National Aeronautics and Space Administration

NASA's Armstrong Flight Research Center

Research, Technology, and Engineering Report

2021

www.nasa.gov

From the Director for Research and Engineering

It is an honor to endorse the 2021 NASA's Armstrong Flight Research Center *Research, Technology, and Engineering Report*. As we celebrate the 75th anniversary of NASA's Armstrong Flight Research Center in Edwards, California, our talented researchers, engineers, and scientists continue to create innovative solutions to address some of the most pressing challenges facing the aerospace community.

A key Armstrong strength is the ability to develop and apply new techniques, technologies, and test methodologies to the relevant aerospace problems of the day. As we expand beyond traditional flight research projects to target improvements in subsonic and supersonic transport, we're excited to apply that strength to emerging aviation concepts in NASA's Electrically Powered Flight Demonstrator (EPFD) and Advanced Air Mobility (AAM) Projects. Our researchers will contribute to these efforts by identifying and addressing gaps in vehicle and system certification requirements; flight crew and flight deck requirements; integrated vehicle, ground and airspace infrastructure needs; and much more.

As we support NASA's aerospace research and development missions, we strive to ensure that the public is aware of our advancements. This report is a compilation of the wide range of work being conducted at NASA Armstrong, along with contact information for the associated technologists responsible for each effort. We encourage you to reach out to these researchers for more information or to discuss collaboration ideas.

Bradley C. Flick
Director for Research and Engineering

ARMSTRONG FLIGHT RESEARCH CENTER 75 1946-2021

The X-56B remotely piloted aircraft ground crew prepares the aircraft for a new flight series.

Who We Are

- **Engineers** and **technical staff** with experience in a wide range of aircraft, flight regimes, systems, and test approaches
- **Highly experienced pilots** and **technicians** with the skills to execute the most demanding flight test operations and missions
- **Project managers** and **financial analysts** with the skills to ensure that research is performed on time and within budget, maximizing value to our customers

What We Do

- Conduct **high-risk atmospheric flight research** and test projects
- Perform flight research and technology integration to **revolutionize aviation** and pioneer aerospace technology
- **Validate** space exploration concepts
- Conduct **airborne remote sensing** and science observations
- Operate platform aircraft to gain **world-class Earth science data**
- **Rapidly demonstrate promising space technologies** through suborbital testing with industry flight providers

Why We Do Research

- Make our **skies safer**, our **fuels cleaner**, and **get people to their destinations faster**
- **Lead safe transformation** of the way people and products will move in the emerging air taxi and drone delivery markets
- **Develop green technologies** that make flight more efficient (winglets alone have reduced more than 21 million tons in carbon dioxide emissions)
- Contribute to the **value-added economic activity** from aviation and related sectors, which is more than 5% of U.S. GDP
- **Reduce the environmental impact and cost** of passenger and freight air transportation
- **Deliver revolutionary aviation capabilities** to previously underserved local, regional, intraregional, and urban areas
- **Enhance American competitiveness** in the global aviation industry

How We Get It Done

- Unique **testing** and **simulation** facilities
- Wide range of **manned and unmanned aircraft**
- Internationally recognized **integrated approach to risk management**
- Expertise in **creative test development** and evaluation
- **Collaborative network** of aerospace researchers and developers
- **Quality management** and **safety systems** to meet the challenges of complex system development and testing
- **Strong center management** and **governance models** to ensure on-time and cost-effective program performance

The remotely piloted X-56B multi-utility testbed advanced researchers' understanding of the interactions between a flight controller and a flexible aircraft's structure.

From the
Center Chief Technologist

I am delighted to present this report of accomplishments at NASA's Armstrong Flight Research Center in Edwards, California. Our dedicated innovators possess a wealth of performance, safety, and technical capabilities spanning a wide variety of research areas. They not only perform tasks necessary to safely and successfully accomplish Armstrong's flight research and test missions, they also support NASA missions across the agency.

NASA Armstrong's project teams tackle the nation's most complex flight research projects. They develop novel solutions that advance emerging technologies from the concept stage and on to experimental formulation and final testing. Among the many projects taking place across the center, researchers are developing and refining technologies for electric propulsion vehicles, a low-boom flight demonstrator, ultra-efficient aircraft, and experimental X-planes. Two of our research teams were awarded NASA Early Career Initiative (ECI) awards in 2020 and 2021, and a situational awareness technology won the 2021 NASA Commercial Invention of the Year Award.

This document highlights key results and benefits from research efforts undertaken by Armstrong researchers. The projects span focus areas including electrified aircraft, supersonics, autonomous systems, flight vehicle efficiency, sensing systems, instrumentation technologies, hypersonics, and much more. The appendix includes point of contact information for researchers of each project, and we encourage you to contact them for more information.

I am proud of the work we do here at Armstrong and am pleased to share these details of our work. We welcome opportunities for partnership and collaboration, so please contact us to learn more about these cutting-edge innovations and how they might align with your needs.

David Voracek
Center Chief Technologist

Engineers from NASA Armstrong and Empirical Systems Aerospace prepare a cruise motor controller for use on the all-electric X-57 aircraft for vibration testing.

Table of Contents

Electrified Aircraft Technologies

Jet aircraft today are 80% more fuel efficient than jets of the 1960s, yet future aircraft will need to shift from carbon-based fuel to more renewable sources. Among the most straightforward means to accomplish this transition is electrified aircraft.

While electric aircraft show promise in reducing carbon emissions, the challenges in creating a practical electric aircraft are immense. Current energy storage solutions such as batteries and fuel cells possess significantly less energy density based on volume and weight than fossil fuel sources. Developing and integrating these new energy sources into aircraft requires completely new design, development, and deployment processes than what are used today. NASA's Armstrong Flight Research Center in Edwards, California is in a unique position to contribute to the advancement of this technology due to our years of experience integrating and testing new aircraft components and systems and the center's expertise in system engineering and development of fully functional flight vehicles.

NASA Armstrong Preps for First Flight of All-Electric X-57 Experimental Aircraft

NASA will use the X-57 experimental aircraft to demonstrate that electric propulsion can make planes quieter, more efficient, and more environmentally friendly. The X-57 is NASA's first all-electric aircraft. Its first flight is planned in 2022.

Distributed electric propulsion technology is based on the premise that closely integrating the propulsion system with the airframe and distributing multiple motors across the wing will increase efficiency, lower operating costs, and increase safety.

Design goals for the X-57 include a 500% increase in high-speed cruise efficiency, zero in-flight carbon emissions, and flight that is much quieter for ground communities. NASA envisions the aircraft will have a cruise speed of 172 mph, maximum operational altitude of 14,000 feet, and a range of approximately 100 miles.

The first of three X-57 aircraft configurations arrived at NASA Armstrong in October 2019 for testing and preparation for flight tests. Dubbed Modification II (Mod II), this configuration underwent ground tests in 2020 and 2021. High-speed taxi tests and first flights are planned in 2022. System design and fabrication are continuing in parallel on Mods III and IV.

A goal of the X-57 project is to help develop certification standards for emerging electric aircraft markets, including urban air mobility vehicles, which also rely on complex distributed electric propulsion systems. NASA will share the aircraft's electric propulsion-focused design and airworthiness process with regulators and industry, which will advance certification approaches for aircraft utilizing distributed electric propulsion. Another goal is to establish the X-57 as a reference platform for integrated approaches of distributed electric propulsion technologies.

Following are highlights of recent accomplishments and a look at what lies ahead in several key areas.

High-Voltage Testing

The X-57 successfully completed high-voltage testing in 2021. Researchers applied high voltage to the aircraft from an auxiliary power supply to test the functionality of the integrated systems under full power. They verified the voltage going to the aircraft, spun the motors, and checked them through the complete voltage range, confirming that they are working properly and ready for the next integration phase. Powering the aircraft externally allowed researchers to work out safety mitigations, become familiar with applying high voltage to the aircraft, and vet the internal system to ensure it is ready for verification and validation testing.

The X-57 aircraft undergoes high-voltage ground testing. Principle goals of the X-57 project are to share the design and airworthiness process with regulatory and standards organizations and establish the aircraft as a reference platform.

Battery Design and Validation

As an all-electric aircraft, the X-57 will be powered with lithium-ion battery systems. With NASA's help, contractor Electric Power Systems developed an active battery management system that enables the many cells within a battery pack to discharge at variable rates, thereby increasing battery life, reducing maintenance, and avoiding thermal runaway. Innovations in cell welding and thermal management design improved safety without adding weight. Testing validated that the battery system can power the entire flight profile and demonstrated the system's ability to isolate any rapid temperature increase to prevent it from spreading and escalating into a fire. The battery system will be integrated into the X-57 Mod II configuration for testing before high-speed taxi and flight tests occur in 2022.

Aero Database Development

Researchers at Armstrong and NASA's Ames and Langley research centers ran more than 2,500 computational fluid dynamics (CFD) cases using a variety of CFD codes to support the development of an X-57 aerodynamic database. It was implemented at NASA Langley, and Armstrong piloted simulations for controls analysis and airworthiness evaluations.

Systems Integration and Test Planning

Armstrong researchers conducted scores of build-up tests for Mod II, including weight and balance, vibration, and verification. Hardware and software upgrades were implemented to improve propulsor efficiencies. Instrumentation data will be transmitted from the vehicle to the control room, and combined systems tests will check for electromagnetic interference and compatibility issues.

Wing Loads Testing

Following the Mod II phase, Mods III and IV will feature a high-aspect ratio wing, which was tested at Armstrong's Flight Loads Laboratory to calibrate installed strain gauges for real-time loads monitoring. The new wing will permit repositioning of the electric cruise motors to the wingtips. The Mod IV configuration will include 12 smaller high-lift motors to produce distributed electric propulsion.

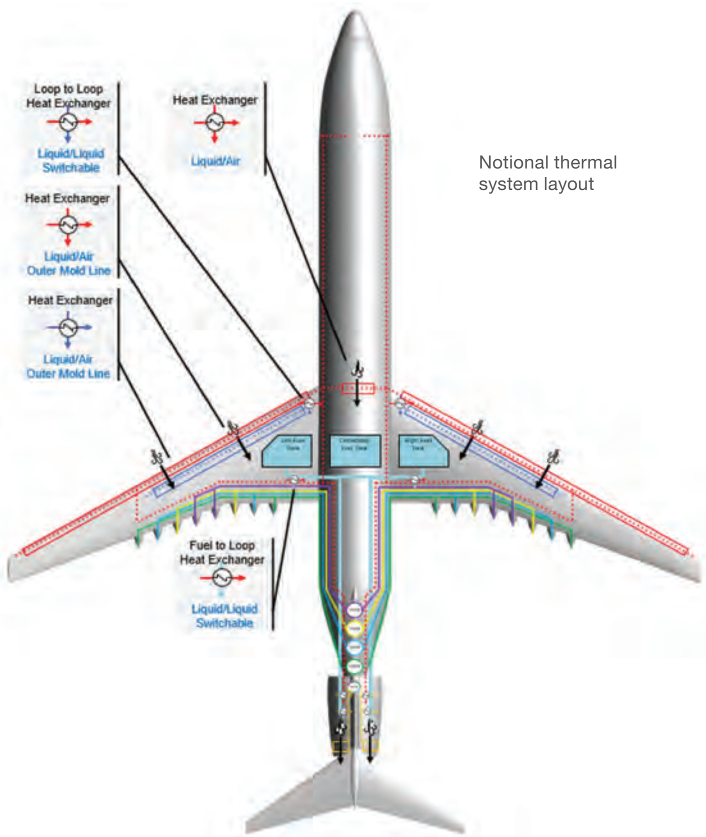
Collaborators: NASA's Langley Research Center, Glenn Research Center, Ames Research Center, and Johnson Space Center; Empirical Systems Aerospace; Joby Aviation; Xperimental; Scaled Composites; Electric Power Systems; TMC Technologies; and Tecnam

Benefits

- **Enables cleaner flight:** Electric propulsion provides a five- to 10-factor reduction in greenhouse gas emissions with current forms of electricity generation and essentially zero emissions with renewable-based electricity.
- **Reduces lead emissions:** Electric propulsion provides a technology path for small aircraft to eliminate the use of 100 low-lead (100LL) avgas, which is the greatest contributor to current lead emissions.
- **Reduces total cost of ownership for small aircraft:** This project will demonstrate high-performance electric motors, controllers, and power delivery systems that are more reliable and easier to maintain than traditional hydrocarbon-based systems.

PI: Sean Clarke | 661-276-2930 | Sean.Clarke@nasa.gov

NASA Armstrong Contributes to Subsonic Single Aft eNgine (SUSAN) Electrofan Development



Notional thermal system layout

NASA is developing a new hybrid-electric aircraft concept that uses 10 megawatt-class electric aircraft propulsion (EAP) in transport-category aircraft. The Subsonic Single Aft Engine (SUSAN) Electrofan aircraft will leverage alternative fuels and distributed electric propulsion to significantly reduce emissions while retaining the size, speed, and range of large regional jets. SUSAN is a multi-center research effort supported by NASA's Convergent Aeronautics Solutions (CAS) program to evaluate the feasibility of integrating hybrid-electric aircraft into the future airspace as well as existing airport architecture. NASA Armstrong is supporting this effort with thermal management system and control system designs.

Work to date: Subscale flight research vehicles will demonstrate the integrated flight, power, and propulsion controls approach. Armstrong is leading the effort for a 5%-scale vehicle, which was completed in 2021 and is undergoing phased flight tests at the center. Dubbed SUSIE, for Subscale Unmanned Systems Integration Effort, the aircraft features an all-electric propulsion system layout similar to the full-scale vehicle. It is designed to provide a rudimentary demonstration of flight controls with differential thrust to support development of a larger-scale higher-fidelity research vehicle. A 25%-scale vehicle being developed at NASA's Glenn Research Center is in the design stage and is tentatively planned to be flown at Armstrong, which is also supporting that effort with control system design and preliminary thermal analysis.

Full-scale concept vehicle

In addition to its work with flight research vehicles, Armstrong provided preliminary trade space evaluation for the thermal management system for the full-scale concept vehicle. The thermal management system is designed to create three levels of isothermal zones optimized for the battery, electrical system, and turbofan system heat management. Armstrong researchers also contributed to early-phase architecture design with modeling using the Transport Class Model.

Looking ahead: In addition to the phased research flights for the SUSIE vehicle, next steps include optimizing the thermal management system design and beginning the control system design for both the full-scale concept and the quarter-scale research vehicles.

SUSIE vehicle

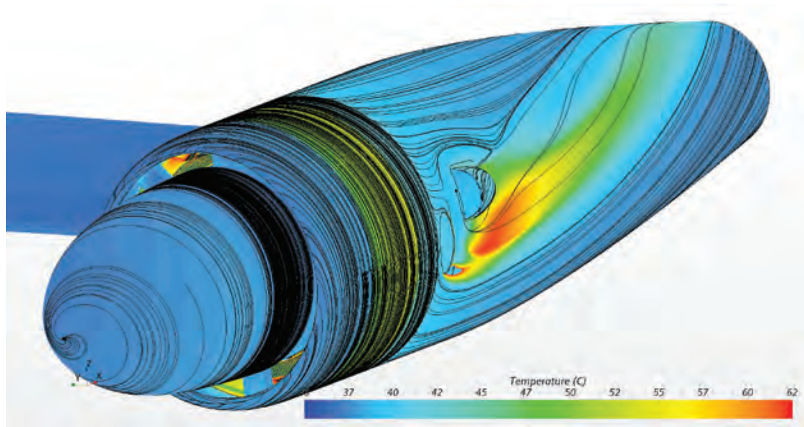
Partners: NASA's Ames Research Center, Glenn Research Center, and Langley Research Center

Benefits

- **Enabling:** Aims to identify and overcome barriers to implementing electric propulsion
- **Advanced:** Designed to prove feasibility of control architecture with subscale flight research vehicles

POC: Nic Heersema | 661-276-6112 | Nicole.A.Heersema@nasa.gov

CFD Simulations Evaluate Cooling Airflows for Electric Aircraft Motors



Visualization of the CFD skin temperatures over the X-57 Mod III electric cruise motor nacelle

The electric cruise motor of the X-57 experimental aircraft relies on the internal air flow inside the motor nacelle to dissipate any excessive heat that motor components generate as part of their operation. This approach keeps the temperature of critical motor components below normal operating limits and prevents motor failure due to overheating during aircraft operation. Working as part of a multi-interdisciplinary technical team with participants from NASA's Langley and Glenn research centers and Empirical Systems Aerospace (ESAero), NASA Armstrong researchers contributed a computational fluid dynamics (CFD) analysis model to simulate 3D air flows inside and outside the cruise motor nacelle of the X-57 aircraft.

The CFD model includes relevant rotating and stationary motor components, as well as all relevant flow physics such as prop wash, heat generation from motor hardware components, air conduction and convection heat transfer, and hot air buoyancy. Given a set of aircraft and motor operating conditions, the Armstrong-developed CFD model provides a complete description of internal and external motor air mass flow rates, velocities, temperatures, and pressures. NASA Glenn researchers use this information to determine the temperatures of the various motor hardware components, which can then be compared to established component temperature limits to determine whether the electric cruise motor nacelle configuration satisfies thermal requirements for the aircraft operating conditions under consideration.

Work to date: Detailed 3D CFD models were developed and used to analyze the complex thermal environments inside the X-57 Mods II and III cruise motors. The models were instrumental in identifying shortfalls in cooling airflows and then identifying configuration modifications that solved cooling design problems at various critical aircraft operating conditions.

Looking ahead: The research team will validate the model with data obtained during the flight research phase of the X-57 Mods II and III. The models could be further refined and adapted for use in other electric aircraft motor configurations for future flight research efforts.

Partners: NASA's Glenn Research Center, Langley Research Center, and Empirical Systems Aerospace (ESAero)

Benefits

- **Enabling:** Evaluates internal cooling airflows for aircraft electric motors to support thermal design for motor nacelles
- **Efficient:** Presents the ability to evaluate future changes to the X-57 electric cruise motor cooling requirements and for troubleshooting cooling issues that may arise during research flights

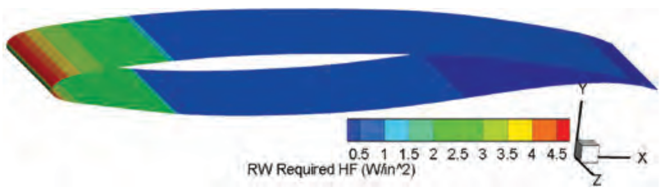
Applications

- Cooling system analysis and design for electric aircraft motors

PI: Trong Bui | 661-276-2645 | Trong.Bui-1@nasa.gov

The electric motors for X-57's Mod II vehicle and their propellers were powered up and spun together as part of an integrated spin test.

Ice Protection System Analysis for High-Efficiency Electric Aircraft



Heat flux required to maintain ice-free leading edge of wing section for selected icing conditions

NASA's High-Efficiency Electrified Aircraft Thermal Research (HEATheR) activities involve developing technologies that leverage the performance benefits of high-power, megawatt-class electric aircraft propulsion and minimize the mass, drag, and power penalties of the associated thermal management systems. Sponsored by NASA's Convergent Aeronautics Solutions (CAS) program, the HEATheR effort evaluated three hybrid-electric concept aircraft.

NASA Armstrong's analysis identified requirements for a wing ice protection system. Historically, anti-icing systems have been driven by engine outputs (e.g., venting waste heat onto aircraft wings). However, architecture changes to support electric propulsion impact this capability, meaning that ice protection system requirements must be considered early in the aircraft design process.

Work to date: Armstrong researchers determined the requirements for a wing ice protection system for all three HEATheR concept aircraft. From these requirements, conclusions could be drawn that while an anti-ice system would work for single-aisle aircraft, a de-ice system must be considered for the other aircraft concepts, requiring additional analysis.

The Armstrong team also contributed to work on the thermal management system design.

Looking ahead: This research will continue under the CAS-sponsored Subsonic Single Aft eNgine (SUSAN) project. In addition, work at NASA's Glenn Research Center on icing analysis for the Revolutionary Vertical Lift Technology (RVLT) project continues.

Benefits

- **Informative:** Provides designers of hybrid-electric or all-electric aircraft concepts with rough estimates for requirements for a wing ice protection system when designing and sizing the powertrain architecture

POC: Nic Heersema | 661-276-6112 | Nicole.A.Heersema@nasa.gov

Flight Dynamics Analysis of PEGASUS Vehicle Concept

PEGASUS concept aircraft

The Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) vehicle is a regional aircraft concept that uses electric and hybrid-electric propulsors located strategically to achieve aerodynamic and mission benefits. New analysis tools are needed to fully understand potential impacts of design choices on the dynamic response of the PEGASUS concept and other distributed electric propulsion aircraft as well as their implications for operability, safety, and certification. Researchers at NASA Armstrong developed a simulation framework and flight dynamics toolset to study potential benefits and challenges of distributed electric propulsion from a flight dynamics and controls perspective. This work is part of a multi-center NASA effort to advance distributed electric propulsion concepts.

Simulation framework: Researchers developed a six degrees of freedom (6DOF) nonlinear simulation of the PEGASUS concept vehicle for autopilot design and stability and control analysis. They evaluated the simulation at the cruise fight condition against flying qualities standards for transport-class aircraft. Results showed that with the addition of a yaw damper, the PEGASUS meets Level 1 and 2 flying qualities criteria.

Modeling toolset: The Armstrong team also developed and evaluated a flight dynamics modeling toolset that allows users to automatically update PEGASUS models based on latest design iteration outputs from the aircraft's conceptual design tool. The modeling toolset has been evaluated at the cruise flight condition and low speed flight against flying qualities for three PEGASUS design changes, and all configurations are dynamically stable. Results have been documented and published in an American Institute of Aeronautics and Astronautics (AIAA) AVIATION paper.

Looking ahead: There is potential to extend the simulation to include powertrain dynamics and evaluate it in the terminal flight phase, including a variety of crosswind and one-engine inoperative (OEI) conditions.

Partners: NASA's Glenn Research Center and Langley Research Center

Benefits

- **Enabling:** Permits efficient flight controls and flight dynamics assessments of new and modified electrified aircraft configurations
- **Advanced:** Furthers NASA's understanding of potential benefits and challenges of DEP from a flight dynamics and controls perspective
- **Innovative:** Offers the potential to help new transport-class aircraft designs realize the full benefits of DEP

PIs: Felipe Valdez | 661-276-3330 | Felipe.Valdez@nasa.gov
Curtis Hanson | 661-276-3966 | Curtis.E.Hanson@nasa.gov

Supersonics Technologies

Supersonic flight over land is severely restricted because sonic booms created by shock waves disturb people on the ground and can damage property. Innovators at NASA's Armstrong Flight Research Center in Edwards, California are working to solve this problem through a variety of techniques that measure, characterize, and mitigate sonic booms. The development of the X-59 Quiet SuperSonic Technology (QueSST) experimental plane is advancing as part of NASA's Low-Boom Flight Demonstration mission. When the new X-plane arrives from Lockheed Martin Aeronautics Company's Skunk Works® facility, NASA Armstrong researchers will qualify and flight test it.

> *"A new sonic boom recording system incorporates many new technologies and will enable us to complete our research. It's the next generation of sonic boom–and soon to be quieter sonic thump–recording systems."*

Larry Cliatt, technical lead for the acoustic validation phase of the Low-Boom Flight Demonstration mission

Shock-Sensing Probe Provides Key Sonic Boom Information

A new shock-sensing probe in development at NASA Armstrong is expected to provide researchers with key information about sonic booms. The Armstrong probe is mounted on the nose of an F-15B aircraft that flies through the shock waves of another supersonic aircraft. In addition to measuring the static pressure through the shock waves, the probe measures the change in Mach number and flow angularity. Researchers are comparing these measurements to computational fluid dynamics (CFD) models to verify those predictions. If successful, the probe will be used for the Low-Boom Flight Demonstration mission.

Work to date: In 2020 and 2021, new probe hardware was designed, fabricated, and installed to simplify assembly. A new heater/controller design was developed to ensure the internal pressure transducers remain at a constant temperature in flight. Researchers performed on-aircraft calibrations of the probe instrumentation in preparation for summer 2021 flights.

Looking ahead: The probe will be integrated on Armstrong's F-15D TN 884 and flight tested in 2022 using X-59 flight conditions. It then will be used for near-field probing of the X-59 aircraft during Phase 2 of its flight test program.

Benefits

- **High performance:** Measures flow speed, static pressure, and angularity
- **Improved measurement:** Allows for probing to be conducted at a higher closure rate, due to reduced pneumatic lag

Applications

- Facilitating aircraft design that may ultimately enable overland supersonic flight

PI: Mike Frederick | 661-276-2274 | Mike.Frederick-1@nasa.gov

NASA Armstrong Prepares for Arrival of X-59 Quiet Supersonic Aircraft

Illustration of the completed X-59
Credit: Lockheed Martin

The Low-Boom Flight Demonstration mission seeks to enable the possibility of boarding a commercial supersonic airliner and flying across the United States in half the time it takes today. To support this goal, NASA is developing the X-59 Quiet SuperSonic Technology (QueSST) airplane, which features a unique shape and technology designed to turn sonic booms associated with faster-than-sound flight into barely perceptible sonic thumps. NASA Armstrong researchers are making significant contributions to this project, particularly in the areas of studying, characterizing, quantifying, and measuring sonic booms as well as work with an external vision system, which is necessary due to the plane's unusual design. These achievements are highlighted in the following pages.

NASA will fly the X-59 above select U.S. communities to measure and record public response to its noise while flying supersonic. The resulting statistically valid data will be used to consider changing the regulation to be based on an acceptable sound level rather than a prohibition that has been in place since 1973.

Fabrication and testing continue on the 100-foot-long revolutionary aircraft. In late 2021, Lockheed Martin shipped the X-59 from Palmdale, California, to a sister facility in Ft. Worth, Texas, where ground testing will occur to ensure the aircraft can withstand the loads and stresses that typically occur during flight. There, the team also will calibrate and test the fuel systems before the X-59 returns to Lockheed's Palmdale facility for more tests.

In 2023, NASA will fly the X-59 over the test range at Armstrong to prove it can produce a quieter sonic thump and is safe to operate in the National Airspace System. More than 175 ground recording systems will measure the sound coming from the aircraft. NASA spent nearly $6 million to modernize a state-of-the-art hangar at Armstrong to house the aircraft.

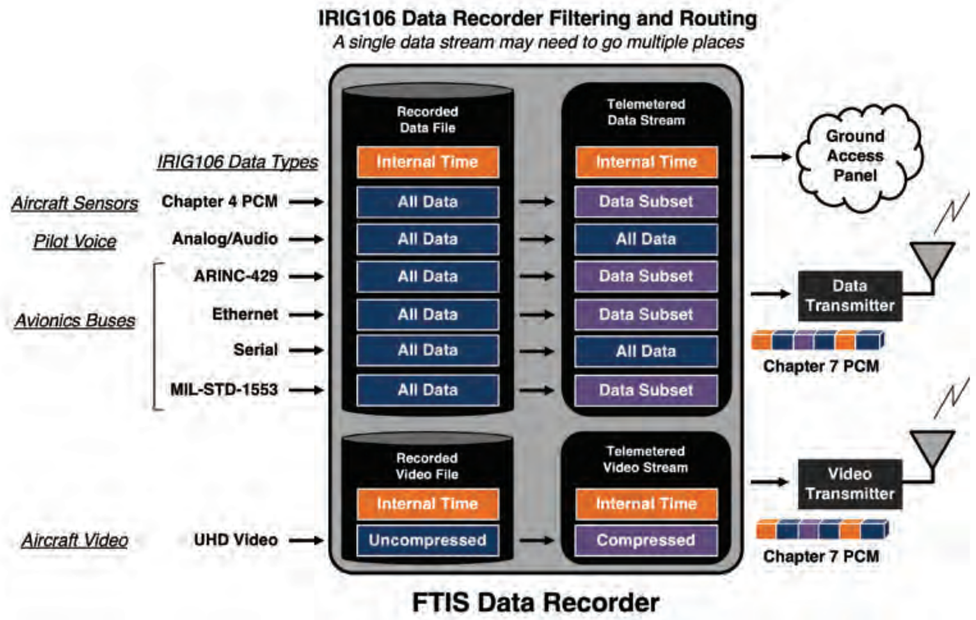
In 2024, NASA will fly the X-59 over several communities around the nation to gauge people's response to the sonic thump sound produced by the aircraft. The data collected will be provided to the Federal Aviation Administration and the International Civil Aviation Organization for their consideration in changing the existing bans on supersonic flight over land. If rules change because of NASA's data, a new fleet of commercial supersonic aircraft could become viable. Though the single-piloted X-59 will never carry passengers, aircraft manufacturers may choose to incorporate its technology into their designs.

Construction and assembly of the supersonic X-59 QueSST research plane at Lockheed Martin Aeronautics Company's Skunk Works® factory
Credit: Lockheed Martin

PI: Heather Maliska | 661-276-2843 | Heather.A.Maliska@nasa.gov

Instrumentation System Heralds New Paradigm in Flight Test Data Architecture

The Flight Test Instrumentation System (FTIS) for the Low Boom Flight Demonstrator project represents a new paradigm in flight test data architecture. This sophisticated and robust Ethernet-based system significantly increases data recording and monitoring capabilities over conventional instrumentation systems at NASA Armstrong.



The Low Boom Flight Demonstrator project will produce more than 20 gigabytes of data per hour. The FTIS is designed to acquire, process, record, and telemeter aircraft and research measurement data, eXternal Vision System (XVS) video, and pilot audio. More than 570 analog sensors will be installed on the X-59 Quiet SuperSonic Technology (QueSST) airplane to collect airworthiness and research data, and the system will process parameters from more than 60 digital avionics buses.

Whereas Armstrong's conventional instrumentation systems offer capabilities that include up to five data streams and thousands of parameters, the FTIS offers hundreds of data streams and tens of thousands of parameters.

Data Recorder Is System Core

Armstrong's existing instrumentation systems use several remote encoders to capture data from various analog sensors and periodically extract select measurements from digital avionics buses. This data is then sent to master encoders, which generate pulse code modulation (PCM) streams that are telemetered to a ground control station for real-time monitoring. If researchers need more sensors, measurements, or data subsets, then additional PCM streams, encoders, transmitters, computers, and wiring modifications may be required and often cost more time, weight, power, aircraft space, and resources.

In this updated Low Boom Flight Demonstrator FTIS architecture, a more versatile and functional data recorder replaces the PCM encoder as the core of the system. Rather than functioning simply as a data repository, the recorder acquires, processes, filters, and reroutes raw data streams in real time, thus eliminating previous sampling constraints. For more functionality, the recorder also combines multiple streams into data groups that then can be recorded to multiple files, telemetered by multiple transmitters, or sent to multiple onboard aircraft systems. For example, with a modest software change, the recorder can simultaneously archive a proprietary data stream, telemeter a subset of that data to a ground control station, and transmit a non-sensitive data subset to a chase vehicle. This change in design architecture allows for an increase in sensors, encoders, and avionics bus streams at a reduced aircraft modification time, weight, and cost.

The NASA, Lockheed Martin, and Edwards Air Force Base partnerships have been essential to getting this technology to work for Low Boom Flight Demonstrator. Throughout the FTIS development, the Armstrong Flight Instrumentation and Systems Integration branch, responsible for encoding and describing the research aircraft data it collects, and the Dryden Aeronautical Test Range (DATR), responsible for decoding and displaying the data, have expanded their knowledge in modern data acquisition and developed new tools and capabilities to support this new paradigm in flight test data architecture. The joint effort involved in making this new instrumentation scheme work will enable Armstrong researchers to support new sensors and innovations for emerging technologies and systems in the years to come.

The system hardware has been delivered to Lockheed Martin and integrated into the aircraft. The team is conducting system checkouts and calibration tests on the aircraft to prepare for the upcoming first flight.

Partners: Lockheed Martin, Edwards Air Force Base

Benefits

- **Compact:** Combines several technologies into a single system
- **Flexible:** Quickly reprogrammable to support various research test changes
- **Powerful:** Expands streams/parameters up to 100-fold, depending on design
- **Efficient:** Reduces time and cost of instrumentation modifications

PI: Shedrick Bessent | 661-276-3663 | Shedrick.B.Bessent@nasa.gov

SCHAMROQ Preps Tools and Test Techniques for Supersonic Flight

NASA Armstrong flight tested the ALIGNS visual navigation system, which is designed to enhance precise aerial positioning between two aircraft in supersonic flight. The system will be critical for acoustic validation efforts for the X-59 aircraft.

The Schlieren, Airborne Measurements, and Range Operations for Quiet SuperSonic Technology (QueSST), or SCHAMROQ, project is overseeing the testing that will validate the acoustic signature of the X-59 QueSST experimental aircraft. Specifically, the SCHAMROQ team is developing, refining, and testing the tools and techniques that will be used to characterize the near and mid-field shock structure of the X-59.

Examples include the shock-sensing probe, a device that will evaluate the characteristics of the X-59's shock waves while in flight; a schlieren photography technique to visualize the aircraft's shock waves as they distort light through a camera; and navigation software that will allow pilots to fly accurately during X-59 tests. All this technology will be placed on a NASA research aircraft that will take on the role of a chase plane and follow the X-59 during flight tests to collect data.

Work to date: In 2020 and 2021, the SCHAMROQ team performed a successful dual aircraft combined systems test (CST) of the Airborne Location Integrating Geospatial Navigation Systems (ALIGNS), which utilized a staffed control room. The ALIGNS uses dual aircraft GPS data to give the pilot a display tool to enable precision flight. The dual aircraft CST was preceded by the NASA F/A-18 CST, which transmitted GPS data as a surrogate test platform for the X-59. The Dryden Aeronautical Test Range (DATR) team proactively planned for control room operations and back shop range support, resulting in a safe and successful control room operation.

Researchers continued to develop and refine schlieren techniques of capturing shock waves through imagery. Critical to these advances was the successful flight clearance of the Airborne Turret Infrared Measurement System (ATIMS)-V pod, located on the wing of F-15 aircraft.

Looking ahead: The SCHAMROQ team will continue to refine the shock-sensing probe and schlieren systems that will measure and visualize the shock waves around the X-59 in flight. The F-15D instrumentation team also will continue to advance progress in the areas of on-aircraft integration, environmental testing, fabrication, and design.

PI: Matthew Moholt | 661-276-3259 | Matthew.R.Moholt@nasa.gov

Flying Qualities for Low-Boom Vehicles

Innovators at NASA Armstrong are developing guidelines and evaluating stability and control characteristics for the planned supersonic Low-Boom Flight Demonstration mission. In addition to stability and control evaluations, Armstrong researchers are developing a supersonic autopilot to control aircraft parameters, such as the flight path and changes in Mach speeds to prevent coalescence of shock waves and minimize perceived sonic boom noise levels on the ground.

Work to date: The Armstrong team developed a pilot-in-the-loop and batch non-linear simulation based on the initial models. They used the simulation to analyze vehicle stability, controllability, and handling qualities and to design trade studies on speed brakes, gear brakes, and approach and landing control system types. The team successfully demonstrated the trajectory-tracking autopilot in the simulation environment to fly a desired test trajectory without focusing a sonic boom on the ground for a trajectory that would otherwise be intractable by human pilots due to diminutive parametric thresholds. This methodology was also used to verify the accuracy of the fuel-burn estimation tool. The team is developing a reversionary controller to enable pilots to safely land the aircraft in the event of an in-flight air data failure. Also under development are control room displays to enable comparison of real-time flight data to predicted stability data to determine whether models match flight data and to ensure flight safety.

Looking ahead: As design iterations continue, the team will refine stability and control characteristics. Next steps also include further developing the trajectory-tracking autopilot to include real-world sources of errors and aircraft limitations, as well as continued progress on the air-data reversionary autopilot. Control room displays and algorithms to provide real-time stability margins are being developed to support upcoming flight research and ensure flight safety during envelope expansion flights.

Partners: NASA's Langley Research Center and Lockheed Martin

Benefits

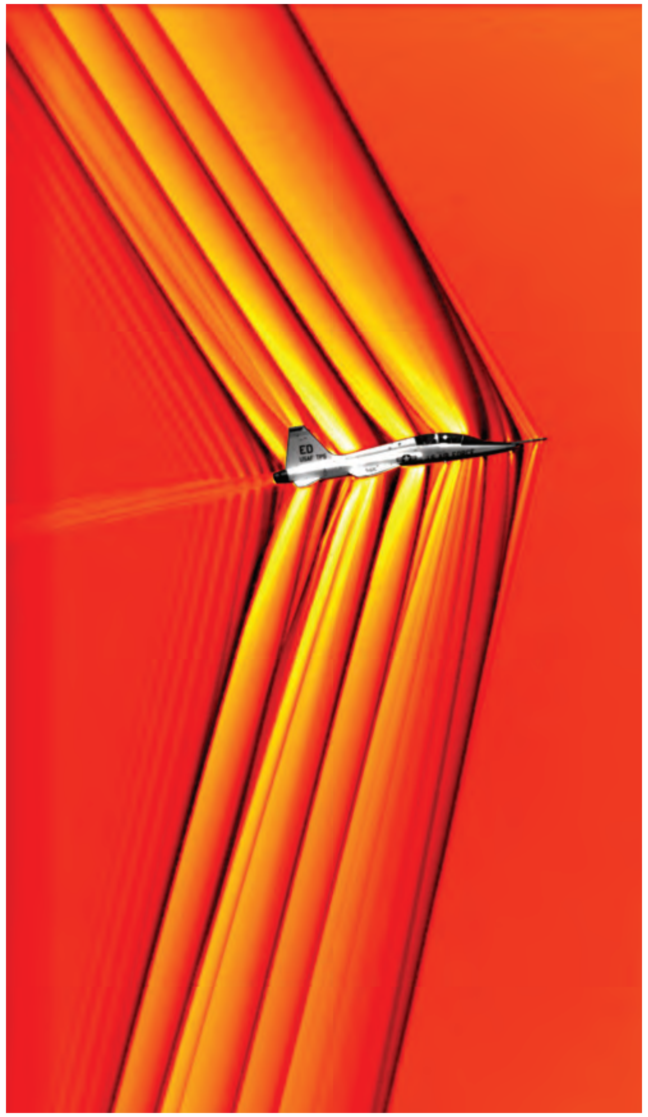
- **Integrated research:** Enables NASA to become more aware of relevant issues due to independent analysis of stability and control characteristics
- **Advanced:** Works to manage sonic boom noise levels through innovative autopilot design

Applications

- Low-Boom Flight Demonstration mission support
- Commercial supersonic aircraft design

PIs: Jesse Brady | 661-276-5990 | Jesse.C.Brady@nasa.gov
Brent Cano | 661-276-5843 | Brent.R.Cano@nasa.gov

Using Schlieren Techniques to Understand Sonic Booms



Research efforts at NASA Armstrong have advanced the use of schlieren photography to capture images of shock waves emanating from aircraft in supersonic flight. In 1993, a researcher at NASA's Langley Research Center first used a ground-based telescope to track a supersonic aircraft crossing the limb of the sun and processed schlieren images showing the shock waves. Since then, Armstrong researchers have developed both ground-based and in-flight, air-to-air schlieren techniques to track sonic booms. Some of these techniques use the entire face of the sun–while a supersonic aircraft eclipses it–to visualize the flow of in-flight supersonic aircraft. These advanced techniques reveal significantly more shock wave detail and capture vortical flow from wings and control surfaces.

Flow visualization is one of the fundamental tools of aeronautics research. Background-oriented schlieren (BOS) techniques use a textured background to visualize air density gradients caused by aerodynamic flow. These images allow researchers to study life-sized aircraft flying through Earth's atmosphere, which provides more informative results than modeling or wind tunnels.

NASA is progressing on its work with the U.S. Navy to develop an airborne pod to image the X-59 Quiet SuperSonic Technology (QueSST) aircraft. This pod will offer the opportunity to obtain air-to-air images of the X-59 shock wave structure using both the sun and the ground as backgrounds. These techniques were pioneered with the Background Oriented Schlieren Using Celestial Objects (BOSCO) and Air-to-Air Background Oriented Schlieren (AirBOS) technologies. The data will be instrumental in validating prediction codes and correlating with ground-based sonic boom acoustic data.

Work to date: Researchers continue to expand schlieren flight test techniques. The AirBOS with Simultaneous Referencing (AirBOS-SR) approach enables multiple frames of close-up images from various angles, including a side-view perspective. This technique also enables images of multiple flight conditions, such as acceleration and aircraft configuration changes.

A related effort, Sky-Based Background Oriented Schlieren (SkyBOS) is exploring the possibility of using sky backgrounds for BOS-type imaging near the horizon, such as very oblique angles of the Earth's surface, the horizon line, and phenomena immediately above the horizon. This capability would greatly improve the usability and value of schlieren techniques for flight testing.

Looking ahead: In addition to its work with the Navy, the team continues to develop SkyBOS capabilities, with plans underway to perform bench tests of systems to perform horizon area measurements, modify the center's "shock lab" to perform shock studies with various sensors, and modify algorithms to better process image data. Future work also includes imaging subsonic aircraft flow fields such as helicopter vortex structures and fixed wing-tip vortices.

Partners: NASA's Ames Research Center, U.S. Navy (Naval Air Systems Command, Point Mugu, California), and the U.S. Air Force Test Pilot School

Benefits

- **Real-world visualization:** Schlieren techniques enable visualization of shock wave geometry in the real atmosphere with real propulsion systems, which cannot be duplicated in wind tunnels or computer simulations.
- **Improved data:** Studying life-sized aircraft flying through Earth's atmosphere provides better results than modeling, helping engineers design better and quieter supersonic airplanes.

Applications

- Studying shock waves for supersonic and subsonic aircraft
- Understanding flow phenomena for wing-tip vortices, engine plumes, wind tunnels, and rotorcraft

PIs: Dan Banks | 661-276-2921 | Daniel.W.Banks@nasa.gov
Ed Haering | 661-276-3696 | Edward.A.Haering@nasa.gov

Quantifying and Measuring Sonic Booms

As part of the CarpetDIEM flight series, NASA will test a new ground recording system using traditional sonic booms from an F/A-18 in supersonic flight.

Because the Federal Aviation Administration (FAA) has not yet defined a maximum allowable sonic boom loudness, NASA Armstrong innovators are researching ways to identify a loudness level that is acceptable to both the FAA and the public. The Armstrong team and a number of industry, academic, and NASA partners have identified and validated several methods and techniques for capturing and measuring booms and their impacts. Activities range from collecting data above and below sonic booms via a sophisticated array of microphones to gathering information from remote sensors and wireless network–controlled microphones strategically placed within communities.

Work to date: The Carpet Determination In Entirety Measurements (CarpetDIEM) flight campaigns are smaller efforts within the Acoustic Validation, Test Preparation, and Execution (AVTPE) project. AVTPE is aimed at validating the sonic boom carpet and prediction/design tools for the new X-59 Quiet SuperSonic Technology (QueSST) aircraft, using various measurement techniques. CarpetDIEM is a series of campaigns focused on measurement systems testing, flight techniques, and field operations.

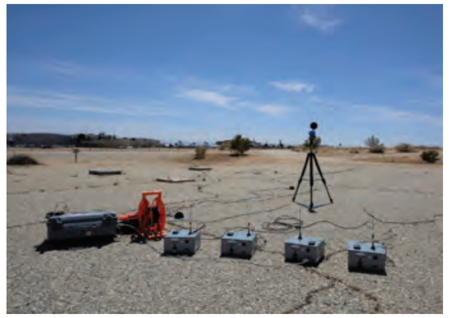
The Quiet Supersonic Flights 2018 (QSF18) campaign is defining techniques and instrumentation required to perform sonic boom community-response testing. Researchers are assessing possible recruitment, sampling, and surveying methods for effectively analyzing the impact of sonic booms on communities. The campaign also is developing new instrumentation and analysis tools to correlate sonic boom noise levels with human responses across large communities. QSF18 was NASA's first low sonic boom community-response research effort performed with a community unaccustomed to hearing sonic booms. Previous sonic boom noise response efforts have focused on tools and methodology and were performed at small military locations that frequently experience sonic booms. QSF18 used a unique F/A-18A dive maneuver known as a low-boom dive that simulates what future quiet commercial supersonic airplanes may sound like. The QSF18 research flights were conducted in Galveston, Texas.

The Armstrong team, along with industry and academic partners, also has identified and validated several methods and techniques for capturing and measuring sonic booms. One notable method is the Boom Amplitude and Direction Sensor (BADS), which employs six pressure transducers widely spaced on the vertices of an octahedron. The Supersonic Pressure Instrumentation Kit Ensemble (SPIKE) combines a high-quality microphone recording system and accurate time tagging in a solar-powered and rugged case to withstand the harsh desert environment where most of the tests are performed. This ground recording system (GRS) array will span several miles to measure the full extent of a sonic boom footprint and could be deployed throughout cities for future large-scale community response testing.

The new sonic boom measurement system will need to remotely manage up to 150 GRS devices. Therefore, NASA is developing multiple concepts of unattended triggering systems for the GRS. One such system is the Trigger Hardware and Observation Recorder (THOR). It uses data transmitted from a supersonic airplane to predict the arrival time of a sonic boom and then sets the GRS to record. Another system, Boom Universal Recorder Satellite Trigger (BURST), uses satellite communications to transmit a signal to the GRS, commanding it to record.

The team also uses the Shock-Sensing Probe (SSP), an F-15B equipped with a special probe for measuring shock waves near an aircraft. Taking measurements as close as 100 feet below an aircraft, the SSP is capable of capturing shocks that will create sonic booms on the ground. Such measurements will help with designing the body of future quiet supersonic aircraft.

Also in use is the Airborne Acoustic Measurement Platform (AAMP), a TG-14 motor glider with a high-quality microphone mounted on its wing. This platform measures sonic booms up to 12,000 feet above the ground. This test also equipment records sonic booms generated above Earth's atmospheric turbulent boundary layer. NASA uses these "clean" sonic boom measurements to validate propagation tools before the sonic boom is affected by turbulence.



A sonic boom test with THOR and BURST systems, which use data transmitted from supersonic aircraft and satellites to a ground recording system.

Looking ahead: Future sonic boom community-response projects will implement the newly developed strategies and technologies on large communities across the country that are representative of the national demographic. These activities will play a key role in testing the X-59 supersonic aircraft.

CarpetDIEM Phase II will focus on evaluating GRS prototypes and testing GRS with the THOR and BURST unattended trigger systems. It also will test the robustness of these systems under various flight conditions and ground measurement array configurations.

As part of the AVTPE effort, planning is also underway for measuring and characterizing the sonic boom footprint of the X-59. Before flying over communities, NASA will need to validate that the sonic boom produced by the X-59 has noise levels on the ground that are comparable to the design target levels. This effort will require measuring the greater than 30-mile sonic boom carpet on the ground, using the AAMP to measure the sonic boom above the ground, the SSP to measure the shocks just below the aircraft, and schlieren photography techniques to image and measure airborne shock waves.

Partners: NASA's Langley Research Center and Kennedy Space Center, KBRwyle, Pennsylvania State University, The Boeing Company, Gulfstream Aerospace, Lockheed Martin, Applied Physical Sciences Corp., Volpe National Transportation Systems Center, Eagle Aeronautics, Gaugler Associates, Fidell Associates, and Crystal Instruments

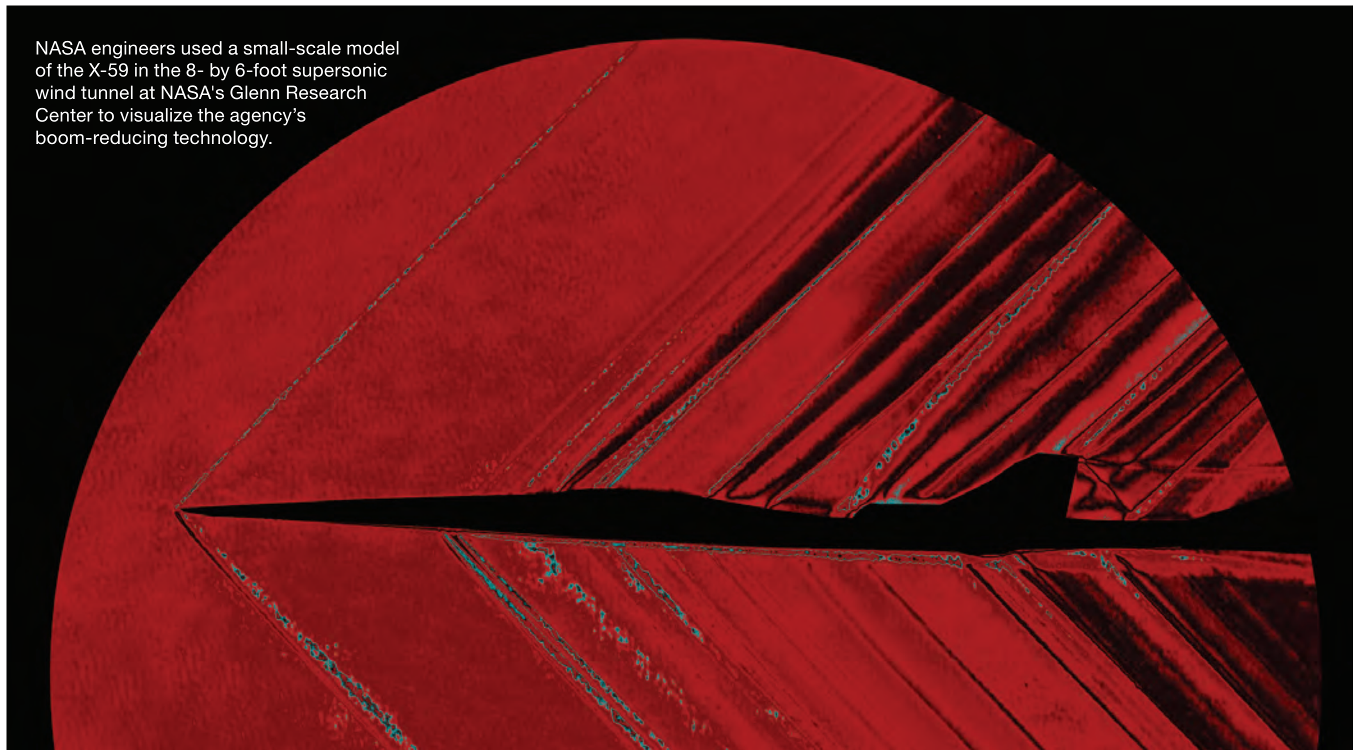
Benefits

- **Advanced:** Produces valuable data to help characterize key elements of sonic booms (e.g., evanescent waves, sonic boom propagation effects, impact of flight maneuvers)
- **Instructive:** Informs designs of future supersonic aircraft
- **Quantifying:** Enables data acquisition from public reaction, which will be critical as the FAA considers allowing overland supersonic flight

Applications

- Supersonic aircraft design
- Flight planning
- FAA approval of overland supersonic flight

PIs: Larry Cliatt | 661-276-7617 | Larry.J.Cliatt@nasa.gov
Ed Haering | 661-276-3696 | Edward.A.Haering@nasa.gov



NASA engineers used a small-scale model of the X-59 in the 8- by 6-foot supersonic wind tunnel at NASA's Glenn Research Center to visualize the agency's boom-reducing technology.

Real-Time Display and Mitigation of Sonic Booms

NASA Armstrong innovators are advancing unique technology that will permit pilots to make in-flight adjustments to control the timing and location of sonic booms. The Cockpit Interactive Sonic Boom Display Avionics (CISBoomDA) is a software system capable of displaying the location and intensity of shock waves caused by supersonic aircraft. The technology calculates an airplane's sonic boom footprint and provides real-time information, allowing pilots to make the necessary flight adjustments to control the impact of sonic booms on the ground. It can be integrated into cockpits and flight control rooms, enabling air traffic controllers to analyze flight plans for approval, monitor aircraft in flight, and review flight data to enforce regulations.

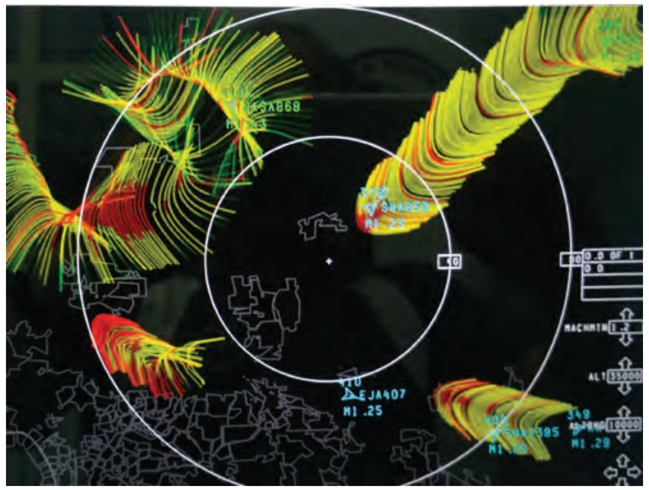
Work to date: The real-time cockpit display system has been demonstrated during supersonic flights on an F/A-18, which compared computations with boom measurements on the ground. A collaboration with Rockwell Collins (now Collins Aerospace) helped advance the system and implement the capability to utilize a worldwide terrain database to predict where and how a sonic boom will impact the ground as well as at what sound pressure level. Recent updates include:

- Incorporating real-time loudness prediction, including display of contours based on loudness thresholds rather than pressure thresholds
- Depicting multiple supersonic targets based on supersonic Automatic Dependent Surveillance-Broadcast (ADS-B) data for future ground controllers
- Enhancing and decluttering the interactive display
- Redesigning communications for faster display updates

Researchers plan to integrate the software system into the ground controller stations in the mobile operating facility (MOF) to aid flight tests of the X-59 Quiet SuperSonic Technology (QueSST) aircraft. This technology has significant commercialization potential once civil supersonic flights become a reality.

Looking ahead: Next steps are to define noise standards. Enhancements will be integrated into the X-59 simulator to elevate the system's technology readiness level.

Partner: Collins Aerospace (formerly Rockwell Collins)



Benefits

- **Enables overland supersonic travel:** Because pilots can control the location and intensity of sonic booms, the system may allow future-generation supersonic aircraft to fly overland.
- **Improves operational control:** Because ground controllers can see the real-time location and magnitude of the loudness associated with aircraft flying at supersonic speeds, they can better control traffic and improve the overall airspace efficiency.
- **Provides a tool for the Federal Aviation Administration (FAA):** Software such as CISBoomDA could provide the FAA with the ability to approve flight plans, monitor flying aircraft, and review flight data to enforce regulations.

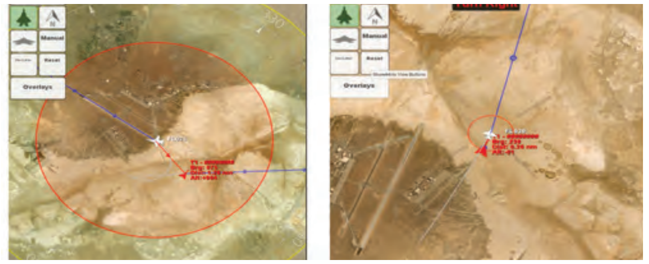
Applications

- **In flight:** Enables pilots to avoid producing sonic booms or control their location and intensity
- **On the ground:** Allows the FAA to approve and monitor plans for supersonic flights

PI: Sriram Rallabhandi | 757-864-9554 | Sriram.Rallabhandi@nasa.gov

Technicians perform installation work in the mid-bay on the X-59 aircraft. Credit: Lockheed Martin

Enhanced ADS-B System for Supersonic Aircraft



Enhanced vision display for collision avoidance

NASA Armstrong researchers have collaborated on flight tests that could help a new generation of supersonic commercial jets meet a government mandate requiring aircraft to be equipped with Automatic Dependent Surveillance-Broadcast (ADS-B) Out radios that broadcast GPS position and identity. This flight research effort combined an ADS-B system adapted for supersonic vehicles with an enhanced vision display designed for ADS-B traffic information and alerting to provide increased situational awareness. The goal of this research effort is to develop a robust ADS-B system for commercial supersonic aircraft that could allow safe integration into the national airspace.

Work to date: NASA conducted three flight tests, reaching speeds of Mach 1.4 and accelerations of 5 *g*. Researchers from NASA and the Federal Aviation Administration (FAA) evaluated the ADS-B tracking from FAA ground stations to verify position accuracy throughout the subsonic and supersonic flights. The flights furthered the development and certification of the technology in four key areas: ADS-B flights at supersonic speeds, enhanced vision display, conflict detection algorithm, and use of artificial intelligence algorithms for accurate flight trajectory predictions.

Looking ahead: The collaborative research team is working to demonstrate a similar system on hypersonic platforms and commercial space vehicles.

Partner: Vigilant Aerospace Systems

Benefits

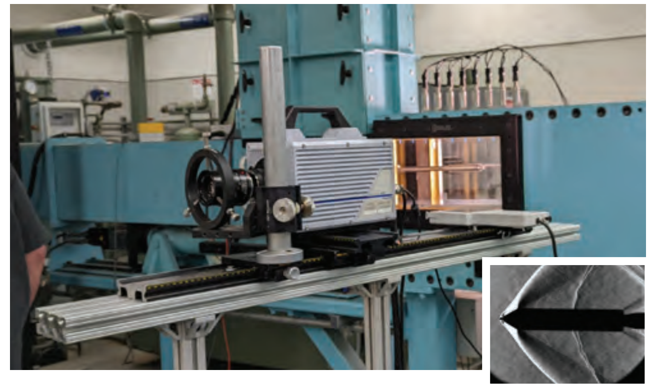
- **High performance:** Meets the ADS-B Out FAA-mandated accuracy of 304 feet at speeds up to Mach 2.0
- **Improves safety:** Enhances collision avoidance capabilities to maintain self-separation for supersonic aircraft
- **Accurate and fast:** Broadcasts position 120 miles in every direction every 1 to 10 seconds
- **Leverages AI Neural Network:** Predicts the flight trajectories within 48 feet during supersonic maneuvers for a more accurate conflict detection

Applications

- Supersonic military and commercial aircraft
- Hypersonic aircraft and commercial space vehicles

PI: Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov

Supersonic Plasma Acoustic Reduction Concept (SPARC)



Plasma-based energy deposition via electric discharge has been shown in small-scale wind tunnel tests to modify shock waves generated by basic aerodynamic shapes in the near field. NASA Armstrong researchers are working to acquire data farther away from a model to determine whether these positive effects extend to the far field. Positive far-field data would indicate this plasma-based electric discharge is a viable method of sonic boom mitigation worthy of further study toward full-scale implementation.

Work to date: With Center Innovation Fund (CIF) resources, the SPARC team built and tested a high-voltage power supply and cone-cylinder-shape test article and demonstrated the ability to generate an electric arc discharge at the nose of the model in three different environments: still air, Mach 1.6 flow from an open air blow down rig at Armstrong and Mach 1.6 air flow at California Polytechnic University Pomona's supersonic wind tunnel with freestream pressure of approximately 0.74atm. At the wind tunnel test, researchers demonstrated that the model can successfully arc in a wind tunnel environment with minimal damage after multiple runs and that the power supply can withstand multiple cycles with minimal damage. This is required for testing at a larger wind tunnel. The team is also working on a multielectrode model designed to generate an approximate axisymmetric discharge.

Looking ahead: Next steps are to conduct testing in the 4x4 Supersonic Wind Tunnel, part of the Unitary Plan Wind Tunnel complex at NASA's Langley Research Center. Positive results would pave the way to more in-depth research into the practicality of this technology. A flight test is also planned to further investigate effects away from the test article.

Partner: NASA's Glenn Research Center

Benefits

- **Advances research:** Increases database relating to the impact of plasma on shock waves generated by aerodynamic shapes in supersonic flow
- **Informative:** Contributes to the understanding of plasma and supersonic flow interactions

PI: Aliyah Ali | 661-276-5533 | Aliyah.N.Ali@nasa.gov

Autonomous Systems

NASA has committed to developing systems to support the increasing demand for reliable automation and autonomy in aviation with a focus on intelligent machine systems that can safely handle complex situations. Technology and airspace management advancements will make possible a safe, economically sustainable Urban Air Mobility transportation system where semi and fully autonomous vehicles provide new services in and around cities large and small.

The pioneering research conducted at NASA's Armstrong Flight Research Center in Edwards, California has the potential to be applied beyond aviation. These technologies could be adapted for use in any vehicle that has to avoid a collision threat, including aerospace satellites, automobiles, marine vehicles, and more.

FlightHorizon is a trademark of Vigilant Aerospace Systems.

NASA Armstrong Tech Wins NASA's Commercial IOY Award

A situational awareness technology developed at NASA Armstrong won the 2021 NASA Commercial Invention of the Year (IOY) Award. Developed by a team led by Ricardo Arteaga, the innovation is an algorithm that uses an Automatic Dependent Surveillance-Broadcast (ADS-B) System technology developed to enhance aircraft command-and-control operations and communications. This agencywide award was granted by the NASA Inventions and Contributions Board. It is one of just two prestigious IOY awards; the other recognizes an innovation for government use.

The Armstrong-developed innovation offers improved traffic situational awareness, conflict/collision detection and correction, real-time weather monitoring, and navigation. It provides a 3D view of collision threats and real-time aircraft location-state display. Its advanced detect-and-avoid (DAA) algorithm was specifically designed for the short-range trajectories typically associated with unmanned aerial systems (UAS).

Transforming the UAS Market

The first embodiment of this technology was exclusively licensed by Vigilant Aerospace Systems in February 2016. The next is a patented DAA system that combines ADS-B and radar surveillance for detection of cooperative and non-cooperative aircraft. In June 2020, Vigilant signed a new license adding coverage for radar use in DAA and unmanned traffic management for drones. This non-exclusive license covers the use of miniaturized radar to extract target data for DAA systems on a UAS.

Vigilant has used the technology in its FlightHorizon™ product to provide detect-and-avoid and airspace management. The technology is being used in testing a much wider range of operations than are typically permitted under Federal Aviation Administration (FAA) rules, including flights beyond visual line-of-sight, package delivery, routine flights over people, and other advanced operations. Flights are supporting missions like infrastructure inspection, asset and environmental monitoring, precision agriculture, emergency response, and other innovative uses for drones.

PI: Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov

Resilient Autonomy Project Develops Evaluation Methodology

The Resilient Autonomy project team conducted basic functional flight tests of the EVAA-modified HQ-90, a vertical lift and transition remotely piloted aircraft.

NASA Armstrong researchers are leading an effort to develop a framework for autonomous aircraft that the Federal Aviation Administration (FAA) could leverage to establish certification standards. The goal of the Resilient Autonomy effort is to create a robust methodology for evaluating unmanned and autonomous systems using an approach known as Multi-Monitor Run-Time Assurance (MM-RTA). The approach uses open access Expandable Variable Autonomy Architecture (EVAA) software testbeds to ensure safe operations. The framework coordinates various functionalities with risk-based logic, safely binding untrusted behavior and relieving the requirement to certify all guidance logic possibilities. The EVAA is structured to allow the addition and removal of monitors, sensors, and aircraft models with minimal validation and verification requirements.

Work to date: The EVAA software has been expanded to include geo-fence, well clear, obstacle spacing, ground and obstacle avoidance, air traffic avoidance, in-flight route re-planning, and emergency forced landing. The COVID-19 pandemic prevented taking the system to flight test; however, the project team pivoted to an extensive simulation evaluation. The EVAA was adapted to and tested on a general aviation aircraft demonstrating ground and air collision avoidance capabilities on a piloted aircraft. The software was also adapted to and evaluated in simulation on a L3Harris-built Hybrid Quadrotor 90C (HQ-90) unmanned aircraft vehicle (UAV). Path-following and terrain-following systems were developed to accomplish medium- and low-altitude missions mimicking long-range rural package delivery.

Extensive simulation evaluations have been conducted over a variety of extreme terrain, obstacle, and weather conditions, successfully demonstrating the EVAA's ability to ensure safety under a wide variety of contingency conditions. Functional flight tests were accomplished on the two baseline HQ-90s that were delivered to Armstrong. Additionally, limited testing was accomplished on both vision navigation systems to be used by the EVAA.

Looking ahead: Researchers concluded Resilient Autonomy in 2021. Simulation demonstrations of the EVAA's capability were provided for a variety of audiences. Basic functional flights of the EVAA-modified HQ-90 were completed, and technical evaluation reports and design and certification guides will be published.

NASA's Advanced Air Mobility project team is developing plans for including the EVAA as part of its National Campaign series. The FAA funded flight tests of the software on a general aviation aircraft, work that is scheduled to be completed in 2022. The FAA also plans to continue to use EVAA as a reference implementation of a highly autonomous aircraft for the purposes of expanding certification guidance for autonomy. Finally, the Department of Defense (DoD) is formulating plans for funding flight tests of the EVAA HQ-90 in 2022. Various projects and offices within the DoD are beginning the transition of the EVAA onto a variety of platforms.

Partners: FAA, DoD, Terra Pixel, Amazon Prime Air, Skyward, Scientific Applications & Research Associates (SARA), U.S. Southern Command, U.S. Special Operations Command, and U.S. Air Force Research Laboratory

Benefits

- **Revolutionary:** Informs standards and best practices that will accelerate the certification of autonomous systems
- **Reliable:** Uses supervisory control as a deterministic and trustworthy way to ensure safety

POC: Nelson Brown | 661-276-5039 | Nelson.Brown@nasa.gov

Improved Ground Collision Avoidance System (iGCAS)

NASA Armstrong's iGCAS can be used for a variety of aircraft, including general aviation, helicopters, and unmanned aircraft. The technology has been incorporated into an application for tablets and other handheld/ mobile devices.

NASA Armstrong's improved Ground Collision Avoidance System (iGCAS) leverages leading-edge fighter jet safety technology, adapting it to civil aviation use as an advanced warning system. It offers high-fidelity terrain mapping, enhanced vehicle performance modeling, multi-directional avoidance techniques, efficient data-handling methods, and user-friendly warning and cuing systems. The algorithms in the technology also have been incorporated into an application for mobile devices that can be used by pilots in the cockpit, enabling significantly safer general aviation. This feature will give pilots access to this lifesaving safety tool regardless of the aircraft type. The system can also be incorporated into electronic flight bags (EFBs) and avionics systems.

The payoff from implementing the system, which was designed to operate on a variety of aircraft (e.g., military jets, unmanned aircraft, general aviation airplanes) with minimal modifications, could be billions of dollars and hundreds of lives and aircraft saved.

Furthermore, the technology has the potential to be applied beyond aviation and could be adapted for use in any vehicle that has to avoid collision threats, including satellites, ships, automobiles, scientific research vehicles, and marine charting systems.

Work to date: This improved approach to ground collision avoidance has been demonstrated on small unmanned aircraft, a Cirrus SR22, and an experimental Cozy Mark IV aircraft while running the technology on a mobile device. These tests proved the feasibility of the mobile app-based implementation. The testing also characterized the flight dynamics of the avoidance maneuvers for each platform, evaluated collision-avoidance protection, and analyzed nuisance potential (i.e., the tendency to issue false warnings when the pilot does not consider ground impact to be imminent).

The COVID-19 pandemic prevented 2020 planned flight tests of the system on NASA's Langley Research Center's Lancair aircraft. However, extensive simulation testing was accomplished with the system adapted to a Cessna 172 and an L3Harris-built Hybrid Quadrotor 90C (HQ-90) unmanned aircraft vehicle (UAV). The Armstrong team also completed, in conjunction with the Federal Aviation Administration (FAA), a project-specific certification plan for iGCAS on a general aviation aircraft.

New in this portion of iGCAS development has been the addition of leeward-ridgeline downdraft compensation. This first-ever capability of its type in a ground proximity warning system has demonstrated exceptional performance. Evaluators have rated the iGCAS as clearly exceeding human capability. Continuing in 2021 under the Resilient Autonomy effort, the team coordinated with the FAA to integrate a fully automatic version of iGCAS embedded in Expandable Variable Autonomy Architecture (EVAA) with a commercial autopilot on the Cozy Mark IV aircraft.

Looking ahead: The Armstrong team conducted aircraft flight tests of the EVAA iGCAS in the Cozy aircraft in late 2021 and will continue in early 2022. This work will be used to further refine and add depth to the certification process for highly autonomous systems on general aviation aircraft.

Partner: Federal Aviation Administration

Benefits

- **High-fidelity terrain mapping:** Armstrong's patented approach to digital terrain encoding enables the use of maps with fidelity that is two to three orders of magnitude better than existing systems.
- **Flexible platforms:** This tool can be used with a variety of aircraft, including general aviation, helicopters, unmanned aircraft, and fighter jets such as the General Dynamics F-16, with the ability to incorporate the specific maneuvering performance for each aircraft type into the platform.
- **Nuisance-free warnings:** The iGCAS technology ensures that alarms will be triggered only in the event of an impending collision, reducing the risk of false alarms that may cause pilots to ignore the safety system.
- **Multi-directional maneuvers:** Unlike existing systems that recommend only vertical climbs, this innovation can recommend various turns to avoid a collision, making it more appropriate for general aviation and unmanned aircraft.
- **Proven technology:** A follow-on to a system currently flown in F-16 test aircraft will be integrated into the aircraft's next generation for the U.S. Air Force's fleet.

Applications

- General aviation
- Military aircraft
- Drones/unmanned aircraft
- Helicopters
- Digital autopilots

POC: Nelson Brown | 661-276-5039 | Nelson.Brown@nasa.gov

Ubiquitous Weather Sensing

Concept for a ubiquitous weather sensing pod for advanced air mobility vehicles. A sensor pod and the vehicle itself potentially could be used to collect atmospheric measurements during flight.

NASA researchers are working to identify transformative, cost-effective technologies that use advanced air mobility vehicles to measure atmospheric conditions. These measurements can be used to improve weather nowcasts that could enable safe and reliable high-intensity urban air operations, for example. Sponsored by NASA's Convergent Aeronautics Solutions (CAS) project, this effort will help researchers develop and prototype weather-sensing technologies for advanced air mobility as well as methods for quantifying their benefits.

Work to date: During the synthesis phase, the team identified the potential use of advanced air mobility vehicles, including cargo and human transport vehicles, for atmospheric and environmental sensing. A partnership was formed between CAS and NASA's Transformational Tools and Technologies (TTT) distributed sensing project.

Looking ahead: The team is working to define high-level goals and objectives. A framework of the opportunity will include:

- System-level impacts and potential transformations
- Critical barriers and potential solutions to desirability, economic viability, and technical feasibility
- Work elements/prototypes and associated attributes/criteria for minimum success
- Anticipated interactions with potential handoff/infusion partners
- Execution work plan, inclusive of execution team

Partners: NASA's Ames, Glenn, and Langley research centers and Virginia Polytechnic Institute and State University

Benefits

- **Efficient:** Develops a positive feedback loop between advanced air mobility operations (including air traffic and route planning) and measuring the atmosphere through which vehicles fly
- **Advanced:** Potentially extends the range of local weather conditions in urban settings within which advanced air mobility vehicles can safely operate
- **Informative:** Advances current understanding of Earth systems, including atmospheric and environmental phenomena through direct measurement

Applications

- Safe and reliable weather-tolerant operations for advanced air mobility

POC: Luke Bard | 661-276-2756 | Luke.J.Bard@nasa.gov

Advanced Air Mobility (AAM) National Campaign

(top right) Joby Aviation's prototype aircraft Credits: Joby Aviation (bottom right) Flight Research Inc.'s Bell OH-58C Kiowa helicopter hovers over a helipad after completing an urban air mobility approach at Armstrong.

NASA's Advanced Air Mobility (AAM) National Campaign is helping emerging aviation markets safely develop an air transportation system that moves people and cargo between places previously not served or underserved by aviation – urban, suburban, rural, and regional environments – using revolutionary new aircraft. Researchers at NASA Armstrong are contributing to NASA efforts to develop and conduct the AAM National Campaign in a series of events that seek to accelerate certification and approval by:

- Identifying and addressing gaps in vehicle certification, pilot licensing, landing surfaces, and operational approval using a targeted research approach
- Developing preliminary guidelines for flight procedures and related airspace design criteria
- Integrating infrastructure including communication, navigation, and surveillance; detect and avoid; weather; ground operations; airspace services; and vertiports
- Demonstrating airspace architecture and scalable operations
- Conducting research and obtaining acoustic data for human response research

Based on validated operational concepts, simulations, analyses, and results from demonstrations, the AAM National Campaign will deliver aircraft, airspace, and infrastructure system and architecture requirements to enable sustainable and scalable medium density advanced air mobility operations.

Work to date: The team conducted developmental tests to refine requirements for the first set of National Campaign tests (NC-1) and assess industry readiness. These tests included Range Agnostic Mobile Operations Facility verification and validation flight testing, Urban Air Mobility (UAM) surrogate flights using a Bell OH-58C Kiowa helicopter, and acoustic flight tests with partner Joby Aviation.

The team completed UAM surrogate flights to inform the NC-1 flight test plan. Three flight partners, seven airspace partners, and five infrastructure partners signed Space Act Agreements to participate in NC-1 integrated flight test demonstrations through 2022.

An integrated dry run test was completed using a Bell OH-58C Kiowa helicopter provided by Flight Research Inc. as a stand-in AAM vehicle to better understand how a future UAM vehicle will need to operate in a congested urban air environment. The Federal Aviation Administration and Flight Research test pilots flew different types of maneuvers with the helicopter at Armstrong to help assess procedures and infrastructure while also developing a data baseline for future industry partnership flight testing.

NASA and Joby Aviation completed developmental testing with Joby's prototype aircraft. As the aircraft flew planned test scenarios in August and September 2021, NASA's AAM National Campaign team collected information about how the vehicle moved and sounded, and a NASA Provider of Services operated in the background to collect surveillance data.

Looking ahead: This data will be used to accomplish NC-1, slated for 2022, which will include more complex flight scenarios and other industry vehicles.

Partners: NASA's Ames and Langley research centers, Federal Aviation Administration, and commercial aerospace partners, including vehicle, airspace, and infrastructure providers

Applications

- When fully integrated into the national airspace, AAM will provide an efficient and affordable system for passenger and cargo transportation, and other public good emergency response missions. This system could include aircraft like package delivery drones, air taxis, and medical transport vehicles.

POC: Starr Ginn | 661-276-3434 | Starr.R.Ginn@nasa.gov

AI Computer Vision Enhances Situational Awareness of Intelligent Vehicle Systems

Credit: Circle Optics

Drone detect-and-avoid (DAA) technology developed at NASA Armstrong is part of a portable airspace safety system that monitors air traffic conflicts, provides traffic alerts, and provides near-real-time avoidance guidance for drone pilots. The unmanned aerial system (UAS) uses artificial intelligence (AI) and an advanced camera system to detect and classify objects and patterns during flight and store those objects and their locations in a local Earth geo-browser. The goal is for an AI-enabled UAS to locate survivors, aircraft debris, and key flight recording instrumentation and then geo-tag all elements of a crash site to create a debris map.

Work to date: NASA conducted a staged mishap exercise to demonstrate the use of an AI-enabled small UAS to locate the aircraft's flight black box instrumentation. The team sent a drone's live video feed to Armstrong at 2.5 megabits per second, 30 frames per second, and with a 3-second lag on live-stream video via an LTE mobile WiFi hotspot. The flights furthered the development of the technology in two key areas: UAS vision-based object detection and classification using AI algorithms and live stream using 4G/LTE (in the future, likely an embedded 5G network in the drone).

Looking ahead: The collaborative research team is working to demonstrate a similar system on larger Urban Air Mobility (UAM) platforms as part of NASA's Advanced Air Mobility project. The system will leverage an electro-optical/infrared (EO/IR) 360-degree camera with 72 megapixels to enhance situational awareness through its real-time, ultra-high resolution, wide field of view, and low distortion capabilities.

Partner: Circle Optics

Benefits

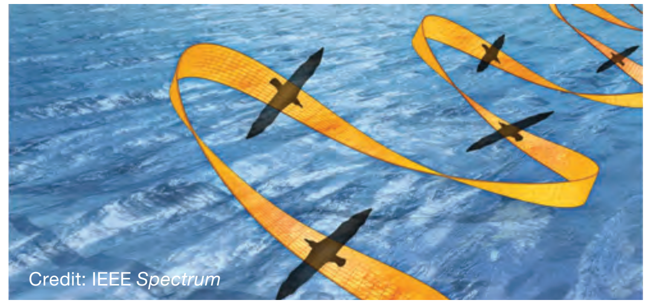
- **Intelligent:** Enhances situational awareness for hazards perception
- **Drone-based:** Enhances real-time detection of aircraft debris, people, and black box instrumentation
- **Live-streamable:** Leverages low-latency, high-resolution video, and mobile WiFi to share real-time information with the Federal Aviation Administration, NASA, and the National Transportation Safety Board (NTSB)

Applications

- Hazards perception for UAM vehicles
- Aviation mishap investigations
- Search-and-rescue operations
- Damage assessments
- Surveillance and security

PI: Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov

NASA Autonomous Soaring Study



Credit: IEEE *Spectrum*

Autonomous soaring technology has the potential to drastically increase flight endurance while significantly reducing emissions and fuel expenses. Autonomous soaring capabilities will benefit projects and programs across NASA directorates and may enable extreme-endurance autonomous operation and remote sensing in a wide range of environments, including the atmosphere and seas of Earth and extraterrestrial planets.

The purpose of this study was to identify the current state of the art in autonomous soaring (with a concentration on dynamic boundary layer soaring), define the barriers prohibiting the application of this novel technology to real-world scenarios, and develop a one- to five-year strategy roadmap for NASA to successfully lead the development and enable the application of dynamic soaring technology.

Work to date: With Center Innovation Fund resources, NASA Armstrong researchers conducted a literature review of past and current autonomous soaring research. They developed a top-level testing plan to advance state-of-the-art autonomy soaring technologies:

- Improve the existing low-altitude boundary layer corresponding to the altitude range in which the albatross flies
- Improve the existing atmospheric model of airflow about a hill where manual radio-controlled (RC) dynamic soaring is currently being performed
- Analyze data captured during manual RC dynamic soaring maneuvers
- Develop an autonomous soaring unmanned aerial vehicle (UAV)
- Test autonomous soaring UAV in progressively advanced environments

Looking ahead: Further literature review is required to develop a one- to five-year strategy roadmap and progress to the testing plan. This technology has the potential to vastly increase the endurance of autonomous operations on Earth and other planets.

Benefits

- **Informative:** Defines barriers of real-world application and adoption
- **Collaborative:** Identifies research organizations performing this research and commercial entities investing in this research

PI: Jesse Brady | 661-276-5990 | Jesse.C.Brady@nasa.gov

Technologies to Enable Urban Air Mobility

NASA is leading a national effort to develop technologies and analysis methods for small (four to six passengers) electrically powered aircraft – a key component to the emerging concept of Urban Air Mobility (UAM). The UAM envisions a safe and efficient air transportation system where electric air taxis and air ambulances operate alongside small-package delivery drones above populated areas.

Much like traditional helicopters, electric vertical takeoff and landing (eVTOL) aircraft use rotors for propulsion and flight control. Unlike traditional helicopters, many eVTOL designs take advantage of the scalability and flexibility of electric motors to employ distributed electric propulsion, which replaces one large rotor with many smaller rotors distributed across the airframe. Smaller rotors and high-torque electric motors enable variable speed control, potentially providing a simpler and lighter-weight alternative to traditional collective blade pitch control. The goal at NASA Armstrong is to improve the safety and reliability of this new class of air vehicles by developing innovative tools and methods, and by contributing to the evolving standards, guidelines, and best practices for the industry.

Research at Armstrong began in 2019 and is currently focused on pilot handling qualities and passenger ride quality studies.

Pilot Handling Qualities

The eVTOL aircraft have different flight dynamics and operational requirements than helicopters or fixed-wing aircraft. Time-tested handling qualities metrics developed for modern traditional civil aircraft may not apply to UAM eVTOL designs. The distributed electric propulsion nature of many eVTOL configurations presents additional challenges with complex and highly coupled powertrain and flight control dynamics that are difficult to analyze using traditional techniques. Further complicating the analysis problem are the effects of component temperature, battery state of charge, and failure conditions. The Armstrong team has developed high-fidelity electric powertrain models that are suitable for handling qualities predictions and real-time piloted simulations. Initial testing will be performed in the Armstrong fixed-base piloted simulation, with follow-on testing at the NASA Ames Vertical Motion Simulator.

Passenger Ride Quality

Public acceptance of UAM requires eVTOL aircraft to be safe, reliable, affordable, and comfortable. The UAM aircraft are much more maneuverable than other modes of transportation that the public is familiar with, such as automobiles, trains, and airliners. Their large windows and flight paths through urban landscapes have the potential to produce vertigo or other visually induced discomfort. Noise and vibration from the rotors can also make passengers uncomfortable. Armstrong researchers are developing experiments to gather UAM passenger assessments of various factors that affect ride quality. These studies will be performed in the virtual reality-based Armstrong Ride Quality simulator using human test subject volunteers. The results will be used to provide ride quality guidance and metrics to aircraft manufacturers, vertiport designers, and operators to ensure that the UAM transportation experience is a positive one.

Work to date: Armstrong researchers are in the process of releasing high-fidelity powertrain models for real-time simulation.

Looking ahead: In 2022, Armstrong researchers will complete construction of the ride quality simulator and oversee eVTOL pilot handling qualities testing at the NASA Ames Vertical Motion Simulator.

Benefits

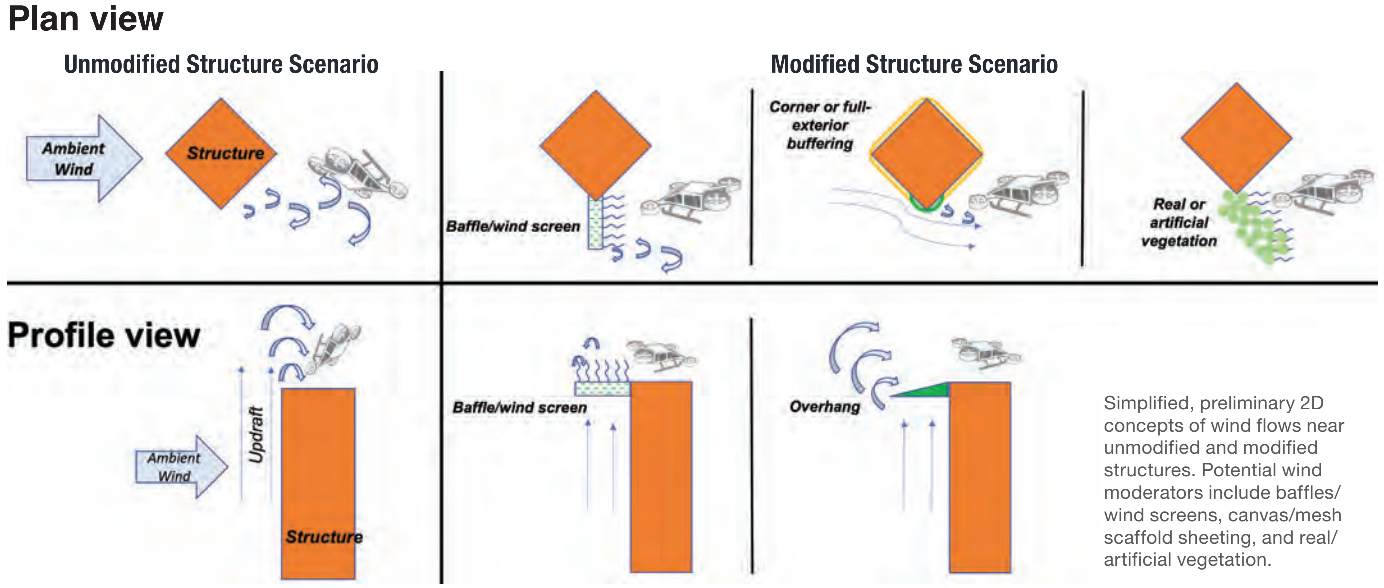
- This research effort is pioneering new concepts in the field of distributed electric propulsion and will provide the community with new tools, methods, and guidelines to help ensure passenger safety and acceptance of a potentially revolutionary advance in human transportation.

Applications

- Design metrics for traditional aircraft handling qualities and passenger ride quality have been developed and refined over decades of civil aviation. The emerging UAM transportation system does not have a similar experiential database to draw from. NASA research into the requirements for good handling qualities and passenger ride quality of eVTOL aircraft will help to ensure the success of UAM.

PI: Curtis Hanson | 661-276-3966 | Curtis.E.Hanson@nasa.gov

Micro Weather Moderation



Simplified, preliminary 2D concepts of wind flows near unmodified and modified structures. Potential wind moderators include baffles/wind screens, canvas/mesh scaffold sheeting, and real/artificial vegetation.

NASA researchers are studying a micro weather moderation concept to assess the feasibility of developing cost-effective technologies that moderate or change micro weather conditions to enable safe and reliable high-intensity urban air operations. This work is part of NASA's Convergent Aeronautics Solutions (CAS) project, which invests in seemingly improbable ideas that might lead to solutions to problems that plague aviation and impact safety, environmental and community impact, and the global growth in air traffic. The micro weather moderation research is planned to be used to develop and prototype micro weather moderation technologies and methods for quantifying benefits of these technologies.

Work to date: Researchers are determining goals/objectives and planning for data collection and modeling efforts. These efforts build on a preliminary wind survey conducted for NASA's Advanced Air Mobility National Campaign subproject, and a feasibility assessment for a virtual windsock concept using computational fluid dynamics and machine learning models for real-time wind estimation.

Looking ahead: The team is developing its work and resource plans. Immediate steps are to solidify project requirements and work with CAS leadership on a project execution agreement. To better understand wind flows near buildings and identify potential wind moderation techniques, plans are underway to collect data from field experiments and to conduct water/wind tunnel tests and computational fluid dynamics modeling.

Partners: NASA's Ames, Glenn, and Langley research centers

Benefits

- **Enabling:** Potentially extends the range of local weather conditions in urban settings in which advanced air mobility vehicles can safely operate

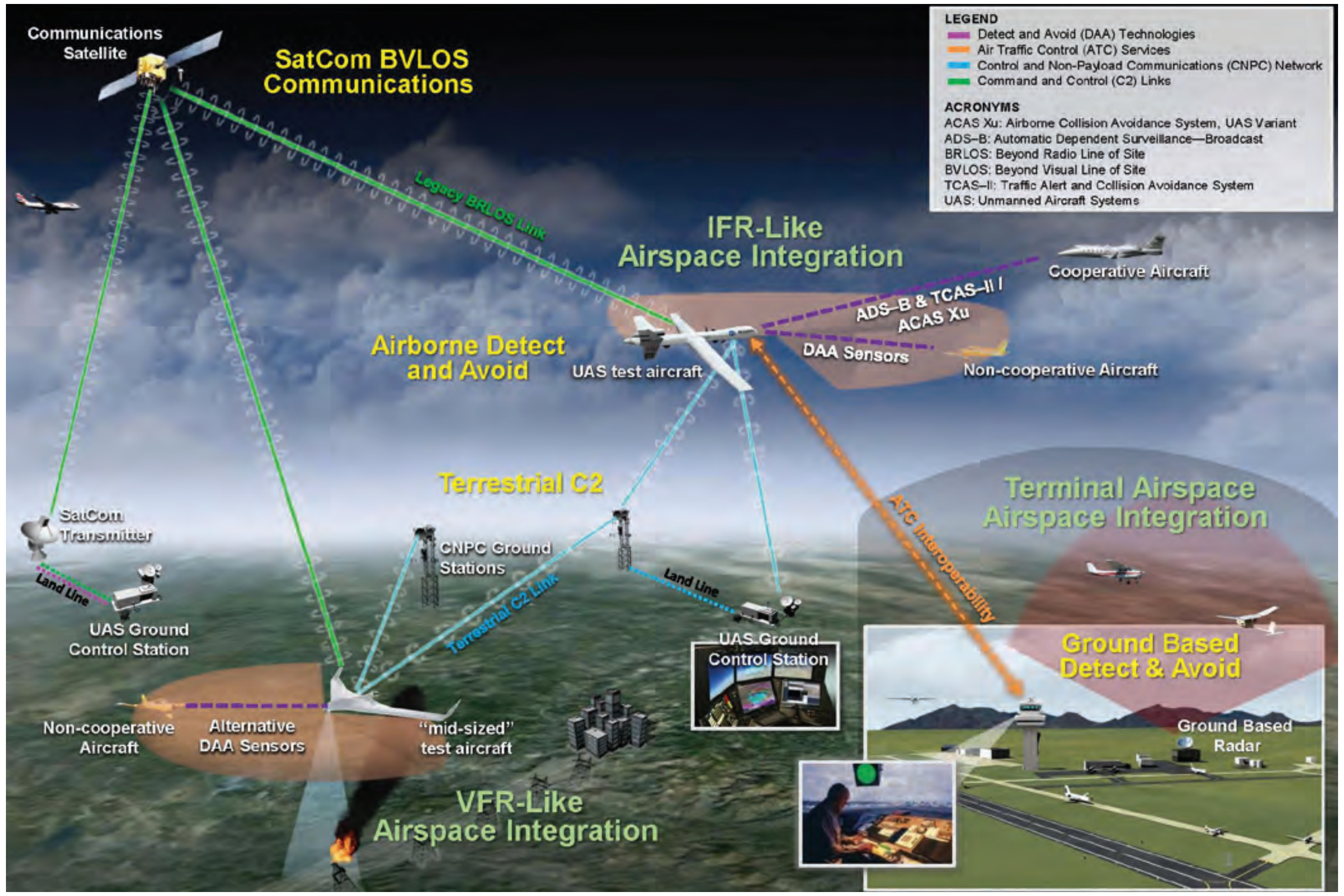
Applications

- Advanced air mobility operations

PI: Luke Bard | 661-276-2756 | Luke.J.Bard@nasa.gov

NASA's B-377SGT Super Guppy Turbine cargo aircraft arrives at NASA Armstrong for maintenance in April 2021.

Unmanned Aircraft System (UAS) Integration in the National Airspace System (NAS) Project



The multi-center UAS in the NAS research project was designed to develop operational concepts and technologies to aid in establishing and evaluating performance standards with industry to make it possible for unmanned aircraft to fly routine operations in U.S. airspace. Unmanned aircraft offer new ways of increasing efficiency, reducing costs, and enhancing safety. As new uses for these vehicles are considered, project partners are working to overcome safety-related and technical barriers to their use, such as a lack of detect-and-avoid (DAA) technologies and robust communications systems.

Providing critical data to such key stakeholders as the Federal Aviation Administration (FAA) and the RTCA Special Committee 228, the project conducted system-level tests in relevant environments to address safety and operational challenges. The project fell under the Integrated Aviation Systems Program in NASA's Aeronautics Research Mission Directorate.

The project's research addressed two technical challenge areas:

- Develop DAA operational concepts and technologies in support of standards to enable a broad range of UAS that have communication, navigation, and surveillance (CNS) capabilities consistent with instrument flight rules (IFR) operations and are required to detect and avoid manned and unmanned air traffic
- Develop satellite and terrestrial-based command and control (C2) operational concepts and technologies in support of standards to enable the broad range of UAS that have CNS capabilities consistent with IFR operations and are required to leverage allocated protected spectrum

A capstone demonstration effort, System Integration and Operationalization (SIO), worked to advance routine commercial UAS operations in the NAS. NASA entered partnerships with three companies to collaborate in bringing their proposed commercial mission demonstrations through review and approval processes with the FAA. All three partners helped develop aspects of the assessment process and gained FAA approval to execute their proposed demonstrations. Lessons learned from the activity will help advance type certification assessments.

Work to date: NASA Armstrong's contribution to the project included overall project management and integrated test and evaluation functions. The first phase research portfolio (2011–2016) was successfully completed and addressed larger UAS transitioning through the NAS encountering cooperative (i.e., equipped with a means of electronic identification, such as a transponder or Automatic Dependent Surveillance-Broadcast [ADS-B]) and non-cooperative traffic. These activities provided critical research and flight test validation that culminated in the release of RTCA Minimum Operational Performance Standards (MOPS), which were then translated into FAA Technical Standard Orders (TSOs) for UAS DAA, airborne radar, and C2 systems.


The Navmar Applied Sciences Corporation TigerShark aircraft flew over Edwards Air Force Base in July 2019 during a series of flight tests to support development of DAA standards for medium-sized UAS.

Leveraging the new TSOs addressing UAS operations in the NAS, Armstrong successfully presented a safety case to the FAA and in June 2018 obtained approval and successfully conducted a No-Chase Certificate of Authorization (COA) flight demonstration in non-segregated airspace with its Ikhana UAS.

This demonstration showcased an alternate means of compliance with the see-and-avoid requirements, employing only onboard DAA capabilities. This activity was recognized with the Aviation Week Network's Laureate Award for Commercial Aviation in the Unmanned Systems category in 2019.

The second phase research portfolio (2017–2020) addressed expanded operations in the NAS for a broader class of UAS. These activities included refining and expanding the UAS DAA MOPS to include extended operations in the NAS for mid-size UAS. Armstrong's Phase 2 activities included the integration of low size, weight, and power (SWaP) DAA systems onto a mid-size TigerShark XP UAS to enable flight test data collection to inform the update to the DAA MOPS. These flight test activities wrapped up with the employment of a live, virtual, and constructive (LVC) distributed environment. During these test flights, multiple U.S. Air Force UAS pilots flew the TigerShark XP UAS against live and simulated cooperative and non-cooperative traffic thanks to the integration with the LVC. The test allowed for the safe assessment of UAS operations in congested traffic environments.

In 2020, the UAS-NAS project provided test results and reports that informed RTCA's update to DAA and C2 MOPS. Having successfully completed its goals, the project documented the work accomplished and closed out the project. Lessons learned were also collected from and applied toward SIO activities, including those that completed in 2021. The SIO demonstration used three types of remotely piloted aircraft demonstrating different commercial missions in the NAS:

- In April 2020, General Atomics Aeronautical Systems used its SkyGuardian UAS to demonstrate a commercial mission for performing inspections. This included monitoring miles of rail, power line, and communication and canal infrastructure; agriculture and topological surveys; and wildfire and flood monitoring.
- In September 2020, Bell Textron Inc. used its APT 70 UAS to perform a representative urgent medical transport mission. It is envisioned in the future that an operational APT 70 could provide rapid medical transport for blood, organs, and perishable medical supplies.


General Atomics Aeronautical Systems Inc. flew its SkyGuardian remotely piloted aircraft to conduct a NASA Systems Integration and Operationalization demonstration activity in April 2020. Credit: General Atomics Aeronautical Systems Inc.


The Bell Textron Inc. APT 70 UAS flew for 10 minutes from Bell's facility on Floyd Carlson Field, near Fort Worth, Texas, in September 2020. Credit: Bell Textron Inc.


American Aerospace Technologies, Inc.'s AiRanger UAS flew with the Citabria plane observing the flight during NASA's Systems Integration and Operationalization demonstration in February 2021. Credit: American Aerospace Technologies Inc.

- In February 2021, American Aerospace Technologies flew its AiRanger to demonstrate aerial inspections of several miles of gas and petroleum pipelines. The use of UAS for these types of inspections can help identify pipeline leaks early to prevent environmental disasters.

Collaborators: FAA; RTCA Inc.; General Atomics Aeronautical Systems Inc.; Bell Textron Inc.; Aerospace Technologies Inc.; PAE ISR; Navmar Applied Sciences Corporation; Honeywell Aerospace; Collins Aerospace; LinQuest Corporation; Virginia Tech Mid-Atlantic Aviation Partnership; Northeast UAS Airspace Integration Research; MIT Lincoln Laboratory; U.S. Air Force Research Laboratory; and NASA's Ames, Langley, and Glenn research centers

Benefits

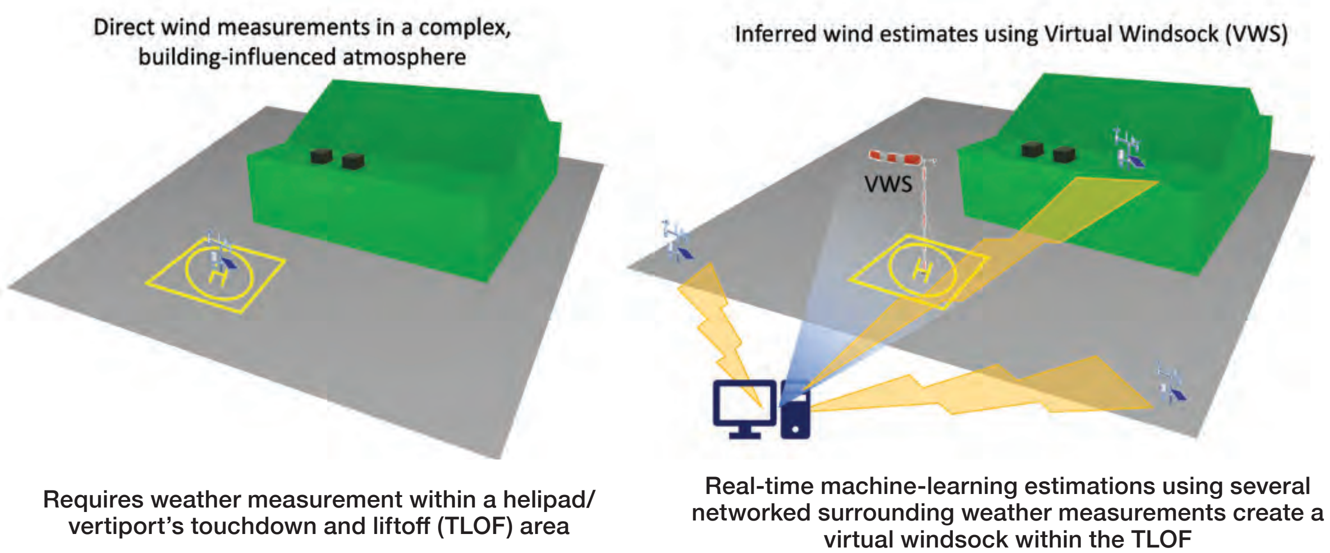
- This DAA, C2, and vehicle-level research provided information to the FAA as it develops policies and procedures to integrate UAS into the NAS.
- The research will advance MOPS for UAS and low SWaP airborne radar models.

Applications

- Rapid medical transport
- Commercial and environmental inspections
- Urban air mobility

PI: Clint St. John | 661-276-5306 | Clint.W.St.John@nasa.gov

Machine Learning Enables Virtual Windsock



A virtual windsock concept enabled by machine learning could help researchers better understand wind flows in the urban setting and to develop a method to estimate real-time surface wind conditions. The method could be particularly useful for locations where urban air mobility operations may occur such as helipads and vertiports on rooftops and in wind-blocked areas behind buildings. Using a prototyped machine learning algorithm, researchers from NASA's Armstrong and Ames research centers are conducting a study to estimate wind speed and direction in the touchdown/liftoff area of a mock helipad located at ground level next to a building. Wind estimates are based on measurements of nearby surface weather conditions and atmospheric boundary layer wind profiles.

Work to date: A weather data collection effort at the site of the former X-33 operations center was conducted as part of a preliminary wind survey for the Advanced Air Mobility National Campaign subproject. The team collected measurements throughout 2020 in free-stream and building-modified wind flows. This historical data set is being used to train the model. Researchers are using a prototype algorithm to estimate surface wind conditions at a mock helipad located in the wake of the X-33 hangar. Preliminary results are pending evaluation.

Looking ahead: The team is writing a technical memorandum with anticipated publication in 2022. An extension to the study to include NASA Armstrong's ramp area is in progress. A weather dataset is being collected as part of a preliminary wind study for the National Campaign, and subsequent runs of the machine learning algorithm will be conducted.

Partner: NASA's Ames Research Center

Benefits

- **Advanced air mobility:** Has to potential to provide weather information at helipads/vertiports with fewer resources, in locations where taking measurements is impractical, and when sensors are inoperative
- **Numerical weather prediction:** May advance micro weather nowcasting techniques, which could enable safer and more efficient commerce and increase confidence when making decisions to fly in marginal weather conditions

Applications

- Advanced air mobility operations
- Numerical weather prediction techniques

PI: Luke Bard | 661-276-2756 | Luke.J.Bard@nasa.gov

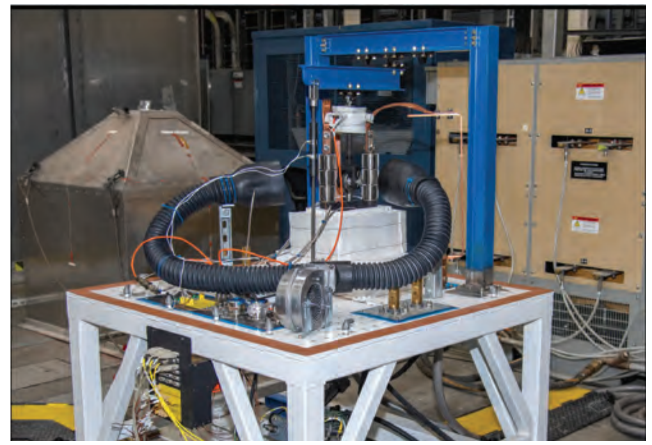
Elroy Air's vertical take-off and landing cargo delivery vehicle will join other industry partner vehicles to prepare for NASA's Advanced Air Mobility National Campaign. Credit: Elroy Air

Flight Loads Laboratory

The Flight Loads Laboratory (FLL) at NASA's Armstrong Flight Research Center in Edwards, California is a unique national facility that supports flight research and aircraft structures testing. It continues to thrive after five decades because it provides a mix of valuable capabilities: dynamic thinking to meet challenges and a culture that reinforces getting the work done. From the X-15 and YF-12 of the early years to modern marvels such as the X-57 and X-59 experimental aircraft and dozens of major accomplishments in between, the highly skilled staff is positioned for the future.

> *From the inception of the lab, we have been continually adding to the understanding of advanced flight vehicles and structures through thermal and structural testing. Our goal is to deliver a high-quality product that satisfies our customer's requirements and to do this on time and on budget by doing it right the first time.*
>
> Larry Hudson, FLL chief engineer

Coincident Heating and Loading Technique Supports Structural Tests



The Flight Loads Laboratory at NASA Armstrong has successfully completed prototype testing of a new and unique methodology to support the thermal and pressure loads testing of re-entry, high-speed, and hypersonic vehicle structures. Historically, the ground test application of combined thermal and structural loads has been achieved by applying mechanical loads outside of the radiantly heated zones. Armstrong researchers are developing a new technique that coincidently heats and pressure loads a test article. The new technique, dubbed Coincident Heating and Loading (CHeLo), is a modified load pad with an embedded heating element and is made from materials that can function at extreme temperatures.

Work to date: The CHeLo prototype design and fabrication was completed in 2021. Prototype testing included:

- Room-temperature structural testing to 50 pounds per square inch (psi)
- Thermal testing to 3,100 degrees Fahrenheit
- Combined thermal-structural testing to 50 psi at 2,700 degrees Fahrenheit)

Looking ahead: The team will continue to refine the CHeLo design to generate faster thermal response times and investigate thermal control strategies for large-scale testing.

Benefits

- **Informative:** Enables flight-like ground testing of re-entry, high-speed, and hypersonic vehicle structures that encounter significant thermal and pressure loads
- **Quantifying:** Provides significant risk reduction for projects prior to flight testing

Applications

- Re-entry, high-speed, and hypersonic vehicle structures
- Propulsion system components
- Exhaust washed structures

POC: Larry Hudson | 661-276-3925 | Larry.D.Hudson@nasa.gov

F/A-18E Super Hornet Loads Calibration Testing

The Flight Loads Laboratory (FLL) at NASA Armstrong began one of its largest loads calibration efforts in the last 50 years with Naval Air Station Patuxent River's F/A-18E Super Hornet. This testing is instrumental before the aircraft can serve as a test vehicle for determining whether it can safely manage maneuvers and proposed upgrades. Testing is divided into three sections: horizontal tail spindle testing, wing testing, and vertical tail testing. Loads will be applied to the wings, vertical tails, and horizontal tail spindles. The test program will include 87 load cases to exercise structural response using more than 50 hydraulic actuators simultaneously. Load conditions covering the flight loads envelope will be applied to the aircraft, allowing multi-gauge load equations to be derived that will enable real-time determination of in-flight aircraft loads. Maximum upload will equal more than four times the weight of the aircraft.

Work to date: The horizontal tail spindle testing, consisting of 11 load cases, began in September 2021 and was completed in October 2021. The F/A-18E aircraft arrived at Armstrong in October 2020. The aircraft was configured for testing by removing parts not needed for the calibration (e.g., radome, gear doors, antenna), and installing test-specific hardware where necessary. A pre-test nondestructive inspection was performed to ensure any existing structure defects (since the aircraft is not coming directly off the production line) would not be exacerbated by the loads calibration.

Aircraft wing and tail pad bonding surfaces were prepared by removing the radar absorbent material and paint coatings and applying a fresh layer of primer to promote load-pad adhesion. Armstrong completed buildup of all 180 load pads and assembled whiffle trees needed to distribute prescribed hydraulic actuator loads, load pad bonding onto the aircraft, and horizontal tail and wing test fixture fabrication efforts. The F/A-18E was brought into the FLL and attached to the floor tracks with restraining hardware.

Looking ahead: Wing testing began in late 2021 and will continue into 2022 with 62 load cases. When wing testing is complete, the FLL will reconfigure for vertical tail testing, which consists of 14 load cases. The overall effort is expected to be complete by summer 2022, at which time test-specific hardware will be removed and the aircraft will be configured for flight and returned to Naval Air Station Patuxent River. From the test data gathered, Armstrong will deliver calibrated loads equations for shear, bending moment, and torque for the vertical tail, horizontal tail spindle, wing root, wing fold, and wing leading edge control surfaces.

Partner: Naval Air Station Patuxent River

Benefits

- **Improves flight safety:** Enables loads on the aircraft to be monitored in real-time during flight tests
- **Permits training:** Enables team to maintain specialized skills and knowledge in loads calibration testing and allows for training of newer or inexperienced team members

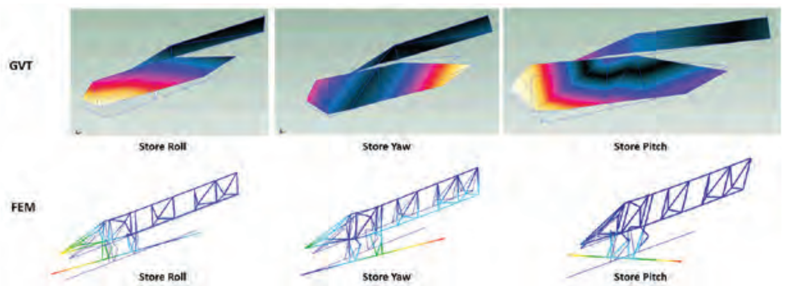
Applications

- Real-time monitoring of aircraft loads during flight

POC: Larry Hudson | 661-276-3925 | Larry.D.Hudson@nasa.gov

F-15 Wing Store Structural Dynamics Airworthiness Clearance

(Above) F-15D TN 897 with new wing store (STA 2) during a compatibility flight profile flight in 2020; (below) GVT and FEM mode shape comparisons of F-15 wing pylon and new wing store; and (right) lateral impact hammer excitation on wing store during GVT



NASA Armstrong provided airworthiness clearance of a new F-15 wing store referred to as the Airborne Schlieren Pod—mounted on either wing station (STA 2 or STA 8)—for the F-15B/D aircraft. To show adequate flutter/divergence margin for the aeroelastic airworthiness clearance, the F-15B/D with the new wing store installed must maintain a 15% margin on the flutter boundary of the planned flight envelope. This was the first F-15 wing store Armstrong cleared for flight. The center has experience with F-15 centerline stores that do not affect the aircraft flutter mechanism, but engineers were unfamiliar with how these new wing stores would affect the F-15 flutter mechanism. To clear the new F-15 wing store for flight, Armstrong's structural dynamics engineers merged two airworthiness approaches: 1) clearance by analysis and test and 2) clearance by similarity to other comparable F-15 wing stores and external fuel tank.

The new wing store analyses and tests with flutter clearance approach used finite element models (FEMs), modal and flutter analyses, a moment of inertia (MOI) test, and a ground vibration test (GVT). Several FEMs were created during the project lifecycle and connected to Armstrong's F-15B FEM. The GVT and MOI tests were completed with the new wing store. Multiple F-15 wing store flutter analyses were performed, and the wing store beam FEM was updated with only MOI data.

The wing store flutter clearance approach by similarity contained two parts. The first part compared the similarity of other similar wing store flutter analyses with different store flight configurations. The second part relied upon documentation from the U.S. Air Force SEEK EAGLE Office and its experience with clearing other wing stores and the external fuel tank on F-15 wing stations. With that documentation, the final wing store GVT on the F-15 was descoped to a smaller effort. The clearance flights included a chase aircraft, no telemetry data, and was qualitatively assessed by the pilot and post-flight inspectors.

Work to date: The new F-15 wing store clearance flights—referred to as Compatibility Flight Profile (CFP) flights—were flown on F-15D tail number (TN) 897 in November and December 2020 to check aircraft handling qualities and store structural integrity tests. The new F-15 wing store is now supporting reimbursable project missions.

Looking ahead: The new Airborne Schlieren Pod will house NASA schlieren equipment for future X-59 Quiet SuperSonic Technology (QueSST) aircraft flights.

Benefits

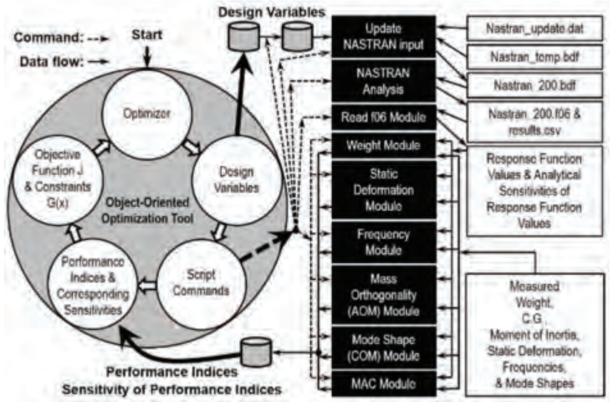
- **Enabling:** Permits F-15 wing store to house research equipment

Applications

- Ground vibration testing
- Flight aeroelastic airworthiness clearance

PIs: Natalie Spivey | 661-276-2790 | Natalie.D.Spivey@nasa.gov
Shun-fat Lung | 661-276-2969 | Shun-Fat.Lung-1@nasa.gov
Samson Truong | 661-276-2998 | Samson.S.Truong@nasa.gov
Scott Stebbins | 661-276-6141 | Scott.L.Stebbins@nasa.gov

Structural Model Tuning Tool



Block diagram of analytical sensitivity-based structural model tuning tool

Finite element (FE) modeling of an aircraft structure is critical for accurate prediction of aeroelastic as well as aeroservoelastic behavior during flight. Yet a trial-and-error approach for structural model tuning remains widespread due to limited time between ground vibration testing (GVT) and early flight tests. NASA Armstrong researchers have developed an FE tuning tool for a structural FE model that uses NASA Structure Analysis (NASTRAN)-generated analytical sensitivity values. The new tool is based on sensitivity values computed using a NASTRAN code as well as in-house pre- and post-processing codes. Target data to be matched during the tuning procedure include total weight, center of gravity location, moment of inertia (if available), frequencies, mode shapes, and static deformation.

Work to date: Armstrong researchers validated the structural model tuning tool using a cantilevered aerostructure test wing IV. They determined the three most important modes for primary flutter that cover 99.7% of primary flutter modes. Results demonstrated that weight-related errors, including total weight and x and y center of gravity locations, are less than 3% and that the most important primary frequency error is less than 1%. These values are important because military standards require that the frequency error should be less than 3% for primary modes. Results demonstrated that the FE model correlates with test data.

Looking ahead: Next steps are to validate an FE model for a scaled commercial transport aircraft, with respect to a proof test and ground vibration test data.

Benefits

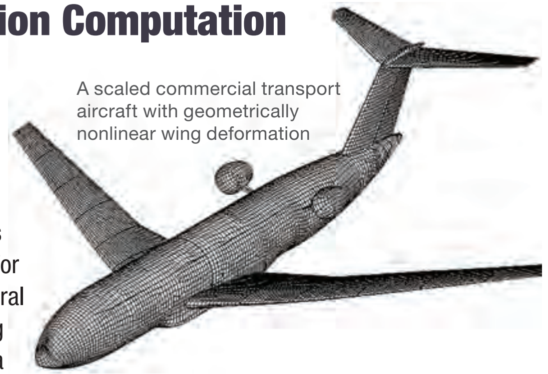
- **Improves model accuracy:** Enables gradient-based structural FE model tuning, improving sensitivity computations
- **Enhances efficiency:** Uses GVT and proof test data to model aeroelastic and aeroservoelastic behavior in flight

Applications

- Structural FE model tuning for research aircraft
- Launch vehicles

PI: Chan-gi Pak I 661-276-5698 I Chan-Gi.Pak-1@nasa.gov

Geometrically Nonlinear Structural Deformation Computation



A scaled commercial transport aircraft with geometrically nonlinear wing deformation

NASA Armstrong researchers have developed a basis function method for predicting structural deformation using sparse strain data to enable monitoring the health and behavior of a complex 3D structure such as an aircraft in flight. Measuring the wing deformation during flight is important to perform flexible motion control (i.e., active sonic boom control, gust/maneuver load alleviation, and divergence/flutter suppression). The proposed basis function method will be applied to a high-aspect-ratio rectangular wing model, the proof/calibration tests model of the X-59 Quiet SuperSonic Technology (QueSST) aircraft, and a scaled commercial transport aircraft. Specifically for the jig-shape optimization study for the X-59, an active trim shape control will be needed to minimize the sonic boom strength on the ground to minimize the error between the aeroelastic trim shape and the target trim shape at cruise flight speed since jig-shape is not optimum at different flight conditions and weight configurations.

Work to date: Researchers validated the structural shape sensing method using a high-aspect-ratio rectangular wing and the stabilator of the X-59. In high-aspect-ratio wing cases, results from the basis function method give better correlation with target values than the results from the linear and geometrically nonlinear two-step theories. The basis function method for the X-59 stabilator simulation provided excellent correlation with target values. Indeed, relative percentage prediction differences using the nonlinear basis function method are less than 0.3% and the correlation with nonlinear two-step theory is less than 2.2%.

Looking ahead: Next steps are to apply the method to the scaled commercial transport aircraft and to the X-59 aircraft.

Benefits

- **Enabling:** Provides accurate linear and geometrically nonlinear wing deformation data during flight with limited strain data.

Applications

Measuring deformation for active flexible motion control:

- Trim shape control
- Gust load alleviation
- Maneuver load alleviation
- Active sonic boom control
- Flutter and divergence suppression

PI: Chan-gi Pak I 661-276-5698 I Chan-Gi.Pak-1@nasa.gov

Improving Aerospace Vehicle Efficiency

Increasing efficiency in aerospace vehicles is a key goal across the spectrum of NASA operations. Researchers at NASA's Armstrong Flight Research Center in Edwards, California, are are constantly striving to build efficiency into all phases of flight projects, through development, fabrication, and operations processes.

From wing designs that could exponentially increase total aircraft efficiency to novel test techniques that evaluate sensor suites and calibration systems, our researchers are finding unique solutions that boost efficiency.

This work has applicability beyond flight safety and design optimization, as lessons learned with experimental aircraft can be applied to other vehicles, such as supersonic transports, large space structures, and unpiloted aircraft.

Multi-Utility Testbed Advances Aeroservoelastic Technologies

Longer and more flexible wings are considered crucial to the design of future long-range, fuel-efficient aircraft. Because these wings are more susceptible to flutter and the stress of atmospheric turbulence, NASA is investigating key advanced control technologies for active flutter suppression and gust load alleviation. The remotely piloted X-56A Multi-Utility Technology Testbed (MUTT) was developed by Lockheed Martin for the U.S. Air Force Research Laboratory to test active aeroelastic control technologies for flutter suppression and gust-load alleviation on flexible wing structures. The aircraft was tested using flight profiles where flutter occurs to demonstrate that onboard instrumentation not only can accurately predict and sense the onset of wing flutter but also can be used by the control system to actively suppress aeroelastic instabilities.

An X-56B configuration used the same center body as the earlier X-56A but used a new wing design developed by Northrop Grumman to further researchers' understanding of the interactions between a flight controller and a flexible aircraft's structure. The X-56B wings were designed with a decreased bending to torsional stiffness ratio to be flown at negative static margins. Wing tip gyros were included in the wing set and accelerometers were relocated to test various feedback control methodologies.

Work to date: Testing with the X-56A concluded in 2019 with the modern controller clearing the flight envelope to 120 knots and actively suppressing flutter 10% above flutter speed. Follow-on ground testing with the X-56B configuration – Northrop wing and NASA center body – was conducted in 2020 and 2021. Five flights were completed.

Partners: U.S. Air Force Research Laboratory, Northrop Grumman

Benefits

- **Enabling:** Facilitates construction of longer, lighter, more flexible wings for crewed and remotely piloted aircraft
- **Configurable:** Supports a vast array of future research activities for wing sets, tail sections, sensors, and control surfaces

PIs: Jacob Schaefer I 661-276-2549 I Jacob.Schaefer@nasa.gov
Matt Boucher I 661-276-2562 I Matthew.J.Boucher@nasa.gov
Alex Chin I 661-276-2681 I Alexander.W.Chin@nasa.gov
Jeff Ouellette I 661-276-2152 I Jeffrey.A.Ouellette@nasa.gov

Glider Swarm Sensor Distribution

A Prandtl-M 24-inch model glider drops from a tethered blimp.

Martian surface observations are collected remotely via satellites or with localized landers and rovers. Researchers from NASA Armstrong and NASA's Jet Propulsion Laboratory (JPL) are collaborating to create preliminary concepts, systems development, and prototypes for small unmanned aerial systems (UAS) capable of deployment and flight on Mars. This swarm of gliders must fit in a small enclosure, unfold, and carry as much payload as far as possible in the thin atmosphere of Mars to create a distributed mesh sensor network. Preliminary designs of the prototype Mars glider with wingspans of 13 inches, 18 inches, and 24 inches were developed in the first phase of the Center Innovation Fund (CIF) award. The technology could also be used on Earth for atmospheric observations.

Work to date: The 24-inch model was fabricated and flown on an unmanned aerial vehicle (UAV) mothership. To prototype the glider swarm on Earth, a balloon/blimp concept of operations was developed. A gondola was designed, developed, and operated from a tethered blimp. The 24-inch model was then test flown from the tethered blimp conducting release, handling, and glider performance flights. The 13-inch model mold was redesigned to incorporate updated avionics and the first prototype vehicles were fabricated. A series of familiarization flights of the 13-inch model were conducted off a UAV mothership.

Virtual work and restricted on-site operations resulted in a major shift for this research activity. The project team focused on improving the fidelity of the aerodynamic prediction tools, automating and optimizing the vehicle design and analysis workflow, and designing a new series of vehicles in the 13-inch, 18-inch, and 31.25-inch system demonstrator size. This work was based on the quantitative and qualitative flight performance of previous vehicles in this design family.

Collaborators: NASA's Jet Propulsion Laboratory

Benefits

- **Breakthrough:** Characterizes small glider distribution performance in free and directed flight
- **Efficient:** Provides a low-cost, low-mass sensor distribution architecture for novel atmospheric observations
- **Innovative:** Enables NASA Armstrong researchers to analyze, develop, and test in a new flight regime while participating in planetary science platform development

Applications

- Collect weather and landing site information for future human exploration of Mars

POCs: Jason Lechniak | 661-276-2620 | Jason.A.Lechniak@nasa.gov
David Berger | 202-358-2473 | Dave.E.Berger@nasa.gov

System Identification for Flexible Aircraft

This research effort focused on designing multi-sine programmed test inputs for use in flexible aircraft system identification situations. In this context, system identification is the process of exciting aircraft and control system dynamics, collecting flight data measurements, and constructing models from the data. For the X-56A Multi-Utility Technology Testbed (MUTT) aircraft, system identification was needed to refine and validate preflight aerodynamic and aeroelastic predictions and to verify robust stability of flight control laws. System identification as applied to the X-56A aircraft entailed modeling the response to as many as 10 separate control surfaces and two engines.

The team at NASA Armstrong applied optimization techniques to select excitation frequencies, amplitudes, and phases to efficiently generate data with a high signal-to-noise ratio across a wide frequency band while maintaining a margin with respect to operating limitations. While this approach was tailored toward flexible aircraft, it is applicable to any complex system identification problem where manually tailoring the excitation is impractical. In addition to validating preflight predictions and control system design, the approach is useful for computational fluid dynamics simulation to reduce expensive computation time.

Work to date: The X-56A flexible wing flight test campaign included 29 flights. Low-order equivalent systems and state-space models were estimated from the flight data, in some cases at flight conditions beyond the flutter boundary. The multi-sine programmed test inputs were applied to the X-56B configuration data in 2020, reducing required flight test time and reducing costs for future industry partners.

Partner: NASA's Langley Research Center

Benefits

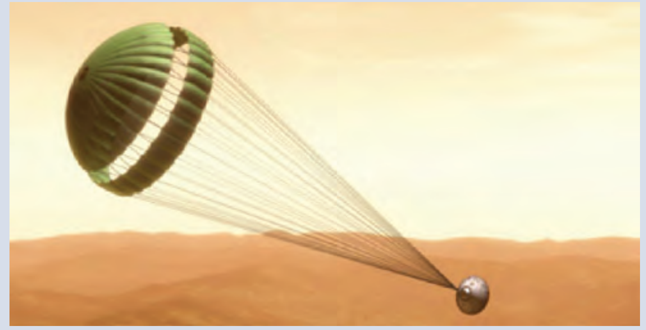
- **Powerful:** Generates high-quality flight data quickly and safely
- **Efficient:** Promotes real-time and onboard data reduction for control room monitoring

Applications

- Fundamental research
- Control system requirements verification

PI: Matt Boucher | 661-276-2562 | Matthew.J.Boucher@nasa.gov

NASA Armstrong Wins Two Early Career Initiative Awards



Two NASA Armstrong research teams won prestigious Early Career Initiative (ECI) awards in 2020 and 2021. The teams receive $2.5 million over two years to support their research.

The FY2022 award is for the project **Enhancing Parachutes by Instrumenting the Canopy (EPIC)**, which will investigate reducing mission risks through parachute canopy instrumentation. Led by principal investigator Erick Rossi De La Fuente, along with Armstrong co-investigators Lydia Hantsche and Dan Budolak and NASA's Ames Research Center's Matthew Nguyen, the team will adhere highly elastic strain sensors to the surface of parachute canopy material. Supersonic parachutes used for Mars entry, descent, and landing suffer from poorly understood structural margins and unvalidated structural models due to lack of flight data. Canopy instrumentation could collect that data. Out of 15 nominations submitted in this application year from across NASA, only four were selected for funding.

"The ECI team did an outstanding job connecting with NASA researchers across the agency, as well as with industry and university experts, to identify a significant gap that has not yet been addressed," said Tim Risch, Armstrong's associate director for research. "The tenacity the team exhibited in developing their research proposal in coordination with these partners was certainly a key factor in their win."

Another Armstrong team was awarded an FY2021 ECI award to develop a **Dust-Tolerant Magnetic Coupler for Cryogenic Fluids** for applications on the Moon and Mars. Led by Armstrong researchers working in collaboration with NASA's Glenn Research Center and Kennedy Space Center, as well as a commercial partner, the team is working to lab-demonstrate an electrostatic cryogenic coupler that employs patterned magnets. *(For more on this effort, see page 58.)*

The Armstrong-led research team includes Shideh Naderi (PI), Jonathan Lopez, Paul Bean, Nic Heersema, Scott Stebbins, and William Manley.

Begun in FY2015 as part of NASA's Center Innovation Fund (CIF), ECI's goal is to engage NASA early-career researchers with world-class partners to develop the innovative leaders and technologies of the future, invigorating NASA's technological base and best practices for project management.

Prandtl Flying Wing

(Above) NASA Armstrong's original Prandtl-D wing is autographed by all the interns who worked on the project. The wing is featured in the Innovation Gallery of the Smithsonian Institution's National Air and Space Museum.

Researchers at NASA Armstrong are continuing to test a new wing shape that could significantly increase aircraft efficiency. The team has built upon the research of German engineer Ludwig Prandtl to design and validate a scale model of a non-elliptical wing that radically reduces drag by simultaneously optimizing aerodynamics, structure, and control. By allowing for longer wingspans, the new design produces 12% less drag than current solutions. Research data proves that adverse yaw has been overcome and aircraft response is proverse yaw, without relying on rudders or complex computerized flight controls to accomplish it – exactly as birds maneuver with no vertical tail. In a propeller application using analogous theory, gains in efficiency and acoustic levels are predicted. If the concept continues to prove its value, it could advance NASA's research goals to verify technologies leading to significant fuel economy, emissions reduction, and reduced acoustic signature.

Work to date: The team developed, demonstrated, and validated scale models of an improved Preliminary Research Aerodynamic Design to Lower Drag (Prandtl-D) wing, and flight experiments have unequivocally established proverse yaw. The Prandtl-D Phase 1 innovation was patented, and research has led to work on an autopiloted Preliminary Research Aerodynamic Design to Land on Mars (Prandtl-M) Phase 2. In 2018 and 2019, the team completed test flights incorporating pressure sensors embedded in the wing. Preliminary data demonstrated the projected lift distribution. The Prandtl-M Phase 2 activity is being studied in partnership with NASA's Jet Propulsion Laboratory for a swarm sensor network concept to carry as much payload as far as possible in the thin atmosphere of Mars. Phase 2b activity with a larger Prandtl-D testbed is being flown for data gathering.

Looking ahead: Researchers are exploring ways this innovation can benefit NASA projects. In addition, the wind energy industry is open to new bladed designs that improve efficiency, and this market segment is large and growing.

Partner: NASA's Jet Propulsion Laboratory

Benefits

- **Highly efficient:** Increases total aircraft efficiency by as much as 65%, including efficiency increases in drag reduction (12%) and when used in propeller systems
- **Economical:** Improves fuel efficiency by allowing aircraft to fly more efficiently for the same structural weight
- **Safer:** Reduces adverse yaw in roll, resulting in coordinated turns and lowering or eliminating the need for rudder corrections

Applications

- Mid-size commercial aircraft
- Drones and uncrewed aircraft
- Energy delivery systems
- Wind turbines
- Industrial fans

POCs: Jason Lechniak | 661-276-2620 | Jason.A.Lechniak@nasa.gov
David Berger | 202-358-2473 | Dave.E.Berger@nasa.gov

Integrated Flight Dynamics and Aeroservoelastic Modeling and Control

This research effort is developing flight control systems and mathematical models that integrate structural and flight dynamics. As modern aircraft become more flexible and these disciplines converge, conflicts arise between independently developed modeling methodologies. Because the structural and flight dynamics of the X-56A Multi-Utility Technology Testbed (MUTT) aircraft are acutely coupled, resulting models can capture the requirements of both disciplines.

Work to date: The modeling approach developed during the X-56A flutter suppression flights was applied to the new X-56B configuration and the models were used to successfully design control laws for the vehicle. The unsteady aerodynamic and structural data have been integrated with a non-linear piloted simulation. The piloted simulation allows for evaluation of the dynamics and development of pilot techniques in highly non-linear conditions, such as takeoff and landing, enabling the safe operation of the aircraft.

Partner: U.S. Air Force Research Laboratory

Benefits

- **More design freedom:** Enables the design of lighter, larger, and more flexible wing profiles
- **Economical:** Increases fuel efficiency
- **Safer:** Reduces likelihood of structural damage
- **Innovative:** Advances the state of the art for higher-aspect-ratio wings and enables future N+3 commercial aircraft concepts (i.e., three generations beyond the current commercial transport fleet)

PIs: Jeffrey Ouellette | 661-276-2152 | Jeffrey.A.Ouellette@nasa.gov
Jacob Schaefer | 661-276-2549 | Jacob.Schaefer@nasa.gov
Peter Suh | 661-276-3402 | Peter.M.Suh@nasa.gov

Practical Modal Filtering

Distributed sensors such as those within the Fiber Optic Sensing System (FOSS) offer a significant number of measurements of an aircraft's structure, which has significant potential for controls and model validation. However, traditional approaches are unable to handle the large number of measurements and their performance degrades. A modal filtering approach was designed to exploit the large number of measurements and to translate them into a smaller and more easily interpreted number of parameters. NASA Armstrong researchers are building upon previous theoretical studies to generate a modal filter that will work reliably in a flight environment. This work will address the challenges in implementation and identify new potential challenges for future programs.

Work to date: Researchers have used simulated data to demonstrate the accuracy of the modal filtering approach. The same modal filtering has been applied to the X-56 flight test data to demonstrate the effectiveness in a flight environment and the robustness to realistic sensor noise.

Looking ahead: The technology is being applied to other ongoing projects such as the Integrated Adaptive Wing Technology Maturation wind tunnel test.

Benefits

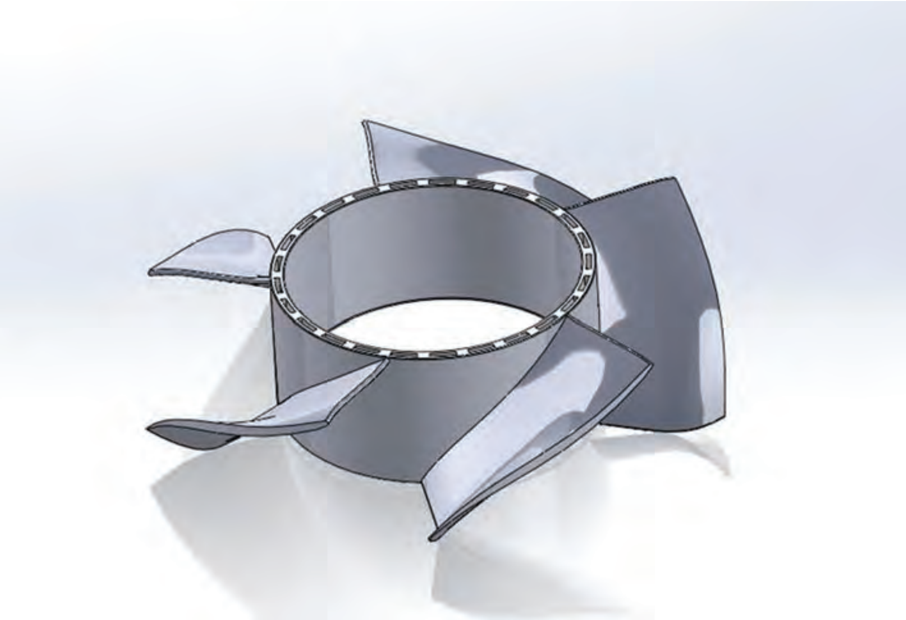
- **Improved insight:** Enables insights to characteristics and the state of an aircraft's structure in flight
- **Improved control systems:** Permits more robust control laws to reduce loads and suppress flutter

Applications

- Aeroelastic model validation
- Aeroelastic state estimation for control systems
- Distributed sensor noise characterization

PI: Jeffrey Ouellette | 661-276-2152 | Jeffrey.A.Ouellette@nasa.gov

New Propeller/Fan Increases Efficiency



NASA Armstrong researchers are working on design processes for propeller blades that are intended to increase efficiency and reduce aerodynamic noise. Based on wing design improvements derived from the Preliminary Research Aerodynamic Design to Lower Drag (Prandtl-D) and Preliminary Research Aerodynamic Design to Land on Mars (Prandtl-M) aircraft, this innovative design uses an alternative spanload to redistribute the propeller loading. The theory shows that altering the twist distribution changes lift distribution, resulting in a significant reduction in the strength of the tip vortex drag. The designs are intended to optimize the power needed to rotate a propeller or fan. Initial estimates indicate 15% improvement in propulsive efficiency and noise reduction. Currently, the analysis and design optimization are showing positive results. If successful, the benefits could be realized for a wide range of propeller and fan designs.

Work to date: Work has focused on verifying and automating the design processes by improved understanding of the math and theory behind the designs. Additionally, the project has worked to identify optimization parameters to apply to design iterations that trace back to the theory. The project has identified that the designs applied to the propellers could include a range of distributions that are constrained differently than wing designs. The design process for the Prandtl propellers improves efficiency at one operating design point. Performance and efficiency in off-nominal operations will be assessed during design and evaluation.

Researchers will continue to use the modeling and analysis of a known and tested propeller to generate models, compare these results to physical testing, and refine a workflow to assess future propeller configurations. The end result is expected to be a simplified design process resulting from modeling and testing.

Looking ahead: The team will refine the propeller design and implementation processes and then test the propeller and fan designs.

Partner: California State University, San Bernardino

Benefits

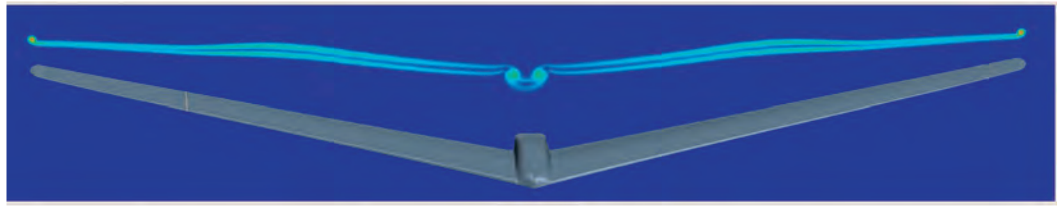
- **Efficient:** Redistributes lift and drag along the propeller or fan blade, reducing power consumption while producing the designed thrust
- **Economical:** Allows blades to use less power, reducing fuel costs
- **Quieter:** Produces less noise than conventional blade designs
- **Compatible:** Provides a solution that can be coupled with several airfoil designs

Applications

- Propellers
- Industrial fans

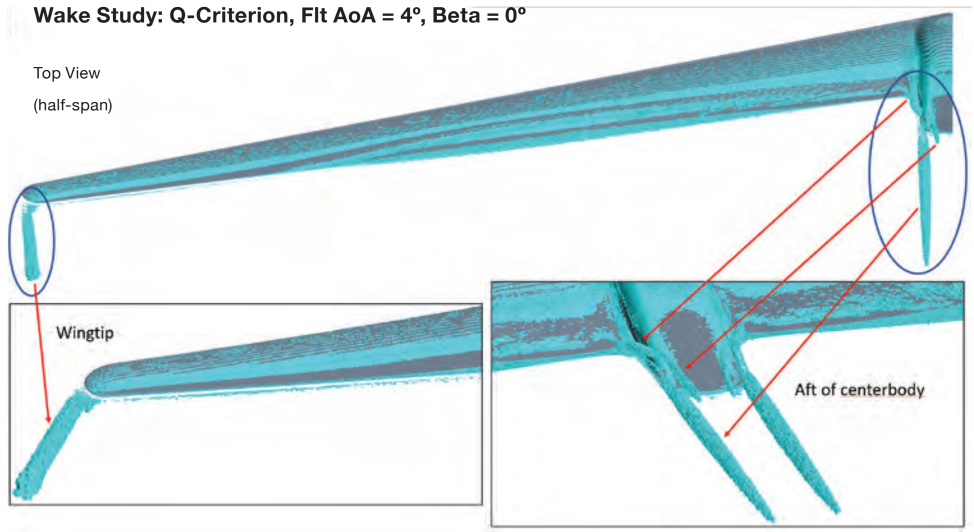
PI: Jason Lechniak | 661-276-2620 | Jason.A.Lechniak@nasa.gov

CFD Analysis of a Low-Speed Swept Wing with a Bell-Shaped Lift Distribution



A computational fluid dynamics (CFD) solution of a low-speed swept wing with a bell-shaped lift distribution (Prandtl-D Phase 3c wing glider) showing visualization of the wing (gray) and its wake on a vertical plane (blue) behind the wing for an angle of attack of 4 degrees

NASA Armstrong researchers initiated a computational fluid dynamics (CFD) analysis to provide detailed flow physics for a low-speed swept wing with a bell-shaped lift distribution. This CFD model is based on the subscale Preliminary Research Aerodynamic Design to Lower Drag (Prandtl-D) Phase 3c glider with a wingspan of 24.6 feet. Although flight data were collected during flight tests at Armstrong, it was difficult to fully understand the detailed flow physics due to the limited and sparse data set. A CFD analysis model could provide a more comprehensive description of the flow field over the wing and would go a long way toward increasing understanding of this wing's aerodynamics, such as the wing's proverse yaw aerodynamic characteristic observed in flight. The knowledge gained from this research effort could support various wing designs for future crewed and remotely piloted high-efficiency aircraft.



CFD visualization of the trailing wing-tip vortex and wing-fuselage junction vortices (magenta) for the wing (gray)

Work to date: Armstrong researchers developed a preliminary CFD model with articulating elevons based on the flight test vehicle. They also developed an OpenVSP vortex lattice model with empirical viscous correction for the same wing to compare with the CFD model. Early CFD analysis results showed good second-order CFD solution grid convergence characteristics. Although grid refinement studies showed that volume mesh refinement in the wing wake region is needed to capture the fine details of the wing wake flow physics, this wake mesh refinement is not necessary for accurate wing forces and moments predictions.

There is reasonable agreement between the CFD and the vortex lattice results. The CFD model provides excellent agreement with the original Prandtl bell-loading spanwise lift distribution at the incoming angle of attack of -1 degree. The wing-tip vortex is insignificant at this design condition, as expected for this bell-loading wing design. At other angles of attack, the wing's spanwise lift distribution diverges from the Prandtl bell-loading lift distribution, and the wing-tip vortex becomes stronger. Differential deflections of the elevons also cause the wing's spanwise lift distribution to diverge from the design Prandtl bell load. In addition to the wing-tip vortices and the wing-fuselage junction vortices, the elevon gap vortices are detected when the elevons are deflected.

Looking ahead: To validate the CFD model, researchers will compare CFD results to the relatively sparse set of sectional wing pressure flight test data that were collected. Then they will analyze the detailed flow physics provided by the validated CFD model for a CFD run matrix of different flight angles and elevon deflections to further understand the aerodynamics of low-speed swept wings with bell-shaped lift distribution. Any aerodynamic benefits found in this effort for the Prandtl-D Phase 3c wing will be noted for possible use in future aircraft designs.

Benefits

- **Informative:** The subscale Prandtl-D Phase 3c wing glider has been found to perform well during flight tests at Armstrong in coordinated flights without the conventional airplane's tail and rudder. Although the flight data that were collected indicated the presence of proverse yaw, for example, the flight data were sparse. This research will expand our understanding of the aerodynamics of low-speed swept wings to benefit future high-efficiency aircraft designs.

Applications

- Long endurance unmanned aircraft vehicles (UAVs)
- Mars gliders

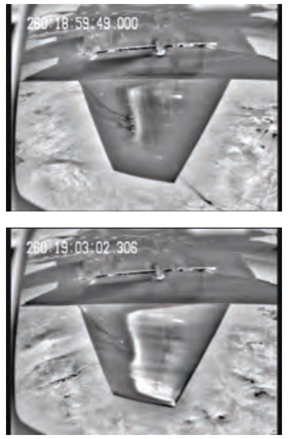
PI: Trong Bui | 661-276-2645 | Trong.Bui-1@nasa.gov

Investigating Laminar Flow

Researchers at NASA's Langley Research Center have developed a new crossflow suppression technique for aircraft wings with moderate sweep. NASA Armstrong is contributing to the effort with flight tests to confirm that the new technique works as predicted in a flight environment. Known as Crossflow Attenuated Natural Laminar Flow (CATNLF), the technique enables laminar flow by reshaping wing airfoils to obtain specific pressure distribution characteristics that control the crossflow growth near the leading edge. This research could potentially be useful in future commercial transports to reduce aerodynamic drag and increase efficiency. The CATNLF research includes three flight test efforts.

Resistive Heating for the Evaluation of Aerodynamic Transition (ReHEAT)

The ReHEAT effort was the first flight test of a technology previously tested in a wind tunnel to improve flow visualization of the boundary layer. Testing involved painting a carbon-based, electrically conductive coating onto a test surface. An electrical current was passed through the coating to heat the surface. In a wind tunnel, the coating was covered with temperature-sensitive paint for flow visualization. During flight tests, an infrared camera was used for visualization.



An electrically conductive heating layer and infrared camera enabled flow visualization of the boundary layer during flight tests.

Work to date: The coating was applied to a supersonic natural laminar flow test article at Armstrong. The coated test article was flown on the centerline pylon of the F-15B research testbed, along with an infrared camera system. During flight tests in 2019, the heating layer worked as expected, and the infrared camera successfully visualized the state of the boundary layer.

Looking ahead: The coating will be applied to the CATNLF test article to achieve similar improvements to the flow visualization of the boundary layer.

Centerline Instrumented Pylon (CLIP) Flow Rake

The CLIP Flow Rake effort is a vertically oriented instrumentation rake with air data and disturbance probes that will map the flow field under the F-15B testbed to support the follow-on test with the CATNLF laminar flow test article. Flow field mapping will be instrumental for understanding the data that will be collected during the CATNLF flight tests.

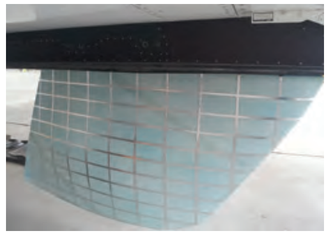
Work to date: A contractor completed the mechanical design and fabrication and delivered the rake to Armstrong in April 2020. Aeroprobe Corporation fabricated and calibrated the hemispherical five-hole probes to be installed in the rake and delivered them in December 2020. Calspan Corporation designed and fabricated the flow rake ground support cart and delivered it to Armstrong in January 2021.

Looking ahead: Build-up of the flow rake was scheduled to begin in late 2021 with integration on the airplane and flight tests slated for spring 2022.

CATNLF Laminar Flow Test Article

The CATNLF laminar flow test article is a stub wing mounted vertically under the F-15B testbed aircraft. NASA Langley researchers are designing the test article to achieve significant runs of natural laminar flow at Reynolds numbers up to 30 million. A leading-edge sweep of 35 degrees will demonstrate that the technology can attenuate the crossflow boundary layer transition mechanism, which is the dominant transition mechanism on wings with moderate to high sweep.

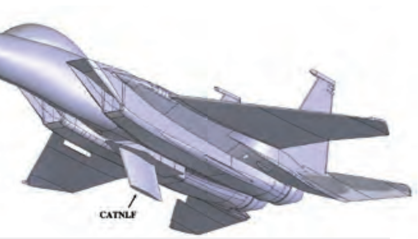
Work to date: A contract was awarded to Calspan Corporation for the detailed mechanical design and fabrication of the CATNLF and ground cart. Armstrong's Model Shop fabricated a foam mock-up of the test article and installed it on the airplane to verify the infrared (IR) camera look angle. A critical design review was completed, and the test article is ready for fabrication.



Foam mock-up of the CATNLF test article fabricated by Armstrong's Model Shop

Looking ahead: Fabrication of the CATNLF test article began at Calspan in August 2021. Delivery of the completed test article and ground support cart to Armstrong is planned for early 2022. Build-up and integration will begin in late summer 2022, with flights planned for fall 2022.

Partner: NASA's Langley Research Center



CAD model of F-15B testbed aircraft with CATNLF test article mounted to the centerline

Benefits

- **Informs wing design:** Helps researchers and designers understand key laminar flow phenomena
- **Enables access to actual flight conditions:** Allows data to be collected in conditions similar to those faced when wings are integrated into an aircraft design

Applications

- Commercial subsonic transports

Lead: Mike Frederick | 661-276-2274 | Mike.Frederick-1@nasa.gov
PI: Michelle Lynde | 757-864-9097 | Michelle.N.Lynde@nasa.gov (NASA Langley)

NASA Armstrong Lends Flight Expertise to Pilot Safety Effort

NASA Armstrong researchers are contributing to an agency effort to increase pilot safety. The NASA Engineering and Safety Center (NESC) Pilot Breathing Assessment (PBA) project worked to better understand what causes pilots to experience potential life-threatening physiological episodes (PEs) resulting in cognitive impairments, numbness, tingling, lightheadedness, behavioral changes, and fatigue. The NESC tapped Armstrong to conduct the PBA flights to leverage the center's flight research expertise with F/A-18A/B and F-15D aircraft. Past research has focused on studying aircraft to reduce PEs. The NESC is now working to understand pilot response to various flight conditions. NASA will use the data gathered through PBA flights to quantify how the complex human system (i.e the pilot) interacts with the complex aircraft system operating in the complex flight environment.

Work to date: At Armstrong, the effort involved five pilots, six aircraft, two aircrew equipment configurations, and approximately 150 hours of flight. Pilots flew six scripted profiles representing a variety of conditions experienced throughout the aircraft operating envelope, including high-altitude, long-duration flights above 40,000 feet; aerobatic flights that simulated basic fighter maneuvering; medium altitude, low breathing effort flights, low-altitude flights below 8,000 feet pressure altitude; flights with cabin pressurization removed, and functional check-type flights to evaluate system interactions.

Key Accomplishments:

- **PBA Final Report:** The assessment team completed flying at the end of 2020 and published findings in a two volume, 800-page technical report that was authored by 20 subject matter experts spanning multiple aerospace disciplines (NESC Pilot Breathing Assessment).
- **Getting the word out:** After completion, the PBA team briefed senior military leaders and aerospace contractors from 10 organizations of the results from their assessment. In October 2021, a technical overview by the project pilot and the project principal engineer was presented at the Society of Experimental Test Pilot's (SETP) Annual Symposium in Anaheim, California.
- **Follow-on work:** In November 2020, a follow-on case study was initiated to document the lessons learned for pilot breathing systems based on systems engineering and human factors principles. Armstrong pilots and subject matter experts in systems engineering and life support contributed to the final report, "Understanding Pilot Breathing – A Case Study in Systems Engineering", NASA/TM-20210018900, July 2021. Armstrong personnel included the center's chief engineer, test pilots, operations engineers, and life support specialists.
- **A new oxygen mask for aerospace and beyond:** A major deliverable was the development of a new and innovative oxygen mask that provides accurate, real-time feedback to the pilot regarding anomalous carbon dioxide concentrations. This innovation can effectively diagnose breathing problems in oxygen-regulated systems, keeping pilots and astronauts safer for future missions. The mask has wide-spread application both across NASA and for the medical community. The new mask can serve as an early warning for onset of physiological impairment during aeronautics and space flight applications. The mask is also useful for patient care in emergency medical settings and in hospitals.

Looking ahead: NESC and Armstrong are actively responding to requests for technical interchange meetings with military organizations who are seeking to evaluate new aircraft breathing systems.

Benefits

- **Improves pilot safety:** Extends understanding of physiologic responses to various flight conditions

Applications

- Military and research aircraft
- Spacecraft

PI: Lance Richards | 661-276-3562 | Lance.Richards-1@nasa.gov

SBIR/STTR's Cutting-Edge Contributions to Armstrong

Serving as "America's Seed Fund," the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs provided more than $5 million to 17 R&D projects managed at NASA's Armstrong Flight Research Center in Edwards, California, in 2021. Conducted by small businesses – sometimes in partnership with research institutions (i.e., for STTR) – these R&D efforts focus on:

- Scaling, performance, aerodynamics, and acoustics investigations for electric vertical takeoff and landing (eVTOL) aircraft
- Enabling aircraft autonomy
- Flight test and measurement technologies
- Vehicle sensor systems to enable situational awareness
- Integration of flight control with aircraft multidisciplinary design optimization
- Hot structure technology for aerospace vehicles
- Terrestrial balloons and planetary aerial vehicles

As they progress through the two-phase program, U.S. small businesses work closely with NASA personnel and commercialization partners. Below are two current examples.

Active Battery Management System (ABMS) for Electric Aircraft

Electric Power Systems Inc. | A2.01-9699

This Utah-based small business is refining an innovative approach to meet the demands for energy storage systems on aircraft with distributed electric propulsion and hybrid-electric architectures. Their ABMS enables the many cells on such vehicles to discharge at variable rates, thereby increasing battery life, reducing maintenance, and avoiding thermal runaway. The current project is focused on developing advanced algorithms, providing predictive health monitoring, life-based management, and physics-based cell modeling. Not only are these improvements designed to benefit the X-57 Maxwell aircraft and the NASA Revolutionary Vertical Lift Technology (RVLT) project, but they also will be used in creating a commercial eVTOL product in collaboration with Bell Textron Inc.

COR: Kurt Kloesel | 661-276-3121 | Kurt.J.Kloesel@nasa.gov

A New Approach to UAS Reliability Assessment

Systems Technology Inc. | A2.02-8755

Located in Hawthorne, California, this small business is continuing its effort to develop multiple algorithms working in parallel to detect faults on unmanned aircraft system more reliably. This so-called algorithmically redundant approach reduces the need for hardware-based redundancies, addressing size, weight, and power constraints. Based on theoretical analysis, simulation runs, and flight tests, this novel approach can serve as a vital step toward Federal Aviation Administration (FAA) certification of UAS in the National Airspace (NAS). The current project is expanding the technology to the wider Urban Air Mobility (UAM) market, with equal contributions coming from the FAA and NASA's SBIR/STTR program.

COR: Shaun McWherter | 661-276-2530 | Shaun.C.Mcwherter@nasa.gov

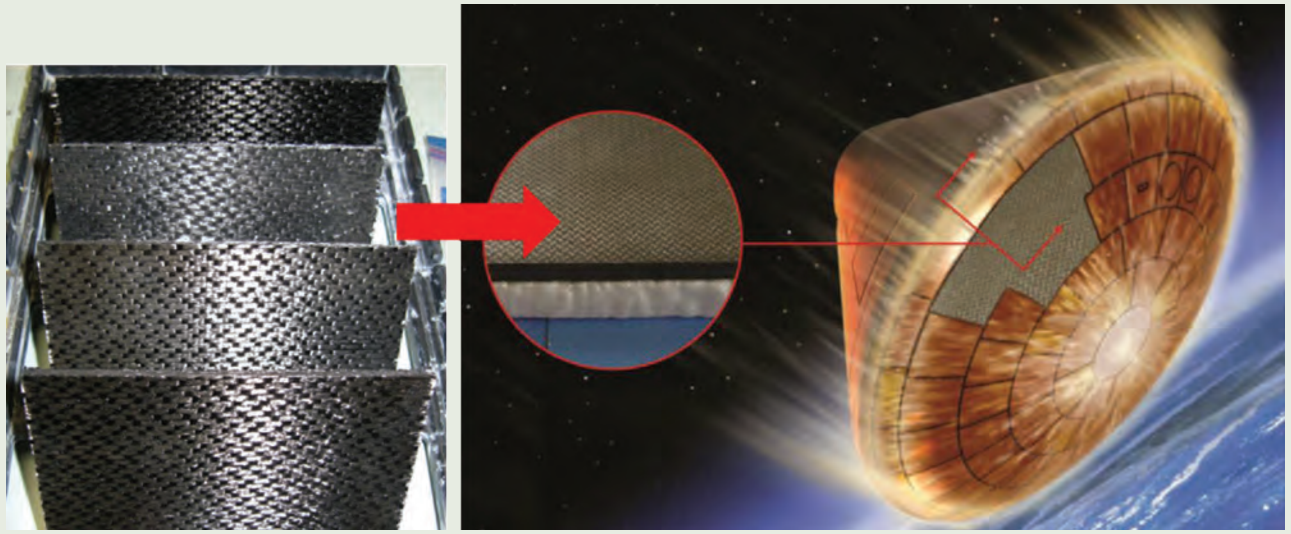
Other NASA Armstrong-Managed Projects

The table below lists the Phase II projects that were awarded in the past two years of the program. In addition to these two-year prototype development projects, SBIR/STTR awarded 12 Phase I "idea generation" projects in 2021.

Project and Small Business	Focus	COR
Acoustic Detection, Ranging and Improved Situational Awareness System (A2.02-3874) | Scientific Applications & Research Associates	Integrating an acoustic sensor's advanced detect-alert-avoid capabilities, flight testing them in a simulated urban environment	Jinu Idicula 661-276-2892 jinu.t.idicula@nasa.gov
ARGUS-4AHM: Adaptive Ruggedized Ubiquitous Sensor Network for Aircraft Health Monitoring (A1.09-3425) | American GNC	Demonstrating a system that provides flexible non-intrusive wireless connectivity in NASA aerospace vehicles	Thang Quach 661-276-2871 thang.t.quach@nasa.gov
Low SWAP-C Imaging Radar for Small Air Vehicle Sense and Avoid (A2.02-6569) | KMB Telematics	Developing a detect-and-avoid system to allow small UAS to safely fly in the NAS National Airspace	Jinu Idicula 661-276-2892 jinu.t.idicula@nasa.gov
Rapid Manufacturing of Carbon-Carbon Composites (C/C) for Thermal Management (H5.02-5399) | TDA Research	Formulating and manufacturing C/C parts in days/weeks instead of months	Larry Hudson 661-276-3925 larry.d.hudson@nasa.gov
Self-Diagnosing Nanomembrane Based Sensors for Flight Testing Applications (A2.01-4968) | NanoSonic	Developing and testing a low-profile pressure sensor with minimum power consumption and fast operation time	Aliyah Ali 661-276-5533 aliyah.n.ali@nasa.gov
Urban Air Mobility (UAM) Terminal Area Ride Quality and Safety Assessment Tool (T15.01-3500) | Continuum Dynamics and Pennsylvania State University	Developing an assessment tool suite to perform gust alleviation and optimize ride qualities	Curtis Hanson 661-276-3966 curtis.e.hanson@nasa.gov
Use of Pilot Models to Support Design, Analysis, and Certification of UAM Vehicles (A1.06-4899) | Systems Technology, Inc. (STI)	Developing a prototype software system toolbox to assess safety/handling and comfort/ride quality of UAM vehicles	Shaun McWherter 661-276-2530 shaun.c.mcwherter@nasa.gov

More Information

For more information about NASA's SBIR/STTR program, visit https://sbir.nasa.gov or contact Armstrong's Acting Center Technology Transition Lead (CTTL) Gray Creech at 661-276-2662 or Gray.Creech-1@nasa.gov.



Under the SBIR program, Colorado-based TDA Research Inc., is developing a faster, less expensive process for manufacturing carbon fiber–carbon matrix composites needed for hot structures in a variety of aerospace propulsion systems. Credit: TDA Research Inc.

Fiber Optic Sensing System (FOSS)

Sensor Suite Supports Aeronautics and Space Applications

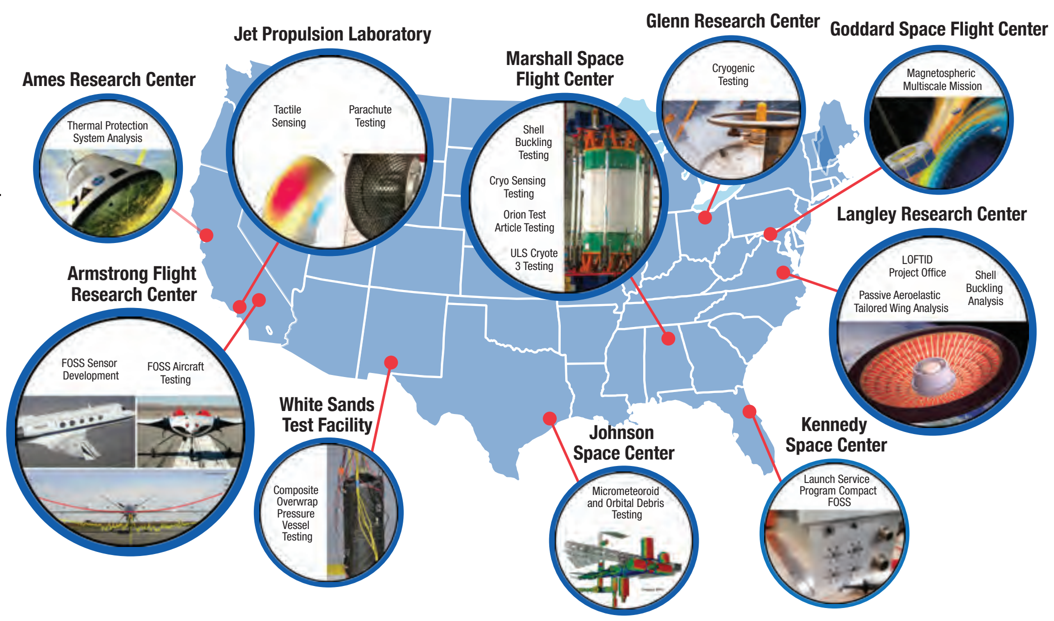
What began as a research tool to collect aerodynamic data from research aircraft is now solving technical challenges within the agency and beyond. NASA's patented, award-winning Fiber Optic Sensing System (FOSS) technology combines advanced strain sensors and innovative algorithms into a robust package that accurately and cost-effectively monitors a host of critical parameters in real time. It is being widely used throughout NASA to support research projects as varied as investigating next-generation flexible wings, measuring liquid fuel levels, and monitoring strain on spacecraft.

FOSS uses up to a 40-foot, hair-like optical fiber that provides up to 2,000 data points each. The state-of-the-art system processes information every quarter inch along the fiber at rates up to 100 times per second to measure strain, shape deformation, temperature, liquid level, and operational loads.

Through the years, the FOSS team at NASA's Armstrong Flight Research Center in Edwards, California, has optimized the technology to refine the infrastructure and speed with which the system collects and transmits data, and the technology's easy-to-integrate elements now complement and add color to existing instrumentation. For example, NASA's unmanned Ikhana aircraft was the first to fly with a FOSS wing shape sensor. In that test, researchers placed FOSS sensors in the same locations as conventional strain gauges but also ran fibers the length of the wing. While the FOSS sensors matched well with the results from the conventional sensors, they also revealed unexpected high stress points at locations between the conventional sensors – data that would have been missed if not for FOSS.

FOSS enables researchers to verify finite element models to a high degree of spatial resolution. It also allows researchers to identify unexpected phenomena in cases where a model is not completely accurate or does not contain enough degrees of specificity. FOSS enables both validation and discovery, making the entire research process more effective and efficient.

FOSS Addresses Technical Challenges Across the Agency



In recent years, the FOSS team has pivoted from an aeronautics focus to developing innovations to support space applications. This effort has required taking a new look at how the electronic components are packaged and assembled to meet the demands of a space environment. Upcoming space launches incorporating FOSS technology are planned on Blue Origin's New Shepard rocket-based system, NASA's Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID), and other commercial launch providers. Likewise, NASA's plan of returning to the Moon has created a need for the continued development of cryogenic liquefaction (the process of liquefying gases) and storage technologies. The FOSS technology can provide added insight as researchers develop new cryogenic systems to support this mission.

The FOSS team continues to refine algorithms to support additional applications, with the goal of adding the sensor suite to assets across the agency.

FOSS Team:
Paul Bean | 661-276-2451 | Paul.Bean@nasa.gov
Patrick Chan | 661-276-6170 | Hon.Chan@nasa.gov
John Del Frate | 661-276-3704 | John.H.Delfrate-1@nasa.gov
Philip Hamory | 661-276-3090 | Philip.J.Hamory@nasa.gov
Jonathan Lopez-Zepeda | 661-276-7778 | Jonathan.Lopez-Zepeda@nasa.gov
Eric Miller | 661-276-7041 | Eric.J.Miller@nasa.gov
Allen Parker | 661-276-2407 | Allen.R.Parker@nasa.gov
Francisco Peña | 661-276-2622 | Francisco.Pena@nasa.gov
Anthony Piazza | 661-276-2714 | Anthony.Piazza-1@nasa.gov

'Rocket Box' FOSS to Fly on Launch Vehicles

Researchers from NASA Armstrong and Kennedy Space Center have collaborated for years to ruggedize the Fiber Optic Sensing System (FOSS) so it can be used to measure aggressive launch loads on spacecraft. Further collaborations with industry partners have resulted in durable instrumentation, and Armstrong researchers are now readying a new combination of mechanical enclosure and instrumentation for launch on several rocket systems. This compact FOSS, known as the FOSS rocket box, can take thousands of measurements along a fiber-optic wire about the thickness of a human hair. The goal is to fly these rocket boxes on Blue Origin's New Shepard rocket-based system, NASA's Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID), and other commercial launch providers.

Work to date: The FOSS team assembled five rocket boxes and completed early-stage environmental testing to simulate rocket launch conditions. One of the systems has been integrated with a self-contained experiment and will be tested on a future launch of Blue Origin's New Shepard rocket-based system with support from NASA's Flight Opportunities program. Another rocket box completed required environmental testing and was delivered to the LOFTID program at NASA's Langley Research Center for use on the vehicle during re-entry.

Looking ahead: Next steps for the remaining three rocket boxes are to complete thermal vacuum (TVAC) testing, burn-in, lightning testing, vibration testing, shock testing, and electromagnetic interference/electromagnetic compatibility (EMI/EMC) testing at NASA Langley for final environmental evaluation. The goal is to validate that FOSS can provide critical parameter measures (e.g., strain, load, temperature, shape) in aggressive launch environments.

Partners: NASA's Kennedy Space Center and Langley Research Center, Blue Origin, United Launch Alliance

Benefits

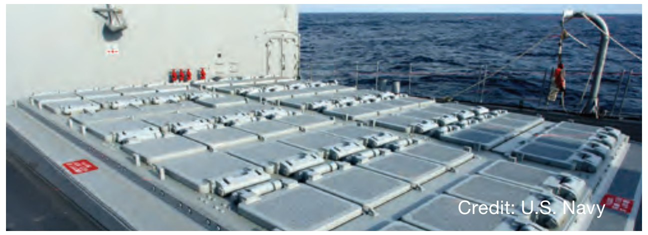
- **Advanced:** Provides validated structural design data that could enable future launch systems to be lighter and more structurally efficient
- **Ruggedized:** Allows FOSS to be used effectively in many more practical applications that require a more robust system

Applications

- Rockets
- Re-entry vehicles
- Jet engines
- Inflatable wings and airships
- Test aircraft

PI: Allen Parker | 661-276-2407 | Allen.R.Parker@nasa.gov

Micro FOSS Technology Leverages Low-Cost Components for High-Performance Tasks



Credit: U.S. Navy

NASA Armstrong researchers are reducing the Fiber Optic Sensing System (FOSS) technology's overall cost, size, weight, and power requirements to effectively extend opportunities for broader fields of application. Applying lessons learned during development of the rocket box technology, the team designed a compact package useful for monitoring a host of critical parameters in real time. Dubbed micro FOSS, this version of the technology is smaller, less expensive, and more robust. It leverages electronics that are commonly available for the smartphone and tablet industry, departing from the expensive military-grade processors and components of previous versions. As in previous versions that have gone through ruggedization efforts, the FOSS team has formed partnerships with the U.S. Navy and the company Rocket Lab to push the technology forward.

Work to date: Armstrong is partnering with the Naval Surface Warfare Center Port Hueneme Division and Naval Research Laboratory to develop a naval- and flight-ruggedized micro FOSS. The goal of this partnership is to move the technology toward a flight-capable mission and transition the technology to the Navy. Armstrong has provided laboratory units to the Navy to support its near-term applications.

Looking ahead: Armstrong will continue partnering with the U.S. Navy to transition the technology for integration into naval vessels. The team will ship the laboratory units to Rocket Lab in fiscal year 2022 to support its development of a space-rated system.

Partners: Naval Surface Warfare Center Port Hueneme Division, U.S. Naval Research Laboratory, and Rocket Lab

Benefits

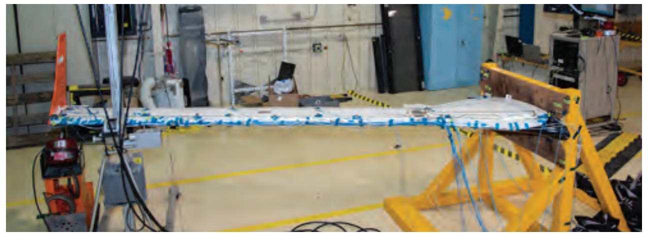
- **Compact:** Requires less associated hardware than existing systems
- **Low cost:** Leverages electronics designed for the smartphone and tablet industry
- **Reliable:** Features components designed for aggressive environments without compromising the form factor

Applications

- Aeronautics and space applications
- Oil drilling, wind energy, and industrial processes

PI: Allen Parker | 661-276-2407 | Allen.R.Parker@nasa.gov

Doppler FOSS Validates Velocity Measurements and Algorithms



The real-time processing capability of the Fiber Optic Sensing System (FOSS) benefitted NASA research involving the unmanned X-56A Multi-Utility Technology Testbed (MUTT). The X-56A, a modular, remotely piloted experimental aircraft, was tasked with investigating flexible wings to improve safety, efficiency, and ride quality. Testing used flight profiles where flutter occurred to demonstrate that onboard instrumentation can predict, sense, and suppress aeroelastic instabilities. By quickly collecting strain data, FOSS enabled researchers to see dynamic changes on the wings that could result in flutter.

The key innovative feature of the next generation FOSS for future flight and space applications is the capability of viewing raw interferograms. An interferogram can be created by comparing light from two different sources, but in this case a laser provides a light source that is split into a reference beam and a test beam reflected from the sensor. The strain rates are obtained by processing raw interferogram data and extracting a Doppler shift in the carrier frequency of each individual fiber Bragg grating (FBG) installed, at 50 Hertz in this application, along the span of the structure. Doppler FOSS enables full state feedback control based on direct measurements, which improves controller robustness and performance. These improvements also enable implementation of new control laws for applications such as controlling flexible vehicles.

Work to date: NASA's Center Innovation Fund (CIF) supported the Doppler FOSS effort, which underwent a ground vibration test (GVT) using the X-56A wings to validate velocity measurements and algorithms for future aerospace vehicle control applications.

Looking ahead: The team is looking into methods to improve the speed of the Doppler FOSS analysis algorithm as well as benefits from advances in laser technology.

Benefits

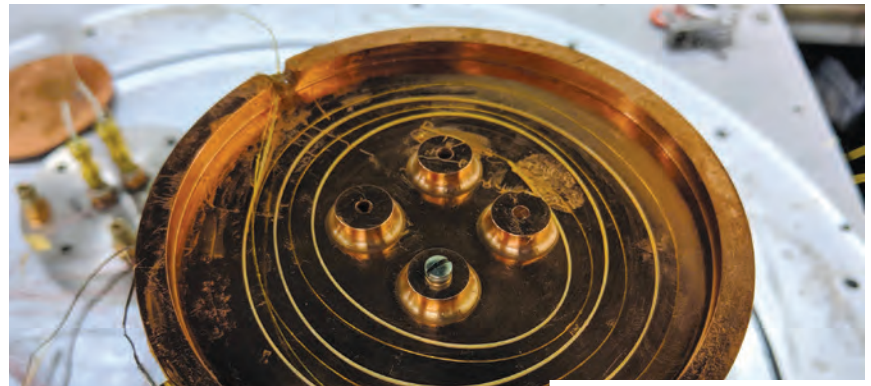
- **High spatial resolution:** Enables measurements approximately every 0.25 inches
- **Small and light:** Offers 100 times the number of measurements at 1/100 the total sensor weight

Applications

- Aeronautics

PIs: Francisco Peña | 661-276-2622 | Francisco.Pena@nasa.gov
Allen Parker | 661-276-2407 | Allen.R.Parker@nasa.gov

Fiber Optic Technology Enables Cryogenic Monitoring Capabilities



(Left) Cryogenic prototype tank at NASA's Glenn Research Center

(Above) Cryogenic sensor characterization test at NASA's Ames Research Center

(Right) Temperature-tuned FOSS laboratory unit

Safe and efficient liquefaction (the process of liquefying gases) of cryogenic propellants is critical to future Moon and Mars missions. The Cryogenic Fluid In-Situ Liquefaction for Landers (CryoFILL) NASA team consists of members from multiple centers and was established to demonstrate critical cryogenic capabilities representative of what will be needed for initial production plants and landers being planned for the lunar and Martian surfaces. Initial CryoFILL efforts have focused on prototype systems for liquefying oxygen.

NASA Armstrong's Fiber Optic Sensing System (FOSS) team partnered with CryoFILL to develop cryogenic fiber-optic temperature measurement sensors and to support upcoming cryogenic testing. This collaboration is an opportunity to improve the sensitivity and uncertainty of the sensors at extremely low temperatures (as low as 15 degrees Kelvin). Unlike gauges that rely on discrete measurements to give broad approximations of liquid levels, Armstrong's cryogenic FOSS technology provides measurements at half-inch intervals within a tank. Originally designed to monitor a rocket's cryogenic fuel levels, the technology offers numerous benefits for a variety of other industries, including the oil and gas industry, where users need to determine boundary layers between different fluids and substances, such as oil, water, detergent, sand, and gravel.

Work continues on the system interrogators. Low-cost and low-size, weight, and power (SWaP) instrumentation to measure thermal and structural response is critical to validating models and maturing liquefaction technologies. The team also is continuing work on the temperature-tuned FOSS interrogator, a simpler system more conducive to lower sampling rates. By employing a temperature-tuned laser interrogator, the result is a new system with reduced weight, cost, and complexity over existing state-of-the-art systems.

Work to date: The FOSS team completed the cryogenic fiber-optic temperature sensor fabrication to support CryoFILL prototype testing at NASA's Glenn Research Center. Dozens of measurement sensors reside in the 12 feet of sensor fiber encapsulated by a polytetrafluoroethylene (PTFE) support sleeve. The team characterized the sensors using liquid nitrogen at Armstrong in November 2020 before shipping the sensors to Glenn for installation into the test setup.

Looking ahead: The team plans to support prototype testing at NASA Glenn in fiscal year 2022. The team will continue developing FOSS interrogators in collaboration with Sensuron under a Space Technology Mission Directorate 2020 Announcement of Collaboration Opportunity.

Partners: NASA's Glenn Research Center and Sensuron LLC

Benefits

- **Reliable:** Provides validated cryogenic temperature data that could enable systems for safe and efficient liquefaction and storage of cryogenic propellants

Applications

- Aerospace cryogenic liquid monitoring
- Chemical and refinery plants
- Industrial tanks

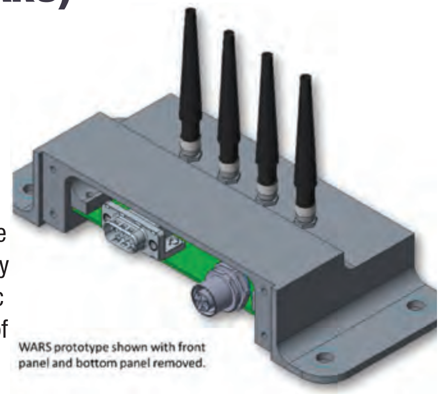
PI: Patrick Chan | 661.276.6170 | Hon.Chan@nasa.gov

Avionics and Instrumentation Technologies

Innovators at NASA's Armstrong Flight Research Center in Edwards, California, design and integrate data acquisition systems for research, support, and one-of-a-kind platforms. In many cases, these systems leverage commercial off-the-shelf parts to keep costs low and facilitate integration with legacy systems. At the same time, these cutting-edge data systems are finding innovative ways not only to collect data efficiently, but also to flexibly configure collection parameters.

> *Integration is the hardest part of any instrumentation system. We are able to pull together requirements, design a system, then install and validate it. If there is a way to get the data, we can get the data.*
>
> Joe Hernandez, senior instrumentation engineer

Waveguide Augmented Radiometric System (WARS)



WARS prototype shown with front panel and bottom panel removed.

In-flight temperature measurements of high-speed vehicles and high-temperature structures on re-entry has been problematic since the beginning of hypersonic flight. Thermocouple attachment methods can result in a lower temperature limit than the melting points of different thermocouple types. Additionally, contact sensors like thermocouples can have or cause other problems, such as sensitivity to electromagnetic interference (EMI) and vehicle integration challenges. WARS seeks to solve these problems by developing a low size, weight, and power (SWaP) non-contact temperature measurement system to measure temperatures less than 60 degrees Fahrenheit (F) (replacing or augmenting traditional high-temperature thermocouple measurements [Type S, B, R, C, D]).

Work to date: With Center Innovation Fund (CIF) resources, researchers designed the initial (non-compact) system, purchased components, and fabricated a prototype system, which is undergoing performance characterization.

Looking ahead: After the prototype completes characterization testing, it will be vibration tested to determine where there might be design weaknesses. Design is underway for a second version that is expected to be less expensive, faster to build, and much more compact. That system will incorporate improvements from initial characterization and vibration testing and will be built and tested. In parallel, a long-wave infrared (LWIR) capability will be developed to extend the minimum measurement temperature closer to room temperature.

Benefits

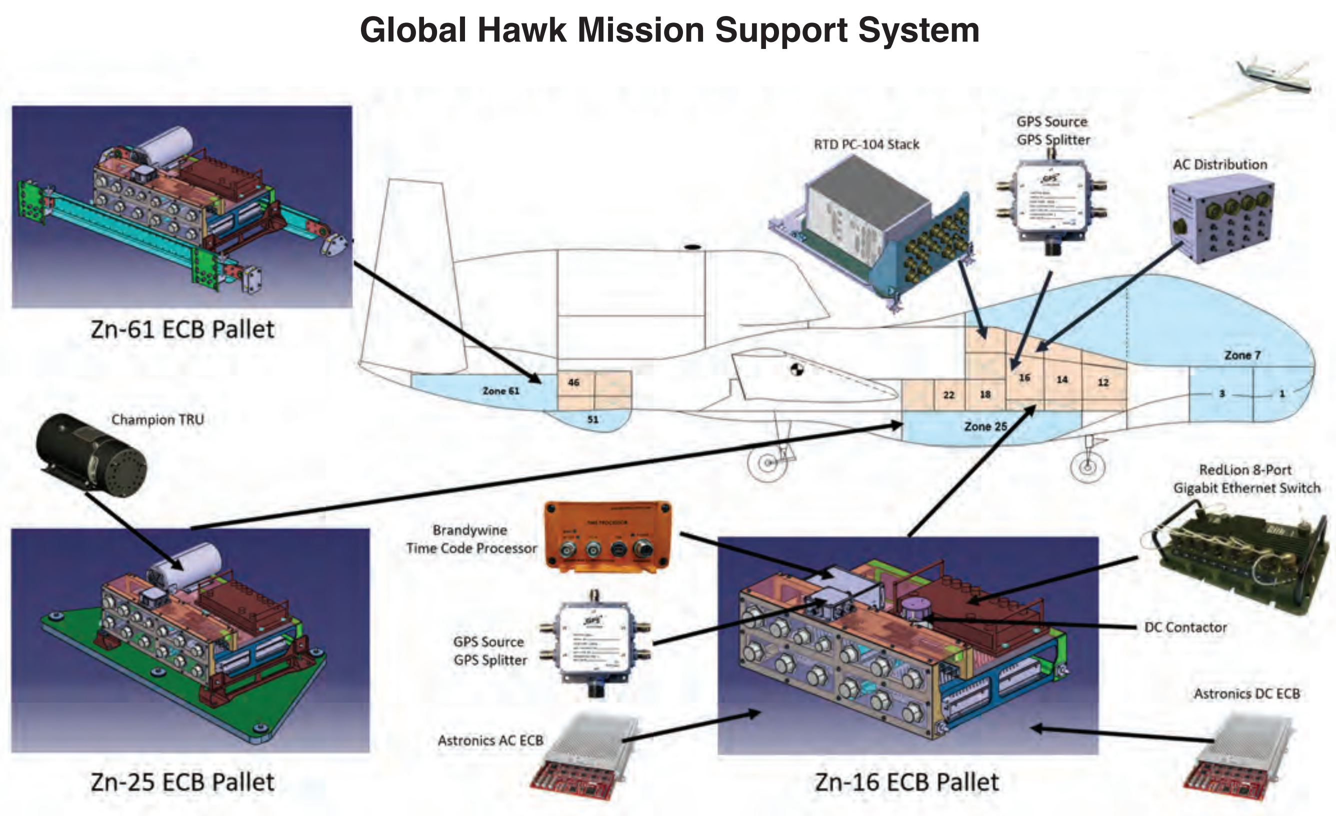
- **Enabling:** Provides reliable high-temperature measurements during ground and flight tests of re-entry vehicles and high-speed aerospace structures through a low SWaP system
- **Efficient:** Significantly increases the return on investment of flight tests, collecting data to characterize vehicle thermal response, and to tune models for better predictions

Applications

- Ground and flight tests for re-entry or high-speed vehicles that would benefit from having a non-contact temperature measurement system

PI: Chris Kostyk | 661-276-5443 | Chris.B.Kostyk@nasa.gov

New Mission Support System Increases Functionality and Reliability



NASA Armstrong researchers are developing a novel system for providing common interfaces typically required by flight vehicle payloads and will implement it first on the Global Hawk aircraft. The Mission Support System (MSS) is designed to increase functionality and reliability and will replace the Airborne Payload Command, Control, & Communication System (APCS). It is comprised of multiple subsystems including GPS distribution, time synchronization, mission support network, and power distribution.

Network-based control and monitoring will be provided in the control room by satellite communications in conjunction with software hosted on an embedded controller on the aircraft. A custom graphical user interface (GUI) will provide operators with individual control and monitoring of 99 circuit breakers that offer up to 8.3 kilowatt (kW) AC and 2.4 kW DC power to payloads. After successful implementation on Armstrong's three Global Hawk aircraft, it is anticipated that it will be replicated on additional aircraft within the U.S. Department of Defense's Test Resource Management Center SkyRange project.

Work to date: Researchers designed the system as a modular assembly of commercial off-the-shelf (COTS) parts to increase availability and serviceability and reduce complexity. Laboratory and aircraft electrical wiring diagrams have been designed and reviewed. Designs for mechanical integration of the components onto the aircraft are complete. Mechanical fabrication of pallets has begun.

Looking ahead: Electrical wiring of pallets and the aircraft began in late 2021 and will continue in 2022. Software development will continue alongside functional testing of pallets, culminating in integrated verification and validation (V&V) in the lab, aircraft and in flight.

Benefits

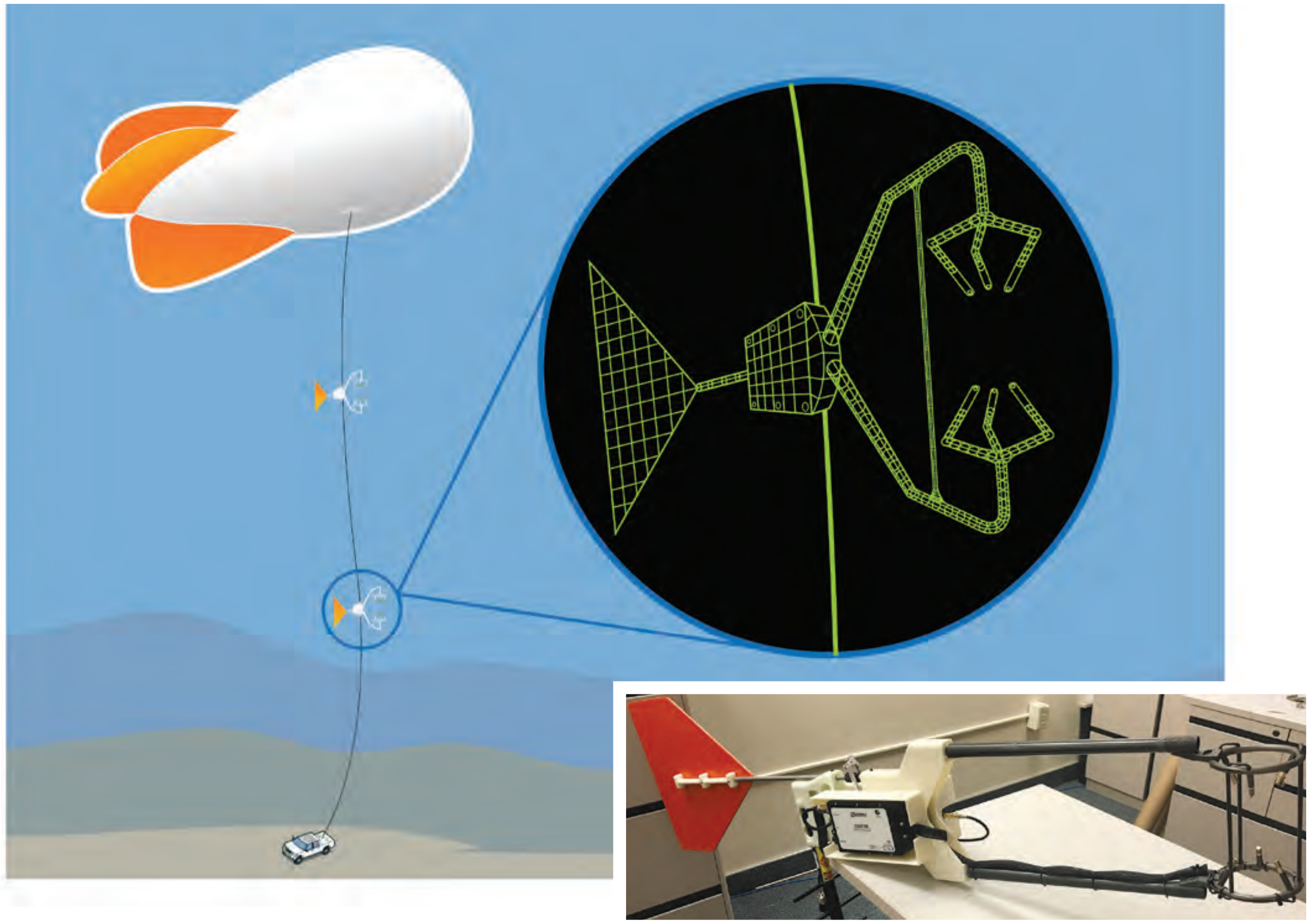
- **Efficient:** Enables every payload in an aircraft to be monitored and controlled in real time throughout a mission by controllers in an operations center
- **Modernized:** Increases functionality and reliability of mission support operations

Applications

- Aircraft mission support

PI: Russell Franz | 661-276-2022 | Russell.J.Franz@nasa.gov

SonicSonde: Instrumentation for a Tethered Atmospheric Sensor Suite



The SonicSonde project aims to develop an advanced tethered instrumentation suite for in situ atmospheric sampling capable of prompt, repetitive, and reliable vertical ascent data. The suite is designed to measure atmospheric pressure, temperature, relative humidity, air quality, and 3D wind velocities, targeting the vertical column from the surface to 5,000 feet above ground level. Customizable computer software will support and display real-time data streaming. Successful demonstration of this capability will support a wide variety of research endeavors by producing a comprehensive snapshot of a vertical column of the atmosphere that includes 3D wind data to a degree and resolution currently not obtainable in tethered instrumentation.

Work to date: Initial development has focused on the fabrication of the prototype and integration of a sonic anemometer as the basis for wind data collection. With Center Innovation Fund (CIF) resources, researchers attained and tested a custom-built lightweight sonic anemometer, completed the rigid-frame design and construction of a prototype, and successfully demonstrated remote data retrieving capability between the SonicSonde and a ground station laptop. Researchers also produced a successful beta version of the custom computer software to be paired with the SonicSonde.

Looking ahead: Researchers will continue to examine and hone the accuracy of the sonic anemometer as the basis of wind data collection on a moving platform, finalize the full suite of sensors by including temperature, pressure, relative humidity, and air quality sensors onboard, and finalize the custom computer software to incorporate live-streaming data from all sensors onboard.

Benefits

- **Comprehensive:** Permits wide-ranging capture of atmospheric data
- **Versatile:** Enables flexibility to tailor data output and displays to specific research objectives
- **Modernized:** Employs a 3D sonic anemometer as a means for wind data collection; all sensors onboard offer high-resolution sampling capability
- **Cost-effective:** Eliminates cost per use, reducing shipping costs for deployments

Applications

- Climate and atmospheric research
- Acoustic studies

PI: Kimberly Bestul | 661-276-3315 | Kimberly.A.Bestul@nasa.gov

ARMD Flight Data Portal (AFDP)

NASA Armstrong is taking the lead on an agency-wide effort in the Aeronautics Research Mission Directorate (ARMD) that will enhance flight research and test capabilities by improving the management of test data. The AFDP will replace the legacy Flight Data Access/Archival System (FDAS), in place since 1980. An effective resource for its time, FDAS archives flight data but offers no corresponding analysis or related information. The new data portal will archive all test flight data for the four NASA centers involved in flight testing along with contextual information needed to understand and analyze the data. Such information includes mission overviews, flight profiles, daily summaries, mission debriefs, and more. A robust search mechanism and intuitive graphical user interface (GUI) will further make the AFDP a meaningful flight test resource. Online and accessible to all with NASA credentials, the AFDP will increase collaboration across NASA centers.

Work to date: Work is proceeding in three phases. Phase 1 involves the upfront work to build the portal, and Armstrong is leading this effort. The team is focusing on the X-57 experimental aircraft as a test case, including all flight data and contextual information to ensure the portal operates as intended. Recent accomplishments include updates to support controlled unclassified information (CUI) agency requirements and to support making deployments more flexible (e.g., deploying to a cloud). Researchers anticipate a Phase 1 go-live date in early 2022.

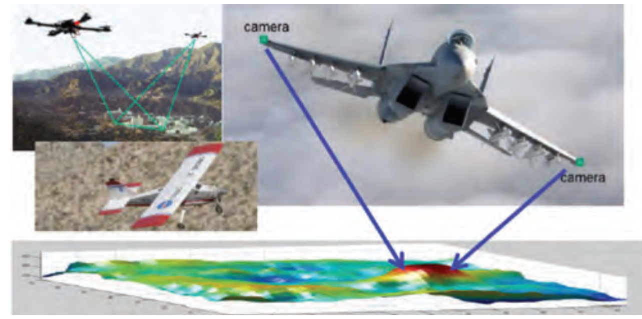
Looking ahead: Future phases will include various flight test projects from NASA's other three ARMD centers – Ames, Glenn, and Langley research centers. NASA has identified this project as an ARMD flagship in its digital transformation effort.

Benefits

- **Enhances research capabilities:** Enables rapid location of test flight, simulation, and loads test data along with corresponding contextual information
- **Increases collaboration:** Provides access to all NASA personnel via online system and allows for further partnering and collaboration opportunities in flight data discovery, retrieval, and governance
- **Is easy to use:** Features a user-friendly GUI and search mechanism

PI: Jason Holland | 661-276-3035 | Jason.L.Holland@nasa.gov

Visual Radar



Researchers at NASA Armstrong and Jet Propulsion Laboratory (JPL) are collaborating to validate and test a stereo vision technology for terrain-relative navigation. Stereo vision utilizes two cameras with the same field of view to generate ranging data from a binocular image using the known distance between the cameras. JPL researchers developed the technology for robust, vision-based, terrain-relative navigation based on two non-static cameras. Armstrong researchers are integrating and flight testing the new technology on an F-18 aircraft. The innovation could lead to advances in aircraft sensor systems.

Work to date: With funding from NASA's Center Innovation Fund (CIF), Armstrong and JPL researchers collaborated to develop flight hardware to validate the technology. The Armstrong team integrated the cameras into two instrumentation pods that will be fitted onto the wing tips of an F-18 aircraft. To save resources, researchers used existing aircraft and instrumentation pod wiring. Significant accomplishments include:

- Retrofitted U.S. Navy instrumentation pods with camera systems
- Completed environmental testing
- Finalized flight planning
- Completed integration design

Looking ahead: Functional/calibration and combined systems testing – along with a flight readiness review – will occur prior to flight. Following integration and flight testing, the system will be used for autonomy research.

Benefits

- **Innovative:** Demonstrates the ability to use cameras as visual sensors
- **Advanced:** Enables a new type of 3D mapping for the unmanned aircraft world
- **Rugged:** Useful for detecting hazards in flight environments

Applications

- Autonomous flight techniques
- Automatic collision avoidance technologies
- 3D modeling of terrain and structures
- Passive object detection

PI: Matthew Versteeg | 661-276-3902 | Matthew.L.Versteeg@nasa.gov

Wireless Miniature Biosensor

This research effort produced a wireless miniature biosensor for real-time in-flight physiological monitoring of the air crew in high-performance aircraft. The size of a postage stamp, this battery-free sensor measures oxygen saturation, heart rate, heart rate variability, and body temperature. The device was designed specifically to monitor a pilot's brain oxygen saturation during high-*g* flight maneuvers. Current oxygenation measurement devices are large and bulky, thus not suitable for use on pilots in high-*g* conditions. Though designed for pilots, this biosensor offers uses for astronauts, athletes, military personnel, and patients in acute trauma situations.

Work to date: The sensor technology is functional. Remote sensing and reflective capabilities increased its ease of use and variety of potential applications.

Looking ahead: The biosensor's light weight and small size enable the possibility of developing similar sensors to measure additional parameters. For example, cuffless blood pressure monitoring would be useful in high-performance aviation and numerous other situations.

Partners: Wearifi Inc. and Northwestern University's Center for Bio-Integrated Electronics

Benefits

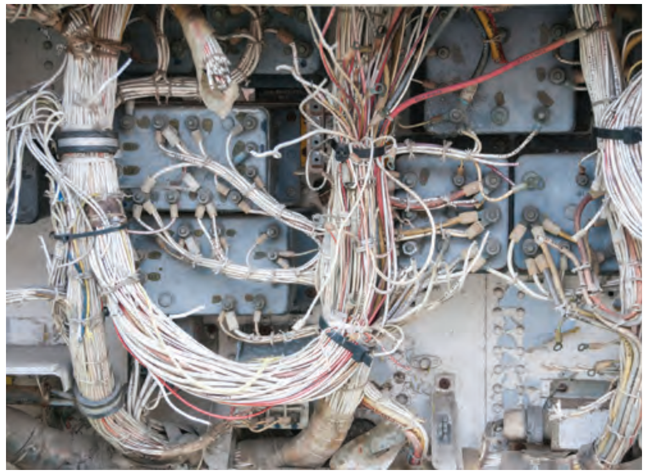
- **Powerful:** Enables real-time physiological monitoring
- **Compact:** Features a small and lightweight form factor ideal for use in high-*g* conditions

Applications

- Aviation
- Spaceflight
- Athletics
- Acute care medicine
- Trauma care

PI: Dwight Peake I 661-276-3217 I Dwight.Peake-1@nasa.gov

Advanced Wireless Flight Sensor System



NASA Armstrong researchers are developing a system that eases integration of wireless sensors into existing aircraft avionics. Currently, adding wireless sensors to avionics systems is time-consuming and expensive due to integration requirements. This innovation streamlines that process, eliminating the need to overhaul preexisting avionics systems to integrate new sensors. Key to the innovation is a software-defined radio device that integrates into the software the capabilities of individual wireless protocols and systems. If applied throughout the aviation industry, this approach would enable a clear transition path from experimental use of wireless sensors to practical implementation.

Work to date: Benefitting from NASA's Center Innovation Fund (CIF), researchers purchased software-defined radio devices and created a preliminary architecture. The team demonstrated in the laboratory the ability for dissimilar wireless devices to communicate without any hardware modifications. The group also worked with two small businesses to test the unique wireless technology on Armstrong aircraft. A resulting analysis recommends its adoption in wireless avionics.

Looking ahead: Next steps are to continue to test the technology in aircraft.

Benefits

- **Time-saving:** Streamlines testing and implementation of wireless technology
- **Capability-enhancing:** Allows new mechanisms and devices to be added to aircraft
- **Cost-effective:** Simplifies the process of integrating wireless sensors

Applications

- Avionics
- Instrumentation systems
- System health monitoring

PI: Matthew Waldersen I 661-276-5708 I Matthew.Waldersen@nasa.gov

A Bell OH-58C Kiowa helicopter on a helipad at NASA Armstrong, where it was used as a surrogate urban air mobility vehicle to develop and implement infrastructure to support safe operation of these vehicles.

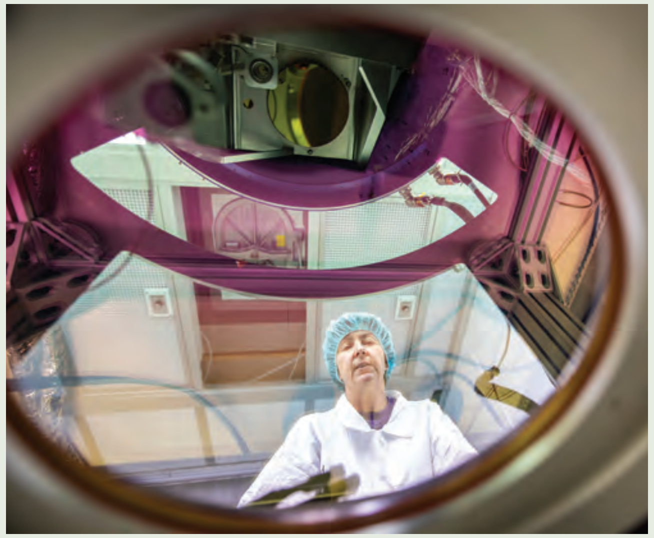
Specialized Aircraft Support Worldwide Science Efforts

NASA's Armstrong Flight Research Center at Edwards, California, operates a fleet of highly specialized aircraft that collect data to support the world's scientific community, including investigators from NASA and other federal, state, academic, and foreign institutions. Researchers around the world use this data to understand and explain humanity's environmental impact on Earth, from documenting climate change and its impacts on ice, sea level, and weather patterns, to monitoring the health of forests and the movement of fresh water.

SOFIA

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is the world's largest flying observatory. It flies up to an altitude of 45,000 feet, enabling studies of the universe at infrared wavelengths. SOFIA flew 93 science flights in 2021 and will deploy to the southern hemisphere in 2022 to attempt challenging observations of Venus for the first time.

DC-8

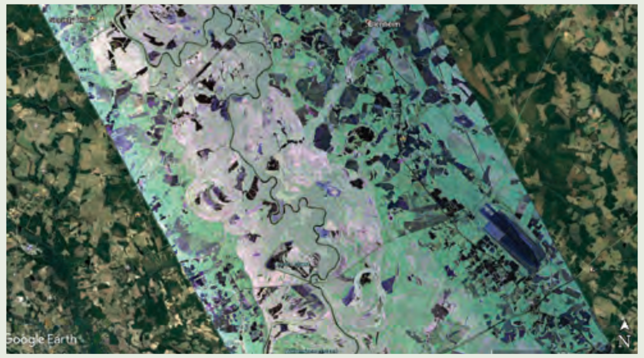


The DC-8 aircraft and its complement of on-board sensors provide a readily deployable remote sensing platform that supports U.S. scientific research. In 2021, it supported a joint experiment with European Space Agency partners to acquire profiles of the Earth's wind on a global scale.

ER-2

The ER-2 high-altitude aircraft collects data that helps researchers understand the world's ecosystems and provides critical information on natural disasters. Sophisticated imaging technologies enable it to study environmental impacts caused by wildfires.

C-20A



The C-20A is equipped with NASA's Jet Propulsion Laboratory's UAV synthetic aperture radar (UAVSAR) and an Armstrong-developed precision autopilot. In 2022, flights will support study of earthquakes' fault zones, volcanoes, wetlands, and glaciers, and the aircraft will be ready to respond to emergencies related to oil spills, wildfires, floods, and more.

Space and Hypersonics Technologies

A key objective of space research at NASA's Armstrong Flight Research Center in Edwards, California, is to leverage our center's expertise in aircraft flight testing, instrumentation, avionics development, simulation, and operations to assist NASA with space exploration. Our researchers are discovering innovative ways to use aircraft to develop new space capabilities and test space technologies in a relevant environment.

Hypersonics research is important both to aeronautics and space research to enable extremely fast travel on Earth as well as for future space exploration. NASA Armstrong has a long history of pioneering research in this area.

Dust-Tolerant Cryogenic Magnetic Coupler for Space Applications

This research effort is developing a prototype for a dust-tolerant cryogenic magnetic coupler for lunar applications. The functional prototype will demonstrate the integration of three subsystems: a cryogenic fluid coupler, patterned magnets, and dust mitigation. This innovation has the potential to fulfill multiple gaps associated with cryogenic fluid transfer and dust-mitigation technologies. It received a FY2021 Early Career Initiative (ECI) award and will receive $2.5 million over two years to support its work.

Work to date: The team is collaborating with NASA's Kennedy Space Center to develop a cryogenic low force disconnect (LFD) coupler that will enable transference of cryogenic fluid in a lunar representative environment. This coupler has an innovative design that enables the two halves to be connected with minimal force. This research is supporting the continued development of NASA Kennedy's LFD technology, developed initially under a Center Innovation Fund (CIF) award.

The magnetic subsystem involves the use of patterned magnets developed by an external vendor. Patterned magnets are tailored to achieve a desired behavior and deliver stronger local force. Conventional magnets generally have far-reaching and weak magnetic fields, whereas printed magnetic poles keep magnetic loops tight and strong. Reduced magnetic field distance also reduces electromagnetic interference (EMI) concerns. The patterned magnetic technology used in this project was also originally studied under an Armstrong CIF award, and this ECI funding has allowed the team to continue to advance the technology.

The erosive and abrasive nature of lunar regolith dust can cause severe damage to equipment and systems. It can degrade coatings used to seal equipment and erode surfaces. The dust mitigation subsystem aims to protect the cryogenic fluid from dust contamination and the coupler's mechanisms from damage.

Looking ahead: System integration and testing will occur at NASA Armstrong, Kennedy, and Marshall Space Flight Center.

Benefits

- **Innovative:** Combines an LFD coupler that requires less force to mate coupler halves with patterned magnets that customize force as needed per project
- **Protective:** Shields cryogenic coupler and fluid from dust contamination

Applications

- Transference of cryogenic fluid in a lunar environment

PI: Shideh Naderi | 661-276-3106 | Shideh.Naderi@nasa.gov

Store Separation Analysis Toolset Quantifies Risks, Validates Mitigation

Store separation analysis NASA Armstrong provided to Virgin Orbit enabled the team to acquire significant flight test data and refine its models. Credit: Virgin Orbit

Researchers at NASA Armstrong have developed an analysis toolset to help quantify risks associated with store separation events and validate processes designed to mitigate those risks. Dubbed the Flowfield Loads Influence Prediction Trajectory Generation Program (FLIP TGP), the toolset includes U.S. Air Force-developed modeling software as well as other simulation tools that enable users to analyze risks associated with the moment that a store – often a rocket or other payload – is released from an aircraft. The goal is to ensure that, under specific flight conditions at the time of separation, the store falls away and does not hit the aircraft.

Armstrong is one of several partners providing store separation analysis to Stratolaunch, as it plans to launch a hypersonic testbed. (Credit: Stratolaunch)

The air-launch technique – where a rocket is launched, for example, from under the wing of an aircraft rather than from a traditional launch pad on the ground – permits flexible and cost-effective access to space. This approach could contribute to launching small satellites to orbit quickly, reliably, and affordably.

Armstrong has a rich history of experience in vehicle integration, air launch, and flight test research so is uniquely suited to this enterprise. The team has worked with several companies to quantify and mitigate store separation risks. The aim is to share expertise by working alongside a company until its team gains the expertise and capability to continue on its own.

Work to date: The team worked with Generation Orbit Launch Services to provide analysis for a captive carry flight test for its orbital air-launch system. Another experience involved analysis for Virgin Orbit, which dropped an inert rocket from its airplane. That effort enabled the Armstrong team to acquire significant flight test data and refine its models. Virgin Orbit has gone on to safely drop rockets and launch satellites into space.

At NASA, the team provided store separation analysis for the Towed Glider Air-Launch System (TGALS) and is working now on a workflow analysis for the Crossflow Attenuated Natural Laminar Flow (CATNLF) test article.

Armstrong's TGALS project benefitted from store separation analysis.

Looking ahead: The team is currently working with Stratolaunch, which plans to launch a hypersonic testbed. Armstrong is one of several partners providing store separation analysis to Stratolaunch to help validate in-house models and to help the company better understand the store-separation behavior of the Talon-A hypersonic testbed vehicle, scheduled for a 2022 inert drop test.

Benefits

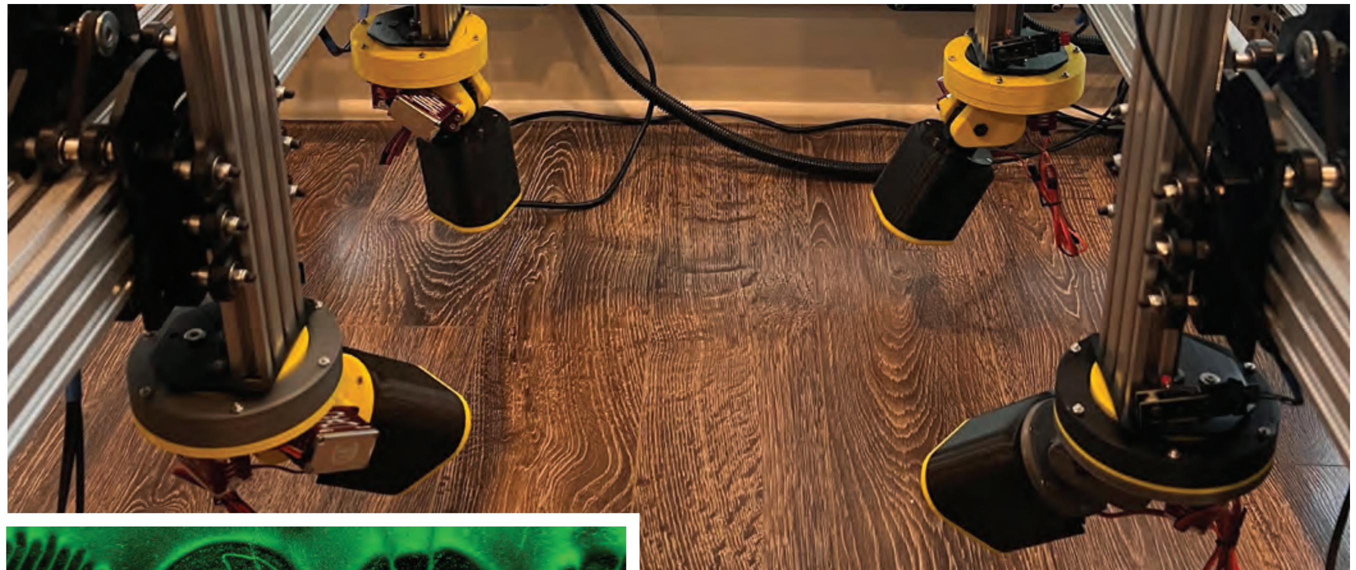
- **Risk-quantifying:** Characterizes separation behaviors
- **Validating:** Corroborates mitigation techniques

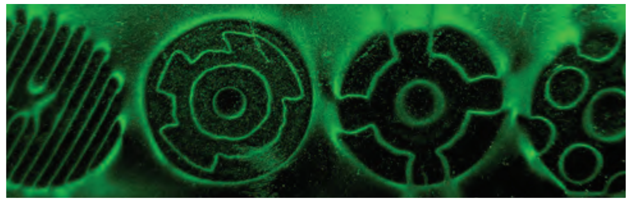
Applications

- In-flight payload release

PI: Christopher Acuff | 661-276-2380 | Chris.Acuff@nasa.gov

Patterned Magnets for Hold-Separate Techniques





Pyrotechnic separation events – such as those involving rockets and drones – are associated with shock and debris, requiring significant measures to protect payloads and aerostructures. NASA Armstrong researchers are testing the feasibility of using finely patterned magnets to enable two-body separation and kickoff techniques. In the approach, magnets hold an object to another main body then through a sequenced rotation engage a release function as defined by magnetic areas within the pattern. Hold-and-release mechanisms involving these flexible and versatile patterned magnets have the potential to revolutionize numerous aerospace activities.

Work to date: The research team has taken a two-path approach to demonstrate the feasibility and practicality of using finely patterned magnets from Correlated Magnetics Research as the basis for separation mechanisms. The team demonstrated that a small cluster of patterned magnets successfully held and released 200 pounds. Designs are progressing through reviews for a 500-pound-rated payload release mechanism. A Preliminary Research Aerodynamic Design to Land on Mars (Prandtl-M) drone was released from a small unmanned aerial vehicle proving feasibility for in-flight operations.

The other path is the development of a series of space-anchoring reconfigurable mechanisms that have been demonstrated in the lab. A two degrees of freedom robotic grappler has been developed and is currently under test. To prove the scalability and adaptability of magnet-based systems, the team has designed a robotic drone carriage system that can autonomously reconfigure itself to hold dozens of different drone shapes. The carriage system is currently under fabrication and testing. Across all applications, to reduce volume and increase holding force, the project is pursuing optimization of magnet dimensions and patterns. Testing continues to identify real-world challenges and the team continues to demonstrate novel solutions.

Looking ahead: With continued positive results, the team plans to investigate the feasibility of using these patterned magnets to reconnect stores – for example, individual drones that could reconnect to a drone mothership after mission deployment. It is also anticipated that the 500-pound-rated payload release mechanism will pass reviews and be tested in a lab environment. Across the board, improvements in holding force, size, and weight are expected. Researchers are working with NASA Armstrong to define safe practices for storage and operation of strong permanent magnets and mechanical-magnetic hybrid systems. The team, which includes a large contingent of interns, continues to pursue flight opportunities to further identify and demonstrate magnetic technologies in target environments.

Benefits

- **Potentially safer and more efficient:** Eliminates design time, costs, and safety measures associated with pyrotechnic separation events
- **Versatile:** Attaches to a wide variety of surfaces and object shapes with minimal reconfiguration
- **Flexible and lightweight:** Increases functionality of magnet systems, opening new application fields

Applications

- In-flight payload release
- Space assembly and docking
- Equipment anchoring
- Drone recapture
- Robotic grappling

PI: Paul Bean | 661-276-2451 | Paul.Bean@nasa.gov

NASA Armstrong Contributes to Successful Artemis Launch Abort Test

NASA Armstrong researchers developed several systems designed to test the launch abort system (LAS) that will pull astronauts to safety during a launch emergency. The three-minute test, called Ascent Abort-2 (AA-2) occurred in July 2019, and was an important safety milestone in the agency's preparation for crewed flights of the Orion vehicle.

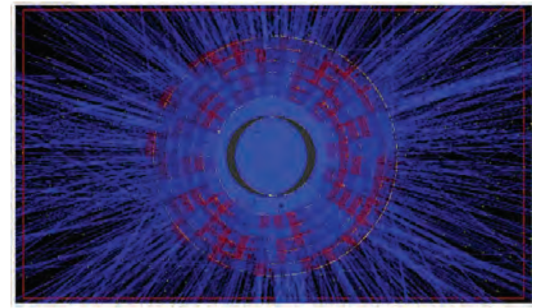
In the AA-2 flight test, a test version of the Orion crew module (CM) launched from Space Launch Complex 46 at Cape Canaveral Air Force Station in Florida. The launch occurred on a modified Peacekeeper first-stage rocket motor procured through the U.S. Air Force and built by Northrop Grumman. The Orion test spacecraft traveled to an altitude of about six miles, at which point it experienced transonic, high-stress aerodynamic conditions expected during ascent. The abort sequence was triggered, and in less than 180 milliseconds the abort motor fired to pull the CM away from the rocket. The attitude control motor flipped the capsule end-over-end to properly orient it. Then the jettison motor fired, releasing the CM for splashdown in the Atlantic Ocean.

Among Armstrong's numerous critical contributions were systems engineering support; the AA-2 developmental flight instrument subsystem, which collected and transmitted all the engineering data; and an onboard separation video system that allowed the Orion engineering team to show that the 38 flight test objectives were achieved. Armstrong team members were on hand at the test to monitor data from the booster, the separation ring, and the video system as well as instrumentation from the CM and LAS.

Launch data were successfully downloaded from all 12 ejectable data recorders. The team has reviewed the data, which NASA will use for final certification that the LAS is safe for human space flight.

POC: David Dowdell | 661-276-2814 | David.B.Dowdell@nasa.gov

Radiation Shielding System



Space radiation can penetrate habitats, spacecraft, equipment, and spacesuits. Minimizing the effects of space radiation exposure is one of the biggest challenges in keeping astronauts healthy and fit during space exploration. Many researchers have proposed forming large electromagnetic fields around a spacecraft to mimic the protection provided by Earth's magnetosphere. The challenge in this approach is to develop a system that can distribute a sufficient magnetic field over a large volume while simultaneously being compact, lightweight, and power efficient. This research effort aims to develop an active radiation shielding simulation architecture that rapidly evaluates how magnetic fields can be oriented to effectively shield astronauts from radiation exposure.

Work to date: NASA Armstrong researchers designed a simulation architecture to evaluate magnetic active radiation shielding configurations that incorporate lattices of Helmholtz coil arrays located at a distance from a spacecraft. They determined that individual rows of Helmholtz coils can be configured to have a magnetic field that points in either the positive or negative direction depending on the direction of the applied current through each coil.

Looking ahead: Next steps are to integrate optimization algorithms into an overarching simulation architecture to reduce the time required to evaluate various shielding configurations.

Benefits

- **Enabling:** Facilitates evaluation of radiation-shielding configurations to determine how magnetic fields can be oriented to shield spacecraft from harmful radiation
- **Flexible:** Enables testing of a variety of shielding configurations

Applications

- Spacecraft and habitats
- Space instrumentation and equipment

PI: Matthew Waldersen | 661-276-5708 | Matthew.Waldersen@nasa.gov

Electrified Aircraft Technologies

NASA Armstrong Preps for First Flight of All-Electric X-57 Experimental Aircraft
Sean Clarke | 661-276-2930 | Sean.Clarke@nasa.gov

NASA Armstrong Contributes to Subsonic Single Aft eNgine (SUSAN) Electrofan Development
Nic Heersema | 661-276-6112 | Nicole.A.Heersema@nasa.gov

CFD Simulations Evaluate Cooling Airflows for Electric Aircraft Motors
Trong Bui | 661-276-2645 | Trong.Bui-1@nasa.gov

Ice Protection System Analysis for High-Efficiency Electric Aircraft
Nic Heersema | 661-276-6112 | Nicole.A.Heersema@nasa.gov

Flight Dynamics Analysis of PEGASUS Vehicle Concept
Felipe Valdez | 661-276-3330 | Felipe.Valdez@nasa.gov
Curtis Hanson | 661-276-3966 | Curtis.E.Hanson@nasa.gov

Supersonics Technologies

Shock-Sensing Probe Provides Key Sonic Boom Information
Mike Frederick | 661-276-2274 | Mike.Frederick-1@nasa.gov

NASA Armstrong Prepares for Arrival of X-59 Quiet Supersonic Aircraft
Heather Maliska | 661-276-2843 | Heather.A.Maliska@nasa.gov

Instrumentation System Heralds New Paradigm in Flight Test Data Architecture
Shedrick Bessent | 661-276-3663 | Shedrick.B.Bessent@nasa.gov

SCHAMROQ Preps Tools and Test Techniques for Supersonic Flight
Matthew Moholt | 661-276-3259 | Matthew.R.Moholt@nasa.gov

Flying Qualities for Low-Boom Vehicles
Jesse Brady | 661-276-5990 | Jesse.C.Brady@nasa.gov
Brent Cano | 661-276-5843 | brent.r.cano@nasa.gov

Using Schlieren Techniques to Understand Sonic Booms
Dan Banks | 661-276-2921 | Daniel.W.Banks@nasa.gov
Ed Haering | 661-276-3696 | Edward.A.Haering@nasa.gov

Quantifying and Measuring Sonic Booms
Larry Cliatt | 661-276-7617 | Larry.J.Cliatt@nasa.gov
Ed Haering | 661-276-3696 | Edward.A.Haering@nasa.gov

Real-Time Display and Mitigation of Sonic Booms
Sriram Rallabhandi | 757-864-9554 | Sriram.Rallabhandi@nasa.gov

Enhanced ADS-B System for Supersonic Aircraft
Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov

Supersonic Plasma Acoustic Reduction Concept (SPARC)
Aliyah Ali | 661-276-5533 | Aliyah.N.Ali@nasa.gov

A technician works on the underside of the X-59 aircraft. Credit: Lockheed Martin

Revolutionary Vertical Lift Technology (RVLT) fixed base simulator

Autonomous Systems

Resilient Autonomy Project Develops Evaluation Methodology
Nelson Brown | 661-276-5039 | Nelson.Brown@nasa.gov

Improved Ground Collision Avoidance System (iGCAS)
Nelson Brown | 661-276-5039 | Nelson.Brown@nasa.gov

Ubiquitous Weather Sensing
Luke Bard | 661-276-2756 | Luke.J.Bard@nasa.gov

Advanced Air Mobility (AAM) National Campaign
Starr Ginn | 661-276-3434 | Starr.R.Ginn@nasa.gov

AI Computer Vision Enhances Situational Awareness of Intelligent Vehicle Systems
Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov

NASA Autonomous Soaring Study
Jesse Brady | 661-276-5990 | Jesse.C.Brady@nasa.gov

Technologies to Enable Urban Air Mobility
Curtis Hanson | 661-276-3966 | Curtis.E.Hanson@nasa.gov

Micro Weather Moderation
Luke Bard | 661-276-2756 | Luke.J.Bard@nasa.gov

Unmanned Aircraft System (UAS) Integration in the National Airspace System (NAS) Project
Clint St. John | 661-276-5306 | Clint.W.St.John@nasa.gov

Machine Learning Enables Virtual Windsock
Curtis Hanson | 661-276-3966 | Curtis.E.Hanson@nasa.gov

Flight Loads Laboratory

Coincident Heating and Loading Technique Supports Structural Tests
Larry Hudson | 661-276-3925 | Larry.D.Hudson@nasa.gov

F/A-18E Super Hornet Loads Calibration Testing
Larry Hudson | 661-276-3925 | Larry.D.Hudson@nasa.gov

F-15 Wing Store Structural Dynamics Airworthiness Clearance
Natalie Spivey | 661-276-2790 | Natalie.D.Spivey@nasa.gov
Shun-fat Lung | 661-276-2969 | Shun-Fat.Lung-1@nasa.gov
Samson Truong | 661-276-2998 | Samson.S.Truong@nasa.gov
Scott Stebbins | 661-276-6141 | Scott.L.Stebbins@nasa.gov

Structural Model Tuning Tool
Chan-gi Pak | 661-276-5698 | Chan-Gi.Pak-1@nasa.gov

Geometrically Nonlinear Structural Deformation Computation
Chan-gi Pak | 661-276-5698 | Chan-Gi.Pak-1@nasa.gov

Improving Aerospace Vehicle Efficiency

Multi-Utility Testbed Advances Aeroservoelastic Technologies
Jacob Schaefer | 661-276-2549 | Jacob.Schaefer@nasa.gov
Matt Boucher | 661-276-2562 | Matthew.J.Boucher@nasa.gov
Alex Chin | 661-276-2681 | Alexander.W.Chin@nasa.gov
Jeff Ouellette | 661-276-2152 | Jeffrey.A.Ouellette@nasa.gov

Glider Swarm Sensor Distribution
David Berger | 661-276-5712 | Dave.E.Berger@nasa.gov

System Identification for Flexible Aircraft
Matt Boucher | 661-276-2562 | Matthew.J.Boucher@nasa.gov

Prandtl Flying Wing
David Berger | 661-276-5712 | Dave.E.Berger@nasa.gov

Integrated Flight Dynamics and Aeroservoelastic Modeling and Control
Jeffrey Ouellette | 661-276-2152 | Jeffrey.A.Ouellette@nasa.gov
Jacob Schaefer | 661-276-2549 | Jacob.Schaefer@nasa.gov
Peter Suh | 661-276-3402 | Peter.M.Suh@nasa.gov

Practical Modal Filtering
Jeffrey Ouellette | 661-276-2152 | Jeffrey.A.Ouellette@nasa.gov

New Propeller/Fan Increases Efficiency
Jason Lechniak | 661-276-2620 | Jason.A.Lechniak@nasa.gov

CFD Analysis of a Low-Speed Swept Wing with a Bell-Shaped Lift Distribution
Trong Bui | 661-276-2645 | Trong.Bui-1@nasa.gov

Investigating Laminar Flow
Mike Frederick | 661-276-2274 | Mike.Frederick-1@nasa.gov
Michelle Lynde | 757-864-9097 | Michelle.N.Lynde@nasa.gov (NASA Langley)

Fiber Optic Sensing System (FOSS)

Sensor Suite Supports Aeronautics and Space Applications
Paul Bean | 661-276-2451 | Paul.Bean@nasa.gov
Patrick Chan | 661-276-6170 | Hon.Chan@nasa.gov
John Del Frate | 661-276-3704 | John.H.Delfrate-1@nasa.gov
Philip Hamory | 661-276-3090 | Philip.J.Hamory@nasa.gov
Jonathan Lopez-Zepeda | 661-276-7778 | Jonathan.Lopez-Zepeda@nasa.gov
Eric Miller | 661-276-7041 | Eric.J.Miller@nasa.gov
Allen Parker | 661-276-2407 | Allen.R.Parker@nasa.gov
Francisco Peña | 661-276-2622 | Francisco.Pena@nasa.gov
Anthony Piazza | 661-276-2714 | Anthony.Piazza-1@nasa.gov

'Rocket Box' FOSS to Fly on Launch Vehicles
Allen Parker | 661-276-2407 | Allen.R.Parker@nasa.gov

Micro FOSS Technology Leverages Low-Cost Components for High-Performance Tasks
Allen Parker | 661-276-2407 | Allen.R.Parker@nasa.gov

Doppler FOSS Validates Velocity Measurements and Algorithms
Francisco Peña | 661-276-2622 | Francisco.Pena@nasa.gov
Allen Parker | 661-276-2407 | Allen.R.Parker@nasa.gov

Fiber Optic Technology Enables Cryogenic Monitoring Capabilities
Patrick Chan | 661.276.6170 | Hon.Chan@nasa.gov

Avionics and Instrumentation Technologies

Waveguide Augmented Radiometric System (WARS)
Chris Kostyk | 661-276-5443 | Chris.B.Kostyk@nasa.gov

New Mission Support System Increases Functionality and Reliability
Russell Franz | 661-276-2022 | Russell.J.Franz@nasa.gov

SonicSonde: Instrumentation for a Tethered Atmospheric Sensor Suite
Kimberly Bestul | 661-276-3315 | Kimberly.A.Bestul@nasa.gov

ARMD Flight Data Portal (AFDP)
Jason Holland | 661-276-3035 | Jason.L.Holland@nasa.gov

Visual Radar
Matthew Versteeg | 661-276-3902 | Matthew.L.Versteeg@nasa.gov

Wireless Miniature Biosensor
Dwight Peake | 661-276-3217 | Dwight.Peake-1@nasa.gov

Advanced Wireless Flight Sensor System
Matthew Waldersen | 661-276-5708 | Matthew.Waldersen@nasa.gov

Space and Hypersonics Technologies

Dust-Tolerant Cryogenic Magnetic Coupler for Space Applications
Shideh Naderi | 661-276-3106 | Shideh.Naderi@nasa.gov

Store Separation Analysis Toolset Quantifies Risks, Validates Mitigation
Christopher Acuff | 661-276-2380 | chris.acuff@nasa.gov

Patterned Magnets for Hold-Separate Techniques
Paul Bean | 661-276-2451 | Paul.Bean@nasa.gov

NASA Armstrong Contributes to Successful Artemis Launch Abort Test
POC: David Dowdell | 661-276-2814 | David.B.Dowdell@nasa.gov:

Radiation Shielding System
Matt Waldersen | 661-276-5708 | Matthew.Waldersen@nasa.gov

Awards and Special Features

Armstrong Tech Wins NASA's Commercial IOY Award
Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov

Armstrong Wins Two Early Career Initiative (ECI) Awards
Daniel Budolak | 661-276-7721 | Daniel.Budolak@nasa.gov
Shideh Naderi | 661-276-3106 | Shideh.Naderi@nasa.gov

Armstrong Lends Flight Expertise to Pilot Safety Effort
Lance Richards | 661-276-3562 | Lance.Richards-1@nasa.gov

SBIR/STTR's Cutting-Edge Contributions to Armstrong
Gray Creech | 661-276-2662 | Gray.Creech-1@nasa.gov

Specialized Aircraft Support Worldwide Science Efforts

NASA Armstrong is conducting load calibrations tests on an F/A-18E Super Hornet from the Naval Air Systems Command (NAVAIR) in Patuxent River, Maryland. This is a view of the test setup.

National Aeronautics and Space Administration

Armstrong Flight Research Center
4800 Lilly Ave.
Edwards, CA 93523

www.nasa.gov/centers/armstrong

www.nasa.gov

All photos and illustrations by NASA unless otherwise noted.

(front cover) Cockpit of the X-59 Quiet SuperSonic Technology (QueSST) airplane. Credit: Lockheed Martin

(back cover) (top left) X-59 simulator (middle) Alta 8 remotely piloted aircraft and NASA photographer Jim Ross (lower) all-electric X-57 aircraft (right) Fenix Space subscale glider

NASA/TM-20220003937