High-Altitude ADS-B Flight Tests on a NASA ER-2 Research Airplane

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Researchers at the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (Edwards, California); the Federal Aviation Administration (FAA); and Regulus Group, LLC (Atlantic City, New Jersey) collaborated for the flight-test demonstration of an Automatic Dependent Surveillance-Broadcast (ADS-B) system equipped on a high-altitude Earth Resources-2 (ER-2) research airplane. The unique ER-2 airplane is a NASA-owned and operated airborne science version of the United States Air Force / Lockheed Martin Aeronautics (Bethesda, Maryland) U-2S airplane. The FAA has mandated that by the year 2020, aircraft operating within certain sections of the United States National Airspace System be equipped with ADS-B Out technology; the research presented in this paper is the first to show how the NASA ADS-B architecture satisfies the mandate for a unique high-altitude aircraft. An exceptional military aircraft design, security protocols, and the performance envelope of the ER-2 airplane made the avionics integration remarkably challenging. The design required the ADS-B avionics to survive the harsh flight environment of the ER-2 airplane. The most prominent challenge was the functional integration of modern civilian avionics into federated military legacy avionics. Flight-test objectives were to certify an ADS-B Out (1090ES) passive surveillance integrated with a Traffic Alert and Collision Avoidance System (TCAS) I active surveillance system on an ER-2 platform for high-altitude

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cruise operations. In April 2022, NASA conducted three flights at Edwards Air Force Base (Edwards, California) - each greater than one-hour flight reaching altitudes above 60,000 ft.

I. Nomenclature

AC = Advisory Circular (FAA)
ADI = Attitude Direction Indicator
ADS-B = Automatic Dependent Surveillance-Broadcast
AHRS = Attitude and Heading Reference System
Alt = altitude
APAD = Autopilot Air Data System
APCU = Autopilot Computer Unit
Baro = barometric
BCDU = Bus Control Display Unit
CDU = Control Display Unit
CFR = Code of Federal Regulations
DIR = director
EPU = estimated position uncertainty
ES = extended squitter
ESIS = Electronic Standby Instrument System
FAA = Federal Aviation Administration
FL = flight level
GPS = global positioning system
HSDB = high-speed data bus
HSI = Horizontal Situation Indicator
IFF = identification friend or foe
ILS = Instrument Landing System
KCAS = knots calibrated airspeed
LRU = Line Replaceable Unit
M = Mach number
MDI = Multiple Display Indicator
Mil = military
MSL = mean sea level
NACp = navigation accuracy category for position
NACv = navigation accuracy category for velocity
NAS = National Airspace System
NASA = National Aeronautics and Space Administration
NIC = navigation integrity category
PAPR = Public ADS-B Performance Report
Rc = radius containment
RF = radio frequency
RTB = Return To Base
SBAS = Satellite-Based Augmentation Systems
SDA = system design assurance
SIL = surveillance integrity level
TAWS = Terrain Avoidance Warning System
TCAS = Traffic Alert and Collision Avoidance System
TIS-B = Traffic Information Services-Broadcast
UAT = universal access transceiver
Vfe = maximum flap-extended speed
Vmo = maximum operating limit speed
WAAS = Wide Area Augmentation System
WJHTC = FAA William J. Hughes Technical Center
WX = weather
XPNDR = transponder

II. Introduction

The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (Edwards, California) has a long history of aeronautics research, more recently in the realm of enabling Automatic Dependent Surveillance-Broadcast (ADS-B) commercial supersonic aircraft and high-altitude subsonic aircraft [1]. Operations above flight level 600 (FL600) in Upper Class E airspace are expected to increase significantly in the coming years [2]. The research described in this paper presents the design of an integrated system architecture that embodies ADS-B Out/In technology and Traffic Alert and Collision Avoidance System (TCAS I) on a unique high-altitude research airplane (a version of the United States Air Force / Lockheed Martin Aeronautics U-2S airplane), with modern display capabilities to provide air-to-air surveillance and increased situational awareness. Section III provides a systems background: description of an ADS-B Out/In system equipped on a high-altitude ER-2 airplane to satisfy the Federal Aviation Administration (FAA) airworthiness requirements for high-altitude flight operations. Section IV describes the flight-test aircraft systems. In Section V, results of the airworthiness tests. Section VI describes the high-altitude flight tests, including flight-test results and analysis and lessons learned. Section VII provides conclusions based on the lessons learned, ADS-B-related design challenges, and offers results of ADS-B Out performance and operational evaluations conducted at high-altitude flight operations.

ADS-B technology is a next-generation surveillance technology incorporating both air and ground aspects. It provides air traffic control with a more accurate picture of the three-dimensional position of the airplane in the en-route, terminal, approach, and surface environments. The airplane provides the airborne surveillance as a broadcast of its identification, position, altitude, velocity, and other information.

The NASA variant of the U-2S airplane, called the Earth Resources (ER-2) airplane, remains unrivaled in the art of sustained high-altitude flight. Capable of routinely cruising above FL650, which had been considered, at inception, the domain of only the most exotic experimental research aircraft types. Nicknamed the “Dragon Lady,” the U-2S research testbed remains one of the most advanced aircraft in the world. The exceptional military design, security guidelines, and performance envelope of the ER-2 airplane made the integration of the avionics more challenging.

III. Systems Background

The ER-2 airplane is being equipped with an ADS-B system to comply with an FAA mandate to operate in the National Airspace System (NAS). Equipage of ADS-B provides the ER-2 airplane with modern display capabilities to provide air-to-air passive surveillance and TCAS active surveillance functions (Fig. 1). The avionics suite capabilities include transmitting and receiving ADS-B data, receiving a Wide Area Augmentation System (WAAS) signal to provide more accurate global positioning system (GPS) data. The ability to power and charge pilot carry-on equipment and a new backup electronic instrument system will provide panel information.

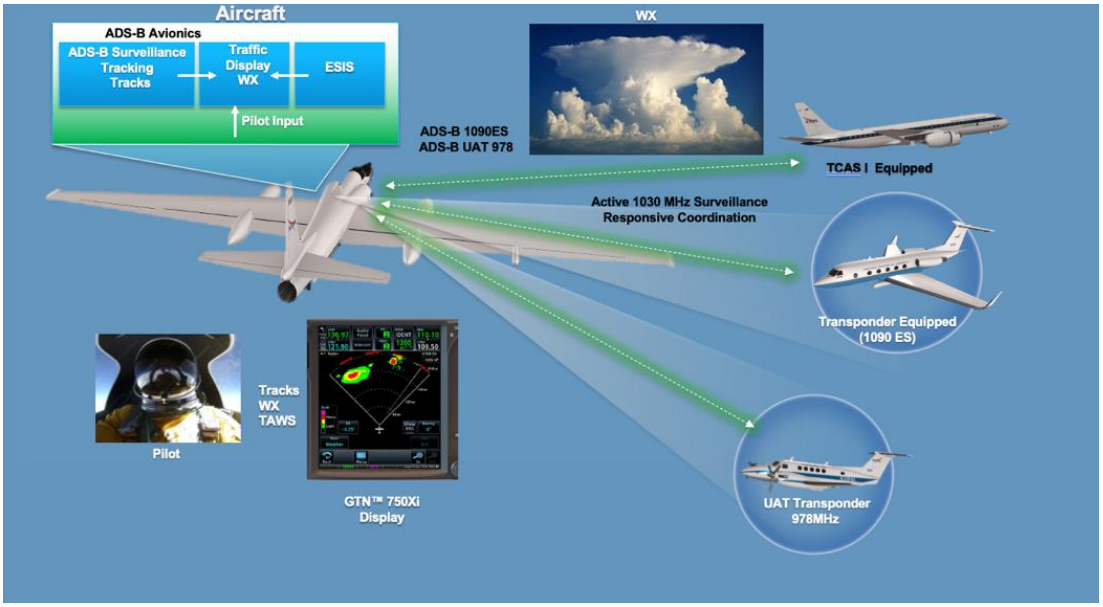


Fig. 1 The concept of operations for Automatic Dependent System-Broadcast (ADS-B) and the Traffic Alert and Collision Avoidance System (TCAS).

A. Architecture

An ADS-B coupled with TCAS-I/identification friend or foe (IFF) equipment for cooperative/active traffic surveillance is shown in Fig. 2(a). The ER-2 ADS-B capable aircraft uses the GPS receiver to derive precise position, speed, and track. ADS-B surveillance combines that information with the aircraft barometric altitude, aircraft type, and aircraft identification number (or flight number). This ADS-B information is continuously broadcast to nearby ADS-B capable aircraft and to an FAA ground-based transceiver network.

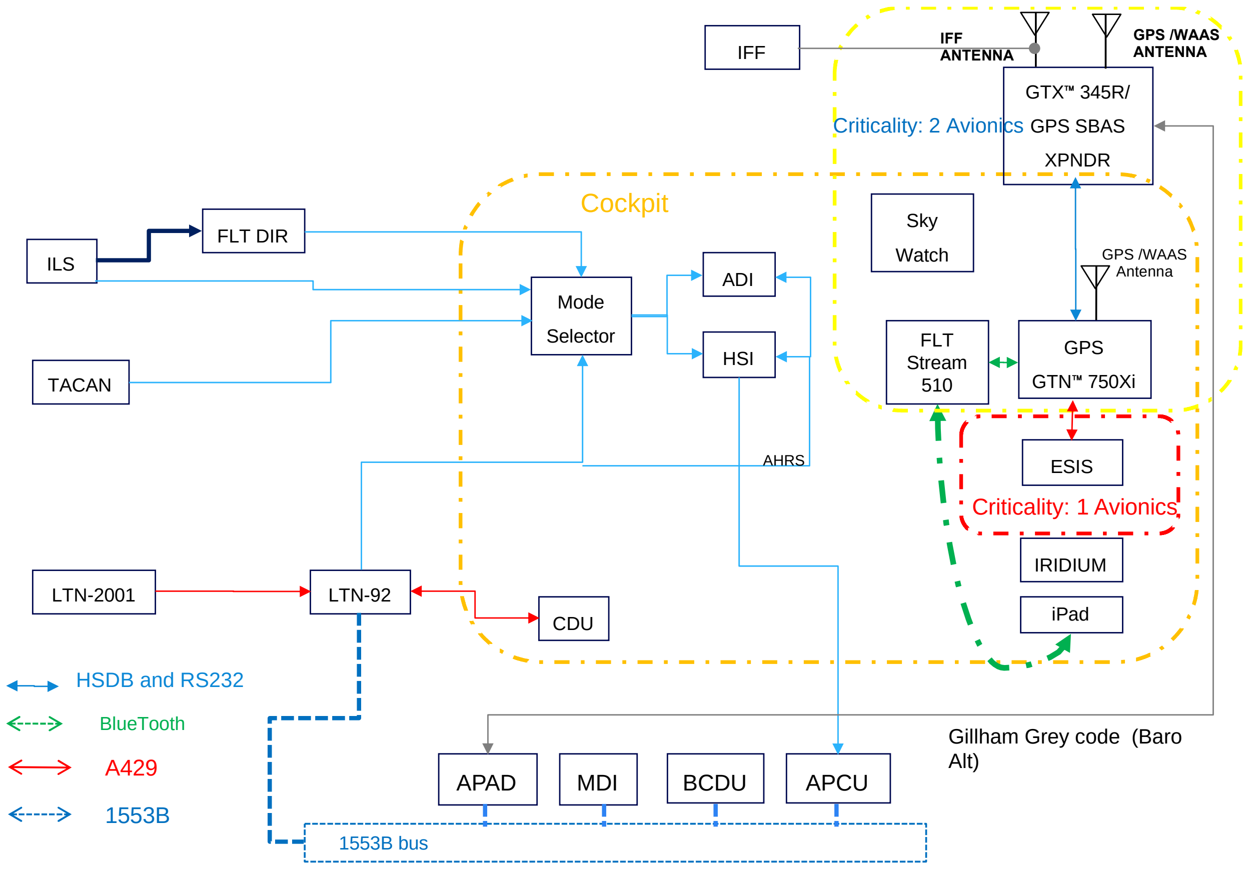


Fig. 2(a) The architecture of the Automatic Dependent Surveillance-Broadcast Out/In system.

The ADS-B compliant architecture comprises several aircraft subsystems and components: the Garmin Ltd. (Olathe, Kansas) GTX™ 345R transponder; the Garmin GTN™ 750Xi touchscreen flight navigator; the Trans-Cal Industries (Van Nuys, California) IA-RS232C-SS interface adapter; an IFF antenna; and a GPS/WAAS antenna. The Garmin GTX™ 345R subsystem is the major portion of the ADS-B Out information. GTX™ 345R transponder, which is compliant with DO-260B [3], provides satellite-based surveillance navigation using a 15-channel GPS/WAAS avionics receiver and a dual-band ADS-B In 1090ES/universal access transceiver (UAT) data link that is configured to broadcast ADS-B Out on 1090 MHz. For this application, as required by the FAA by 14 CFR 91.227 [4], the GTX™ 345R transponder is configured to transmit at the 1090-MHz frequency. GTX™ 345R transponder will also provide other ancillary functions, including storage and retrieval of aircraft configuration data.

The display system of the GTN™ 750Xi touchscreen flight navigator provides ADS-B status, ownship, and traffic and weather information. GTN™ 750Xi display also provides terrain maps and Terrain Avoidance Warning System (TAWS) alerting. Figure 2(b) shows the ER-2 ADS-B Out/In system architecture. The LRU integration of the ADS-B Out (the GTX™ 345R transponder), the ADS-B In (the GTN™ 750Xi touchscreen flight navigator), and the IA-RS232C-SS interface adapter are shown in Fig. 2(b). The L3Harris Technologies (Melbourne, Florida) Electronic Standby Instrument System (ESIS), MAG-3000, and the Mid-Continent Instruments (Van Nuys, California) MD93H Clock/USB are included as new aircraft capability.

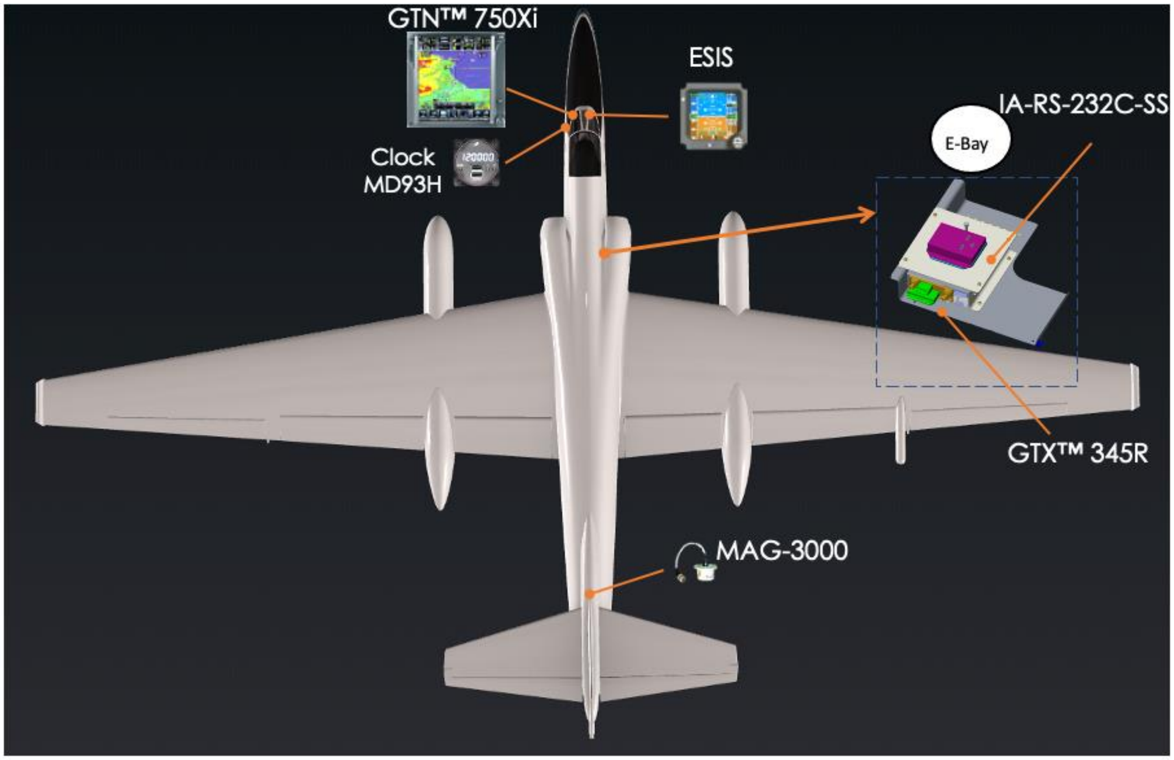


Fig. 2(b) The ER-2 Aircraft LRU Integration.

B. Aircraft Design and Integration

The ADS-B antenna integration posed a major design challenge for radio communications. The challenge was to optimize performance with at least one antenna to cover the full range of 360 deg of azimuth with sufficient radio frequency (RF) link margin for transmission. First, ADS-B signals required the use of a very low-loss RF cable because of the long length of the ER-2 aircraft. The RF cable had a maximum coaxial loss of 2.8 dB per 100 ft. Second, the RF link minimum budget required ADS-B transmission power for 1090 Extended Squitter (ES) is 125 W. The measured RF cable length and connectors had a maximum coaxial loss of 2.8 dB and thus yielded over 125 W minimum at the IFF antenna. Third, limited antenna placement for optimized performance required the ADS-B architecture to use the existing ER-2 IFF antenna mounted at the bottom of the fuselage, along with an RF switch to switch between ADS-B and IFF transmissions for radio communications; see Fig. 2(c) and Fig. 2(d). The surveillance design (security guide) relies on ADS-B transmissions for vehicle flight operations below FL600 and IFF Mode C for altitudes greater than or equal to FL600. Fourth, special consideration was given in the design of the avionics to survive the harsh environment of the ER-2. Fifth, the leading challenge was integration of civilian avionics into federated military avionics. The ER-2 legacy closed architecture used specialized mission computers, 1553 bus standards, and interfaces that apply to military aviation, which are not compatible with modern civilian aviation standards. The NASA approach used a standalone architecture for the embodiment of ADS-B (civil) integration on complex military avionics. The architecture used a separate ADS-B system for civilian operations and an IFF transponder for military operations.

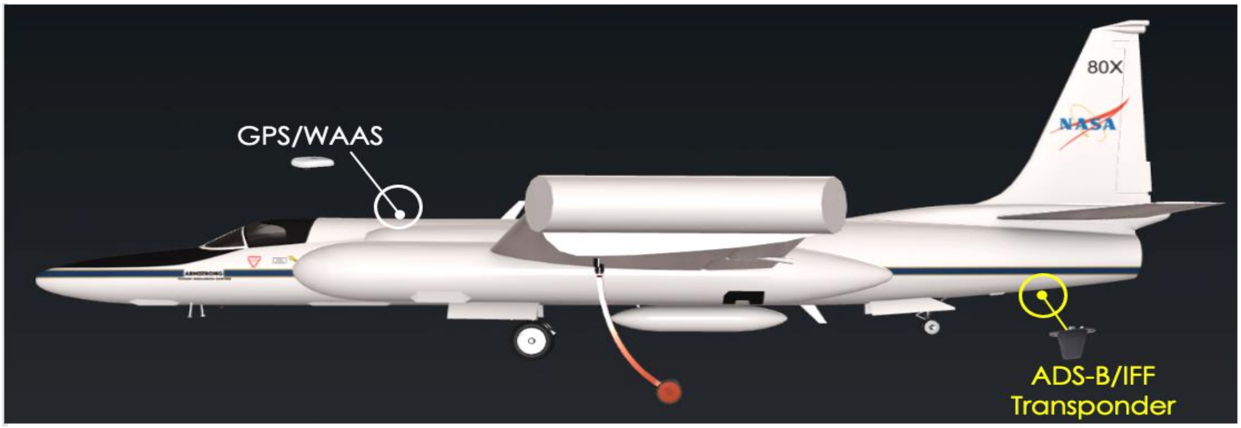


Fig. 2(c) Antenna integration on the ER-2 airplane.

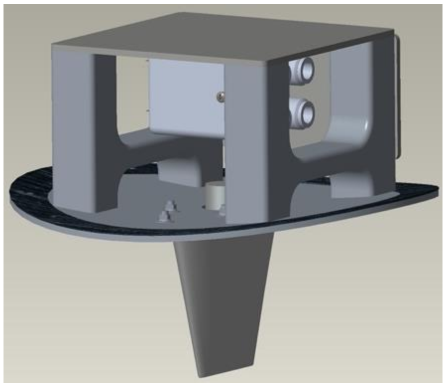


Fig. 2(d) The antenna integration radio frequency switch on the ER-2 airplane.

IV. Flight-Test System

The ER-2 functional capabilities and flight-test objectives are summarized in table 1. During the flight research, the high-altitude definition for all flight conditions is above FL600, which is NAS Upper Class E airspace, and definition of low-altitude is at or below FL600 or within the NAS Class A airspace.

Table 1. Top-level test objectives for flight-testing.

Flight system	Functions	Test objectives
1. ADS-B Out GTX™ 345R System	The Garmin Ltd. (Olathe, Kansas) GTX™ 345R ADS-B Out transponder is a solid-state unit that provides a built-in GPS/WAAS position source and enables the ER-2 airplane to transmit ADS-B Out information, such as position, altitude, and airspeed.	Validate that the ADS-B Out performance requirements per AC 20-165B [5] are met as installed on the ER-2 airplane for low-altitude flight operations.
2. IFF Mode C AN/APX-101 System	The AAMSI (Fort Lauderdale, Florida) AN/APX-101 identification friend or foe (IFF) Mode C transponder provides military and civilian air traffic control interrogation systems to identify aircraft, vehicles, or forces as friendly.	Validate the IFF Mode C performance equipped on the ER-2 vehicle for high-altitude flight operations.
3. Interface Adapter Trans-Cal IA-RS-232C-SS **RF switch**	The Trans-Cal Industries (Van Nuys, California) IA-RS232C-SS interface adaptor is a solid-state microprocessor that receives analog pressure altitude data (Gray code) from the airplane autopilot and converts those data into serialized data onto another output port. The ADS-B Transponder transmits the serialized pressure altitude data. The RF switch selects IFF or ADS-B in Manual and Auto	Validate that the ADS-B system transmits barometric altitude accurately to within 125 ft. Validate the RF Switch equipped on the ER-2 airplane for selection of IFF or ADS-B using a pilot manual switch or automatic at FL600.
4. ADS-B In GTN™ 750Xi Display System	The Garmin Ltd. (Olathe, Kansas) GTN™ 750Xi ADS-B In Display is a solid-state display system with a touchscreen interface, that provides air-to-air situational awareness and weather data to the pilots.	Validate the GTN™ 750Xi performance of the Display information per the ADS-B In Advisory Circular AC 20-172A [6] for the symbolic display of surveillance traffic and alerting with targets of opportunity.
5. ESIS Display System	The L3Harris Technologies (Melbourne, Florida) Electronic Standby Instrument System (ESIS) is a solid-state instrument display system that provides the pilot with attitude, airspeed, altitude, vertical speed, and heading data.	Cross-validate the ESIS flight information with the standby instruments during normal flight operations and takeoff and landings. Use a Cooper-Harper rating scale.
6. Magnetometer (MAG-3000)	The L3Harris Technologies (Melbourne, Florida) MAG-3000 magnetometer is a solid-state device that serves as the external magnetic/heading source for the ESIS.	N/A
7. iPad mini	The Apple (Cupertino, California) iPad mini provides a secondary source for chart sectional maps and display.	Validate that the current flight plan on the iPad mini can be transmitted/loaded on the GTN™ 750Xi using a wireless connection. Cross-validate the iPad mini digital map information with the GTN™ 750Xi display using a wireless connection during flight operations.
8. TCAS I SKY899	The L3Harris Technologies (Melbourne, Florida) TCAS I active surveillance function provides traffic advisories and collision avoidance.	Validate the interoperability of the integrated ADS-B and TCAS I system.

A. Test Van

The test van served as a test platform for the system integration, verification, and validation tests prior to installation on the ER-2 airplane. A van equipped with ADS-B and GPS roof-mounted antennas provided the capability of transmitting the ADS-B messages. The ADS-B-configured parameter elements as required by 14 CFR 91.227 comprised the International Civil Aviation Organization (ICAO) address, emitter category, and call sign of the NASA ER-2 airplane as the transmitting test target. Vigilant Aerospace (Oklahoma City, Oklahoma) commercial off-the-shelf software and a tablet display were used in the test van to verify the ADS-B Out information. All ADS-B data were successfully recorded and monitored by the FAA Technical Center in New Jersey.

B. Test Airplane

The ER-2 airplane (Fig. 3) is configured to carry scientific research and remote sensing payloads in the absence of electronic warfare systems and prime mission equipment. Distinguishing features include an LTN-92 Inertial Navigation System (INS)/LTN-2001 (Litton Aero, legacy) GPS in lieu of the LN-33 PIII (legacy) INS and associated GPS, a standardized interface for payload electrical power and control; and a custom instrument panel and console layout. The NASA ER-2 airplane is a legacy aircraft and does not contain any Block 10 or 20 upgrades, as can be seen in the United States Air Force / Lockheed Martin U-2S aircraft [7].

For all flight-testing, the integrated ADS-B Out system was mechanically installed in the electronics bay, which is in the mid-fuselage of the airplane. The ADS-B In display was installed in the cockpit. The ADS-B design installation on the NASA ER-2 airplane was per the ER-2 ADS-B Interface Control Document (ICD-001) [8] which used the design guidelines of Advisory Circulars ADS-B Out (AC 20-165B) [5] and ADS-B In (AC 20 172B) [6].

Fig. 3 The NASA ER-2 Airborne Science mission support aircraft.

C. Flight-Test Configurations and Displays

The ER-2 ADS-B system was designed to be compatible with the overall cockpit design characteristics (such as access to controls, sunlight readability, and night lighting) as well as the airplane environment. Figure 4 shows the flight crew interface for the controls and operations in flight-test configuration 1. The ER-2 cockpit instrument panel consists of navigation selector switches and digital flight displays, which provide the pilot the means for:

1) basic controls for operating the GTN™ 750Xi touchscreen flight navigator;
2) basic controls for operating the ESIS;
3) selection between the IFF mode C and ADS-B mode S for RF transmissions; and
4) basic controls for the standby analog airspeed indicator.

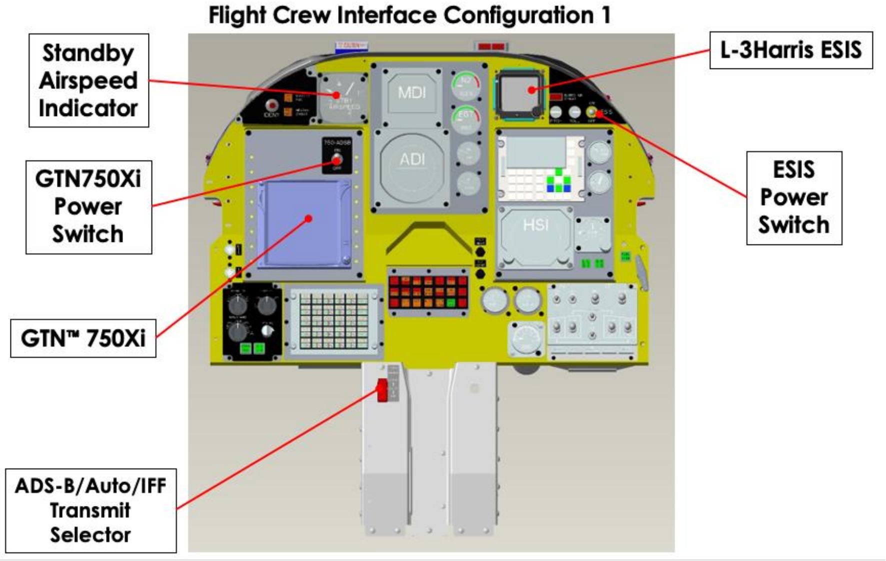


Fig. 4 Configuration 1 of the ER-2 cockpit instrument panel.

The ER-2 cockpit instrument panel shown in Fig. 5 (Configuration 2 or Full Mission) has the standby instrument removed and the TCAS control display installed and configured to be operational in the air traffic environment to validate the interoperability of ADS-B and TCAS in the National Airspace System.

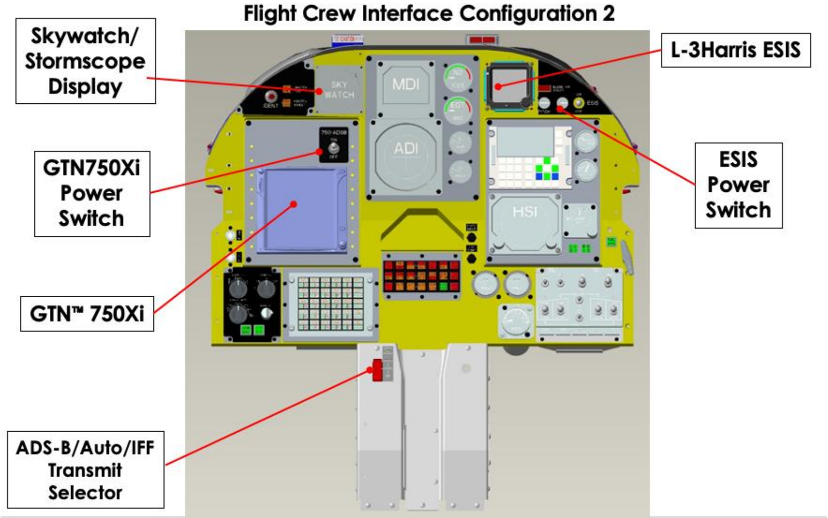


Fig. 5 Configuration 2 of the ER-2 cockpit instrument panel.

The GTN™ 750Xi display, the ESIS glass display, and the TCAS are shown in Fig. 6(a), Fig. 6(b), and Fig 6(c), respectively.

Figure 6(a) shows the intuitive and user friendly GTN™ 750Xi controls and operations in the normal mode. The ER-2 ownship position is overlaid and presented as ownship using a map-oriented display. GTN™ 750Xi display receives and displays ADS-B traffic information from other aircraft, and ground station broadcast information.

The ADS-B In GTN™ 750Xi touchscreen flight navigator displays the ADS-B traffic and weather information, as seen in Fig. 6(a), further improving situational awareness. A dual-band ADS-B GTX™ 345R transponder compliant with Technical Standard Order (TSO-166b) [9] is capable of ADS-B-In reception of air-to-air ADS-B messages directly from nearby aircraft (1090ES and 978 MHz), and air-to-ground Traffic Information Services-Broadcast (TIS-B) messages from ADS-B ground-based transceivers. The air-to-air ADS-B In messages from nearby aircraft and air-to-ground TIS-B messages from ADS-B ground-based transceivers are received, processed, and displayed on the GTN™ 750Xi display. The ESIS display provides dependable back-up for altitude, attitude, airspeed, heading, navigation and flight guidance. The L3Harris SkyWatch display controls the TCAS I active surveillance function and provides traffic advisories for collision avoidance.

ADS-B Out/In Traffic Display
(a)

ESIS Standby Instrument Display
(b)

TCAS SkyWatch-899 Display
(c)

Fig. 6 ER-2 Cockpit displays.

V. Environmental Airworthiness Tests

This section describes the test methods used to show proof of compliance with the airworthiness requirements defined in the ADS-B Environmental Test Plan for the ER-2 airplane. Environmental testing requirements for the ADS-B avionics were tailored and applied based on applicable ER-2 exposure conditions, installation locations, the intended use of the component, and the criticality of the component to meet safety or mission requirements. The environmental success criteria tests that the ER-2 Project team used in determining the suitability of a component for the ER-2 aircraft are shown in table 2. Safety-critical items are highlighted in red; mission-critical items in green. Environmental testing conducted from December 6, 2019 until February 27, 2020 showed the robustness of the current ADS-B design. Analysis of the test results showed that the current ADS-B design, subsystems, and components are expected to perform their full array of intended functions in intended environments and under emergency contingency scenarios.

Table 2 Environmental success criteria.

LRU	Aircraft Location	Pressurized	Vibration	Temp Nominal Conditions	Temp Off-Nominal Conditions	Rapid Decompression	Explosive Decompression
GH-4001	Cockpit	Yes	Operate	Operate	Operate	Operate	Fail Safe
MAG-3000	Dog House	No	Operate	Operate	Operate	N/A	N/A
GTN-750 Xi	Cockpit	Yes	Operate	Operate	N/A	Fail Safe	Fail Safe
GTX-345R	E-Bay	Yes	Operate	Operate	N/A	Fail Safe	N/A
IA-RS232C-SS	E-Bay	Yes	Operate	Operate	N/A	Fail Safe	N/A

A. Temperature

Thermal testing used harsh temperature exposures to obtain data to help evaluate the effects of temperature conditions on equipment safety, integrity, and performance. The thermal response of the L3Harris Technologies

(Melbourne, Florida) MAG-3000 met the high and low constant-temperature exposures. The safety-critical ESIS insulated with an aerogel blanket performed exceptionally well for the worst-case test at -65 ºC and maintained a thermal response of -10 ºC (a positive margin of 55 ºC) during the six-hour test. Thus, the ESIS unit continued to function and permits safe operation at high altitudes under emergency contingencies.

B. Vibration

Vibration tests for the random vibration spectra showed that equipment can be expected to survive the vibration exposures in the designated aircraft locations. Based on the vibration spectral data, the performance of the GTN™ 750Xi unit showed the ability to function within specification limits when subjected to representative flight vibration levels, and that the equipment is sufficiently robust. All the ADS-B subsystems exceeded or passed the vibration requirements for the ER-2 airplane zones, and the equipment has been shown to have a certain robustness.

C. Rapid and Explosive Decompression

The results of assessing the safety hazards of the rapid and explosive decompression tests indicated that the current design exceeded the environmental success and fail-safe criteria. The large instantaneous decrease in atmospheric pressure was accomplished by using an explosive detonation device that shattered the pressurized glass barrier, as illustrated in explosive decompression tests; see Fig. 7(a). All the ADS-B subsystems passed the rapid decompression tests without anomalies and continued to operate. The explosive decompression tests for the MD93H Clock/USB, GTN™ 750Xi unit, and the ESIS unit passed without anomalies and continued to operate and will not endanger cockpit personnel; see Fig. 7(b).

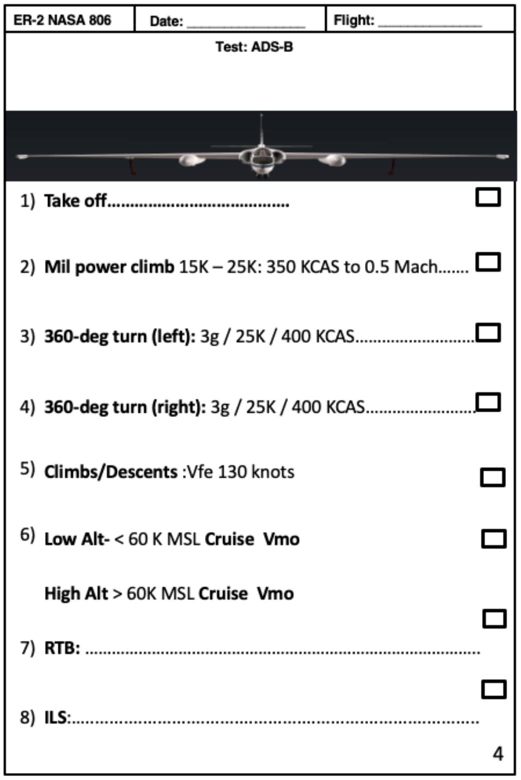
Fig. 7 Explosive decompression testing (photograph courtesy NASA / Ricardo Arteaga).

VI. High-Altitude Flight Tests

This section describes the flight-test methods and encapsulates the ADS-B measurements required from the flight tests. The FAA Surveillance Broadcast Services System (SBSS) Laboratory at the FAA William J. Hughes Technical Center (WJHTC) (Atlantic City, New Jersey) monitored and recorded the flights with the ADS-B ground stations in Mojave, California and Victorville, California. The WJHTC personnel processed the recorded data to create spreadsheets and geographical plots of the flights of the ER-2 airplane.

A. Conduct of Flights and Profiles

The flight-test scenarios flew the ER-2 airplane within its performance envelope. Pilots flew at various altitudes in low- and high-altitude cruise operations. Figure 8(a) shows the ADS B flight-test card and maneuver profiles used for the three flights. The flight profile was flown on all ADS-B system approvals. The profile need not be flown exactly, and variances for air traffic control clearances and vectors were considered. Flight tests, at a minimum, should last for at one hour. The low-altitude and high-altitude profiles discussed in paragraphs 4-3 b (1) through (6) in AC-20-165B are listed below.



ER-2 NASA 806	**Date:** ______________	**Flight:** ____________

Test: ADS-B

1) **Take off**....................................... ☐

2) **Mil power climb** 15K – 25K: 350 KCAS to 0.5 Mach....... ☐

3) **360-deg turn (left):** 3g / 25K / 400 KCAS.......................... ☐

4) **360-deg turn (right):** 3g / 25K / 400 KCAS........................ ☐

5) **Climbs/Descents** :Vfe 130 knots ☐

6) **Low Alt-** < 60 K MSL **Cruise Vmo** ☐

High Alt > 60K MSL **Cruise Vmo** ☐

7) **RTB:** .... ☐

8) **ILS:**...

4

Fig. 8(a) Flight-test maneuver profiles for the ER-2 airplane.

(1) Location of Flight. Pilots conducted flight tests within the NAS and at Palmdale Regional Airport (PMD). The Instrument Landing System (ILS) approaches were accomplished using the PMD approach plate, on which the ground elevation is shown to be 2503 ft mean sea level (MSL). Fig. 8(a), shows the ADS-B flight-test card and maneuver profiles used for the two flights.

(2) Altitudes. Pilots flew at low and high altitudes throughout the flight within the ADS-B coverage region to test the required performance capabilities.

(3) Low-Altitude Flight-Test Profile. The low-altitude flight tests with the ER-2 airplane equipped with ADS-B (RF transmit) were flown below FL600. Maneuver profiles delineated in the test cards were performed. Figure 8(b) shows the low-altitude profile in Class A airspace.

(4) High-Altitude Flight-Test Profile. The high-altitude flight tests with the ER-2 aircraft equipped with ADS-B (RF transmit) will first fly below FL600, perform the maneuver profiles there, and then transition to fly above FL600 with IFF Mode C (RF transmit) in Upper Class E airspace. Figure 8(b) shows the high-altitude profile.

(5) Turns. Pilots performed two left and two right 360-deg turns. These maneuver tests were accomplished to ensure the ADS-B system operated properly over the normal flight regimes of the aircraft under test. Turns used the standard rate unless limited by the aircraft's flight manual.

(6) Climbs and Descents. Pilots accomplished climbs at both the best rate and the best angle of climb. The descents were flown at maximum descent rates specified in the ER-2 flight manual. The ADS-B system was verified to perform properly during climbs and descents.

(7) Instrument Landing System Approach. Pilots performed ILS approaches to evaluate ESIS data versus the Standby instrument.

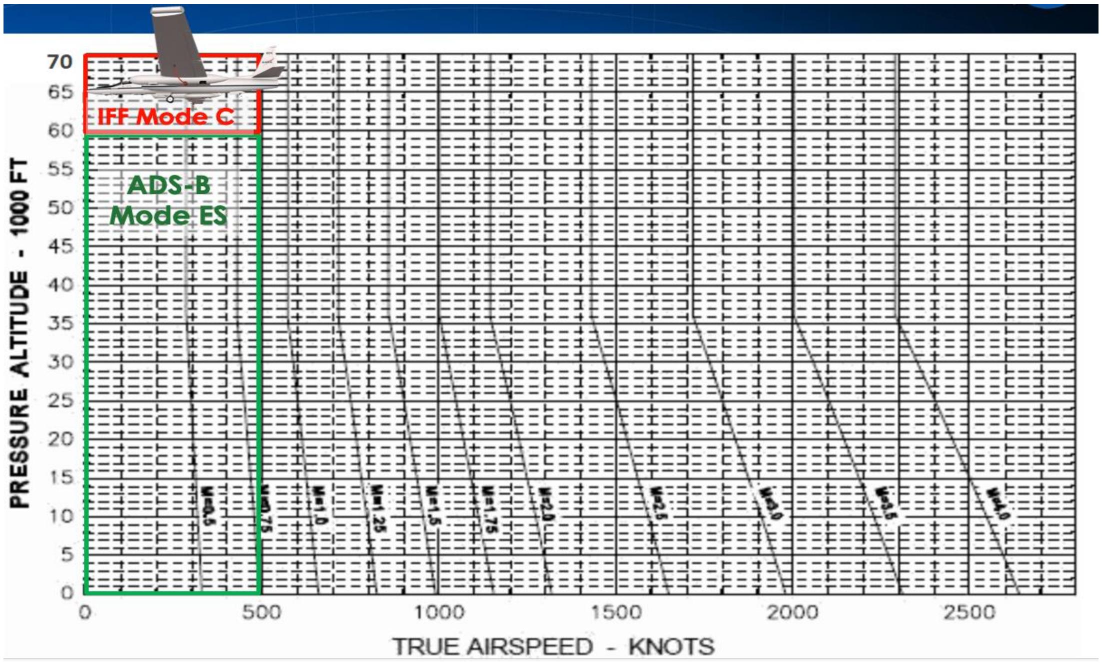


Fig. 8(b) Flight profiles for the ER-2 aircraft: Class A low-altitude airspace < FL600; and Upper Class E high-altitude airspace >FL600.

B. Flight 1

The NASA Armstrong Flight Research Center flew the ER-2 tail number 806 airplane with an ADS-B device on April 7, 2022; see Fig. 9(a). This flight was the first time a very-high-altitude engine airplane had successfully flown with ADS-B. Two FAA Public ADS-B Performance Reports (PAPR) are presented in appendix A. See Fig. 9(a). The flight lasted 2.2 hours, with both hardware and software operating nominally. Pilots flew the airplane and performed several maneuvers profiles designed to test the high-altitude performance of the system. The electronic broadcast of the state vector data of the airplane was visible by NAS ADS-B Ground stations in the Los Angeles En route airspace (Service Volume 166) and the ADS-B messages were recorded at the FAA WJHTC. The flight profile from this analysis is shown in Fig. 9(b).

Fig. 9(a) First successful flight of the ER-2 airplane equipped with an Automatic Dependent Surveillance-Broadcast device, April 7, 2022 (photograph courtesy NASA / Carla Thomas).

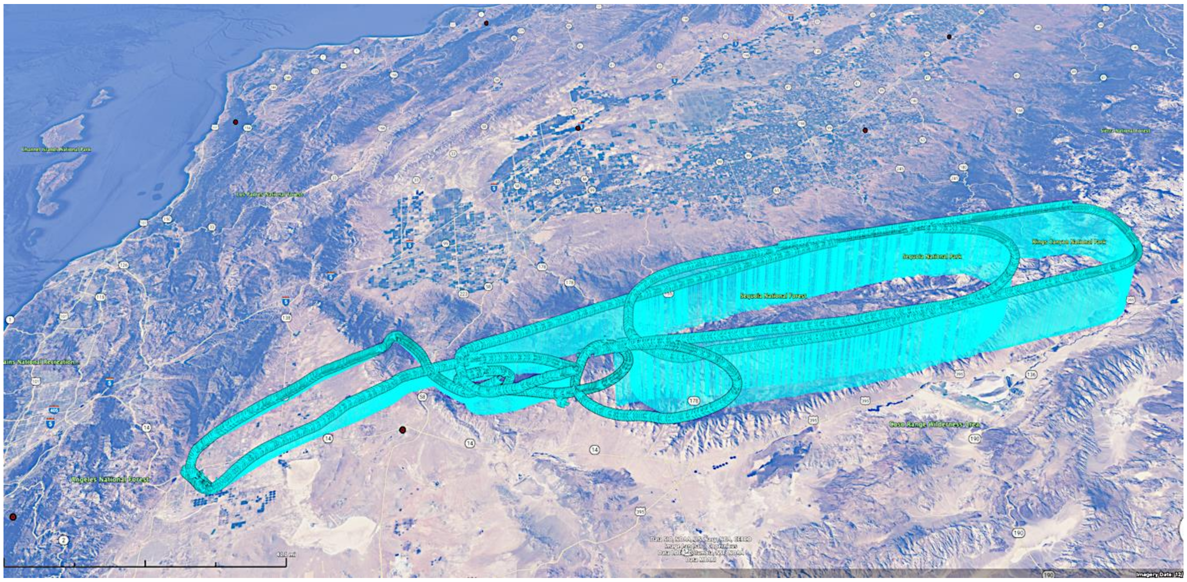


Fig. 9(b) Flight 1, April 7, 2022: Federal Aviation Administration National Airspace System ground-based tracking data (cyan) (photograph courtesy Federal Aviation Administration).

Barometric altitude is a measure of atmospheric pressure altitude at MSL. The ER-2 airplane is equipped with appropriate altimetry systems and IFF transponders for operations above FL600. The altimeter systems were designed to meet military standards. The ER-2 flight computer applies (per security guide) limitations to the Gray code pressure altitude, which limits IFF transponder altitude, reporting to FL600. FAA airworthiness guidelines state that the barometric altitude source should be the same for both an IFF Mode C transponder and an ADS-B device [9]. The legacy IFF Mode C was tested and functional using the pilot RF manual switch, since the RF automated (switch) did not transition to IFF at FL600. Redundancy in the surveillance design was proven because the pilot can manually select the IFF transponder in case of a failure of the ADS-B system.

Analysis of the ADS-B transmitted barometric altitude met the required performance accuracy of ±125 ft from the FAA radar-based surveillance. The ADS-B system received the identical Gray code pressure altitude to match the IFF transponder altitude Mode C via the IA-RS232C-SS interface adapter. The interface adapter, which converted IFF Mode C pressure altitude into serial digital data, was validated. ADS-B flight reported pressure altitudes were limited to FL600 per the ER-2 security guidelines; see Fig. 9(c).

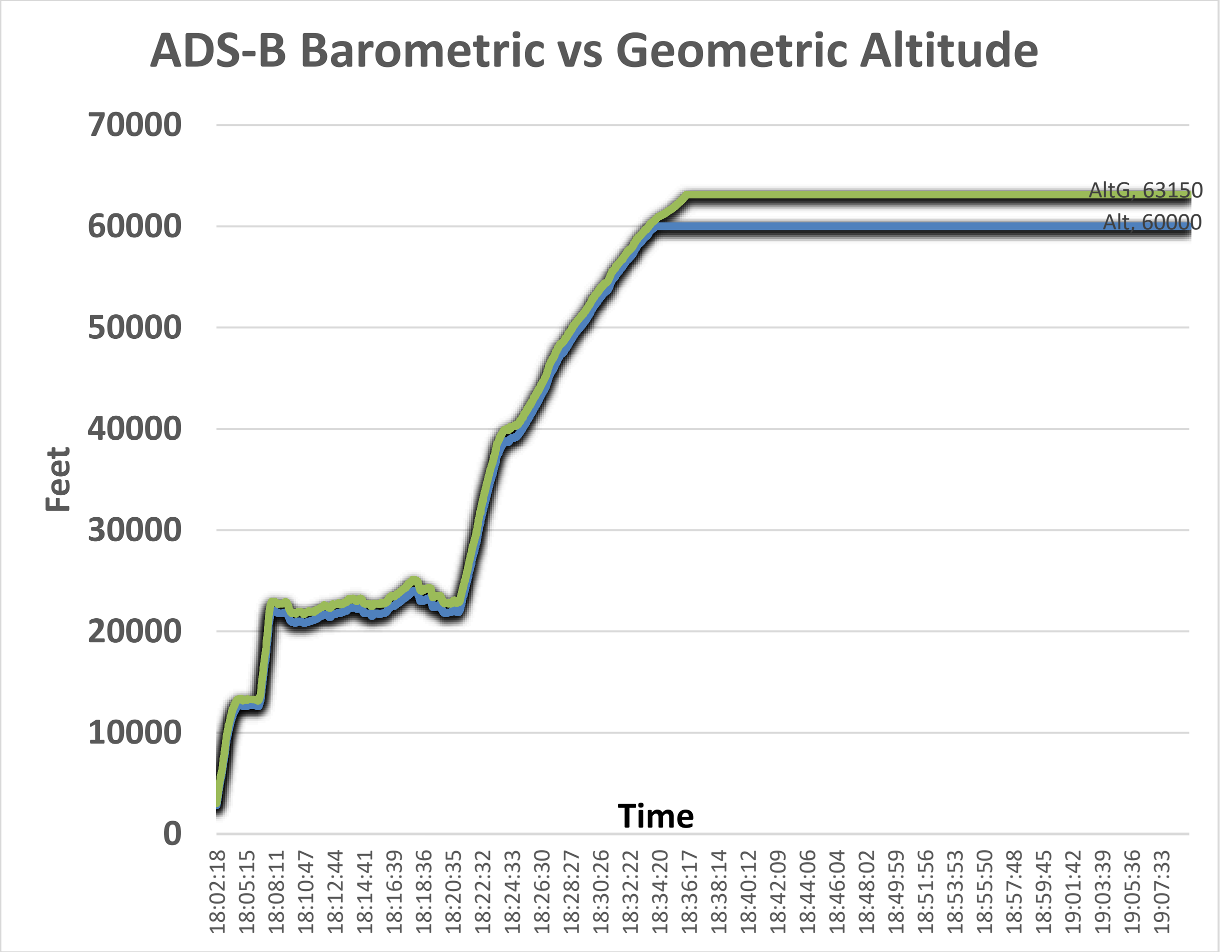


Fig. 9(c) Flight 1, April 7, 2022: Automatic Dependent Surveillance-B barometric (security-limit) versus geometric altitude (DO-260B) limited.

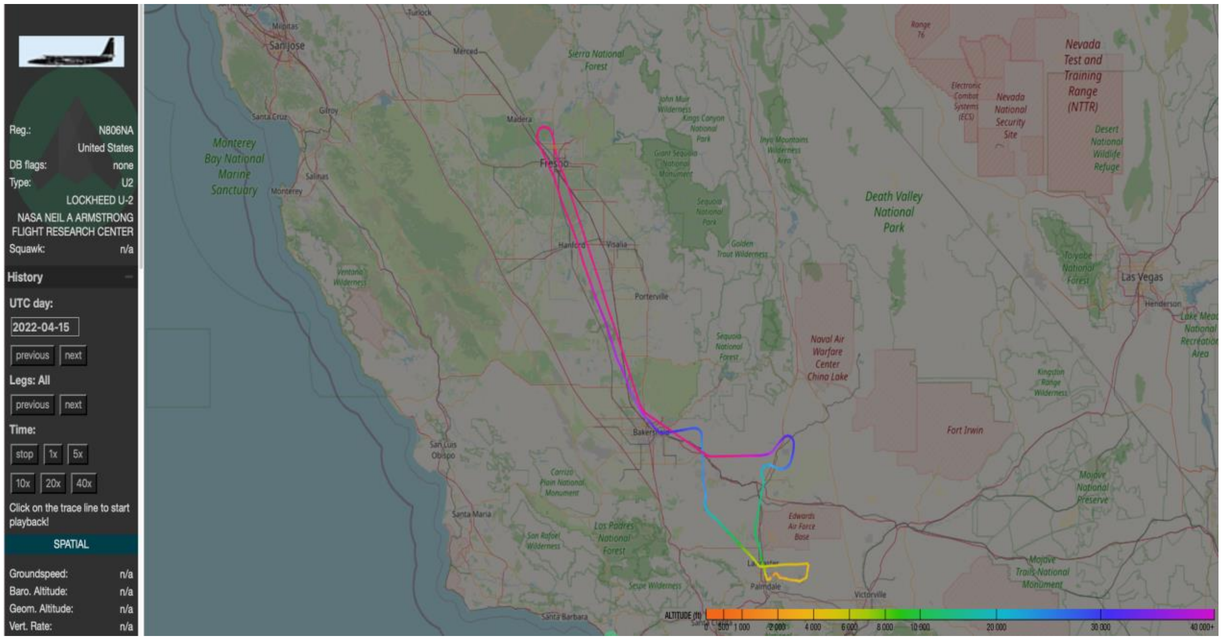
Geometric altitude is a measure of height above the World Geodetic System 1984 (WGS-84) ellipsoid and is required to be transmitted (14 CFR 91.227). The DO-260B [3] specifies a geometric vertical accuracy (GVA) with an encoded value [2] to correspond to 95 percent accuracy of 147 ft (45 m) or less. Therefore, the ER-2 airplane-reported geometric altitude as characterized by the reported GVA encoded value [2] (<45 m) was well within the measure of performance up to 63,150 ft. Geometric altitude measurements provided by many GPS receivers are restricted by International Traffic in Arms Regulations (ITAR) above 60,000 ft. Further, the 1090ES ADS-B version 2 shows geometric altitude as a difference relative to pressure altitude (maximum difference +/-3150 ft), propagating barometric altimeter errors to geometric values. Therefore, the maximum ER-2 airplane-reported geometric altitude was limited to 63,150 ft. In fact, this reporting limitation per the ADS-B standards of geometric altitudes to 63,150 ft eliminated the security requirement for the RF auto switch (interface adapter) that automatically transitions to IFF Mode C surveillance above 60,000 ft. Thus, ADS-B is operational in Class A and Upper Class E airspace within the military security guidelines and is compliant with current FAA regulations. The FAA Public ADS-B PAPR reports are flagged if the reported value for barometric or geometric altitude is greater than 65,616 ft or less than 656 ft.

Assuming that geometric altitude will be available for Upper Class E commercial supersonic and high-altitude vehicles (that is, ITAR regulatory changes that allow unrestricted GPS receivers for supersonic speeds over 1000 kn ground speed and/or altitudes higher than 60,000 ft above mean sea level (MSL) [1]) and DO-260B inherent limitations on geometric values, there are potential options in the future for surveillance in the vertical dimension. Based on atmospheric physics at high altitudes, the space between air molecules increases and air density decreases. Thus, the measurement precision of the barometric sensor is affected at high altitudes. It is believed, based on these phenomena, that barometric altitude provided by most commercial systems is neither accurate nor useful above 60,000 ft, unless designed to military standards. One surveillance option for the Upper Class E airspace is to use geometric altitude for air vehicles flying above 60,000 ft (accuracy +/- 150) for the vertical dimension.

C. Flight 2

The second flight test, shown in Fig. 10(a) was conducted on April 15, 2022, and ADS-B data were obtained. Pilots flew the mission profile using normal aircraft maneuvers, including a subsonic flight up to 45,000 ft MSL. The actual duration in rule flight time was 1.73 hr. Both the hardware and software performed without anomalies. The electronic broadcast of the state vector data of the ER-2 airplane was visible by NAS ADS-B ground stations in the Los Angeles en route airspace (Service Volumes 166, 102) and the ADS-B messages were recorded at the FAA WJHTC. The ADS-B Out flight profile from this trajectory analysis can be seen in Fig. 10(b).

Fig. 10(a) Flight 2, April 15, 2022: NASA pilot Greg "Coach" Nelson prepared for flight on the ER-2 airplane by air crew life support at the NASA Armstrong Flight Research Center (Edwards, California) (photograph courtesy NASA / Carla Thomas).



Reg.: N806NA
United States
DB flags: none
Type: U2
LOCKHEED U-2
NASA NEIL A ARMSTRONG FLIGHT RESEARCH CENTER
Squawk: n/a
History
UTC day: 2022-04-15
Legs: All
Time:
Click on the trace line to start playback!
SPATIAL
Groundspeed: n/a
Baro. Altitude: n/a
Geom. Altitude: n/a
Vert. Rate: n/a

Fig. 10(b) Flight 2, April 15, 2022: Flight track of the ER-2 airplane equipped with an enhanced Automatic Dependent Surveillance-Broadcast device.

According to an analysis PAPR report issued by the FAA, the ADS-B system on the NASA ER-2 N806NA airplane performed exceptionally well, satisfying the mandated requirements. The ADS-B Out performance accuracy and integrity requirements are presented in table 3. An analysis of the flight data from the FAA PAPR report validated that the installed system met the stated accuracy and integrity performance per14 CFR § 91.227(c)(1) requirements, listed below:

1) Ensure NIC ≥ 7 throughout the flight.
2) Ensure NACP ≥ 8 throughout the flight.
3) Ensure SIL ≥ 3 throughout the flight.
4) Ensure NACV ≥ 1 throughout the flight.
5) Ensure SDA ≥ 2 throughout the flight.

Table 3 Federal-Aviation-Administration-mandated accuracy and integrity requirements, flight 2. [5]

Parameter	FAA accuracy and integrity requirements		ER-2 accuracy and integrity measured (flight 2)	
NIC	NIC ≥ 7 nm) (1215 ft)	Rc < 370.4 m (0.2	9	No exceptions
$\mathbf{NAC_P}$	NAC_P ≥ 8 nm) (304 ft)	EPU < 92.6 m (0.05	10	No exceptions
$\mathbf{NAC_V}$	NAC_V ≥ 1	< 10 m/s (32.81 ft/s)	2	No exceptions
SIL	SIL ≥ 3 per sample	≤ $1x10^{-7}$ per hour or	3	No exceptions
SDA	SDA ≥ 2	≤ $1x10^{-5}$ per hour	2	No exceptions

In table 3, the navigation integrity category (NIC) expresses the integrity containment radius; (NACp) expresses the position accuracy in levels; the navigation accuracy category for velocity (NACv) expresses the velocity accuracy in levels; the surveillance integrity level (SIL) specifies the probability of the true position lying outside that containment radius without alerting; and the system design assurance (SDA) indicates the probability of an ADS-B system malfunction causing false or misleading position information.

The NACV parameter reported a value of 2 (<3 m/s) and is used to indicate, with a 95-percent certainty, the accuracy of the ER-2 airplane-reported horizontal velocity. As shown in table 3, an NACV of 1 (<10 m/s) or greater is required by 14 CFR § 91.227. The reported NACv thus satisfies the mandated accuracy.

D. Flight 3

The third flight test was performed at PMD on April 18, 2022. Pilots flew the mission profile using normal aircraft maneuvers, including a flight up to 45,000 ft MSL with an actual flight time of 1.8 hr. The ADS-B hardware operated without anomalies. The ADS-B Out flight profile from this trajectory analysis is shown in Fig. 11.

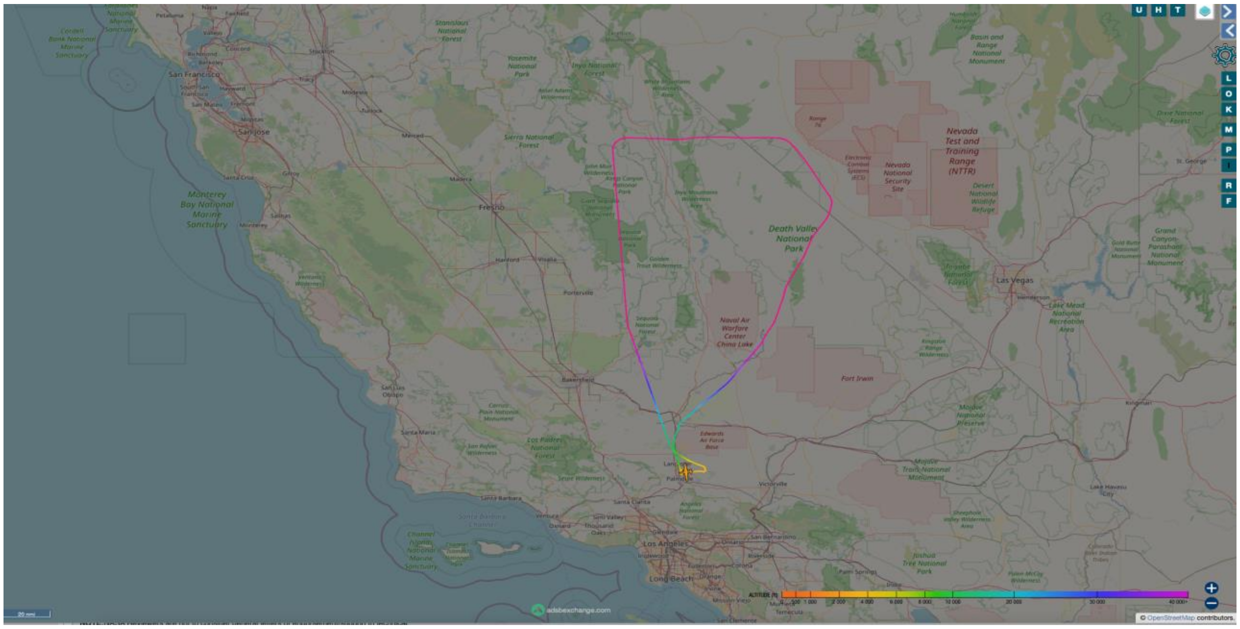


Fig. 11 Flight 3, April 18, 2022: Flight track of the ER-2 airplane equipped with an enhanced Automatic Dependent Surveillance-Broadcast device.

Analogous to the previous flight, the ADS-B system performed without exceptions. According to an analysis PAPR report issued by the FAA, the ADS-B system on the NASA ER-2 airplane performed exceptionally well without exceptions, satisfying the mandated requirements. The ADS-B Out performance requirements are presented in table 4.

Table 4 Federal-Aviation-Administration-mandated accuracy and integrity requirements, flight 3. [5]

Parameter	FAA accuracy and integrity requirements		ER-2 accuracy and integrity measured (flight 3)	
NIC	NIC ≥ 7 nm) (1215 ft)	Rc < 370.4 m (0.2	9	No exceptions
NAC$_P$	NAC$_P \geq 8$ nm) (304 ft)	EPU < 92.6 m (0.05	10	No exceptions
NAC$_V$	NAC$_V \geq$ 1	< 10 m/s (32.81 ft/s)	2	No exceptions
SIL	SIL ≥ 3 per sample	$\leq 1\text{x}10^{-7}$ per hour or	3	No exceptions
SDA	SDA ≥ 2	$\leq 1\text{x}10^{-5}$ per hour	2	No exceptions

E. Automatic Dependent Surveillance-Broadcast In / Traffic Alert and Collision Avoidance System

During high-altitude cruise flight operations, it is critical to convey information regarding aircraft that pose traffic threats and the information necessary for conflict detection and avoidance. The flight combined an integrated ADS-B passive surveillance and TCAS active surveillance system for high-altitude aircraft with enhanced displays designed for ADS-B traffic information and alerting and TCAS to provide increased situational awareness. A transponder-based collision avoidance system has the advantage of providing immediate protection against the vast population of aircraft already equipped with either the current Air Traffic Control Radar Beacon System (ATCRBS) or the ADS-B Mode S transponder. The TCAS active surveillance is also required to validate an ADS-B passive surveillance intruder.

Pilots tested the ADS-B Out/In functionality on the NASA ER-2 airplane for situational awareness. Pilots also evaluated the ADS-B traffic advisories and audio alerts to ensure they were correct, and that the audio could be discerned. Performance was assessed on aircraft targets-of-opportunity that passed by in a relatively close encounter with traffic advisories. Integrated ADS-B/TCAS surveillance reliability was excellent. The integrated system provided traffic advisories (bearing, range, and relative altitude) to assist the pilot in visually acquiring the threat aircraft with aural annunciations (Fig. 12). The following objectives were verified and validated during the flight:

1) Interoperability of the integrated ADS-B and TCAS I system;
2) Absence of interference (self-interrogations) between the ADS-B and TCAS system (TCAS I does not paint itself as a target, that is, TA); and
3) Absence of ghost targets on GTN 750Xi display for cooperative aircraft (four) targets of opportunity.

Fig. 12 The NASA ER-2 airplane equipped with Automatic Dependent Surveillance-Broadcast In device (photograph courtesy NASA / James G. Nelson).

F. Electronic Standby Instrument System

Electronic Standby Instrument System provided backup information for attitude, altitude, airspeed, heading, and navigation for safety of flight redundancy. The safety-critical ESIS (MIL-STD-810) replaced the analog standby airspeed gauges and replaced the standby magnetic compass. Pilots performed several takeoffs and landings to validate the ESIS system-level performance and the flight parameters displayed as required for safe flight. A Cooper-Harper rating was used to assess the ESIS display performance during the normal flight operations, takeoffs, and landings (see appendix B). ESIS performed exceptionally well compared to the analog standby airspeed during flight; the standby analog airspeed was removed after the first flight. Mach number or the ratio of flight speed (V) to the speed of sound (a) using standard day temperature in Eq. (1) was integrated on the upper left, based on pilot's recommendations (Fig. 13). The speed of sound depends on temperature (T) that varies with altitude, as the heat ratio (γ) and the gas constant (R) are constant variables (Anderson, Fundamentals of Aerodynamics, 2017). The ESIS air data system provided the pilot with all needed air data information with sufficient accuracy and reliability to satisfy the safety of flight requirements.

$$M = \frac{V}{a} = \frac{V}{\sqrt{\gamma R T}} \tag{1}$$

Fig. 13 Electronic Standby Instrument System display (photograph courtesy NASA / Ricardo Arteaga).

G. Lessons Learned

The lessons learned from the ADS-B high-altitude flight tests were uniquely challenging. These lessons learned include:

1) Use a standalone architecture for the embodiment of ADS-B (civil) integration on complex military avionics. Use a separate ADS-B system for civilian operations and an IFF transponder for military operations.
2) Surveillance redundancy, use a manual RF switch to enable the pilot to switch from using ADS-B to using IFF for recovery from a single failure.
3) Use the build-up approach (as in Configuration 1 and 2) for conversion of analog gauges to the state-of-the-art technology “glass cockpit” on legacy aircraft.
4) Human Factor evaluations of touch-sensitive screens should be performed with actual space gloves.
5) Garmin commercial off-the-shelf ADS-B had un-announced (or unexpected) features that were beneficial to the project: touchscreen displays that work with pressure-suit gloves and an environmental capability that was well beyond specifications.

VII. Conclusion

This paper presented an integrated system architecture that embodies Automatic Dependent Surveillance-Broadcast (ADS-B) Out/In technology and Traffic Alert and Collision Avoidance System (TCAS I) in a high-altitude research airplane. The unique airplane used for system testing was a National Aeronautics and Space Administration (NASA) ER-2 806 research airplane (a version of the United States Air Force / Lockheed Martin Aeronautics U-2S airplane) equipped with ADS-B and TCAS avionics. During the ADS-B design and integration on the unique high-altitude airplane, lessons were learned in solving problems with the airplane installation. Although the flight research focused on the airworthiness certification of the civil ADS-B avionic system for high-altitude flight operations, military vehicles can also benefit using a civilian ADS-B standalone architecture to satisfy the Federal Aviation Administration 2020 mandate, given that the Department of Defense is not exempt from the ADS-B Out mandate.

In early April 2022, ER-2 airworthiness flights were performed at high altitudes approaching 65,000 ft near the Palmdale Airport in California. The flight-research campaign analyzed the ADS-B Out reported data, identification friend or foe (IFF) Mode C and TCAS I surveillance data. All three flights satisfied the research objectives: 1) certify the ADS-B Out performance requirements as installed on the ER-2 airplane for low-altitude flight operations; 2) validate the IFF Mode C performance for high-altitude flight operations; and 3) validate the interoperability of the integrated ADS-B and TCAS I system. The certification of an ER-2 airplane equipped with integrated ADS-B/TCAS I avionics is fully compatible with the conventional air traffic control system and is ready for science missions.

In conclusion, this flight-test paper presented the design of an integrated ADS-B system based on the requirements for the ER-2 airplane equipage and regulatory performance standards. The AC 20-165 B airworthiness requirements, military and industry standards were analyzed, which governed the design for operations in the National Airspace. Verification and validation tests describe the ER-2 airworthiness tests, ground tests, and flight-test results for high-altitude flight operations. The contributions of this paper are relevant because the design ensures that ER-2 aircraft equipped with ADS-B/TCAS avionics will receive protection from midair collisions. The goal was to sustain the NASA ER-2 global mission of safety and efficiency to conduct science missions in the high-altitude flight regime.

Appendix A: Federal Aviation Administration Public ADS-B Performance Reports

U.S. Department of Transportation
Federal Aviation Administration
ADS-B Aircraft Performance Monitor

Public ADS-B Performance Report

Broadcast ICAO: AAF954 (52574524) **Tail Number:** N806NA **ADS-B ID:** NASA806
Period: 04/15/2022 15:16:17 - 04/15/2022 17:00:52 **Flight Plan ID:** NASA806

Operation Analysis Overview

	Analysis
Airborne 1090	☑
Airborne UAT	☐
Surface 1090	☐
Surface UAT	☐

Prepared By

Surveillance and Broadcast Services (SBS) Program
ADS-B Performance Monitor
April 16, 2022

Note: Items highlighted in red within this report indicate the ADS-B Out system installed on this aircraft failed to meet the corresponding performance requirement as specified in § 91.227.

For more information on this report, reference the User's Guide.

OMB Control Number 2120-0728 | Expiration Date 4/30/2017

Airborne 1090 Analysis Summary

Start Time: 04/15/2022 15:16:17
End Time: 04/15/2022 17:00:52

Duration: 1:44:36
Dur Modified: 1:44:33
Dur in Rule: 1:22:13

Total Reports: 23816
Processed Reports: 7088

Reported ICAO Address: AAF954 (52574524)

Tailnumber: N806NA

Link Version: 2

Out Capability: 1090

In Capability: DUAL

Flight ID: NASA806

☐ Vert Velocity Baro
☑ Vert Velocity Geo

Antenna(s): Single
SILsupp: 0

Emitter Category: 2 - Small

Exceptions:

NIC	NACp	NACv	SIL	SDA
No	No	No	No	No

Airborne 1090 Analysis

Page 3 of 4

Missing Elements

Category	NACp	NACv	Vel	Flight Id	Mode 3A	Emit Cat	BAlt	Galt
% Fail	0.04%	0.00%	0.03%	0.00%	0.00%	0.00%	0.00%	0.00%
Max dT	0:00:01	0:00:00	0:00:01	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00
MCF	2	0	2	0	0	0	0	0

Integrity & Accuracy

Category	NIC	NACp	NACv	SIL	SDA
% Fail	0.01%	0.00%	0.00%	0.04%	0.04%
Max dT	0:00:01	0:00:00	0:00:00	0:00:01	0:00:01
MCF	1	0	0	2	2

Category	NIC	NACp	NACv	SIL	SDA
Avg	9.0	10.0	2.0	3.0	2.0
Min	0	10	2	0	0
Max	9	10	2	3	2

Kinematics

Category	Velocity	Position Δ	Baro Alt	Baro Alt Δ	Geo Alt	Geo Alt Δ
% Fail	0%	0%	0%	0.07%	0%	0.07%
MCF	0	0	0	1	0	1

Other Checks

Category	Emitter Cat	Mode 3A
% Fail	0.00%	0.00%
Max dT	0:00:00	0:00:00
MCF	0	0

Category	Flight ID	Tail # Mismatch	Non-US	No "N"	Only "N"	Partial	Spaces	All Spaces	Illegal Char	Unavail Char	FP ID Mismatch
% Fail	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Max dT	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	
MCF	0	0	0	0	0	0	0	0	0	0	

Category	Air on Ground
% Fail	0.00%
Max dT	0:00:00
MCF	0

U.S. Department of Transportation
Federal Aviation Administration
ADS-B Aircraft Performance Monitor

Public ADS-B Performance Report

Broadcast ICAO: AAF954 (52574524) **Tail Number:** N806NA **ADS-B ID:** NASA806
Period: 04/18/2022 16:19:20 - 04/18/2022 18:08:40 **Flight Plan ID:** NASA806

Operation Analysis Overview

	Analysis
Airborne 1090	☑
Airborne UAT	☐
Surface 1090	☐
Surface UAT	☐

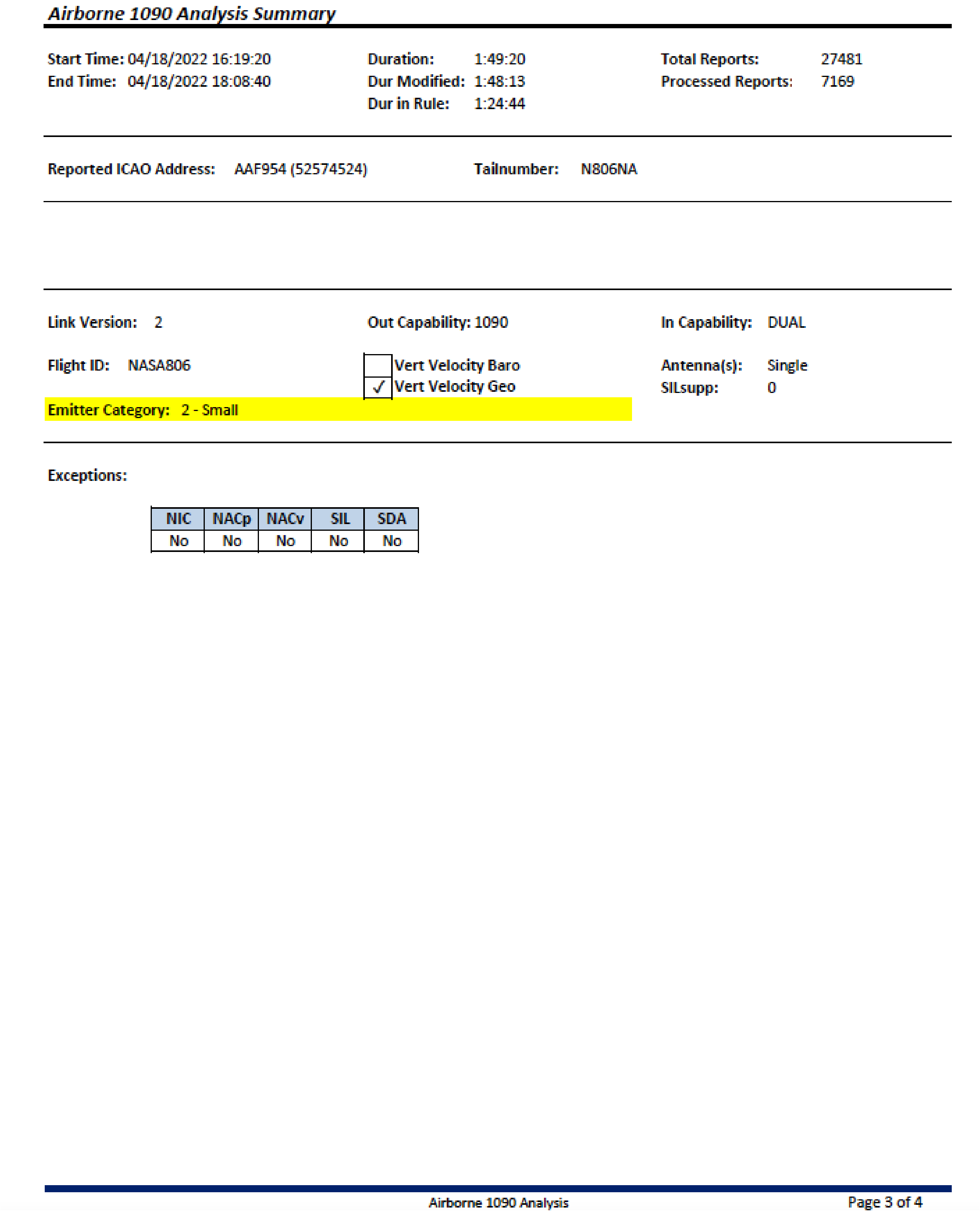
Prepared By

Surveillance and Broadcast Services (SBS) Program
ADS-B Performance Monitor
April 18, 2022

Note: Items highlighted in red within this report indicate the ADS-B Out system installed on this aircraft failed to meet the corresponding performance requirement as specified in § 91.227.

For more information on this report, reference the User's Guide.

OMB Control Number 2120-0728 | Expiration Date 4/30/2017



Airborne 1090 Analysis Summary

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End Time: 04/18/2022 18:08:40

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Dur in Rule: 1:24:44

Total Reports: 27481
Processed Reports: 7169

Reported ICAO Address: AAF954 (52574524)
Tailnumber: N806NA

Link Version: 2
Out Capability: 1090
In Capability: DUAL

Flight ID: NASA806
☐ Vert Velocity Baro
☑ Vert Velocity Geo
Antenna(s): Single
SILsupp: 0

Emitter Category: 2 - Small

Exceptions:

NIC	NACp	NACv	SIL	SDA
No	No	No	No	No

Missing Elements

Category	NACp	NACv	Vel	Flight Id	Mode 3A	Emit Cat	BAlt	Galt
% Fail	0.00%	0.00%	0.17%	0.00%	0.00%	0.00%	0.00%	0.00%
Max dT	0:00:00	0:00:00	0:00:11	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00
MCF	0	0	5	0	0	0	0	0

Integrity & Accuracy

Category	NIC	NACp	NACv	SIL	SDA
% Fail	0.00%	0.00%	0.00%	0.00%	0.00%
Max dT	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00
MCF	0	0	0	0	0

Category	NIC	NACp	NACv	SIL	SDA
Avg	9.0	10.0	2.0	3.0	2.0
Min	9	10	2	3	2
Max	9	10	2	3	2

Kinematics

Category	Velocity	Position Δ	Baro Alt	Baro Alt Δ	Geo Alt	Geo Alt Δ
% Fail	0%	0.03%	0%	0.03%	0%	0.03%
MCF	0	1	0	1	0	1

Other Checks

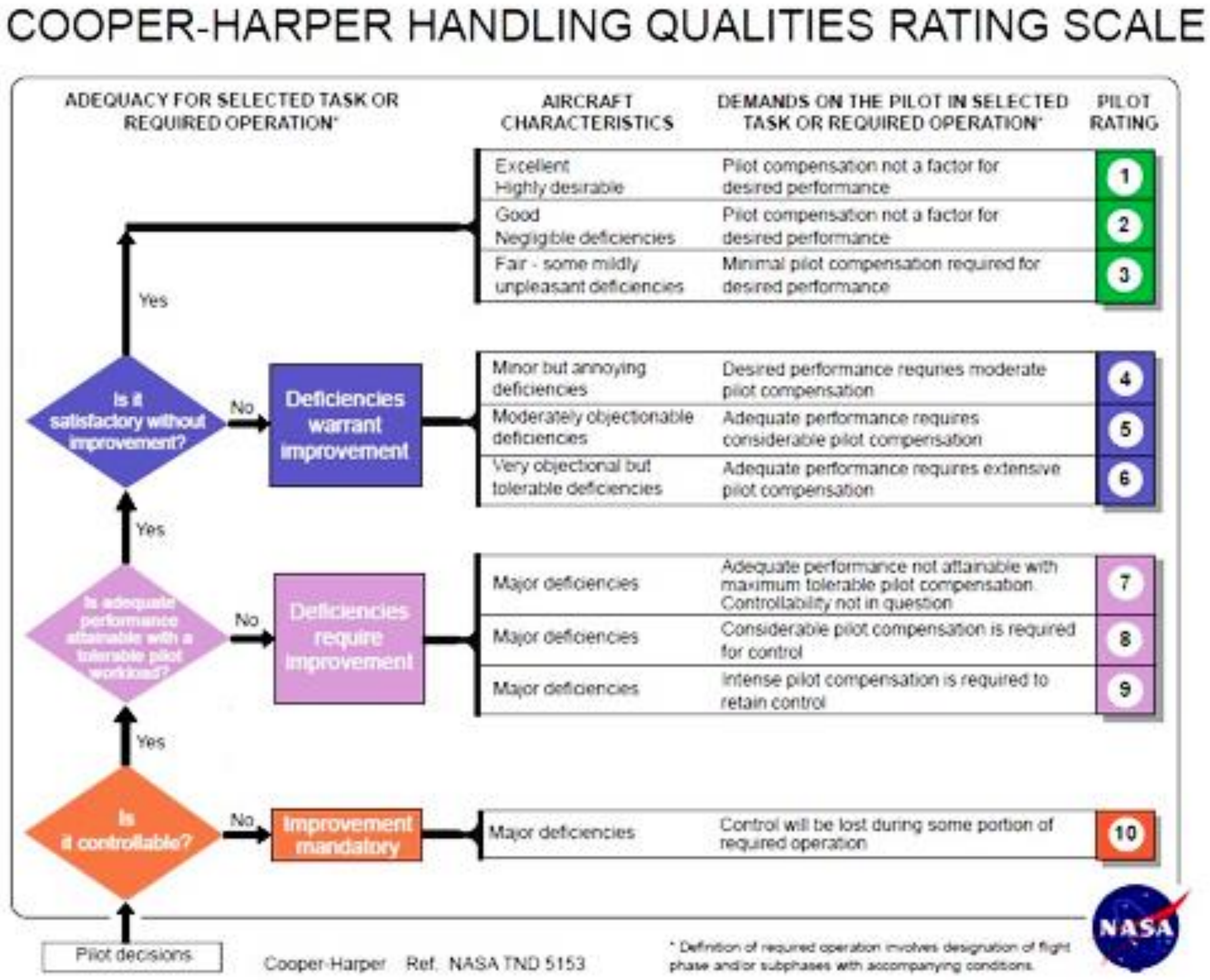
Category	Emitter Cat	Mode 3A
% Fail	0.00%	0.01%
Max dT	0:00:00	0:00:01
MCF	0	1

Category	Flight ID	Tail # Mismatch	Non-US	No "N"	Only "N"	Partial	Spaces	All Spaces	Illegal Char	Unavail Char	FP ID Mismatch
% Fail	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Max dT	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	0:00:00	
MCF	0	0	0	0	0	0	0	0	0	0	

Category	Air on Ground
% Fail	0.00%
Max dT	0:00:00
MCF	0

Appendix B: Post-Flight Analysis Cooper-Harper Ratings

A Cooper-Harper rating will be used to assess the performance of the Electronic Standby Instrument System display during the normal flight operations, takeoffs, and landings tasks.



Acknowledgements

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NASA Engineers: Justin A. Azadnia, Robert York, Mike Dandachy, Jeffery A. Nelms, Justin R. Chulyak.

NASA Avionics: Jesse F. Orellana, Bobby Henderson, Greg Bantilan, Steven J. Evans, Frank Lightbourn, Michael R. Dorval.

NASA Maintenance and Support: Alistair F. Ma, Raul E. Cortes, Darin L. Whittington, Wason Miles, Joseph R. Barr, Kevin Kraft, Cathy Freudinger.

NASA Inspector: Wissam Habbal, Alvin C. Mitchell.

Garmin Military and Government Business Development: Rick Roscoe Warren.

Dedication

This paper is dedicated to my NASA mentor, the beloved Dr. William L. Ko, inventor and artist, who recently passed away. A reproduction of one of his works of art is presented immediately below.

References

[1] Arteaga, R., et al., “Enhanced ADS-B Flight Tests on F-18 Supersonic Aircraft,” June 2020.

[2] Lehmer, R., and Smith, J., “Independent Market Study Commercial Hypersonic Transportation,” NASA Delivery Order 80HQTR20F0177, Apr. 2021.

[3] RTCA, Inc., “Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Services - Broadcast (TIS-B),” RTCA/DO-260B, RTCA, Inc., Washington, DC, Dec. 2009.

[4] U.S. Government, “Automatic Dependent Surveillance-Broadcast (ADS-B) Out equipment and performance requirements,” 14 CFR 91.227, 91-316, 75 FR 37712, June 30, 2010, U.S. Government Printing Office, Washington, DC, 2010.

[5] U.S. Department of Transportation Federal Aviation Administration, “Airworthiness Approval of Automatic Dependent Surveillance - Broadcast OUT Systems,” AC 20-165B, Dec. 2015.

[6] U.S. Department of Transportation Federal Aviation Administration, “Airworthiness Approval for ADS-B In Systems and Applications,” AC 20-172B, May 2015.

[7] https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-006-DFRC.html [accessed 19 Oct. 2022].

[8] NASA Armstrong Flight Research Center, “ER-2 ADS-B Interface Control Document,” ICD-001 Arteaga, Apr. 2018.

[9] U.S. Department of Transportation Federal Aviation Administration, “Extended Squitter Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Service - Broadcast (TIS-B) Equipment Operating on the Radio Frequency of 1090 Megahertz (MHz),” TSO-C166b, Dec. 2009.