AirSTAR Beyond Visual Range UAS Description and Preliminary Test Results

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The NASA Airborne Subscale Transport Aircraft Research Unmanned Aerial System project's capabilities were expanded by updating the system design and concept of operations. The new remotely piloted airplane system design was flight tested to assess integrity and operational readiness of the design to perform flight research. The purpose of the system design is to improve aviation safety by providing a capability to validate, in high-risk conditions, technologies to prevent airplane loss of control. Two principal design requirements were to provide a high degree of reliability and that the new design provide a significant increase in test volume (relative to operations using the previous design). The motivation for increased test volume is to improve test efficiency and allow new test capabilities that were not possible with the previous design and concept of operations. Three successful test flights were conducted from runway 4-22 at NASA Goddard Space Flight Center's Wallops Flight Facility.

ADS-B   =   Automatic Dependent Surveillance - Broadcast
AGL   =   above ground level
AirSTAR =   Airborne Subscale Transport Aircraft Research
BVR   =   beyond visual range
C&C   =   command and control
COA   =   certificate of authorization
ConOps   =   concept of operations
CPLD   =   complex programmable logic device
EICAS   =   Engine, Instrumentation, and Crew Alerting System
FAA   =   Federal Aviation Administration
FCC   =   flight control computer
FCU   =   Flight Control Unit
FCL   =   flight control law
FCS   =   flight control system
FTS   =   flight termination system
INS   =   inertial navigation system
KIAS   =   knots indicated airspeed
MOS   =   Mobile Operations Station
NASA   =   National Aeronautics and Space Administration
PDU   =   Power Distribution Unit
PWM   =   pulse width modulation
RPA   =   remotely piloted airplane
UAS   =   unmanned aerial system
UPS   =   uninterruptable power supply

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I. Introduction

THE AirSTAR facility is the combination of a ground control station, airborne avionics/telemetry systems, and the operational procedures required for conducting flight research using unmanned vehicles. The vehicles of interest are models, typically scaled versions of manned aircraft, for which unique flight-dynamics data are desired. Flight data from conditions outside the nominal operating envelope (e.g., stall, post-stall, etc.) is often difficult or impossible to acquire for full scale commercial transport airplane due to a variety of reasons. The data, however, are important to the validation of simulation databases that can be used with confidence in the training of pilots for loss-of-control conditions in commercial transports.[1,2] These and other (e.g., vehicle health monitoring, flight controls technology, etc.) applications motivated the design of the AirSTAR system, which has an emphasis on reliable operations of remotely piloted airplanes (RPA) in abnormal flight conditions.

This application of scaled free-flight models for obtaining flight dynamics data has a long history in NASA's aeronautics program.[3,4] Improvements in the miniaturization of avionics and other recent unmanned aerial systems (UAS) technologies has made the use of unmanned flight models even more attractive as a research tool. The NASA/Boeing X-48B program on blended wing-body vehicles[5] and the NASA/Lockheed X-56A program with an aero-elastic research vehicle[6] are two recent examples focused on novel vehicle configurations. In support of aviation safety, the AirSTAR facility has focused on models representative of contemporary commercial transport aircraft. The work described herein involves an extension of past research[7,8] to support larger test volume and wider variety of test techniques while providing a flexible and efficient research environment. The design decisions made both in architecture and in procedures were structured to provide a high degree of confidence in flight safety, while enabling the exploration of flight conditions for which aircraft stability and control may be difficult to accurately predict prior to the experiment.

The ground station design, described in detail in this paper, differs from many UAS ground stations in that it places a significant emphasis on pilot-in-the-loop flight and on providing a rich set of system-level displays for a mission support team. Under the AirSTAR concept of operations (ConOps), the mission support team works closely with the pilot and test conductor to perform the flight research. The remote piloting approach also drove the system towards a telemetry solution that has minimal latency, both on video feeds (from the aircraft) as well as on the command and control link. Airborne avionics were designed to have a large capacity for instrumentation, with analog, pulse modulation, serial, and Ethernet connections. Multiple layers of instrumentation redundancy were applied in the system design so that high value assets can be tested with reduced risk.

Another unique feature of the system is the capability to host research control laws that may have limited verification compared to flight critical software systems. The flight computer design partitions the research processor both physically, in a separate board, and logically as a system that is managed by the primary flight controller and can be ignored if operational bounds are exceeded (e.g., timing overrun, out-of-bounds command, etc.). Under the beyond visual range (BVR) development effort (known internally as "AirSTAR phase V"), described herein, the flight control system was moved from a ground-based computer to the airborne avionics system. Although the implementation is different, the software architecture had no significant changes and remains as described in previous publications.[9]

II. System Overview

The AirSTAR BVR system is designed to operate using an integrated system composed of an RPA and a ground control station. Because the purpose of the initial flight tests was to evaluate the readiness of the design, the vehicle avionics were installed on a commercial, off-the-shelf RPA. Other new avionics comprising the integrated system were installed in the existing ground control station, the AirSTAR mobile operations station (MOS). The RPA and MOS are shown in Fig. 1 and Fig. 2.

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Figure 1. Photo of remotely piloted airplane used for test of the AirSTAR beyond visual range system.

Figure 2. Photo of AirSTAR mobile operations station.

A. Test Airplane

The test airplane, a "Bat-4", is a commercial product that was developed by and procured from MLB Company in Santa Clara, California. The Bat-4 test airplane is a pusher-propeller configuration with fixed landing gear. Primary flight control surfaces included two ailerons and two inverted ruddervators. It is also equipped with simple trailing edge flaps. The straight wing has an aspect ratio of 8.3 and area of 18.8 square feet. The nominal takeoff weight of the airplane, as tested, was 115 lbs. At that weight, the idle power, flaps up/down stall speed was 35/31 knots indicated airspeed (KIAS); a typical climb speed was 50 KIAS; and a typical cruise speed was 55 KIAS.

B. Concept of Operations

The mission of the AirSTAR project is to use RPAs to test and validate technologies designed to improve aviation safety and reduce the possibility of airplane loss of control. The tests focus on stability and control aspects of the vehicle at both low and high angle of attack, including post-stall flight conditions. The need for reliability at stall and post-stall flight conditions drove many decisions relating to the design of the systems and ConOps.

Previous tests with earlier versions of the AirSTAR design used a research pilot, located inside the MOS, and a safety pilot, located outside the MOS. The research pilot was tasked with technical flight research operations such as the execution of flight test techniques. The safety pilot (using model airplane radio controls) was tasked with performing takeoff, landing, determining position relative to range boundaries, and ensuring safe control using visual observation. That ConOps required the vehicle to remain within the safety pilot's visual range (0.5 nautical miles horizontally and 1,200 feet vertically) at all times. This resulted in a horizontally and vertically compressed test range for the normal operating speeds (80 knots for the jets that were being tested with the previous ConOps). Typically, this allowed only 20 seconds of time on target test conditions. The compressed test volume required frequent turns and limited both the number of viable test techniques and the extent of loss-of-control scenarios which could be explored. Overcoming these limitations and improving test efficiency were the motivations to evolve the systems design to allow beyond visual range (BVR) operations.

The resulting new design, of both the system and ConOps, is referred to as the "BVR design". It uses a single pilot, operating the vehicle, in all phases of flight, from inside the MOS to provide a BVR capability. The term "beyond visual range" refers to the visual range limitations of a single ground based observer. Although a goal is to allow future research to be performed with large, complex unmanned vehicles, the initial system test and evaluation was performed with the relatively simple Bat-4 vehicle acting as a surrogate research vehicle (to reduce programmatic risk). One of the goals of the design is to provide the ability to operate at an airfield and runway that is capable of supporting operations with large, complex unmanned vehicles. Thus, runway 4-22 at NASA Goddard Space Flight Center's Wallops Flight Facility was used for the initial flight test of the design and ConOps.

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The BVR ConOps for test flights (at Wallops) involves transitioning from the airfield (for takeoff and landing) to restricted airspace. The takeoff and landing operations are performed in Wallops class-D airspace under a Federal Aviation Administration (FAA) UAS certificate of authorization (COA). The new ConOps test volume extends to a maximum of 10 nautical miles from the MOS and altitude to 10,000 feet above ground level (AGL). The vast majority of the test area is in the adjacent special use airspace (R-6604A, R-6604B, and a portion of W-386). The ConOps for ground operations involves locating the MOS on the ramp adjacent to the runway. The pilot (located in the MOS) uses an on-board camera view, synthetic vision display, and electronic maps to navigate both on the ground and in the air. Ground operations include taxing between the ramp and runway 4-22. The test area is shown in Fig. 3 and Fig. 4.
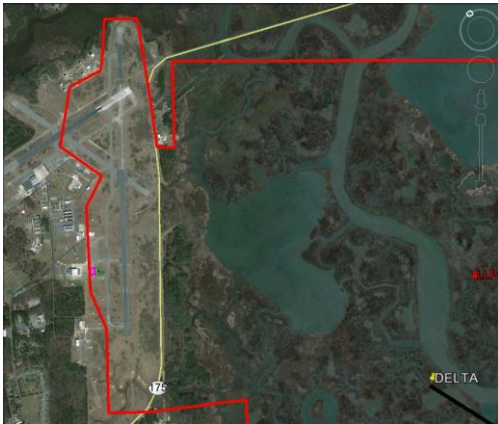
Figure 3. Map (aligned to Wallops runway 4) showing absolute range boundaries (for the AirSTAR BVR test flights) near the Wallops Flight Facility airfield.
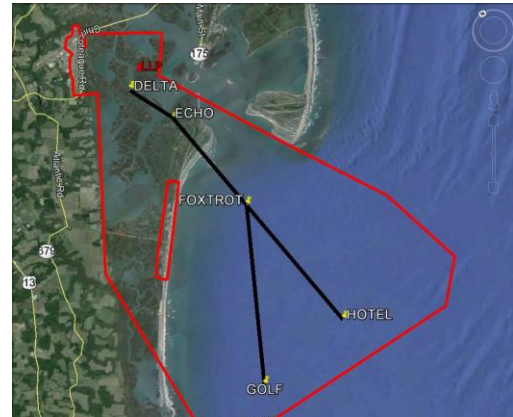
Figure 4. Map (aligned to Wallops runway 4) showing range boundaries (for the AirSTAR BVR test flights), and navigational routes with waypoints.

The COA under which this test was conducted requires the use of a ground based spotter while the UAV is flown outside special use airspace. The AirSTAR spotter is located directly adjacent to the MOS. The primary role of the spotter is to independently maintain positional awareness while scanning for potential collision hazards. If communication of potential collision avoidance information is required, the spotter has constant two-way communications with the pilot by intercom (primary) and VHF radio (backup).
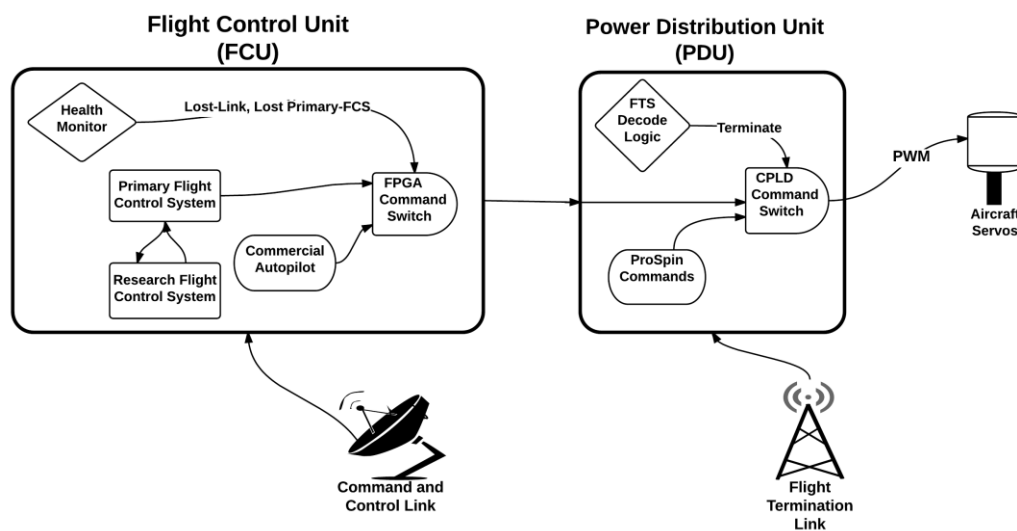
C. Airborne Systems

The AirSTAR phase V avionics system was installed in the Bat-4 airframe shown in Fig. 1. Since the Bat-4 was procured to test the integrated avionics design, the airframe was delivered without production avionics. Several new core avionics systems were installed in addition to sensors and avionics typically used for flight test. The new core systems are the power distribution unit (PDU) and the flight control unit (FCU). The high-level functional relationship of the PDU and FCU is graphically illustrated in Fig. 5.

The purpose of the PDU is twofold. The first purpose is to regulate and manage the distribution of electrical power to onboard systems. Electrical power is supplied by battery and the PDU provides battery health awareness by monitoring battery voltage and electrical system current. If the PDU detects low primary battery voltage, it will automatically switch to a backup battery. The second purpose of the PDU is to regulate (pulse width modulation, PWM) servo command signals. This is performed with a complex programmable logic device (CPLD) that is located within the power distribution unit. The CPLD receives PWM signals and state signals from both the FCU and a flight termination signal receiver that is installed onboard the vehicle. The CPLD performs decode logic and PWM switching to route the appropriate commands to the flight control actuators.

The purpose of the FCU is to provide control of the vehicle. This is accomplished by interfacing with all of the major subsystems and generating command signals for the flight control servo actuators. These major subsystems include flight control processor boards, air data, inertial navigation, fuel, telemetry, and contingency systems. The flight control unit provides analog-to-digital converter sampling, digital filtering, and telemetry message formatting.

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Within the FCU, functionality is distributed between two distinct flight control system (FCS) processor boards. The two processors in this system are called the "primary FCS" and the "research FCS". The primary FCS includes a reversionary flight control law (FCL) as well as all functionality for normal vehicle operations. If the research FCS fails, reversion to the primary FCS is always possible and would permit a normal return to base. The research FCS provides functionality to support the flight research aspects of the vehicle's mission. This includes: the ability to select and use any of a number of available experimental flight control laws, the ability to select and emulate any of a number of vehicle failures (servo failures, increased command latency …), and the ability to select any of a number of onboard control perturbation profiles (called "wavetrains"). Vehicle control failure emulation is engaged by activating a failure emulation module to modify flight control surface commands. Similarly, a wavetrain module controls and generates command perturbations from arbitrary user-defined profiles. The purpose of the wavetrains is to provide onboard excitation perturbations for system identification technology related research. The perturbations are added to the active command signals, either on the control stick signal path or directly to the servo commands. Both the failure emulation and wavetrain modules are located within software which is processed in the research FCS.

Figure 5. High level diagram of airborne systems functionality.

An additional important onboard subsystem is the command and control (C&C) telemetry subsystem, which provides the communication of cockpit and vehicle state data between the FCU and the MOS at a rate of 200 Hertz. The telemetry system is comprised of dual transceivers. Each of the transceivers provides both an uplink and a downlink stream for redundancy. The transceivers operate on diverse frequencies to help mitigate the risk of radio frequency (RF) interference. Each of the transceivers has a dedicated RF communication antenna. The two antennas are mounted at the wingtips and oriented with 45 degree outboard slant to provide polarization diversity.

In addition to the two uplink/downlink pairs, three other RF systems comprise the aircraft onboard system design. Those transmitters independently provide supplemental information to the ground control station. The three additional systems are: video (from a tail mounted video camera), automatic dependent surveillance broadcast (ADS-B), and a flight termination system signal receiver.

D. Ground Systems

All ground systems required for C&C of the AirSTAR vehicle are a part of the MOS (Fig. 2). A cockpit (Fig. 6), control room, and researcher/guest area are contained within the 32 foot long enclosure (Fig. 7). The primary C&C telemetry link is provided by a high-gain (parabolic dish) antenna located on the roof of the MOS. Downlink telemetry received by the antenna is decoded by computers located in the MOS. From that, derived and auxiliary data is calculated and distributed by local network connection to other MOS systems such as display computers and the antenna control unit. The MOS ground processing computer also receives analog and discrete signals from the cockpit,

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engineering stations, telemetry transceivers, antenna control unit, etc. The output signals from the ground processing computer system are used for decision making, pointing the parabolic antenna, and as inputs to the airborne flight control unit.

In addition to data computation and distribution, equipment in the MOS is used to receive and distribute voice communications and video signals. Voice communications are provided via an intercom system. The intercom system integrates operator stations in the MOS with conventional voice communication radios and with wireless intercom units worn by ground crew located outside the MOS. The voice communications radios include two standard aviation VHF radios (for communications with air traffic control) and two VHF radios capable of communications using either analog or a standard digital communications protocol (for interoperability with test range personnel). A dedicated channel on the intercom is used to ensure continuous, uninterruptable communications between the pilot and a visual spotter via a wireless intercom unit.

Four video camera sources are distributed to viewing screens in the MOS via a matrix switching unit which allows users at the individual stations to select their desired source. The video sources are the airplane tail camera and three cameras located on the MOS. One of the MOS based cameras is mounted on top of the parabolic dish antenna and thus tracks the UAV. The remaining two cameras are mounted on the port and starboard sides of the MOS. Those cameras, used for ramp and runway surveillance, are controlled (azimuth, elevation, and zoom) by an operator in the MOS.

Electrical power is supplied to the MOS power distribution unit via an external 60 kilowatt generator. The power distribution unit provides electrical power to four uninterruptible power supplies (UPS). The UPS then supply conditioned electrical power to all ground system equipment required for either normal or abnormal flight operations. In the event external electrical power were to be lost, the UPS would continue to allow normal operations for a minimum of 30 minutes.

Figure 6. Photo of the remotely piloted airplane cockpit located in the AirSTAR mobile operations station.

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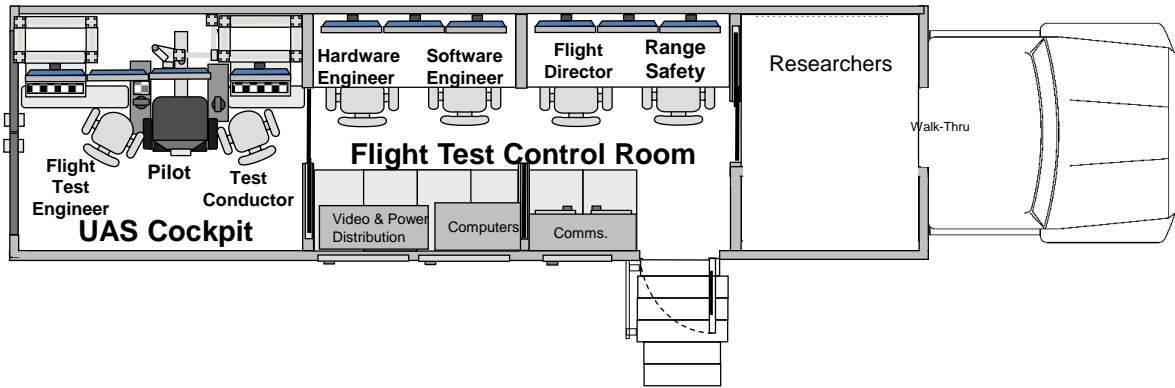
Figure 7. Diagram of the AirSTAR Mobile Operations Station showing functional layout.

III. Safety Aspects of the Design and Concept of Operations

An important goal for the system design and concept of operation is to ensure safety of the public and property in the event of system anomalies during flight operations. A multiple element approach is taken to reach that goal. The foundational element of the approach is the use of independent reviews of the system design and operational plans to ensure compliance with NASA's Range Flight Safety Program and other safety requirements. Some other important elements of the approach include:

- Use of redundancy
    - For low level subsystem failures
        - Three independent GPS receivers
        - Dual independent air data systems, each with alpha/beta vanes and pitot-static systems
        - Dual processor flight computer unit, with primary and research systems
        - Dual redundant battery system
    - For high level system failures causing loss of trajectory control
        - Contingency system "A" (an autopilot-independent telemetry and FCU capability)
        - Contingency system "B" (a flight termination capability)
- Use of system health monitoring
    - 44 signals monitored in real-time with associated cautions and warnings
    - Selectable sources ("primary" or "reversionary") for critical display parameters (e.g., location, speed, etc.)
- Use of high fidelity simulation
    - Simulation capability for failures (GPS outage, engine loss, aerodynamic prediction, control upset, etc.)
    - Emulation of avionics and telemetry systems within aircraft model
    - Integration of commercial autopilot emulator with aircraft simulation.

In this system, the use of redundancy to mitigate risks associated with component failures is a straightforward use of additional alternate hardware components to provide backup information if a primary component (e.g., a single telemetry transceiver, research FCS processor, etc.) fails. To mitigate the risks associated with loss of trajectory control (e.g., due to loss of both C&C links, failure of the flight control unit, etc.) a layered contingency system approach is used. The goal of this approach is to provide two contingency systems, each of which is capable of constraining the vehicle trajectory to within the pre-defined flight operations boundaries. It should be noted that in the event of C&C telemetry failure, airplane positional awareness in the MOS would be maintained. To do this, the MOS ground processing algorithms (and displays) would automatically switch to use the data provided by the ADS-B system. This is possible because the ADS-B data is received in the MOS by a radio frequency link that is independent of the C&C telemetry link.

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A. Contingency System "A"

The first line of defense for loss of trajectory control is referred to as Contingency System "A" (CS-A). This system is designed to provide control via a popular commercial autopilot intended for UAS applications. The autopilot unit independently provides (without use of primary systems): air data pressure sensors, GPS receiver, inertial navigation capability, guidance, control surface commands, and built-in integrity monitoring. Part of the unit's guidance, navigation, and control capability includes the ability to store and use a (user defined) lost link flight plan profile. Bidirectional communications between the autopilot and flight control unit are provided by a hardwire connection. There are three ways by which the autopilot can be engaged: first, by uplink of an activation command from a toggle switch in the cockpit; second, by commands generated in the onboard flight control unit which would occur if onboard health monitoring algorithms detect that both the C&C links are inoperative for more than 0.75 seconds; third, by the autopilot if it detects a loss of communication with the FCU (e.g., a failure of the FCU and its "heartbeat" signal). For these initial tests at Wallops, activation results in a flight plan profile to orbit a pre-approved lost-link waypoint located in restricted airspace (over a marsh). The trajectories are configured to orbit the lost-link waypoint counter-clockwise if the uplink command is lost or the autopilot is engaged from the ground station cockpit. However, if the cause of the autopilot engagement is due to the lack of a heartbeat signal from the flight control unit, the resulting lost-link orbit would have a clockwise sense. This allows some level of failure assessment to be made from the ground station with ADS-B monitoring alone, and no downlink information available. Several representative CS-A trajectories, generated from different initial positions, are shown in Fig. 8. In all cases, when the autopilot is activated, a PWM switch routes servo commands from the autopilot such that both the primary and research FCS servo outputs are bypassed.


Figure 8. Illustration of CS-A trajectories from several potential activation locations to the lost link point.

B. Contingency System "B"

Contingency System "B" (CS-B) is designed as a backup to CS-A. It is the flight termination component of the AirSTAR BVR system. It is intended for use only in the event of failure of both the C&C links and the simultaneous failure of CS-A to keep the vehicle within approved operational boundaries. The system uses common, commercial flight termination system (FTS) hardware to transmit, receive, and decode flight termination tones. The 25 watt transmitter and antenna are located on the roof of the MOS. The signal is received onboard the vehicle by either one of the dual receiver antennas which are orthogonally mounted on the lower fuselage of the Bat-4. The decoded state from the flight termination receiver is monitored and processed by the onboard PDU. When the appropriate tone is detected, the PDU PWM switch will override both the autopilot commands and the flight control unit commands to send pre-defined flight termination control surface position commands to the servos. (Note that this system is ground tested before and after each flight.) The purpose of the flight termination aerodynamic control surface commands is to achieve a steady spin/spiral motion resulting in a near-vertical trajectory. No parachutes or explosive devices are used for this application because simulation studies indicated the aerodynamic controls provide a predictable termination strategy, and had the least secondary complication to the concept of operations. Figure 9 illustrates typical simulated spin entries and trajectories for a zero wind case and also for a case with a direct 30 knot tail wind.

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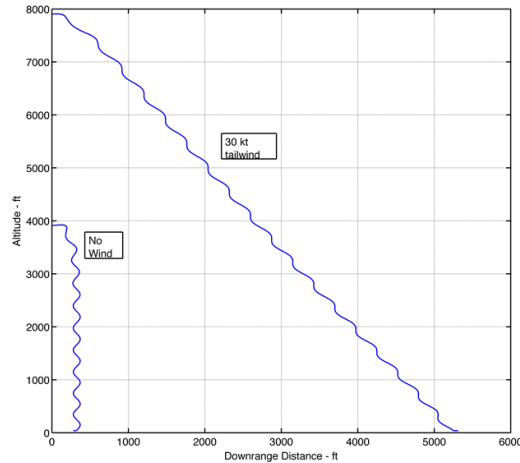
Figure 9. Plot of flight termination simulations showing spin trajectory profiles for no wind and winds aloft at 30 kts (maximum limit) – 60 knots calibrated airspeed entry speed.

C. Impact Point Predictor

The CS-B system includes ground-based software that displays, in real time, the predicted point of impact if flight termination was to be commanded. The Impact Point Predictor (IPP) algorithm is based on prediction of the drift distance due to winds while in a sustained spin. Allowances for drift due to effects of initial spin entry and inertial velocity decay are included in the prediction. The (two standard deviation) accuracy goals for predicted distance are as follows:

- +/- 200 ft per 1000 ft altitude
- +/- 100 ft during takeoff and landing
- +/- 2000 ft from 10,000 ft AGL.

The IPP algorithm computes descent rate in a sustained spin based on drag coefficient, time to impact, and the resulting drift distance based on estimated wind profiles. During flight, the algorithm is run in a Monte Carlo fashion where wind speed, wind direction, drag coefficient, and spin entry parameters are varied via uniform distribution to predict the probabilistic footprint for impact. Nominal wind speed and direction are based on weather balloon measurements made immediately prior to flight. This Monte Carlo approach is considered the worst-case drift prediction for the purposes of boundary protection. The impact point (Fig. 10) is displayed (as a red circle that encompasses all predicted impact points) on a range display in the MOS. The range display (Fig. 11) shows the location of the predicted impact footprint and aircraft position relative to range boundaries and navigation waypoints. This prediction is updated and displayed at a rate of 4 Hertz, allowing it to be used for time critical flight termination decisions. It serves as the primary means to ensure the vehicle would remain within the pre-defined hazard area under all failure scenarios. Operationally, a flight termination signal would be transmitted if the vehicle control had been lost and a range boundary violation (by the IPP footprint) was imminent. Hence, the pilot always maneuvers the airplane so that the IPP footprint remains clear of range boundaries.

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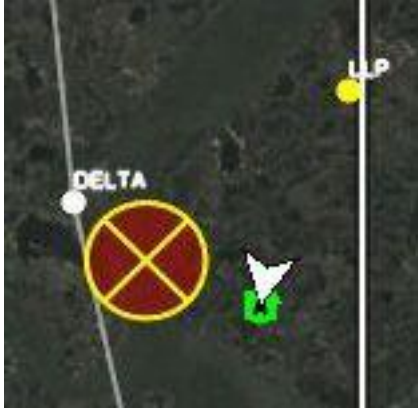
Figure 10. Close up image from the MOS Range Display showing: impact point footprint location, aircraft location, waypoints, and planned route.

Figure 11. Image of MOS Range Display, showing navigational information and predicted impact point information relative to operational and range boundaries.

D. System Health Monitoring

Because the AirSTAR BVR UAS system design is complex, system health monitoring and real-time crew alerting are considered to be important design elements for risk mitigation. Health monitoring algorithms are implemented both in the aircraft FCU and in the ground processing software in the MOS. The dual implementations ensure both air and ground based algorithms will continue to receive health monitoring information if telemetry C&C links fail. Health monitoring is accomplished by several means, including:

- Direct reporting of built-in component integrity monitoring (primary INS, CS-A autopilot/INS, ADS-B)
- Comparison of similar parameters measured by different sensors (fuel quantity gauge vs fuel totalizer, …)
- Comparison of sensor outputs with database of expected measurement ranges (electrical system current and voltage, signal strength, FCU and transceiver temperatures, engine RPM, data latency, etc.).

All system health anomalies are annunciated in the MOS on an Engine, Instrumentation, and Crew Alerting System (EICAS) display (Fig. 12). This is accomplished with the use of discrete indicators (Fig.13), color coded bars, and areas of color-coded reverse video. The color coding for indicators is: green indicating normal, white representing an advisory, yellow representing a caution status, and red representing a warning status. Activation of any caution or warning status is accompanied by a master caution or master warning aural alert sound cue. It should be noted that the EICAS display is not intended for use by the pilot. It is intended be used by other members of the test team for the early identification (and resolution) of any system problems.

A secondary means of vehicle health monitoring is available during flight via the onboard video link. The tail mounted camera allows real-time visual inspection of the engine, propeller, exhaust system, main landing gear, and much of the fuselage. The video also provides integrity monitoring of the altimetry, ADS-B position and the INS positions. Audio from an onboard microphone is also transmitted as part of the video system telemetry. The audio is available in the cockpit to support assessment of engine performance, airspeed awareness, and mechanical integrity.
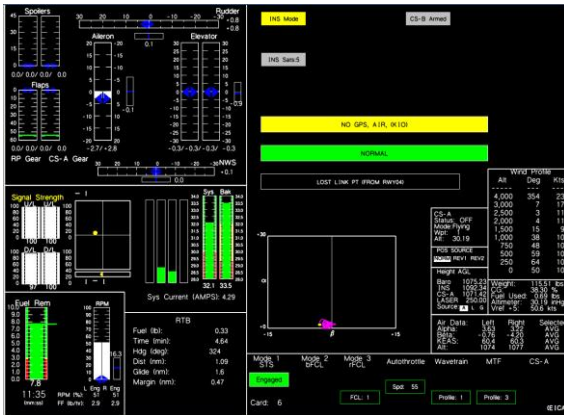
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Figure 12. An image of the MOS Engine, Instrumentation, and Crew Alerting System display.
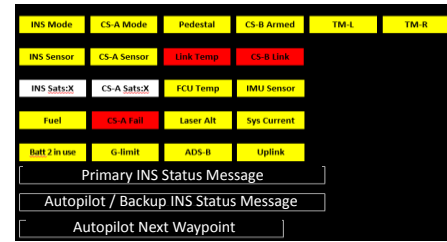

Figure 13. A close up image illustrating discrete annunciators on the MOS Engine, Instrumentation, and Crew Alerting System display in test mode.

E. Use of Flight Simulation

The AirSTAR simulation is considered an essential tool for the AirSTAR BVR system. The AirSTAR six degree-of-freedom piloted simulation, hosted in the MOS, combines the use of ground system hardware and the use of software emulation of aircraft systems. The same flight control system software is used both during flight and during simulation. Because the simulation is hosted in the MOS, the cockpit, control room and displays used during simulation are identical to those used during flight. The aerodynamic model of the Bat-4 airplane was developed by combining Bat-4 aerodynamic coefficient estimates with characteristic trends from a wind-tunnel database of a similar airplane. The Bat-4 aerodynamic coefficient estimates were developed using system identification techniques on data from a previous Bat-4 flight test (using hobby radio control, prior to design of the BVR system). The simulation was validated using time history comparison to flight test data and subjective pilot evaluation.

The ways in which the AirSTAR simulation are used include: profile planning (normal and "flameout"), mission rehearsals, normal and abnormal procedure proficiency (including INS failure), crew workload assessment, stall and unusual attitude recovery procedure, etc. These uses, and overall approach to the use of high-fidelity simulation, are consistent with those of earlier phases of the AirSTAR system design.[7-10] A new use of the simulation is the (frequent) simulation of scenarios requiring the use of CS-A and/or CS-B. One important aspect of those scenarios is to ensure test team familiarity with anticipated display degradation associated with the loss of C&C link data. During lost link, the displays use data provided by (or derived from) the ADS-B at 1 Hertz.

IV. Test Results

All three test flights of AirSTAR BVR system were performed at NASA Goddard Space Flight Center's Wallops Flight Facility. The primary purpose of the test was to demonstrate a significant increase in test volume (relative to what was used with the previous, within-visual-range, developmental phase). In the previous phase, all operations were required to stay within 0.5 nautical miles distance and 1,200 feet height of the pilot. For this test, thresholds for the measures of performance used to evaluate the test volume increase were flight to a minimum distance of 6 nautical miles and minimum height of 3,000 feet.

The first flight of the system was performed using the Southwest (4,500 foot) portion of Wallops runway 22. A special safety procedure was used for the first flight of the new system. To ensure public safety during this 12 minute flight, test range personnel stopped (and cleared) traffic from the section of highway 175 (Fig. 3) that is adjacent to runway 4-22 and underlies the planned flight path. The purpose of the first flight was to conduct functional, stability, and control checks to demonstrate the as-planned safe operational capability. To accomplish this, the following actions were performed:

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- Taxi and takeoff
- Controllability check during initial climb
- Climb to 2,000 feet, including climb performance check
- Level, maneuvering flight at 2,000 feet
- Small amplitude, low frequency pilot inputs for pitch, roll, and yaw axis stability and control assessments
- Landing (flap) configuration check
- Descent performance and trim check
- Normal approach, landing, taxi, and shutdown
- Post-flight debrief, data review, and performance of a detailed airplane mechanical inspection.

The second flight of the system provided an unplanned demonstration of the crew alerting system. Shortly after takeoff (100 feet altitude) an advisory discrete appeared. The advisory indicated the primary INS had an abnormally low number of satellites in view. Seconds later a master caution aural cue sounded as a new (yellow) "INS mode" discrete appeared on the EICAS display. That indicated the primary INS had entered an abnormal operating mode. Concurrently, the INS status verbose message box changed from a green background to a yellow background with a new message that the INS was now in "no GPS, air" mode. This is pictured in Fig. 12 (elongated yellow box in top-right quadrant of image). That mode means that a loss of GPS data had just occurred and degradation of the navigation solution could occur. A cross-check of the 3 position (primary INS, secondary INS, and ADS-B) indicators (green symbols shown overlaid in Fig. 10) immediately revealed excellent agreement of all three position data. Thus, it was known the primary INS position was still valid and that the use of the secondary INS source data was not yet indicated. In less than 10 seconds the abnormal modes cleared (indicated valid GPS data had now been received), but intermittently recurred throughout the remainder of the flight. When the airplane reached traffic pattern altitude, the abnormal situation was discussed and appropriate abnormal (to abort the mission) procedures were executed. This resulted in a closely monitored, but normal, landing 4 minutes later.

The GPS problem was resolved by replacing the affected GPS antenna, cable, and connector. It should be noted that the secondary INS and ADS-B position sources were not affected because they used a different, redundant GPS antenna. Because built-in integrity signals from those systems were monitored and used in the crew alerting system, the valid status of both backup position sources was known in real time. The isolated scope of the problem was immediately obvious and facilitated the measured execution of the appropriate abnormal procedure. Although it was a short, 5 minute flight, it provided a valuable demonstration of the crew alerting system.

The third flight of the system was performed with all systems functioning normally throughout the one hour flight. The primary test objective, demonstration of a significant increase in test volume, was met during this flight by expanding the operating altitude to 4,000 feet above ground level and expanding the operating range to a distance of 6 nautical miles from the MOS. During this distance expansion profile, 360 degree turns were made periodically (Fig. 14). The purpose of the turns was to assess the performance of the C&C link antenna configuration with various relative geometries to the MOS high gain tracking antenna. During this expansion the telemetry signal strength indicators on the EICAS display were closely monitored by discipline engineers. Several drops in signal strength were isolated to the signal coming from one of the two wingtip mounted antenna and were attributable to the fuselage blocking the signal during the 360 degree turns (an expected finding). The use of an antenna mounted on each wingtip appeared to provide a continuous, robust C&C telemetry capability for this configuration. Similarly, dual CS-B receiver antennas mounted on the left and right sides of the lower fuselage provided a continuous link with that system during the whole flight. Other accomplishments during the flight included:

- Airspeed envelope expansion
- Stall speed identification
- Air data calibration
- System identification technology research.

The accomplishments relating to system identification technology included real-time frequency response estimation for aircraft health monitoring,[11] as well as efficient maneuver design and nonlinear global aerodynamic modeling in real time[12]. The details of these investigations are presented in Ref. 11 and Ref. 12. Aspects of those investigations that related to the test of the AirSTAR BVR system design were: failure emulation,[9] excitation wavetrains applied to pilot inputs as well as multiple control surfaces simultaneously, longer maneuver times, increased altitude range, and real-time 50 Hertz flight data provided to researchers (and

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directly interfaced with MATLAB® based analysis tools) via the MOS Ethernet network. Failures that were emulated on this flight included stuck aileron, stuck ruddervator, and incremental command path latency. Similar to the approach taken during the earlier phases of the AirSTAR system design, multiple wavetrains designed to collect flight data for various modeling purposes were tested during this flight. A notable improvement was that the expanded test volume allowed a single wavetrain to include new, additional excitation at significantly lower frequencies, and time on condition. This is important because more time (and space) is needed to acquire the necessary flight data for dynamics at lower frequencies or for flight conditions associated with altitude loss, such high angle of attack. The previous, smaller test volume would have required maneuvers to be performed three (or more) times to get the equivalent information, and in some cases, the investigation could not have been done at all because of the requirement for a longer continuous maneuver.
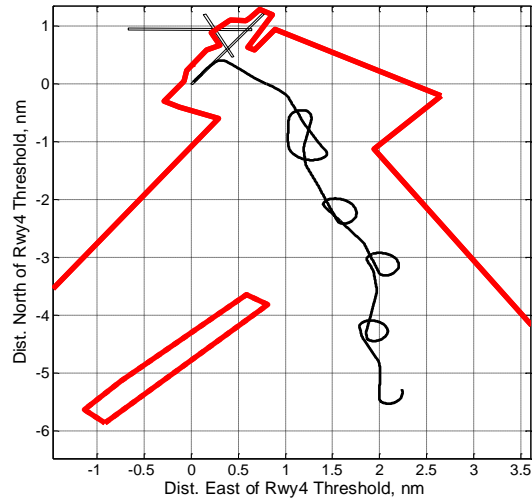
Figure 14. Plot of the Bat 4 trajectory during range expansion to a distance of 6 nautical miles from the MOS.

V. Concluding Remarks

The AirSTAR unmanned aerial system design was enhanced to allow the conduct of flight research operations at distances beyond the visual range of a ground based spotter. New safety related aspects of the design include the use of redundant equipment and a double layer of contingency management systems. The design was tested during a series of three successful flights at NASA Goddard Space Flight Center's Wallops Flight Facility. The use of a new crew alerting capability was demonstrated when the primary inertial navigation system suffered an unplanned, intermittent loss of GPS signal. During the test campaign, significant increase in test volume, improved flight research efficiency, and new capability were demonstrated.

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Acknowledgments

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