low SWaP DAA algorithm. NASA Langley also provided expertise on sensor technologies as well as testing and analysis of potential radome materials.
- **Navmar Applied Sciences Corporation (NASC)**: NASC was responsible for providing a TigerShark XP unmanned aircraft and integrating the NASA provided low SWaP system to serve as ownship during flight test, a ground control station for launch and recovery, and staff to support and operate TigerShark.
- **Honeywell Aerospace:** Honeywell was responsible for providing the low SWaP Digital Active Phased Array (DAPA) Lite Surveillance Radar. Honeywell was also responsible for providing hardware, software and technical support for the DAPA Lite radar, DAA processor, and sensor fusion and tracker algorithm.

4.2. Test Objectives

Flight Test 6 was a research effort focused on informing SC-228 Phase 2 MOPS development for DAA Systems featuring low SWaP non-cooperative surveillance system integrated on a Group 3 UAS. Three top-level test objectives were developed:

1) Inform Phase 2 MOPS development of requirements for low SWaP airborne non-cooperative surveillance system.
2) Inform Phase 2 MOPS development of requirements for DAA Well Clear (DWC) alerting and guidance for UAS equipped with a low SWaP surveillance system.
3) Characterize pilot response in a full-mission environment to validate Human Systems Integration (HSI) simulation work for UAS equipped with a low SWaP surveillance system.

The flight test approach to meet these top-level test objectives was comprised of an integration and checkout phase called System Checkout (SCO) and Radar Characterization, and a data collection phase called Scripted Encounters and Full Mission. Upon completion of the SCO and Radar Characterization flight tests, data analyses were performed to evaluate system performance and determine readiness to proceed into the data collection flight test phase.

4.2.1. Ground Test Objectives

The purpose of the FT6 ground tests was to conduct elements of system verification and validation (V&V) and ensure the FT6 systems were ready for SCO flight testing. The specific ground test specific test objectives were to:

1) Perform ground control station system checks.
2) Perform ops checks of core TigerShark UAS after AFRC systems integration.
3) Perform critical systems regression checks to ensure payload integration has not degraded or unintentionally altered systems integral to safe operations of the TigerShark UAS.
4) Demonstrate connectivity between ground control stations.
5) Demonstrate functionality of the DAA payload systems.
6) Demonstrate EMI/EMC compatibility between the TigerShark UAS and DAA payload systems.
7) Determine system compatibility between payload under test and aircraft systems.
8) Demonstrate end-to-end data flow from aircraft sensors to LVC distributed environment in the Scripted Encounters configuration.
9) Demonstrate end-to-end data flow from aircraft sensors to LVC distributed environment in the Full Mission configuration.
10) Demonstrate operation of end-to-end FT6 system during a 4-hours continuous shakedown test.
11) Perform FT6 Mission Rehearsal for Scripted Encounters and Full Mission using all ground control stations and facilities.

Successful completion of ground testing is marked by executing all applicable test points delineated in the FT6 System Test Plan (STP) (ref. 16). This included documenting discrepancies and developing resolutions or workarounds to ensure specific test objectives could be achieved for the SCO flight test phase.

4.2.2. System Checkout Specific Test Objectives

The purpose of the SCO flights was to validate flight test and system requirements as delineated in the Systems Requirements Documents (SRD) and Flight Test Requirements Document (FTRD) (refs. 15 and 17) and ensure that the FT6 systems were ready to support data collection for Scripted Encounters and Full Mission test phases. SCO flights were divided between system performance/readiness evaluation and operational risk reduction. The specific SCO test objectives were to:

1) Conduct Familiarization (Fam) Flights
2) Perform Basic Payload Checks
3) Demonstrate RGCS C2 Checks:

4) Complete V&V of the requirements from the FTRD and SRD and ensure readiness to proceed into Data Collection phases.
5) Exercise the end-to-end process for data collection, distribution, and archiving

Successful completion of SCO is marked by executing all applicable test points delineated in the FT6 STP (ref. 16) and characterizing the performance of the FT6 systems. This included documenting discrepancies and developing resolutions or workarounds to ensure specific test objectives could be achieved for the data collection flight test phases. The end-to-end process for data collection, distribution, and archive is demonstrated in accordance with the FT6 Data Management Plan (DMP) (ref. 18).

4.2.3. Radar Characterization Test Objectives

Radar Characterization was complementary to SCO in that its purpose was to conduct an integration and checkout of the Honeywell low SWaP DAPA Lite radar system and ensure its readiness to support the data collection phases.

The TigerShark UAS few encounters designed to collect radar performance data to determine the surveillance system capability against a variety of manned intruder aircraft of varying size and configuration. Specific Radar Characterization specific test objectives were to:

1) Demonstrate functionality of DAPA Lite radar system against intruders of various Radar Cross Sections (RCS).
2) Determine the detection range, track accuracy, and FOR of each DAPA Lite radar panel.
3) Test track correlation between DAPA Lite radar panels.
4) Validate radar model used in low SWaP DAA simulations.

Successful completion of Radar Characterization is marked by executing all applicable test points delineated in the FT6 STP (ref. 16) and documenting the performance of the low SWaP radar system. This included documenting discrepancies and developing resolutions or workarounds to ensure specific test objectives could be achieved for the data collection flight test phases.

4.2.4. Scripted Encounters Test Objectives

The purpose of Scripted Encounters flight tests was to conduct air-to-air encounters to collect performance metrics of low SWaP DWC alerting and guidance with a reduced surveillance volume. Scripted Encounters specific test objectives were to:

1) Evaluate low SWaP DWC alerting and guidance stability with ADS-B and radar surveillance.
2) Determine mitigated separation at closest point of approach using pilot response times from Low SWaP Human in the Loop (HITL) simulations.
3) Evaluate the effectiveness of the low SWaP DAA system in resolving conflicts.

Successful completion of Scripted Encounters is marked by executing all priority 1 and 2 test points delineated in the FT6 Flight Test Plan (ref. 14). In addition, data is collected, distributed, and archived in accordance with the FT6 DMP (ref. 18) to support timely data analyses on system performance and inform low SWaP DAA requirements development.

4.2.5. Full Mission Test Objectives

The purpose of the Full Mission flight tests was to collect UAS pilot performance metrics of low SWaP DWC alerting and guidance with limited surveillance volume during an operationally representative mission. Full Mission specific test objectives were to:

1) Measure and characterize a UAS operator's naturalistic behavior in an operational scenario.
2) Gather metrics to investigate the effects of a low SWaP sensor on pilot performance in an operationally representative mission and validate HITL research.
    a) Reaction times to corrective/warning.

b) Loss of DAA Well Clear (LoDWC) rate.
c) Horizontal/vertical separation at closest point of approach.
d) Maneuver decisions.
e) ATC coordination.
f) UAS pilot subjective questionnaire responses and feedback.
g) Acceptability of guidance, alerting, and sensor range.
h) C2 latency impacts.

Successful completion of Full Mission is marked by data collection on at least 6 UAS pilots. Data is collected in accordance with the FT6 DMP (ref. 18) to support timely Data analyses on system performance and validate low SWaP DAA system performance assumptions, surveillance models, and the results of previous low SWaP HITL simulations.

4.3. Working Groups

Throughout the flight test activity, communication was critical in order to achieve proper coordination, meet schedule deadlines, and reach project milestones. For this reason, several working groups (WG) were created and regularly met to facilitate planning activities. Each working group was comprised of personnel from AFRC, ARC, LaRC, Honeywell, and NASC. Three working groups were established: Operations Working Group (OWG), Integrated Working Group (IWG), and System Safety Working Group (SSWG). The purpose of each working group is described below.

4.3.1. Operations Working Group

The FT6 Operations Working Group was a fundamental collaborative effort between all stakeholders and participants for FT6. The OWG core membership met weekly to discuss all FT6 planning, ground, and flight operations topics. This working group was responsible for all flight planning, developing CONOPS, coordination amongst the various project engineering disciplines and partners, test encounter geometry development, flight test card development/review, assigning/reviewing action items within the group, identification of safety concerns which fed into the System Safety Working Group (SSWG), hardware and software integration and testing discussions which would feed into the Integration Working Group (IWG). The group also supported the development of training requirements, roles and responsibilities of the various team positions, and readiness for conducting the test. The OWG pedigree was built upon from the beginning of the project (ACAS Xu 2014 flight test) and has been a fundamental element for achieving a successful flight test campaigns in the past.

4.3.2. Integration Working Group

The primary goal of the IWG was to ensure that FT6 stakeholders continued to operate under the same assumptions as multiple development tasks in disparate locations were underway. The meetings were regularly scheduled and included FT6 stakeholders to discuss the development and testing of the flight test architecture. Communication between stakeholders was particularly critical for FT6, as stakeholders were distributed across the country and several organizations. The members of the IWG included the principal investigator, AFRC IT&E, ARC IT&E, DAA subproject researchers from ARC, representatives from Honeywell and NASC as well as the UAS in the NAS project office. The IWG meetings were led primarily by the principal investigator on a weekly basis and covered a wide range of topics including but not limited to development and testing progress, technical interfaces, researcher requirements beyond what was documented in the FTRD (ref. 17) and implementing risk mitigations. Reviewing and updating the integration and flight test schedule was a particularly critical task as each of the FT6 stakeholders needed to stay apprised of what level of staffing was needed at what date. The IWG meeting also provided the opportunity to communicate how the research objectives would be accomplished in each flight test phase as the dates for development milestones shifted as described in Section 9 Test Results and Analysis.

4.3.3. *System Safety Working Group*

The System Safety Working Group was comprised of personnel from across all project disciplines/skill sets, and provided the forum where participants reviewed potential hazards introduced by the project CONOPS. This forum created an atmosphere where formal technical discussions and interactions between team members could take place that were crucial to fully recognize the causes of a potential hazard and its subsequent effects, and to develop strong mitigation actions. It is important to mention, that a complete buy-in from the entire project team (internal and external) was needed in order to complete a comprehensive hazard analysis. The UAS-NAS FT6 SSWG was comprised of personnel from AFRC, ARC, LaRC, Honeywell, and NASC. SSWGs were conducted on average of one per week, however, there were occasions when it was necessary to conduct as many as three per week in order to thoroughly address the identified hazards to meet project goals.

4.4. Flight Schedule and Roadmap

The IT&E operations team developed a detailed roadmap to help identify specific items and when they need to be completed by. Figure 2 shows this detailed roadmap. The red triangles represent specific deliverables that the IT&E ops team had to submit ranging from mission Rules, tech briefs, and flight cards. The yellow triangles are high priority events such as mission rehearsal, EAFB 412th TW briefing, and tabletop training.

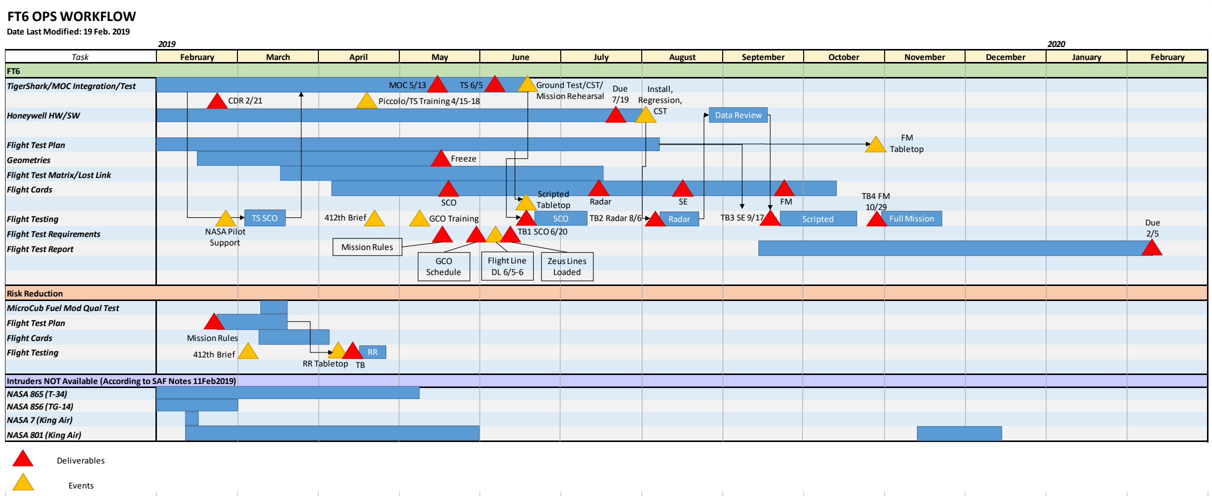


Figure 2. FT6 Ops Roadmap.

In addition to the FT6 operations roadmap, the project carried an IT&E schedule that encompassed all of FT6 major tasks and milestones. Figure 3 shows this baseline schedule and sequence of events to complete FT6.

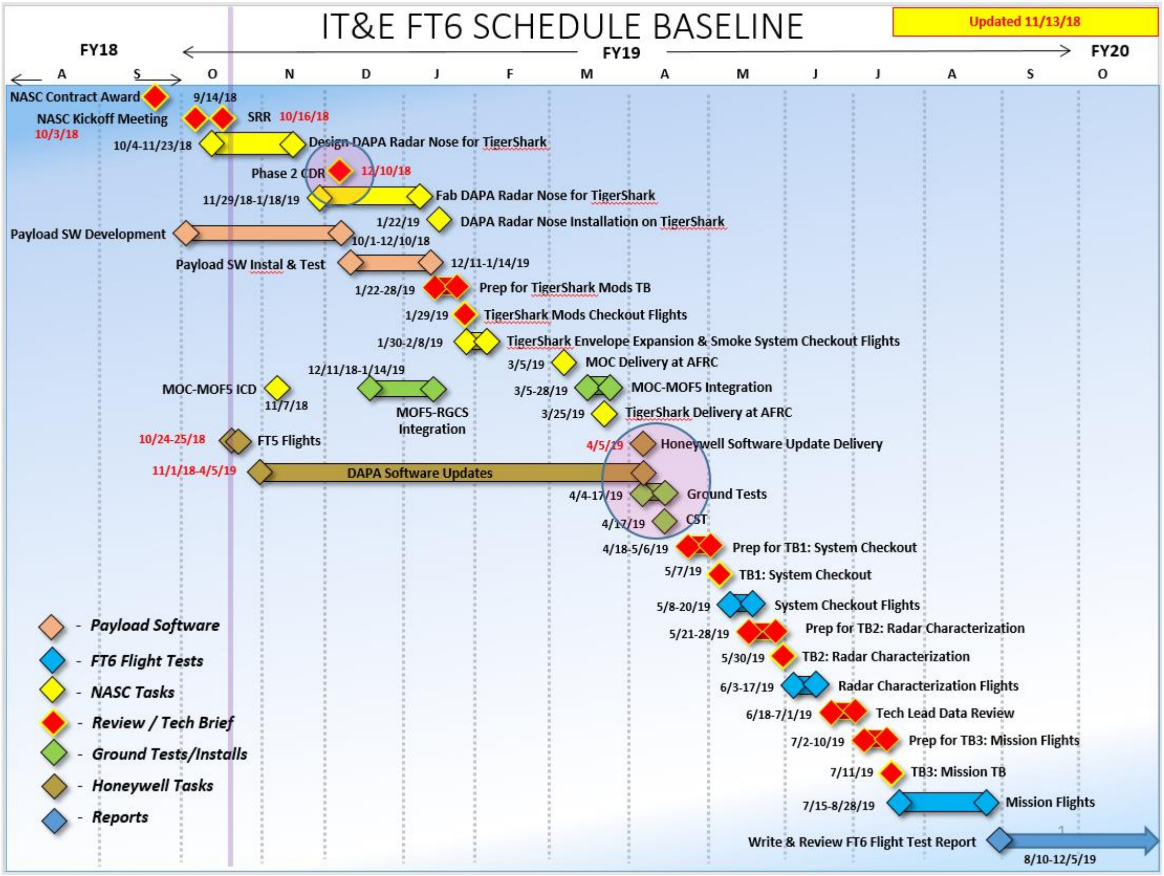


Figure 3. Flight Test 6 IT&E Baseline Schedule.

5. System Architecture Description

The UAS-NAS IT&E FT6 system, shown in figure 4, was primarily architected around the reuse of the LVC Distributed Environment (DE) that was successfully used in previous flight test campaigns (e.g. ACAS Xu, FT3, and FT4). Reuse of previous designs helped reduce risks and expedite the design of the new systems that were required to support the FT6 mission.

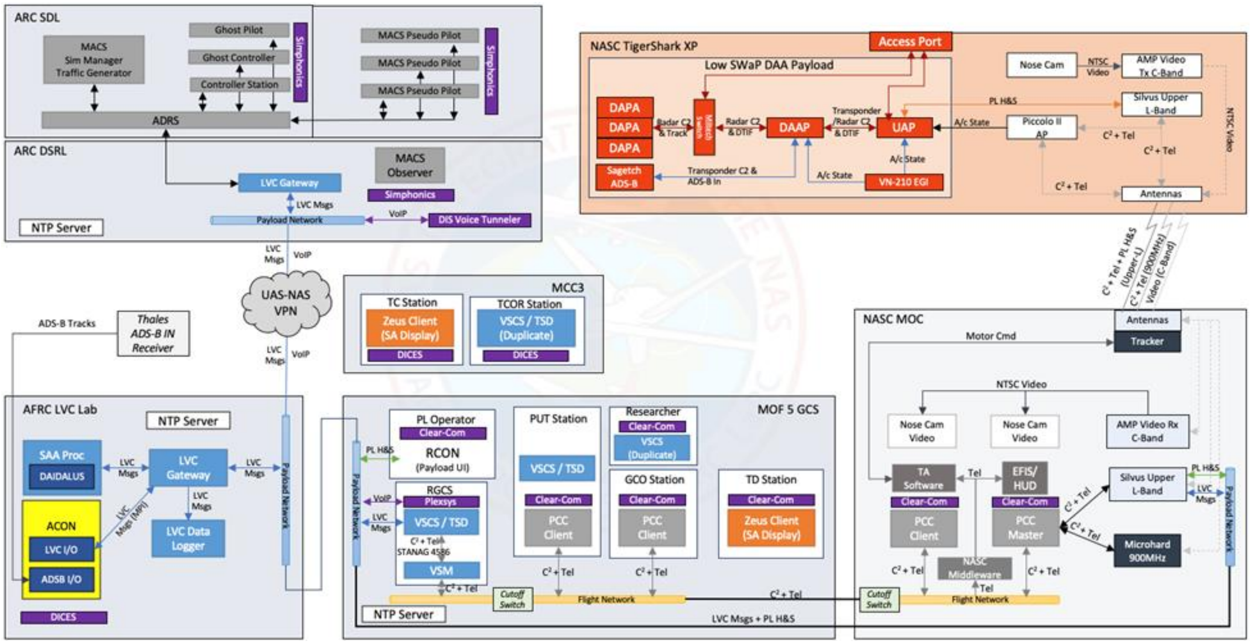


Figure 4. Flight Test 6 System Architecture.

In the FT6 architecture, intruder and ownship tracks from the TigerShark sensors were downlinked to the NASC MOC ground station in the LVC format. During test execution, the MOC essentially acted as a Ground Data Terminal (GDT) used to transmit and receive C2 and payload data from the aircraft. The LVC tracks eventually ended up at the LVC Gateway (GW) in the AFRC LVC lab through a series of point-to-point network switches in the MOC, MOF5, and AFRC LVC lab. Once the track data was available at the LVC GW, the DAA algorithm (SaaProc) subscribed to the data, processed it, and published DAA alerts and guidance to the GW. Finally, Vigilant Spirit Control Station (VSCS), displayed the traffic, guidance, and alerts on its Tactical Situation Display (TSD). For Full Mission, ARC LVC published virtual traffic to the LVC environment to increase the traffic density the subject pilot in the Research Ground Control Station (RGCS) observed on the VSCS TSD. To simulate Oakland Center radar scans for the virtual Air Traffic Controllers (ATC) at ARC, the AFRC Thales ADS-B console (ACON) received 1Hz target data from live local Edwards traffic, filtered tracks by Flight ID, and published the filtered tracks at 0.21Hz to the LVC environment in the MPI format.

To execute the flight test, the pilot stations in MOC and MOF5 were used to perform launch & recovery, airspace transitions, and mission execution. The MOC served as the Launch and Recovery Element (LRE) where the following functions were performed:

- Aircraft staging
- Aircraft pre-flight
- Payload startup
- Takeoff and landing
- Payload shutdown/restart
- Emergency Procedures

In MOF5, the GCO and PUT worked together to transfer TigerShark between the UAS Work Area and the test area. Once in the test area, the PUT maintained Pilot in Command (PIC) duties. The Piccolo Command Center (PCC) was used to command the aircraft during these phases of flight. In addition to the inline network cutoff switches, this PCC architecture was setup with the MOC PCC as the server and MOF5 stations as clients to ensure that the MOC always maintained direct link with the aircraft in case of an emergency. In an Emergency Procedure (EP) scenario, the NASC team had the ability to completely isolate the MOC from the research systems.

The Mission Control Center 3 (MCC3) was used by the Test Conductor (TC) to execute the test. The Test Director (TD) was located in MOF5 and was responsible for overall test safety. The communication system consisted of the following systems:

- Clear-Com/Land Mobile Radio (LMR) (MOC, MOF5, and TigerShark ground crew)
- Digital Integrated Communications Electronic System (DICES) (AFRC LVC and MCC3)
- Plexsys (MOF5 RGCS and ARC DSRL)
- SimPhonics (ARC DSRL)

Video from the MOF5 Systems Under-Test (SUT) was also distributed to the AFRC LVC lab using the same point-to-point fiber optic architecture that was used in previous flight tests. The LVC distributed the video feeds to MCC3 and the ARC Distributed Simulation Research Lab (DSRL). Additionally, MOF5 was interfaced to Dryden Aeronautical Test Range (DATR) systems to allow Long Range Optics (LRO) video to be shown to the MOF5 crew for situational awareness of the aircraft's location and status during takeoff and landing phases.

5.1. LVC Environment

The LVC Distributed Environment (LVC-DE) at ARC and AFRC was designed to provide local researchers the onsite opportunity to assess the DAA capabilities of a low SWaP sensor-equipped UAS. The environment at AFRC and ARC were connected through LVC gateways located at each site. These gateways allowed for two-way exchange of data that populated the subsystems at both centers. The data messages within the LVC environment are defined in the LVC Interface Control Document (ICD) for the LVC Gateway (ref. 22). Figure 5 shows the major elements of the LVC-DE.

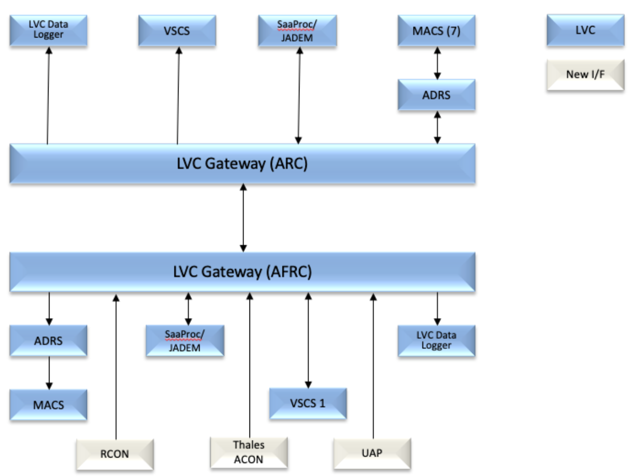


Figure 5. ARC/AFRC LVC-DE Elements.

The NASA AFRC LVC lab (figure 6) in Building 4840 Room 224 functioned as the main hub for data flow from the research systems and distribution of data and video to the ARC DSRL. The NASA LVC labs were connected with two LVC Gateways through a UAS-NAS Virtual Private Network (VPN) tunnel. The AFRC Gateway was setup as a server and received connections from multiple LVC clients:

- LVC Gateway (GW): The ARC GW was configured as a client to the AFRC GW server. This allowed ARC to "shadow" scripted encounter flights with their own set of clients and also passed data to AFRC during the Full Mission flights.

- Sense and Avoid (SAA) Processor: The SaaProc was a software application that provided DAA alerts and guidance using the Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) algorithm that was developed during Phase I MOPS. It was capable of invoking range filters for ADS-B and radar sensors based on Flight ID selection. It also had the ability to "offset" the altitude of intruder tracks such that DAA alerting and guidance could be flight tested with safe altitude separation between the ownship and intruder aircraft. Conflict results from the DAA algorithm were sent to the LVC GW to be forwarded to the traffic display.
- LVC Logger: The LVC Logger recorded all the LVC GW messages coming in and out of the system.
- Sensor Surveillance Adapter (SSA): The SSA translated LVC flight state messages between the Multi-Aircraft Control System (MACS) and the SaaProc and Vigilant Spirit Control Station (VSCS)
- Multi-Aircraft Control System (MACS): High fidelity environment for conducting real time controller and pilot simulations. MACS generated and injected virtual traffic into the LVC environment. Pseudo-pilots at Ames also used MACS stations to maneuver the virtual targets to inject realism into the scenario.
- Aeronautical Datalink and Radar Simulator (ADRS): Central communications process that enables data transfer between all MACS stations and other external components.
- VSCS: The Air Force Research Lab (AFRL) VSCS served as the research traffic display and the C2 interface to the TigerShark UA during Full Mission. Intruder traffic and DAA guidance that was processed by the SaaProc was displayed on the VSCS TSD. The VSCS was also integrated to the Piccolo system through the use of a Vehicle Specific Module (VSM) that translated data and C2 messages between STANAG 4586 and Piccolo.
- Thales ADS-B Console (ACON): the ACON translated the ASTERIX CAT21 Ed. 0.26 messages from the Thales AX680 ADS-B ground station to LVC MPI flight state messages. These messages were published in 4 second intervals to emulate TRACON area radar scan rates. The application included traffic filters that were activated to filter traffic out by range, location, # of targets, and/or flight ID to reduce traffic clutter.
- Unmanned Aircraft Processor (UAP): The UAP passed the aircraft ownship and intruder data to the LVC environment.
- Remote Console (RCON): The RCON payload operator interface with an internal traffic map capable of displaying LVC ownship and intruder data. Mainly used during development and ground testing to monitor LVC data.

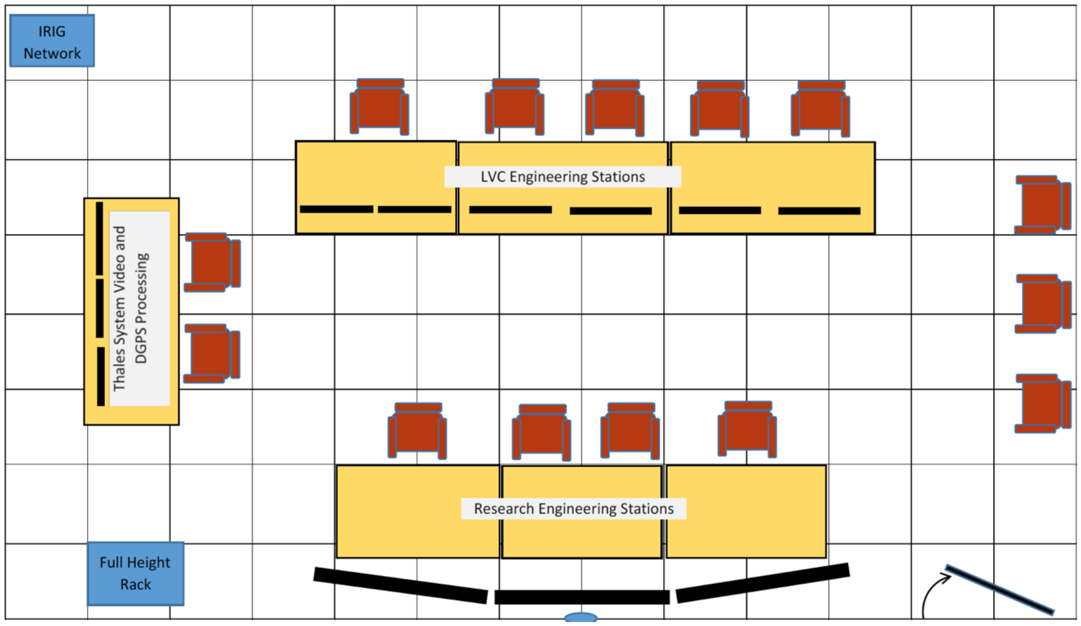


Figure 6. AFRC LVC Lab Layout.

In addition to management of LVC data, the AFRC LVC lab distributed three video feeds from MOF5 SUTs to MCC3, DSRL, and DATR. The DATR feeds were used to provide video to the AFRC Integrated Support Facility (ISF) during VIP events.

The major sub-systems that comprise the LVC/DE infrastructure at the NASA Ames Research Center were located in the DSRL, room 240, and the SDL, room 262, in Building N-243. Layouts of the laboratory environments are shown in figure 7, and figure 8.

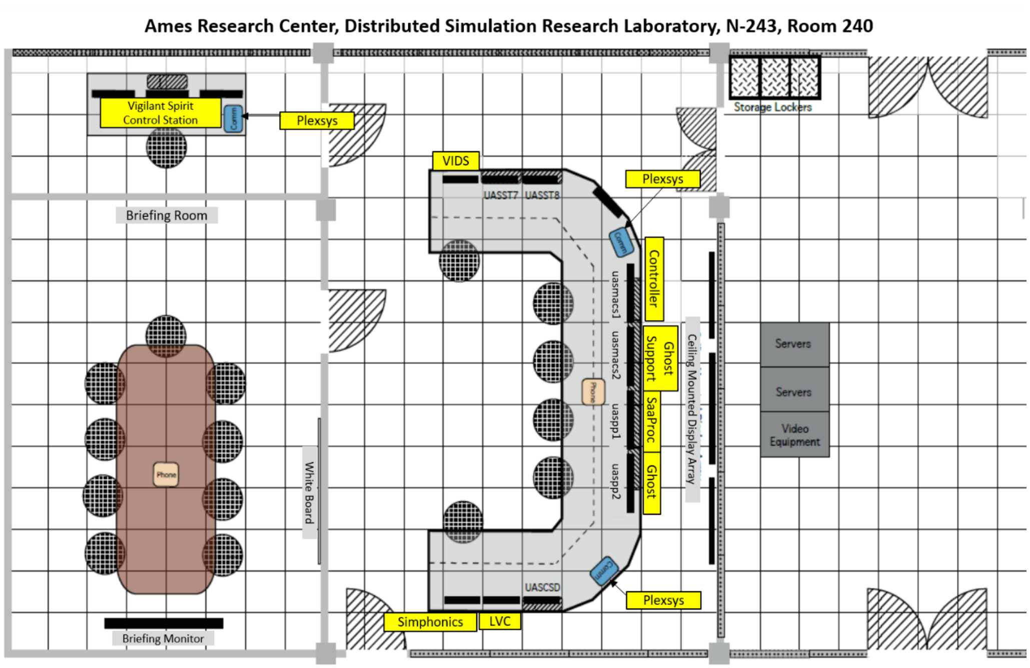


Figure 7. ARC DSRL Layout.

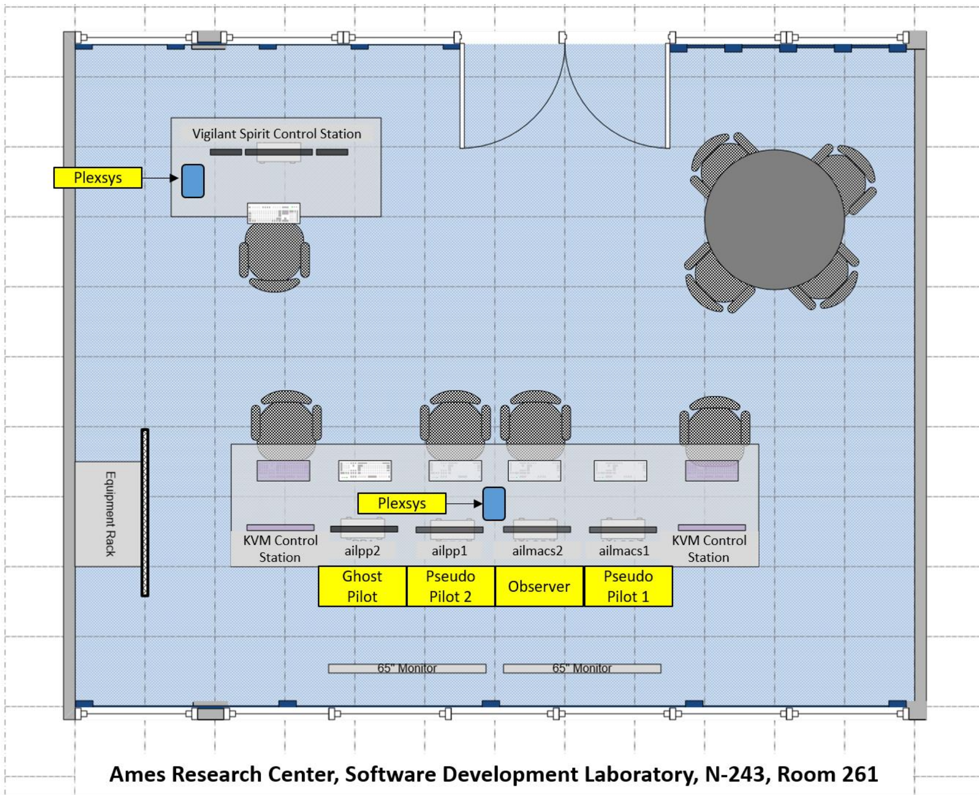


Figure 8. ARC SDL Control Room.

5.2. Ground Control Station Architecture

Command and control of TigerShark was performed from two separate ground control stations: NASC MOC and NASA AFRC MOF5.

5.2.1. NASC Mobile Operations Center (MOC)

The NASC Unmanned Systems Mobile Operations Center (figure 9) is a self-contained, field deployable UAS command center complete with Ground Control Station, provisions for UAS transport and ground support equipment. The highly customized trailer provides the self-sufficiency required to operate a UAS from practically any location. Integrated in the MOC is a Piccolo based GCS that enables full autonomous or manual UAS flight operations. The NASC GCS incorporates primary and secondary command and control (C2), video downlink, Global Positioning System (GPS), and Differential GPS. The rack mounted GCS provides pilot selectable directional and omni-directional antennas for each C2 and video downlink. The directional antennas are utilized for long range C2 and video downlink with a 360 degrees Pan/Tilt tracker head on a MOC mounted 30 ft. telescoping antenna mast. The NASC GCS interfaces with a Windows desktop or laptop computer loaded with the Piccolo Command Center (PCC) software from Cloud Cap Technology. PCC software, Electronic Flight Information System (EFIS), Heads Up Display (HUD), and Nose Camera Video Switch software are displayed on the laptop or monitors that provide flight critical information.

The MOC was used for launch and recovery operations of TigerShark. The MOC was considered the primary GCS for flight operation in that it provided the host for the PCC server used by clients within MOF5 and was the default GCS in the event of a contingency that required immediate Return To Base (RTB) due to an in-flight emergency (IFE).

Figure 9. NASC Mobile Operations Center (MOC).

5.2.2. AFRC Mobile Operations Facility 5 (MOF5)

The FT6 mission was also executed from the MOF5 GCS, which hosted two pilot stations, a Flight Test Director (TD) station, and the Research Ground Control Station (RGCS). MOF5 was interfaced to the NASC MOC, AFRC LVC, AFRC Communication Building, and DATR. Below is a short description of the primary FT6 systems that were in MOF5, as shown in figure 10:

1) Ground Control Operator (GCO) Station: Hosted the Piccolo Command Center (PCC) software to provide full command and control (C2) of the TigerShark UA. A NASA or NASC qualified GCO served as the pilot for this station. The GCO served as the safety pilot and could take over C2 during off-nominal situations.
2) Pilot Under Test (PUT) Station: Hosted the PCC and VSCS (standalone display) to provide C2 of TigerShark in response to VSCS guidance during Scripted Encounters. A NASA pilot was positioned at this station and served as the PIC during test operations.
3) Flight Test Director (FTD) Station: Hosted the Zeus situational awareness traffic display. A NASA FTD coordinated the test execution with the Test Conductor (TC) and GCO/PUT from this station.
4) Research Ground Control Station (RGCS): Hosted the integrated VSCS system with the capability to provide C2 of the TigerShark UA. A rotation of various subject pilots under test manned this station during the Full Mission LVC flights.
5) Clear-Com Consoles: All stations had Clear-Com voice communication panels that interfaced to the DICES system to provide communications to all test entities on different nets.

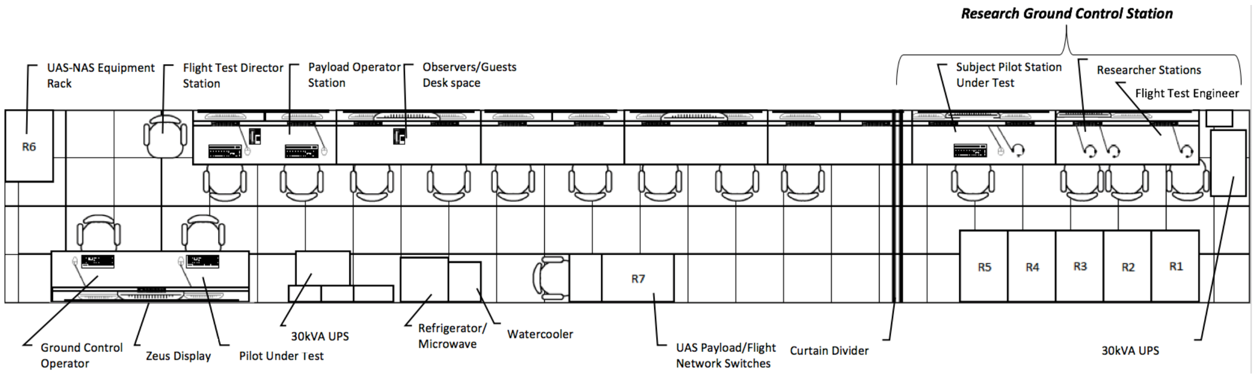


Figure 10. MOF5 GCS Layout

The RGCS, pictured in figure 11, consisted of the following systems:

- Subject Pilot Under Test Station (SPUT): Control station for the subject pilot consisted of three monitors, keyboard and mouse, and a headset interfaced to virtual ATC voice communication.
- Researcher Stations: Used by the UAS-NAS HSI researcher and ops liaison to observe the subject pilot's actions during the Full Mission experiment. The stations provided a mirror display of the VSCS TSD, Zeus display, and two Clear-Com voice communication panels.

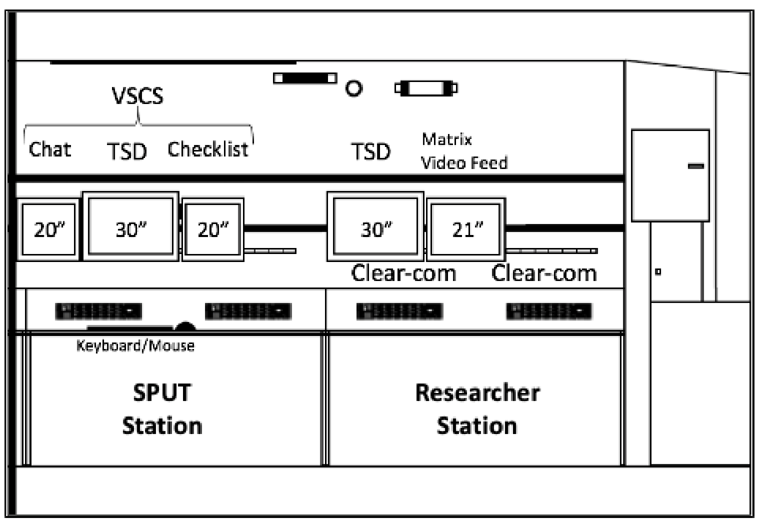


Figure 11. RGCS Layout.

For the FT6 Full Mission flights, Human in the Loop (HITL) testing was performed with a SPUT at the RGCS controlling the TigerShark UA. To immerse the pilot in the LVC simulation environment, the RGCS was segregated from the primary area of operation in MOF5 with an industrial curtain to reduce distractions from visual, noise, and physical intrusions that would disrupt the experiment. As shown in figure 10, the RGCS was located towards the front end of the 53 foot trailer while the main operations area was located on the opposite end to reduce noise. The main operations area, shown in figure 12 below, was used to maintain situational awareness (SA) of the live environment and allowed for easy intervention by the PUT or GCO if the Full Mission scenario impacted safety or operational constraints.

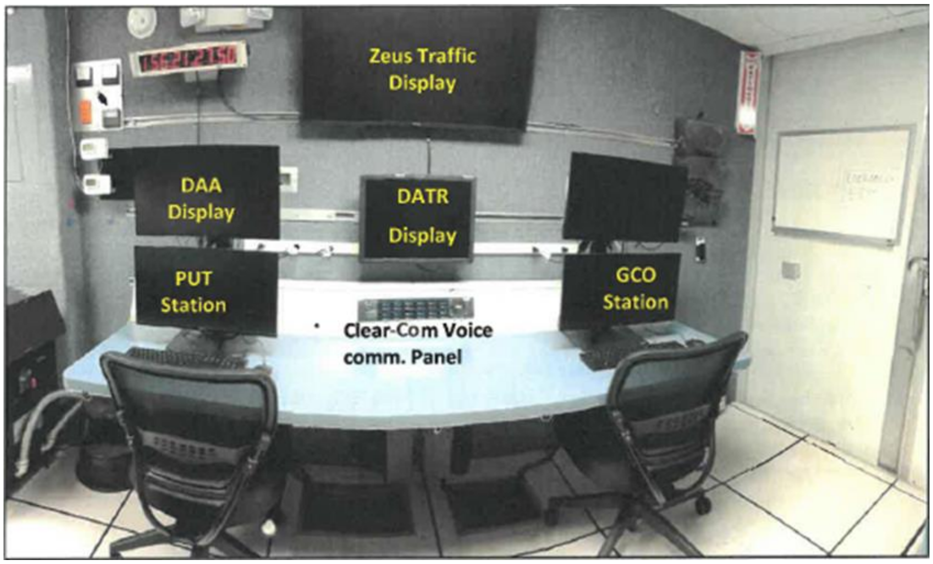


Figure 12. MOF5 Operations Area PUT and GCO Control Stations.

5.2.3. Mission Control Center 3 (MCC3)

The DATR MCC3 served as the mission control facility for FT6 to coordinate, manage, record and execute the flight test (figure 13). The test conductor, test coordinator and test recorder staffed MCC3, along with the IT&E subproject manager. The room was configured with three workstations, two of which were dedicated to supporting intercept-type flight test encounters. Each workstation was configured with DICES Voice over Internet Protocol (VoIP) voice comm system for two-way communications with the rest of the team, as well as ATC and intruder pilots. Several display monitors (e.g. Zeus, specific video sources, and PCC traffic display) were available for situational awareness.

The Raytheon Solipsys Zeus provided a real-time, multi-source correlated situational awareness picture for the test conductor to monitor and manage flight test encounters. Zeus displayed all air traffic in the airspace of interest. Traffic was presented to the test conductor from a moving map type display, and the test conductor used features such as zoom, map repositioning, track attributes, track-to-track latching to enable specific encounter management and for decision-making. This product proved to be an exceptional tool for executing intercept type encounters.

Figure 13. Mission Control Center 3 in Building 4800 at AFRC.

5.3. Voice Communication System

The voice communication system at AFRC was designed around a distributed VoIP network that interfaced to analog/digital channel banks which were configured to talk to Land Mobile Radios (LMRs) and/or UHF/VHF radios. This system allowed multiple communication nets to be setup at each station with capability for inter-communication through the VoIP network and/or communication to live ground/air assets (e.g. participating aircraft, ATC, ground tower, ground crew). As shown in figure 14, this network was used in FT6 to provide communication between: MOC, MOF5, LVC, MCC3, ground crew, intruder aircraft, Joshua Control, SPORT, and Edwards AFB Tower. The Clear-Com Eclipse system was used in MOF5 and MOC while the rest of the facilities used the Quintron DICES VoIP system. VoIP translators via a client server configuration enabled compatibility.

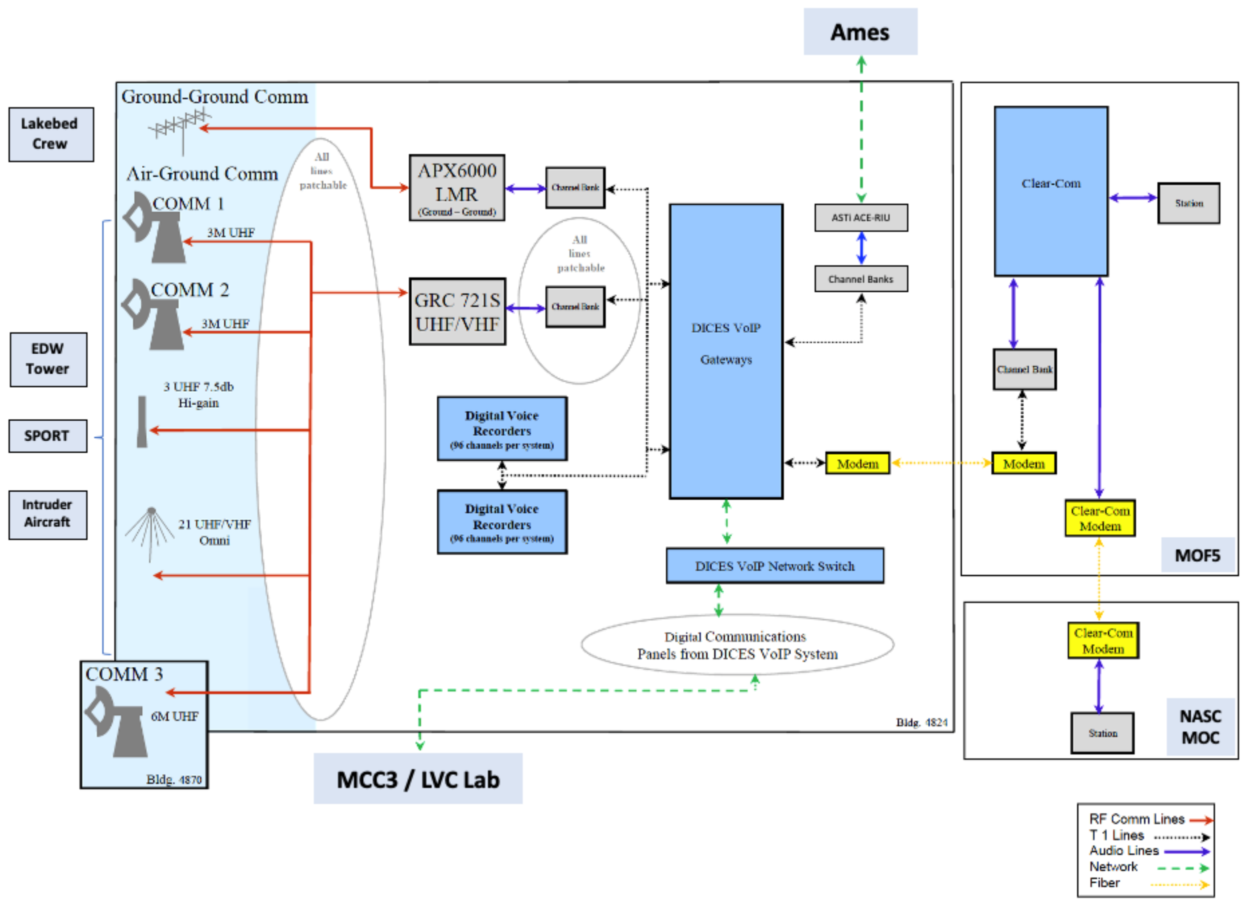


Figure 14. DATR Voice Comm Architecture.

The NASA ARC voice comm network was designed around the SimPhonics and Plexsys VoIP systems that are commonly used in LVC simulation environments. To interface the ARC networks to the DATR architecture, two ACE Remote Interface Units (ACE-RIU) were used to convert the ARC VoIP data to signals compatible with the AFRC channel banks. This configuration provided bi-directional communication with ARC. An additional server/client application was used between the LVC labs to tunnel the multicast SimPhonics/Plexsys data to unicast through the UAS-NAS VPN connection. The PlexsysVR application was used in the RGCS to provide communication and audio recording between the subject pilot and the virtual ATC environment during Full Mission. The Roselli Tunneler provided a secure conduit for communication between the gateways connecting ARC and AFRC.

The communications architecture between laboratories at NASA Ames used the PLEXComm Virtual Radio (PLEXCommVR). The system was installed using a software client at the Controller position. The other positions were connected to the communications network though PLEXComm T3 standalone consoles. The SimPhonics Record Playback system, located in DSRL, provided recording capability.

ARC operated with five communications networks. Connectivity for the primary networks at ARC is shown in figure 15. The Virtual ATC network used a discrete frequency and emulated Air to Ground (A/G) communications between the SPUT, the pseudo-pilots, and the Oakland Air Route Traffic Control Center (ZOA) Sector 40/41 virtual air traffic controller. All transmissions on this frequency were recorded to meet research requirements. Audio data was collected and forwarded to AFRC at the conclusion of daily operations for archiving.

The Ghost network, on frequency 132.2, facilitated communication between positions at ARC. The Ghost and Ghost Support positions relayed information and control instructions to the Ghost Pilot. The Ghost Pilot disseminated these transmissions to the Pseudo Pilots, as required.

The Engineering Network, on frequency 126.6, connected the Ghost at ARC with the Test Director at AFRC. The Test Director used this network to communicate required actions to the Ghost. This frequency also allowed for coordination between the Test Director, Ghost, research team, and Payload.

Frequency 120.55 allowed the AFRC LVC position and Ghost to coordinate actions concerning the LVC environment at the direction of the Payload position. All system related issues, such as startup, shutdown, and troubleshooting were coordinated on this frequency.

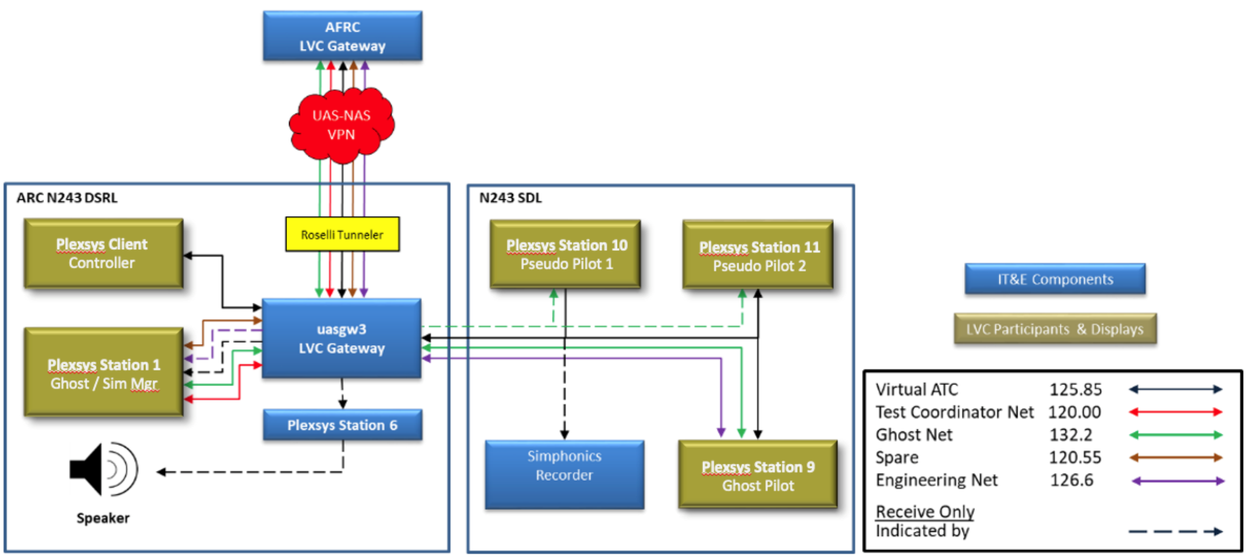


Figure 15. FT6 ARC Communications Network.

5.3.1. Communication Network

Critical to the success of the test campaign was a well-defined communication plan between all test team members. When compared to previous flight test campaigns for the UAS-NAS project, the communications requirements for FT6 has increased in complexity. The addition of the NASC TigerShark system meant that communications networks needed to include the MOC and the lakebed staff for launch and recovery of TigerShark. Since FT6 included a HITL research activity (Full Mission), communication nets was required with the staff located at NASA Ames.

Communications networks between MOC, MOF5, MCC3 and LVC lab were managed by the AFRC DATR. Several comm network nodes including: Mission, TC Net, Engineering, LMR, Tower, Ghost Net, Virtual ATC, and phone line, were available to team members. Assignments of specific nets were captured and presented as part of the airworthiness and flight safety review process.

Mission frequency was initially planned for VHF communications, however, the team switched to UHF when certain intruder aircraft experienced poor communications with SPORT. Once the switch was made, no further communication issues were experienced with mission frequency. Also, early in the campaign, there were several instances of the Clear-Com channelization not matching the desired set of mission frequencies, causing a delay for re-channelization and/or reconfiguration prior to launch; this was resolved by mid-campaign.

The following sections describe the communication networks based on phase of flight and specific test activity.

5.3.1.1. Communication Network for Launch and Recovery

Figure 16 shows the communication plan for the Launch and Recovery phase. MOC and the lakebed launch and recovery crew required some form of remote communications due to the physical separation between the two groups. Normally the Navmar preflight team is co-located with the MOC and a wired comm system enables the crew chief to communicate with the Air Vehicle Pilot (AVP) in preparation for flight. For FT6, the aircraft and ground crew were separated approximately 2 miles from each other for launch and recovery, therefore, the plan was to use discrete frequency LMR for these operations. Besides the specific launch and recovery operations, communication with the rest of the test team located in MOF5 and MCC3 was required. Finally, the MOC crew needed to communicate with Edwards Tower for permission to launch and during Class D flight operations. Figure 16 green lines depict VHF communication, while local comm is shown as brown lines.

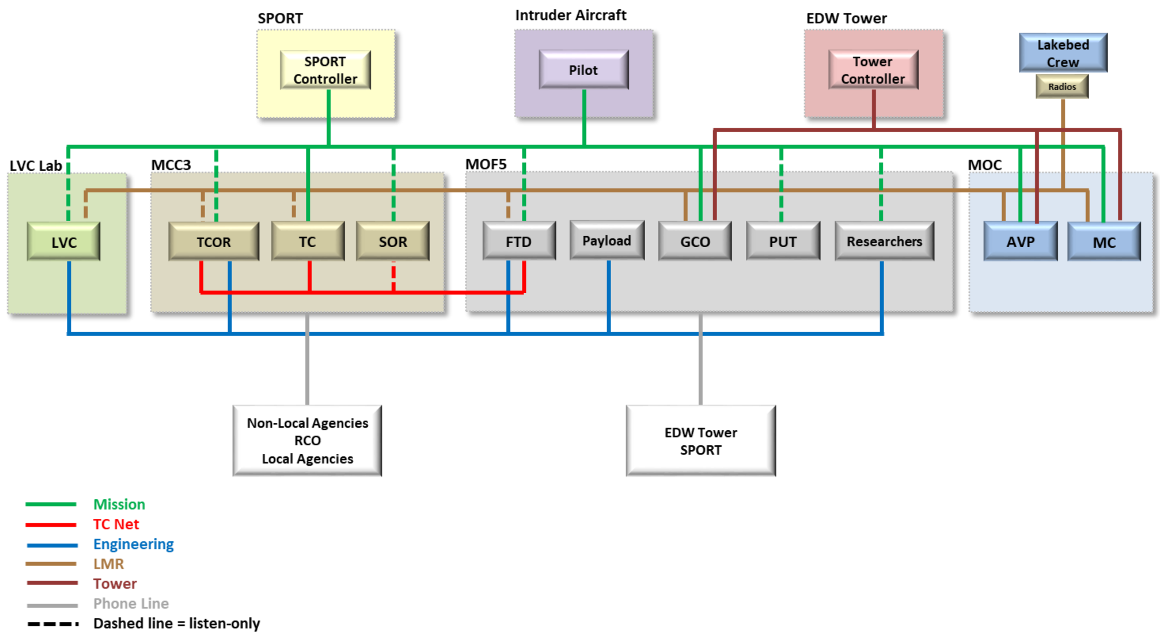


Figure 16. FT6 Flight Test Communication Structure, Launch and Recovery.

5.3.1.2. Communication Network for Scripted Encounters

Scripted Encounters communication featured a primary net setup to support communication on mission frequency and several “back channel” communication nets available to support test team secondary communications (figure 17). After launch, the AVP communicated with the PUT on mission frequency for the handover. Once the handover was completed, either the Safety GCO or PUT communicated on mission frequency for TigerShark throughout the Scripted Encounters. The TC communicated with all mission net players, including the Safety GCO (or PUT), SPORT, and the intruder aircraft on mission frequency. Within the MCC3, the TCOR had a greater responsibility than previous flight tests, as the role took on responsibility to communicate back channel information to the TC, Flight Test Director (FTD), the Senior Operations Representative (SOR), and other agencies. Since the mission control team was physically separated for FT6 (FTD located in MOF5), a specific net was dedicated for control communications (TC net). Once the Scripted Encounters were completed and all aircraft were RTB, the comm reverted back to that of the L/R phase procedures.

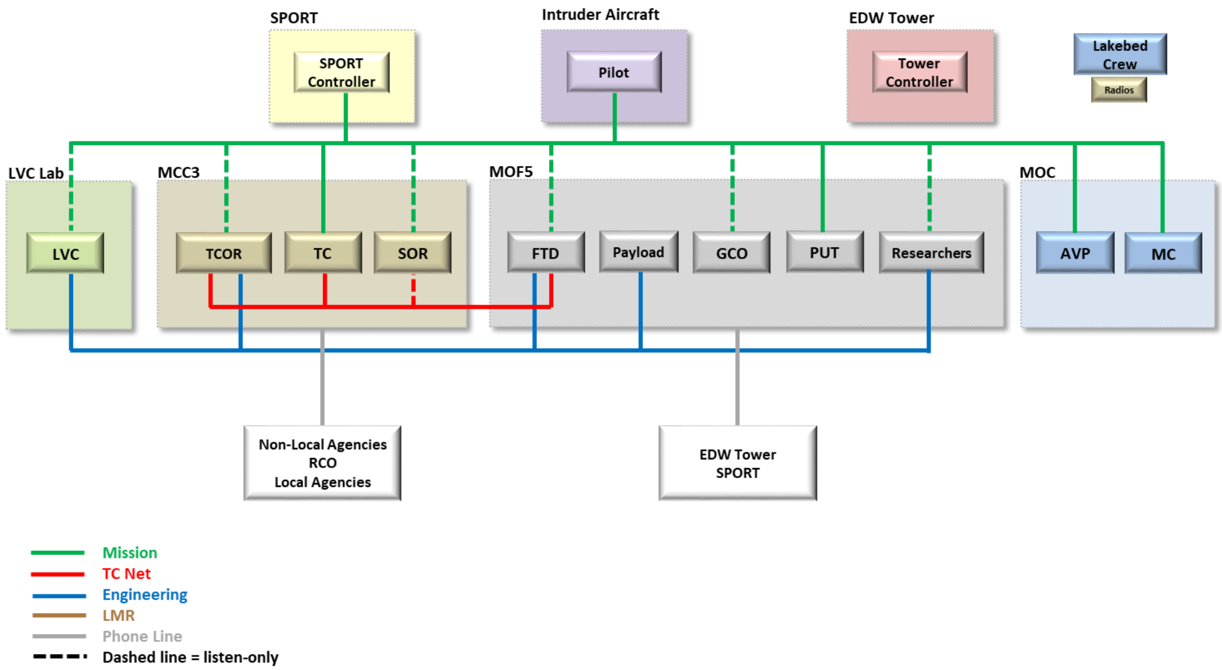


Figure 17. FT6 Flight Test Communication Structure, Scripted Encounters.

5.3.1.3. Communication Network for Full Mission

Like Scripted Encounters, Full Mission began with the L/R phase. During Full Mission data collection, depicted in figure 18, the additional element of the Virtual ATC (staffed by NASA Ames) was added (shown in lavender). While all participants on VHF (green) were flying the mission in the “real world”, the RGCS pilot communicated separately on the Virtual ATC net. To the RGCS pilot, it was as if he or she were flying within Oakland Airspace, both in terms of their navigation display and audio communications, while the ownship was actually flying in R-2515. Virtual ATC communicates with the RGCS pilot and pseudo pilots, as a representative operation in that airspace. The Ghost Controller provided communication with the ARC team when the simulation required a restart, when debriefs were going on, and other real-time communications through the Engineering net. The channel was primarily dedicated to the FTD and Ghost Controller to manage the simulated environment. On VHF, the TC monitored the test, and was able to call an abort, if required, for the “live” intruder aircraft. The TCOR communicated on the Engineering net to the FTD and Ghost Controller when airspace was being lost and at other times when the test needed to be modified in some way. After completion of Full Mission, the communication plan returned to the L/R phase procedures for RTB.

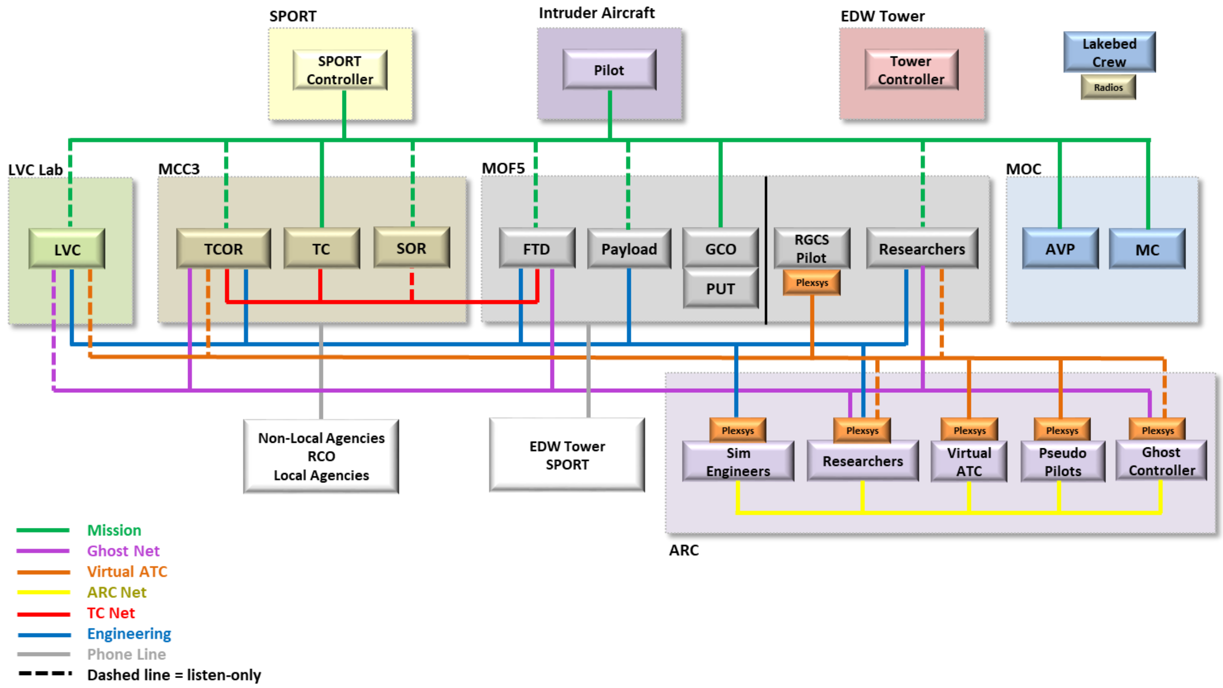


Figure 18. FT6 Flight Test Communication Structure, Full Mission.

6. Aircraft and Test Configuration

The aircraft and integrated DAA system used to support FT6 data collection is described in this section. The test required two aircraft per test mission: ownship and intruder. A NASC TigerShark XP Group 3 UAS, tail number N1750X, was used as the ownship. The aircraft was modified from its original configuration in order to support FT6.

A DAA system payload was integrated on TigerShark to support all test configurations for FT6. The DAA system included the following subsystems: Unmanned Aircraft Processor (UAP), VectorNav Embedded GPS/INS (EGI), Piccolo II autopilot, Honeywell DAPA Lite radar, Sagetech ADS-B, Honeywell DAA Processor, Honeywell Fusion Tracker, smoke system and associated datalink radios. The Piccolo II autopilot was organic to the baseline TigerShark but was an integral subsystem for data collection.

Intruder aircraft were sourced from the NASA AFRC support aircraft fleet. These aircraft included the TG-14, T-34C and B200. The aircraft were primarily used as an intruder to provide the DAA system sensors with real-world data and supported some test activities as a chase aircraft. During testing, the intruder aircraft carried at least two people to aid in cockpit flight test activities.

6.1. NASC TigerShark Block3 XP (N1750X)

The NAVMAR Applied Sciences Corporation (NASC) TigerShark XP Block 3 Unmanned Aircraft (UA) (figure 19) is a DoD Group 3 system with a high wing design and a single pusher engine that is flown via the Cloud Cap Technology (CCT) Piccolo II autopilot. In the standard configuration, the TigerShark is capable of flight durations of 8 to 12 hours, based on mission configuration and environmental factors. The TigerShark has an engine driven alternator that provides a continuous charge to the onboard battery. The overall size characteristics of the TigerShark UA are:

- Wingspan: 21.27 ft
- Length: 14.14 ft
- Height: 3.5 ft
- Weight: 515 lbs. Max Gross Takeoff Weight

Figure 19. NASC TigerShark XP Block 3, T/N N1750X, Ownship Aircraft. (NASA Photo).

The TigerShark is capable of carrying a maximum payload of 100 lbs. with 900 Watts of power available to the payload systems. This met the Detect and Avoid (DAA) payload weight and power requirements of 30 lbs. and 300W, respectively.

6.2. Detect and Avoid (DAA) System

The low SWaP DAA system design was derived from the Airborne Functional View architecture described in the Phase I DAA Minimum Operational Performance Standards (MOPS) (ref. 9). From a high-level description, this payload system integrated into TigerShark was comprised of a cooperative (ADS-B) and non-cooperative (radar) surveillance sensors, a track processor (including a tracker), a UA DAA processor, data link, and the UA flight systems. To support the Phase 2 MOPS development, the design of the DAA payload system included a low SWaP requirement, NASA LVC connectivity, modular architecture, and the integration of the Honeywell DAPA Lite radar panels. Integration support, such as availability of Software Development Kits (SDKs) and Application Programming Interfaces (APIs), from vendors was also considered during the design process. The primary design objective of the payload system was to provide ownship and intruder data to the LVC system. Secondary objectives were to provide health and status information on the payload systems and real-time C2 of the payload configuration to the mission team on the ground. The TigerShark DAA components and functional interfaces that were flown in FT6 are shown in figure 20.

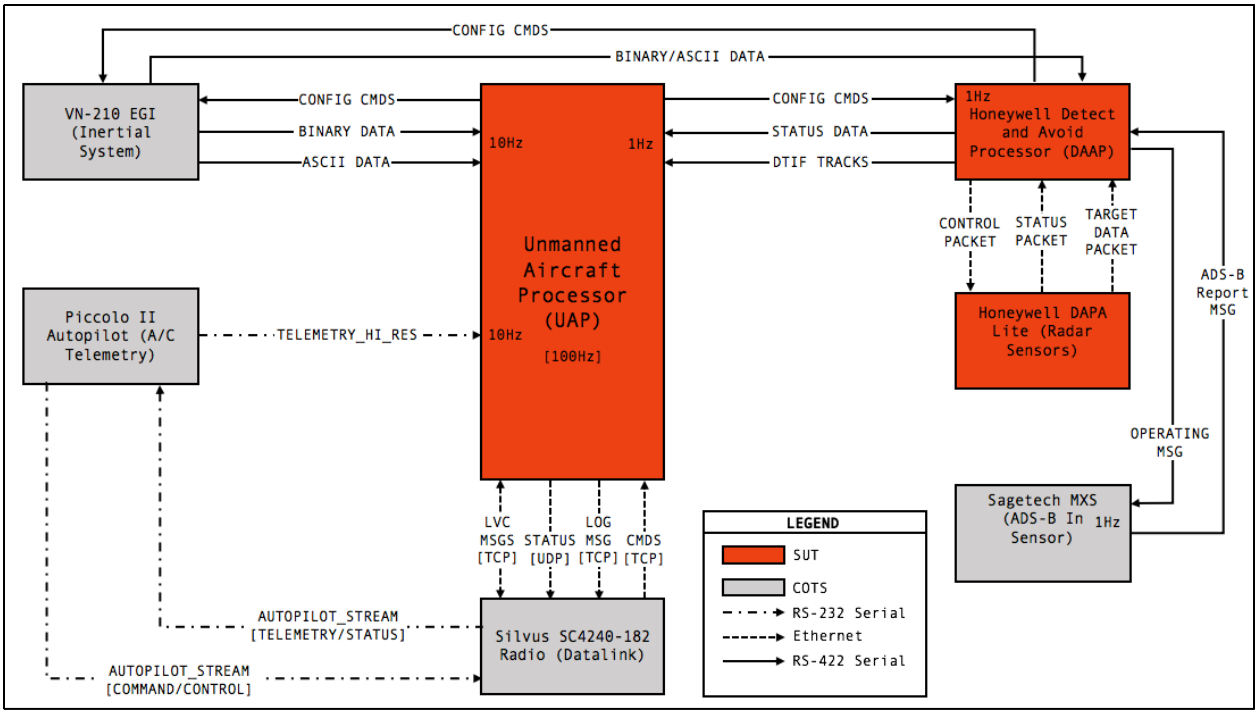


Figure 20. TigerShark DAA System and Functional Interfaces.

6.2.1. Unmanned Aircraft Processor (UAP)

At the hub of the DAA payload was the UAP, which served as the primary interface for payload components and provided payload management functionality (figure 21). The UAP was comprised of a custom RTD High Reliability Data Acquisition Node (HiDAN) plus (HDP1168AN) PC-104 stack with four PCIe/104 boards. This configuration provided a 190W MIL-STD power supply, Intel i7 Quad Core processor with 16GB DDR3 of memory, 4-port RS-232/422/485 serial, and 4 1-GigE capable Ethernet ports. LVC data and payload commands were transmitted between the aircraft and ground elements through the Silvus data link. The interfaces of the UAP included the following:

- VectorNavIO: Interface to the VN-210 Embedded GPS/INS unit. The EGI provided 90% of the ownship state data required by the LVC ownship message.
- PiccoloIO: Interface to the Piccolo II autopilot. The Piccolo provided the air data parameters not provided by the VN-210 EGI.
- HonTrackerIO: Interface to the Honeywell Detect and Avoid Processor (DAAP). The DAAP provided the intruder tracks received from the Honeywell DAPA Lite radar and/or the Sagetech MXS ADS-B receiver. The UAP could also send commands to the DAAP to control the sensor configuration and the radar transmitter state.
- LvcGwClient: Interface to the LVC Gateway (GW). In the LVC test environment, this interface served as the LVC Live AirCraft Interface (LACI). The UAP provided ownship (AcTrackStateOS) and intruder (AcTrackState) tracks to the LVC GW. The UAP also provided house-keeping messages, such as “dummy” flight plans to the GW.
- CmdServer/CmdStatus: Provided command interface, log messages, and UAP status to the Remote Console (RCON) system in MOF5.
- TrafficMon: Provided filtering (e.g. range filtering, location filtering, and flight ID filter in/out) of ownship and intruder tracks. In FT6, the Flight ID filter was used to filter out the “N1750X” track that was created by the TigerShark Sagetech XP transponder.

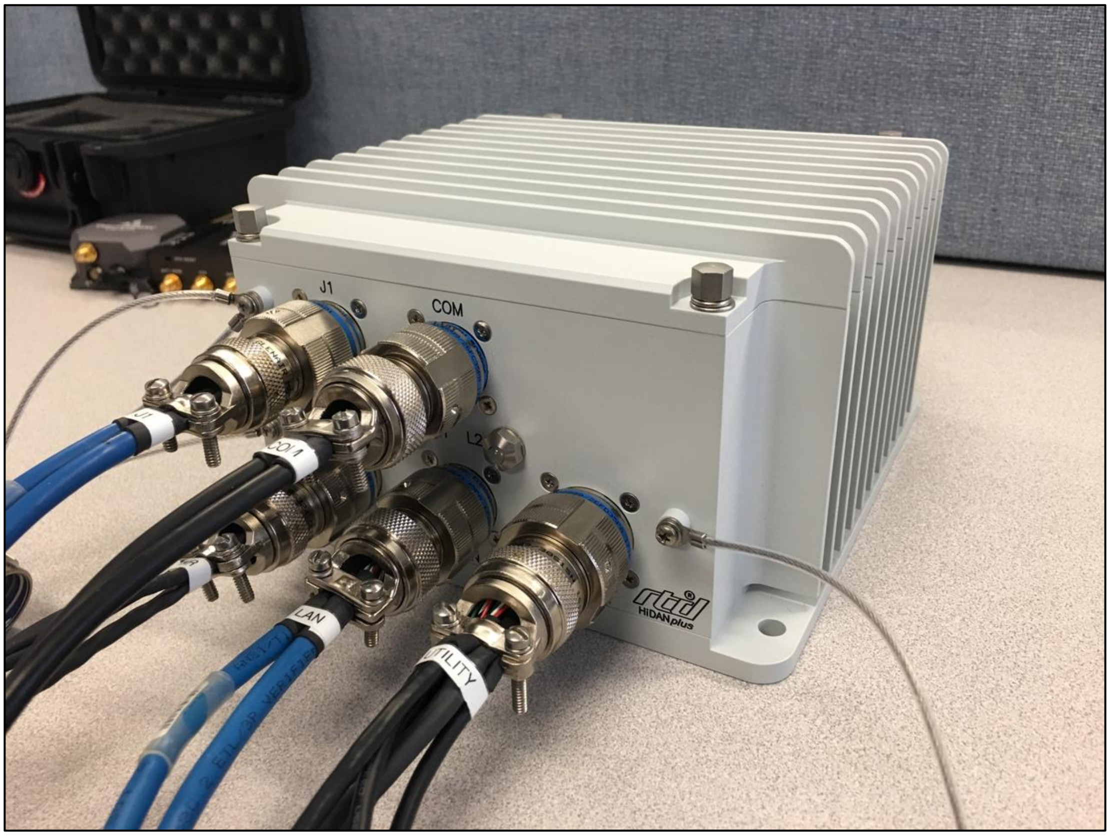


Figure 21. UAP HDP1168AN Front View.

6.2.2. VectorNav (VN-210) EGI

The VectorNav (VN-210) EGI is a tactical grade, low SWaP, GNSS-Aided Inertial Navigation System (INS) that incorporates accelerometers, gyros, and magnetometers on all 3-axis (figure 22). It provided the following data to the UAP:

- Position Estimates in the following reference frames:
  - Latitude, Longitude, and Altitude
  - X, Y, Z position in Earth Centered Earth Fixed frame
  - X, Y, Z position in North, East, Down frame
- Velocity Estimates in the following reference frames:
  - X, Y, Z velocities in Earth Centered Earth Fixed frame
  - X, Y, Z velocities in the North, East, Down frame
- Attitude Estimates:
  - Yaw, Pitch, Roll
  - Quaternions
  - Rotation Matrix
- INS Filter Uncertainties
  - Position, Velocity, & Attitude
- GPS Time
  - GPS Time of Week
  - UTC Time
- Angular Rate Measurements:
  - Bias compensated angular rates
  - Calibrated gyro measurements

- Acceleration Measurements:
    - Bias compensated acceleration
    - Calibrated acceleration measurements
    - Gravity vector
- Magnetic Measurements
- Temperature Measurements

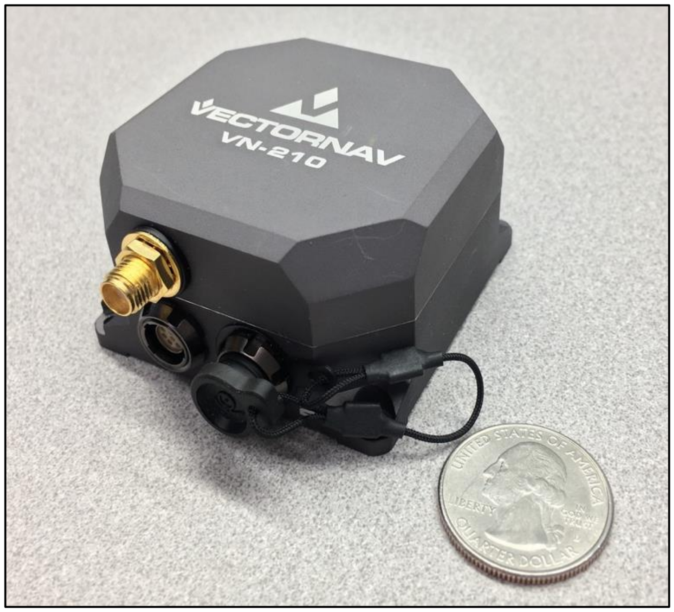


Figure 22. VectorNav VN-210 EGI.

6.2.3. Cloud Cap Technology Piccolo II Autopilot

The CCT Piccolo II autopilot is a self-contained flight management computer that consists of built in 3-axis accelerometers, 3-axis gyros, GPS, command and control (C2) radio, and various inputs/outputs (I/Os) to interface with external components (e.g. servos, research payloads, transponders). The system provided automatic flight control of the aircraft and interfaced via datalink with the portable ground control station located in the MOC for user control of the system.

For FT6, the Piccolo II provided NMEA GPS messages to the Sagetech MXS ADS-B unit through an RS-232 serial interface to supply this data to the LVC. A second serial port on the autopilot was interfaced to the UAP to provide telemetry from the air data system that was not available from the VN-210 EGI. As a safety mitigation, the autopilot serial port was configured to “Comms no flow (output only)” to prevent the autopilot from receiving unexpected commands from the UAP. The interface to the Piccolo was developed to read data from 2.2.4.d firmware. Although the UAP received all telemetry data from the Piccolo autopilot, only the parameters listed below were used to support the functions of the UAP.

- UTC Time
- Serial Number
- Pressure Altitude
- True Airspeed
- Outside Air Temperature
- Board Temperature

Additional Piccolo I/O signals (Pulse Width Modulation, discrete) were used to trigger the smoke system pump and shed power to the payload. The latter technique was used in FT6 to cycle power to the payload system if a subsystem failed and could not be cycled through an uplink command (e.g. DAAP software fail, Sagetech MXS fail).

6.2.4. DAPA Lite Radar

The Honeywell DAPA Lite Radar was used as the non-cooperative low SWaP surveillance sensor (figure 23). The sensor generated radar track data that was correlated amongst the three radar panels and then sent to the DAAP. The radar panels were installed on the nose section of the NASC TigerShark UAS in a three panel configuration. The radar Field of Regard (FOR) was ±15° elevation and ±55° azimuth for each panel. The three panels provided a combined FOR of ±15° elevation and ±110° azimuth.

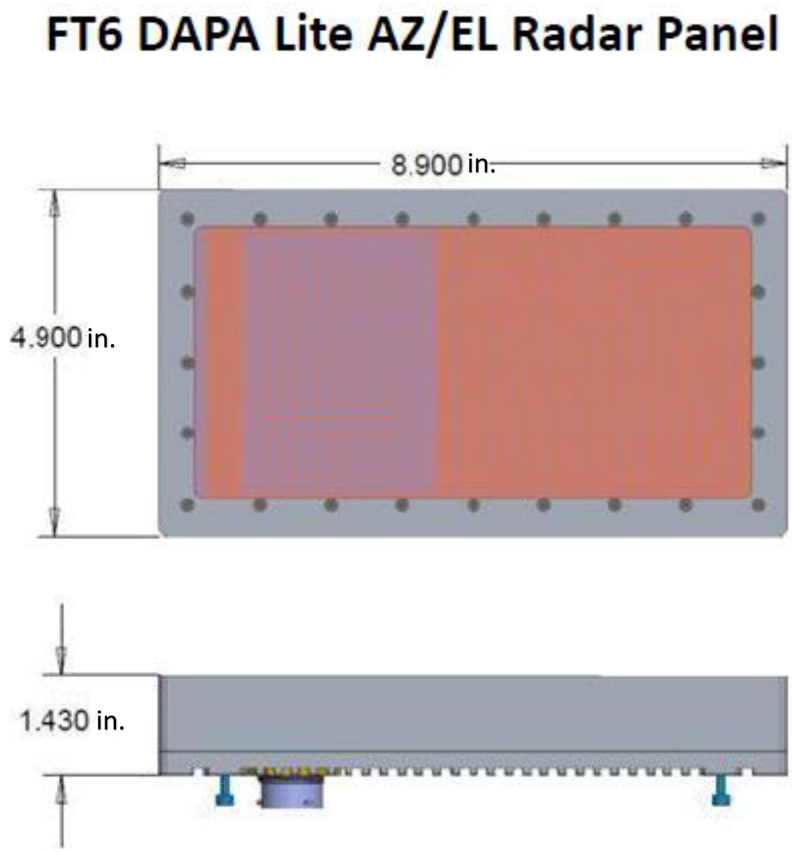


Figure 23. FT6 DAPA Lite AZ/EL Radar.

6.2.5. ADS-B In

A prototype Sagetech MXS ADS-B transponder was used for FT6 to receive cooperative traffic data and provide it to the LVC environment. During the conceptual phase of the DAA architecture, a low SWaP ADS-B unit with ADS-B In/Out capability was required to support the FT5/FT6 mission. AFRC had experience interfacing Sagetech systems in Piccolo equipped UAs, the MXS was selected since it provided this capability in a single unit. The transponder was also in the process of being certified by the manufacturer to TSO standards. In the integration phase, it was discovered that the MXS could not be interfaced with the current (2.2.4.d) version of the Piccolo autopilot. Provisions were designed in the DAAP and UAP software to provide transponder command functionality from the RCON software. Later in the program, the FT5 efforts were rescoped into FT6 and the TigerShark platform was selected to replace the NASA Sensor Integrated Environmental Remote Research Aircraft (SIERRA-B) UAS. In the TigerShark configuration, the UA was equipped with a Sagetech XP transponder that provided ADS-B Out services. The team decided to use both transponders in FT6 but disable ADS-B Out on the MXS. Sagetech modified the MXS firmware to enable ADS-B In only functionality.

The Sagetech MXS, shown in figure 24, was configured to receive NMEA GPS messages from the Piccolo on Com0 (RS-232), provide traffic reports to and receive heartbeat messages from Honeywell DAAP on Com1 (RS-232), and with the top antenna only. Due to the performance issues with the Honeywell DAPA Lite radars, the MXS provided all intruder track data to the LVC for Scripted Encounters and Full Mission. Although the double transponder configuration ultimately worked in FT6, it caused unforeseen issues during the flight checkout phase that could have been prevented if the original single transponder configuration was implemented.

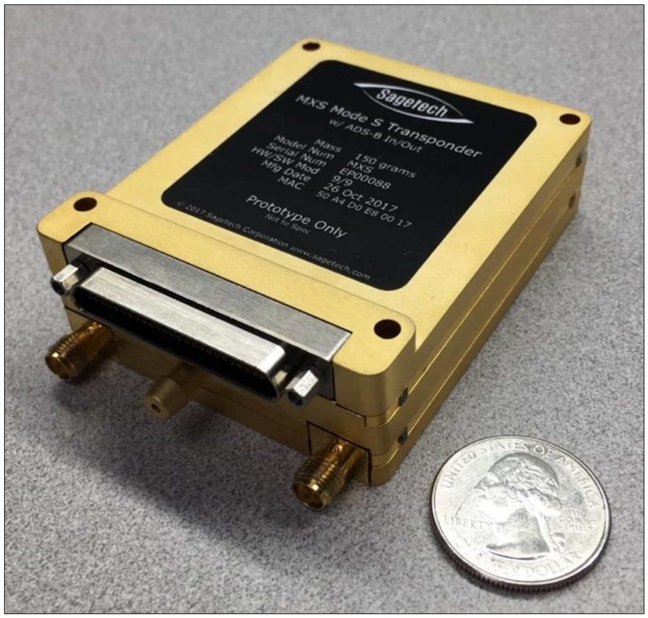


Figure 24. Sagetech MXS ADS-B Transponder.

6.2.6. Detect and Avoid Processer

The Honeywell Detect and Avoid Processor (DAAP) served to interface DAA systems, condition track data for downlink to the GCS, and archive data for post-flight processing. The DAAP fused the radar and ADS-B tracks to provide a single correlated Display of Traffic Information File (DTIF) track to the DAA system. The DAAP also hosted the Honeywell proprietary Fusion Tracker which correlated intruder tracks from multiple surveillance sensors (ADS-B and radar) into a fused track.

6.2.7. Vigilant Spirit Control Station (VSCS) TSD

The VSCS TSD provided the SPUT and PUT with a moving map view of the ownship aircraft against geo-referenced airspace. The pilot controlled ownship using the VSCS display interface, shown in figure 25. This user interface provided the pilot with multiple input methods using touchscreen or mouse to maneuver the aircraft. The most commonly used were the Vehicle Steering Command (e.g. heading, altitude, speed hold commands) and Air Vehicle Position Waypoint command (e.g. follow uplinked mission route, waypoint navigation). In addition to providing C2 of the air vehicle, the TSD displayed air traffic information and DAA alerts and guidance using the DAIDALUS algorithm integrated into the LVC environment.

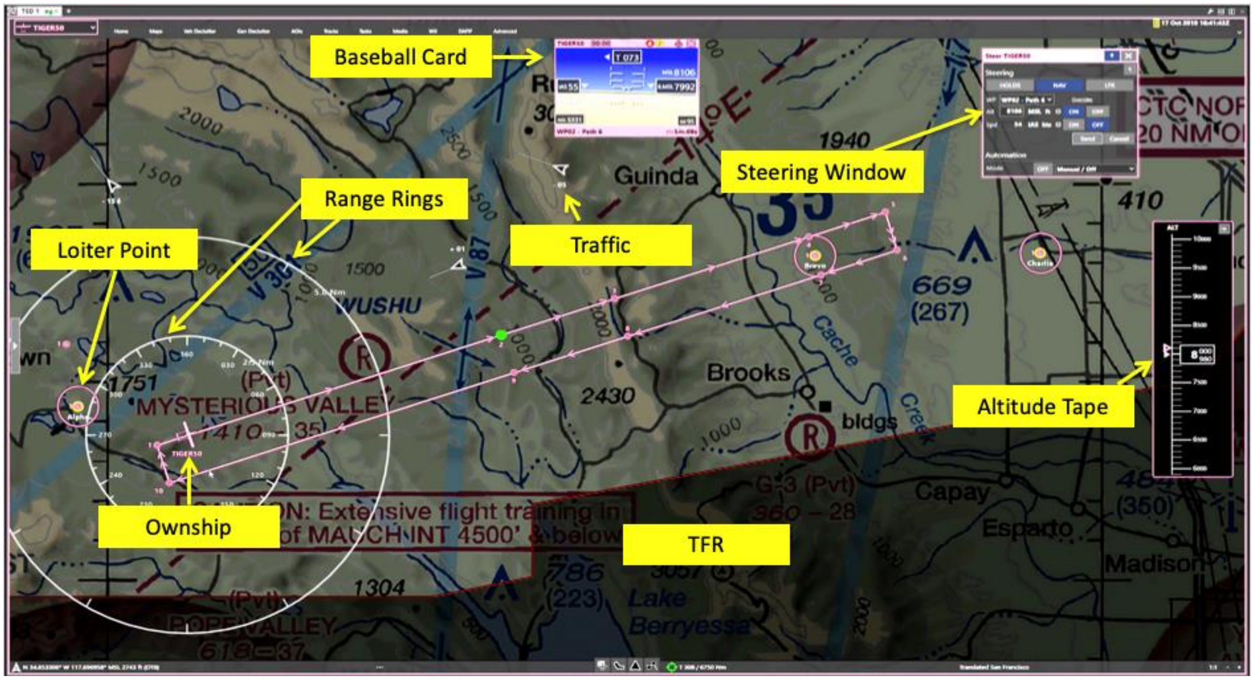


Figure 25. Vigilant Spirit Control Station Tactical Situation Display.

6.2.8. DAA Alerting and Guidance

The DAA system generated DAA alerting and guidance, both of which support the remote pilot's ability to maintain DAA well clear from nearby traffic. Against "cooperative" traffic (i.e. intruders with an operational transponder) in the en route environment, DAA well clear is defined as a horizontal miss distance of 4000 ft, a vertical miss distance of ±450 ft and a modified Tau of 35 sec (refs. 27 and 29). Tau roughly translates to 'time to closest point of approach', and "modified" Tau adds a spatial component (a horizontal distance), within which, Tau is automatically violated. In effect, a modified Tau parameter protects against cases where an intruder has a very slow closure rate (i.e. an intruder is directly behind the ownship and at a similar speed, therefore generating a very long time to closest point of approach) but is in close physical proximity to the ownship. Therefore, a loss of DWC is recorded when all three of the components (horizontal miss distance, vertical miss distance, and modified Tau) are simultaneously violated. Against "non-cooperative" traffic (i.e. intruders without an operational transponder), the DWC definition is reduced to a horizontal miss distance of 2200 ft horizontal miss distance and a vertical miss distance of ± 450 ft (ref. 38). There is no modified Tau component in the non-cooperative DWC definition. In the flight test, buffers were added to the both DAA well clear definitions to better account for sensor uncertainty and ensure stable DAA system performance.

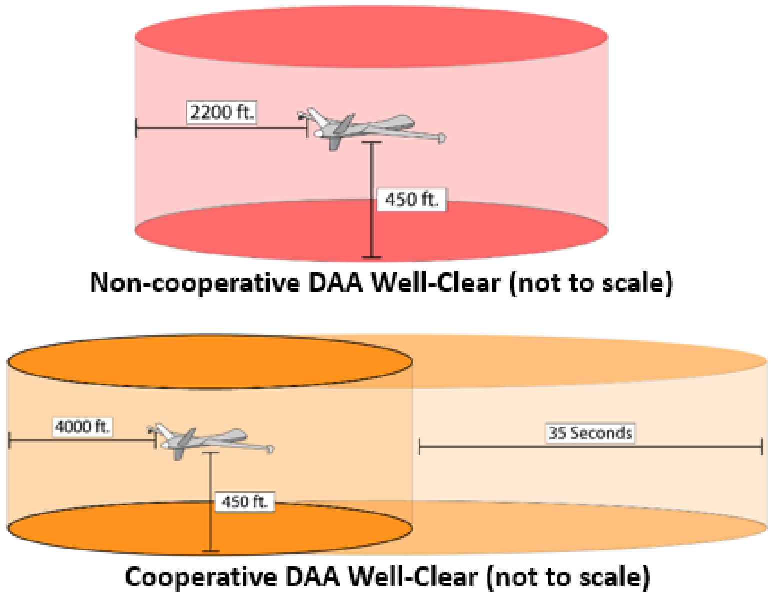


Figure 26. FT6 DAA Well Clear Thresholds.

The DAA alerting and guidance structure, as defined in RTCA DO-365 (Minimum Operational Performance Standards for UAS DAA Systems) (ref. 9), includes two caution-level alerts and one warning-level alert (table 3). One of the caution-level alerts is referred to as a "*preventive*" DAA alert. The preventive alert notifies the pilot to proximate traffic that is not currently predicted to lose DAA well clear but is close enough in altitude to warrant their attention. A second, higher-priority caution alert is referred to as a "*corrective*" DAA alert, which does indicate that a loss of DAA well clear is predicted to occur. The visual and aural alerting informs the pilot that a maneuver is required in order to remain DAA well clear after the pilot has coordinated that maneuver with ATC. In the event that a corrective DAA alert is not resolved, it will progress to the "*warning*" DAA alert. At this level of alert, the visual and aural alerting notifies the pilot that a maneuver is needed immediately, and that ATC coordination can occur after the maneuver has been made. In addition to the visual and aural alerts, the DAA system provides maneuver guidance, which can help the pilot identify potential trajectories (e.g. headings, altitudes, vertical speeds) that will remain DAA well clear from conflicting traffic. This is done by providing corrective and warning-level "banding" predicted by the DAA which, if avoided, ensures the UAS will remain well clear. The DAA guidance is calculated by assuming default vehicle performance parameters, such as turn rate and vertical rate, in order to convey the range of appropriate (or inappropriate) trajectories as accurately as possible. In the flight test, a turn rate of 7°/sec and a vertical rate of 100 feet per minute were assumed by the DAA system. The result of a relatively fast turn rate and a relatively slow vertical rate was that the horizontal DAA guidance banding typically presented safe headings for a much longer portion of the encounter compared to how long the vertical DAA banding presented safe altitudes. From the pilot's perspective, this meant that the DAA system was encouraging them to almost always avoid conflicts by making heading changes rather than altitude changes.

Table 3. DAA Alerting Structure.

Symbol	Name	Time to LoDWC	Pilot Action	Aural Alert Verbiage
	DAA Warning Alert	30 sec	• ***Immediate action required to remain DAA well clear*** • **Prior ATC coordination not required**	"Traffic, Maneuver Now"
	Corrective DAA Alert	60 sec	• On current course, ***corrective action required to remain DAA well clear*** • **Coordinate with ATC**	"Traffic, Avoid"
	Preventive DAA Alert	N/A	• **No action required to remain DAA well clear** • Not currently a threat; monitor for potential increase in threat level • Between 500 – 700 ft vertically	"Traffic, Monitor"
	Guidance Traffic	N/A	• **No action required to remain DAA well clear** • Traffic generating guidance bands outside of current course	N/A
	Basic Traffic	N/A	• **No action required to remain DAA well clear** • No coordination required	N/A

Predicted to lose well clear

The following VSCS TSD sequences in figure 27, figure 28, and figure 29, show the progression of DAA alerting and guidance during a head-on encounter from corrective to warning to well clear recovery. Due to the low climb/descent performance of a typical Group 3 UAS, DAA maneuver guidance was provided only in the horizontal as heading bands to avoid loss of DWC, or in the case of well clear recovery, headings to steer towards to regain DWC.

Figure 27. Corrective Alerting and Guidance.

Figure 28. Warning Alerting and Guidance.

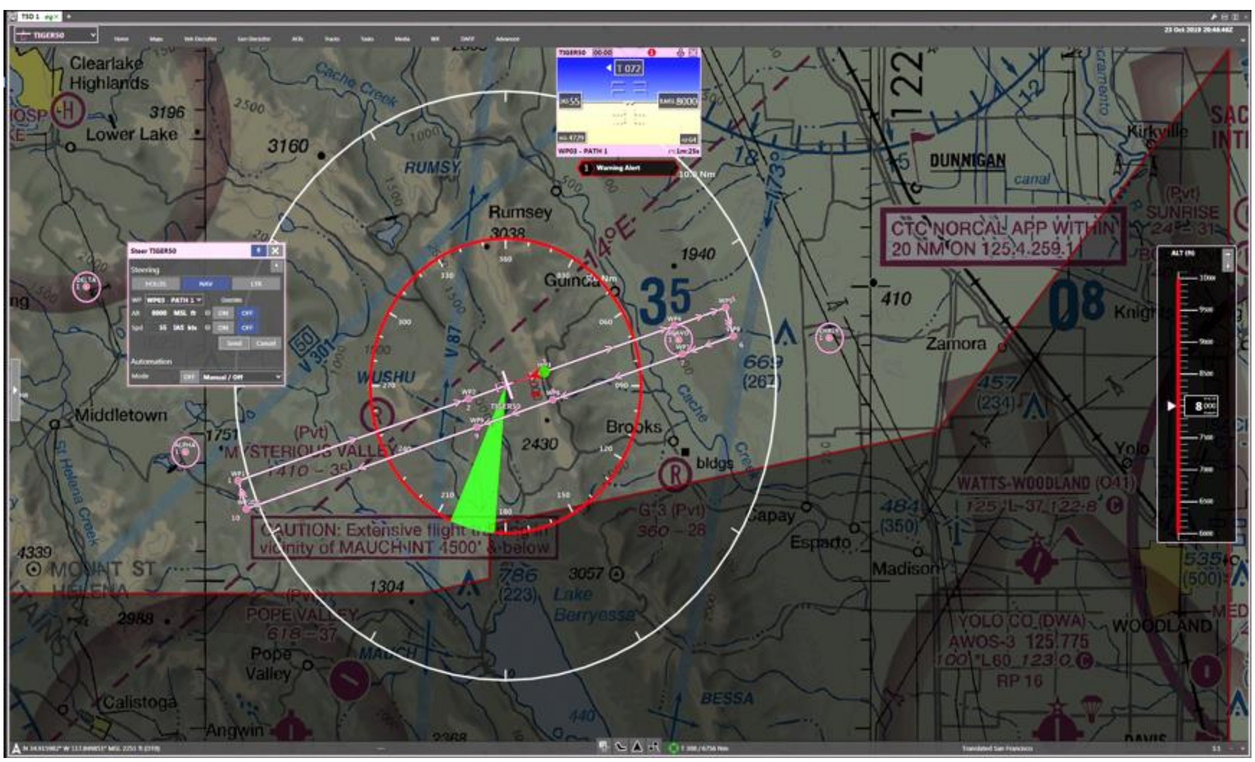


Figure 29. Well Clear Recovery Alerting and Guidance.

6.3. DAA System Payload Integration

For the FT6 configuration, the standard Block 3 outer mold line (OML) was modified to accommodate the 3-radar Honeywell DAPA Lite configuration (figure 30 and figure 31). The TigerShark's video link and secondary datalinks were changed to meet R-2515 airspace spectrum requirements (described in Section 6.5).

The design intent behind installing the radar panels on the nose was to minimize impacts to the OML of the TigerShark UAS while maintaining full functionality of the radar panels. NASC and Honeywell teams collaborated to ensure the DAPA radar field-of-regard was not obstructed by the cowling or mounting structure. NASC engineering completed analysis of the nose on the existing TigerShark airframe and noted no major changes to the performance or flying characteristics of the aircraft.

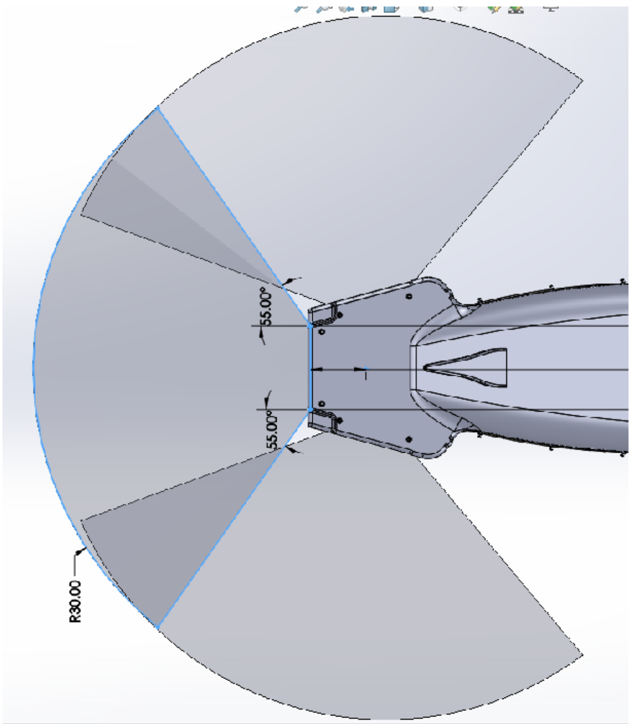


Figure 30. Top Down View of Radar Field of Regard.

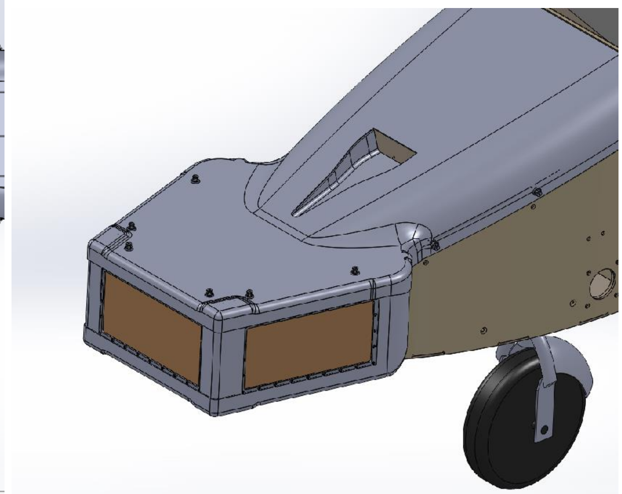


Figure 31. Profile View of DAPA Radar Nose Panels

The DAPA Lite payload suite was built on an existing payload tray in the middle payload bay of TigerShark. This design made the payload easily removable for testing during the flight campaign. Figure 32 shows where some of the DAA system payload components where placed including: EGI (shown in purple), NUC data recorder (shown in yellow), Miltech-308 ethernet switch (shown in green), Sagetech ADS-B transponder (shown in beige), DAAP (shown in gray located directly below top tray components) and UAP (shown in pink, lower shelf). A list of major DAA system hardware items installed on TigerShark for FT6 are captured in table 4.

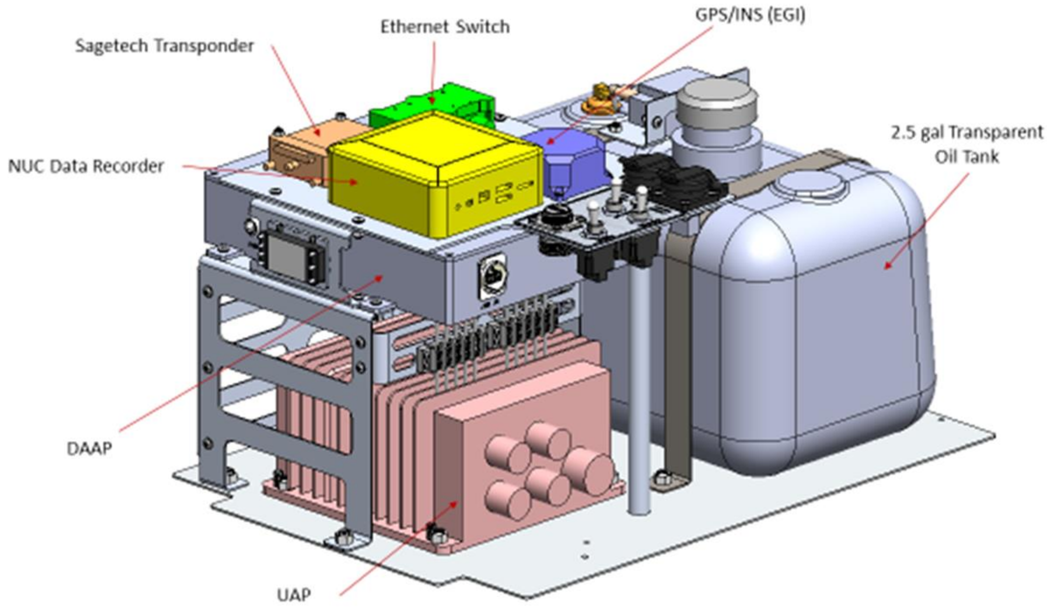


Figure 32. NASA UAS-NAS Payload Tray for the TigerShark XP.

Table 4. TigerShark Flight and Payload Systems.

Hardware Configuration Item	Version	Frequencies	Description
CCT Piccolo II Autopilot	2.2.4.d	N/A	Flight management computer
Microhard Nano 900MHz Radio	N/A	902.4-927.6 MHz (1W)	Short range C2 Link; used for launch and recovery
Silvus SC 4240-182 Transceiver	N/A	1790-1850 MHZ (4W)	Long range C2 Link; used for launch and recovery & payload
AMP VHT1 Video Transmitter	N/A	4400-4900 MHz (10W)	Launch and Recovery Video Link
Sony Exmor Analog 2.4MP Camera	N/A	N/A	Launch and Recovery Video Camera
RTD High-Reliability Data Acquisition Node	HDP1168AN	N/A	Payload management computer. PC/104+ Stack running RT CentOS
Unmanned Aircraft Processor (UAP) Software	v1.0		Payload management software. NASA developed.
Honeywell DAPA Lite Radar Panels (3x)	N/A	24.3 GHz	Non-cooperative surveillance sensor.
Honeywell DAAP (Raspberry PI3)	Model B	N/A	Interface to DAPA Lite and Sagetech MXS transponder. Manages tracks from both sensors. Outputs DTIF tracks to payload management computer.

Honeywell Intel NUC	N/A	N/A	DAPA Lite data recorder
Sagetech MXS ADS-B In/Out Transponder	N/A	1090 MHz	Aircraft transponder. Receives ADS-B In traffic.
VN-210 Embedded GPS/INS (EGI)	v1.1.2.0	N/A	Provides ownship state data to payload systems.
Sagetech XP	N/A	1090 MHz	Provides ADS-B Out function.

6.4. Smoke System

The NASC and NASA teams worked together on engineering and integrating a smoke system for the TigerShark. The smoke system was designed to enhance visual identification for the intruder pilot. The design included a smoke pump, a 2.5 gallon smoke oil tank integrated on the payload tray and one smoke nozzle installed in each exhaust stack. The smoke pump was controlled using an NASC-built software (figure 34) that enable the smoke pump to match the command signal of the throttle servo (figure 33).

Figure 33. Surface Telemetry Table.

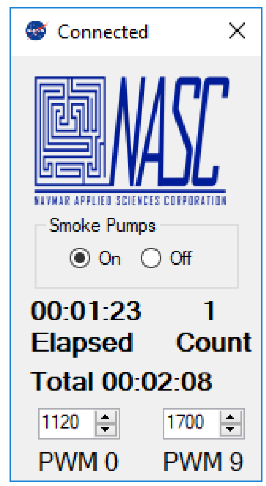


Figure 34. NASC Smoke Pump Software.

The Pilot Under Test and Safety GCO operated the aircraft throughout the test mission and would be required to turn the smoke pump on or off during encounters. NASC software engineering inserted a test file through the MOC PCC control allowing the PUT or GCO to control the smoke pump.

6.5. Datalinks

The Silvus Technologies StreamCaster 4240 2x2 MIMO radios (SC-4240-182-EB) were used to transmit data to/from the UAP server and RCON client. Additionally, it acted as the “primary” C2 link during FT6 Scripted Encounters and Full Mission operations. Although NASC TigerShark UAS used similar Silvus radios in their baseline system, new Silvus radios had to be integrated to conform to the EAFB spectrum requirements. Except for a specific area in the test range, the radios performed exceptionally well throughout the test envelope with plenty of link margin available to the onboard systems. The C2 and payload data only used about 1-3% of the radio throughput and latency with encryption activated and was well within acceptable margins (400-600ms).

Radio frequency requirements for the test required NASC to change the analog video frequency along with the secondary command and control/payload data link from their standard configuration to frequencies approved for use within R-2515 airspace. NASC RF engineers considered the link distance between the ground station and aircraft as well as the amount of payload data required. NASA Flight Test

6 required the aircraft be flown up to 40 nautical miles from the GCS demanding enough bandwidth for C2 and payload data. Analog video is required for manual or auto takeoff and landing (ATOL) which requires a safe analog video picture. NASC pilots used the analog video to taxi the aircraft to the runway as well as for takeoff and landing.

NASC TigerShark and GCS supported two datalink radio systems used to uplink/downlink C2 and payload data. The Silvus SC4240-182 radio was configured to operate in upper L-band (1790-1850 MHz) and served as the primary datalink for FT6 missions. The Microhard MHX operated within the 900MHz ISM unlicensed band and was used as the secondary datalink radio (table 5).

Table 5. NASC TigerShark Datalink configuration for FT6.

UAS-NAS Configuration	
Software Configuration	FW 2.2.4.d
Data Link (s)	Microhard MHX 900 MHz; Silvus SC4240-182
Autopilot and Version Number	CCT Piccolo II Autopilot; v2.2.4.d
Ground Controller	NASC Ground Station; Silvus SC4240-182
Ground Control Software	Piccolo Command Center (PCC) v2.2.4.d
Payload	UAS-NAS DAA Payload

6.6. Flight Test 6 Intruders

The project used three different aircraft from the NASA Armstrong Support Aircraft Fleet to support FT6 as intruder aircraft. The aircraft were selected due to their RCS and multi-place seating capability. Each aircraft served a dual role: first as an intruder for data collection and second as chase when the team desired to obtain airborne photo or video images of TigerShark. The aircraft could also serve as safety chase in the event that TigerShark had an IFE. On every mission, the intruder pilots flew with a Stratus 2S/3 ADS-B receiver to record Wide Area Augmentation System quality flight data as a truth source (positional accuracy <1 meter) for data analysis.

6.6.1. T-34C Turbo Mentor (NASA865)

The NASA Armstrong T-34C Turbo Mentor is a turbo-prop single engine aircraft that seats two pilots in tandem (figure 35). The T-34C supported the test mission as the primary ADS-B equipped intruder aircraft. The T-34 was considered to be a medium-sized RCS for non-cooperative sensor testing.
General Performance Characteristics:
Wingspan: 33 ft
Weight: 4,300 lb
Speed: 214 kt
Ceiling: 25,000 ft
Endurance: 4 hr

Figure 35. NASA AFRC, T-34C Turbo Mentor, T/N NASA865, Intruder/Chase Aircraft. (NASA Photo)

6.6.2. *Beechcraft B200 (NASA801)*

The NASA Armstrong Beechcraft B200 is a twin engine turbo-prop aircraft (figure 36). The B200 supported the test mission as an ADS-B and TCAS I equipped intruder aircraft. The platform was the primary aircraft desired for Radar Characterization missions. The B200 was considered to be a large-sized RCS for non-cooperative sensor testing.

General Performance Characteristics:
Weight: 12,500 lb
Speed: 292 kt
Ceiling: 35,000 ft
Endurance: 4.5 hr

Figure 36. NASA AFRC, Beechcraft B200, T/N NASA801, Intruder Aircraft. (NASA Photo)

6.6.3. *Ximango TG-14 (NASA856)*

The NASA Armstrong Super Ximango AMT 200S (TG-14) is a single engine motor-glider aircraft (figure 37). NASA856 supported the test mission as a low speed, ADS-B equipped intruder aircraft. The aircraft was used during System Checkout to validate operational concepts such as smoke system

performance, TigerShark chase procedures, altimeter calibration methodology, and pilot VID techniques. The TG-14 was considered to be a small-sized RCS for non-cooperative sensor testing.
General Performance Characteristics:
Wingspan: 57 ft
Weight: 1,874 lb
Speed: 132 kt
Ceiling: 10,000 ft
Endurance: 3.5 hr

Figure 37. NASA AFRC, Ximango TG-14, T/N NASA856, Intruder/Chase Aircraft. (NASA Photo)

7. Test Planning

Flight Test 6 introduced new test planning requirements for the project. This section describes the flight planning approach of operating a Group 3 UAS in restricted airspace at Edwards AFB. The first two sections describe an in-depth review of how the project approached the issue of aircraft system maturity that played a large role in operational mitigations required by Edwards AFB authorities. Since Edwards hosts many experimental aircraft, system maturity analysis is a proven method for determining residual risk of the system. In addition, this section describes airspace, route development and mission profiles. This section also describes unique test procedures designed to ensure safety of flight and describes test card design, roles and responsibilities, team qualification and training processes. Finally, this section describes mission specific safety analysis and mission rules that contributed to safe test conduct.

7.1. Group 3 UAS Maturity Plan Development

To support the flight test objectives, a comprehensive test matrix of air-to-air encounters was developed similar to the project's previous DAA flight test campaigns with the much larger Group 5 Ikhana UAS. These prior flight test campaigns helped to inform the Phase 1 MOPS. The Ikhana UAS was based on the operational MQ-9 Predator B with over 2 million flight hours and therefore declared safe to conduct flight operations in Edwards R-2515 airspace with air-to-air encounters against manned intruders on conflicting trajectories. FT6 execution required an equivalent level of safety. However, the smaller Group 3 TigerShark UAS platform does not have the operational metrics of the MQ-9 Predator B. The project had to provide evidence of the required maturity of its Group 3 UAS to execute the FT6 safety critical mission activities.

The project's Group 3 UAS maturity plan was driven by the UAS maturity guidelines documented in Edwards Air Force Base Instructions (EAFBI) 13-100 Chapter 14 (ref. 7). These guidelines provided a means for declaring the maturity of the UAS from an unproven platform with the most operational restrictions and safety mitigations to an experimental, provisional, and finally a mature platform with the least operational restrictions and safety mitigations, as shown in table 6. To meet its FT6 test objectives, the project required at least a provisional maturity designation in order to safely operate the aircraft in Edwards R-2515 airspace necessary for the air-to-air encounters. The provisional and higher maturity designation would enable the aircraft to utilize the Mercury Spin Area (footprint down to 7k ft MSL) and Four Corners UAS Work Area without needing to employ a Flight Termination System (FTS), a requirement for compliance with geofencing and other range boundary restrictions that would have made mission planning and execution much more complex and thus increased risk to mission success.

Table 6. UAS Maturity Level and Entry/Exit Criteria IAW EAFBI 13-100 Chapter 14.

Maturity Level	Entry Criteria	Exit Criteria
Unproven	Untested system	➢ 5 consecutive takeoffs/landings ➢ 5 test periods (sorties) ➢ Zero safety of flight critical failures ➢ Zero deviations from planned parameters
Experimental	Developmental flight test	➢ Basic flight envelope and handling testing complete ➢ 30 consecutive takeoffs/landings (cycles) ➢ 15 test periods (sorties) ➢ System reliability 0.9 with 0.95 confidence level ➢ Failure modes tested and understood
Provisional	Baseline developmental flight test complete	➢ Airframe operational testing ongoing ➢ Project executing specific flight test goals
Mature	Aircraft declared operational.	➢ Platform operational ➢ Comply with Test Safety Package requirements

The project presented the UAS maturity plan to the AFRC Chief Engineer (CE), and Chair of the Airworthiness and Flight Safety Review Board (AFSRB), during an FT5 Preliminary Design Review on January 23, 2018 when the NASA SIERRA-B UAS was still the Group 3 platform selected for FT6. The SIERRA-B was an updated version of the SIERRA-A aircraft which was engaged in science missions with Ames Research Center prior to a mishap in July 2013 which resulted in the loss of the aircraft. Many lessons learned and refinements were incorporated into the SIERRA-B aircraft. The project's UAS maturity plan for the unflown SIERRA-B aircraft followed the EAFBI 13-100 guidelines (ref. 7):

1) Complete basic airworthiness and envelope expansion flight tests to transition the aircraft from "unproven" to "experimental" UAS with demonstrated consistent system performance without any flight critical failures over 5 takeoff and landing cycles. The plan with SIERRA-B was to conduct these flight tests in the FT6 configuration that included OML changes to support the Honeywell DAPA Lite radar system.
2) Upon completion of envelope expansion flight testing in the FT6 configuration, conduct a minimum of 30 takeoff and landing cycles with demonstrated consistent system performance without any flight critical failures to show system reliability meets 0.9 with a 0.95 confidence level.
3) These tests were planned to be conducted at either the Crows Landing Airport (low altitude up to 2,500 ft MSL), Camp Roberts (med altitude up to 14,000 ft MSL), or at the EAFB UAS Work Area.

The AFRC CE agreed to the project's UAS maturity plan; however, he tasked the project to apply additional engineering and safety assessment rigor to determine the suitability of the popular COTS Cloud Cap Technology (now Collins Aerospace) Piccolo II UAS Autopilot that controlled the aircraft. Due to the safety critical classification of conducting air-to-air encounters, coupled with perceived Piccolo system deficiencies based on several incidents at AFRC with other Piccolo equipped subscale

UAS, the CE recommended that the project complete the following additional assessments as part of the upcoming Critical Design Review (CDR) entrance criteria:

1) Review past Piccolo II system performance for acceptability as a safety critical system
2) Perform a hazard analysis of the system to assess residual safety risk
3) Develop a plan to obtain approval of the Piccolo II system for safety critical use

Unfortunately, significant development delays with the SIERRA-B aircraft forced the project to abandon it as the Group 3 UAS in late August 2018 and shift its efforts to the NASC TigerShark Block 3 XP for FT6. The TigerShark XP aircraft has similar attributes to the SIERRA-B including the Piccolo II UAS autopilot, but it is an operational commercial UAS based on the combat proven RQ-23A. NASC has over 100,000 flight hours of experience with the TigerShark family of aircraft equipped with the Piccolo II autopilot. The project heavily leveraged this operational experience to develop UAS maturity artifacts to meet the required system reliability of 0.9 with a 0.95 confidence level. The UAS maturity plan was modified as follows:

1) Complete basic airworthiness and flight controls gain tuning flight tests with the required Piccolo II firmware v2.2.4.d (necessary for proper integration with VSCS) of the production TigerShark B3 XP configuration (unmodified) to baseline stability and control
2) Modify the aircraft to the FT6 configuration with OML changes to accommodate the Honeywell DAPA Lite radar system and complete basic airworthiness and envelope expansion flight tests
3) In lieu of conducting a minimum of 30 takeoff and landing cycles to show system reliability meets 0.9 with a 0.95 confidence level, utilize Mean Time Between Failure (MTBF) data acquired by NASC for its flight critical components to meet the required reliability criteria
4) Conduct a more rigorous assessment of the Piccolo II autopilot to determine its suitability for safety critical operations as requested by the AFRC CE

The NASC TigerShark Block 3 XP variant flight critical components have undergone improvements since the TigerShark Block 3's initial introduction in 2009. With in-house component testing, MTBF data, and over 10 years and 100,000 flight hours of Block 3 operational experience, system reliability was computed for flight critical systems such as the engine, flight control servos, and airframe in excess of 0.99 with a confidence level of 0.95. The Piccolo II autopilot was computed to be over 0.95 reliable with a confidence level of 0.95 based upon just NASC's experience. The Piccolo's manufacture reports a higher (>0.99) reliability figure as no known failures have been reported to them in >1 million flight hours. With the above flight critical component reliability metrics, redundant flight control surfaces, and successful completion of the FT6 configuration envelope expansion, the TigerShark XP easily met the UAS maturity classification of "mature" allowing access to the required airspace without an FTS or geo-fence restriction.

The final Maturity Plan task that the project had to complete was to evaluate the suitability of the Piccolo II autopilot to execute safety critical FT6 air-to-air encounters. Since the Piccolo II is a COTS UAS autopilot and essentially a "black box" that's integrated into the aircraft, this assessment heavily leveraged NASC's over 13 years of operational experience with the autopilot system, NASC's expertise and certification to provide Piccolo System Training, and AFRC's own operational experience with its subscale UAS. As mentioned previously, NASC has a wealth of experience with the Piccolo UAS autopilot system and it has never experienced an anomaly with the autopilot that resulted in uncommanded responses or loss of control. The Piccolo autopilot system has demonstrated excellent performance capturing and maintaining commanded airspeed, altitude, and course.

7.2. Group 3 UAS Maturity Plan Flight Testing and Results

Prior to any modifications to the TigerShark XP aircraft for FT6, stability and control evaluations had to be performed with the unmodified TigerShark XP aircraft (XP1) since the Piccolo II firmware v2.2.4.d was updated from v2.2.2k to v2.2.4.d. These evaluation flights were successfully completed in mid-March 2019 at Griffiss International Airport (KRME), Rome, NY. As expected, only minor changes were required in the longitudinal gains to reduce small pitch oscillations. The TigerShark XP was previously operated with Piccolo II firmware v2.2.2.k. Manual takeoffs and landings and one autoland were successfully accomplished.

After finishing the FT6 OML design, mockup panels were integrated to further the XP1 envelope expansion tests. These additional flight tests were conducted in late-March 2019 to evaluate stability and control effects due to the DAPA Lite radar OML changes. No gain adjustments were necessary during up and away phase of flight. However, during autoland approaches, the aircraft had a tendency to balloon slightly when flare (reduction in V_{rate}) was commanded resulting in rapid airspeed decay approaching stall speed when the aircraft was still several feet above the runway surface. As testing continued to characterize this effect better, one autoland approach resulted in the aircraft stalling approx. 6 to 7 feet AGL before the AVP could intervene and command a go-around. The aircraft landed hard and suffered significant damage to the nose and main landing gears and the DAPA Lite attach structure. Data analysis revealed that the Piccolo II autoland parameters needed to be changed to enable better airspeed management on final approach. The changes included a glideslope reduction and improved final approach speed management by enabling more throttle authority during the flare phase. The updates were incorporated in TigerShark XP2 and successfully flight tested in Rome, NY in late April 2019. Although airspeed got too slow on some approaches and the touchdown distances were more dispersed and further down the runway, it was deemed acceptable for FT6 operations on Rogers Lakebed at EAFB where autoland would only be used in a full lost link contingency event.

Data analysis from the FT6 envelope expansion flight tests clearly showed the TigerShark XP maintaining the above flight parameters to the required accuracies to safely execute DAA air-to-air encounters. The project performed a hazard analysis on potential failures with the Piccolo II autopilot system that could lead to loss of separation and resulting in a mid-air collision. Piccolo failure modes such as autopilot processing errors, software lockup, and corrupted commands were examined and their probability of occurrence determined to be remote when factoring in the robust design of the core Motorola MPC555/6 32-bit Microcontroller motherboard including software error detection and reset capability. The robustness of this design was substantiated by several AFRC subscale UAS flight tests after several anomalies were reported with Piccolo autopilot equipped UAS. Upon closer examination of these reports, the anomalies were either attributable to installation issues with GPS interference or procedural errors with incorrect ground and flight system configurations. During troubleshooting for an attitude roll off anomaly experienced on a single fuselage glider flight test in 2017, it was discovered that the incorrect attitude was present before takeoff and persisted throughout the flight suggesting an issue with system initialization. Flight testing on the AFRC subscale lab's Carbon Cub was performed in an attempt to duplicate the attitude anomaly with the exact Piccolo autopilot (s/n 1183) during aerobatic maneuvering with the GPS antenna partially disconnected and fully disconnected. The Piccolo attitude remained accurate throughout the aggressive maneuvering and never "tilted" as reported in the anomaly demonstrating the robustness of the inertial sensor assembly. This Piccolo unit was also returned to the manufacture who ran diagnostic tests and could not duplicate the anomaly.

The TigerShark XP safety critical systems reliability data, robust Piccolo II autopilot design findings, and systems level testing plan to ensure compatibility of the Piccolo II functionality and health and status reporting with the FT6 payload equipment all contributed to the project's "mature" UAS declaration to the AFRC CE who agreed with the project's assessments during a CDR presentation on February 21, 2019.

7.3. Airspace

Flight Test 6 was conducted entirely within the R-2508 Complex (ref. 8), and specifically within R-2515 (figure 38). Launch and recovery operations were conducted within the Edwards (KEDW) Class D airspace which included main base runways (used by the intruder aircraft) and north Rodgers Dry Lakebed (used by TigerShark). Five special use airspaces (within R-2515) were used during FT6: UAS Work Area, UAS Corridor, Precision Impact Range Area (PIRA), Mercury Spin, and Four Corners (figure 39).

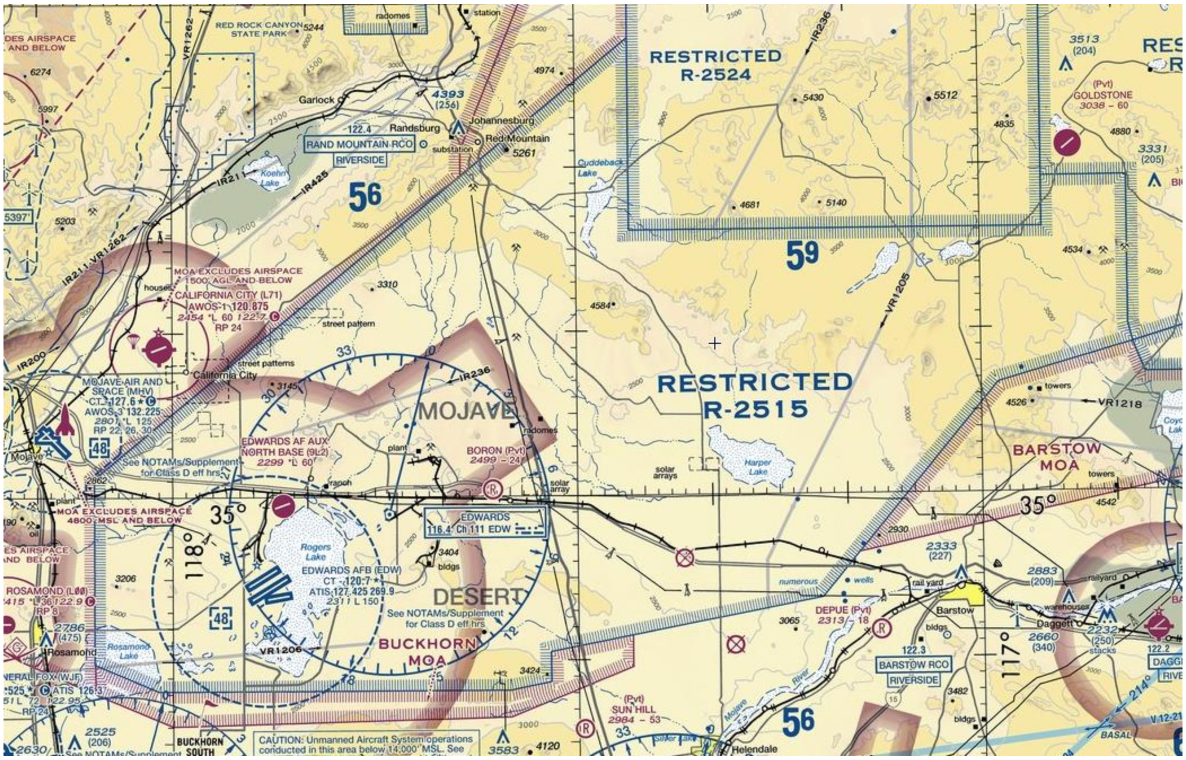


Figure 38. R-2515 Restricted Airspace and KEDW.

Test planning for Flight Test 6 increased in complexity by the introduction of a Group 3 UAS (TigerShark). In previous flight tests, the project employed the NASA Ikhana aircraft (MQ-9) as ownship. Ikhana (a group 5 UAS) used the Edwards main base runways for takeoff and landing operations. With TigerShark, the ops team needed to schedule the north Rogers Dry Lakebed (within the UAS Work Area) as a launch and recovery location, since Group 3 UAS operations at the Edwards Main base runway were not permitted. This presented the problem of how TigerShark would transition from the lakebed to the test area located in the Precision Impact Range Area (PIRA) and adjacent airspace. The PIRA East and West Ranges comprise the bulk of the airspace used for testing, but the project referenced the area as Mercury Spin, although technically the spin area terminates below 11,000ft MSL. After conferring with 412TW Airspace Office, the agreement was that the Mercury Spin “footprint” was the test range boundaries for FT6 while operating within the PIRA. The team coordinated to use the UAS Corridor airspace that was previously developed for MQ-1/9 operations but had not been used for several years nor previously with smaller class UAS.

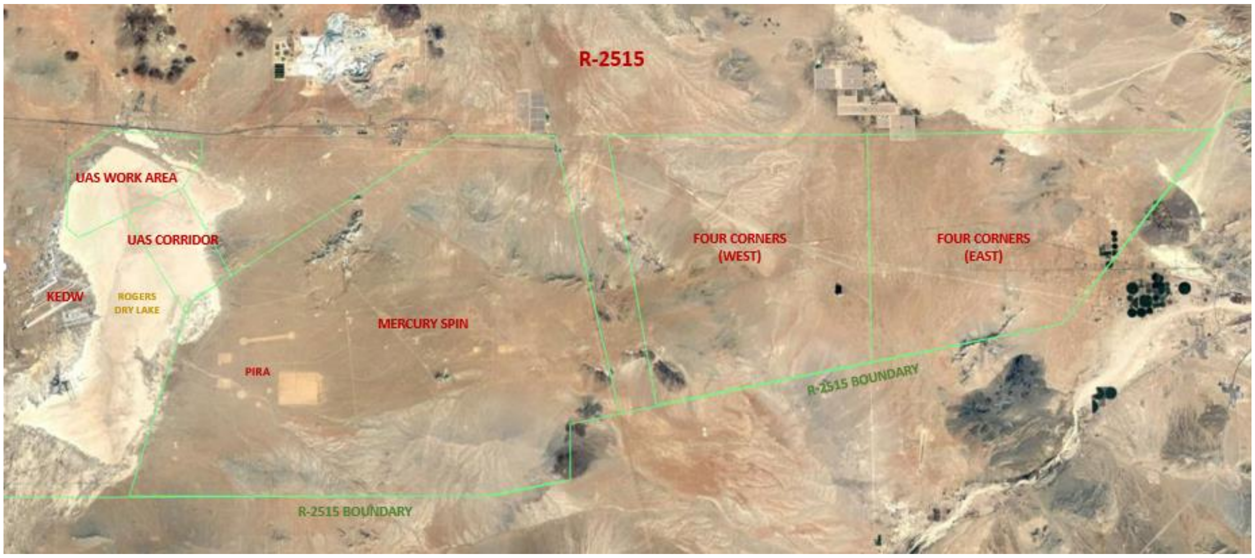


Figure 39. FT6 Work Areas within R-2515 Test Range.

Since the UAS Corridor airspace crosses perpendicular to Edwards main base runway 22 approach traffic flow, the team developed and coordinated with SPORT several contingency plans that would enable RTB via alternate routes to the UAS Work Area in the event that the corridor was closed, such as during an inflight emergency to main base runway. The contingency routing was used a few times during FT6 and proved to be both useful and uneventful.

The Lost Link (LL) routing was designed and coordinated early in the planning phase and required the use of the UAS Corridor. As a mitigation to potentially disrupting main base traffic in the event of a TigerShark lost link event, the project designed a 15 minute loiter in the PIRA (at point ALPHA) to provide time for the TC to coordinate with SPORT, who in turn, coordinated with Edwards Tower and is described in further detail later in this section.

Airspace reservations and coordination for each flight was scheduled through the AFRC Business Information Tracking System (BITS) process. BITS inputs are processed and transferred over to the EAFB 412th Center Scheduling Enterprise system (CSE). Command and control of R-2515 is through the Edwards Military Radar Unit known as “SPORT”. A “SPORT Brief Sheet”, shown in figure 40, was submitted 24 hours in advance of flight test activities which described the CONOPS for a given test day.

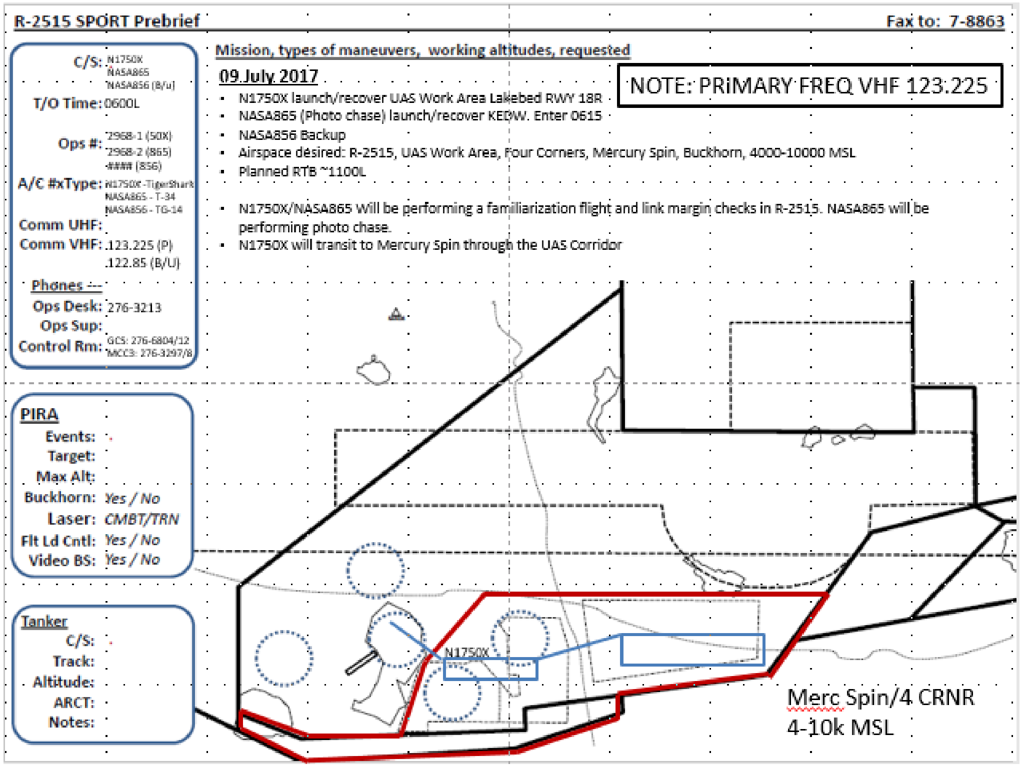


Figure 40. EAFB 412th TW Sport Brief Sheet.

7.4. Route Development

The IT&E ops team used previous project test campaigns as a starting point for developing mission routes for FT6. Since TigerShark is Piccolo operated by means of waypoint navigation, routes for FT6 needed to support that flight management methodology. Early on, Piccolo experts from the project flight systems group provided significant guidance in the route design and provided Piccolo flight simulation results that helped to validate the baseline FT6 route plans. NASC was also involved in route development as the plans matured.

Flight planning typically started with FalconView as a route design tool. The mission planner created the route and saved it as both a .rte file and a .shp file. The shape file was imported into Google Earth to create routes presented with the satellite-derived earth imagery. Rendering of these routes were typically used for presentation purposes.

FalconView proved to be highly valuable since the plotted flight plans and encounter lines with the Joint Operation Graphics (JOG) aeronautical chart underlay provided the top-down graphic view for the test cards. Coordinates from FalconView were imported into Piccolo Command Center and Zeus to display routes and encounter lines respectively.

Flight test cards depicted both Degrees, Minutes (N00° 00.0000’) and Degrees, Minutes, Seconds (N00° 00’ 00.00”) in order to provide pilots with coordinate formats that were required for their aircraft’s flight navigation systems (see Flight Cards section for more information).

Piccolo assigned unique waypoint numbers for the imported coordinates in each flight plan. These numbers often were different from the numbers used for the waypoints displayed with VSCS since it had its own unique method for identifying waypoints. To avoid confusion between the Controller and the Subject Pilot, waypoints were identified using the waypoint numbers in the VSCS and MACS databases rather than Piccolo generated numbers.

For Full Mission, ARC plotted initial coordinates on a Los Angeles Sectional Map based on track parameters provided by the AFRC ops team and then identified as specific waypoints. These waypoints were then forwarded to AFRC for review. Once agreement was reached on the location and design of the track, database files containing the waypoints were compiled for the VSCS and MACS displays in preparation for the Full Mission test. In order to reconcile the differences in waypoint nomenclature, the AFRC ops team created a database that depicted all coordinates (regardless of source), plus the associated waypoint number, and shared this information with the entire team for reference purposes during testing.

The geographic coordinate format for the various flight development tools used during FT6 proved to be a minor factor in route development. Route developers used tool default settings which were later determined to be sufficiently different (when rounding or decimal truncating was used) to change the position of route points and proved to be a nuisance (table 7). Later in the project campaign, the team decided to use degree coordinates (N00.00000°) as the standard unit for flight planning.

Table 7. Coordinate Reference System.

Coordinate Reference System			
Source	Format	Elevation	Datum
FalconView	Degrees, Minutes (N 00° 00.0000')	Ft MSL	WGS84
Google Earth	Degrees, Minutes, Seconds (N 00° 00' 00.00")	Ft AGL	EGM96
Piccolo Cmd Ctr	Degrees (N 00.00000°)	Ft MSL	DTED, STRM

Five route plans (or flight plans) were designed: land plan, transition plan, Scripted Encounters, Full Mission and lost link. NASC designed the land plans for TigerShark operations. The term “land plan” comes from the CCT Piccolo II PCC flight management software that enables the user to create takeoff and landing plans that can be stored in memory and used as required. Figure 41 shows the airport diagram for the Edwards AFB / Rogers Lakebed runways, along with the TigerShark lakebed runway 18 traffic pattern in magenta. The land plan was designed to for takeoff and landing of TigerShark from the Roger Dry Lakebed and into the UAS Work Area airspace (figure 42). Two land plans were created to support operations on Edwards Lakebed Runway 18/36 UAS (north and south options), plus two oriented to favor the prevailing winds (05/23) which required surveying the lakebed and capturing key coordinates to create the land plan.

The transition plan was used in order to “transition” TigerShark from the UAS Work Area, through the UAS Corridor, and into the “Test Area” which was comprised of the Mercury Spin and Four Corners areas (figure 44, figure 46). The Scripted Encounters plan was a racetrack timing orbit located in the Mercury Spin area (primary) and Four Corners (alternate) (figure 44). The Full Mission route was a large racetrack included both areas within the Test Area, plus two truncated racetrack plans (alternate routes) that were designed to keep TigerShark in either one of the two areas located within the Test Area (figure 46).

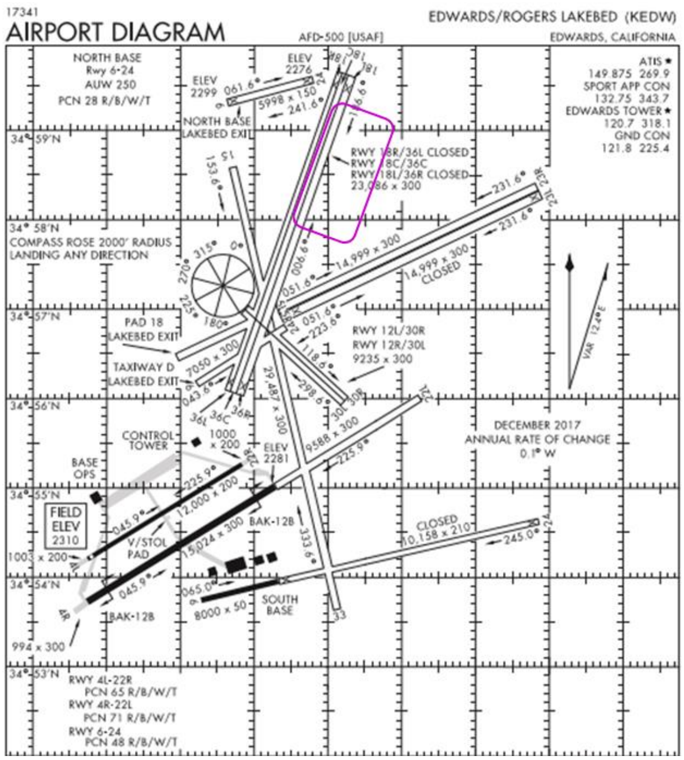


Figure 41. Edwards/Rogers Lakebed Airport Diagram.

Initially Lakebed Runway 18 UAS was used exclusively for takeoff and landing, but an event occurred during a high crosswind landing that resulted in TigerShark deviating significantly from runway centerline during rollout. This event led the team to create a 05/23 option that was designed and used during times when the winds favored that direction (figure 42).

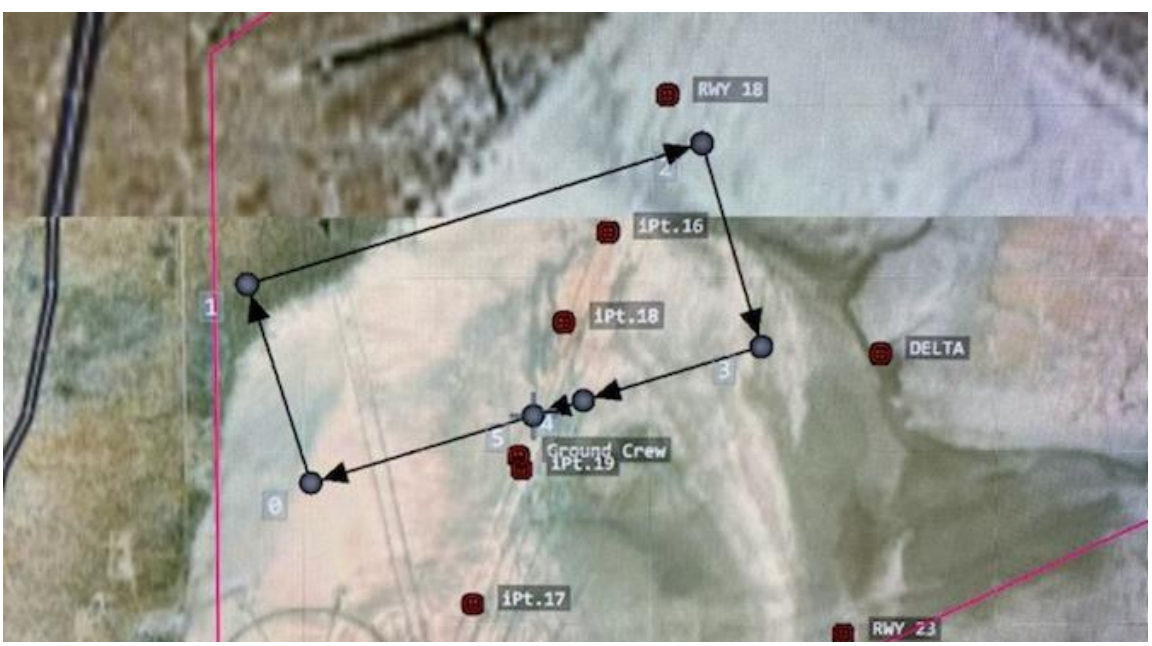


Figure 42. Alternate Land Plan within UAS Work Area on Rogers Dry Lakebed.

The transition plan included both loiter point DELTA (located in the UAS Work Area) and point ALPHA (located in the PIRA) and was designed to permit TigerShark to “transition” from the UAS Work Area to the Mercury Spin test area (Figure 43). This required the use of the UAS Corridor as a transit airspace between the two areas. Loiter points also provided key geographic spots to support other transition points within a given flight. First, loiter points provided a place for TigerShark to hold in a given airspace. Loiter points gave TigerShark a spot to climb or descend at convenient locations along the route of flight. The points also provided a place for the Test Conductor to position TigerShark in preparation for the start of Full Mission and as aforementioned hold points in the event that the team needed to stop the test or for other administrative purposes. Points ALPHA and BRAVO served as hold points that the virtual controllers would clear Tiger 50 (virtual callsign for N1750X) during Full Mission. Point CHRLY was positioned in Four Corners East as a hold point in the event that SPORT pushed TigerShark out of Mercury Spin and Four Corners West. Lastly point ALPHA was used as the start (hold) point for altimeter calibrations.

Figure 43. FT6 Loiter Points.

The transition plan was used in order to “transition” TigerShark from the UAS Work Area, through the UAS Corridor, and into the “Test Area” which was comprised of the Mercury Spin and Four Corners areas (figure 44). The Scripted Encounters plan was a racetrack timing orbit located in the Mercury Spin area (primary) and Four Corners (alternate) (figure 44). The Full Mission route was a large racetrack included both areas within the Test Area, plus two truncated racetrack plans (alternate routes) that were designed to keep TigerShark in either one of the two areas located within the Test Area (figure 45).

Figure 44. FT6 Scripted Encounters Flight Plan.

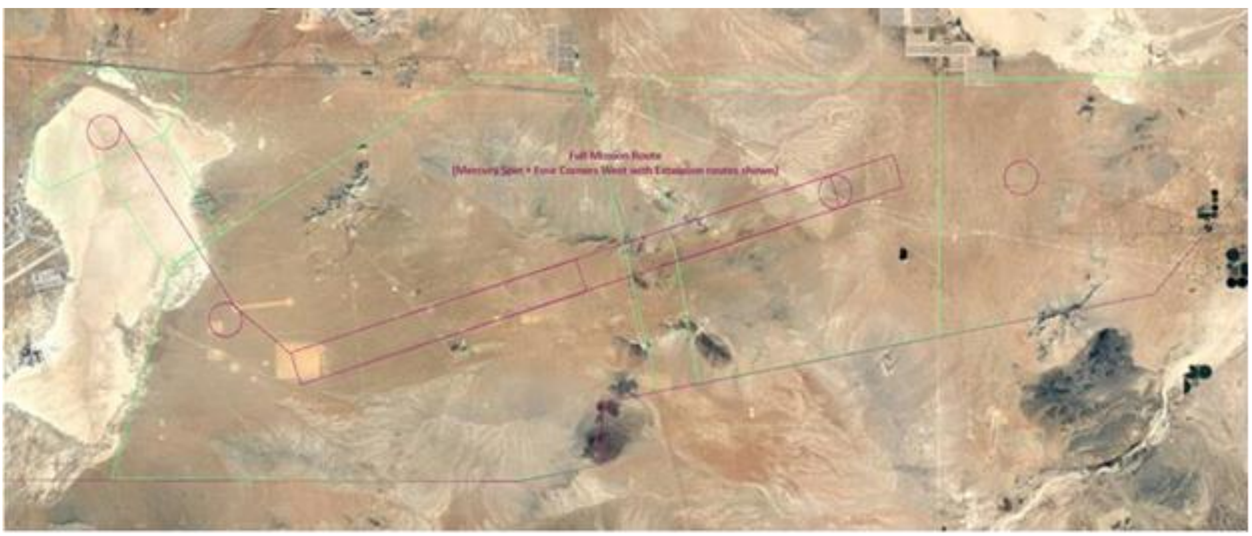


Figure 45. FT6 Full Mission Flight Plan.

The Scripted Encounters flight plan was specifically designed in the Mercury Spin area as a single source plan for all scripted geometries. A duplicate flight plan was designed for the Four Corners Area as an alternate in the event that the Mercury Spin Area was not available (figure 44). These contingency mission plans enabled the test to continue to maximize test efficiency. Planned for 60 knots ground speed, the design included a 1 minute orbit, 1 minute lead-in leg and a 2 minute run-in leg and was purpose designed for scripted type encounters using a waypoint navigation flight navigation system (figure 46).

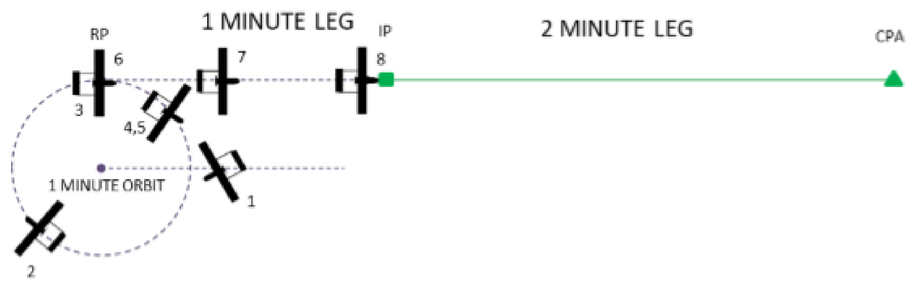


Figure 46. Scripted Encounters Ownship Timing Flight Plan.

During the timing orbit(s) and lead-in leg, the GCO used the Piccolo Command Center software to adjust the IAS to match a groundspeed of 60 knots. In the PCC software, the “Custom Telemetry” window was used to monitor the groundspeed while the “Command Loops” window was used to command the airspeed to match a desired groundspeed. This design was first developed for FT5 and refined during actual flight test using the NASA Armstrong Dryden Remotely Operated Integrated Drone (DROID) UAS as a testbed prior to FT6. Geometries for meeting test objectives required the intruder aircraft to reposition for the Initial Point (IP) to Closest Point of Approach (CPA) run-in while ownship remained anchored in the timing flight plan.

Full Mission flight plan design was a collaborative effort that began with test objectives as a starting point (refer to section 4). Because Full Mission involved NASA ARC HSI human-in-the-loop research, the Armstrong ops team reached out to the Ames IT&E team for route design support. Ames HSI and IT&E teams were already conducting HITL experiments during the planning phase of FT6, so their experience in performing HITLs provided relevant details of what was needed from the research objectives to help develop the Full Mission flight plan.

The initial plan for mission routing was to replicate the ARC Oakland airspace HITL flight simulation route overlaid into R-2515 airspace. Unfortunately, Edwards airspace usage and constraints limited that implementation. Instead, the ops team requested a minimum mission time required to meet test objectives and designed a route that fit within the airspace generally assigned for project use that met the requirement. This meant designing a simple racetrack type route of flight that provided the timing requirement and was designed to provide ownship maneuvering space for traffic avoidance while remaining within the assigned airspace. Consideration was also given to the proximity of the track to the Los Angeles Air Route Traffic Control Center (ZLA) common boundary with R-2515 and the Buckhorn MOA. ARC developed a virtual Temporary Flight Restriction (TFR) from the surface up to and including 10,000ft MSL. The northern boundary of the TFR, depicted to the controller and subject pilot, was collocated on common boundary of R-2515, the Buckhorn MOA, and ZLA. The ownship was required to remain at least 1.5 NM away from the TFR to protect the ZLA boundary.

The initial design had eight waypoints in the Full Mission route to help the team to manage airspace constraints that frequently occurred during test. R-2515 is a high demand airspace and NASA missions typically receive lowest priority for airspace usage, so the route was designed with the flexibility to enable the experiment to continue in response to airspace restriction clearances provided by SPORT. The only exception was if SPORT assigned the FT6 test aircraft to Four Corners East, at which point, the experiment would stop and all aircraft would hold at point CHRLY. Fortunately, that situation did not occur during FT6.

For Full Mission, a “circuit” meant that the ownship flew once around the Full Mission racetrack route. Point BRAVO was placed at the end of the original route (east end) to compliment point ALPHA located in the Mercury Spin area (figure 46). These points were created to serve as hold points between test circuits which was a normal stopping point for researchers to conduct a short interview with the subject pilot. Early planning called for a 10-minute delay between circuits, however, this plan was eventually abandoned due to consideration for intruder aircraft flight duration limitations. Ultimately, all interviews were conducted during the “slack” time between encounters and this proved to be very test efficient for performing Full Mission.

The original Full Mission ‘Primary’ route was 17nmi in length (east-west) with 1nmi turn legs on each end of the racetrack route (figure 47). The route originated at waypoint 1 (RGCS waypoint 50) at the northwest corner (over PB-8 in the PIRA) and progressed northeasterly to waypoint 4 or RGCS waypoint 53 (approximately 2nmi north of Hawes Field) sequencing back to the west in a clockwise manner. The primary route remained unchanged for FT6. Two alternate routes (Mercury Spin and Four Corners) comprised four waypoints out of the primary route set (1-2-7-8 for Mercury Spin and 3-4-5-6 for Four Corners).

Contingency plans (also called “alternate” routes) were developed in anticipation that airspace constraints would likely result from the demands of conflicting airspace activities. This was a lesson learned from previous test campaigns. These plans were designed to keep the ownship on a portion of the Full Mission Route and allow for continued encounters by the intruder aircraft. The Mercury Spin Route, shown in blue in figure 47, was designed to contain the ownship within the Mercury Spin operating area if the Four Corners area became unavailable. The track provided a shortened racetrack pattern consisting of WP1, WP2, WP9, and WP10. The Four Corners Route, shown in red, moved the ownship into the Four Corners area when the Mercury Spin area was constrained. The Four Corners racetrack pattern consisted of WP3, WP5, WP6, WP8, and intermediate waypoints.

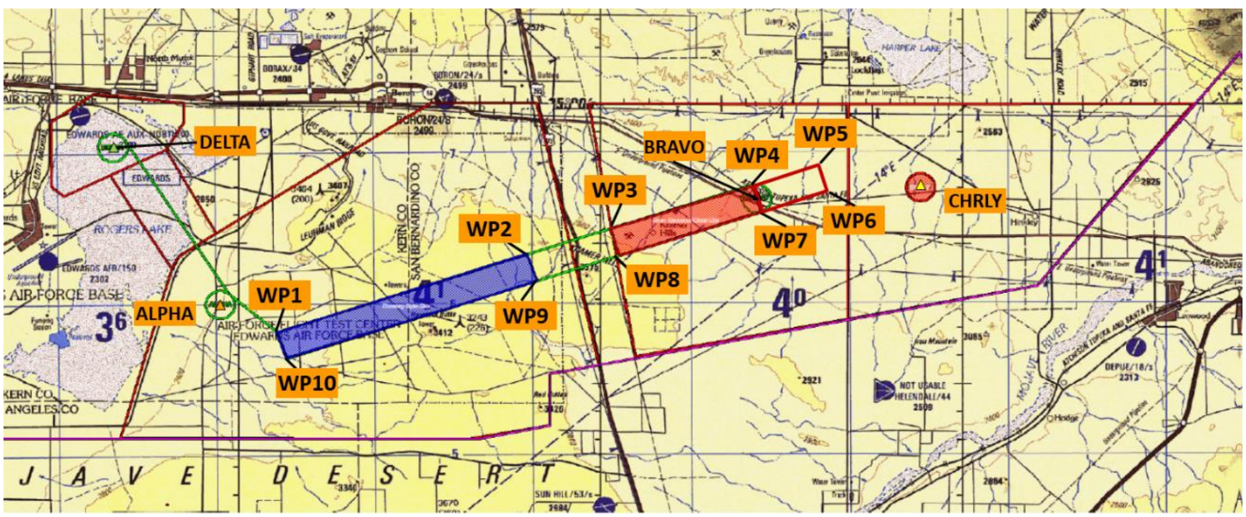


Figure 47. FT6 Full Mission Flight Plan with Waypoints Numbered.

The Four Corners Extension was developed when the original length of the Four Corners Route created difficulty with some encounters on the inbound leg of the pattern. The extension defined by WP4, WP5, WP6, and WP7 became part of the Four Corners Route when the test was restricted to the Four Corners Area. A clearance for the Four Corners Extension was also applied to the Full Mission Route if more distance and or time was needed to accomplish encounters or complete SPUT debriefings. The Full Mission Route with the Four Corners Extension clearance departed WP4 and flew the extension to WP7 then continued on the Full Mission Route. This flexibility in the route design proved to be highly effective for performing actual human research flight experiments in a non-exclusive airspace environment.

In addition to the normal RTB routing, an alternate Return-to-Base flight plan was developed in order to mitigate a situation where the test aircraft were operating in the Four Corners area and the Mercury Spin Area was unavailable for the return flight. Aircraft transitioned north of Mercury Spin, proceeded west just south of highway 58 and then turned south to re-enter the UAS Work Area to Point DELTA.

The last route set developed for FT6 were the lost link routes (figure 48 and figure 49). The Piccolo autopilot treated lost link much differently than ownship aircraft used during previous campaigns. Knowing this fact required additional forethought and planning in order to maintain intruder safety, and safety to other aircraft flowing into the EAFB main base runways. The Piccolo autopilot uses a GCO selected comm timer to execute its lost link mission plan. The LL route would activate once the user specified time value expired due to command link failure. Since the TigerShark had the capability to perform an automatic landing through the autopilot, this was used as a mitigation in the event that the NASC team was unable to re-establish command and control link with the UAS. With this in mind, lost link was not considered as an in-flight emergency.

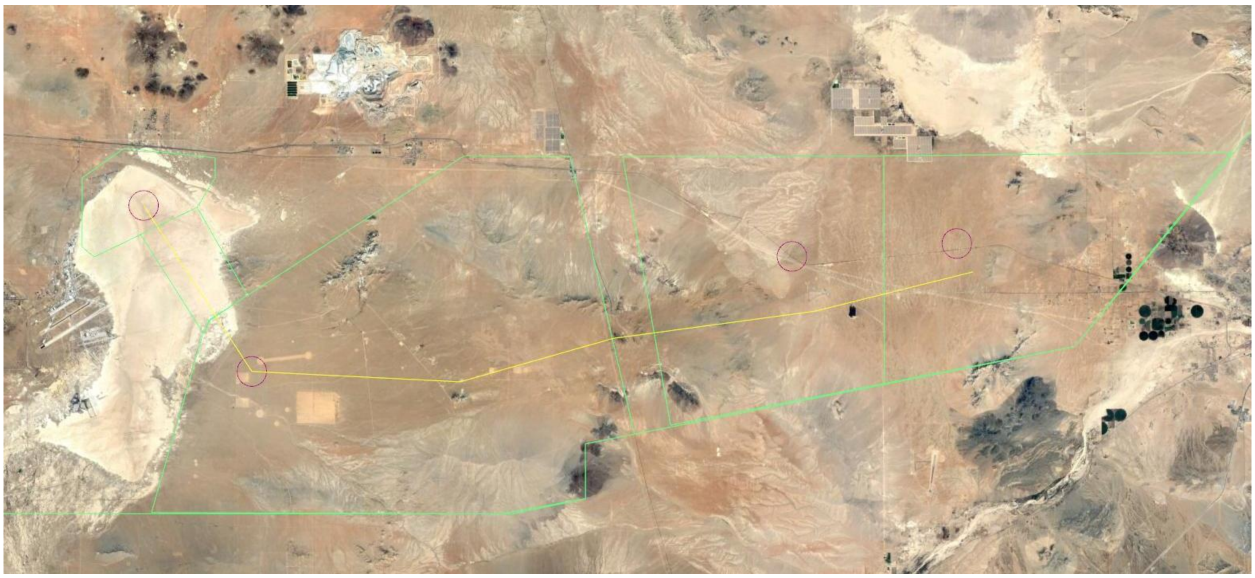


Figure 48. FT6 Test Area Lost Link Flight Plan.

There were two lost link flight plans designed for the FT6 flight test. The first LL plan was designed for normal test operations within the test area. This plan is shown in figure 48 and illustrated by the yellow line. One major consideration the team had to contend with was whether or not to interrupt the landing traffic pattern at EAFB should a lost link event occur. The team consulted with the EAFB Tower and SPORT personnel to discuss this issue and ultimately decided to include a 15-minute hold at Point ALPHA in the lost link plan in order to give the Tower controller enough time to clear the normal landing corridor of other traffic before TigerShark could transit through the UAS corridor. This LL plan allowed the project to reuse it for every test mission since the mechanization of the Piccolo LL system links the aircraft to the nearest segment of the route by way of direct to navigation.

Figure 49 shows an example of the second LL flight plan that was used in a contingency scenario where the PUT was required to RTB via an alternate route in order to get back into the UAS Work Area. This situation would occur if a higher priority mission was occupying the Mercury Spin area when the test was complete and TigerShark needed to RTB. The PUT would create and uplink a new lost link plan once SPORT cleared TigerShark to initiate the alternate RTB routing and was designed to closely match the routing flight path.

Figure 49. FT6 Alternate RTB Lost Link Flight Plan.

If the TigerShark UAS was still lost link once it was established back inside the UAS Work Area, it would continue to fly its orbit at Point DELTA until the flight timer expired (reached 0:00:00). TigerShark would then transition to the landing flight plan that was loaded into the Piccolo autopilot and attempt to perform an automatic landing.

7.5. Mission Profile

As mention previously in the airspace section, FT6 used several work areas within R-2515 to conduct the flight test. Each area served a specific purpose for flight test operations. These areas were tied to the various mission phases (Launch and Recovery, Transition, and Test) developed to help the test team understand the mission profile and flight procedures designed for flight operations to and from the test area and are shown in figure 50. Each mission phase had specific procedures and objectives that were developed, rehearsed, and executed during actual test flights.

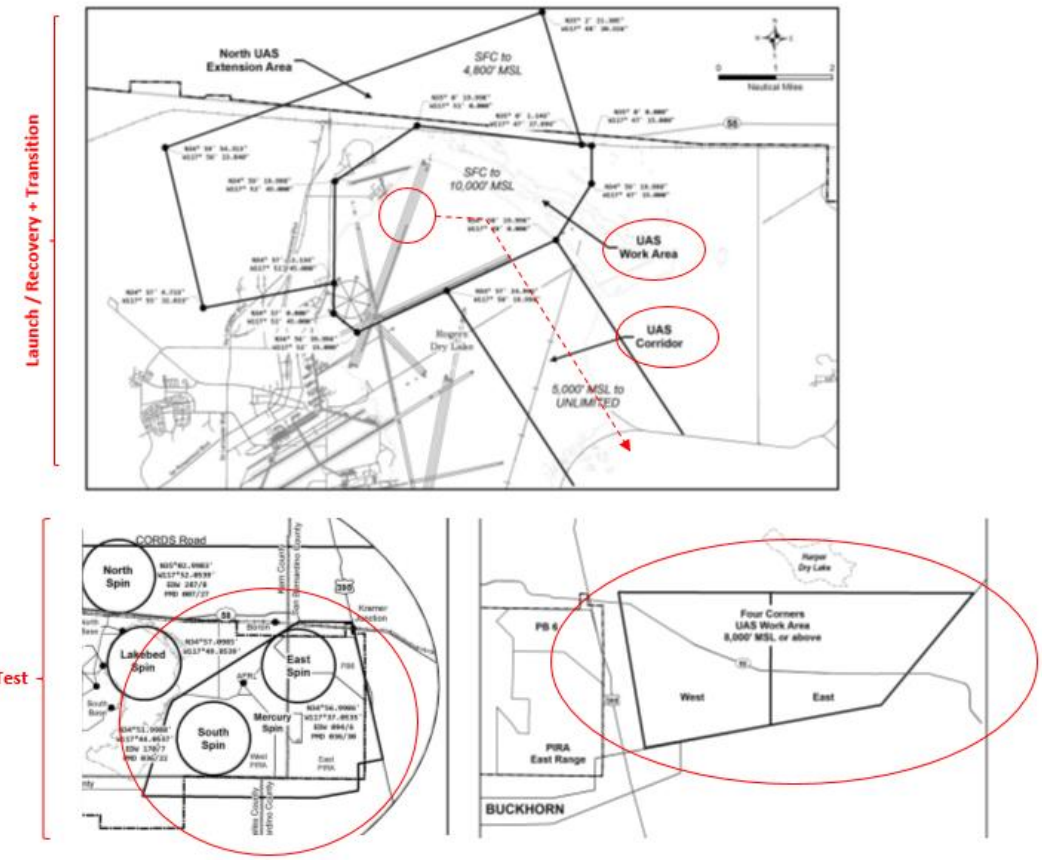


Figure 50. FT6 Mission Phases.

The TigerShark UA was launched and recovered from the MOC in manual mode by the AVP through a Pilot Control Box interfaced to the Piccolo II GCS system. This allowed full stick to control surface authority of the aircraft. The AVP was further aided by the nose camera video feed with a Heads-Up Display (HUD) overlay and the NASC designed Electronic Flight Instrument System (EFIS) display. Shortly after launch, the AVP would set the UA autopilot to Auto mode, then transition the UA to a holding waypoint (point DELTA) within the UAS Work Area. Once aircraft system and payload checks were complete, command and control (C2) of the UA was transferred to the GCO and PUT in the MOF5 via radio procedure. Voice communications started with Edwards Tower, who would handoff TigerShark to SPORT during the climb in the UAS Work Area.

Once TigerShark climbed above 5,000ft MSL, the pilot would request clearance to transition to the Mercury Spin area via the UAS Corridor while continuing the climb to 8,000ft MSL and navigating to loiter point ALPHA. Generally, TigerShark arrived at ALPHA at around 6,500ft MSL and entered holding. The elapsed time from takeoff to ALPHA was about 20 minutes. The Test Conductor would release the intruder crew to takeoff when TigerShark entered holding at ALPHA. This technique worked out very well in that by the time the intruder was airborne and headed toward ALPHA, TigerShark would be established at 8,000ft MSL and ready to start the altimeter calibration procedure that is described later in this section.

The ops team scheduled an altitude block of 7,000ft to 9,000ft MSL. TigerShark remained at 8.0K' MSL for the entire time that it was operating in the test area. The intruder aircraft would maneuver both in terms of position and altitude as required (or cleared by the TC) to meet test card parameters. RTB was a reverse of the entry profile, with the handover from MOF5 to MOC occurring soon after re-entering the UAS Work Area.

During Full Mission rehearsal and early actual Full Mission sorties, the test conductor noted significant variance in how the intruder aircraft set up for the initial encounter. The flow had a significant effect on the ability to successfully complete the first encounter during Full Mission. It was standard procedure for the intruder pilot to delay his takeoff until TigerShark was established at point ALPHA and the Full Mission start sequence checklist was well underway. The ops team created a mission entry flow procedure whereby the intruder would follow a flow pattern leading into the first encounter (see figure 51).

Not only did this procedure help provide adequate separation between ownship and the intruder during cooperative (ADS-B) encounters (FULL-07 and 08) to help limit the subject pilot's awareness of the live intruder versus virtual traffic prior to the intruder being ready for the encounter, but the timing and spacing of the intruder aircraft as it flowed into the first encounter completely resolved aforementioned issues yielding 100% success rate of the first encounter as compared to early Full Mission tests. More details on encounter execution is described in section 8.

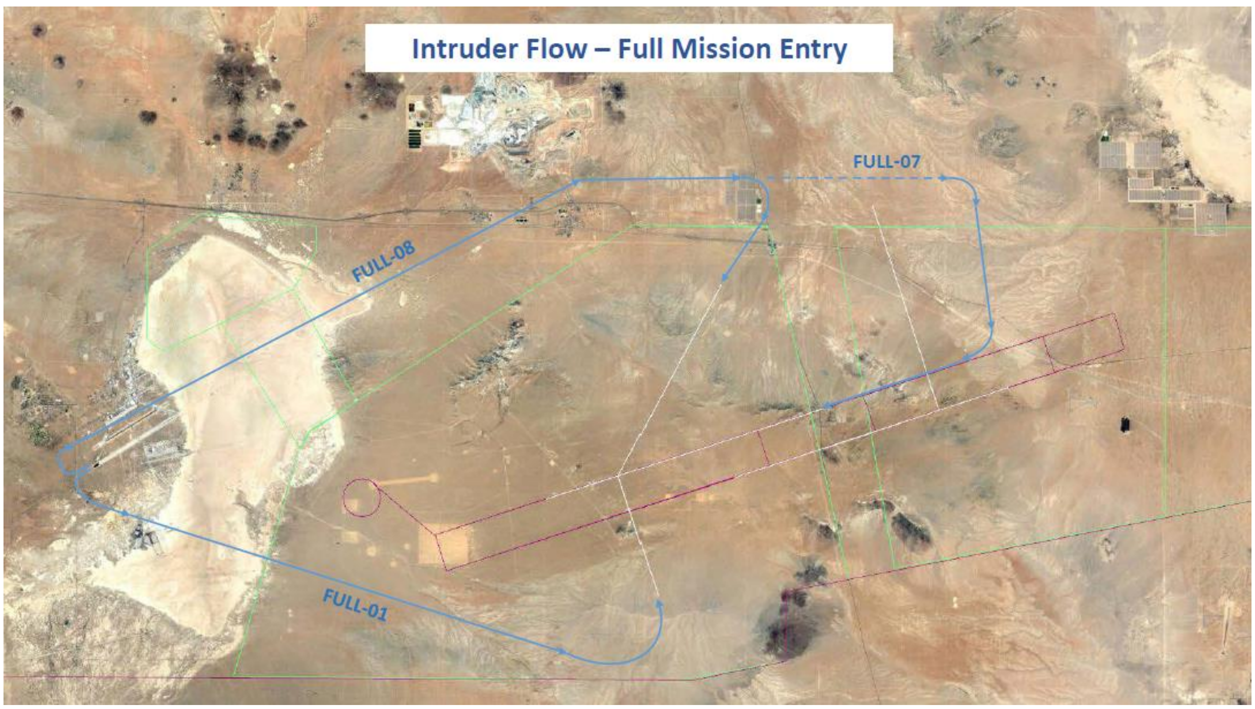


Figure 51. Full Mission Intruder Aircraft Entry Flow Procedure.

7.6. Visual Identification "11 Second Rule"

For flight safety reasons beginning with ACAS Xu FT1, the project has carried a visual identification (VID) requirement for all encounters designed with less than 500 ft vertical separation for flight safety reasons. This visual requirement was based on the "11 second rule". The rule established the minimum lateral separation in time between the ownship aircraft and intruder aircraft where the intruder pilot was required to obtain a visual during the intercept encounter. Rate of closure played a critical factor in calculating the VID range and this rate helped the project determine a new minimum separation for FT6. Due to the design of the intercept geometries, the VID requirement normally occurred when the two aircraft reach proximity to the closet point of approach. If the pilot failed to obtain VID by the minimum range, an abort call was required per mission rule. Included in the 11 second timeline was a 3 second decision time that allowed the pilot time to decide to abort, make the abort call, and apply control inputs to maneuver the intruder aircraft in accordance with the test card abort procedure. As an aid to VID, the team installed a smoke generation system on TigerShark that under certain conditions (most notably during head-on encounters) provided the intruder pilot with a means to acquire the ownship aircraft early. Through experience, however, the system proved to be of very limited effectiveness during FT6.

Flight Test 6 was the first time that this visual requirement was reduced from 1 nmi lateral separation (slant range) to two different ranges due to faster closure rates and smaller visual footprint of a Group 3 UAS. However, the 11 second rule was still adhered to. Based on the maximum closure rate of 230kts, the new requirement for visual identification was reduced to 0.7nmi. The minimum closure rate was 120kts which reduced the visual requirement to 0.4nmi. Figure 52 shows the 0.7 nmi VID requirement including test parameters, procedures, and incorporation of the 11 second rule.

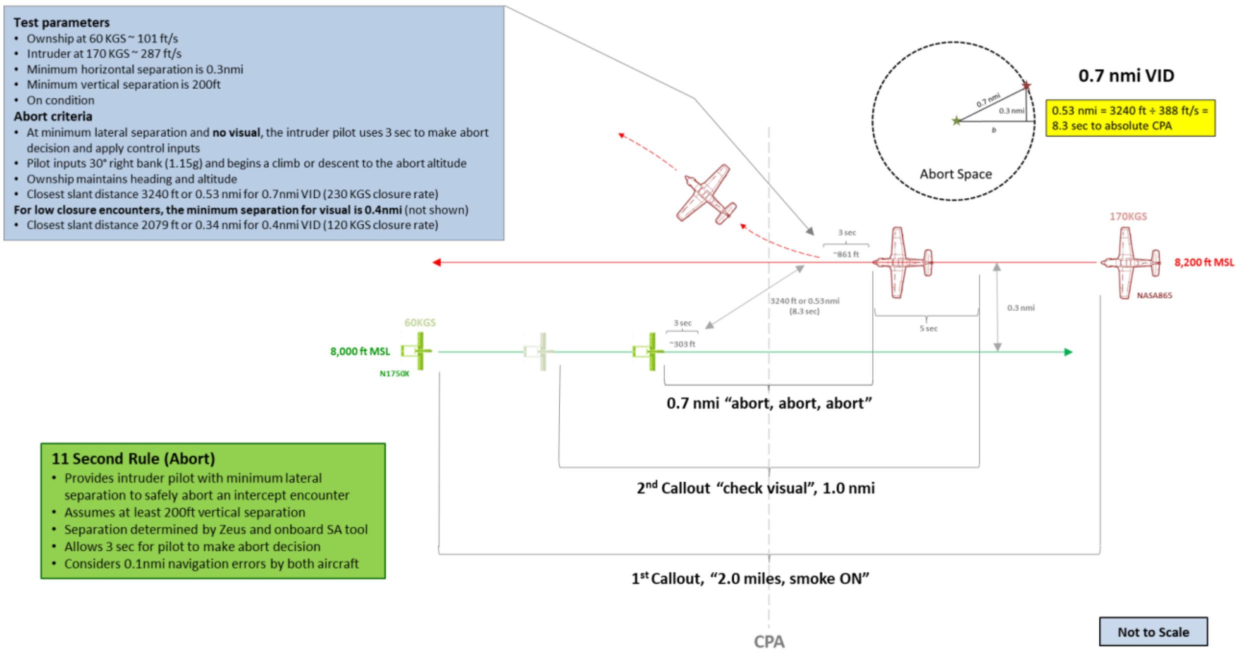


Figure 52. FT6 0.7 nmi VID Requirement.

7.7. Test Encounter Sequencing

The test team utilized a "Build up" approach to conducting encounters for FT6. This approach is specifically looked at and applied to each test day to ensure it is followed. To the maximum extent possible considerations were made as followed each test day:

Per Test Day:

- Performed encounters with standard separation and then VID required encounters.
- Performed "simple" geometries, non-maneuvering fly through encounters first.
- Grouped similar encounters together.
- Grouped encounters with the same mission plan.
- Altimeter calibration completed prior to executing encounters with less than standard separation.
- Once the encounter type is cleared, proceed through the deck as planned.

7.8. Flight Test 6 Encounters

In order to meet the SCO, Radar Characterization, Scripted Encounters, and Full Mission objectives, specific geometries were designed to stress the system under test. The UAS-NAS Principle Investigator (PI) created 148 geometries based on the information needed by RTCA SC-228 and industry partners. These geometries were developed and iterated upon throughout the OWG process. Once flight tests commenced, it was discovered that more geometries were needed to thoroughly test the radar along with testing an ADS-B mitigation to continue collecting data. This is discussed in greater detail in section 8 Test Approach and Execution.

7.8.1. Encounter Nomenclature & Geometries

A unique nomenclature, shown in table 8 below, was created to easily identify each encounter, test card, along with which flight phase it's for.

Table 8. Flight Test 6 Encounter Nomenclature.

Name	Definition
SCO	System Checkout
DAPA	DAPA Lite Radar Checkout
RDR	Radar Characterization
DAA	DAA Scripted Encounters
FULL	Full Mission

Each phase of FT6 had a unique set of geometries designed to meet those specific objectives. Due to the large number of encounters that were developed, below in figure 53 are test objective examples for each phase.

For System Checkout, there were plans for six encounters, four following the traditional pinwheel geometry and two for the Full Mission objectives. Due to system performance issues observed during ground testing, additional DAPA Lite radar system checkout geometries were created to fully checkout that system more fully.

There were 64 Radar Characterization geometries and 72 DAA Scripted Encounters geometries. Each would vary the intruder, altitude, complexity, speed etc. Turns were standard rate unless identified differently on the test card. Ownship always attempted to achieve a turn rate of 7° per second as permitted by the Piccolo autopilot. A majority of the Radar Characterization flight cards were flown during the system checkout phase to evaluate system performance.

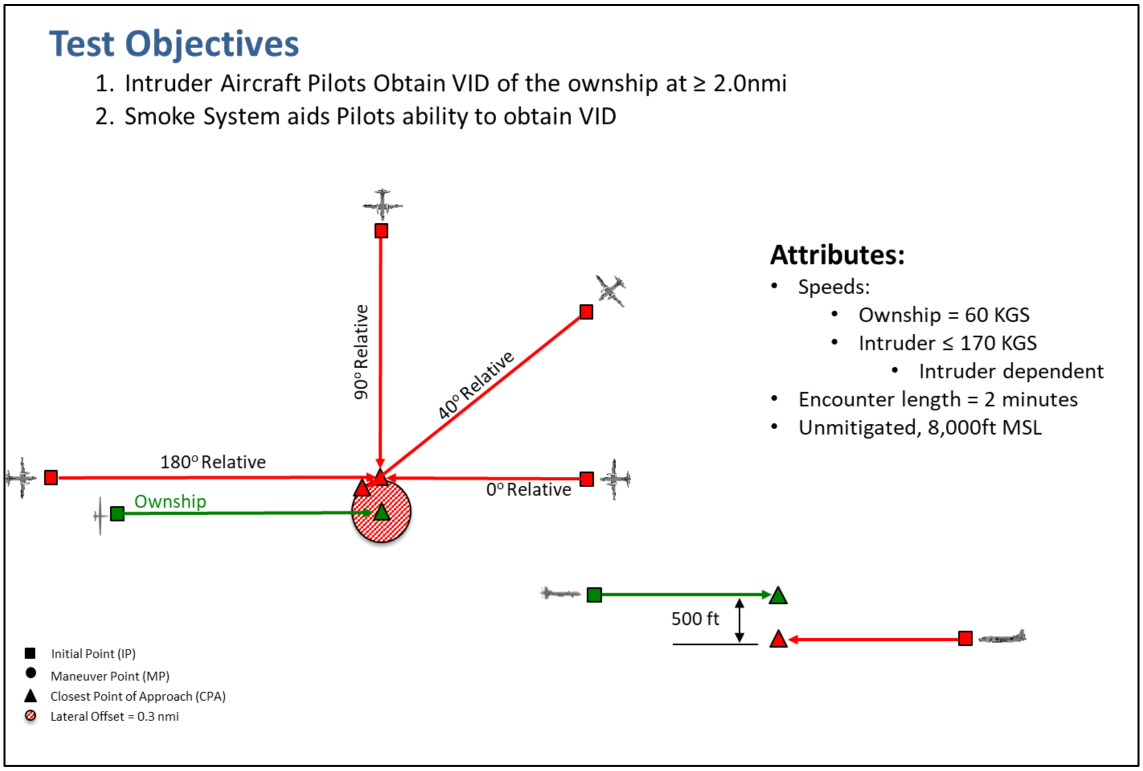


Figure 53. System Checkout Geometries Example.

An overlay of these example geometries can be found in figure 54. This figure depicts the basic pinwheel geometries located in the Mercury spin airspace with the intruder line represented in red and ownship line in dark green.

Figure 54. Radar Characterization and Scripted Encounters Example Geometries within Mercury Spin Airspace.

Full Mission contained six encounter geometries with two being completed each circuit (figure 55). The subject pilot would fly three circuits per flight. During the Full Mission rehearsals, the DAA & HSI team evaluated the “blunder” or maneuvering geometry and deemed it not required. This geometry was replaced with a fast, cooperative head-on encounter, since the PI decided that blunder encounters did not result in the research data desired for Full Mission. The final set of geometries flown during Full Mission including the primary set (red lines), Mercury Spin set (yellow lines) and Four Corners set (green lines) are shown in figure 56.

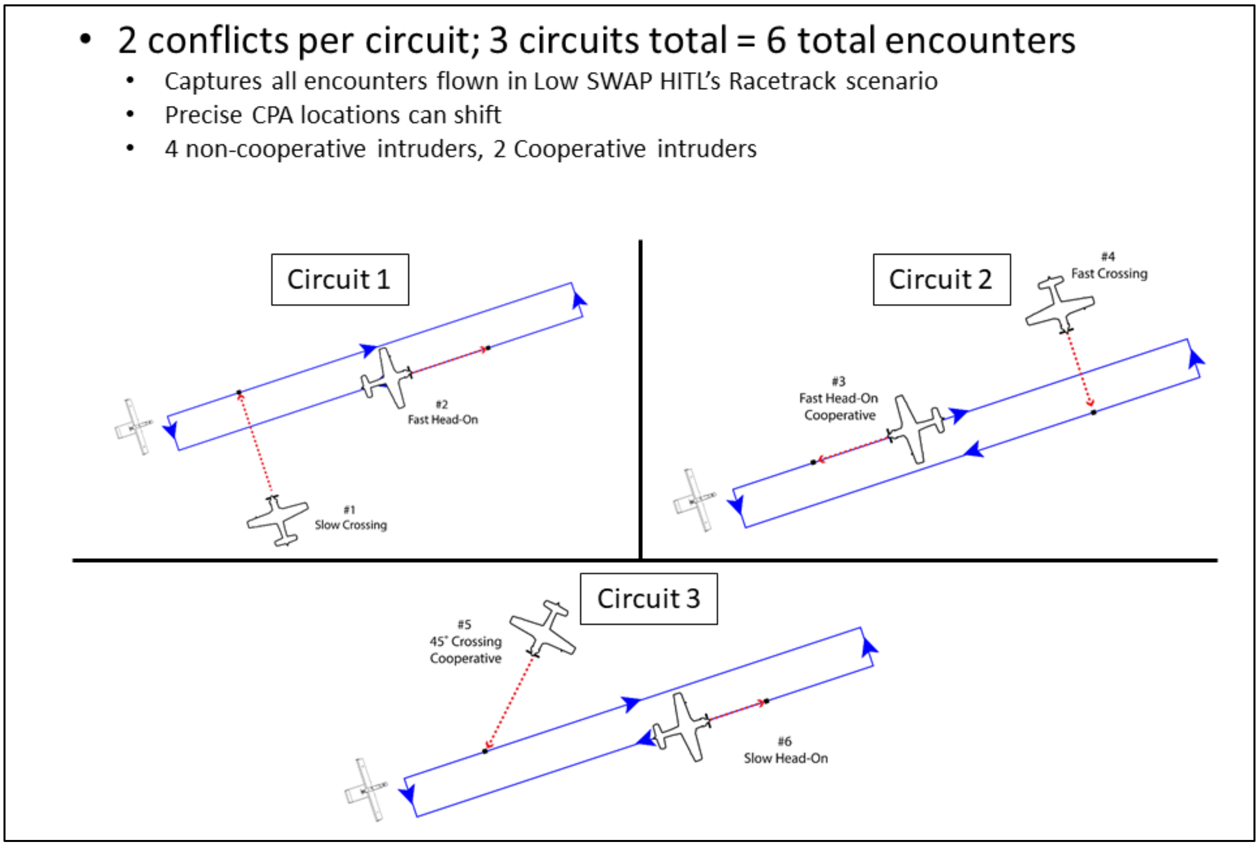


Figure 55. Full Mission Geometries Per Circuit.

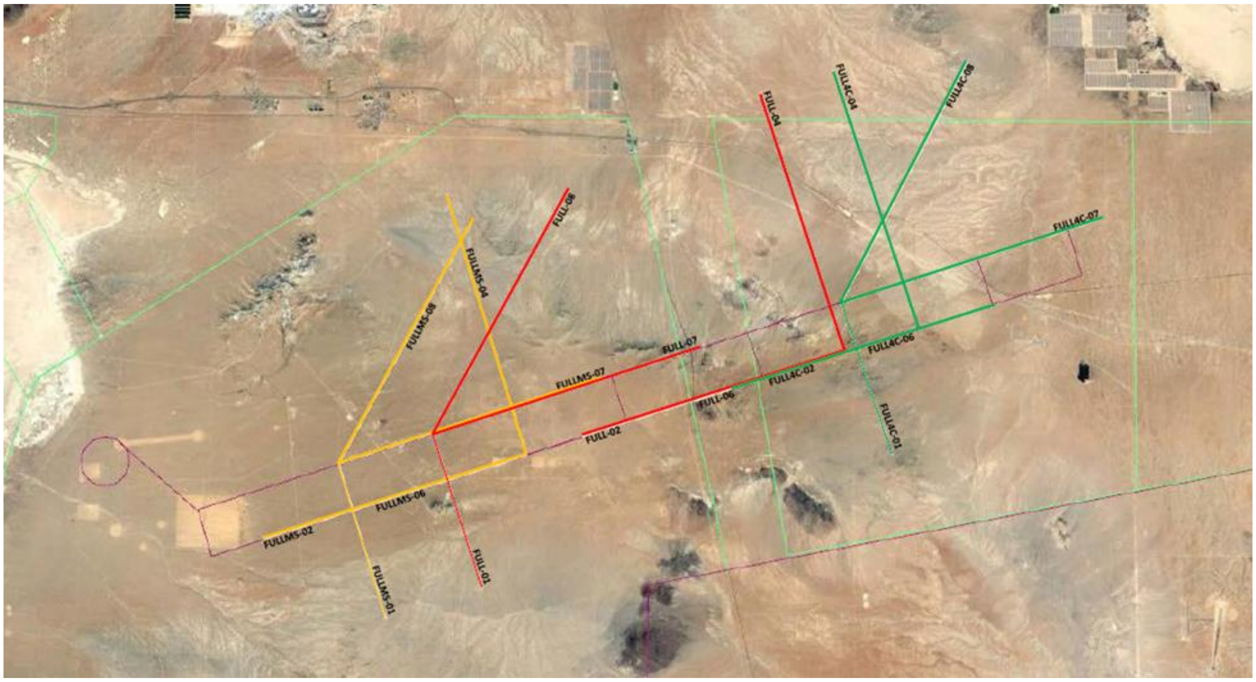


Figure 56. Full Mission Encounters Along the Full Route and Alternate Routes.

In order to ensure the integrity of subject pilot performance results, the HSI & DAA team determined that it would be best to mix up the circuit order for Full Mission. This would allow the greatest uncertainty between the subject pilots. Table 9 shows how the order would change for each subject pilot.

Table 9. Subject Pilot Circuit Order for Each Encounter.

	Circuit # Order		
Subject	**1st**	**2nd**	**3rd**
1	1	2	3
2	3	2	1
3	2	1	3
4	3	1	2
5	1	2	3
6	3	2	1
7	2	1	3
8	3	1	2
9	1	2	3
10	3	2	1

Circuit	**Encounter 1**	**Encounter 2**
1	FULL-01	FULL-02
2	FULL-07	FULL-04
3	FULL-08	FULL-06

A complete list of geometries and objectives is captured in the FT6 Flight Test Plan (ref. 14).

7.9. Flight Test Matrix

A detailed flight test matrix was built for the FT6 encounters based on the objectives and requirements described in section 4.2. The encounters were grouped into multiple matrices based on the flight phase they were designed for.

Because the use of such a test matrix was highly successful in previous flight campaigns, this approach was used again for FT6 with a couple of caveats that will be discussed later on in this section. The purpose of the matrices was to capture requirements/objectives for each encounter, as well as all required test geometries and planned coordinates in order to populate the flight cards.

The matrix was built in Microsoft Excel® and used Visual Basic for Applications for calculating pertinent values, such as GPS Coordinates in multiple formats. Excel was useful for calculated Initial Point (IP) to Maneuver Point (MP) and CPA using dead-reckoning equations. Below is an example list of the column titles and definitions used to capture the parameters for each encounter in a test matrix. A sample of the matrix spreadsheet is shown in table 10 for the System Checkout phase. The Ownship is captured as "OWN" with the Intruder titled as "INT".

- **Scenario (Encounter) Number (S/N):** The Scenario Number was the most critical number for each encounter. This number served as an identification number for the unique geometry.
- **Type:** The type of encounter is based on the geometry and specific objective.
- **Name:** Names were based on the type of encounter. The Name was a quick reference to gain Situational Awareness (SA) on what type of encounter.
- **OWN True Course:** True Course of the ownship. This value was used to calculate GPS coordinates (magnetic course was later calculated in a separate table).
- **Leg Time:** This is a partial time of the encounter. It is calculated based on the airspeed of the aircraft and length of the encounter line.
- **Angle Into:** Relative angle of the intruder into the ownship for that geometry. This value was used to calculate GPS coordinates.
- **Vertical Offset:** Smallest vertical separation between ownship and the intruder at CPA. If the vertical separation necessary for an encounter was ≤500 ft, a lateral offset was required for safety.
- **Lateral Offset:** A lateral offset of 0.3 nmi (~1,800 ft) was calculated into the geometry for encounters with a vertical separation of <500 ft. This was to ensure that if visual was not acquired according to mission rule, there would still be a safety buffer.
- **GS OWN:** Groundspeed of the ownship. Groundspeed was preferred for calculations to remove atmospheric variabilities.
- **GS INT1:** Groundspeed of the intruder. Most encounters required the intruder to fly at 100 or 170 KGS. For high-speed encounters, intruders were required to fly 170 KGS. For low-speed encounters, usually 60 KGS was used.
- **Ownship Initial Altitude:** Initial altitude for the ownship. The ownship flew at a constant 8,000ft MSL with no altitude changes throughout the encounter.
- **Ownship Vertical Velocity:** This column was not used for the FT6 Matrix. The ownship made no vertical changes.
- **Ownship Final Altitude:** The ownship remained at a constant 8,000ft MSL
- **Intruder 1 Initial Altitude:** The intruder's altitude at the IP.
- **Intruder 1 Vertical Velocity:** Based on the encounter, the intruder would initiate a positive or negative vertical velocity. This is the intruder's vertical velocity. Most common rates required were either 1,000 fpm (climb) or -1,000 fpm (descent).
- **Intruder 1 Final Altitude:** The desired final altitude of the intruder 1 aircraft at the end of the encounter.
- **CPA OWN:** Ownship CPA identification number based on its coordinates. The CPA for the ownship was the GPS coordinate where the ownship and intruder would be nearest in space for each encounter. The CPAs were used in a lookup table to build GPS coordinates for all geometries.
- **CPA OWN Lat/Lon:** Chosen latitude and longitude for each CPA in Decimal Degrees (DD) format. The CPA latitude/longitude was found using FalconView.

- **IP OWN:** The Initial Point identification number for the ownship based on its coordinates. For encounters that used the same IP, an identical IP ID was used. The IP was also used on the flight cards for reference on the top view.
- **IP OWN Lat/Lon:** Calculated latitude and longitude of the ownship IP from the CPA using dead reckoning equations, in DD format. The IP of the ownship was chosen to fit within the airspace and to accommodate for the encounter lengths. The IP served as the point where the encounter would start and where the aircraft needed to be at the Commence Exercise (COMEX).
- **IP OWN DME:** Calculated distance in nmi from the CPA to the IP for ownship.
- **IP INT:** The same procedure was used for intruder IP as for ownship.
- **IP INT Lat/Lon:** Calculated latitude and longitude of the initial point for intruder from the CPA in DD format.
- **IP INT DME:** Calculated distance in nmi from the CPA to the IP for intruder.
- **CPA INT:** Intruder CPA identification number. Similar to the ownship, the CPAs for the intruder were also grouped based on GPS coordinates. However, since the geometries for the intruders were built around those for the ownship, there were many more CPAs for intruders than for the ownship (due to various angles into, groundspeeds, etc.).
- **CPA INT Lat/Lon:** Calculated latitude and longitude of the intruder CPA in DD. The CPA for the intruder was either the same as the ownship (>500 ft vertical separation) or calculated to be 1,822 ft away (<500 ft vertical separation) from ownship CPA using the relative angle into.
- **MP INT:** ID number for the intruder Maneuver Point. For some encounters, an MP was required in the middle of the encounter for the ownship or intruder to create a "blunder" type scenario. Maneuver points once again held the same ID if they had the same GPS coordinates.
- **MP INT Lat/Lon:** Calculated latitude and longitude in DD that the intruder was expected to begin their standard rate turn to the CPA.
- **On Condition Tolerance:** Each encounter required that the aircraft be on condition in terms of speed & location a certain number of seconds from CPA. This was to ensure that the algorithm would have enough time to pick up the aircraft in the encounter for their required conditions (speeds, altitudes, vertical speed, etc.). If this criteria was not met, the encounter may have to be repeated. This value was determined from simulation by the researchers or from previous experience.
- **TigerShark Lost Link:** In the case that TigerShark would lose link, a Lost Link mission plan was programmed into the Piccolo Autopilot. This ID number determined which plan would be used.

Table 10. Summarized FT6 System Checkout Matrix.

Scenario Number	Area	Priority (1-high, 2-medium, 3-	Name	Leg Time (min)	Angle Into Int 1	Vertical Offset Int 1 (ft)	Lateral Offset INT1 (ft)	GS OWN	GS INT1	Ownship Initial Altitude	Ownship Vertical Velocity	Ownship Final Altitude	Ownship Abort Alt	Ownship Abort Hdng	Intruder 1 Initial Altitude	Intruder 1 Vertical Velocity	Intruder 1 Final Altitude	Intruder 1 Abort Alt
001	UAS Work Area	1	001-U-S5N	2.0	0	500	0	60	100	5500	0	5500	5500	V TO NEXT W	5000	0	5000	4500
002	UAS Work Area	1	002-U-S5N	2.0	45	500	0	60	100	5500	0	5500	5500	V TO NEXT W	5000	0	5000	4500
003	UAS Work Area	1	003-U-S5N	2.0	90	500	0	60	100	5500	0	5500	5500	V TO NEXT W	5000	0	5000	4500
004	UAS Work Area	1	004-U-S5N	2.0	180	500	0	60	100	5500	0	5500	5500	V TO NEXT W	5000	0	5000	4500
005	UAS Work Area	1	005-U-S2V	2.0	0	200	2430	60	100	5200	0	5200	5200	V TO NEXT W	5000	0	5000	4200
006	UAS Work Area	1	006-U-S2V	2.0	45	200	2430	60	100	5200	0	5200	5200	V TO NEXT W	5000	0	5000	4200
007	UAS Work Area	1	007-U-S2V	2.0	90	200	2430	60	100	5200	0	5200	5200	V TO NEXT W	5000	0	5000	4200
008	UAS Work Area	1	008-U-S2V	2.0	180	200	2430	60	100	5200	0	5200	5200	V TO NEXT W	5000	0	5000	4200

In addition to the flight matrix above that was used for initial calculations, the information above was then put into an excel spreadsheet to be imported into MATLAB®. This excel sheet is shown below in Table 11. This MATLAB® flight card generator tool was able to read this matrix and compile every flight card automatically.

Table 11. MATLAB® Excel Flight Test Matrix.

card_name	extended_r	aircraft	aircraft_desi	prior	card_num	aircraft_nu	waypoint_se	add_floor_(	altitu	visua	formatio	vv	speed	limit	tolerance	instructions
SCO-01	1.a.1	Tiger50	OWNSHIP	1	1	1	IP1, CPA1		8000	1		0	60	NO DESCENT	±8 sec	Once Intruder calls "Visual," PUT toggle smoke off
SCO-01	1.a.1	NASA 856	INTRUDER 1	1	1	2	IP2, CPA2		7500	1		0	100		±8 sec	Obtain Visual Identification at greater than 0.4
SCO-02	1.e.40.1	Tiger50	OWNSHIP	1	2	1	IP1, CPA1		8000	1		0	60	NO DESCENT	±8 sec	Once Intruder calls "Visual," PUT toggle smoke off
SCO-02	1.e.40.1	NASA 856	INTRUDER 1	1	2	2	IP3, CPA3		7500	1		0	100		±8 sec	Obtain Visual Identification at greater than 0.4
SCO-03	1.f.90.1	Tiger50	OWNSHIP	1	3	1	IP1, CPA1		8000	1		0	60	NO DESCENT	±8 sec	Once Intruder calls "Visual," PUT toggle smoke off
SCO-03	1.f.90.1	NASA 856	INTRUDER 1	1	3	2	IP4, CPA4		7500	1		0	100		±8 sec	Obtain Visual Identification at greater than 0.4
SCO-04	1.g.120.1	Tiger50	OWNSHIP	1	4	1	IP1, CPA1		8000	1		0	60	NO DESCENT	±8 sec	Once Intruder calls "Visual," PUT toggle smoke off
SCO-04	1.g.120.1	NASA 856	INTRUDER 1	1	4	2	IP5, CPA5		7500	1		0	100		±8 sec	Obtain Visual Identification at greater than 0.4
SCO-05	1.a.1	Tiger50	OWNSHIP	1	5	1	IP1, CPA1		8000	1		0	60	NO DESCENT	±8 sec	Once Intruder calls "Visual," PUT toggle smoke off
SCO-05	1.a.1	NASA 856	INTRUDER 1	1	5	2	IP2, CPA2		8500	1		0	100		±8 sec	Obtain Visual Identification at greater than 0.4
SCO-06	1.e.40.1	Tiger50	OWNSHIP	1	6	1	IP1, CPA1		8000	1		0	60	NO DESCENT	±8 sec	Once Intruder calls "Visual," PUT toggle smoke off
SCO-06	1.e.40.1	NASA 856	INTRUDER 1	1	6	2	IP3, CPA3		8500	1		0	100		±8 sec	Obtain Visual Identification at greater than 0.4
SCO-07	1.f.90.1	Tiger50	OWNSHIP	1	7	1	IP1, CPA1		8000	1		0	60	NO DESCENT	±8 sec	Once Intruder calls "Visual," PUT toggle smoke off
SCO-07	1.f.90.1	NASA 856	INTRUDER 1	1	7	2	IP4, CPA4		8500	1		0	100		±8 sec	Obtain Visual Identification at greater than 0.4
SCO-08	1.g.120.1	Tiger50	OWNSHIP	1	8	1	IP1, CPA1		8000	1		0	60	NO DESCENT	±8 sec	Once Intruder calls "Visual," PUT toggle smoke off
SCO-08	1.g.120.1	NASA 856	INTRUDER 1	1	8	2	IP5,CPA5		8500	1		0	100		±8 sec	Obtain Visual Identification at greater than 0.4

The use of this flight card generator was a great improvement from previous tools and processes used in previous flight test campaigns to develop flight cards. There was close to a 100% reduction in time required to generate a flight card in FT6 as compared what was needed to generate a similar card in FT3. The MATLAB® tool was able to generate a flight card in an average of 22.5 seconds for FT6 where as FT3 averaged 4 hours per flight card. The accuracy of this tool also greatly reduced the time it took to review each flight card for errors since in almost every case the cards were correct. There were only a few errors found within the matrix due to how the flight card looked when going through a review. More information on this flight cards can be found in the next Section.

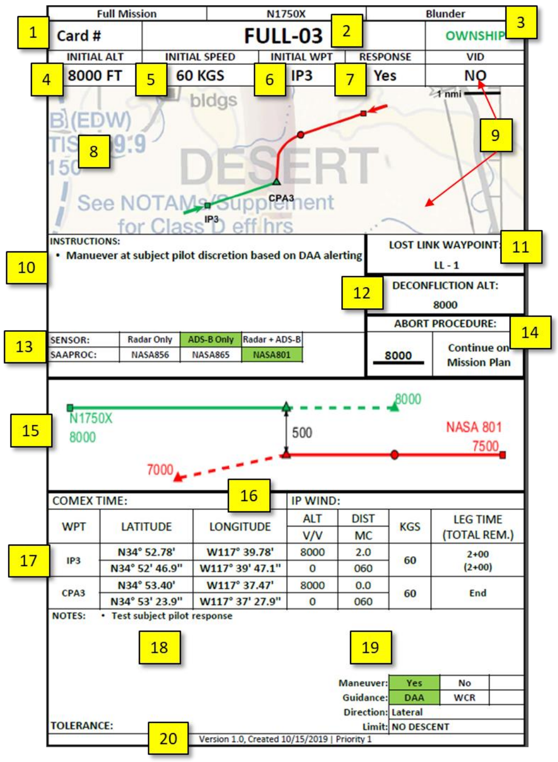
7.10. Flight Cards

The project leveraged the methodology used from a legacy of previous, successful flight test campaigns for the development of the cards for FT6. Flight cards developed were based on cards created during FT3, FT4, and ACAS Xu FT2, which in turn were based on cards generated for the ACAS Xu SS flight program by personnel from Massachusetts Institute of Technology (MIT) Lincoln Laboratory. Those campaigns used similar types of encounters during their missions.

Given the successful history for the use of these flight cards, a similar format was adopted for Flight Test 6. With the collaborative effort of FT6 TigerShark Operations, Armstrong IT&E Operations, and researcher input, the product was designed to provide a simple, easy-to-use, and easily modifiable card. The cards also presented a familiar format to that of an instrument approach plate which enabled the aircrew to quickly determine test parameters and critical flight information.

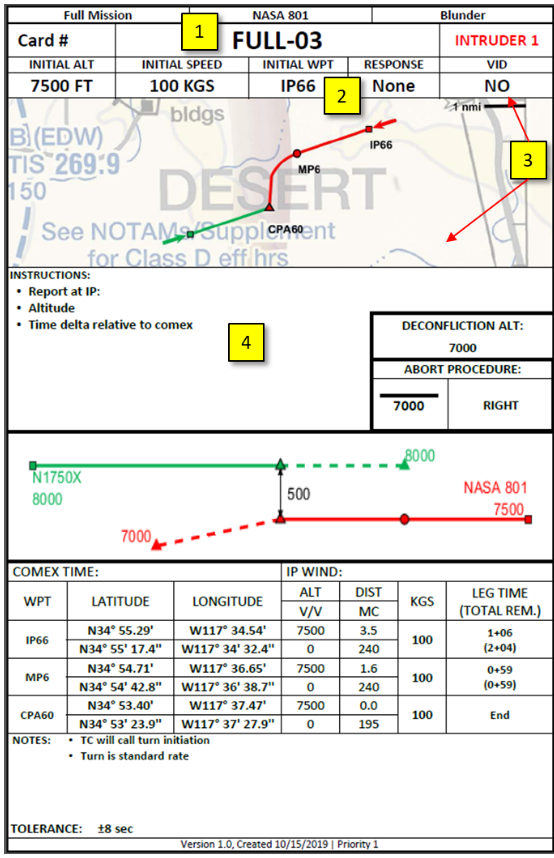
The cards were designed to fit on an 8.5" x 11" sheet of paper, with one half dedicated to ownship and the other to intruder. This allowed users to either cut the deck in half or fold their card to the one of interest.

There were 10 flight cards for the FT6 SCO, 83 flight cards for Radar Characterization, 68 Scripted Encounters flight cards, and 6 Full Mission flight cards. Each flight phase has unique properties and characteristics from each encounter and also a few administrative cards. Pictured below in figure 57 is an example ownship flight card that was used. Figure 58 shows an intruder flight card for the same encounter. Each flight card had its own slide and the cards were later converted into PDF, packaged into a document for that particular flight day, and distributed in soft- and hard-copy form to all FT6 participants.



Item	Description
1	**Card Number**. Filled in by hand for each day of flight based on that day's sequencing.
2	**Card Name**. Letters before hyphen are card category. Category-number pairs are unique.
3-6	**Aircraft Name and Designation, Initial Altitude, Initial Speed, Initial Waypoint**
7	**Response**. If response to alerts desired, special instructions provided. Options include none for no response or Yes indicating that a maneuver is desiderd.
8	**Horizontal Plot**. Aircraft trajectories plotted to scale on Los Angeles VFR sectional chart.
9	**Visual ID Requirement**. VID is required when less than 500ft vertical separation. The VID box by the top arrow would highlight green and YES would written. The bottom arrow is where additional VID text will be displayed to the pilots to This text will only be present when the vertical separation was less than 500ft Separation. (see mission rules)
10	**Instructions**. Includes DAA response instructions and any additional instructions. For TigerShark, also would include toggling smoke for intruder aid in acquiring VID when required.
11	**Lost Link**. For TigerShark only. Numerical code representing instructions for aircraft if link to ground is lost.
12	**Deconfliction Altitude**. Almost always equal to abort altitude (contact NASA for clarification)
13	**DAA System Configuration**. Menu designed to resemble ground-based system interface to be used during testing. **SENSOR**: sensors used by DAA Researchers to generate alerts. Any combination involving at least one sensor can be selected**. SAAPROC**: The Payload Operator would be able to change which intruder call sign to be used by the DAA system.
14	**Abort Procedure**. Left side: altitude to fly to during abort procedure. Bar below represents "at or above," bar above represents "at or below," double bar represents "maintain." Right side: lateral instructions during abort procedure.
15	**Vertical Plot**. Waypoint altitudes and abort procedure (dashed lines). Not to scale.
16	**COMEX TIME and IP WIND**. Test personnel should notate commencement time of test card (COMEX) and wind speed and direction when aircraft is at initial point (IP).
17	**Waypoint Table**. Summary of waypoints. WPT = waypoint; ALT = altitude; V/V = vertical velocity; DIST = total remaining distance; MC = magnetic course; KGS = knots ground speed. Test card design accommodates up to four printed waypoints (additional waypoints of type "guidance" used internally by MATLAB code but not printed are permissible)
18	**Notes**. Other useful information. Includes items such as lateral separation to intruder(s), requirements on Pilot response, airspace considerations for intruder pilot, etc.
19	**Encounter Specifics.** This section of the flight card depicts certain characteristics of the encounter and what guidance/limitations for the encounter. **Maneuver:** PUT will maneuver the TigerShark based on the guidance received. **Guidance:** PUT will use specific guidance for the menuever. **Direction:** Provides an expected direction for the maneuver. **Limit:** Provides specific limitations of the encounter i.e. "NO DESCENT"
20	**Footer Information.** Includes flight test name, test card version, and creation date.

Figure 57. FT6 Ownship Test Card Setup.



Item	Description
1	**Card Name**. Same name as TigerShark ownship card.
2	**Response.** Intruder pilots will gain additional situational awareness on if the ownship will be maneuvering against the specific encounter.
3	**Visual ID Requirement**. VID is required when less than 500ft vertical separation. The VID box by the top arrow would highlight green and YES would written. The bottom arrow is where additional VID text will be displayed to the pilots to This text will only be present when the vertical separation was less than 500ft Separation. (see mission rules)
4	Items present on Ownship card but not appropriate for manned intruders (ground configuration, lost link) are not present.

Figure 58. FT6 Intruder Test Card Setup.

Flight cards were built using an automated MATLAB® generator that was directly linked to the Excel flight test matrix. This automated tool had the capability of generating all of the information on the card by using look-up tables to populate a blank PowerPoint template. It also had the ability to generate both top and horizontal graphics using a sectional and line plots automatically. Top view graphics, horizontal view graphics, IP/CPA names and coordinates, altitudes, headings, distances, ground speeds, sensor selection, abort procedures etc. were all entered automatically. No manual input was required for FT6 flight cards unlike previous campaigns where there was some manual effort in populating a flight card.

7.10.1. Altimeter Calibration Flight Card

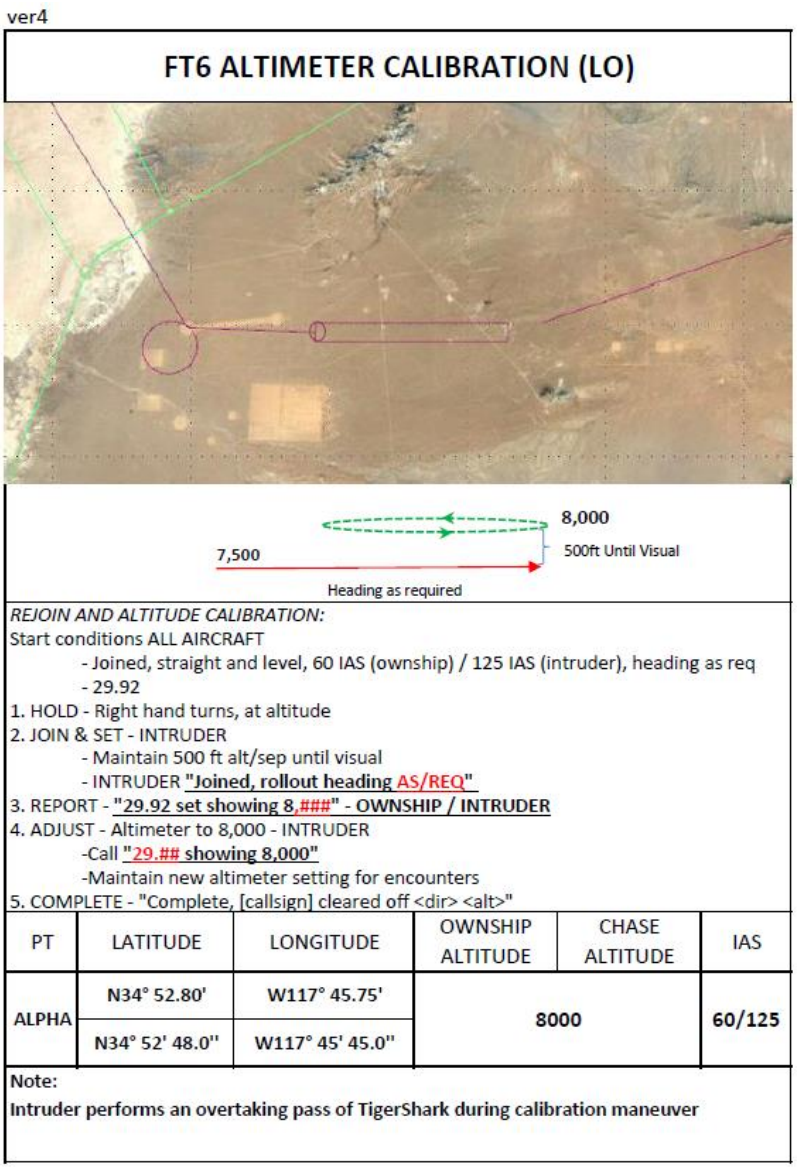
The altimeter calibration was designed to remove standard errors found within the pitot-static systems in order to ensure the planned vertical separation was as close to planned as possible. If completed successfully, both aircraft will report the same altitude. According to Federal Aviation Regulation (FAR) 91.411 (ref. 13) and Appendix E of Part 43 (ref. 41), aircraft pitot-static systems must be within 75 ft of field elevation when dialed into the local altimeter setting. Additional errors come with changes in altitude and airspeed. Since some of the planned encounters were with a 200 ft vertical separation, it was possible to be much closer with the errors identified above if they were not mitigated with the calibration.

The calibration was conducted at a flight condition that closely approximated all the planned encounters. In order to accomplish the calibration, TigerShark acted as the lead aircraft with intruder aircraft joining on the TigerShark wing in overtaking close formation. The TigerShark platform set standard 29.92 inHg and the intruder aircraft adjusted its altimeter setting to indicate the same altitude readout. At those conditions the intruder aircraft pilot observed and called out the difference from TigerShark.

An altimeter calibration was required for all encounters where the vertical separation between intruders and ownship was less than 500 ft (MRFT6-02). This and all other FT6 Mission Rules can be found in section 7.13.1.

Early versions of the altimeter calibration card were tailored to the specific intruder aircraft used for a given flight. Following feedback from test pilots supporting the flight test, a single card was used that captured both low and high speed encounters using a single indicated airspeed (125 IAS). This airspeed provided a reasonable compromise between the low speed test points (100 KGS) and high speed test points (170 KGS).

If required, the altimeter calibration was performed prior to starting encounters using the flight card shown in figure 59.


ver4

FT6 ALTIMETER CALIBRATION (LO)

8,000

500ft Until Visual

7,500

Heading as required

REJOIN AND ALTITUDE CALIBRATION:

Start conditions ALL AIRCRAFT

- Joined, straight and level, 60 IAS (ownship) / 125 IAS (intruder), heading as req
- 29.92

1. HOLD - Right hand turns, at altitude
2. JOIN & SET - INTRUDER
   - Maintain 500 ft alt/sep until visual
   - INTRUDER **"Joined, rollout heading AS/REQ"**
3. REPORT - **"29.92 set showing 8,###" - OWNSHIP / INTRUDER**
4. ADJUST - Altimeter to 8,000 - INTRUDER
   -Call **"29.## showing 8,000"**
   -Maintain new altimeter setting for encounters
5. COMPLETE - "Complete, [callsign] cleared off <dir> <alt>"

PT	LATITUDE	LONGITUDE	OWNSHIP ALTITUDE	CHASE ALTITUDE	IAS
ALPHA	**N34° 52.80'**	**W117° 45.75'**	**8000**		**60/125**
	N34° 52' 48.0"	**W117° 45' 45.0"**			

Note:

Intruder performs an overtaking pass of TigerShark during calibration maneuver

Figure 59. Version 4 Altimeter Calibration Card.

7.11. Roles and Responsibilities

To make sure every team member understood their specific role, the team developed a thorough Roles and Responsibilities plan. This was also iterated on throughout the OWG process. The FT6 roles and responsibilities were divided according to the phase of the flight test and by crew positions on the team. Table 12 below shows an outline of the FT6 overall roles and responsibilities at AFRC, described by station, position, displays, and description. Additional information for Scripted Encounters roles and responsibilities can be seen in figure 60. A more detailed explanation of the Full Mission Roles and Responsibilities can be found in figure 61.

Table 12. AFRC Roles and Responsibilities by Station, Position, Displays, and Description.

STN	Position	Displays	Roles & Responsibilities
MCC3	**Test Conductor**	Zeus, VSCS, PCC repeater, LRO	Overall responsibility for execution of flight test, makes final go/no go decisions during test operations (except during emergencies where decision making resides with each aircraft PIC), runs test cards, communicates with air assets + ATC on mission freq.
	Test Coordinator	Laptop data logger, Zeus, VSCS, PCC repeater, LRO, Internet (FlightRadar24, weather)	Records test activities, coordinates with terrestrial based team assets, liaison with FTD and SOR.
MOF5	**Flight Test Director**	Zeus	Flight safety monitor, inter-GCS coordinator, makes go/no-go recommendations to TC, interfaces with RGCS researchers + ARC
	Safety GCO	PCC, Zeus, VSCS	Monitors H&S of UA (via PCC) during test, flight safety PIC during test phase (protects UA from airspace boundary violations), updates UA flight plan during enroute portion (transition+test area) of flight.
	Pilot Under Test	PCC, Zeus, VSCS	Acts as UA PIC during test execution, executes ownship test cards, communicates with TC+ATC on mission freq. NASA Mission Commander.
	Payload	Sensor data health & status	Monitors H&S of onboard DAA payload.
	Senior Ops Representative	Zeus, VSCS	Assigned by Director of Flight Operations to monitor flight test.
	Subject Pilot Under Test	VSCS	RGCS pilot, controls UA via VSCS interface, communicates with Virtual ATC.
	Researchers	VSCS, engineering displays	Responsible for meeting test objectives, makes recommendations to TC (via FTD), interfaces with the RGCS Pilot.
MOC+Lakebed	**MOC Commander**	PCC, Video, HUD, Zeus	Mission lead for the MOC crew, pre-mission support, backup UA pilot
	Air Vehicle Pilot	PCC, Video, HUD, Zeus	UA pilot (PIC) for launch, recovery & emergencies, Piccolo system expert.
	UAS Technician	N/A	UA crew chief, observer, liaison between lakebed crew and MOC.
	Observer	N/A	Visual observer, liaison between lakebed ops and FTD.
LVC	**LVC**	LVC engineering, RGCS, Zeus	LVC gateway coordinator, AFRC system monitor, DAA and HSI SME, VIP location.

7.11.1. Scripted Encounters

The graphic below in figure 60 shows each of the responsible test positions required for Scripted Encounters including the launch and recovery crew. Note that the RGCS Pilot and Researchers are greyed out due to not being required for Scripted Encounters.

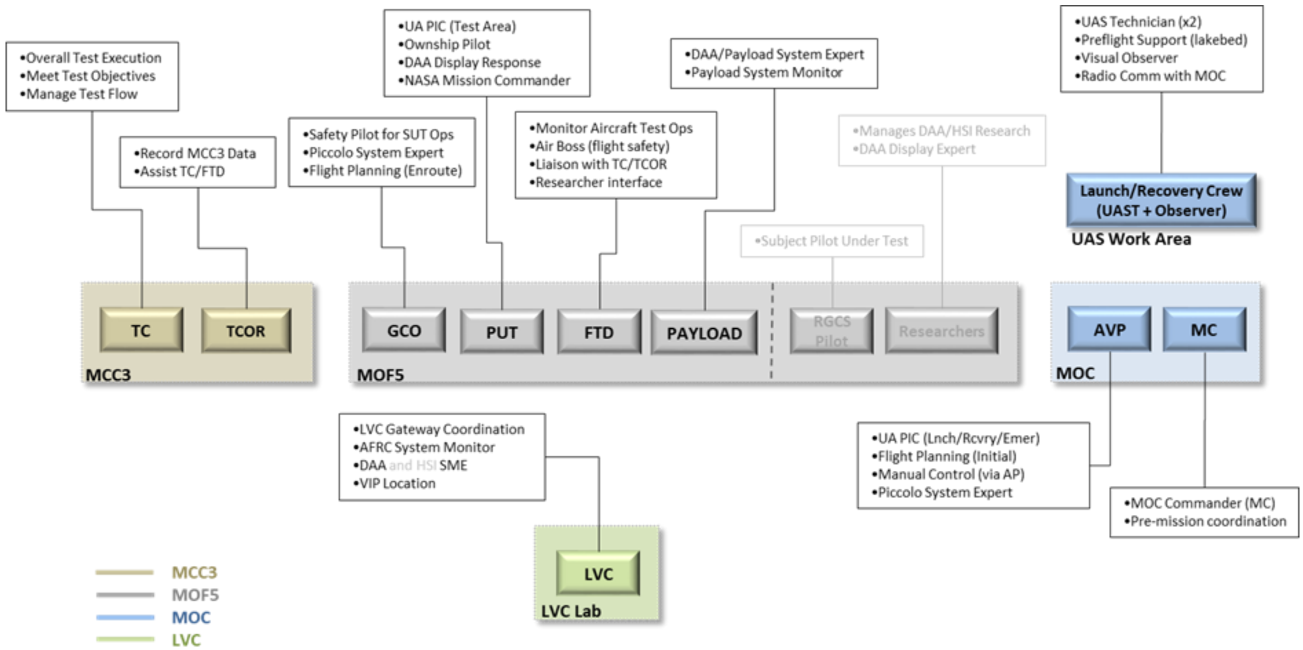


Figure 60. Flight Test Roles & Responsibilities, Scripted Encounters.

7.11.2. Full Mission

Figure 61 shows the required positions along with a short bulleted description for Full Mission flights. The purple block shows the NASA Ames DAA, HSI, and IT&E team members who were added for mission support required for the simulated part of the experiment.

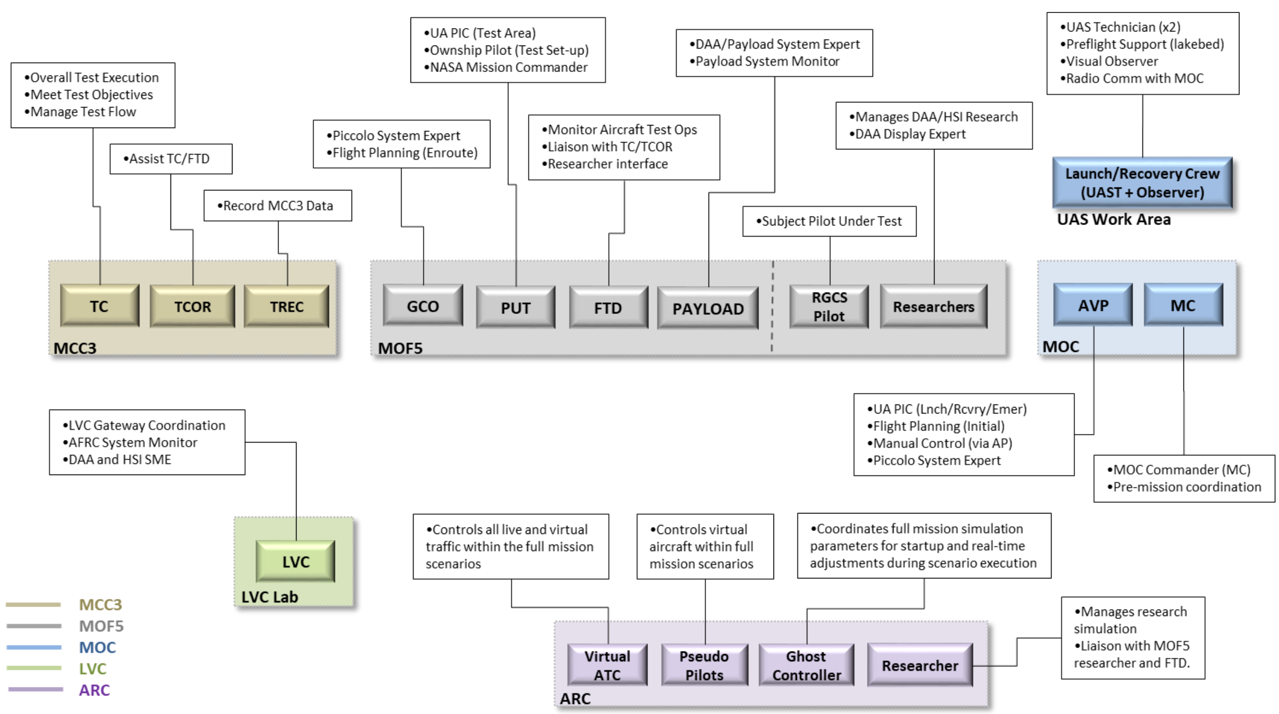


Figure 61. Flight Test Roles & Responsibilities, Full Mission.

Full Mission is where the Subject Pilot Under Test and the researchers were now required in the back side of MOF5 to achieve the other objectives for FT6. The NASA Ames Personnel positions and roles and responsibilities are elaborated in table 13.

Table 13. ARC Roles and Responsibilities, Full Mission.

STN	Position	Roles & Responsibilities
ARC DSRL	**Controller**	• Controls all live and virtual traffic within the Full Mission scenarios.
	Pseudo-pilots	• Controls virtual aircraft within Full Mission scenarios. • Interacts with the en route Controller. • Responds to request of the Ghost Controller
	Ghost Controller	• Coordinates Full Mission simulation parameters for startup and real-time adjustments during scenario execution. • Oversees the test environment and monitors the health of the ARC system. • Acts as the focal point for trouble shooting at ARC. • Acts as other ATC facilities and ZOA sectors including ZOA 40/41.
	Ghost Pilot	• Provides technical support for the test environment. • Provides assistance to the Pseudo-pilots.
	Researchers	• Manages research simulation. • Liaison between MOF5 researcher and FTD.

7.12. Qualifications and Training

The UAS-NAS project assignments, qualifications and training for the various staff positions in support of FT6 were developed with reference to NASA Procedural Requirements, *Aircraft Operations Management*, NPR 7900.3D (ref. 1) and center documents addressing these requirements. NASA AFRC staff complied with local operational procedures, plans and guidance documents, as required.

Aircrew staffing requirements for TigerShark operations supported from MOF5 were sourced from the Armstrong pilot office and the Model Lab. NASA pilots with prior UAS experience were assigned to the project and supported as the PUT and subject pilot under test during SCO flights leading up to Full Mission. The PUT was also the UAS PIC for the test portion of each mission. The PUT position required the pilots to qualify as an AFRC GCO in accordance with the AFRC sUAS GCO training plan. The Safety GCO position was staffed by personnel assigned to the AFRC Model Lab or those with an AFRC sUAS GCO qualification. The PUT and Safety GCO gained experience of operating the TigerShark through the Piccolo Training discussed in section 7.12.4. Intruder pilots were sourced from the Armstrong pilot office.

Pilots who staffed the MOC and were assigned to operate TigerShark during launch and recovery and at other times were qualified in accordance with NASC pilot qualification requirements. The NASA UAS-NAS project pilot reviewed NASC training reports and provided a summary to the AFRC Chief Pilot who approved those individuals to support FT6. In addition to staffing the MOC, NASC pilots were qualified to staff MOF5 as Safety GCO; however, the project did not exercise this option during FT6. The specific training exercises the team developed and implemented are described in the sections below.

7.12.1. Tabletop Training Event

The FT6 tabletop training was based off of training plans used in previous UAS-NAS flight test campaigns. All pertinent test team members were required to participate in this training before flights began which allowed all the team members to be on the same page before executing the mission. Given the experience of the test team along with the experience of NASC, the tabletop was conducted as a full refresher of flying a Group 3 UAS and conducting encounters within R-2515. This training agenda covered the following:

Admin / Overview

- Introductions (Roll Call)
- Training Plan
- FT6 CONOPS
- Required Aircraft
- Flight Schedule
- Ops Planning

Test Admin / Mission Specifics

- Staffing
- Roles and Responsibilities
- Safety
- Mission Rules & Go/No-Go
- R-2508 & R-2515 Airspace Brief
- Communication Plan
- Motherhood / Contingencies / Aborts / Lost Link / VID
- Timeline (Test Day / Test Encounter)
- Test Day Specifics
- Altimeter Calibration
- Project Pilot Comments
- Crew Resource Management
- Objectives / Success Criteria
- Brief / Debrief Plan
- Weather

Test Execution

- Test Card / Geometries Review
- DAA System Interface briefing

7.12.2. Mission Rehearsals

Given the complex architecture of FT6, the project decided to perform multiple mission rehearsals to ensure that each crew member was refreshed and ready to perform his/her responsibility. The first mission rehearsal was done by completing a simulated script the team developed and was completed the day after the tabletop training event. All control rooms and GCS's were powered on and staffed without any aircraft airborne. This rehearsal proved very worthwhile to the entire test team as it allowed the crew members to practice voice communications, DAA alerting and guidance display refresher, overall situational awareness, task saturation awareness, and contingencies for the future FT6 missions.

The second and third Mission Rehearsals were actual flights performed prior to the Full Mission flight phase. This again proved to be very valuable as many lessons learned were generated and carried through when Full Mission data collection started. These two rehearsals allowed the team to practice several contingencies that were also executed during actual Full Mission flights. The most important contingency was transitioning between the primary and alternate flight routes. This contingency identified task saturation issues amongst multiple crew members and required all team members to understand the situation and come up with the best solution. There were times where an encounter had to be changed due when ATC (SPORT) required TigerShark to vacate airspace due to a higher priority mission. This, in turn, required Virtual ATC to clear the subject pilot to an alternate route. The greatest lesson learned the team gathered from these rehearsals was that working together and maintaining positive communication was key when executing complex flight test architectures.

Another positive outcome from all of the mission rehearsals was the ability to thoroughly iterate flight test procedures and start up sequences. The Full Mission start sequence went through multiple revisions throughout these rehearsals and proved worthwhile during actual flight operations. This allowed for a seamless Full Mission start where the subject pilot takes control of the aircraft and releases it onto the Full Mission route. This start sequence can be seen within a typical Full mission test sequence depicted below in figure 62.

Point ALPHA

1. FTE start FM simulation (in coordination with Ghost)
2. FTE informs TD that RGCS is ready
3. SPUT requests 'Full Control' on VSCS
4. TD, PUT, and GCO verify Full Control via VSCS2
5. TD informs TC net and Engineering net that SPUT has control
6. TD poll team for readiness for Full Mission start (Go call) on ENG net (First circuit only)
   - PUT, GCO, Researcher, Payload, TCOR, DSRL, LVC
7. TC calls "Go for Full Mission" on mission frequency (First circuit only)

Team Ready

8. Researcher instructs SPUT to contact ATC (Oakland Center) (First circuit only)
9. SPUT calls controller to request clearance for "Full Mission route" (First circuit only)
10. When cleared, SPUT sends Tiger50 to WPT1

Between encounters

11. Researcher informs TD if encounter was successful (Good encounter/Bad encounter)
12. SPUT continues flying route or navigates to ALPHA or BRAVO as cleared by controller if more time is needed
13. Researcher informs TD when debrief is complete and ready for next encounter
14. Repeat steps 11-13 for second encounter

Circuit Complete (two successful encounters)

15. SPUT continues flying route or navigates to ALPHA or BRAVO as cleared by controller if more time is needed
16. Researcher informs TD when debrief is complete and ready for next circuit
17. Repeat start sequence from step 11

Complete

18. Researcher will inform TD via Eng net that data collection is complete and RGCS is in monitor only
19. TD will inform TC net and Eng net that test is complete and RGCS no longer has control
20. TC will inform MSN that test complete, RTB at own discretion.

Figure 62. Full Mission Sequence Procedure.

7.12.3. Detect and Avoid Display Training

Pilots Under Test for FT6 were given a briefing and a presentation on the VSCS display and interface. This included basic features of the display and where to find basic information such as heading, airspeed, and altitude and navigation mode. The PUT's were briefed on how to enter heading, altitude, airspeed, and autopilot modes into the VSCS through the steering window feature and how to command headings using the heading bug. An overview of the DAA alerting and guidance was also provided as needed in person before flights.

7.12.4. Piccolo II Autopilot & TigerShark Training

As one of the few organizations certified by the autopilot manufacturer to provide Piccolo II autopilot training, a NASC instructor conducted ground training with the FT6 Team over a four-day period at AFRC in April 2019. The training included hands-on, interactive instruction with the PCC software running in simulation mode on the team's laptops. Piccolo II firmware v2.2.4.d, targeted for FT6, was used during the training. The training covered PCC sim mode initialization and execution, the 15 autopilot modes and logic, navigation and mission planning details, TigerShark XP performance/gain tuning, and contingency operations including lost link. A test was administered at the end of the training to assess the student's understanding of the autopilot system and certify select personnel in preparation for their GCO qualifications required to support FT6. The NASC instructor also covered the development history of the present day TigerShark Block 3 XP variant to the radio controlled-only Mako unmanned aircraft of 2003. This information proved useful when the project approached AFRC's airworthiness and safety review board to declare the TigerShark B3 XP as a mature UAS.

7.12.5. AFRC Control Room Training

The UAS in the NAS project qualified test controllers using a unique training plan developed with reference to AFPL-7900.3-001 (ref. 3), Mission Control Qualification & Training Plan. The controller team positions that required certification included the Test Conductor and the Test Director (also referred to as Flight Test Director). For FT6, the two positions were physically split with the Test Conductor positioned in MCC3 (AFRC B4800/2527) and Test Director positioned in MOF5 (near AFRC B4833). The TC position was one-deep for most of the test campaign. The TD position was expanded from initially one to three qualified TDs. This provided the opportunity to qualify one of the three TDs as a backup TC.

With the TD positioned in MOF5 rather than MCC3, the TCOR position, as compared to earlier UAS-NAS campaigns, was repurposed to sit next to the TC and perform some of the duties that historically were accomplished by the TD. Duties included backing the TC with reference to the test cards, communicating on back channels for the TC, coordinating with the Test Recorder. The TD role expanded from being the overall flight safety monitor to being the liaison between the TC in MCC3, Researchers/Payload operator/ and PUT in MOF5, along with the NASC Pilot in the MOC. Communications management was a key requirement for the TD.

The Test Recorder (TREC) role was created to pick up some of the duties formerly performed by the TCOR. This position required mostly on the job training.

7.12.6. Pilot Under Test Training for Full Mission

In addition to the Piccolo II autopilot & TigerShark training, the PUT acquired additional training for Full Mission. During the Shakedown and Full Mission Rehearsal flights, the PUTs acted as the SPUTs. To act in this capacity, they were given hands-on training for the VSCS display prior to the flight test campaign. During this training, PUTs learned how to command heading and altitude as well as interact with various tools available within the software. PUTs were also able to familiarize themselves with the alerting logic that would be crucial during the Flight Test.

7.12.7. Subject Pilot Under Test Training

Requirements for qualifications and training subject pilots under test was first considered during an OWG in November 2018. At that time the team was exploring what the qualification requirements were for the selection process and which organization would lead the effort to identify and vet candidates. The project decided that NASA Ames HSI was the right organization to lead the activity. NASA Armstrong had specific requirements for UAS aircrew in AFOP-7900.3-006 (ref. 2) derived from NPR 7900.3 (ref. 1). The AFRC Chief Pilot was the final approval authority for permitting all subject pilots to operate the TigerShark from the RGCS during FT6. Since the SPUT was not deemed as a safety critical position, the AFRC Chief Pilot was able to assess and approve their qualifications before they received any specific training from the UAS-NAS team. Once the OWG resolved the SPUT qualification issue, they focused on training requirements.

The subject pilot training for the Full Mission configuration consisted of two main components: the Day Before Training and the Day of Training. The training format for both pieces alternated between a PowerPoint slide deck briefing and hands-on practice with a research ground control system. The actual ground control station used for the flight test was not available to the subject pilots outside of the flight hours. A duplicate (i.e., research) ground control station was created instead, however, which replicated the display functionality and the vehicle model of the system under test.

The Day Before Training was conducted during the afternoon prior to the flight day and lasted approximately four hours. The Day Before briefing material covered the Full Mission Daily Schedule and other flight test logistics. After covering that information, the Day Before Training provided a high-level overview of the UAS-NAS project before switching to specific information about the pilot's responsibilities during the test and the test vehicle's performance. Once this background information was completed, the Day Before Training consisted of three different training blocks, with each block finishing with a 30-minute hands-on practice session on the material covered in that section. These three training blocks were: Display Training covered the essential functions of the ground control station interfaces, such as how to maneuver the vehicle and respond to chat messages. DAA System Training covered the DAA alerting and guidance levels and expected pilot responses. Mission Training covered mission-specific elements of the flight test, such as how to coordinate with virtual ATC and the primary and backup mission routes. At the end of this four-hour session, the participants were sent home with a printout of the briefing packet so that they could review the information at their convenience that evening.

The Day of Training was conducted during the two hours immediately preceding the flight test. It started with a slide deck brief that reiterated the most important elements of each training block from the day prior. The Day of Training finished with a one-hour hands-on practice session. A researcher walked through the critical components of the test by referencing a training checklist. Once the subject pilot demonstrated proficiency with each training element, the training at the research ground control station was considered complete. At that point, the subject pilot and researcher walked over to the MOF and sat at the actual ground control station. While the vehicle and flight test components were going through the startup procedures, the researcher and subject pilot went over final preparation materials (such as a review of the various mission routes and ATC communication procedures) at the station. This final review continued until the flight test was ready to begin, at which point the researcher confirmed with the pilot that they were ready to begin the Full Mission flight and commence the test.

7.12.8. Virtual ATC Training

The Virtual ATC Training objectives focused on ensuring that the participants were knowledgeable about the UAS research being conducted during Full Mission. They ensured that each participant was familiar with operations written materials, laboratory layout, and equipment used at ARC to conduct the simulation. Each air traffic controller and pseudo-pilot was expected to know the ATC procedures used for the Full Mission including startup procedures, contingency plans, and holding patterns.

Two retired Air Traffic Controllers provided ATC services to both the ownship and the virtual traffic during FT6. These controllers retired from the ZOA domestic areas less than 5 years prior to their participation in Flight Test 6. Per research team requirements, both individuals had been qualified as Certified Professional Controllers (CPC) and held an area rating in their respective areas of responsibilities at ZOA.

Three Pseudo Pilots acted as the pilots of the virtual aircraft in the FT6 traffic scenario. These pilots had private pilot licenses with an instrument rating. One pilot held a commercial license and was recently retired from commercial service.

Virtual ATC Training stated above was conducted over five days. The first day provided eight hours of classroom instruction. The second and third days consisted of sixteen hours of laboratory training including four three-hour simulated practice runs. Days four and five were scheduled as rehearsals with the full system under test and the ownship and intruders in flight.

The classroom instruction provided participants with a series of briefings. The curriculum included the following:

- Safety Briefing - The Safety briefing informed the participants of the requirements and information in included in the FT6 Mishap Preparedness and Contingency Plan and the ARC N-243 Building Emergency Action Plan.

- Project overview - The Project Overview familiarized the participants of the project, research and experiment goals and design. The characteristics of the live aircraft were discussed and DAA and radar field of view (FOV) were explained.
- System layout - Participants learned how the laboratories and communications systems were configured. Support materials and their locations were reviewed.
- Participant responsibilities - The participants were informed of the roles and responsibilities of all of the players at AFRC and ARC. Emphasis was placed on how these positions interacted and how they were incorporated into the overall experiment.
- FT6 procedures - Participants received information on the airspace environment including arrival and departure routes, traffic flow, and VFR operations. The transformation process and operations area for ZOA Sector 40/41 was detailed. Flight test procedures were taught explaining how flight test operations interacted with ATC and other members of the test environment. The participants learned the simulation procedures and terminology specific to the flight test. A thorough explanation of nominal and contingency operations with the associated clearances and ATC procedures was provided. Pseudo-pilots were taught procedures for VFR interactions with ATC and flight operations near a TFR.

The curriculum included training questions to ensure that participants understood and retained the information being presented.

The virtual ATC participant's main focus during hands-on MACS training was to ensure that their skill level provided quality of service comparable to the NAS environment in and around ZOA-40/41. During these practice runs, the Pseudo- Pilots had the opportunity to familiarize themselves with the scripts that supported the FT6 scenario. The scripts provided tasks the Pseudo-pilots had to initiate or request at specific times during the simulation. These tasks included checking in departures, requesting VFR flight following, and changing the altitude and/or routes of various aircraft throughout the simulation. The Controllers applied and practiced the air traffic procedures in accordance with FAA JO 7110.65 (ref. 40), Air Traffic Control and procedures specific to the Full Mission flights. Controllers issued clearances to the ownship for the Full Mission and contingency routes, startup procedures, and holding. Controllers also observed the ownship C2 failure (Lost Link) procedure. All participants used these training runs to practice controller and pseudo-pilot relief briefings.

The Full Mission rehearsals provided all participants from ARC and AFRC the opportunity to practice operations with the live aircraft flying in the Full Mission environment. Virtual ATC controllers worked the MACS traffic around the ownship and intruder aircraft. This training exposed the participants to actual flight conditions and the expected length of typical flight operations. Participants were able to apply the training they received and the practice the skills they learned in the classroom, including the ability to respond to simulated problems.

7.13. Mission Rules and Go / No-Go Criteria

The NASA airworthiness and flight safety process mandates certain procedures to be in place for flight test operations. Mission rules and go /no-go criteria are paramount to safe test flights as they help bound certain mission decisions during operations, especially during critical phases of flight.

7.13.1. Mission Rules

The Mission Rules for Flight Test 6 can be found in table 14. Mission rules were critical to ensuring the safety of the mission and were adhered to during the execution of a mission. Some of these mission rules were based on previous flight tests and were updated for FT6. During the Mission Rules Working Group (a part of the OWG), Mission Rules would continuously be developed and re-evaluated depending on the phase of flight test that was being conducted at the time. New rules, e.g. MRFT6-12 through MRFT6-19, were created due to the complex operational architecture of FT6. Where multiple individuals were assigned to a specific Mission Rule, the responsibility was shared amongst those assigned.

Table 14. FT6 Mission Rules.

Rule #	FT-6 Mission Rule Description	Rationale / Hazard Report	Notes	Responsible Position
MRFT6-01	Test runs will be aborted if intruder aircraft do not have visual on all aircraft within 0.5 nmi (low/medium closure) or 0.8 nmi (high closure) and less than 500' vertical separation, except when aircraft are diverging. During altimeter calibration, the intruder aircraft has visual responsibility for both aircraft.	11 Second Minimum for VID (closure rate) FT6-02A mitigation 5 FT6-02B mitigation 4 FT6-02C mitigation 2	Consider: Airspeed, heading, altitude divergence, etc. Low/medium closure is defined as up to and including 170 KGS closure. High closure is defined as over 170 KGS closure. Smoke System aids in visual.	TC/Intruder PIC
MRFT6-02	Intruder aircraft will abort the test run if their situational awareness tools (including visual) indicate an unsafe condition caused by non-participating aircraft AND have SA on all participating aircraft.	Standard Practice FT6-02A mitigation 9 FT6-02B mitigation 7 FT6-02C mitigation 8	ADS-B display provides situational awareness for TG-14/T-34. B200 will use TCAS display.	Intruder PIC
MRFT6-03	If Comm Loss (C2 Link) occurs during an encounter, abort immediately.	Pre-flight check FT6-02A mitigation 14 FT6-02A mitigation 15 FT6-02C mitigation 4 FT6-02C mitigation 5 FT6-02C mitigation 6 FT6-02C mitigation 13	Comm Loss is defined as Comm Status indicator becoming red. This indicator shows Comm loss for 10 seconds.	PUT/Safety GCO/AVP
MRFT6-04	Flight operations outside of the approved TigerShark operational limitations are prohibited.	Standard Practice Defined in NASC procedures and TigerShark limits	Will be reviewed at T-1. Encompasses flight envelope and structural limitations.	PUT/Safety GCO/AVP
MRFT6-05	Abort the encounter for the following reasons: loss of situational awareness, task saturation, environmental conditions, encounter not setup as planned, emergency condition, or mission rule violation.	FT6-02A mitigation 15	Abort criteria will be briefed during T-1/T-0	TC
MRFT6-06	All participants will ensure their navigation quality error does not exceed 0.1 nmi prior to starting encounters.	FT6-02A mitigation 10 FT6-02B mitigation 8 FT6-02C mitigation 9	FOM for each aircraft Piccolo (PDOP) - Cross Track Intruders – Navigation System (to include potential GPS Jamming)	PUT/Safety GCO/ Intruder PIC/TC
MRFT6-07	Confirm each participant's time management tools match the time hack made during the T-0.	Standard practice	TC will initiate Time Hack	TC
MRFT6-08	During encounters when within 1 nmi, maintain at least 150ft vertical separation of other aircraft's planned altitude.	Standard Practice Mission Success FT6-02A mitigation 11 FT6-02B mitigation 9 FT6-02C mitigation 10	TC will provide range calls.	Intruder PIC/PUT/Safety GCO/ TC
MRFT6-09	Test runs will be conducted with the following environmental criteria: - 3 or greater statute miles visibility - Clear of clouds 1000' above and below the planned test block (including abort maneuvers) -No greater than Light turbulence -No flight through visible moisture	Standard Practice FT6-02A mitigation 13 AFRC UAS Mission Rules NASC SOP	Reported and/or observed Light turbulence limitation Intruder PIC can provide PIREP Ownship remains VMC	FTD/Intruder PIC/AVP
MRFT6-10	Between test runs, until directed by the TC: -All participating aircraft shall establish and maintain deconfliction altitude from previous encounter -Each participant shall confirm the next encounter number prior to execution	Standard practice / Test Plan FT6-02A mitigation 3 FT6-02B mitigation 2		TC/Intruder PIC/PUT
MRFT6-11	All participating aircraft will conduct an altimeter calibration using TigerShark as the baseline prior to executing encounters with less than 500' planned vertical separation. Aircraft will maintain altitude and/or lateral separation until visual acquisition is confirmed.	FT6-02A mitigation 2	Per flight day	TC/IntruderPIC/ PUT

MRFT6-12	In the event of a TigerShark emergency, the AVP shall take command of TigerShark and isolate MOC via C2 cutoff switch.	NASC Emergency Procedure checklist	MOC AVP takes over C2 from MOF5. Voice Comms will still be functional	MOC/AVP
MRFT6-13	In the event of a contingency during the execution of Full Mission, the Pilot Under Test will isolate MOF5 from the RGCS via C2 cutoff switch. e.g. -Airspace restrictions, trouble shooting payload, ATC priority, Intruder reported anomaly.	Full Mission Contingency FT6-02A mitigation 12 FT6-02B mitigation 11 FT6-02C mitigation 12	Pilot Under Test (PUT) takes over C2 of the TigerShark. Subject Pilot will no longer have control.	FTD/TC/Safety GCO/PUT
MRFT6-14	If Zeus is inoperable in MCC3 and MOF5, encounters are limited to ≥500ft vertical separation.	Ground RADAR AND ADS-B data 12 second ground RADAR delay Min requirement is MCC3 Go/No-Go 3		TC
MRFT6-15	For test runs, the AVP will set the autopilot lost link timer to 30 seconds to ensure range boundary compliance in the event of lost link.		Piccolo Mission Limits will be verified before takeoff	AVP
MRFT6-16	UAS PIC is managed by positive exchange of aircraft control to AVP, Safety GCO, PUT, Subject Pilot.	FT6-02A mitigation 12 FT6-02B migitation 11 FT6-02C mitigation 12	PIC will verify control by requesting waypoints from TigerShark FTE will command heading change from VSCS	AVP, Safety GCO, PUT
MRFT6-17	Encounters are limited to ≥500ft vertical separation when the Intruder is staffed with only one crewmember. Simple encounters <500ft vertical separation are permitted with a chase qualified pilot.	FT6-02A mitigation 19	Intruder staffing	TC/Intruder PIC
MRFT6-18	At the discretion of the PIC, the most appropriate takeoff/landing plan (Lakebed runway 18 UAS or alternate landing site) will be used based on reported winds actively monitored by ground crew on the lakebed.	Go/No-Go 11	TMOC/MCC3/MOF5/Ground Crew will be polled for final go/no-go.	AVP, MC, Ground Crew, TC, TD, Safety GCO, PUT
MRFT6-19	Ground crew will be positioned well clear and prior to the intended touchdown point.	NASC Hazard – Close proximity to surface vehicles / structures NASC Hazard – Momentary loss of video during critical phases of flight (Takeoff and/or landing)		AVP, Ground Crew

As previously mentioned, mission rules were re-evaluated throughout the flight test phases. An example of this is MRFT6-13. When this rule was originally written, the Safety GCO would be the only pilot in MOF5 monitoring the subject pilot. After further review and discussions, it was determined that the Pilot Under Test was required for Full Mission flights hence the mission rule was updated to reflect this.

Two Mission Rules, MRFT6-18 and MRFT6-19, were also added later in the campaign due to consideration of high wind conditions, lakebed runway orientation, and TigerShark safety margins required for takeoff and landing.

7.13.2. Go / No-Go

In addition to the Mission Rules, prior to executing a mission, a set of “Go / No-Go” criteria were required to be met in order to begin the flight. Similar to the Mission Rules, the Go / No-Go criteria were built upon pedigree of past campaigns with new additions from number 6 through 11. The FT6 Go / No-Go Criterion are found in table 15.

Table 15. FT6 Go / No-Go Criteria.

	FT6 Go/No-Go Description	Rationale	Notes
1	Strobe/anti-collision lights – FUNCTIONAL	Mission Requirement	In accordance with MEL or applicable Flight Manual requirements
	Position/Nav lights – FUNCTIONAL	Mission Requirement	
	Transponder – FUNCTIONAL	Mission Requirement	
2	Two voice radios – FUNCTIONAL	Mission Requirement (Test and Airspace Requirements)	Required for ATC and Test Conductor coordination and comm with GCS
3	ZEUS display – FUNCTIONAL	Mission Requirement (Test Command & Control) FT6-02A mitigation 4 FT6-02B mitigation 3 FT6-02C mitigation 1	Encounters limited when Zeus is inoperable to 500 ft vertical separation and visual required
4	Situational awareness display – FUNCTIONAL	Mission Requirement FT6-02A mitigation 9 FT6-02B mitigation 7 FT6-02C mitigation 8	ADS-B receiver
5	Navigation system and time management tools – FUNCTIONAL	Mission Requirement FT6-02A mitigation 10 FT6-02B mitigation 8 FT6-02C mitigation 9	As equipped Stratus 2s required for intruder. Data provided post flight
6	Barometric Altimeter – FUNCTIONAL and Meets Maintenance Standards		*MX standard specific to TigerShark. Baro checks done in pre-flight
7	Smoke system – FUNCTIONAL	Mission Requirement	Required for VID augmentation
8	C2 cutoff switches – FUNCTIONAL	Mission Requirement	MRFT6-12, MRFT6-13
9	DAA System – FUNCTIONAL	Mission Requirement	Mission Success
10	MOC Generator – FUNCTIONAL	Mission Requirement	Required for backup MOC power.
11	Anemometer – FUNCTIONAL	Mission Requirement	MRFT6-18

7.14. Safety Analysis

AFRC IT&E Safety representatives led the development of the hazard and range safety analyses by following the processes described in AFOP-8715.3-005 (ref. 5) and AFOP-8715.3-007 (ref. 7). All participants of the FT6 supported and contributed to the flight safety development process as a collaborative team effort.

7.14.1. Hazard Analysis

All operations were conducted in accordance with NASA AFRC safety policies outlined in DPL-8621.1-001 *Center Mishap Preparedness and Contingency Plan* (ref. 4) and AFOP-8715.3-005 *Hazard Management Procedure* (ref. 5). A safety representative was present for all operations planning and was responsible for chairing the SSWG. All encounters and configurations were reviewed and concurred with the by the safety representative. At the UAS-NAS FT6 Phase 1 CDR, the hazard analysis presented was incomplete and confusing to the Independent Review Team. This resulted in the generation of Request for Action (RFA) # 17, *Failure Modes and Effects Analysis Not Adequately Documented.*

The project presented 44 hazards, some of which were legacy hazards carried over from previous flight test campaigns. However, they were not updated to reflect the current flight test series. Many of the presented hazards, were not individual hazards, but rather a list of various causes or effects, that when thoroughly examined by the SSWG, either contributed to, or were the result of 2 potential failure scenarios: a Loss of Both Vertical and Horizontal Separation Resulting in Midair Collision or a Loss of Both Vertical and Horizontal Separation Resulting in Near Midair Collision.

These consequences were then further analyzed and determined to occur either during Flight Test Encounters or between Flight Test Encounters, and as a result of either Human Error, DAA Fault, or UAS Fault. Information was incorporated and/or omitted as to only pertain to FT6. This process resulted in the identification of 4 hazards:

- Loss of Both Vertical and Horizontal Separation Resulting in Midair Collision (Human Error)
- Loss of Both Vertical and Horizontal Separation Resulting in Near Midair Collision (DAA Fault)
- Loss of Both Vertical and Horizontal Separation Resulting in Midair Collision (UAS Fault)
- Loss of Both Vertical and Horizontal Separation Between Encounters Resulting in Midair Collision.

The aforementioned hazard examination process resulted in the identification of 3 additional hazards:

- EMI/EMC with TigerShark Flight Critical Systems resulting in Loss of Aircraft Control
- Hardware Modification Damages/Interferes with Safety Critical Flight System Resulting in Loss of Aircraft
- Human Exposure to Payload Radiation.

The SSWG also played a key role in the refinement of the NASC TigerShark aircraft specific hazard analysis. Previously documented hazards were reviewed and revised as required to assure compliance with the Armstrong Flight Research Center (AFRC) hazard analysis process. In addition, gaps in the current analysis were identified, and 2 new hazards were generated:

- NASC Hazard - Direct Beam and Reflected Laser Energy Hazard to Ground Personnel
- NASC Hazard - Momentary Loss of Video during Critical Phase of Flight (Takeoff and/or Landing)

NASA required all Centers to implement a radio frequency safety program to prevent and control risks associated with exposure to electromagnetic fields from Radio Frequency (RF) sources in the frequency range between 3KHz to 300GHz. Based on this requirement, an evaluation of the potential health hazards associated with the electromagnetic fields produced by the Honeywell DAPA Lite Radar installed on the nose of the TigerShark aircraft was performed.

The AFRC Radiation Frequency Safety Officer (RFSO) provided the project with a comprehensive health hazard analysis of the DAPA Lite Radar within the Health Hazard Evaluation and Category Identification Report. Information from the report was then used to complete the required RF permit. The report and permit showed slight differences in the hazard distances that were more conservative based on the Category tier levels (CAT 1-4). The Federal Communications Commission (FCC) analysis showed a distance of 8.0 inches for workers, whereas, the calculation based on the Institute of Electrical and Electronics Engineers (IEEE), showed the limit for trained personnel (CAT 2) to be at 1.0 foot from the radar and an operational limit of 3 inches (CAT 3), where no one is permitted when the radar is operating.

To confirm the IEEE calculated hazard distance analysis, direct measurements were performed using a calibrated NARDA RF Survey Meter to assess power levels, and define safety parameters for workers at various locations. These measurements showed the calculated distances were more conservative, as expected, due to the protected nature in the IEEE standard.

In order to ensure personnel were cognizant of the hazard associated with potential DAPA Lite Radar exposure, a unique, project-specific hazard (Human Exposure to Payload Radiation) was generated. In addition, RF Safety training was provided to help understand the principal hazard control to prevent exposure.

TigerShark-specific RF (command and control) hazards were addressed as part of the analysis provided by NASC and were reviewed by the AFRC RFSO to assure that adequate controls were in place.

7.14.2. Range Safety Analysis

Range safety analysis for the NASC TigerShark UAS was based on an analysis conducted by the AFRC Range Safety Office for the AFRC µCub UAS during the FT5 timeframe. Since the route of flight and general CONOPS for µCub matched TigerShark CONOPS for FT6, leveraging the µCub UAS range safety analysis seemed reasonable. This analysis can be seen in table 16.

The µCub analysis assumed a vehicle probability of failure of 50% per hour and Pc/Ec numbers met AFRC acceptability criteria. Assumptions used to determine µCub Pc/Ec included the following criteria: vehicle reliability 50%, vehicle would come down in one piece, geo-fence will contain on-course debris within flight areas, debris was non-explosive, debris was non-toxic, population was non-sheltered, total Ec was based on on-course and fly-away risks, Ec included road population, Ec was for one hour of flight time in each flight area, and nominal flights conducted within R-2515. Since the reliability of TigerShark was calculated to be ~99.99% per hour, and Pc/Ec numbers scale with reliability, the calculations for µCub which met the range safety criteria for operations within R-2515 would be acceptable for TigerShark as well.

Table 16. FT6 Range Safety Analysis & Probabilities.

Risk Parameters	UAS Work Area	UAS Corridor	Mercury Spin Area	Four Corners Area
E_c	4.0×10^{-6}	3.6×10^{-6}	4.3×10^{-6}	4.5×10^{-6}
P_i	$<< 1 \times 10^{-3}$	$<< 1 \times 10^{-3}$	$<< 1 \times 10^{-3}$	$<< 1 \times 10^{-3}$
P_c	$<< 1 \times 10^{-6}$	$<< 1 \times 10^{-6}$	$<< 1 \times 10^{-6}$	$<< 1 \times 10^{-6}$

Range Safety Acceptable Risk Criteria *		
	AFRC	NPR 8715.5
E_c	$\leq 30 \times 10^{-6}$	$\leq 100 \times 10^{-6}$
P_i	$\leq 1 \times 10^{-3}$	$\leq 1 \times 10^{-3}$
P_c	$\leq 1 \times 10^{-6}$	$\leq 1 \times 10^{-6}$

* Values exceeding the acceptable limits need to go thru the Waiver Approval Process per NPR 8715.5, Range Flight Safety Program.

Based on the project CONOPS and calculated risk values, the Armstrong Range Safety Office supported TigerShark flights as proposed.

8. Test Approach and Execution

The test approach for FT6 was executed in a buildup progression evaluating the TigerShark XP's airworthiness through envelope expansion flight tests with the aircraft modified for FT6. The DAA payload was not functional during these flights and mass simulators or mockups were used to replicate FT6 equipment. With envelope expansion tests completed at NASC's flight test facility in Rome, NY, the aircraft and MOC were shipped to NASA AFRC to commence payload integration and systems tests comprised of ground tests, SCO, Scripted Encounters, and Full Mission.

8.1. Envelope Expansion

Envelope expansion testing was completed to ensure the changes made to the nose of the TigerShark UAS ownship was airworthy and would not impact the safety of conducting flight tests for FT6. It also verified the upgrade of the Piccolo autopilot software. These Envelope Expansion flights were conducted in Rome NY at the NY UAS Test Site.

Before integrating the new nose configuration to accept the DAPA radar panels on the TigerShark UAS, the NASC flight team integrated the DAPA Lite payload tray into the aircraft and conducted systems checks prior to flight testing. The NASC flight team completed a series of ground tests that included frequency attenuation, engine runs, and taxi checks before completing a Functional Check Flight (FCF) on the aircraft. The first flight consisted of basic acceptance checks with a software upgrade on the Piccolo autopilot (2.2.4.d). The flight team also conducted ATOL system tests. The FCF took place in the pattern and verified the 2.2.4.d. gain set at altitude completing turns, climbs, descents, and ATOL approaches.

After the successful FCF of 2.2.4.d, the new nose configuration was installed and a second FCF was conducted on the aircraft repeating the same flight profile. During ATOL checks, the aircraft completed an ATOL approach and transitioned through the landing autopilot modes as normal. When Piccolo transitioned to "touchdown", the throttle was pulled back to idle and the aircraft pitched to maintain a set descent rate. At this time, the indicated airspeed became very slow and resulted in a low-level stall. The resulting hard landing damaged the aircraft and forced NASC to use its second corporate TigerShark XP UAS asset.

All DAPA radar and payload brackets were rebuilt and integrated on XP-2 and the NASC flight team repeated the Envelope Expansion test plan. One major change to the ATOL testing was increasing the touchdown speed fraction in Piccolo which allowed the throttle to control the airspeed and prevented the aircraft from slowing down too much during landing. ATOL testing was completed with an eighty-five percent success rate. NASC and NASA determined that the ATOL system would not be used as a primary launch and recovery method, but rather as a worst case scenario backup if link was lost. Envelope Expansion flight tests were completed with a chase aircraft and validated aircraft performance and behavior between 7000 to 9000 MSL. The smoke system was also tested and verified at altitude and a smoke oil burn rate was established for the FT6 campaign.

8.2. Ground Tests

Ground testing was conducted at the systems level with a buildup approach that added each major FT6 system element culminating with combined systems tests and mission rehearsals. Standalone checks with the MOF5 and the TigerShark XP UAS were performed followed by incremental integrated testing with dataflow connectivity. The specific ground tests conducted were:

1) MOF5 core systems checks.
    a) Communication between test entities from MOF5.
    b) Zeus client in MOF5.
    c) Video distribution from MOF5 to AFRC LVC and MCC3.
    d) MOF5 UAS-NAS stations.
    e) Local connectivity from MOF5 to AFRC LVC system.
    f) LVC distributed connectivity with RGCS.
2) Ops check of core TigerShark XP UAS after AFRC systems integration.
3) Critical systems regression check to ensure payload integration has not degraded or unintentionally altered systems integral to safe operations of the TigerShark XP.
4) Connectivity test between ground control stations.
5) Functionality check of the DAA payload systems.
6) EMI/EMC compatibility test between the TigerShark UA and DAA payload systems.
7) System compatibility test between payload under test and aircraft systems.

8) End-to-end data flow test from aircraft sensors to the LVC-DE in the Scripted Encounters configuration.
9) End-to-end data flow test from aircraft sensors to the LVC-DE in the Full Mission configuration.
    a) Aircraft sensors to LVC-DE.
    b) Virtual and constructive traffic flow to RGCS.
    c) Command and Control (C2) and telemetry of TigerShark from RGCS station.
    d) Live targets from ground ADS-B displayed on the Virtual ATC screens at ARC.
12) End-to-end FT6 system operation during a 4-hours continuous shakedown test
13) Mission Rehearsals for Scripted Encounters and Full Mission.
    a) Dry-runs of Scripted Encounters and Full Mission from takeoff to landing.
    b) Operational checklists and procedures.
    c) Contingency plans for cybersecurity vulnerabilities and system failures.

Ground tests were scheduled by the NASA flight systems team or the NASC team to perform formal tests or ops checks of the UAS. Ground tests were also performed to support Honeywell troubleshooting of the DAPA Lite radar. A day prior to a ground test, the operations team would submit a form to the BITS to request range assets that would be required for the test. This included support for MOF5 operations and configuration/pre-flight of the voice communication system. The BITS process was also used for all flights. The BITS request would usually be approved within 24 hours. Coordination with the flight ops office was also required to receive approved frequencies for the ground operations. If radar power-ups were planned for the test, a center-wide email would be sent out with the location of the test site and keep-out zone.

Due to the hot weather at Edwards AFB during the summer months, staging of the aircraft in the test area started at 0700L. The TigerShark UA and GCS would be powered up and ready by 0730L. If a formal test was performed, a test objectives and safety briefing would be performed prior to start of test. After tests/checks were completed, the test team would release the range assets and frequencies. Regression tests were also performed to test fixes to discrepancies that were discovered during these ground tests. The level of regression testing depended highly on the system(s) being tested.

8.3. System Checkout

The SCO flights were designed, as described in the FT6 STP (ref. 16) to validate the aircraft and payload system requirements in a flight environment. This flight test phase commenced with a familiarization flight, in a buildup approach, to acclimate the NASC crew to EAFB operations with a group 3 UAS as well as evaluate basic TigerShark XP autopilot and C2 datalink performance. The flight was conducted entirely by the NASC pilots with the FT6 payload subsystems unpowered. Follow-on flights incrementally expanded testing to C2 handoffs between the NASC MOC pilots and the NASA MOF5 pilots, payload C2 and health and status checks, DAPA-Lite radar functionality, and dataflow evaluations between the aircraft to all ground systems. The SCO flights also offered the NASA Operations team the opportunity to perform operational check such as airspace coordination, refinement of lakebed launch and recovery procedures and C2 hand-off sequencing.

A sample flight card for SCO Flight Test #1 (SCO-1) is shown in figure 63.

SCO 1 - TigerShark XP Fam Flight		v20190705
AVP: GCO: PUT:	Date:	TO: LAND:

Objectives:
Demonstrate flight of TigerShark XP in EAFB test range.
Demonstrate positive datalink margins throughout test envelope.
Demonstrate autopilot performance meets UAS-NAS requirements.
Perform climb/descent and turning maneuvers.
Demonstrate timing technique for scripted encounters.

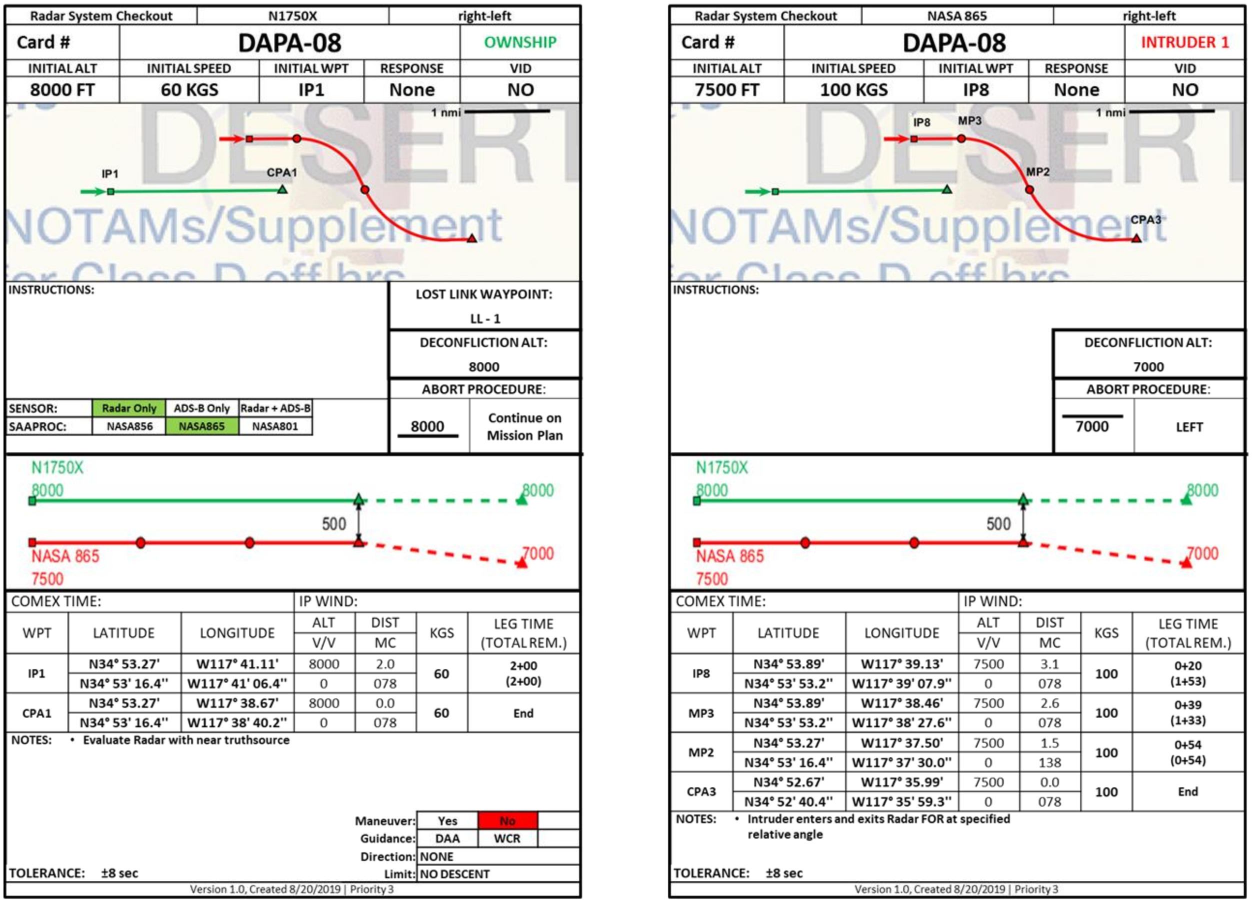
Check	Action
	DEPARTURE
	[AVP] Climb to 5000 ft MSL to Orbit Hold (D)
	[AVP] Check C2 datalink for positive margins
	[AVP->GCO/PUT] Perform handoff to GCO/PUT *SMOKE CHECK
	[GCO] Transition through UAS Corridor at approved altitude *IF JOSHUA, CLIMB 8000
	TEST AREA - MERCURY SPIN
	[GCO] Enter orbit hold in Mercury Spin
	[GCO] Climb to 8000 ft MSL
	[AVP] Check C2 datalink for positive margins
	~~[GCO->PUT] Perform handoff to PUT~~
	[PUT] Set IAS = ON; set IAS = 60 kts
	AUTOPILOT PERFORMANCE CHECKS - MERCURY SPIN
	[PUT] Send 50X to racetrack pattern
	[PUT] Check 50X on condition: 60kts; 8000 ft; leveled-off; tracking line
	Check 50X maintains altitude +/- 20 feet of commanded altitude
	Check 50X maintains IAS +/- 5 knots of commanded airspeed
	Check X-track error; verify 50X stays within +/- 0.1nmi [607 ft] of centerline
	CLIMB PERFORMANCE CHECKS - MERCURY SPIN
	[PUT] Stabilize 50X on upwind or downwind leg: 60kts; 8000 ft; leveled-off; tracking line
	[PUT] Climb to 8500 ft MSL and level-off
	[PUT] Descend to 8000 ft MSL and level-off
	[FTE] Record climb/descent rates

Figure 63. Sample Flight Test Card for SCO Flight.

8.4. Radar Characterization

Radar Characterization utilized intruder aircraft of varying RCS signatures – small, medium and large. A powered glider was considered a small RCS intruder, a single engine aircraft the size of a Beechcraft Bonanza was considered as medium RCS, and a multi-engine aircraft the size of a King Air B200 was considered large RCS. These definitions were based on RTCA DO-366 (ref. 10).

The initial plan was to characterize the radar after performing a basic radar functionality check during SCO. However, it was discovered during the first radar checkout flight (SCO-6) that the radar was not mature enough to proceed into Radar Characterization and that additional development was required. Therefore, additional SCO flight tests were required to checkout updates to radar firmware. Figure 64 and figure 65 depict DAPA Lite radar checkout flight cards for the ownship and intruder aircraft that were employed to collect radar data as an intruder swept past multiple radar panels.



Radar System Checkout	N1750X	right-left
Card #	DAPA-08	OWNSHIP

INITIAL ALT	INITIAL SPEED	INITIAL WPT	RESPONSE	VID
8000 FT	60 KGS	IP1	None	NO

INSTRUCTIONS:

LOST LINK WAYPOINT: LL - 1

DECONFLICTION ALT: 8000

ABORT PROCEDURE: 8000 | Continue on Mission Plan

SENSOR:	Radar Only	ADS-B Only	Radar + ADS-B
SAAPROC:	NASA856	NASA865	NASA801

COMEX TIME: | IP WIND:

WPT	LATITUDE	LONGITUDE	ALT / V/V	DIST / MC	KGS	LEG TIME (TOTAL REM.)
IP1	N34° 53.27'	W117° 41.11'	8000	2.0	60	2+00
	N34° 53' 16.4"	W117° 41' 06.4"	0	078		(2+00)
CPA1	N34° 53.27'	W117° 38.67'	8000	0.0	60	End
	N34° 53' 16.4"	W117° 38' 40.2"	0	078		

NOTES: • Evaluate Radar with near truthsource

Maneuver:	Yes	No
Guidance:	DAA	WCR
Direction:	NONE	
Limit:	NO DESCENT	

TOLERANCE: ±8 sec

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Radar System Checkout	NASA 865	right-left
Card #	DAPA-08	INTRUDER 1

INITIAL ALT	INITIAL SPEED	INITIAL WPT	RESPONSE	VID
7500 FT	100 KGS	IP8	None	NO

INSTRUCTIONS:

DECONFLICTION ALT: 7000

ABORT PROCEDURE: 7000 | LEFT

COMEX TIME: | IP WIND:

WPT	LATITUDE	LONGITUDE	ALT / V/V	DIST / MC	KGS	LEG TIME (TOTAL REM.)
IP8	N34° 53.89'	W117° 39.13'	7500	3.1	100	0+20
	N34° 53' 53.2"	W117° 39' 07.9"	0	078		(1+53)
MP3	N34° 53.89'	W117° 38.46'	7500	2.6	100	0+39
	N34° 53' 53.2"	W117° 38' 27.6"	0	078		(1+33)
MP2	N34° 53.27'	W117° 37.50'	7500	1.5	100	0+54
	N34° 53' 16.4"	W117° 37' 30.0"	0	138		(0+54)
CPA3	N34° 52.67'	W117° 35.99'	7500	0.0	100	End
	N34° 52' 40.4"	W117° 35' 59.3"	0	078		

NOTES: • Intruder enters and exits Radar FOR at specified relative angle

TOLERANCE: ±8 sec

Version 1.0, Created 8/20/2019 | Priority 3

Figure 64. DAPA-08 Radar System Checkout Flight Card.

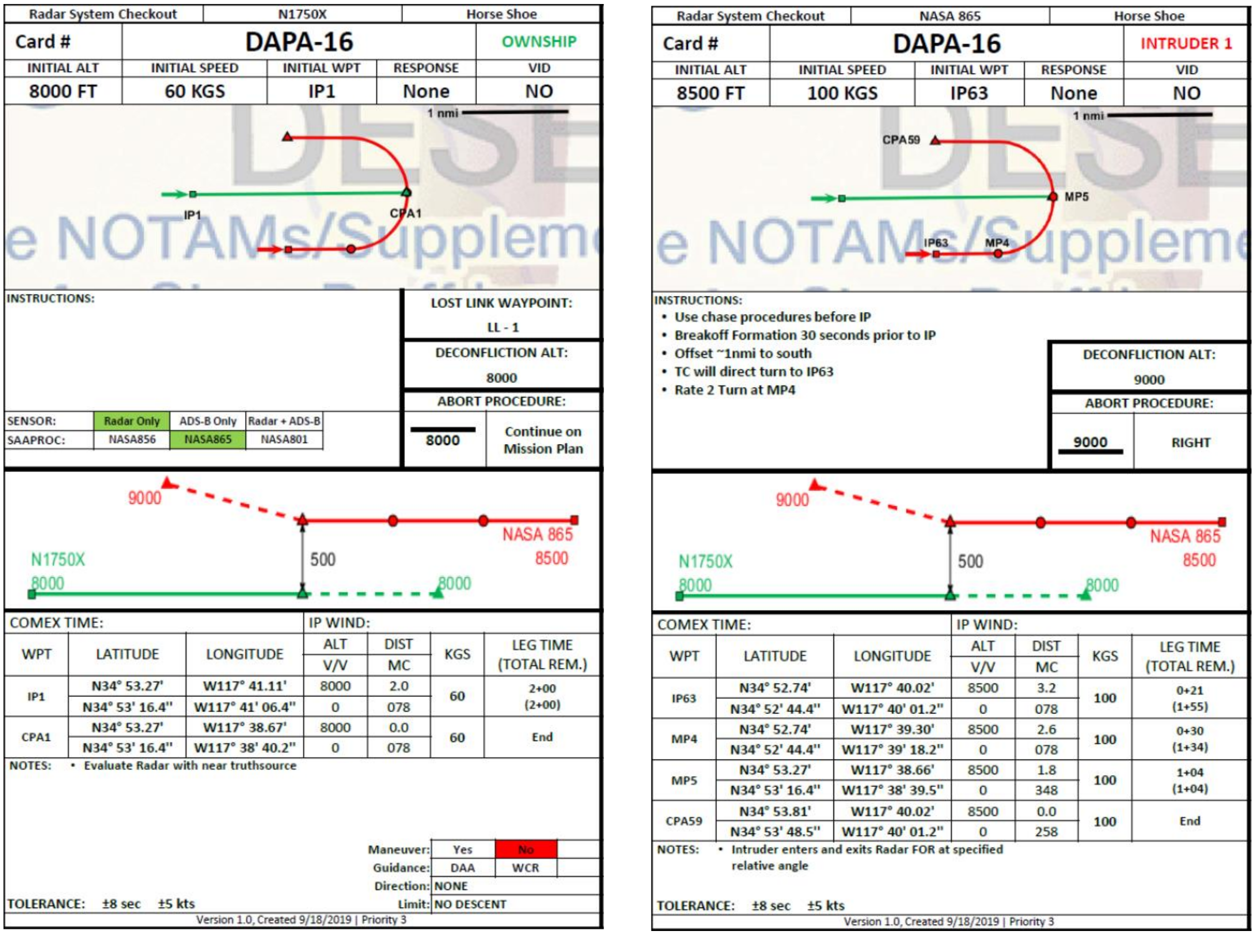

Figure 65. DAPA-16 Radar System Checkout Flight Card.

With SCO-9, the team created the “Lasso” radar card, shown in figure 66, which was designed to provide the radar set with an object that would test both a persistent source, as well as, an object that would stress the radar tracker logic. Training on executing the lasso test card was provided during the T-1 briefing.

ver-6

FT6 LASSO CARD (T-34 Specific)

TEST AND MANEUVER SEQUENCE:

1. Start conditions **OWNSHIP**
   - Fly Full Mission Mercury Spin route at 8Kft
2. Start Conditions **INTRUDER**
   - Start the encounter using chase procedures for entry/exit
   - Obtain/maintain VID to maximum extent possible
   - Fly encouter 500ft below Ownship (east bound leg); 200ft above (west bound leg)
3. **INTRUDER** Maneuver Sequence
   - Parallel ownship track ~1.25nmi (1.0-1.5nmi) lateral separation for 35-55 sec
   - Perform 35° 'merge' maneuver to close to ~0.3nmi from ownship track (~1 min)
   - Turn to parallel ownship track ~0.3nmi lateral separation for 20-40 sec (TC call)
   - Turn 180° into ownship (30° bank turn)
   - Terminate abeam ownship; then 180° turn away (repeat same sequence)

PT	LATITUDE	LONGITUDE	OWNSHIP ALTITUDE	CHASE ALTITUDE	G/S
ALPHA	**N34° 52.80'**	**W117° 45.75'**	**8000**	**7500 (*8200)**	**70/100 KGS**
	N34° 52' 48.0"	**W117° 45' 45.0"**			

*Note:
Intruder performs eastbound maneuvers 500ft below, westbound maneuvers 200ft above ownship; TC will direct altitude change during 180° right turn to west
Remain within 2nmi of ownship during encounter

Figure 66. T-34 LASSO Radar System Checkout Flight Card.

8.5. Scripted Encounters

The test approach for the FT6 Scripted Encounters phase was to evaluate the performance of the DAA system in a controlled environment while systematically varying several encounter variables. These variables were encounter geometry, intruder speed, vertical offset, sensor selection to the DAA algorithm, conflict mitigation, and maneuver trigger. The variables were derived from simulations performed by the DAA subproject. A test point matrix was derived from the combination of the levels of each variable and test points that were redundant or not of interest were removed.

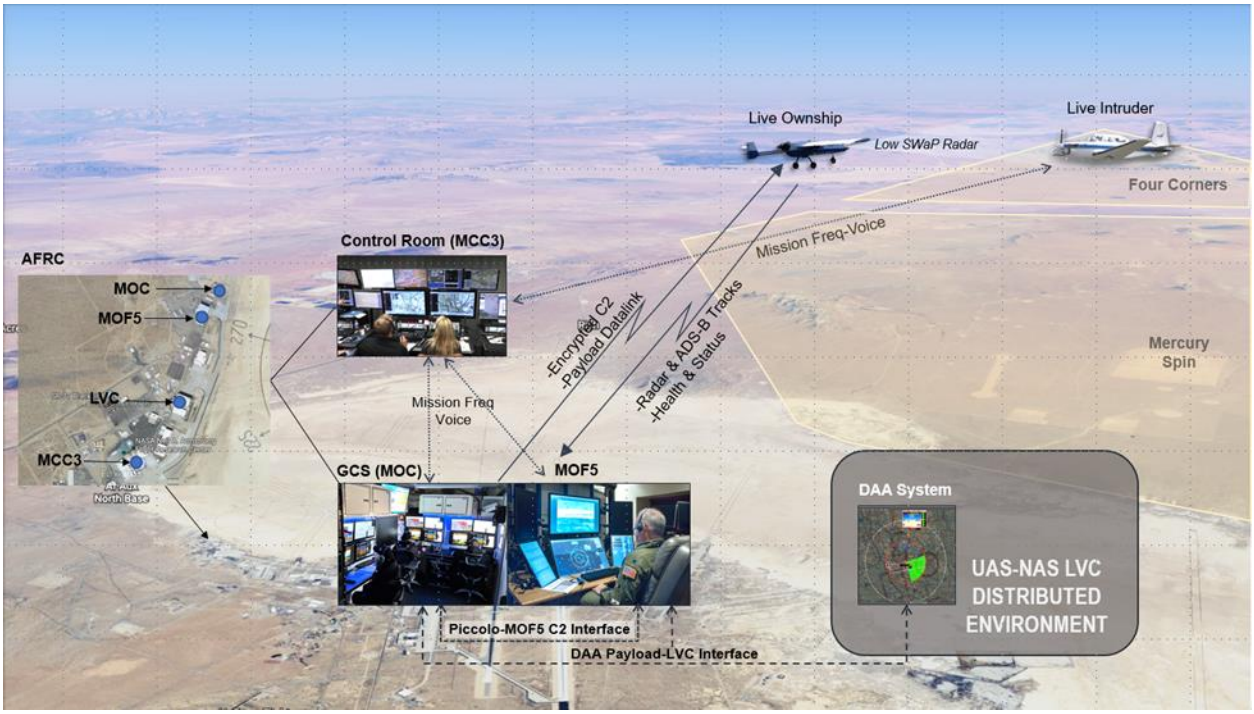

Figure 67. FT6 Scripted Encounters System Environment.

The Scripted Encounters System Environment is depicted in figure 67. The procedure for the Scripted Encounters called for the UAS and the intruder aircraft to fly predefined flight paths. Most of the encounters were designed to excite the DAA alerting and guidance algorithm. However, a small number of encounters were designed to trigger an alert only if the positional uncertainty of the selected sensor was high. Each test point included instructions for how the UAS PUT was to maneuver. The PUT was asked to not maneuver until a predetermined duration of time (per the test card) after the onset of either the caution level corrective alert or warning alert to simulate the reaction time of an operational UAS pilot. The PUT was then asked to maneuver the UAS to follow the DAA guidance in the form of heading "bands." The PUT was instructed to maneuver so the heading of the UAS was within 15° of the edge of the heading bands. If the bands are removed from the display entirely during the encounter time window, the PUT was instructed to return to the original course.

The encounter geometry variable allowed the researchers the ability to evaluate how the DAA system worked at various closure rates between the UAS and the intruder and azimuth angles relative to the planned closest point of approach. The first set of encounter geometries involved the UAS and intruder on stable unchanging courses at azimuth angles relative to the planned CPA of 0°(head-on), 40°, 50°, 60°, 80°, 90°, 120°, and 160°. A subset of the encounters involved the intruder aircraft maneuvering during the test window either horizontally or vertically. The intruder speed varied between 60, 100, and 170 knots ground speed, a distribution of speeds that were found to be mostly inclusive of traffic that would be encountered under 10,000 ft. MSL. Vertical offset between the UAS and the intruder was varied between 200 ft., 300 ft., 400 ft., and 500 ft. Encounters with either 200, 300, or 400 ft. were expected to cause alerts, although alerting for 400 ft. encounters was expected to be intermittent with the non-cooperative sensor. Encounters with a 500 ft. vertical offset were not expected to alert under nominal conditions, although high degrees of sensor uncertainty would likely result in intermittent alerting.

Sensor selection as input to the DAA algorithm was planned to be varied between ADS-B only, and radar only. However due to the difficulties with the development of the radar, radar only Scripted Encounters were not flown. In lieu of using the radar as an input, the radar only test points were flown using ADS-B tracks which were filtered in the SaaProc software to limit the azimuth, elevation and range to values which emulated a radar system. This allowed the researchers to investigate the impact of several fields of regard on the DAA system.

Encounters were also split between those where the PUT were expected to maneuver (mitigated) and those where the PUT was instructed to not maneuver (unmitigated). Mitigated encounters were meant to investigate the efficacy of the DAA guidance whereas the unmitigated encounters were meant to collect a cross section of DAA behavior without input from a pilot. Mitigated encounters were split into either those where the PUT maneuvered after the DAA corrective alert was triggered and those where the PUT maneuvered after the DAA warning alert was triggered. The PUT was instructed to wait until 8 seconds after a DAA corrective alert and 3 seconds after a DAA warning alert passed before executing a maneuver to account for a UAS pilot's naturalistic behavior in an operational scenario.

8.6. Full Mission

Achieving the FT6 objective to characterize pilot response data required the creation of a NAS scenario that combined the live elements of the UAS and manned intruder with the simulated elements of background traffic with pseudo-pilots, and a virtual ATC. The simulated and live elements of Full Mission were combined to create the illusion of an operational UAS mission in order to observe and document the naturalistic behavior of the SPUT while controlling the UAS. The Full Mission System Environment is depicted in figure 68.

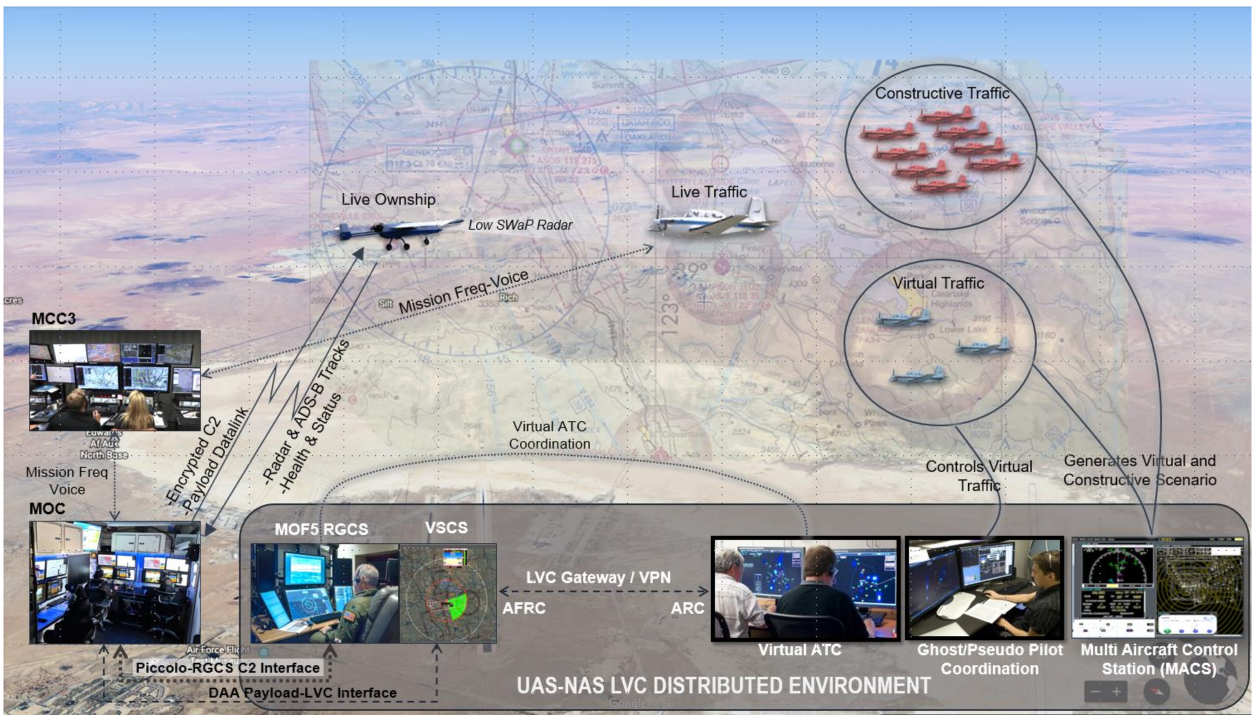

Figure 68. FT6 Full Mission System Environment.

The scenario used for Full Mission evolved from the high fidelity scenarios used in TOPS1, TOPS2, ACAS-Xu, and low SWaP projects. The scenario was designed to run up to four hours to accommodate airspace contingency plans and other off-nominal situations and included 300 virtual aircraft.

The airspace simulated in FT6 Full Mission was a sector inside of Oakland Center north of the San Francisco Class B complex. In order to create the illusion of flying in the Oakland airspace, the background reference map used in the VSCS software was changed to a VFR sectional map which represented the area of interest. A TFR which reflected the shape of the southern boundary of the Edwards R-2515 airspace where the flight operations were conducted was added to the VSCS display as an overlay to restrict the SPUT from maneuvering outside the test airspace. ARC provided support for the FT6 FM by providing virtual ATC services in Oakland Air Route Traffic Control Center (ZOA) Sector 40/41 airspace with representative traffic and complexity. ARC also provided audio recording capabilities for FT6 Full Mission.

Background traffic consisted of both cooperative and non-cooperative aircraft. Constructive traffic, or simulated traffic which navigates without human input was added to the simulation on routes that were determined to be typical for the airspace. These aircraft did not communicate with ATC and were assumed to be in an adjacent sector. Virtual traffic, or simulated traffic which navigated through a pseudo-pilot station was also added to the simulation and were under positive control from the ATC. The addition of constructive and virtual traffic added realism to the scenario by presenting visual clutter on the display and congestion over the radio channels the SPUT was communicating on. The traffic within the simulation was based on the actual traffic tracks displayed at sector 40/41 and consisted of VFR and IFR traffic. VFR traffic included cooperative and non-cooperative targets. Cooperative targets squawked a beacon code of “1200”. Additional ATC services were provided to a portion of these aircraft. Non-cooperative targets were displayed as primary targets, which do not provide transponder information. Instrument Flight Rules (IFR) traffic primarily consisted of commercial traffic departing from or arriving at the San Francisco Bay area.

Five simulated aircraft were modified to ensure that the VSCS displayed surrounding traffic. This traffic was also used to generate preventive alerts for the ownship. The LVC-DE environment inserted live aircraft, N1750X (ownship) and NASA865 (intruder) into the virtual ATC environment. This environment allowed NASA research teams at Langley Research Center (LaRC) and ARC to assess the Detect and Avoid capabilities of an UA equipped with sensors to detect uncooperative aircraft.

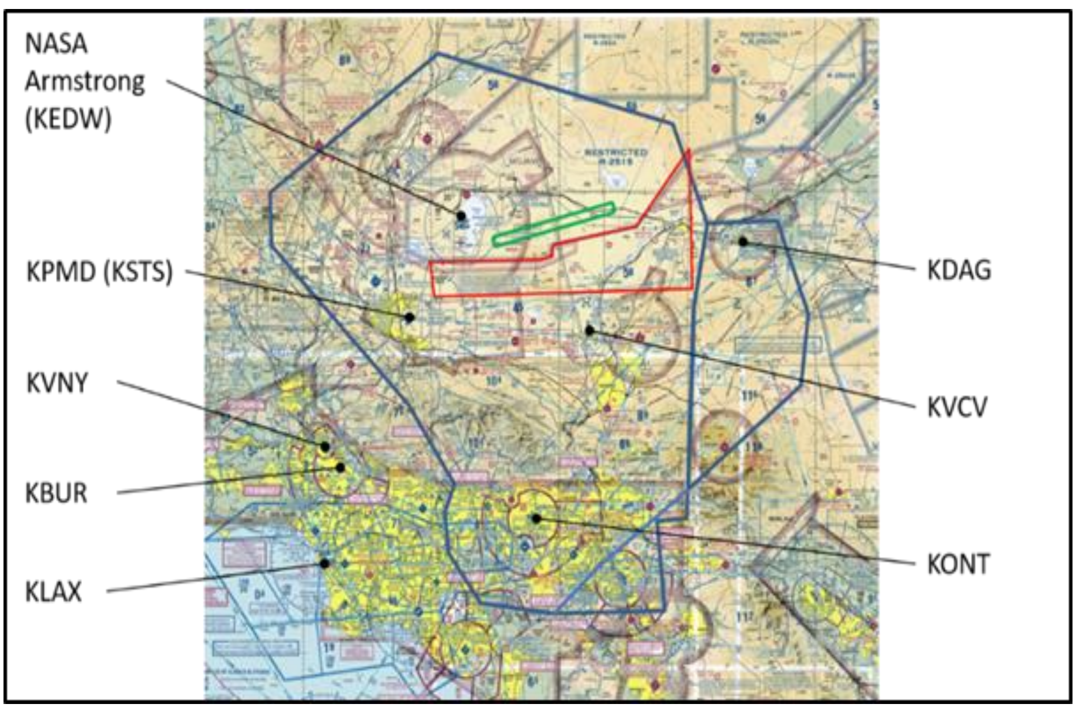

Figure 69. ZOA-40/41 Relocated Over R-2515.

MACS was configured to emulate the ATC environment at Oakland Air Route Traffic Control Center Sector 40/41 (figure 69). This airspace was selected because the sector interfaces with Class A, B, C, D, E and G airspace types. This allowed the research team to test in both positive control and uncontrolled test environments. The NAS environment that included ZOA-40/41 was relocated to the area encompassing

R-2515 and Edwards Air Force Base. This allowed the live aircraft to operate within protected airspace during Full Mission.

Virtual traffic was developed to provide representative aircraft interactions and air/ground transmissions without creating excessive workload for the air traffic controller. The traffic load on the sector is equivalent to moderate traffic for the combined sector, ZOA-41/40. This traffic was provided by the MACS constructive traffic generator.

The primary task of the SPUT in FT6 Full Mission was to operate the UAS around a racetrack-type primary flight plan and remain well clear of other traffic. As the UAS progressed through the primary flight plan, encounters with the live manned intruder were induced through coordination with the operations team. Once a conflict was detected by the DAA system, the SPUT was instructed to either coordinate a maneuver with the ATC over the voice channels or maneuver immediately to remain well clear. The SPUT would determine which action to take based on the alert presented – a caution level corrective alert would prompt coordination with ATC while a warning level alert would prompt an immediate maneuver. The SPUT was instructed to command the heading of the UAS so that it did not fall within the range of the DAA guidance bands. The SPUT was also instructed to coordinate with ATC to rejoin the primary flight plan once the guidance bands were no longer present. The SPUT was also given a secondary task to complete which simulated parts of an operational UAS mission. The tasks were presented to the SPUT through a secondary chat window and included requests to report distance from landmarks, fuel remaining, and other aircraft state data. After each encounter, the SPUT was asked to complete a post-encounter questionnaire to provide subjective ratings of several facets of the DAA system. After the completion of the mission, the SPUT was asked to complete a post-simulation briefing and a verbal debriefing interview with the researchers.

Each SPUT was exposed to 6 different encounters over 3 complete circuits of the Full Mission flight plan. Each encounter varied in geometry, intruder speed and intruder equipage. The encounter geometry varied between 0° (head-on), 45°, and 90° (crossing). The intruder speed was varied between 100 kts and 170 kts ground speed. The intruder equipage varied between non-cooperative and cooperative and was simulated through the filtering of ADS-B tracks in the SaaProc software. For non-cooperative intruders, the field of regard of a low size, weight and power radar was simulated by filtering out ADS-B tracks that were greater than 2.5 nmi, +/- 15° elevation, and +/-110° azimuth from the nose of the UAS. No field of regard was imposed on cooperative intruders. The experimental matrix for FT6 Full Mission is shown in table 17. An illustration of the encounter geometries is shown in figure 55.

Table 17. FT6 Full Mission Experimental Matrix.

Geometry	Intruder Speed	Intruder Equipage	
		Cooperative	Non-Cooperative
Head-on	100 KGS		1
	170 KGS	1	1
45°	170 KGS	1	
Crossing	100 KGS		1
	170 KGS		1

Collecting data from the SPUT during the FT6 Full Mission phase required 2 researchers, a SPUT liaison and an operations liaison. The SPUT liaison was the researcher responsible for coordinating events surrounding the SPUT. The SPUT liaison was responsible for administering the SPUT training and collecting the background information questionnaire before the data collection flight. During the flight the SPUT liaison would assist the SPUT with initiation of the simulation, administer the subjective feedback questionnaires, and relay pertinent information to the SPUT in unusual events (such as a lost-link). The operations liaison was responsible for coordinating with the operations team executing the data collection flight. The operations liaison would attend the T-1 briefing to gain an understanding of how the data collection flight would be conducted including changes due to weather, procedural changes for starting the simulation, and how the encounters would be conducted. The day of the data collection flight, the operations liaison attended the T-0 briefing to learn of any changes from the day prior including gathering a winds aloft report which would be forwarded on to the SPUT. During the flight, the operations liaison relayed information between the SPUT liaison and the test conductor regarding whether the SPUT had completed the subjective questionnaire and was ready for the next encounter. The operations liaison relayed whether the encounter as flown was acceptable and whether a re-fly of the same encounter was necessary. The operations liaison also relayed information about the status of the flight from the test conductor to the SPUT liaison when necessary.

The Controller was in direct communication and provided ATC services to the ownship and virtual traffic flying in the Full Mission. Intruder operations were directed by the TC at AFRC. The Controller managed all traffic during Full Mission flights using standard operating procedures for ZOA-40/41 and procedures designed for the FT6 Full Mission. ATC did not issue traffic calls to the ownship during planned encounters until the ownship responded to a DAA alert and a maneuver was initiated to ensure researcher goals for the encounter were met.

Two Pseudo-pilot positions supported the FT6 Full Mission flights. These positions controlled virtual aircraft within the scenario and were in direct communications with the Controller. These pilots followed scripts to ensure scenario fidelity and responded to the instructions of the Ghost Pilot and Controller. They also communicated with each other to ensure equitable distribution of traffic.

ARC support for each FT6 flight began with the T-1 and T-0 briefings conducted prior to the scheduled departure of the ownship. These briefings were attended by the Ghost and provided ARC with the planned schedule and objectives for the flight. Following the T-0 brief, the DSRL and SDL laboratories were prepared for the flight. The LVC environment was started and the connection between NASA research centers was verified. Once all ARC systems were online and verified ready for test, ARC advised AFRC that the ARC Startup Procedures were complete. Controllers and Pseudo-pilots were briefed on the day's operations then staffed at their assigned positions for the flight. The Virtual ATC frequency (125.85) was checked with Pseudo-Pilots and the SPUT by the Controller. The mission started when the Controller cleared the aircraft onto the Full Mission Route. Full Mission continued until all planned encounters were completed and the ownship began its trip back to KEDW.

9. Test Results and Analysis

This section provides a summary of the test results and a high level analysis of the data collected. Detailed data analyses are documented in other FT6 reports referenced in this section.

9.1. Ground Test Results

Ground testing commenced on 5/1/19 with initial MOF5 core systems checkouts. With the arrival of the TigerShark and MOC on site on 5/6/19, payload installation work began leading to successful integrated ground tests with a build-up of FT6 capabilities that supported CST, system shakedown tests, and ground mission rehearsals with all FT6 mission elements. Due to the delayed delivery of the FT6 version of the DAPA Lite radar system, ground checkouts were initially conducted with the FT5 version of the DAPA Lite radar panels to test interfaces with the rest of the payload systems.

The FT6 version of the DAPA Lite radar system commenced ground testing on 8/5/19. Initial results were not favorable as the system failed to consistently develop and maintain radar tracks during Honeywell prescribed ground tests with corner reflectors and moving vehicles. To reduce ground and background clutter, testing was relocated to the lakebed surface. When these tests showed comparable inconsistent results, the project elected to proceed to airborne tests and evaluate the system in its operational environment.

With the exception of the DAPA Lite functional checks, all 11 ground test specific test objectives delineated in Section 4.3.1 were successfully completed.

The following discrepancies were discovered during ground tests:

1) UAP Segmentation Fault:

   - The fault caused the UAP software to crash. A workaround procedure was developed to restart the UAP software. The root cause was later traced to a multi-thread race condition occurring with the Piccolo II interface, but by that time FT6 was executing Full Mission and nearly complete.
2) VSCS Magnetic Heading:
   - The Piccolo II system does not provide magnetic variation as an output to the VSCS VSM. This resulted in the magnetic variance on VSCS not being updated and always displaying the compass rose aligned to True Heading. Due to the difficultly in updating the Piccolo II software, a workaround was developed to conduct flight operations with VSCS using True headings.
3) Mismatched VSCS waypoint numbering:
   - The RGCS Full Mission waypoints did not match the numbering scheme used by the PUT/GCO and caused communication confusion when referencing what waypoint the SPUT was maneuvering towards. Due to the difficultly in updating the Piccolo II software and/or the AFRL VSCS software, training was conducted and waypoint look-up tables developed to ensure the test team referenced the correct waypoints.

A ground mission rehearsal with all the FT6 system elements was completed on 6/27/19 and highlighted operational deficiencies with voice communications and Full Mission start procedures. This resulted in many lessons learned and revisions to the communications plan, Full Mission start procedures, and more robust team training to ensure mission success.

9.2. System Checkout Flight Test Results

SCO flights were used to validate flight test and system requirements and ensure the FT6 systems were ready to support the Scripted Encounters and Full Mission data collection phases. Refer to Section 4.2.2 for SCO specific test objectives.

Ten SCO flights were conducted from 7/9/19 to 10/16/19 for a total of 28.0 flight hours. The SCO flight test phase took longer to complete than anticipated to complete due to multiple system discrepancies and the low maturity of the DAPA Lite radar. Radar performance and the marginal C2 datalink and lack of ADS-B In targets were the major issues that required additional flights to troubleshoot, determine root causes, and implement fixes or workarounds for future operations. Refer to Section 11.2 FT6 Flight Summary for more details on the sequencing of the flight tests.

The following discrepancies were discovered during SCO flights:

1) Marginal Silvus C2 Datalink:
   - During C2 range checks on SCO flight #1, the C2 datalink performance was unexpectedly degraded leading to a lost link event. The aircraft executed its lost link routing as planned until C2 was reestablished. The issue was traced to co-channel interference in the C2 frequencies assigned to the team. A unique feature of the Silvus radios enabled airborne spectrum sweeps when C2 was transferred to the backup Piccolo II 900 MHz system. The external source of the RF interference was not determined and subsequent flights were assigned frequencies without co-channel interference.
2) Lack of ADS-B In Targets:
   - This was a critical discrepancy as it was the only airborne DAA sensor given the DAPA Lite radar issues. The root cause of the issue was a disconnected GPS data serial cable between the Sagetech MXS ADS-B transponder and the Piccolo II. Improper configuration management led to the oversight and ground testing limitations precluded its discovery until flight tests.
3) Intermittent C2 and Telemetry in MOF5:
   - The root cause was a failing ETHIO5 card in the Apogee MUX unit located in the NASC MOC. The intermittent and low occurrence nature of this failure posed difficulties in

troubleshooting. Replacement of the card resolved the issue. C2 of the TigerShark was never at risk since the MOC maintained datalinks independent of this unit.

4) Marginal TigerShark Climb Performance:
    - Climb performance, averaging approximately 300 fpm at 5k ft MSL, was lower than the expected 500 fpm averaging approximately. The low climb rate did not impact data collection as the test objectives only required horizontal maneuvers to achieve DWC. The Operations Team adapted airspace transition procedures to accommodate the low climb rate and more efficiently transfer the TigerShark to the test areas.
5) Honeywell DAAP Fail:
    - On occasion, the data connection between the UAP and DAAP was lost. The root cause was not found. An inflight workaround was developed to power cycle the DAAP which restarted the DAAP software.
6) PCC Software Lag:
    - On occasion, the PCC user interface would temporarily freeze on one of the MOF5 stations. The issue was not persistent, so it made it difficult to troubleshoot. The root cause was not found. Since the GCO and PUT PCC stations were redundant, a station was always available when one of the systems froze. Additionally, the MOC always operated as the PCC server, so C2 was maintained and safety of flight was never compromised.
7) Persistent Ownship "Doppelgänger" DAA Warnings:
    - ADS-B Out broadcasts from the TigerShark Sagetech XP transponder were received by the Sagetech MXS ADS-B In transponder. This data was passed as an intruder target to the LVC system which caused a persistent DAA warning from the Doppelgänger ownship. The issue was resolved with an update of the UAP software that filtered out the Doppelgänger target from the LVC system.
8) TigerShark ADS-B "Doppelgänger" Split Tracks Displayed on Zeus:
    - ADS-B Out broadcasts by the Sagetech XP and MXS transponders caused split tracks on Zeus as the Zeus Multi Source Correlator Tracker struggled to correlate the data. Integration team assumed that Sagetech had disabled all ADS-B Out functions on the MXS transponder when it delivered a custom firmware to NASA. However, it was discovered that the MXS still broadcasted ADS-B Out messages. This was a nuisance condition and the Test Team was trained on how to identify this false target and ignore it. Neither safety of flight nor mission success was impacted.
9) DAA Band Saturation Resulting from Large Error Estimates:
    - Unexpected DAA band saturation from the DAA system was observed. The issue was traced to an error in the DAAP software incorrectly checking the Sagetech MXS ADS-B vertical velocity validity flag and setting it to false which resulted in the fusion/tracker estimating large errors. This error was fixed with a DAAP software update.

All 5 SCO specific test objectives, delineated in Section 4.3.2, were successfully completed to include system requirements validation and end-to-end data collection, distribution, and archiving. The discovery of system discrepancies and their resolution ensured that the FT6 systems were ready to support Scripted Encounters and Full Mission test phases.

9.3. Radar Characterization Flight Test Results

The main purpose of Radar Characterization was to conduct an integration and checkout of the Honeywell low SWaP DAPA Lite radar system and ensure its readiness to support the data collection phases. Two dedicated Radar Characterization flights were conducted as part of SCO flight tests to characterize the DAPA Lite radar with medium (T-34C) and large (B200) RCS target aircraft. Refer to Section 4.3.3 for Radar Characterization specific test objectives.

In total, 44 radar flight cards were flown. Unfortunately, the radar detection and track performance did not improve with airborne testing. The radar lacked target aircraft detection consistency and was unable to maintain track to support DWC evaluations. As a result, the project adapted target aircraft ADS-B data to emulate the radar by constraining the ADS-B field of regard and reducing detection range for the target of interest. This radar emulation was performed by the SaaProc software and applied the radar scan volume constraints of ±15° in elevation and ±110° in azimuth based on ADS-B flight ID information from the target aircraft. Although success criteria for the 3 Radar Characterization specific test objectives delineated in Section 4.3.3 could not be met, the Project determined that meaningful data could still be collected with a radar emulation to complete top-level objectives 2 and 3.

9.4. Scripted Encounters Flight Test Results

The purpose of Scripted Encounters flight tests was to conduct air-to-air encounters to collect performance metrics of low SWaP DWC alerting and guidance with limited surveillance volume. Refer to Section 4.3.4 for Scripted Encounters specific test objectives.

Three flight tests dedicated to Scripted Encounters specific test objectives (SE #1, SE #2, and SE#3) were completed in early October 2019. Additionally, air-to-air encounters conducted as part of SCO during SCO #5 through SCO #10, provided good research quality data such that they are included in the overall research data set for Scripted Encounters. As a result, a total of 96 encounters, taking 29.8 flight hours, was completed.

Emulated radar scan volume of ±15° in elevation and ±110° in azimuth with radar declaration ranges of 3.0 nmi, 2.5 nmi, and 2.0 nmi, were tested. Due to the small airspeed range of the TigerShark XP (from ~50 KIAS to 80 KIAS), winds aloft at test altitude impacted the ownship's ability to achieve flight card ground speed conditions typically at 60 KGS. The researchers were mindful of these conditions and adjusted their data analysis to account for the differing ground speeds when validating modeling and simulation runs with flight test data.

Analyses showed that effective alerting, guidance, and well clear maneuvers could be achieved with a low SWaP radar declaration range of 3.5 nmi. Although the prototype DAPA Lite radar was not used for these encounters, simulating its performance with ADS-B filtering techniques offered a viable means to collect data and inform Phase 2 MOPS requirements for a low SWaP non-cooperative surveillance system. Reference NASA/TM-2020-220515 (ref. 50) for a detailed analysis of the FT6 Scripted Encounters flight test phase.

All 3 Scripted Encounters specific test objectives, delineated in Section 4.3.4, were successfully achieved with complete data collection, distribution, and archiving.

9.5. Full Mission Flight Test Results

The purpose of the Full Mission flight tests was to collect UAS pilot performance metrics of low SWaP DWC alerting and guidance with limited surveillance volume during an operationally representative mission. At the time of completion of this FT6 overview document, an FT6 Full Mission data analysis document had not been published. Therefore, some initial details of the FT6 Full Mission test results are presented herein.

Dedicated flights to conduct a Full Mission practice and two mission rehearsals were completed in mid to late-October 2019. The Full Mission practice flight was used to refine the virtual traffic simulation start and restart procedures, virtual ATC communications, and encounter setups. Mission rehearsals were conducted with refined test procedures and flight cards to exercise the entire end-to-end Full Mission timeline. For both the practice and mission rehearsal activities, the SPUT duties were fulfilled by NASA pilots.

Full Mission data collection commenced on 10/31/19 with SPUT #1 and concluded on 11/21/19 with SPUT #7 after achieving good data collection with more than the minimum number of SPUTs required for data analysis.

The preliminary FT6 Full Mission data analysis indicate that generally, the DAA system and SPUT performances were similar to those observed in HITL simulations. The FT6 Full Mission mean time to loss of DAA well clear at first alert was similar to what was gathered in the low SWaP HITL 2 performed at ARC. This suggests that the DAA system did not necessarily alert any sooner or later than in a laboratory study, and that a valid comparison can be made between FT6 Full Mission and HITL simulations. Corrective alerts were generated for 81% of non-cooperative encounters, and the mean duration of the corrective alert was 11.6 seconds, which was a longer duration than observed in the HITLs. This difference could be explained by variation in closure rates between the UAS and the manned intruder during the flights. The reaction time of the SPUT was measured from the onset of the alert to the point at which the vehicle responded. The reaction times of the SPUT in FT6 were similar to what was observed in the HITLs with an overall mean reaction time of 8 seconds to warning alerts and 14.57 seconds to corrective alerts. The longest SPUT reaction time was 20 seconds and the shortest reaction time was 6 seconds. The mean SPUT reaction time for the fast head-on encounters (8.29 seconds) was noticeably quicker than the fast crossing (14.67 seconds), the slow crossing (14.33 seconds), and slow head-on (12.17 seconds) encounters. This suggests the SPUT responded quicker to warning alerts and sensed the urgency of a high closure rate encounter, since the fast head-on encounters provided little or no corrective alert time. The proportion of encounters where the SPUT coordinated with the virtual ATC controller (73%) was noticeably higher than in HITLs (36%), which is likely due to the higher proportion of encounters which started with a corrective alert.

The FT6 Full Mission NASA Task Load Index (NASA TLX) subjective findings indicate that mental demand was generally higher for encounters with a fast intruder than encounters with a slow intruder. This was also true for temporal demand, performance demand and frustration. Physical demand was predictably low and consistent across all encounter types. There appears to be agreement across pilots that the guidance bands were useful during the encounters and they were able maintain DWC from the manned intruder. There was also agreement that sensor noise and winds aloft did not significantly impact the execution of the separation task.

All pilots reported that they received sufficient training on the ground control station and the DAA system. The realism of the virtual ATC and the virtual pilots was rated as realistic by most pilots while the realism of the UAS mission profile was rated as very realistic by 3 pilots while 4 rated the mission profile as somewhat realistic. Generally, the pilots rated the datalink latency between the GCS and the UAS as acceptable.

In order to validate the test results, it was necessary to investigate multiple characterizations such as the turn rate of the UAS, the impact of winds, and the achieved ground speeds. Analysis of the turn rates achieved by the TigerShark during FT6 Full Mission indicate that every encounter achieved the target max turn rate of 7°/second. However, it appears the turn rate would stabilize between 4°/second and 6°/second after initially achieving a peak turn rate over 7°/second.

The impact of winds aloft on UAS turn rate was also investigated. When observing the winds as measured by the autopilot of the UAS, it was found that flight FM #6 had noticeably higher winds aloft than the other Full Mission flight tests with wind speeds ranging from 17 kts to 37 kts. However, when comparing the turn rates of flight FM #6 to all other flights it appears there was little, if any difference in turn rate.

Winds aloft did, however, appear to have a small effect on the achieved closest horizontal separation (CPA) between the UAS and the intruder during the encounters. As the mean ground speed of the UAS decreased, it appears it was more difficult for the UAS to maintain DWC with CPA values also decreasing. There was a small but significant correlation between mean ground speed and CPA ($R2 = 0.181$, $p < 0.01$).

The following discrepancies were discovered during Full Mission flights.

1) Intermittent TSD Black Out:
    - The SPUT TSD had an intermittent black out issue that turned into a nuisance during Full Mission flights. Although monitors and cables were switched, the problem persisted throughout the Full Mission campaign. A root cause was never determined since the problem occurred towards the end of the flight test campaign. A workaround to power cycle the video switch prior to flight was sufficient to complete the tests.

2) Unexpected VSCS Commands with Push to Talk Depression:
    - The cause of the issue was a configuration within VSCS that enabled the Game Joystick feature. The problem only occurred if the VSCS computer detected the Plantronics USB headset as USB1, which was interpreted as a gaming controller by the VSCS application. This issue was discovered on FM #4 and the VSCS configuration files were updated for FM #5 through FM #7. Review of data for FM #1 through FM #3, fortunately, showed negligible impact from this issue.

System updates and workarounds enabled all Full Mission specific test objectives, listed in Section 4.2.5, to be completed

10.Conclusion

TigerShark XP2 (N1750X), touched down on its last flight, FM #7, on 11/21/19 to successfully complete the FT6 test campaign with 23 flights, 67.6 flight hours, and 245 air-to-air encounters. FT6 demonstrated that a Group 3 UAS equipped with low SWaP sensors and DAA systems could meet research test requirements, safely execute air-to-air encounters, and collect valuable data to validate modeling and simulations to inform Phase 2 MOPS development. An objective to support the development of Phase 2 MOPS for low SWaP airborne non-cooperative surveillance system was not fully successful as a result of the DAPA Lite radar system's inability to consistently develop and maintain tracks. This highlights technical challenges associated with low SWaP radar systems and that the current state of the art systems require additional maturation. Successful data collection from all of the FT6 flight tests are being further analyzed by the researchers to inform Phase 2 MOPS development for DAA Systems featuring a low SWaP non-cooperative surveillance system.

11. Appendix

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11.2. FT6 Flight Summary

Date		1750X	NASA856	NASA865	NASA801
7/09/19	SCO #1	2.1	2.1		
7/11/19	SCO #2	2.8	2.7		
7/16/19	SCO #3	2.7		2.4	
7/18/19	SCO #4	2.0		2.0	
8/13/19	SCO #5	3.5		3.2	
8/22/19	SCO #6	2.1		1.9	
8/28/19	SCO #7	2.0		1.7	
8/29/19	SCO #8	3.5		3.1	
9/24/19	SCO #9	3.9			3.6
10/01/19	SE #1	4.4			3.9
10/03/19	SE #2	3.5		3.3	
10/08/19	SE #3	3.5		3.0	
10/16/19	SCO #10	3.4			2.9
10/17/19	Full Mission Shakedown	3.3			3.0
10/24/19	Full Mission Rehearsal 1	2.7		2.8	
10/29/19	Full Mission Rehearsal 2	2.8		2.8	
10/31/19	Full Mission Flight Test 1	2.8		2.4	
11/5/19	Full Mission Flight Test 2	2.8		2.2	
11/7/19	Full Mission Flight Test 3	3.1		2.2	
11/13/19	Full Mission Flight Test 4	3.7		3.0	
11/15/19	Full Mission Flight Test 5	2.6		2.1	
11/19/19	Full Mission Flight Test 6	2.5		2.0	
11/21/19	Full Mission Flight Test 7	1.9		1.7	

	1750X	NASA856	NASA865	NASA801
Total Hours:	67.6	4.8	41.8	13.4

	1750X	NASA856	NASA865	NASA801
SCO #1	0	0		
SCO #2	13	13		
SCO #3	4		4	
SCO #4	0		0	
SCO #5	17		17	
SCO #6	10		10	
SCO #7	4		4	
SCO #8	18		18	
SCO #9	18			18
SE #1	26			26
SE #2	24		24	
SE #3	18		18	
SCO #10	12			12
Full Mission Shakedown	11			11
Full Mission Rehearsal 1	9		9	
Full Mission Rehearsal 2	6		6	
Full Mission Flight Test 1	7		7	
Full Mission Flight Test 2	7		7	
Full Mission Flight Test 3	7		7	
Full Mission Flight Test 4	11		11	
Full Mission Flight Test 5	9		9	
Full Mission Flight Test 6	8		8	
Full Mission Flight Test 7	6		6	

	1750X	NASA856	NASA865	NASA801
Total Runs: (including attempted)	245	13	165	67

	1750X	NASA856	NASA865	NASA801
SCO #1	0618-0825	0622-0830		
SCO #2	0609-0857	0624-0908		
SCO #3	0606-0846		0616-0840	
SCO #4	0600-0800		0610-0810	
SCO #5	0719-1050		0730-1041	
SCO #6	0719-0924		0731-0926	
SCO #7	0922-1122		0932-1113	
SCO #8	0611-0939		0625-0930	
SCO #9	0636-1032			0654-1029
SE #1	0636-1101			0655-1049
SE #2	0627-0954		0647-1004	
SE #3	0638-1007		0655-0955	
SCO #10	0643-1008			0723-1015
Full Mission Shakedown	0723-1039			0740-1040
Full Mission Rehearsal 1	0701-0944		0648-0939	
Full Mission Rehearsal 2	0712-0958		0658-0945	
Full Mission Flight Test 1	0731-1018		0748-1012	
Full Mission Flight Test 2	0636-0925		0655-0906	
Full Mission Flight Test 3	0629-0933		0708-0922	
Full Mission Flight Test 4	0627-1007		0650-0952	
Full Mission Flight Test 5	0628-0907		0648-0854	
Full Mission Flight Test 6	0644-0916		0705-0905	
Full Mission Flight Test 7	0630-0823		0645-0825	

Take off time-Landing time

Encounters completed

Date	Event	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	Totals:	
7/09/19	SCO #1																											0	
7/11/19	SCO #2	SQK-6	SCO-04	SCO-04 REP	SCO-01	SCO-02	SCO-03	SCO-08	SCO-08 REP	SCO-05	SCO-06	SCO-06 REP	SCO-07	SCO-07 REP														13	
7/16/19	SCO #3	FM-01	FM-02	FM-02 REP	FM-02 REP																							4	
7/18/19	SCO #4																												
8/13/19	SCO #5	SCO-04	SCO-04 REP	FM-01	FM-02	DAA-37	RDR-31	RDR-44	RDR-53	DAA-19	DAA-20	RDR-60	RDR-65	DAA-03	DAA-12	DAA-27	DAA-28	DAA-43										17	
8/22/19	SCO #6	DAPA-01	DAPA-02	DAPA-03	DAPA-04	DAPA-07	DAPA-08	DAPA-05	DAPA-06	DAPA-09	DAPA-10																	10	
8/28/19	SCO #7	RDR-25	RDR-19	RDR-19 REP	RDR-13																							4	
8/29/19	SCO #8	RDR-13	RDR-36	RDR-53	RDR-40	DAA-04	DAA-03	DAA-12	DAA-11	DAA-38	DAA-37	DAA-20	DAA-19	DAA-28	DAA-27	DAA-43	DAA-43 REP	DAA-42	DAA-42 REP									18	
9/19/19	~~SCO #9~~	WX CNX																											
9/24/19	SCO #9	DAPA-13	DAPA-11	DAPA-12	DAPA-13	DAPA-15	DAPA-16	DAPA-02	DAPA-05	DAPA-06	LASSO	DAA-04	DAA-03	DAA-12	DAA-11	DAA-20	DAA-19	DAA-28	DAA-27									18	
10/01/19	SE #1	DAA-75	DAA-76	DAA-77	DAA-77	DAA-78	DAA-79	DAA-80	DAA-69	DAA-70	DAA-71	DAA-71	DAA-71	DAA-72	DAA-73	DAA-73	DAA-74	RDR-01	RDR-02	RDR-03	DAAb-03	DAAb-04	DAAb-11	DAAb-12	DAAb-19	DAAb-37	DAAb-62	26	
10/03/19	SE #2	DAA-58	DAA-58	DAA-60	DAA-04	DAA-20	DAA-27	DAA-28	DAA-38	DAA-42	DAAb-03	DAAb-04	DAA-83	DAA-84	DAA-84	DAA-85	DAA-86	DAA-86	DAA-87	DAA-88	DAA-89	DAA-90	DAA-91	DAA-91	DAA-94			24	
10/08/19	SE #3	DAA-58	DAA-93	DAA-94	DAA-81	DAA-82	DAA-84	DAA-84	DAA-85	DAA-43	DAA-92	DAA-93	DAA-94	DAA-92	DAA-92	DAAb-58	DAAb-93	DAAb-94	DAAb-92									18	
10/10/19	~~SCO #10~~	WX CNX																											
10/16/19	SCO #10	FULL-06	FULL-05	FULL4C-05	FULL4C-06	LASSO	DAPA-13	DAPA-15	DAPA-16	DAPA-18	DAPA-18	DAPA-18	DAPA-01															12	
10/17/19	Full Mission Shakedown	FULL-01	FULL-02	FULL4C-03	FULL4C-04	FULL4C-05	FULL-06	FULL-01	FULL-02	FULL-05	FULL-04	FULLMS-04																11	11
10/24/19	Full Mission Rehearsal 1	FULL-01	FULL-02	FULL-07	FULL-04	FULL4C-06	FULL4C-08	FULL4C-04	FULL4C-07	FULL4C-02																		9	9
10/29/19	Full Mission Rehearsal 2	FULL-07	FULL-02	FULL4C-01	FULL4C-04	FULLMS-06	FULLMS-08																					6	6
10/31/19	Full Mission Flight Test 1	FULL-01	FULL-02	FULL-07	FULL-04	FULLMS-04	FULL4C-08	FULL-06																				7	7
11/5/19	Full Mission Flight Test 2	FULL-08	FULL-06	FULL-07	FULL-04	FULL-01	FULL-02	FULL4C-08																				7	7
11/7/19	Full Mission Flight Test 3	FULL-07	FULL-04	FULL-01	FULL4C-01	FULL-02	FULL4C-08	FULL4C-06																				7	7
11/13/19	Full Mission Flight Test 4	FULL-08	FULL-06	FULL-01	FULL-02	FULL-01	FULL4C-01	FULL4C-02	FULLMS-02	FULL-01	FULL-04	FULL-07																11	11
11/15/19	Full Mission Flight Test 5	FULL-01	FULL-02	FULL-07	FULL-04	FULL-04	FULLMS-04	FULL-08	FULL4C-08	FULL-06																		9	9
11/19/19	Full Mission Flight Test 6	FULL-08	FULL-06	FULL-07	FULL-04	FULL4C-01	FULL4C-01	FULL-02	FULLMS-02																			8	8
11/21/19	Full Mission Flight Test 7	FULL-07	FULL-04	FULL-01	FULL4C-08	FULL-02	FULLMS-06																					6	6
																												245	81

FM Rehearsal	32			Airspace Contingency encounters: 15
Full Mission	55	42 planned	13 repeats	Airspace Contingency encounters: 15
Scripted Encounters	95	72 Planned		Airspace Contingency encounters: 12
Radar Characterization	44	64 planned	28 unplanned	
System Checkout	19			
	245			