National Aeronautics and Space Administration

NASA's Armstrong Flight Research Center

Research, Technology, and Engineering Report

2023

www.nasa.gov

Aerospace Valley Air Show at Edwards Air Force Base in October 2022.

From the
Director for Research and Engineering

It is an honor to endorse the 2023 NASA's Armstrong Flight Research Center Research, Technology, and Engineering Report. NASA Armstrong continues to demonstrate leadership in aeronautics, Earth and space science, and aerospace technology. Our researchers, engineers, and mission support teams are revolutionizing aviation and adding to our understanding of the universe.

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 prepare for the arrival of the X-59 supersonic research aircraft, we are excited to apply that strength to the X-59's first and subsequent flights. Armstrong will serve as the X-59's base of operations, and our researchers will lead efforts in integrated systems testing, flight loads testing, sonic boom measurement, and much more. With the conclusion of the X-57 all-electric experimental aircraft this year, our research is providing the aeronautics community with hundreds of lessons learned as well as revolutionary developments in areas ranging from battery technology to cruise motor control design.

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.

Stephen C. Jensen
Director for Research and Engineering

Who We Are

Pilots, mechanics, and **technicians** with the specialized skills to execute the most demanding flight test operations and missions

Mission support specialists that ensure the smooth operation of center functions crucial for success

Engineers with experience in a wide range of aircraft, flight regimes, systems, and test approaches

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 **airborne remote sensing** and **science observations**

Conduct **high-risk atmospheric flight research** and test projects

Perform flight research and technology integration to **revolutionize aviation** and **pioneer aerospace technology**

Leading efforts to flight test **supersonic X-Plane**

Rapidly demonstrate promising space technologies through suborbital testing with industry flight providers

Validate space exploration concepts

Operate platform aircraft to **gain world-class Earth science data**

Why We Do Research

Currently **more than 5%** of U.S. GDP

Enhance American competitiveness in the global aviation industry

Make our **skies safer,** our **fuels cleaner**, and get people to their **destinations faster**

Contribute to the value-added economic activity from aviation and related sectors

Deliver revolutionary aviation capabilities to previously underserved local, regional, intraregional, and urban areas

Reduce the environmental impact and cost of passenger and freight air transportation with green technologies

How We Get It Done

Expertise in creative test development and evaluation

Collaborative network of aerospace researchers and developers

Six decades of excellence at the **Flight Loads Lab**

Internationally recognized **integrated approach** to risk management

Quality management and safety systems to meet the challenges of complex system development and testing

Unique **testing** and **simulation facilities** and one-of-a-kind **airspace capabilities** in a location that enables year-round flight testing

Strong center management and governance models to ensure on-time and cost-effective program performance

From the
Center Chief Technologist

I am delighted to present highlights of the tremendous body of accomplishments at NASA's Armstrong Flight Research Center in Edwards, California. Our dedicated innovators possess the skills to safely and successfully accomplish Armstrong's flight research and test missions and to support NASA missions across the agency.

NASA Armstrong's project teams tackle complex flight research projects, crafting innovative 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 a supersonic experimental aircraft, autonomous systems, electrified aircraft, and instrumentation systems.

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

I am proud of the work we do here at Armstrong and am pleased to share these details. 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

NASA research pilots at a simulator entering and testing flight path data to develop navigation codes.
Credits: Joby Aviation

Contents

Quesst Mission

PROJECT SUMMARIES

The X-59 experimental aircraft is at the center of NASA's Quesst mission, which focuses on providing data to help regulators reconsider rules that prohibit commercial supersonic flight over land. The X-59 is expected to fly at 1.4 times the speed of sound, or 925 mph. Its design, shape, and technologies will allow the aircraft to achieve these speeds while generating a quieter sonic thump. Using this one-of-a-kind experimental airplane, **NASA aims to gather data that could revolutionize air travel, paving the way for a new generation of commercial aircraft that can travel faster than the speed of sound.**

NASA's Armstrong Flight Research Center in Edwards, California will serve as its base of operations. Armstrong researchers will lead efforts in integrated systems testing, engine runs, flight readiness, loads testing, and more. This work is featured on the following pages.

After NASA completes flight tests, which are scheduled to begin in 2024, the agency will fly the aircraft over several to-be-selected cities across the United States, collecting input about the sound the X-59 generates and how people perceive it. NASA will provide that data to the Federal Aviation Administration and international regulators.

Engine Integration Activities Pass Key Milestones

The quiet supersonic X-59 aircraft combines new technologies with systems and components from multiple established aircraft. A key task for researchers is to fully integrate the systems and components into the aircraft and ensure they operate as intended.

The General Electric Aerospace F414-GE-100 engine was installed in November 2022. The 13-foot-long engine will power the X-59 as it flies at speeds up to Mach 1.4 and altitudes around 55,000 feet. Engineers at NASA Armstrong have worked with teams of experts from industry and other NASA centers to integrate and validate system operation, known as system check-outs. The team completed 100 percent of system check-outs by early 2024. Key accomplishments include verifying that the engine fits as intended in the engine bay, that the engine and aircraft computers are communicating as expected, and that other interfaces – such as fuel, electrical, and flight test instrumentation – are operating as intended.

Engine integration efforts fall into three main areas: physical, systems interaction, and software.

Physical Integration

These actions include such activities as confirming the engine fits into the aircraft, that fuel and electric lines attach, and instrumentation connects as intended. The NASA team spent three months working with computer-aided design software and then another two months after the engine was installed mitigating "close clearances" – instances where components are less than an inch from the engine. Because the aircraft is shaped in such a way that the engine bay is very tight, the Armstrong team examined and de-risked more than 100 close clearances.

Systems Interactions

These activities include ensuring that peripheral systems function as intended and interact appropriately with each other. Examples include examining whether the fuel supply, electric lines, and sensors operate correctly.

Software Integration

The Armstrong integration team worked with the software team to understand and then conduct tests to ensure that the engine and aircraft computers are communicating as expected.

Other key accomplishments include completion of ground and flight test planning, commencement of control room training, and continued progress in writing the flight and maintenance manuals and emergency procedures.

According to the Armstrong team, the communication between the entities involved, which included industry as well as multidisciplinary NASA experts, was instrumental to project success. These engineers, researchers, and mechanics brought a host of experiences and expertise to the engine integration task, and their varied perspectives were instrumental in ensuring that the engine is safe and operating as intended.

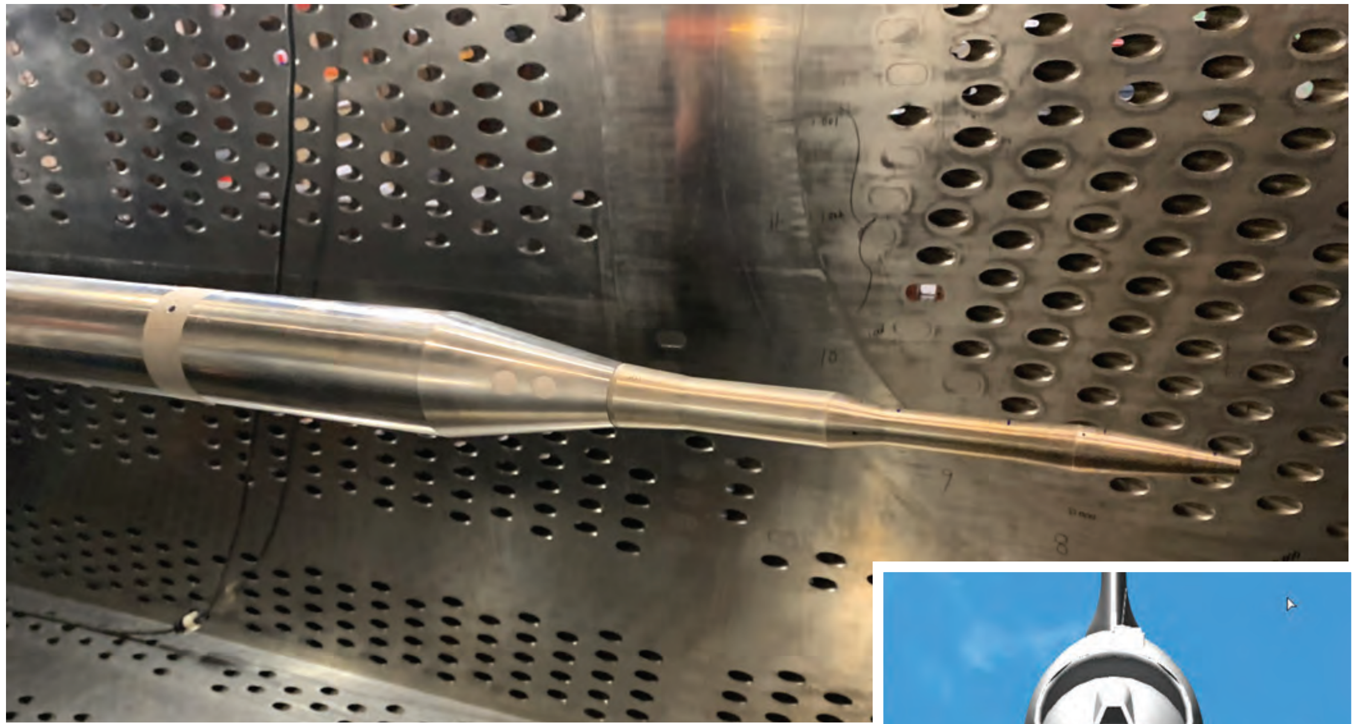
Looking ahead: As the aircraft begins prepping for ground testing, the Armstong integration team will continue testing to ensure that the aircraft and engine communicate and work well together. In addition, they will ensure everyone who will be involved in upcoming tests is adequately prepared.

Benefits

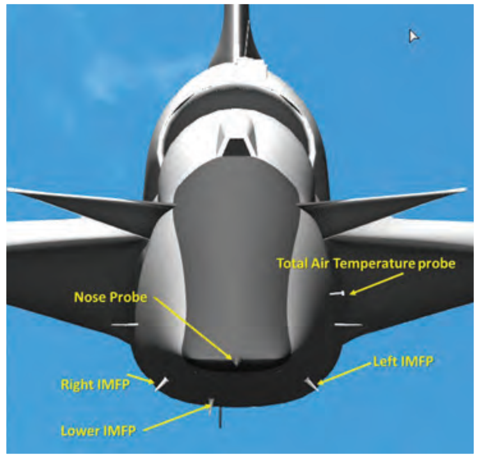
This research offers numerous solutions for engine integration in experimental aircraft, providing significant insights for future X-Planes.

PI: Paul Dees | Paul.M.Dees@nasa.gov | 661-276-3433

Air Data Neural Network Research Pinpoints Key Flight Parameters



The X-59 air data system nose probe in the wind tunnel during calibration tests at NASA's Glenn Research Center.



The X-59 air data system components (as seen from the aircraft nose) include integrated multifunction probes (IMFP) and nose- and air-temperature probes.

An air data system on the X-59 experimental aircraft will employ neural networks to provide critical information to pilots and researchers about key parameters including altitude, speed, angle of attack, and side slip. A neural network is a multi-dimensional curve fit model, computed for a set of user-specific input and output data points. These networks model complicated nonlinear relations for problems that have many input parameters with unknown functional relationships. Neural networks will be used onboard the aircraft to relate real-world probe pressures to real-world aircraft output parameters.

Work to date: NASA Armstrong researchers developed a neural network calibration for the nose-mounted pressure-sensing probe on the X-59 using wind tunnel data from NASA's Glenn Research Center to complement a similar neural network calibration developed by Lockheed Martin. Objectives were to accommodate wind tunnel data that didn't strictly obey expected fluid mechanic relationships, facilitate analysis of off-nominal or otherwise unanticipated conditions, and permit direct estimation of uncertainties and errors introduced by the calibration.

Though researchers developed the neural network calibration independently of Lockheed, they achieved the same accuracy. This is important because NASA will be able to employ this tool for more research tasks after Lockheed's planned exit from the project after first flights. For example, this tool could help researchers measure sonic booms more precisely or in more atmospheric conditions than otherwise envisioned. It also could be used to accommodate failures of individual pressure signals on the nose probe. What started as a backup has become a tool to accommodate future growth.

Looking ahead: The team has developed the neural network calibration, confirmed that it works, and is ready for first flight of the X-59 aircraft. Researchers will refine the network using data collected during early flights to increase accuracy and robustness.

Benefits

- **Highly accurate:** Provides critical information about key flight parameters
- **Robust:** Operates in numerous flight conditions and accommodates failures of one or more pressure ports
- **Forward thinking:** Establishes a knowledge base at Armstrong for neural network development for future X-planes

PI: Kurt Long | Kurtis.R.Long@nasa.gov | 661-276-2258

Piloted Simulations and Flying Qualities Analysis Support Flight Readiness

The X-59 simulator at Armstrong will help pilots prepare for Quesst missions. Quesst is NASA's mission to demonstrate how the X-59 can fly supersonic without generating loud sonic booms and survey what people hear when it flies overhead.

Innovators at NASA Armstrong are evaluating stability and control characteristics and piloted simulations for the X-59 experimental aircraft. This work supports efforts to develop analytical techniques and flight test tools to validate flight readiness and to facilitate safe and efficient phase envelope expansion.

Work to date: The Armstrong team developed pilot-in-the-loop and batch non-linear simulations based on aircraft models. Researchers are using the simulations to analyze the sensitivity of vehicle stability, controllability, and handling qualities to model variations. Piloted simulation evaluations have been conducted in nominal and off-nominal situations to identify undesirable approach, landing, and take-off characteristics, which were subsequently mitigated through flight control law design changes.

Advanced Monte-Carlo techniques were developed and utilized to verify that unsafe stability and control characteristics are not predicted based on inaccurate modeling. Due to inherently high levels of instability in the bare airframe system, the team developed a real-time stability monitoring technique for use in the control room to ensure sufficient levels of stability are maintained during flight. They also used aircraft test data from structural coupling tests to analyze and update stabilator and aileron actuator models.

Looking ahead: Planning for safe and efficient envelope expansion is underway, as well as analysis to verify readiness for first flight. The team is developing flight test continuation criteria for monitoring in the control room during envelope expansion flights to verify that parameters for key flying qualities stay within assumed uncertainties in pre-flight analysis.

Partner: NASA's Langley Research Center, Lockheed Martin Corporation

Benefits

- **Widely applicable:** Provides an algorithm to estimate real-time stability margin in flight that has broad applications for other programs
- **Enhanced probabilistic understanding:** Employs a unique approach utilizing Monte-Carlo techniques to provide a rationale for variance in stability margin requirements

PI: Timothy Cox | 661-276-2126 | Timothy.H.Cox@nasa.gov

Researchers Analyze Structural Test Results to Prepare for First Flights

The X-59 aircraft has undergone numerous structural tests to ensure that its airframe can safely handle the anticipated flight environments in the flight test program.

Flight loads are flight-induced conditions that generate stresses on the airframe, such as rough air, quick turns, takeoffs, and landings. Engineers have installed sensors at critical locations that are designed to tell researchers how much stress the airframe is experiencing at any given flight condition or maneuver. This is accomplished by having a suite of highly calibrated strain gage bridges as sensors. These strain gage bridges were calibrated in the laboratory with known applied loads.

NASA Armstrong researchers are analyzing these structural test data in preparation for ground and flight tests planned for 2024.

Work to date: In 2022, Lockheed Martin shipped the aircraft to its test facility in Ft. Worth, Texas, for structural proof and strain gage calibration tests. In this facility, loads slightly greater than the expected flight loads were applied onto the airframe.

The successful strain gage loads calibration test provided data for researchers to develop loads equations that will enable real-time in-flight loads monitoring. By the end of 2023, the team had reviewed more than 90% of the data generated by all structural tests.

Looking ahead: The Armstrong team will complete their structural review analyses, prepare and set up the final instrumentation suite, and be fully trained for control room operations to support the upcoming 2024 ground and flight tests.

Benefits

- **Enhances capability:** Establishes the toolset for safe flight loads envelope expansion of the X-59
- **Instructive:** Contributes to the Low Boom Flight Demonstrator project's list of artifacts showing preparedness for safe execution of flight test

PI: Ivan Chavez | Ivan.S.Chavez@nasa.gov | 661-276-5893

"...it doesn't get any better than this."

"The Quesst mission and X-59 aircraft are a culmination of decades of work in supersonics. They have the potential to open new markets and opportunities for the future of high-speed flight.

"In 1947, Chuck Yeager broke the sound barrier and we've been trying to fix it ever since. X-59 and Quesst provide that opportunity. It's amazing getting to work on an X-Plane. Everything that goes into the design, review, and testing provides a great opportunity for everyone to work on something exciting and ground breaking.

"X-59 and Quesst are the highlight of my career as a test pilot. Getting to work on a manned supersonic X-Plane…it doesn't get any better than this."

-Nils Larson, NASA test pilot

NASA test pilot, Nils Larson, inspects the X-59 cockpit displays and lighting system during system checkouts. The External Vision System (XVS) is displayed on the top screen, and the avionics flight displays, which can show navigation information or aircraft status, are shown on the bottom two screens.

Ground Vibration Test Measures X-59 Modal Parameters

The X-59 aircraft undergoes ground vibration testing at Lockheed Martin's Palmdale facility.

The ground vibration test (GVT) for the X-59 aircraft was completed in July 2023, at Lockheed Martin's Palmdale site. The GVT objective was to measure the modal parameters (frequencies, mode shapes, and damping) of the as-built, fully assembled X-59 to show that the aircraft is free from flutter, buzz, and aeroservoelastic instabilities. GVT data will be used to update and validate the finite element model (FEM), verify notch-filter frequencies used in the flight controls system, and identify modes to track during envelope expansion flights – all of which are necessary for airworthiness clearance.

Two aircraft fuel configurations were completed for this GVT:

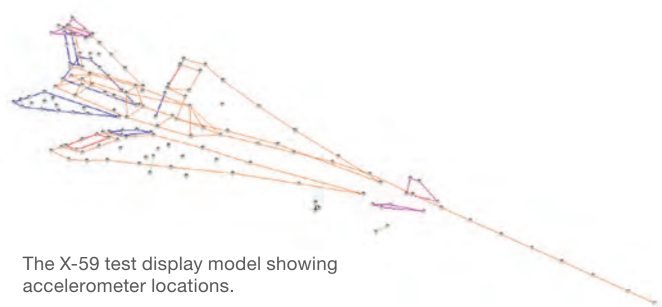
1. Empty or zero-fuel weight (ZFW) and
2. Added fuel to simulate the design take-off weight.

A three-canister pressurized soft support system interfacing with unique X-59 hardware at the aircraft's three jacking locations was used to simulate the free-free boundary conditions of flight and to "float" the aircraft for testing.

The landing gear was up and stowed, and tests were performed with the control surfaces powered on. All six rigid-body modes were measured using manual excitation for the ZFW configuration. Multiple electromagnetic shakers were set up on the wingtips, horizontal stabilators, and vertical tail to assess the aircraft's global modes with burst-random excitation for both fuel configurations. Sinusoidal dwell/decay excitation was performed on the control surfaces, and impact hammer tests were performed on the landing gear doors, aft deck, and flaps. Approximately 175 accelerometer responses distributed along the wings, control surfaces, vertical tail, and fuselage were measured to aid in the post-test modal curve-fitting parameter estimation of the frequencies, mode shapes, and damping. Post-test analysis for most modes compared well to the pre-test FEM predictions, with the exception of the lower-than-expected flap frequency mode.

Work to date: Researchers successfully measured the desired X-59 aircraft frequencies, mode shapes, and damping in summer 2023. They are correlating X-59 FEMs to better match GVT data.

Looking ahead: Next steps are completing the FEM correlation and re-running the X-59 flutter and aeroservoelastic analyses with the updated FEM.



The X-59 test display model showing accelerometer locations.

Benefits

- **Enabling:** Validates X-59 FEM to assist with aeroelastic and flutter airworthiness clearance

Applications

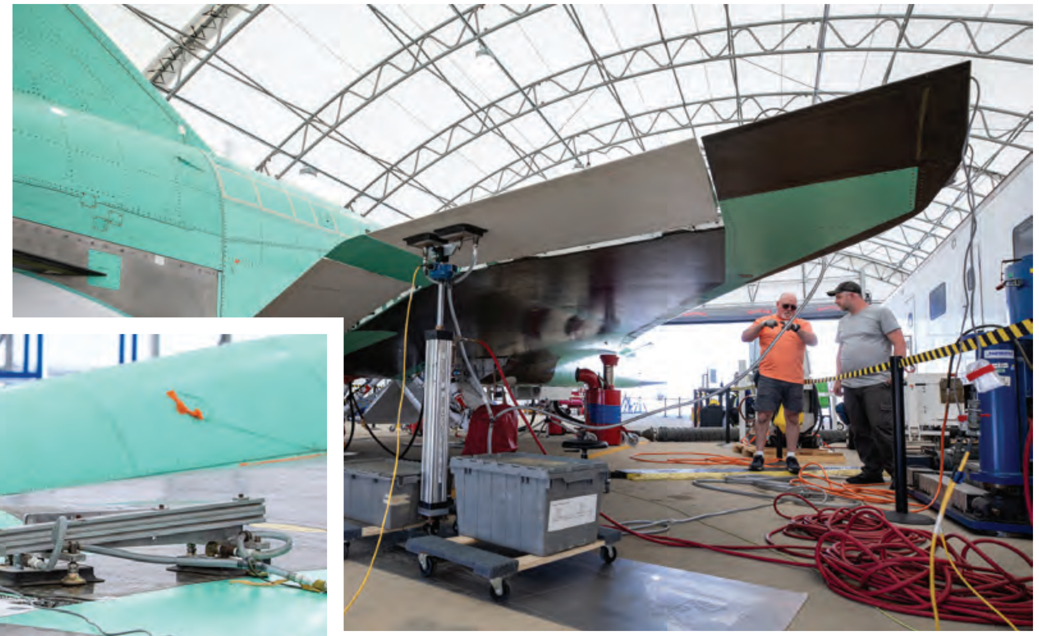
- Ground vibration testing
- Modal testing
- Flight aeroelastic airworthiness clearance

PIs: Natalie Spivey | 661-276-2790 | Natalie.D.Spivey@nasa.gov
Shun-fat Lung | 661-276-2969 | Shun-Fat.Lung-1@nasa.gov
Ben Park | 661-276-5406 | Benjamin.C.Park@nasa.gov

Control Surface Freeplay Testing Conducted to Assist in X-59 Aeroelastic and Aeroservoelastic Airworthiness

(right) The displacement transducer setup and load actuator setup.

(below) The X-59 right aileron freeplay hardware.



Freeplay testing of the control surfaces and landing gear doors for the X-59 aircraft was completed in July 2023 at Lockheed Martin's Palmdale site. The objective of the freeplay test was to measure the rotational freeplay around the hinge line of the movable flight control surfaces and the nose and main landing gear doors to assure freeplay requirements were met through design and/or adjust analyses for airworthiness clearance. Vibrating surfaces increase the wear of actuating mechanisms and hinge points, so freeplay can affect hinge line buzz, limit cycle oscillations, and other aeroelastic and aeroservoelastic phenomena. X-59 freeplay control surface testing included the left and right ailerons, flaps, and stabilators as well as the rudder and T-tail. The freeplay door testing included both nose landing gear doors and both main landing gear doors.

There were two hardware setups for each control surface:

1. A displacement transducer setup used vacuum-padded hardware off the surface and the extended arm with two linear variable differential transformer (LVDT) displacement transducers to measure the forward and aft surface deflections.
2. A vacuum-padded pneumatic actuator imparted loads to deflect the surface while the load cell measured load.

Maximum tension and compression were applied to each surface to achieve the max hinge moment. At least four load cycles were applied for each control surface, with the load actuator at a constant rate, while recording the load and two deflections with the ground test data acquisition system. The first load cycle was considered an exercise, and the remaining three were averaged to obtain the freeplay value.

Two key measurements, the moment arm to the load cell and distance between the two LVDTs, were needed to calculate the control surface rotation. Freeplay limits were referenced from MIL-A-8870C. All freeplay surface requirements were met, but the X-59 flap freeplay on both the right and left sides were higher than desired, especially with the combination of the lower-than-expected flap frequency finding from the ground vibration test. The project is addressing that issue.

Work to date: The X-59 control surfaces and landing gear doors freeplay were effectively measured. Precise pins for the flaps are being manufactured to lower the flap freeplay values.

Looking ahead: Another flap freeplay test will be conducted after precision flap pins are installed. X-59 freeplay will be remeasured after every 100 flight hours to ensure requirements are met or hardware is replaced or modified. Armstrong is designing and fabricating freeplay hardware that will remain with the X-59 aircraft for future freeplay tests.

Benefits

- **Enabling:** Assures freeplay limits are met for aeroelastic and aeroservoelastic airworthiness clearance

Applications

- Control surface freeplay testing

PIs: Natalie Spivey | 661-276-2790 | Natalie.D.Spivey@nasa.gov
John Atherley | 661-276-5269 | John.Atherley@nasa.gov

Trajectory Modeling Software to Aid Community Boom Exposure Tests

Determining the acceptability of the X-59's quiet sonic thump through local community engagement will occur during Quesst Phase III testing. (background) Artist concept of the X-59 in overland flight.

The X-59 aircraft is designed to reduce the sound of sonic booms that occur when an aircraft flies at supersonic speeds to a quiet sonic "thump." This will be demonstrated when NASA flies the X-59 over communities around the United States starting in 2025. The goal of this exercise is to provide data necessary to open the future to commercial supersonic flight over land, which will greatly reduce flight times.

NASA Armstrong researchers are developing software for planning trajectories for community overflights. During these flights, NASA will fly the X-59 aircraft around the country and measure the effects of sonic booms on the communities below. CLEOPATRA – which stands for Community Low-Boom Exposure, Operations, Piloting, and Trimming Analyzer – is a flight path planning software tool developed for planning community overflights. It determines optimal trajectory placement needed to meet mission objectives as well as optimal cruise conditions (e.g., Mach, altitude, heading) needed to achieve desired loudness values.

During the community overflights, researchers will vary noise levels from flight to flight and from day to day to build a robust statistical database of responses to varied sonic boom noise levels. CLEOPATRA software will help researchers develop trajectories to meet these parameters.

Work to date: The Armstrong team began developing CLEOPATRA in 2020. They collaborated with computational fluid dynamics (CFD) researchers at NASA's Ames Research Center and Langley Research Center and with sonic boom propagation experts at NASA Langley. This exchange of ideas between the CFD and propagation teams is essential to CLEOPATRA's success. The team started with a surrogate model that uses CFD to predict pressure around an aircraft. They integrated NASA's PCBoom software for sonic boom propagation capabilities, then they incrementally added different modules and complex CFD data to advance this essential planning tool.

Looking ahead: Researchers anticipate releasing the first official version early in 2024. Future versions will look to increase efficiency and speed calculations.

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

Benefits

- **Expands modeling capabilities:** Enhances the trajectory planning toolset at Armstrong and NASA
- **Informs decisions:** Determines optimal trajectory placement and cruise conditions to achieve objectives
- **Supports collaboration:** Extends cooperation and teamwork among NASA centers

Applications

- Trajectory planning
- Post-flight analysis

PI: Forrest Carpenter | Forrest.L.Carpenter@nasa.gov | 661-276-7559


The GE F414 engine (from the aft deck or rear) before the tail section of the X-59 is lifted into place and attached to the aircraft. The aft deck helps control the shockwaves at the end of the aircraft and reduce the noise of a sonic boom to more of a sonic thump.

Electrified Aircraft Technologies

PROJECT SUMMARIES

X-57 Project Creates Paths Toward Electric Aviation

NASA's X-57 Maxwell all-electric aircraft project concluded aircraft operational activities in 2023. The research from the X-57 project is providing aviation researchers with hundreds of lessons learned, as well as revolutionary development in areas ranging from battery technology to cruise motor controller design.

Finalizing aircraft operations did not include a first flight of the X-57 aircraft. The project encountered several challenges to safe flight, including mechanical issues late into its lifecycle and a lack of availability of critical components required to develop experimental hardware. Given the approaching planned end of aircraft operations, the timeline did not allow the team to reach acceptable flight conditions.

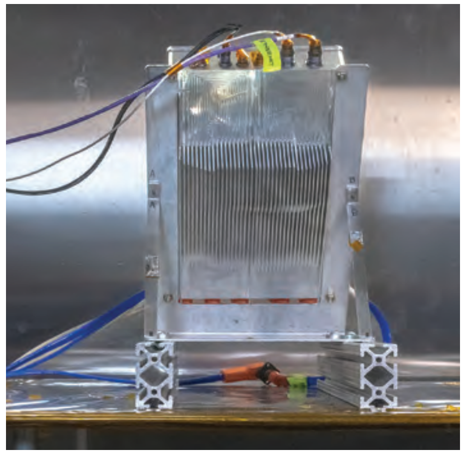
The primary goal of the X-57 project was to share knowledge about the aircraft's electric-propulsion-focused design and airworthiness process with regulators. This information has already impacted and will continue to impact the development of advanced certification approaches for electric propulsion in emerging electric aircraft markets. A key objective was to develop a test platform for technologies and design methods, and the NASA Armstrong team accomplished this, documenting and publishing the technology gaps and their solutions as they were discovered so that industry stakeholders could take advantage of those lessons as soon as possible.

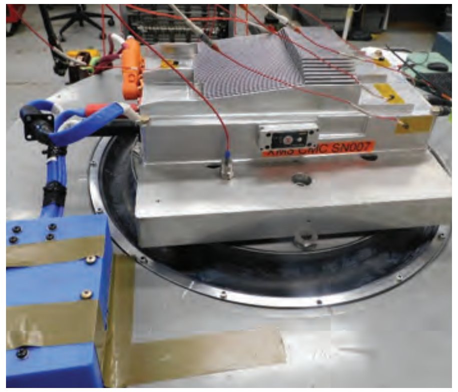
The X-57 is part of NASA's commitment to supporting the U.S. climate goal of achieving net-zero greenhouse gas emissions from the aviation sector by 2050. Since 2016, the project has shared lessons learned about battery technology, electromagnetic interference, motor controller design, and so much more. NASA will continue its research into electric aircraft through other projects, including its Electrified Powertrain Flight Demonstration.

The aircraft was built by modifying an Italian Tecnam P2006T to be powered by an electric propulsion system. Using an existing aircraft design allowed the team to compare their data to that of a baseline model powered by traditional combustion engines.

There were many achievements, some of which are featured in the following pages. The team continues to document and share research findings. Contributions this work has made to date can be found on the technical papers site: https://www.nasa.gov/directorates/armd/x-57-technical-papers/

Flight-Qualified Cruise Motor Controllers (CMCs) Guide Future Electric Powertrain Component Development





Thermal testing at NASA's Glenn Research Center and vibe testing at NASA Armstrong.

One of the many successes of NASA's X-57 project is the development and testing of the flight-qualified CMCs that power the cruise motors of the experimental aircraft. These controllers and the processes the NASA Armstrong team developed to qualify the hardware for flight will be instrumental to new electric powertrain component development.

The Modification II (Mod II) configuration of the X-57 utilized two electric cruise motors that each contain two sets of windings for redundancy. Each motor has two CMCs, and each one supplies half of the torque to each motor. By converting energy stored in the aircraft's lithium-ion batteries, the controllers power its motors, which drive its propellers. The controllers use high-efficiency silicon carbide transistors, have a maximum power output of 55 kilowatts, can achieve 98% efficiency at maximum and nominal power settings (e.g., for high-power take-off and cruise), and are air cooled. The Armstrong team also designed inverters to meet demanding mass and thermal requirements and successfully completed CMC thermal testing.

Because the original CMC design did not pass vibration levels defined by the project, the Armstrong team completely redesigned the controllers. During this process, the team learned many lessons on how to prototype, tune the hardware and software to maximize performance, and develop acceptance and qualification tests to detect defects in workmanship and design.

Airworthiness Acceptance Program a Key Objective

Another project goal was to develop an airworthiness acceptance test program to qualify the hardware for flight and to publish the team's qualification processes for industry to use for guidance. An airworthiness qualification standard for aircraft electric propulsion systems did not exist before this project, so the X-57 team developed their own.

During the development of the CMC hardware, a key objective was to optimize the total system performance of the cruise motors and controllers. Because the motors and controllers use passive air cooling, the system efficiency needed to be maximized to eliminate the risk of overheating the motors or controllers during the peak power phases required in flight. The project team spent a significant amount of time performing thermal/efficiency trades between the motors and controllers. This included creating a switching frequency schedule for the CMC gate drive so that the optimum switching frequency was identified to minimize motor heating. These efficiency studies proved that the Mod II cruise motors and CMC propulsion system could meet the power, thermal, and efficiency requirements for a successful flight campaign.

The flight CMCs were assembled at Armstrong in the Instrument Fabrication Shop. Each controller completed individual printed circuit board/hardware checkouts, functional tests on an unloaded motor, high-power acceptance and proto-qualification tests on a dynamometer test stand, and vibration and thermal testing. The units were declared flight worthy after passing all tests.

Looking ahead: NASA is sharing these designs in technical publications so that industry can use them as a launchpad for new aircraft products. NASA's Glenn Research Center is leveraging these accomplishments in its work on the Subsonic Single Aft eNgine (SUSAN) project.

Benefits

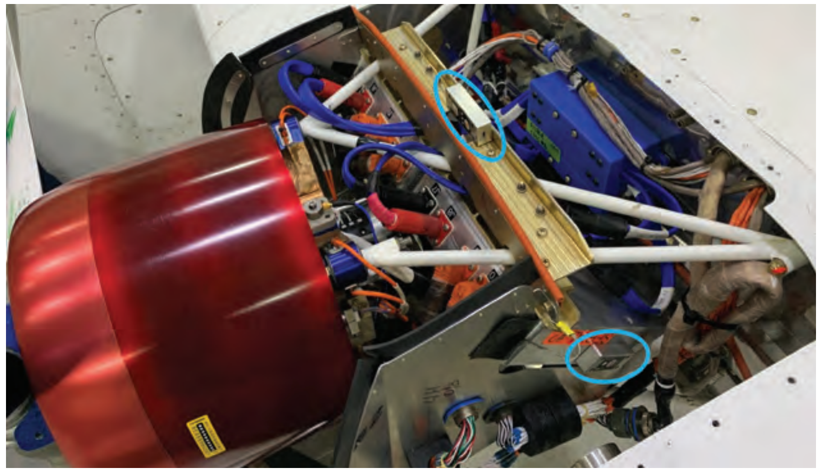
- **Maximize performance:** Provides processes for electric powertrain prototyping and tuning hardware and software to maximize performance
- **Assure qualification:** Provides an acceptance and qualification process for electric propulsion powertrain components
- **Improve quality:** Provides acceptance and qualification tests to detect workmanship and design defects

Applications

The knowledge gained through this integrated approach to electric powertrain design will be used as a guide for ongoing new electric powertrain component development.

POC: Jacob Terry | Jacob.R.Terry@nasa.gov | 661-276-2231

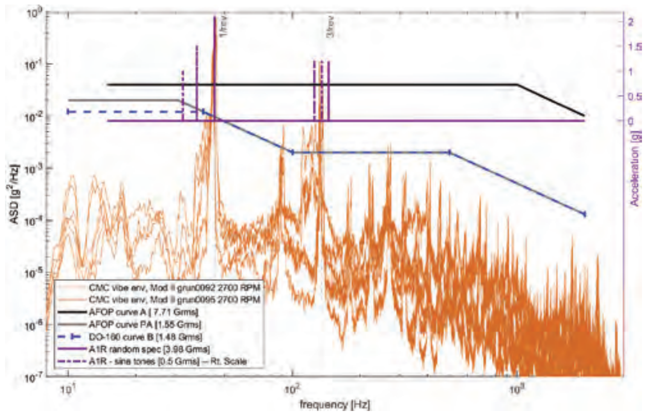
X-57 Cruise Motor / Cruise Motor Controller (CMC) Vibration Testing Informs Standards for Next-Gen Electric Aircraft



The X-57 electric cruise motor (red) is integrated onto the X-57 wing. Motor system vibrations are measured using Slam Stick data recorders (circled in blue).

Aircraft avionics equipment is qualified for flight by vibration and thermal testing in a representative environment. Prior to development of the X-57, NASA Armstrong researchers had no vibration data from which to determine the energy level of a representative environment for a 72-kilowatt-class electric aircraft motor, and they had no existing electric aircraft motor test standards to leverage. Their pathfinding research will inform standards and advance the development of next-generation electric aircraft.

Armstrong researchers measured the electric motor vibration environment during ground motor runs of the X-57 aircraft configuration dubbed Modification II (Mod II). Using standalone vibration data recorders known as Slam Sticks, measurements were taken while the flight test instrumentation system was being integrated into the aircraft (the typical method used to gather vibration data during aircraft operations). **The data demonstrated that an electric motor vibration environment is significantly lower than a comparable power-class combustion motor.** The vibration levels measured on the X-57 cruise motor are similar in magnitude to those experienced by equipment mounted in the fuselage of a transport aircraft.



(orange lines) Slam Stick-measured cruise motor controller (CMC) vibration data, compared to existing vibration test standards (grey, blue, and black lines), with the X-57 tailored CMC vibration test profile (purple line).

To operate the X-57 electric motors, CMCs convert DC battery power to phase-AC power. On the Mod II aircraft, the CMCs are mounted on the motor truss that attaches the cruise motor and propeller to the wing firewall. Failure of CMC hardware in flight would result in loss of propulsion. Environment qualification testing is a key risk reduction step for flight critical hardware like the CMCs. However, given the developmental stage of the CMCs, and the limitations of using bleeding-edge power electronics components inside to achieve required thermal efficiencies, the X-57 CMCs could not pass proto-qualification vibration tests at standard general aviation motor equipment levels. Therefore, measured X-57 data were used to derive a tailored lower-energy sine-on-random vibration test profile to environmentally qualify the CMC hardware. Margin was added to the X-57 tailored test profile compared to the actual vibrations measured on the Mod II aircraft to accommodate possible vibration environment changes resulting from installation differences, motor/propeller imbalance, propeller damage, and/or differences between flight and ground environments.

The aerospace community has little data to inform standards for upcoming electric aircraft, as manufacturers generally do not publish vibration data for electrified aviation due to proprietary restrictions. Data from X-57 research has no such restrictions – in fact, the value of the pathfinding work of NASA's X-57 research is that findings are meant to be shared – and can be used to update aerospace test standards for developing electrified-aircraft avionics.

Looking ahead: Electric-motor aircraft vibration data measured on the X-57 will be shared with the aerospace community and can be used to inform environmental test standards for future electric aircraft.

Benefits

- **Supports advancement:** Provides a method for using vibration data to determine the energy level of an electric aircraft motor
- **Enhances efficient design:** Offers data to inform standards for next-generation electric aircraft

Applications

- Electric motor aircraft component development
- Environmental qualification testing
- Electric aircraft test standard development

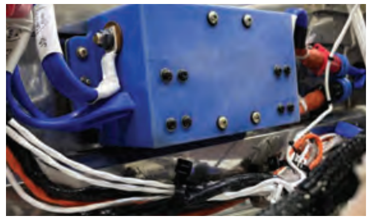
PI: Keerti Bhamidipati | 661-276-7305 | keerti.k.bhamidipati@nasa.gov

Integration Yields Electromagnetic Interference Solution

The aircraft testing setup with batteries on tow cart.

The test campaign for the X-57 aircraft included verifying and validating that the integrated system operated as designed and expected. During the integration phase, the NASA Armstrong team determined that electromagnetic interference (EMI) was causing a loss of critical battery and other system data. After an extensive test series, the team designed, developed, and installed filters that resolved the issue. Their innovative efforts will benefit future electric aircraft component development.

The team conducted its testing in an off-aircraft hardware-in-the-loop (HIL) configuration, providing a flexible environment to identify discrepancies and ensure subsystems operated as intended prior to integration with the aircraft. Since the loss of battery and other system data appeared when the cruise motor controllers (CMCs) began powering the loaded motors, the off-aircraft testing setup consisted of an unloaded motor, one CMC, a contactor pallet, a battery control module, a battery pack (consisting of eight battery modules), and the required wiring and switches to operate the hardware in this configuration.



The final filter design.

Upon discovering the cause of the battery and other system data loss during this testing, the team worked to mitigate the EMI effects in the HIL setup. They first considered isolation techniques but found they did not yield enough benefits for stable operation. They then introduced toroid inductors designed by NASA's Glenn Research Center to the high-voltage traction lines between the contactor pallet and the CMC. Through testing different toroid configurations, they determined the correct solution for the power profile of the HIL setup and developed and tested a prototype that was successful at mitigating the effects of the EMI. The team installed and tested on the aircraft a scaled version of this prototype that met the power requirements of the fully integrated system.

Looking ahead: The Armstrong team is explaining their approach to solving the EMI issue in technical papers that will be shared with industry and the electric propulsion community.

Benefits

This research offers a solution for reducing EMI in electric aircraft component design, providing significant insights to the electric propulsion development community.

POC: Kassidy McLaughlin | Kassidy.McLaughlin@nasa.gov | 661-276-6209

Innovative Machine Interfaces Enable Electric System Monitoring Tools and Safety Mitigation

The Mod II simulator cockpit.

The Mod II aircraft cockpit.

NASA Armstrong researchers developed cockpit displays and controls designed to allow pilots to safely monitor and interface with the research electric system on the X-57 aircraft. A modified Tecnam aircraft, the X-57 Modification II (Mod II) configuration focused on the installation and integration of electrical power systems.

The cockpit interfaces were designed to allow pilots to monitor the energy state of the traction batteries, control and monitor the cruise motors, and maintain situational awareness of the research systems in the Mod II configuration. To retain pilot familiarity with the Tecnam aircraft, the design team used stock avionics systems where appropriate. A team of experts consisting of test pilots, subsystem experts, ground operations personnel, human system integration engineers and safety personnel provided valuable input that resulted in modifications to cockpit gauges, throttle levers, and power switches. The X-57 simulator was a critical tool for developing and verifying cockpit displays, as it provided a means to test displays in a simulated flight environment.

Significant consideration went into the design of the avionics power architecture. The key trait of this architecture was to place all systems required for landing on the essential bus, which allows a pilot to quickly shed power in an inflight emergency while still maintaining the capability to glide the aircraft to a safe landing. This approach provides key safety mitigation in the event of failures with the research traction power system.

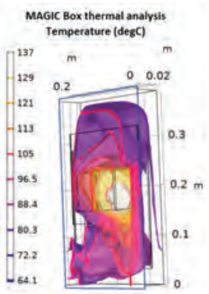
A method for monitoring remaining battery energy leveraged voltage readings from the battery system as the primary indicator, with battery model predictions used to correlate battery energy remaining and voltage states at predefined power settings. Other cockpit interfaces include modifications to the multi-function display, annunciator panel, and torque and prop pitch levers.

POC: James Reynolds | James.R.Reynolds@nasa.gov | 661-276-6017

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

NASA is developing a new hybrid-electric aircraft concept that uses 10 megawatt-class Electrified 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, dubbed SUSIE for Subscale Unmanned Systems Integration Effort. SUSIE has completed the first three phases of flight research to evaluate the impact of vertical tail sizing and differential thrust as well as to collect the data necessary to develop custom control laws. SUSIE is gearing up for the final phase of flight research to implement and test the custom control laws. Planning is ongoing for a 25%-scale vehicle being developed by NASA's Glenn Research Center.



Armstrong is providing support in the areas of mission concept and requirements development, establishing a ground control station with associated simulation for pilot practice and support during research flights and thermal analysis to support the thermal management system design for several components. Also, in support of the 25%-scale flight research vehicle, Armstrong conducted the Small Attritable Research Testbed (SMART) study to evaluate airworthiness and flight processes for small- and medium-sized unmanned aircraft systems (UAS).

In addition to its work with flight research vehicles, Armstrong is contributing to studies for the full-scale concept vehicle by defining requirements for the thermal management system, developing control laws, and creating a fixed-base simulation to enable engineers and pilots to evaluate the controls and flight dynamics.

Looking ahead: In addition to completing the research flights for the SUSIE vehicle, next steps include continued thermal analysis and development of controls for the 25%-scale and full-scale vehicle concepts.

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

Electrified Powertrain Flight Demo to Advance Next-Gen Aircraft

The Electrified Powertrain Flight Demonstration (EPFD) project conducts ground and flight tests of electrified aircraft propulsion (EAP) technologies to enable a new generation of electric-powered aircraft. NASA is collaborating with industry partners to demonstrate these technologies by using existing aircraft that will be modified and flown with EAP systems and components.

EPFD will also assist industry in addressing key technical barriers and risks associated with integrating EAP systems into airliners, as well as help identify and evaluate new standards for future EAP aircraft.

EAP technologies offer innovative solutions to making flight more sustainable – including lighter and more efficient motors, electronics, and materials that can help reduce emission levels and improve fuel efficiency.

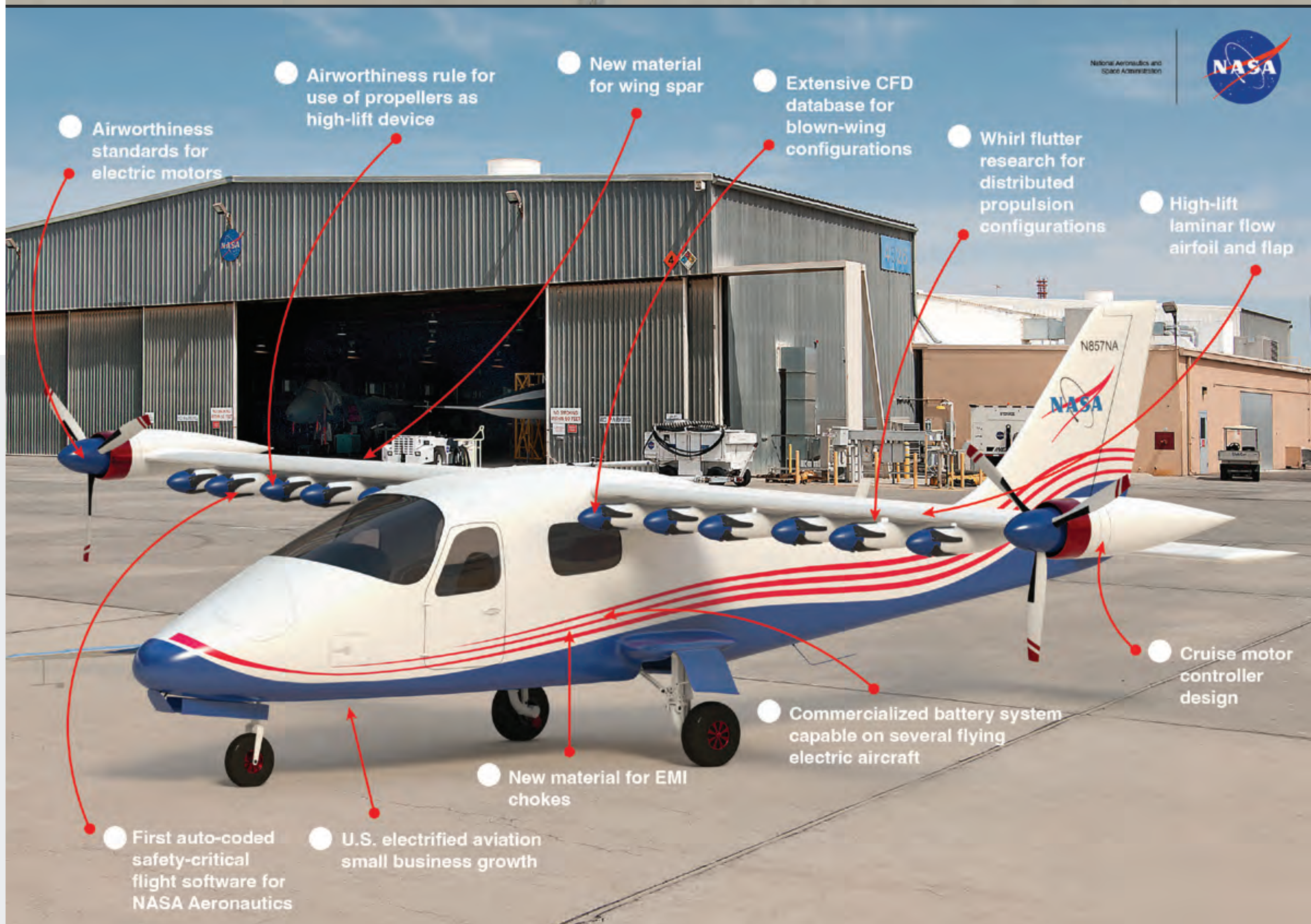
The EPFD project will test these technologies for future use in smaller, regional aircraft with less than 100 passengers, as well as single-aisle commercial airliners designed for around 180 passengers and operating longer-distance flights.

NASA Armstrong is responsible for airworthiness approval and oversight of two hybrid electric powertrain flight demonstrations slated to begin in 2025.

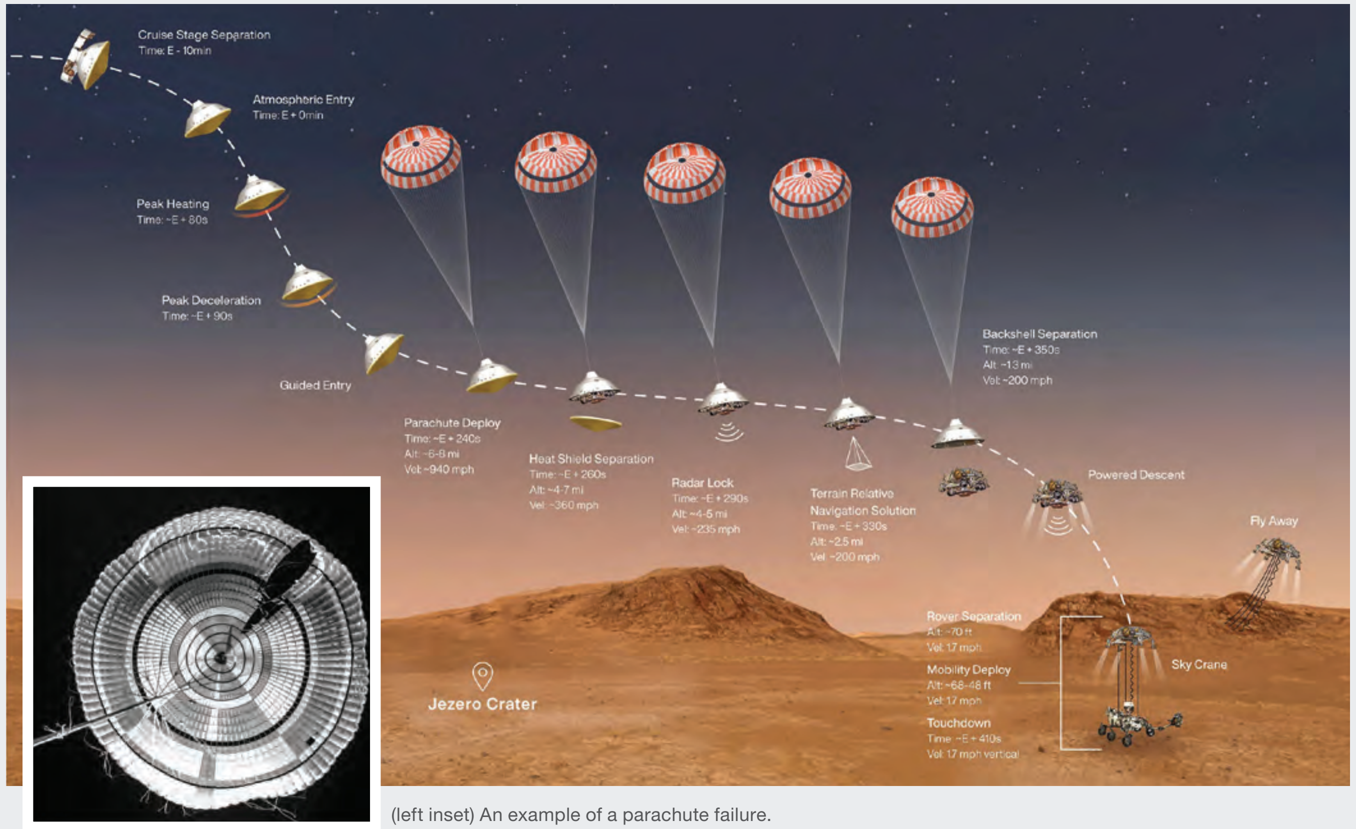
X-57 Aircraft Team

"The X-57 activity has been a huge success. This team has developed new aircraft propulsion technology, shared lessons on taking it from labs to aircraft, and contributed to the standards that will make electrified aircraft safe for the public. From a grassroots team that demonstrated full-scale distributed propulsion at takeoff speeds with a truck test on our lake bed to a full aircraft installation of high performance electric propulsion systems, this team has shared key insights within NASA and with the public research community."

Sean Clarke, PI for X-57 aircraft project

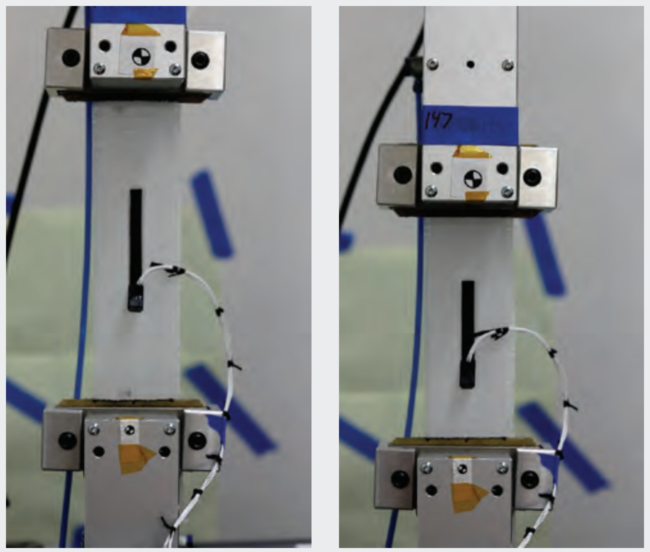


Enhancing Parachutes by Instrumenting the Canopy (EPIC)



(left inset) An example of a parachute failure.

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. Innovators from NASA Armstrong set out to determine how canopy instrumentation can collect that data in a research project funded by a FY2022 Early Career Initiative (ECI) award.



(left) A silicone-based capacitive sensor is attached to ripstop nylon (a common parachute material) in a uniaxial tension test at JPL. (right) The fabric just prior to breaking.

The EPIC project is investigating how to reduce mission risks through parachute canopy instrumentation. Led by principal investigator Erick Rossi De La Fuente and project manager L.J. Hantsche, the team is adhering highly elastic strain sensors to the surface of parachute canopy material to measure strain. Results could help future missions construct better, more reliable parachutes to land on Mars.

Primary goals of the project are to identify candidate sensors that can collect strain data on parachute canopy fabric, validate at least one sensor's ability to collect strain data, and quantify sensor effects on the parachute canopy fabric. The sensors measure location and intensity of stress on a parachute. A key challenge is making sure that the presence of the sensors does not affect the performance of the canopy. The goal is to avoid adding significant stiffness to the material or adding too much mass, as it would alter the parachute dynamics and structural performance.

> *"I'm so proud of this team and what they've been able to accomplish. They've gotten us closer than ever before to getting in-situ data that can help us finally build validated parachute models to better understand mission risk."*
>
> Michelle Munk, Systems Capability Leader: Entry, Descent, and Landing

Selecting Sensors and Adherence Techniques

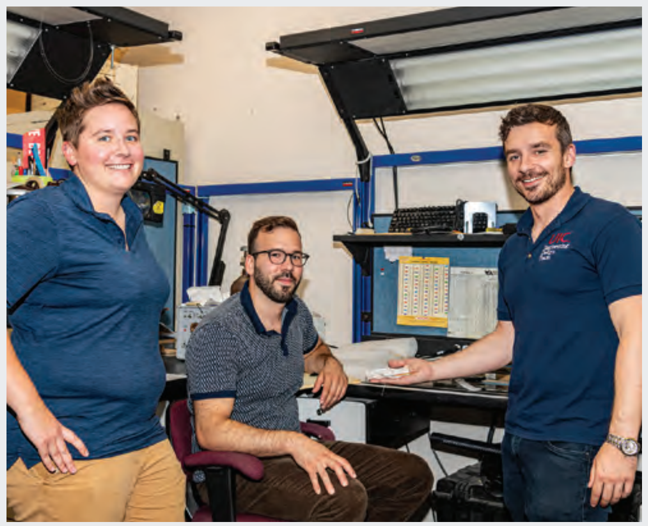
The EPIC team began the project in 2022 by performing a sweeping research effort to find candidate sensors that could potentially be adapted to the parachute application. After identifying more than 50 potential sensors, the team selected 10 of the most promising technologies to pursue. They then investigated adherence methods and ways to attach wires and extract data from them, eliminating sensors that were not robust enough to perform as needed.

An Armstrong data acquisition team developed a portable data acquisition system (PDAS) to interface with the sensors and gather data from them in a lab setting. The PDAS has become very useful for the team's testing efforts at NASA's Jet Propulsion Laboratory (JPL) and NASA's Glenn Research Center. The team set up partnerships and contracts with commercial entities to develop and provide braided sensors, embroidered sensors, and printed graphene-rubber sensors.

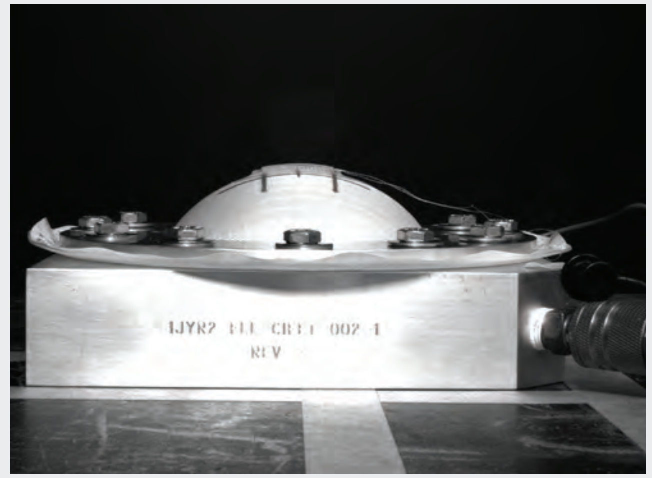
Quantifying Effects on Fabric Performance

The group conducted tests at JPL to quantify the effects of the sensors on fabric performance – known as stiffness testing. This involved comparing and then quantifying the load-strain curves of fabric samples with and without sensors. Their tests of the top three sensors found no significant negative impacts on fabric performance.

The team is working on procedures for uniaxial calibration tests, which will employ a digital image correlation (DIC) technique to measure shape and displacement and to calculate strain. DIC is a non-contact measurement technique that utilizes two digital cameras to triangulate the 3D position of a point on the surface of a test article. Researchers will make a correlation between the sensor output and the true strain state – a measurement that is the core of the research project.



EPIC team members: (left) L.J. Hantsche, project manager; (center) Erick Rossi De La Fuente, principal investigator; and (right) Dan Budolak, engineer.



A capacitive braided sensor undergoing a "bubble test" (a quasi-static 3D inflation test) at Armstrong that simulates the complex rounded shape of an inflating parachute.

At Armstrong, the team developed a test setup and procedure that inflates the fabric into a bubble shape, creating stresses on the fabric that are more similar to an inflated parachute than planar uniaxial tests. After a few more refinements, they'll perform a test series to quantify sensor performance in this 3D state.

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. Award recipients receive up to $2.5 million over two years to conduct their research.

Looking ahead: The team will continue its work with JPL to conduct uniaxial sensor calibration testing and with NASA Glenn to perform high-speed uniaxial testing. At Armstrong, they'll perform a bubble test series.

Partners: NASA's Jet Propulsion Laboratory and Glenn Research Center, NASA In-Space Manufacturing – On-Demand Manufacturing Electronics, the U.S. Army, Alliance Rubber Company/University of Sussex, and Advanced Functional Fabrics of America.

Benefits

- **Qualifying:** Provides a method for measuring strain on parachute canopy fabric
- **Enabling:** Improves parachute systems for planetary missions

PI: Erick Rossi De La Fuente | 661-276-2651 | Erick.R.Rossidelafuente@nasa.gov
PM: L. J. Hantsche | 661-276-2199 | L.J.Hantsche@nasa.gov

Supersonics Technologies

PROJECT SUMMARIES

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. NASA's goal for sonic boom research is to find ways to control and lessen shock wave noise so that federal regulators will allow supersonic flight over land.

The development of the X-59 experimental plane is advancing as part of NASA's Quesst mission. When the new X-plane arrives from Lockheed Martin Aeronautics Company's Skunk Works® facility, Armstrong researchers will qualify and flight test it. The X-59 will be used to help gauge how people respond to the lower intensity "thump" rather than the disruptive sonic boom. Armstrong will be a vital part of measuring its sonic thumps using a new recording system to extract, review, and analyze data.

Skunk Works is a registered trademark of Lockheed Martin Corporation

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 change through the shock waves, the probe measures the change in Mach number and flow angularity. Researchers are comparing these measurements to computational fluid dynamics models to verify those predictions. If successful, the probe will be used for the Quesst mission.

Work to date: In 2022 and 2023, the team installed new instrumentation in the probe that was optimized for the flight altitude of the X-59 aircraft (54,000 feet) and flew a series of flights with the probe installed on the nose of the F-15B tail number (TN) 836 aircraft. The team is building a separate probe for the F-15D TN 884 aircraft and, early in 2024, will complete a final demonstration at X-59 flight conditions where both 836 and 884 aircraft will alternate probing their shock waves. If successful, these flights will demonstrate that the shock-sensing probe is ready to support the X-59 aircraft.

Looking ahead: The probe 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

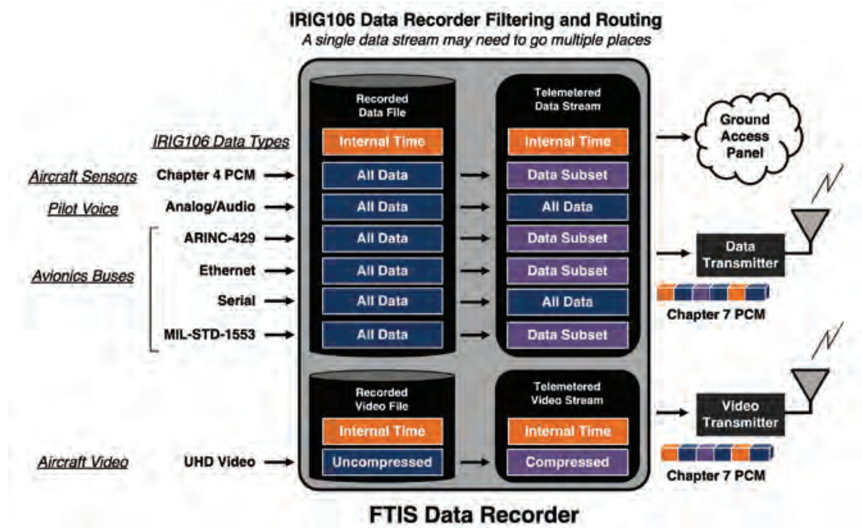
- Facilitating aircraft design that may ultimately enable overland supersonic flight

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

Instrumentation System Demonstrates Readiness to Support Supersonic Aircraft Test Flights

The Flight Test Instrumentation System (FTIS) for the Low Boom Flight Demonstrator (LBFD) 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 LBFD 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 on the X-59 airplane will 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.

Multiple On-Aircraft Accomplishments

The system hardware was delivered to Lockheed Martin in 2021 and integrated into the aircraft. Since then, the team has conducted system checkouts and calibration tests on the aircraft to prepare for flight tests. The FTIS has demonstrated significant accomplishments. Following completion of final lab testing and data verification requirements in February 2023, the FTIS recorded its first set of live data in March 2023. Since then, the system has **supported 88 days of system checkouts; acquired data, audio, and video from all 61 streams; and recorded and delivered 3 terabytes of aircraft data** to the NASA Dryden Aeronautical Test Range and Lockheed Martin Flight Test Data Center for data post-processing.

The team continues to stress test this pioneering new instrumentation system. In just one example, flight tests for the X-59 aircraft are estimated to take 2-4 hours – as much as 2 hours in flight and 1-2 hours on the ground.Next steps for the FTIS are to support F-15 aircraft flights in 2024 as they perform dual-ship missions to prepare for X-59 test flights.

Data Recorder Is the System Core

Conventional 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 the FTIS architecture, a more versatile and functional data recorder replaces the PCM encoder as the system core. 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, while reducing aircraft modification time, weight, and cost.

The NASA, Lockheed Martin, and Edwards Air Force Base partnerships have been essential to readying this technology for the LBFD project. The joint effort involved in developing and implementing the FTIS will enable Armstrong researchers to support new sensors and innovations for emerging technologies and systems in the years to come.

Partner: 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

The Schlieren, Airborne Measurements, and Range Operations for Quesst (SCHAMROQ) project is overseeing testing that will validate the acoustic signature of the X-59 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 2022 and 2023, the SCHAMROQ team integrated an upgraded life-support system on an F-15B to increase its service ceiling to 60,000 feet and permit the aircraft to be used on X-59 chase missions. The team successfully flew the shock-sensing probe calibration flights at the X-59 altitude.

Researchers continued to develop and refine schlieren techniques of capturing shock waves through imagery. The team tested and captured shock through a handheld photography technique that uses the sun edge as a backdrop for image processing. This successful test employed a NASA F-18 and an F-15, each flying supersonic with several miles of separation, in line with the sun.

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. An F-15D will be fitted with a modern instrumentation system and, along with the F-15B, will perform several checkout flights of the SCHAMROQ tools in dual-ship missions in preparation for flight testing to support the X-59.

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

Using Schlieren Techniques to Visualize Supersonic Shock Waves

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. So far, these techniques have used the ground terrain and the entire face of the sun in addition to the sun edge – while a supersonic aircraft eclipses it – to visualize the flow of in-flight supersonic aircraft. These advanced techniques capture vortical flow from wings and control surfaces, while revealing significantly more shock wave detail than previously possible.

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 aircraft. This pod will enable obtaining 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. This technique also enables images of multiple flight conditions, such as acceleration and aircraft configuration changes.

A related effort, AirBOS-Extended, is exploring the possibility of using additional backgrounds for BOS-type imaging, such as near the horizon, (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 schlieren 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, the 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 turbines, 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

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 anticipated to be acceptable to both the FAA and the public. The Armstrong team, along with industry, academic, and other NASA partners, has identified and validated several methods and techniques for capturing and measuring sonic booms and their impacts. Activities range from collecting sonic boom data above and below aircraft using airborne measurement systems to gathering ground data from sophisticated autonomous remote sensor arrays that are designed to be strategically placed within communities.

Work to date: The series of 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 X-59 aircraft, using various measurement techniques. CarpetDIEM is a series of campaigns focused on testing new measurement systems, advanced flight techniques, and remote field operations.

CarpetDIEM Phase I (2019) focused on the logistics and field operations required to perform sonic boom measurements across a very large area, as the X-59 aircraft is expected to produce sonic booms as vast as 50 nautical miles. During CarpetDIEM Phase II (2022) NASA tested its new, state-of-the-art ground recording system (GRS) and autonomous triggering concept called the Trigger Hardware and Observation Recorder (THOR). CarpetDIEM Phase III (2023) was a combination of applying results and lessons learned from the first two efforts, deploying GRS and THOR across a large, remote test location and recording sonic booms from surrogate F-15 aircraft used to perform flight missions anticipated by the X-59 aircraft.

The Armstrong team, with industry and academic partners, has identified and validated several methods and techniques for capturing and measuring sonic booms. One notable method is the Supersonic Aircraft Noise Transgression Array (SANTA), which employs four pressure transducers widely spaced on the vertices of an orthogonal array. The GRS 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. The GRS sensor array spans 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 GRS sonic boom measurement system must remotely manage up to 150 GRS devices. Therefore, NASA is developing multiple concepts of unattended GRS triggering systems. One such system is the patented THOR system. It uses data transmitted from a supersonic airplane to predict the arrival time of a sonic boom and then sets the GRS to record.

For the shock-sensing probe, the team uses 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 probe captures shocks that will create sonic booms on the ground. These measurements will help design 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 and also records 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 the atmospheric turbulence boundary layer near the surface of the Earth.

In addition to quantitative measurements, the Ground-to-Air Schlieren Photography System (GASPS) will provide qualitative shockwave imagery of the X-59 aircraft. GASPS is a ground-based, background-orientated schlieren system that can provide high-resolution images of an aircraft's near-field shock wave structure and the source of those shocks. Aircraft shock waves are responsible for the sonic booms that are produced on the ground.

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 III will focus on evaluating and testing GRS with the THOR unattended trigger systems to capture large areas of sonic booms. 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 50-mile sonic boom carpet on the ground, using the AAMP to measure the sonic boom above the ground, employing the shock-sensing probe to measure the shocks just below the aircraft, and leveraging schlieren photography techniques to image and measure airborne shock waves.

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

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

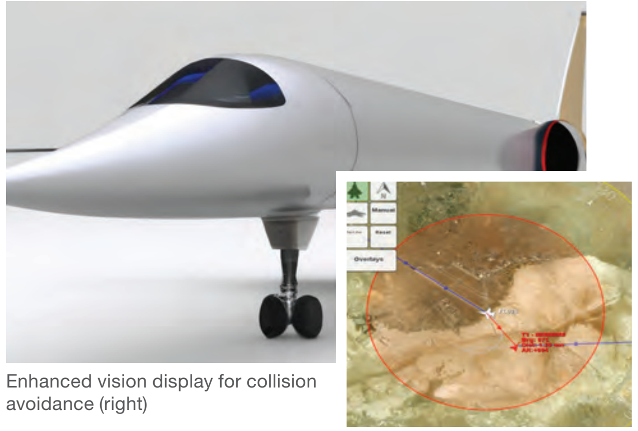
Applications

- 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

The Carpet Determination In Entirety Measurements (CarpetDIEM) Phase III flight campaign deployed and tested a state-of-the-art ground recording system and autonomous triggering technology.

Enhanced ADS-B System for Supersonic Aircraft



Enhanced vision display for collision avoidance (right)

NASA Armstrong researchers 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 that was adapted for supersonic vehicles with an enhanced vision display designed for ADS-B traffic information and alerts 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. Provisional and non-provisional patents have been filed, and there is interest in licensing the technology for commercial supersonic applications.

Looking ahead: The research team is working to demonstrate a similar system on hypersonic platforms and commercial space vehicles. Modifications are underway for an enhanced ADS-B system for research flights on NASA F-15 and F-18 aircraft.

Partner: Vigilant Aerospace Systems, Inc.

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 accurate conflict detection

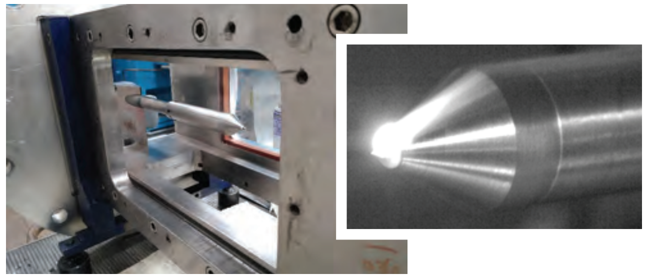
Applications

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

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

CarpetDIEM Phase III flight campaign

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: Armstrong researchers conducted tests in the wind tunnel at California State Polytechnic University, Pomona, where they exercised the power system and model at more extreme freestream conditions than would be experienced in flight. There was no damage to the system. With funding from the Commercial Supersonic Technology (CST) Project and the Center Innovation Fund (CIF), the team tested SPARC at the 6" supersonic wind tunnel at NASA's Glenn Research Center by repeating an experiment first conducted at New York University (NYU) to collect high-speed schlieren data, wall pressures, and voltage data to better understand and model the physics involved with this type of shock wave attenuation. The test article also was subjected to relevant freestream environments and generated consistent arcs.

The geometry of the test article, however, was not updated to match the geometry of the earlier NYU experiment, so there was not enough energy deposited into the flow and no significant changes in the shock wave were observed.

Looking ahead: Despite the setback, researchers gained valuable testing experience. Next steps are to update the geometry, repeat the test at the NASA Glenn supersonic wind tunnel, and advocate for funding to explore practical implementation of this technology.

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

Minimum Fuel Supersonic Test Trajectories

Illustration of the completed X-59

Researchers at NASA Armstrong are investigating ways to solve for and verify minimum fuel supersonic flight test trajectories. Motivated by the Low Boom Flight Demonstrator project, the goal is to maximize the number of sonic boom test points achievable per sortie. Supersonic flight tests at Armstrong offer an ideal test case as they are repetitive, feature well-defined conditions, involve a large flight envelope, and demonstrate clear opportunity for improvement with respect to fuel and test efficiency. This research could lead to reductions in fuel burn, costs, and emissions. Additionally, there is potential for a step-change in the number of supersonic test points per sortie – from three to four, a substantial improvement in test efficiency. More generally, this work could establish a framework for applying aircraft trajectory optimization to other NASA flight operations.

Work to date: Objectives are to complete a set of designs for the minimum fuel test trajectories for F-18 aircraft, flight test the optimal trajectories, and measure real-world fuel savings. With Center Innovation Fund (CIF) resources, researchers constructed a simplified model, optimized trajectories using readily available software tools, and evaluated results in the piloted simulation.

Looking ahead: This project made significant progress toward the practical application of trajectory optimization to supersonic flight tests. The next step is to proceed from trajectory design for a surrogate aircraft to design for the F-18 test vehicle. This technology has the potential to improve flight test efficiency for the F-18 and the X-59 aircraft.

Benefits

- **Innovative:** Improves flight test efficiency for multiple aircraft
- **Advanced:** Contributes to the body of knowledge for aircraft trajectory

Applications

- Fundamental research
- Aircraft trajectory optimization

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

Autonomous Systems

PROJECT SUMMARIES

NASA is 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.

Researchers at NASA's Armstrong Flight Research Center in Edwards, California are collaborating with numerous industry innovators to demonstrate system level safety and integration scenarios within a robust and relevant environment. These activities are critical to safe and scalable commercialization.

Enhancing Precision and Safety on High-Altitude Aircraft

NASA Armstrong is collaborating with the Federal Aviation Administration (FAA) on a project that focuses on integrating and certifying an advanced aviation navigation and surveillance system on the ER-2 high-altitude research aircraft. The core of this integration is the Automatic Dependent Surveillance-Broadcast (ADS-B) and GPS localizer performance with vertical guidance (LPV) technology. These critical technologies will enhance the precision and safety of aircraft surveillance and navigation.

Work to date: In July and August 2023, NASA conducted three successful flight tests in Palmdale, California, achieving altitudes of 65,000 feet, using NASA's ER-2 tail number (TN) 809 aircraft. Tests included GPS LPV approaches in various flight conditions, descending to a decision height of 200 feet above ground level. The primary objective was to certify the ADS-B Out and GPS LPV technology for high-altitude scientific operations, sustaining NASA's global mission of safety and operational efficiency in high-altitude flight regimes.

Looking ahead: Future work will involve integrating the GPS LPV technology onto NASA's ER-2 TN 806 aircraft with subsequent flight tests.

Partner: FAA

Benefits

- **Enhanced navigation accuracy:** Significantly improves the lateral and vertical guidance of aircraft, which is crucial for complex flight paths and operations in instrumental flight rules conditions, ensuring safer and more efficient navigation
- **Improved safety:** Provides real-time precision tracking of aircraft and is instrumental in collision avoidance, a critical factor for both civilian and military aviation
- **Expanded research capabilities:** Enables high-altitude aircraft to safely conduct scientific missions in diverse and challenging environments

Applications

- High-altitude aircraft operations
- Advanced pilot training
- Precision and autonomous navigation

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

Advanced Air Mobility (AAM) National Campaign

(left) Advanced Air Mobility illustration with its many vehicle concepts and potential uses. (above) Vertiport design for AAM vehicle take-off and landing.

As part of its work with the aviation community to identify and address the challenges ahead for Advanced Air Mobility (AAM) concepts, NASA initiated the National Campaign (NC) to plan a series of events that will provide industry with the opportunity to demonstrate system-level safety and integration scenarios within a robust and relevant environment. The NC series supports operational demonstrations with industry as well as R&D needed to support NASA-led research flight demonstrations.

The NC series' key goal is to support AAM requirements and system development through integrated vehicle and airspace demonstrations in operational scenarios that are critical to safe and scalable AAM commercialization. The NC series is designed to bring together flight partners, airspace service providers, and infrastructure providers to help understand the current AAM system maturity levels with respect to vehicle performance, safety assurance, and airspace interoperability and also to develop and demonstrate integrated solutions for civil use. The goal is to promote public confidence and accelerate the realization of emerging aviation markets for passenger and cargo transportation in urban, suburban, rural, and regional environments.

Work to date: The first phase of the NC series was completed in 2021 and included development tests to refine requirements and assess industry readiness. The current phase – referred to as NC-1 and the Integration of Automated Systems (IAS-1) series – focuses on operational safety with an integrated set of scenarios to assess vehicle and airspace interoperability; trajectory planning and compliance; contingencies associated with communication and navigation; and contingencies enroute and during terminal base operations, novel approach, and departure flight procedures, as well as strategic and tactical conflict avoidance.

In 2022 and 2023, industry partners – Joby Aviation, Wisk Aero, North Texas Cohort research team, Reliable Robotics, and Aura Aerospace – flew their innovative simulators and vehicles and developed airspace system and infrastructure-related capabilities. Flight Line Engineering built and delivered a mobile vertipad. Further, NASA contracted with Sikorsky Aircraft for use of its autonomy research aircraft (SARA), a highly modified S-76B helicopter to serve as a representative electric vertical takeoff and landing (eVTOL) platform to test novel NASA automation technologies involving hazard perception/avoidance and flight path management.

To minimize risk, a buildup approach was used during the IAS-1 flight testing. IAS-1 Spiral 1 flight tests were completed in August and November of 2022. Objectives were to verify the integration of IAS-developed middleware with the research aircraft, verify the proper interface of the middleware with research algorithms, and verify vehicle conformance to commanded flight path. IAS-1 Spiral 2 flights included the addition of the Sikorksly H-60 optionally piloted vehicle helicopter and focused on data collection. IAS-1 Spiral 2A and Spiral 2B were completed in February and June 2023. The third and final flight test, Spiral 2C, occurred in fall 2023 and incorporated improved ground collision avoidance system (iGCAS) and autoland capabilities.

Looking ahead: NASA is partnering with AFWERX Agility Prime, AFTC®, the Federal Aviation Administration (FAA), and Joby Aviation to evaluate the Joby S4 eVTOL vehicle in a simulated UAM environment. This partnership will increase knowledge of eVTOL vehicle performance and handling characteristics in a representative operational environment and mature reference flight rules and terminal area procedures to inform FAA rulemaking.

Researchers also will explore the interrelated nature of vehicle design requirements, flight rules and procedures, and gain experience with ground-operating needs of eVTOL vehicles. The goal of this three-year campaign is to conduct feasibility assessment of operations and validations of capabilities through NASA-led and industry/FAA-partnered demonstrations with a series of simulation and flight test activities leading up to a flight demonstration series in 2026.

Partners: NASA's Ames Research Center and Langley Research Center, FAA, 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 emergency response missions for the public good. This system could include aircraft-like package delivery drones, air taxis, and medical transport vehicles.

POC: Cheng Moua | 661-341-8488 | Cheng.M.Moua@nasa.gov

Technologies to Enable Urban Air Mobility (UAM)

NASA is leading a national effort to develop and validate tools, technologies, and concepts to overcome key barriers for vertical lift vehicles, focused on UAM noise, safety, environment, and efficiency. This work is part of NASA's Revolutionary Vertical Lift (RVLT) Project. The UAM effort envisions a safe and efficient air transportation system where small (four- to six-passenger) 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 for researchers at NASA Armstrong is to improve the safety and comfort of this new class of air vehicles by evaluating innovative tools and collecting nonpareil data to help inform the evolving standards, guidelines, and best practices for the industry.

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 vertical motion simulator at NASA's Ames Research Center.

Passenger Ride Quality

Public acceptance of UAM requires eVTOL aircraft to be safe, reliable, affordable, and comfortable. The UAM experience will be unlike anything the general public is familiar with, such as traveling in automobiles, trains, or airliners. UAM aircraft will be highly maneuverable with large windows and may fly close to the ground and near buildings, so passengers may experience vertigo, motion sickness, or discomfort due to turbulence, flight control response, noise, or vibration. Armstrong researchers are developing experimental studies 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 laboratory using human test subject volunteers. Results will provide ride quality guidance and metrics to aircraft manufacturers, vertiport designers, and operators to ensure that the UAM transportation experience is a positive one.

Looking ahead: The NASA UAM ride-quality laboratory is undergoing final checkouts. It is expected to come online for passenger studies in early 2024.

Benefits

This research is pioneering new concepts and expanding our understanding of how pilots and passengers will interact with the burgeoning eVTOL UAM transportation system. New tools, methods, and guidelines will benefit the UAM community and help ensure passenger safety and acceptance.

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.

Handling Qualities PI: Peter Suh | 661-276-3402 | Peter.M.Suh@nasa.gov
Ride Quality PI: Curtis Hanson | 661-276-3966 | Curtis.E.Hanson@nasa.gov

Advanced Exploration of Reliable Operation at Low Altitudes: Meteorology, Simulation, and Technology (AEROcAST)

(left) Researchers work on securing sensors onto the test fixture on the Alta-X aircraft. (right) The Alta-X aircraft flies at NASA's Armstrong Flight Research Center in Edwards, California, as part of the AEROcAST campaign.

NASA Armstrong researchers are studying micro-scale wind patterns to test the feasibility of cost-effective technologies for characterizing the complex urban wind environment and identifying areas potentially hazardous to low-altitude urban flight. This work is part of NASA's Convergent Aeronautics Solutions (CAS) project, which invests in seemingly improbable ideas that could lead to solutions to problems that plague aviation as well as impact safety, the community and environment, and the global growth in air traffic. AEROcAST is an effort that combines earlier CAS micro-weather moderation and ubiquitous weather-sensing activities.

The project focuses on micro-weather challenges hindering urban air mobility (UAM), particularly winds. Current study scenarios involving cities often overlook wind impact on UAM vehicles, which this project aims to remedy through technology prototypes. The project confronts gaps in weather data, the need for validated urban wind flow simulations, and the unknown impacts on electric vertical take-off and landing (eVTOL) aircraft. Field experiments at Armstrong use the former shuttle hangar and surrounding buildings as a proving ground for testing simulations and prototypes.

Work to date: Researchers conducted an outdoor field experiment at Armstrong in summer 2023, and collected atmospheric measurements with numerous instrument platforms, including small unmanned aircraft systems, a dual-Doppler lidar system, various weather stations, and infrared temperature measurements of ground and building surfaces. They are also collecting vehicle navigation and acceleration data from small remotely piloted rotorcraft used for estimating wind and turbulence conditions. These estimates will be compared with the data collected by the rotorcraft payload and ground-based instruments to see how effective the aircraft can be as wind sensors.

Additionally, the Armstrong campaign is amassing a data set of atmospheric conditions and ground and building surface measurements. The research team is developing a digital model of the northern part of the Armstrong campus with geodetic survey measurements, including the shuttle hangar and surrounding buildings. Thermal data are also being collected from these buildings and on the ground between buildings. Researchers will use measurements from the atmosphere and buildings to validate computational fluid dynamics and machine learning models of wind flows around the shuttle hangar and the adjacent helipad on its downwind side.

Looking ahead: Researchers are analyzing data and will present results in 2024.

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

Benefits

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

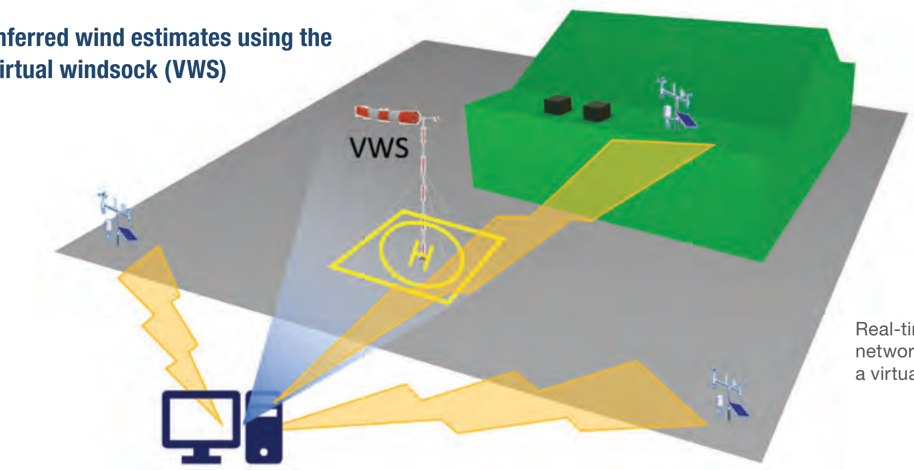
Applications

- Advanced air mobility operations
- Weather nowcasting
- Urban air traffic management

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

Machine Learning Enables Virtual Windsock

Inferred wind estimates using the virtual windsock (VWS)



Real-time machine-learning estimations using several networked surrounding weather measurements create a virtual windsock within the TLOF.

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 Armstrong and NASA's Ames Research Center are conducting a study to estimate wind speed and direction in the touchdown/liftoff areas of mock helipads located at ground level near buildings. Wind estimates are based on measurements of nearby surface weather conditions and atmospheric boundary layer wind profiles.

Work to date: Researchers conducted weather data collection campaigns at Armstrong at the site of the former X-33 operations center and near the former shuttle hangar and from the rooftop weather station at NASA's Langley Research Center. The team collected measurements in free-stream and building-modified wind flows, and these data sets are being used to train the model. Researchers also are using a prototype algorithm to estimate surface wind conditions at a mock helipad at Armstrong.

Looking ahead: Future work integrates the GPS LPV technology onto NASA's ER-2 TN 806 aircraft with subsequent flight tests.

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

Benefits

- **Advanced air mobility:** Has the potential to provide weather information at helipads/vertiports with fewer resources, in locations where taking measurements is impractical, and when sensors are inoperative
- **Increased safety and efficiency:** 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

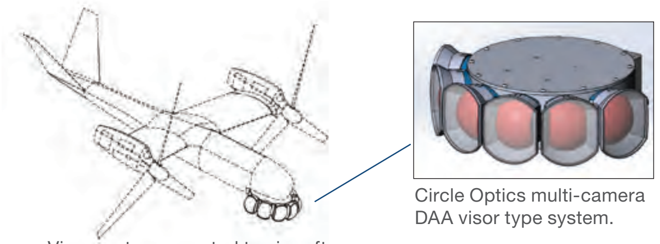
Applications

- Advanced air mobility operations
- Numerical weather prediction techniques

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

Federal Aviation Administration researchers analyze flight altitude data.
Credits: Joby Aviation

Enhanced Detect and Avoid Optical Sensing for Urban Air Mobility (UAM)



Circle Optics multi-camera DAA visor type system.

Visor system mounted to aircraft nose.

As UAM operations increase, so does the need for robust detect-and-avoid (DAA) systems, particularly for drones and aircraft that do not broadcast their positions or intentions. NASA researchers are investigating a unique method to detect and avoid noncooperative targets using an electro-optical (EO) panoramic sensor suite for detection ranges of 3.8 nautical miles, complemented by a wide field of view.

Work to date: Researchers at NASA Armstrong are collaborating with Circle Optics, Inc. to test its multi-camera optical systems technology. Cameras are optically and opto-mechanically designed to control parallax, and in aggregate, capture real-time, stitching-free, panoramic image content of an environment. The technology provides real-time situational awareness for autonomous and human-in-the-loop piloted systems. Through the Small Business Innovation Research (SBIR) program, Circle Optics is developing a prototype system for eventual flight testing, including custom optics and opto-mechanics, system mechanics, and an integrated electronics and software data path.

The system has seven polygonal cameras with 25 megapixel image sensors arranged in an arc to provide simultaneous imaging over a composite panoramic field of view that is ±115 degrees horizontal by ±15 degrees vertical, with an estimated detection range of approximately 3.8 nautical miles.

Looking ahead: The collaborative research team is working to demonstrate a similar system for large UAM platforms.

Partner: Circle Optics, Inc.

Benefits

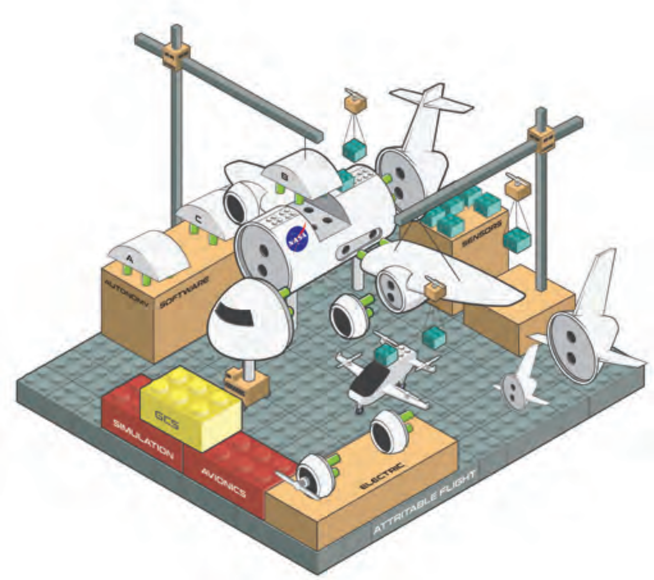
- **Intelligent systems:** Enhances situational awareness in a wide field of view for in-flight hazards perception
- **Multi-camera, low-parallax image capture:** Real-time image capture without image stitching processing burden

Applications

- Airborne and ground-based hazards perception
- Unmanned aircraft system (UAS)-based surveillance and infrastructure inspection
- Firefighting and disaster relief
- Computer vision for autonomous UAS-based mishap investigations

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

Subscale Research Vehicles to Advance Flight Research



Innovators at NASA Armstrong are investigating how to develop and deploy subscale aircraft to accomplish rapid flight research. These new flight research vehicles are unmanned aerial vehicles (UAV) that are designed to be affordable, reusable, and easy to manufacture. A goal is to develop and implement subscale research vehicle architecture that enables cost effective, modular hardware and software leading to fast flight test programs that collect high-quality research data.

Potential research activities could include:

- Carrying payloads to collect data and reduce risk
- Testing guidance, navigation, and control (GN&C) algorithms and other autonomy approaches like deep learning
- Performing custom research by leveraging modular capabilities to tailor platforms for different projects

Wildfire Surveillance Is Potential Research Area

Wildfire surveillance is a use case that is currently being investigated and particularly suited to this approach as UAVs can provide observations that enable predictions of the wildfire path. The concept involves incorporating autonomy features, such as detect-and-avoidance capabilities and autonomous operations. Adding autonomy also extends their use to more situations, such as night-time missions.

NASA's Convergent Aeronautics Solutions (CAS) project has sponsored research activities to advance this aircraft concept and is considering sponsoring a workshop with other government agencies and industry to gain insights from a varied audience.

PI: Jinu Idicula | Jinu.T.Idicula@nasa.gov | 661-276-2892

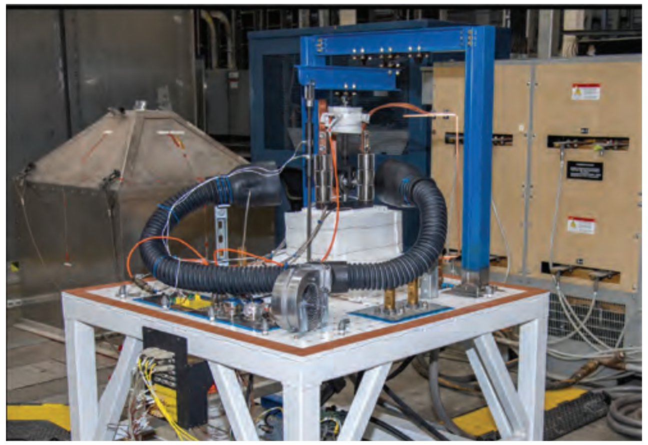
Flight Loads Laboratory

PROJECT SUMMARIES

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 six 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-59 and X-66 experimental aircraft and dozens of major accomplishments in between, the highly skilled staff is positioned for the future.

> "
> *We have entered a new Golden Age of hypersonics research. Uncrewed hypersonic vehicle development has significantly increased, and the FLL team is deeply involved in hypersonic ground testing.*
>
> Darren Cole, FLL project manager

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 has been completed. 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: Chris Kostyk | 661-276-5443 | Chris.B.Kostyk@nasa.gov

F/A-18E Super Hornet Loads Calibration Testing

The Flight Loads Laboratory (FLL) at NASA Armstrong completed one of its largest loads calibration efforts in the last 50 years. The FLL partnered with the Naval Air Systems Command (NAVAIR) Air Test and Evaluation Squadron Two Three (VX-23) at Patuxent River, MD to perform a loads calibration test of their F/A-18E Super Hornet. This testing was instrumental before the aircraft could serve as a test vehicle for determining whether fleet aircraft can safely manage maneuvers with proposed upgrades.

Testing was divided into three phases: horizontal tail spindle testing, wing testing, and vertical tail testing. FLL personnel worked with NAVAIR personnel to design the load cases and plan the test program. The test program included 87 load cases that were designed to measure the necessary structural responses of strain sensors that had been previously installed on the aircraft. The strain sensor responses were used to derive load equations that will enable NAVAIR personnel to monitor aircraft loads experienced during flight testing and make sure that the aircraft does not exceed its flight loads envelope.

The load cases covered approximately 60% of the flight loads envelope for the aircraft. To support the application of loads to the aircraft, FLL personnel bonded 180 load pads to the wings and vertical tails. The distribution and size of the load pads were designed to keep the local pressure loads below aircraft limits while ensuring the application of the total load required for each load case. FLL personnel also installed load introduction and reaction load hardware in addition to hundreds of other items, including load distribution hardware, load cells, actuators, and more than a mile of hydraulic hoses.

The FLL team also utilized an 80-channel load control system with associated hydraulic carts and data acquisition and data monitoring systems. During test operations, test personnel monitored approximately 500 sensors, which included strain, load, and displacement sensors.

NAVAIR personnel were onsite in summer 2023, preparing the aircraft for its return flight to Patuxent River, MD. The aircraft left Armstrong in the fall 2023.

Partners: Naval Air Systems Command Air Test and Evaluation Squadron Two Three at 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

Wing Store Structural Dynamics Airworthiness Clearance

In 2020, NASA Armstrong researchers provided airworthiness clearance for the Airborne Schlieren Pod on the F-15B/D Eagle aircraft. In 2023, the team leveraged this expertise to provide airworthiness clearance for the F/A-18B/D Hornet on both inboard wing stations (STA 3 or STA 7), with/without the external fuel tank installed on the centerline station (STA 5) and without any stores mounted on either wingtip station (STA 1 or STA 9).

Armstrong's structural dynamics engineers cleared the Airborne Schlieren Pod for flight on the F/A-18B/D aircraft via its similarity to an older variant of the pod out to a subsonic envelope of 400KCAS/0.85M. The older pod variant is similar in mass properties (weight, center of gravity, and inertias) to the current variant and has flown subsonic on the F/A-18B/D with no vibration or fatigue issues. The clearance effort included a ground vibration test (GVT) for both pod variants. Modal testing verified that the modal frequencies of the pod's roll, yaw, and pitch modes between the two pod variants were nearly identical.

Work to date: F/A-18 wing store clearance flights were flown on F/A-18B tail number 867 in March 2023, with a build-up approach in Mach and dynamic pressure. No issues were found during system checkouts, and the pod structural integrity post-flight inspections yielded no concerns. Aircraft pilots found no handling quality issues and indicated that the current Airborne Schlieren Pod was similar to the older pod variant at similar flight conditions. The F/A-18 Airborne Schlieren Pod is now supporting other reimbursable project missions.

Looking ahead: The Airborne Schlieren Pod can now fly subsonic on Armstrong's F/A-18B/D and will house NASA schlieren equipment for future flights on the F-15B/D aircraft to support the X-59 Quesst mission flights. More traditional aeroelastic investigations, such as finite element model development and flutter analysis, are needed to safely clear the wing store further into the supersonic F/A-18 flight envelope.

Benefits

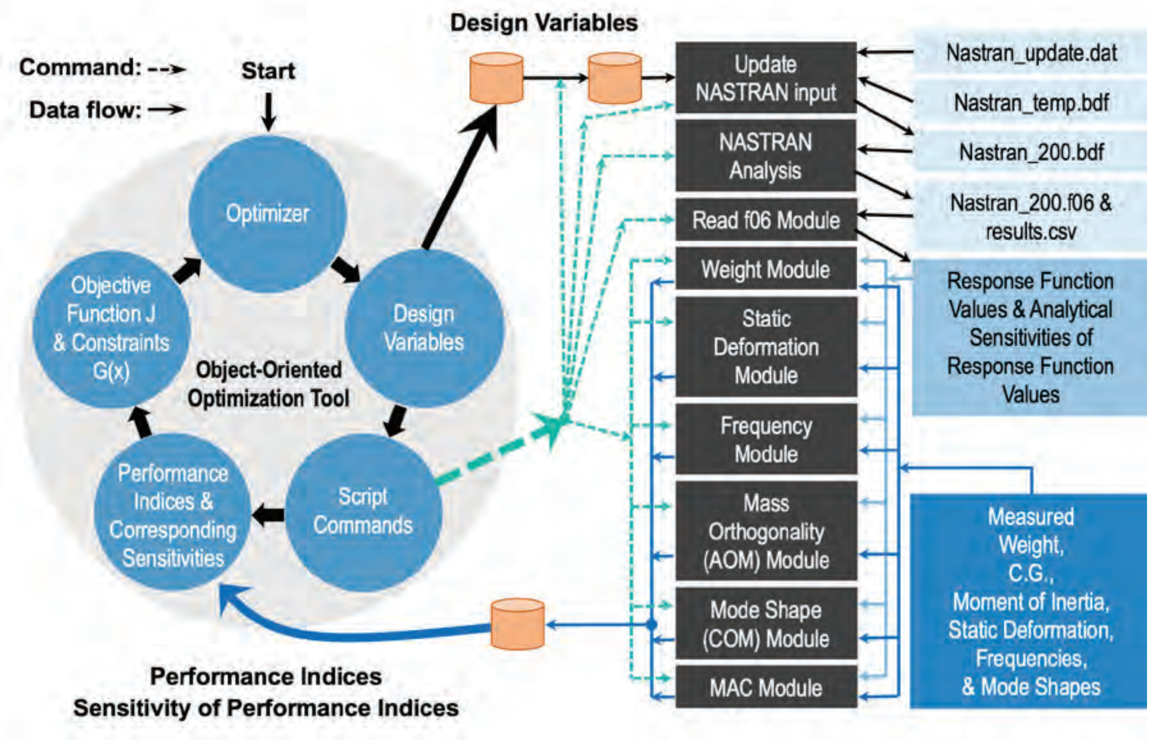
- **Enabling:** Permits F-15 wing store to house research equipment

Applications

- Ground vibration testing
- Flight aeroelastic airworthiness clearance

PIs: Samson Truong | 661-276-2998 | Samson.S.Truong@nasa.gov
Natalie Spivey | 661-276-2790 | Natalie.D.Spivey@nasa.gov
Shun-fat Lung | 661-276-2969 | Shun-Fat.Lung-1@nasa.gov
Benjamin Park | 661-276-5406 | Benjamin.C.Park@nasa.gov

Structural Digital Twin Generation Tool



Block diagram of analytical sensitivity-based structural model tuning tool

Digital engineering leverages advanced computer-aided design software, simulation tools, data analytics, and other technologies to model and visualize engineering projects. It enables engineers to create digital representations of physical systems, conduct virtual experiments, and evaluate performance. This approach helps reduce costs, optimize designs, improve efficiency, and minimize risks associated with traditional trial-and-error approaches.

A key element of digital engineering is the generation of a digital twin, which is a virtual representation of a physical structure. It allows engineers to monitor, analyze, and simulate the performance of the real-world counterpart, enabling predictive maintenance, optimization, and better decision-making. A digital twin generation of an aircraft structure is critical for accurate prediction of aeroelastic and aeroservoelastic behavior during flight. Yet a trial-and-error approach for the generation of a digital twin in finite element (FE) modeling remains widespread due to the limited time between ground vibration testing (GVT) and early flight tests. NASA Armstrong researchers have developed a digital twin generation 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 and 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: Researchers validated the tool using a cantilevered aerostructure test wing. 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 the X-57 Mod II aircraft, with respect to ground vibration test data.

Benefits

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

Applications

- Structural digital twin generation for research aircraft
- Launch vehicles

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

Geometrically Nonlinear Structural Deformation Computation

Artists concept of the Transonic Truss-Braced Wing Airplane with geometrically nonlinear wing deformation. Credits: Boeing

NASA Armstrong researchers have developed a basis function method for predicting geometrically large 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., trim shape control, active sonic boom control, gust/maneuver load alleviation, buckling suppression, 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 experimental 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 reduce the sonic boom strength on the ground. This will 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 X-66 transonic truss-braced wing aircraft and to the scaled commercial transport 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
- Active buckling suppression
- Flutter and divergence suppression

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

Improving Aerospace Vehicle Efficiency

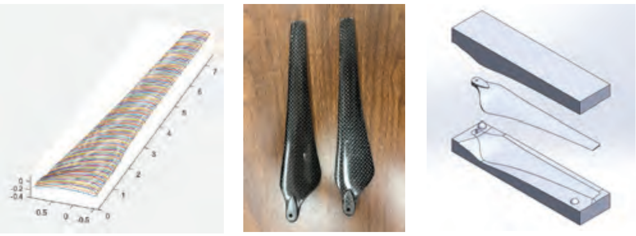
PROJECT SUMMARIES

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 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.

Novel Propeller/Fan Reduces Noise and Improves Efficiency



NASA Armstrong researchers are developing design processes for propeller blades 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 propeller loading. Researchers are investigating techniques to reduce the strength of the tip vortex while improving thrust. Analysis and designs are showing encouraging results; if successful, benefits could be realized for a wide range of propeller and fan designs.

Work to date: Work has focused on verifying and automating manufacturing and testing processes. Several stock configurations were manufactured using molds to make carbon fiber test articles and using 3D printing to make test articles from several materials. Researchers at California State University, San Bernardino (CSUSB) provided initial testing results of stock test articles and worked to reduce error in the test measurement system. Researchers also identified optimization parameters to apply to design iterations that trace back to the Prandtl theory.

Looking ahead: Researchers will continue to generate models, compare results to physical testing, and refine a workflow to assess future propeller configurations. With funding, CSUSB researchers will test stock test articles and progress to testing Prandtl designs and propellers.

Partner: California State University, San Bernardino

Benefits

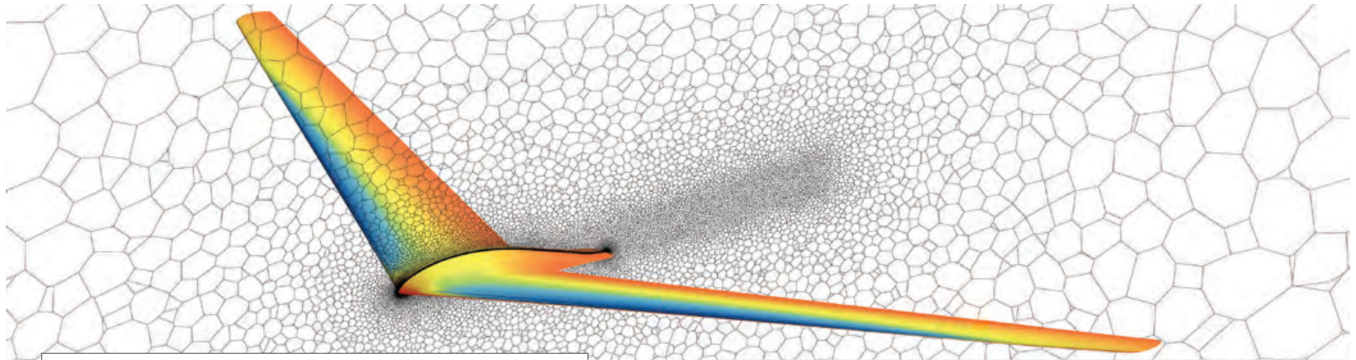
- **Efficient:** Redistributes lift and drag along the propeller or fan blade, reducing power consumption while producing the designed thrust
- **Economical:** Allows blades to use less power, reducing fuel costs
- **Quieter:** Produces less noise than conventional blade designs
- **Compatible:** Provides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

Applications

- Propellers
- Industrial fans

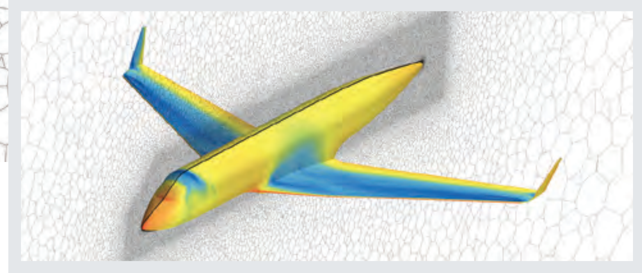
PI: Jason Lechniak | 661-276-2620 | Jason.A.Lechniak@nasa.gov

CFD Analysis of Swept Wings with Bell-Shaped Lift Distribution



L/D	AoA 0°	AoA 2°	AoA 4°
Gulfstream	16.4	22.5	19.8
Bell design	10.7	20.7	21.2

A 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 and its surface pressure distribution (blue: low pressures to red: high pressures)



A CFD solution of the GIII wing-fuselage showing visualization of the wing and fuselage together with the pressure distribution (blue: low pressures to red: high pressures)

Researchers at NASA Armstrong conducted a computational fluid dynamics (CFD) analysis to provide detailed flow physics for both low-speed and high-speed swept wings with a bell-shaped lift distribution. The low-speed wing is based on the subscale Preliminary Research Aerodynamic Design to Lower Drag (Prandtl-D) Phase 3c glider with a wingspan of 24.6 feet, previously flight tested at Armstrong. The high-speed wing is based on the Gulfstream III (GIII) business jet wing.

Although flight data were collected for the glider, 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 increase understanding of wing aerodynamics. Since the glider flew at very low speeds, researchers sought to explore the high-speed aerodynamics of a bell wing by analyzing a hypothetical bell wing for the GIII. CFD results were obtained and compared for both the bell wing and the GIII baseline wing.

Work to date: Researchers developed a preliminary glider CFD model with articulating elevons based on the flight test vehicle. Grid convergence studies showed good 2nd-order CFD solution grid convergence characteristics. They achieved very good agreement between the glider's flight data and the CFD results for the glider wing's pressure coefficient distributions at different wingspan stations. The CFD analysis results determined that the bell lift distribution is sensitive to the glider's angle of attack (AoA) changes. Wing vortices shed inboard of the wing, as previously suggested for Prandtl bell-loaded wings, were not found among the CFD solutions. The CFD solutions did show that the glider's wing tip vortices disappear for its designed AoA as previously postulated for the bell-loaded wing, which was designed to have wing lift tapered to zero at the wing tip. At other AoA values, wing tip vortices are present at values similar to other wing designs.

The subscale Prandtl-D Phase 3c wing glider performed well during flight tests in coordinated flights without the conventional airplane's tail and rudder. Only limited flight data were collected, and these CFD simulation results allowed researchers to examine the flow physics of the bell wing in more detail. The first attempt at a bell wing design for a high-speed business jet did not yield a superior wing as compared to the traditional baseline wing.

The Armstrong preliminary bell-loaded wing design did not perform as well as the original baseline GIII wing for Mach 0.75 high-speed flight. The bell wing design has lower lift over drag (L/D) ratios than the baseline GIII wing for most of the AoAs considered, and the bell wing's L/D ratio was found to be highly sensitive to AoA. For example, the bell wing's L/D decreases by 50% from 20.7 to 10.7 when the AoA is decreased from 2 degrees to 0 degrees. The current GIII bell wing was obtained from simply modifying the wing twist of the legacy GIII wing to obtain the bell-shaped lift distribution. Better aerodynamic performance could potentially be achieved with a more optimized bell wing design.

Benefits

The knowledge gained from this research effort could support various wing designs for future crewed and remotely piloted high-efficiency low-speed aircraft.

Applications

- Long-endurance unmanned aerial vehicles
- Prandtl Mars gliders

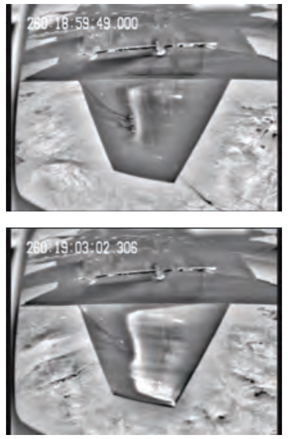
PIs: Seung (Paul) Yoo | 661-276-5247 | Seung.Y.Yoo@nasa.gov
Trong Bui | 661-276-2645 | Trong.Bui-1@nasa.gov

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.

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.

The coating was applied to the completed CATNLF test article in Fall 2022.

Centerline Instrumented Pylon (CLIP) Flow Rake

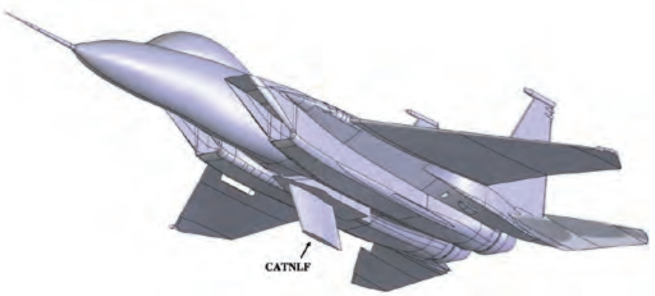
The CLIP flow rake effort is a vertically oriented instrumentation rake with air data and disturbance probes that will map the flow field under the F-15B testbed to support the follow-on test with the CATNLF laminar flow test article. Flow field mapping will be instrumental for understanding the data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

The CLIP flow rake assembly and associated plumbing were completed in 2023 and are awaiting integration on the F-15B aircraft, after which sensor checks will be performed. Flow rake test flights are anticipated in 2024.

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.

A contract was awarded to Calspan Corporation for the detailed mechanical design and fabrication of the CATNLF and ground cart. Calspan delivered the test article to NASA Langley in fall 2022, where technicians installed high sample rate pressure sensors and applied the conductive coating tested during the ReHEAT effort. The test article arrived at Armstrong in summer 2023 and is undergoing instrumentation. Test flights are anticipated for 2024.



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

Partner: NASA's Langley Research Center

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

CATNLF Lead: Mike Frederick | 661-276-2274 | Mike.Frederick-1@nasa.gov
CLIP Flow Rake PI: Aliyah Ali | 661-276-5533 | Aliyah.N.Ali@nasa.gov
CATNLF PI: Michelle Banchy | 757-864-9097 | Michelle.N.Banchy@nasa.gov (NASA Langley)

Prandtl Flying Wing

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 11% less induced 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 – 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, this research 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. Test flights incorporated pressure sensors embedded in the wing, and 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 to gather data.

Looking ahead: Researchers are exploring ways this innovation can benefit NASA projects. Potential applications include small to medium drones and transonic business jet wing replacements. Work continues to enhance the fidelity of design tools and to increase the automation of multidisciplinary design optimization. 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 (11% induced drag), when used in propeller systems and when integrated with novel aircraft configurations.
- **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

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 are collaborating to create preliminary concepts, systems development, and prototypes for small unmanned aircraft 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 were developed with wingspans of 13 inches, 18 inches, and 24 inches during the first phase of a 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 and a gondola was designed, developed, and operated from a tethered blimp. The 24-inch model was then test flown from the tethered blimp as researchers conducted 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 with the 13-inch model were conducted from a UAV mothership.

The project team has 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 24-inch system demonstrator size. This work was based on the quantitative and qualitative flight performance of previous vehicles in this design family.

Looking ahead: The next goals of the project are to evaluate the new designs using high-fidelity computational fluid dynamics followed by high-altitude balloon drop testing. These activities will demonstrate Earth-based weather monitoring capabilities and also serve as a representative flight test for the Martian atmosphere.

Collaborator: NASA's Jet Propulsion Laboratory

Benefits

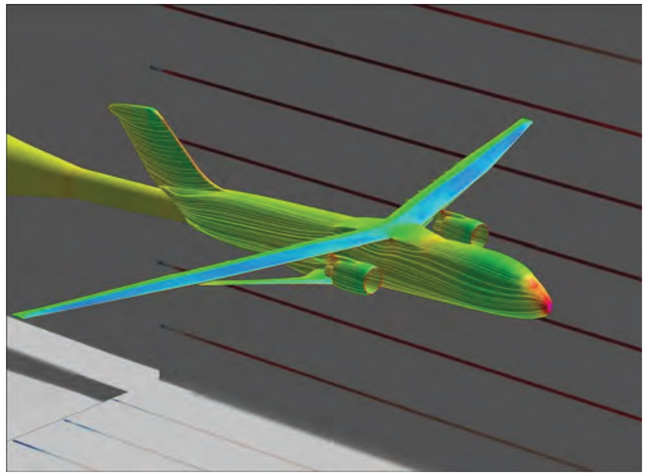
- **Breakthrough:** Characterizes small glider distribution performance in free and directed flight
- **Efficient:** Provides a low-cost, low-mass sensor distribution architecture for novel atmospheric observations
- **Innovative:** Enables Armstrong researchers to analyze, develop, and test in a new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

Integrated Flight Dynamics and Aeroservoelastic Modeling



This research effort is developing 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 modern aircraft are becoming more coupled, resulting models must capture the requirements of both disciplines.

Work to date: The modeling approach was developed during and successfully applied to the X-56A flutter suppression flights and the X-56B flights. The unsteady aerodynamic and structural data have been integrated with a non-linear piloted simulation to enable the safe operation of the aircraft through evaluation of the dynamics and development of pilot techniques in highly non-linear conditions, such as takeoff and landing. Researchers at NASA Armstrong have used the Transonic Truss-Braced Wing to study the requirements to extend the modeling approach to aircraft operating at transonic speeds.

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)

PI: Jeffrey Ouellette | 757-864-2263 | Jeffrey.A.Ouellette@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 great 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 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 challenges in implementation and identify potential challenges for future programs.

Work to date: Researchers used simulated data to demonstrate the accuracy of the modal filtering approach. The same modal filtering was applied to the X-56A Multi-Utility Technology Testbed 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 | 757-864-2263 | Jeffrey.A.Ouellette@nasa.gov

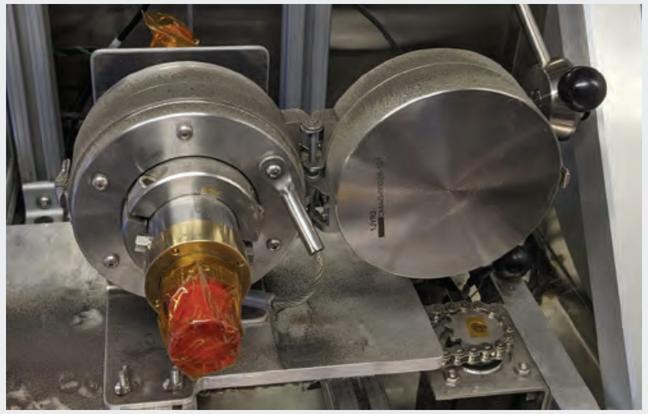
CryoMag Coupler: A Magnetic Cryogenic Dust-Tolerant Coupler for Space Applications

In 2020, NASA Armstrong secured its first Early Career Initiative (ECI) award. The award provided up to $2.5 million over two years to support development of a prototype for a dust-tolerant cryogenic magnetic coupler for lunar applications.

On the lunar surface, life support, in-situ resource utilization, and other systems will require a cryogenic fluid management system to enable transport and storage of various cryogenic fluids. Temporary connections for component parts, performed in-situ by an astronaut or rover, will be a necessary aspect of the system and will face unique challenges posed by the austere lunar surface environment. In addition to the usual problems of cryogenic fluid transfer – for example, leakage and interface purging – dust contamination, low gravity, and a wide temperature range must be considered. To advance the magnet development component of this project, the Armstrong team partnered with NASA's Kennedy Space Center and Correlated Magnetic Research, a patterned magnet development firm.

(top) CryoMag coupler. (bottom) Cryo flow test at Kennedy Space Center.

The ECI research team developed a proof-of-concept cryogenic magnetic (CryoMag) coupler to address this need and meet these challenges. The CryoMag coupler is designed to operate in any region of the lunar surface and within the range of lunar surface temperatures – from 30 Kelvin (K) in the permanently shadowed regions of the lunar poles up to 400 K mean temperature at the lunar equator. The design also mitigates the presence of abrasive, high-iron-content, electrically charged lunar regolith dust. The team completed system-level testing of the coupler in the areas of mechanical/functional evaluation, dust environment exposure, and cryogenic fluid flow.



Dust environmental test at Glenn Research Center.

Looking ahead: Areas to further mature the CryoMag coupler include testing in representative environments (microgravity, vacuum, the full temperature range of the lunar surface, and a combination of environmental factors); optimizing the design and materials for a space environment; testing off-nominal scenarios (side loads, misalignment, bumps/shocks); and evaluating the design for compatibility with other cryogenic fluids.

Benefits

- **Advanced:** Fills multiple gaps associated with cryogenic fluid transfer and dust-mitigation technologies
- **Innovative:** Requires less force to mate coupler halves with patterned magnets that customize force per project
- **Protective:** Shields cryogenic fluid from lunar regolith dust contamination

Applications

- **Fuel transfer for lunar rockets or landers:** Facilitates the transfer of cryogenic fuels from storage tanks to rockets or landers on the lunar surface
- **Life support system maintenance:** Connects and disconnects cryogenic fluid lines in life support systems of lunar habitats
- **In-situ resource utilization operations:** Serves as a key component in systems that extract, process, and store cryogenic fluids from lunar resources

The Armstrong-led research team included 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.

PI: Shideh Naderi | 661-276-3106 | Shideh.Naderi@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 $4 million to 17 R&D projects managed at NASA's Armstrong Flight Research Center in Edwards, California, in 2023. Conducted by small businesses – sometimes in partnership with research institutions (i.e., for STTR) – these R&D efforts focus on:

- Structural efficiency – aeroelasticity and aeroservoelastic control
- Electric vertical take-off and landing (eVTOL) vehicle technologies for weather-tolerant operations
- Flight test and measurement technologies
- Technologies to enable aircraft autonomy
- Aircraft design, optimization, and scaled model testing
- Full-scale (passenger/cargo) eVTOL scaling, propulsion, aerodynamics, and acoustics investigations

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

Active Battery Management System (ABMS) with Physics-Based Life Modeling Topology

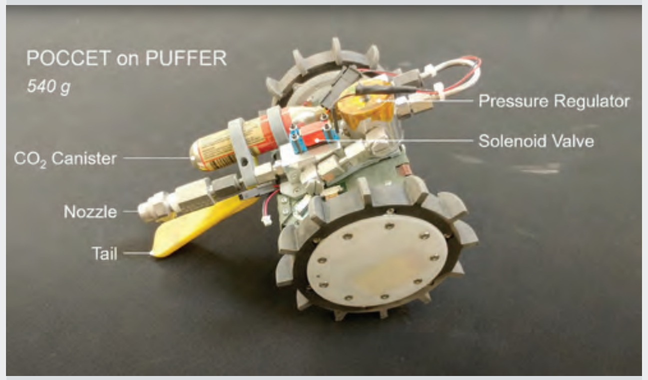
ELECTRIC POWER SYSTEMS, INC.

This Utah-based small business is developing technologies to pave the way for electric aircraft propulsion, specifically Federal Aviation Administration-certifiable batteries and battery management systems (BMS). The current technology has immediate application towards multiple airborne platforms and aircraft. Certification of the central controller of the active battery management system will immediately enable all-electric and hybrid fixed-wing platforms to meet target EIS dates. Additionally, the ability of ABMS to accommodate variability in module capacity has immediate use in ground-support equipment (GSE) applications where second life modules are intended to be used. The shared BMS backbone between the on-board battery and the GSE battery unlocks immediate benefits for all-electric fleet operators.

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

POCCET for Lunar Gravity Flight Tests

HONEYBEE ROBOTICS



Honeybee Robotics has developed a series of pneumatic tools to address challenges associated with lunar exploration. The company is developing a technology that uses compressed gas to remove dust from the scientifically important surface of rocks, regolith-covered ices, sealing services, and key equipment such as solar panels, into a payload that can be tested on a Blue Origin New Shephard capsule during a flight designed to simulate lunar gravity conditions. Honeybee will test the Pop-Up, Flat-Folding Explorer Robot (PUFFER)-Oriented Compact Cleaning and Excavation Tool (POCCET) under simulated lunar gravity conditions to allow technology developers and other researchers interested in pneumatic cleaning and excavating to understand the effects of conditions where gravity is semi-dominant compared to electrostatic forces.

COR: Greg Peters | 661-276-5359 | Gregory.H.Peters@nasa.gov

Other NASA Armstrong-Managed Projects

This table lists the Phase II and Phase IIe projects that were awarded in the past two years of the program. In addition to these two-year prototype development projects, SBIR/STTR awarded 11 Phase I "idea generation" projects in 2023.

Projects and Small Business	Focus	Contact
Integrated Flight Control Design and Multidisciplinary Optimization A1.01-3185 | Bechamo, LLC	Developing a controllability assessment software tool that allows the aircraft to be designed within a multi-disciplinary optimization framework including flight control constraints	**Shaun McWherter** **661-276-2530** **Shaun.C.Mcwherter@nasa.gov**
Use of Pilot Models to Support Design, Analysis, and Certification of Urban Air Mobility (UAM) Vehicles A1.06-4899 I Systems Technology, Inc.	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**
Ruggedized Micro-Electromechanical Systems Tunable Vertical Cavity Surface Emitting Lasers (MEMS-VCSEL) with High-Speed Data Acquisition for Fiber Optic Sensing System A2.01-1708 I Praevium Research, Inc.	Developing a new cost-effective ruggedized laser technology that will accelerate proliferation of optical frequency domain reflectometry (OFDR) fiber optic sensing of physical parameters such as shape, deflection, temperature, and strain	**Patrick Chan** **661-276-6170** **Hon.Chan@nasa.gov**
Enhanced Detect and Avoid (DAA) Optical Sensing for Urban Air Mobility A2.02-2214 I Circle Optics, Inc.	Building and flight testing a seven-channel visible DAA visor system	**Ricardo Arteaga** **661-276-2296** **Ricardo.A.Arteaga@nasa.gov**
A Certification Means of Compliance Process for Advanced Air Mobility (AAM) with Increasing Autonomy A2.02-2358 I Systems Technology, Inc.	Developing the Simulation-based Automation and Failure Evaluations (SAFE) system, exercised via a tablet-based computer, that will provide a method for compliance certification for autonomous and degraded modes that is safe, repeatable, and discriminating	**Jinu Idicula** **661-276-2892** **Jinu.T.Idicula@nasa.gov**
LiDAR-Supported Emergency Landing System for AAM Vehicles (LELSA) A2.02-2693 I Barron Associates, Inc.	Demonstrating an approach that autonomously provides on-board guidance/assistance during an emergency landing for AAM vehicles	**Peter Suh** **661-276-3402** **Peter.M.Suh@nasa.gov**
Acoustic Detection, Ranging and Improved Situational Awareness System A2.02-3874 I Scientific Applications & Research Associates, Inc.	Integrating an acoustic sensor's advanced detect-alert-avoid capabilities and flight testing them in a simulated urban environment	**Jinu Idicula** **661-276-2892** **Jinu.T.Idicula@nasa.gov**
Low Size, Weight, Power, and Cost (SWAP-C) Imaging Radar for Small Air Vehicle Sense and Avoid A2.02-6569 I KMB Telematics, Inc.	Developing a detect-and-avoid system to allow small unmanned aircraft systems to safely fly in the National Airspace	**Jinu Idicula** **661-276-2892** **Jinu.T.Idicula@nasa.gov**
Novel Aeroservoelastic Scaled Model Design, Fabrication, and Testing T15.01-6203 I M4 Engineering, Inc. (with the University of Washington)	Creating technology for rapid aeroelastic scaling of new designs	**Chan-gi Pak** **661-276-5698** **Chan-gi.Pak-1@nasa.gov**
Full-Scale eVTOL Aircraft Performance and Aeroacoustic Test, Evaluation, and Modeling T15.04-1416 I Continuum Dynamics, Inc.	Providing both a computational model and a body of aerodynamic and acoustic flight test data for a full-scale multi-copter eVTOL aircraft	**Jason Lechniak** **661-276-2620** **Jason.A.Lechniak@nasa.gov**
Electric Lift Augmenting Slats (ELAS) T15.04-5017 I CubCrafters Inc.	Develop ELAS and electric, ultra-short takeoff and landing (eSTOL) technology, that can be built into new aircraft or added after-market	**Mike Frederick** **661-276-2274** **Mike.Frederick-1@nasa.gov**

More Information

For more information about NASA's SBIR/STTR program, visit sbir.nasa.gov or contact Armstrong's Center Technology Transition Lead, Gary Laier at Gary.E.Laier@nasa.gov (661-276-2648).

Fiber Optic Sensing System

PROJECT SUMMARIES

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.

The sensor suite 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. 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.

Fiber Optic Technology Aids Wing Calibration Tests

NASA Armstrong's Fiber Optic Sensing System (FOSS) is aiding in the development of new loads calibration techniques for truss-braced structures by the application of distributed fiber optic strain sensors. To support NASA's Transonic Truss-Braced Wing (TTBW) structural research, the Flight Loads Lab at Armstrong is performing pathfinder tests on small-scale metallic test articles (dubbed mock TTBWs). The test articles have representative structural features of the TTBW design for the Sustainable Flight Demonstrator, recently named X-66A. These pathfinder tests are performed to investigate loads calibration methods on a truss-braced wing structure.

Work to date: During testing of the 6-foot mock TTBW, there were a total of 5 FOSS fibers and approximately 1,500 unique strain sensors. The goal of the new strain-based algorithms utilizing FOSS-distributed strain outputs are to simplify loads calibration testing of aircraft wings by potentially lowering the number of required test cases, while simultaneously providing a full-span estimate of the wing bending and shear loads.

The Flight Loads Lab team developed and tested a 6-foot semi-span-scale metallic test article with a strait wing geometry and is designing a 10-foot semi-span metallic test article with swept-wing geometry and a secondary strut called the jury strut. The introduction of multiple struts to the wing structure, as opposed to a cantilever beam setup, produces multiple load paths and changes the conventional strain gage-based loads calibration techniques that have been performed for decades.

Benefits

- **Efficient:** Reduces weight and complexity of instrumentation systems, leading to more efficient use of flight test time
- **Enabling:** Informs models to improve maintenance costs, save testing time, and improve aircraft structural safety models

PI: Francisco Pena | 661-276-2622 | Francisco.Pena@nasa.gov

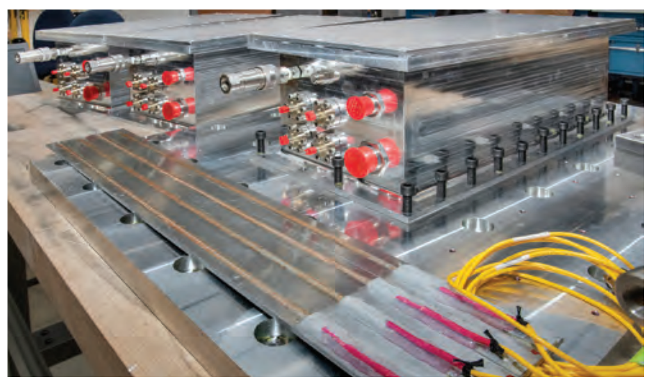
NASA's 'Rocket Box' FOSS Flies on Space Vehicles

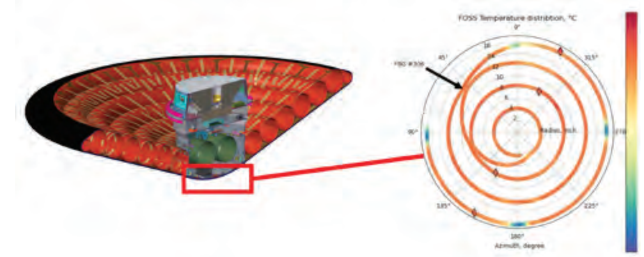
The Low-Earth Orbit Flight Test of an Inflatable Decelerator, or LOFTID, heat shield was recovered from the Pacific Ocean in November 2022, shortly after it completed its demonstration and splashed down. NASA Armstrong Flight Research Center's Fiber Optic Sensing System collected temperature data on LOFTID as it re-entered the atmosphere and landed in the Pacific Ocean. Credits: United Launch Alliance

NASA Armstrong innovators have worked for years to ruggedize the Fiber Optic Sensing System (FOSS) so it can be used to measure aggressive launch loads on spacecraft. Collaborations with industry partners and NASA's Kennedy Space Center and Langley Research Center have resulted in durable instrumentation, and the FOSS team has developed a new combination of mechanical enclosure and instrumentation for launch on several rocket launches. This FOSS unit, known as the FOSS "rocket box," can take thousands of measurements along a fiber-optic wire about the thickness of a human hair.

Work to date: FOSS collected temperature data during the agency's Low-Earth Orbit Flight Test of an Inflatable Decelerator (LOFTID) mission. LOFTID launched in November 2022, aboard a United Launch Alliance Atlas V rocket from California's Vandenberg Space Force Base. It carried 1,400 FOSS sensors on three optic fibers totaling 60 linear feet, placed in a spiral pattern on LOFTID's nose, while the FOSS box was mounted in the vehicle's midsection. FOSS provided a thermal map of the heat LOFTID was subjected to as it re-entered Earth's atmosphere and landed in the Pacific Ocean.

An Engineering Development Unit of the FOSS rocket box, which is a prototype unit to evaluate flight testing, was on board a Blue Origin New Shepard launch vehicle in October 2022, as part of





the Flight Opportunities program. An identical FOSS unit passed numerous environmental validation tests including external shock, random vibration, thermal vacuum cycling, and electromagnetic compatibility testing, and is ready to support future missions at NASA Kennedy.

Looking ahead: Lessons learned from system integration and testing efforts will allow the team to further refine the FOSS technology for future entry, descent, and landing activities.

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

Benefits

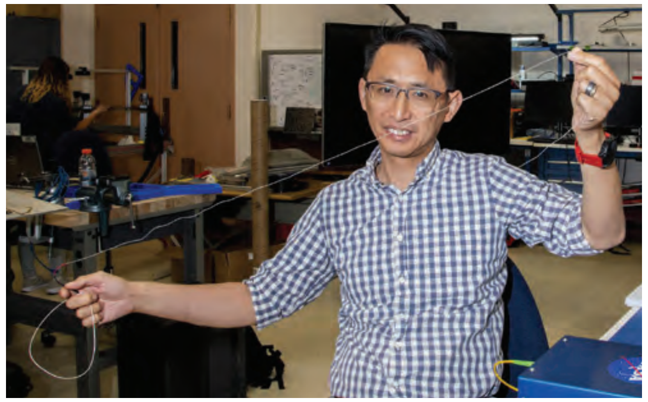
- **FEM data validation:** Provides high-spatial resolution strain and temperature data to validate design data that could enable future launch systems to be lighter and more structurally efficient
- **Ruggedized:** Allows FOSS to be used effectively in many more practical applications that require a more robust system

Applications

- Rockets
- Reentry vehicles
- Jet engines
- Inflatable wings and airships
- Test aircraft

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

Fiber Optic Technology Enables Cryogenic Monitoring Capabilities



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 or -432 degrees Fahrenheit). Unlike gauges that rely on discrete measurements to give broad approximations of liquid levels, Armstrong's cryogenic FOSS technology provides multiple measurements at half-inch intervals within the cryogenic tank with a single optical fiber, eliminating multiple copper wires. 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. Optical fiber is ideal for cryogenic fluid monitoring since it is immune to electromagnetic interference and is oxygen-compatible, which eliminates concerns of arcing that could lead to an explosion.

Work to date: The FOSS team supported CryoFILL prototype testing at NASA's Glenn Research Center in 2022. The sensing system took temperature measurements during tests of a system designed to liquefy oxygen in the same manner it would be done on the lunar surface. During the tests, FOSS tracked the temperatures inside a tank as oxygen chilled and condensed from a gas to a liquid at minus 297 degrees Fahrenheit. The FOSS team produced a support sleeve made of strong, waxy, nonflammable synthetic material to protect the fiber from the cold and make it safe to use in a pure oxygen atmosphere, but still allowed for the sensitivity needed to track temperatures of the liquid oxygen.

CryoFILL testing used a tank 77-inches tall with a storage capacity of up to 528 gallons. The experiments included a 140-inch FOSS strand with 330 sensors. A second temperature measuring system with silicon diodes was also used in the experiments. More than 40 liquefaction tests were conducted from June to November 2022, with researchers looking at various parameters such as flow rate and tank pressurization rates. Individual tests lasted anywhere from 24 hours to over 200 hours (about eight days). A data review determined that FOSS temperature data was comparable to co-located silicon diode measurements and was not adversely affected by electromagnetic interference from the cryofan.

Looking ahead: If the CryoFILL project moves forward with additional testing, the FOSS team will provide additional optic fibers for installation in the liquid oxygen manufacturing tank to provide more data.

Partners: NASA's Glenn Research Center and Sensuron LLC

Benefits

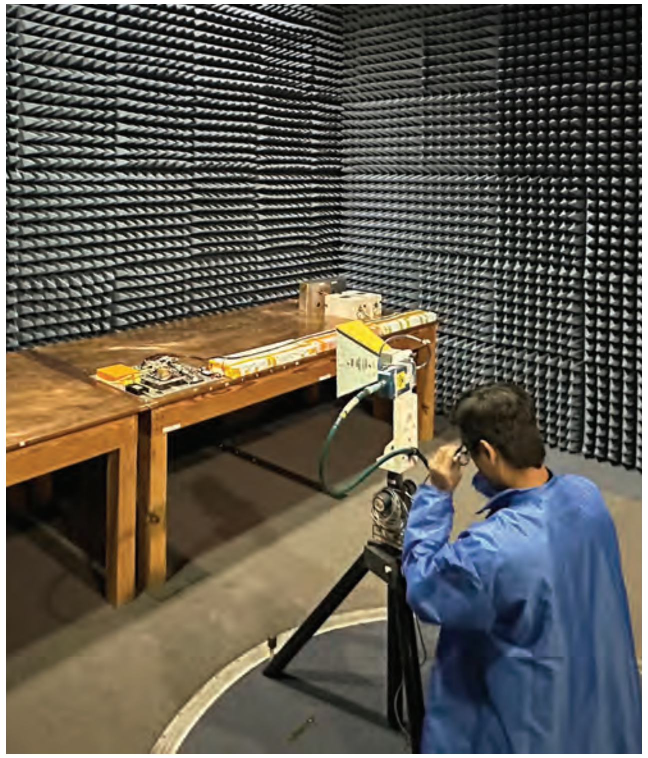
- **Reliable:** Provides validated cryogenic temperature data that could enable systems for safe and efficient liquefaction and storage of cryogenic propellants

Applications

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

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

Next-Generation Laser to Boost Testing Capabilities



The Fiber Optic Sensing System (FOSS) team is developing a space-rated, next-generation interrogator that utilizes a fast-sweeping laser that can withstand the extreme space environment. Co-developed with industry partner Sensuron LLC, the new laser will be integrated into the current Armstrong-developed micro FOSS platform to measure liquid fluid temperature. The work is supported by NASA's Space Technology Mission Directorate.

Work to date: The FOSS team and Sensuron are developing a prototype laser. Individual components have been fabricated and have passed all environmental tests – vibration, thermal cycling, and EMI/EMC – under adverse conditions.

Looking ahead: Next steps are to integrate the prototype laser into a working micro-FOSS laboratory unit and then validate its performance. This innovation will be critical to efforts to mature cryogenic liquefaction technologies.

Partner: Sensuron LLC

Benefits

- **Fast:** Four times faster swept speed versus current laser
- **Robust:** Withstands the rigor of the space environment the extreme space environment

Applications

- Aerospace cryogenic liquid monitoring

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

FOSS Aims to Advance Hypersonic Research

The Fiber Optic Sensing System (FOSS) team at NASA Armstrong is ruggedizing the technology so it can collect in-situ temperature measurements during hypersonic flight. NASA is developing numerous hypersonic capabilities and maintains unique specialized facilities and experts who can explore key fundamental research areas for solving the challenges of high-speed flight. FOSS can provide significant information to key decision-makers responsible for ensuring vehicle performance.

Work to date: The ruggedized FOSS technology leverages a wavelength division multiplexing (WDM)-based data acquisition system. A novel, solid-state, narrowband wavelength-swept laser with no moving parts interrogates the sensors as they respond to strain resulting from stress, temperature, or pressure on a structure.

The team is developing an interrogator that will operate in extreme hypersonic environments. The laser has successfully completed vibration and thermal cycling testing. Computer-aided design techniques are speeding prototype fabrication to support ground and upcoming flight testing. Completed system level testing has shown that the system can be continuously operational during random vibration, extreme temperature, as well as under 30 *g* of centrifuge testing. Researchers are developing software for all components. This work is supported by NASA's Aeronautic Research Mission Directorate's Advanced Air Vehicles Program.

This system will be a self-contained payload on the AgilePod™ on the U.S. Air Force T-38C aircraft to demonstrate that FOSS WDM is able to survive high-*g* maneuvers and to record relevant strain data with co-locating strain gauges.

Partners: U.S. Air Force (USAF) Test Pilot School, USAF Holloman Air Force Base 586th Flight Test Squadron

Benefits

- **Compatible with multiple sensors:** Interrogator enables measurements of fiber Bragg gratings as well as extrinsic Fabry Perot interferometer
- **Robust:** Features components designed for extreme aggressive environments

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

AgilePod is a trademark of the U.S. Air Force.

Avionics and Instrumentation Technologies

PROJECT SUMMARIES

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.

Aeronautics Research Mission Directorate (ARMD) Test Data Portal (ATDP)

The ARMD ATDP provides centralized data storage and retrieval capability to support ARMD flight test and research programs. When fully ready, it will provide NASA researchers with easy access to test data and its supporting information, regardless of researcher location or research mission. At NASA Armstrong, it replaces the legacy Flight Data Archive System.

The web-based ATDP utilizes enterprise system architecture and consists of modern search capabilities that allow researchers unique insight into potentially related test data, providing valuable information for data analysis. The design goals of the ATDP are to bring together, in one system, all research information generated during flight and ground testing conducted by NASA.

ATDP is also an element of the ARMD contribution to the NASA Digital Transformation Initiative and is partnering with the Aerosciences Evaluation and Test Capabilities (AETC) portfolio office to support archiving data from AETC wind tunnels.

Work to date: ATDP archives data from all ARMD Centers as long as the data is formatted in the Hierarchical Data Format 5 (HDF5) file specification, which includes the necessary meta data required to enable a robust search capability for storage and retrieval. The goal is for the ATDP to archive any data format in 2024.

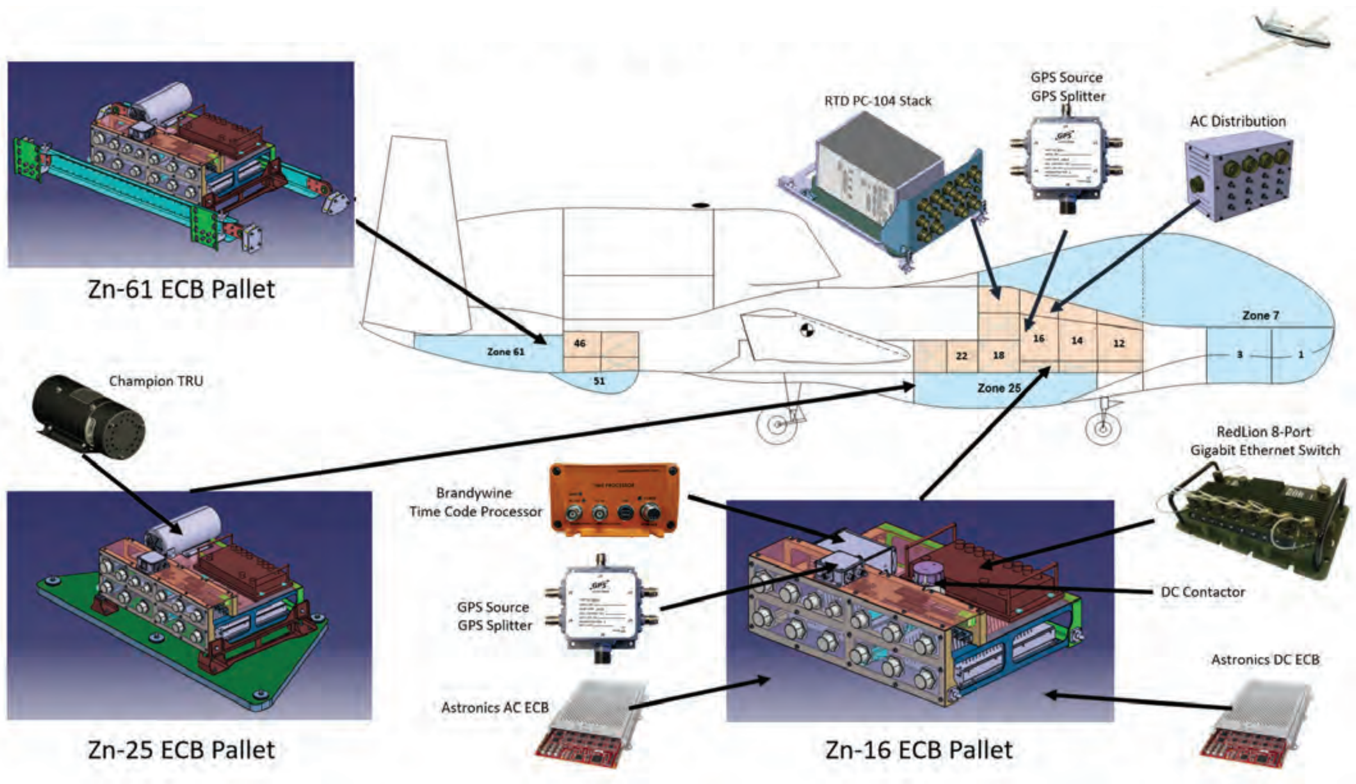
Looking ahead: ATDP will continue as a significant effort to develop new features through FY2026 and then will focus on sustainment system support.

Benefits

- **Increased collaboration:** Provides access to all NASA personnel and allows for further partnering and collaboration opportunities in test data archiving, discovery, time-slicing, and retrieval
- **Comprehensive data governance:** Supports multi-factor authentication, controlled unclassified information document marking, access rights handling, records management, and compliance with government agency and industry requirements and standards
- **Enhanced search capabilities:** Enables rapid location of flight and ground test data and corresponding meta data information
- **Easy to use:** Features a user-friendly graphical user interface and search mechanism, along with time-slice capability

PI: Minh Luu | 661-276-7006 | minh.v.luu@nasa.gov

New Mission Support System (MSS) Increases Functionality and Reliability



NASA Armstrong engineers have developed a novel system for providing common interfaces typically required by flight vehicle payloads and have implemented it first on the Global Hawk aircraft. The MSS is designed to increase functionality and reliability and will replace the existing Airborne Payload Command, Control, & Communication System. It comprises multiple subsystems including GPS distribution, time synchronization, mission support network, and power distribution. System components are palletized and installed in multiple locations throughout the aircraft for ease of payload integration.

Network-based control and monitoring is provided in the control room by satellite communications in conjunction with Armstrong-developed software hosted on an embedded controller on the aircraft. A custom graphical user interface was also developed to 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. Additionally, the system monitors the integrated mission management computer pulse code modulation (PCM) output and an inertial navigation system synchronous serial output. Full-bandwidth data is recorded onboard and select parameters are decommutated, decimated, and made available onboard and in the control room.

Work to date: Fabrication of an initial set of pallets was completed, and the entire system underwent integrated testing in the lab, including formal software verification. Electrical and mechanical modifications were performed on tail number N876NA, and the system completed on-aircraft verification, including end-to-end checks with the control room. The MSS successfully completed a combined systems test (CST) and subsequently a verification and validation (V&V) flight that satisfied all initial operating capability requirements.

Looking ahead: Integration of MSS with an initial payload has begun on N876NA. Software development and testing will continue and culminate when all final operating capability requirements are satisfied. Additional Global Hawk aircraft will be modified to accommodate MSS.

Benefits

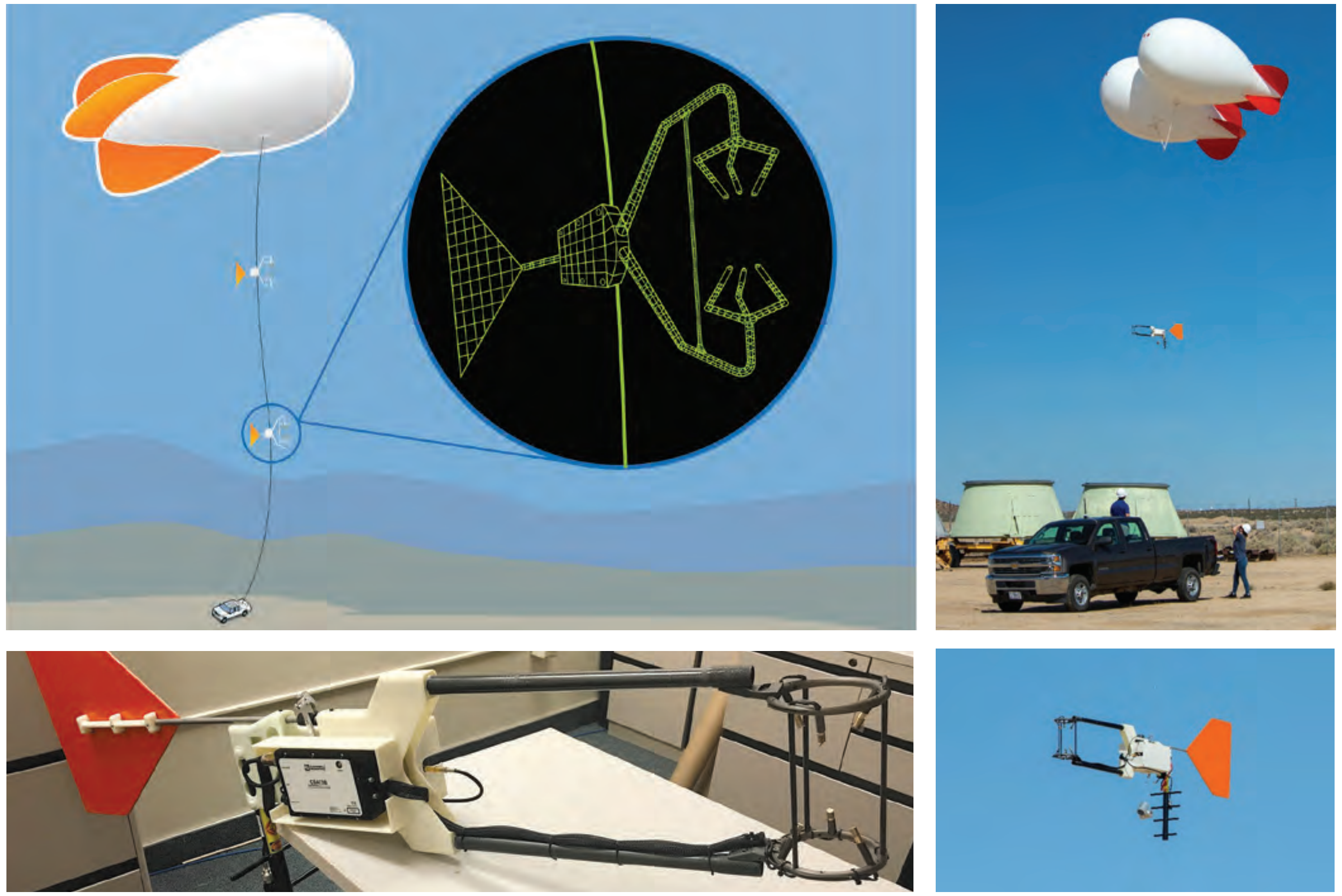
- **Efficient:** Enables controllers in an operations center to monitor and control every payload in an aircraft in real time throughout a mission
- **Modernized:** Increases functionality and reliability of mission support operations

Applications

- Aircraft mission support
- Remote power control and monitoring
- Onboard PCM documentation

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

SonicSonde for Atmospheric Sensing



SonicSonde concept illustration and sensor suite in the lab (left). Full deployment field test and close-up of sensor suite tethered to cable line (right).

The SonicSonde project developed an advanced tethered instrumentation suite for in situ atmospheric sampling. Prioritizing the needs for prompt, repetitive, and reliable vertical ascent data, the suite measures atmospheric pressure, temperature, relative humidity, air quality, and 3D wind velocities – targeting vertical profiles extending from the surface to 5,000 feet above ground level. Customizable computer software supports and displays real-time data via wireless streaming throughout operation. This sensor suite will allow for support of 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: 2022 marked the third and final phase of this development. With Center Innovation Fund (CIF) resources, researchers obtained and tested a custom-built lightweight sonic anemometer, completed the design and construction of the prototype, successfully integrated all atmospheric sensors, demonstrated remote data retrieving capability between the SonicSonde and a ground station laptop, and conducted over one dozen ascent tests while live-streaming the collected data throughout the ascents. Researchers also produced a successful, operational version of the custom computer software to be paired and used with the SonicSonde.

Looking ahead: Researchers will conduct statistical data analyses to quantify performance. Long-term objectives include publishing research findings and engaging with external companies interested in commercialization.

Benefits

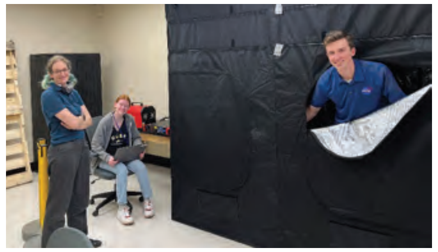
- **Comprehensive:** Permits wide-ranging capture of atmospheric data
- **Versatile:** Enables flexibility to tailor data output and displays to specific research objectives
- **Modernized:** Employs a 3D sonic anemometer as a means for wind data collection; all sensors onboard offer high-resolution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

Applications

- Climate and atmospheric research
- Acoustic studies

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

Adaptable Radiometric Measurement System (ARMS)



Several ARMS team members preparing to perform a low-temperature characterization using the mobile dark room.

Prototype (left) and the more compact system (right).

ARMS system characterization utilizing the small blackbody.

In-flight temperature measurements of high-temperature structures have been problematic since the beginning of hypersonic and re-entry 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 and vehicle integration challenges.

The ARMS research seeks to solve these problems by developing a low size, weight, and power (SWaP) non-contact temperature measurement system to measure temperatures above 240 degrees Fahrenheit (F) and up to approximately 5,400 degrees F, replacing or augmenting traditional high-temperature thermocouple measurements.

Work to date: Resources from the Center Innovation Fund (CIF) supported two lines of effort – system development/characterization and flight opportunity support.

System Development and Characterization

With CIF resources in 2022, researchers designed the initial system (referred to as Mk2), purchased components, fabricated a prototype, and began performance characterization. In 2023, the team continued the Mk2 characterization and commenced designing a similar SWaP system more suitable for flight (referred to as Mk3). The team also conducted random vibration testing and a series of trials to evaluate accuracy and reliability. This research was formerly known as CLAW – which stands for Compact and Long-wave infrared (LWIR)-Augmented WARS (where WARS stands for Waveguide Augmented Radiometric System). However, in 2023, researchers evaluated LWIR components to determine the feasibility of measuring temperatures closer to ambient conditions and whether this approach would significantly increase system costs. The team documented findings and determined that the value proposition for integrating the LWIR capability was not sufficiently high to merit further effort and that the original WARS architecture would be carried forward – hence the new ARMS designation.

Flight Opportunity Support

The team also supported a future flight test opportunity under the NASA Flight Opportunities Program. Two team members traveled to that facility and performed vehicle data acquisition system integration testing for a first evaluation of integrating ARMS with the system. This successful testing led to several action items for both teams prior to the second integration test planned for the spring of 2024.

In preparation for using the system on ground and flight tests, the Armstrong team is designing a test chamber that could be used to generate calibration curves for the specific material/surface to be measured by each channel. As a by-product, the test chamber will be useful for generating temperature-dependent emissivity data for various materials, which will have broader benefits beyond ARMS applications. The team is also in discussions with three other potential flight opportunities.

Looking ahead: The team has determined that this technology can very likely provide data more reliably on hot structures than thermocouples – and provide it at temperatures where no contact sensor or attachment could survive.

The team plans to complete the design of the Mk3 system in 2024 and characterize the performance through vibration testing as well as temperature and altitude simulation in an environmental chamber. The optical calibration test chamber design will be completed, purchased, and operational to support the flight opportunity, which will involve further integration testing in spring 2024. Discussions for the other three flight opportunities will continue to be supported with expectations that within the next 1-3 years ARMS will be able to transition from technology development and demonstration to supporting flight test programs, and possibly transition to industry as well.

Benefits

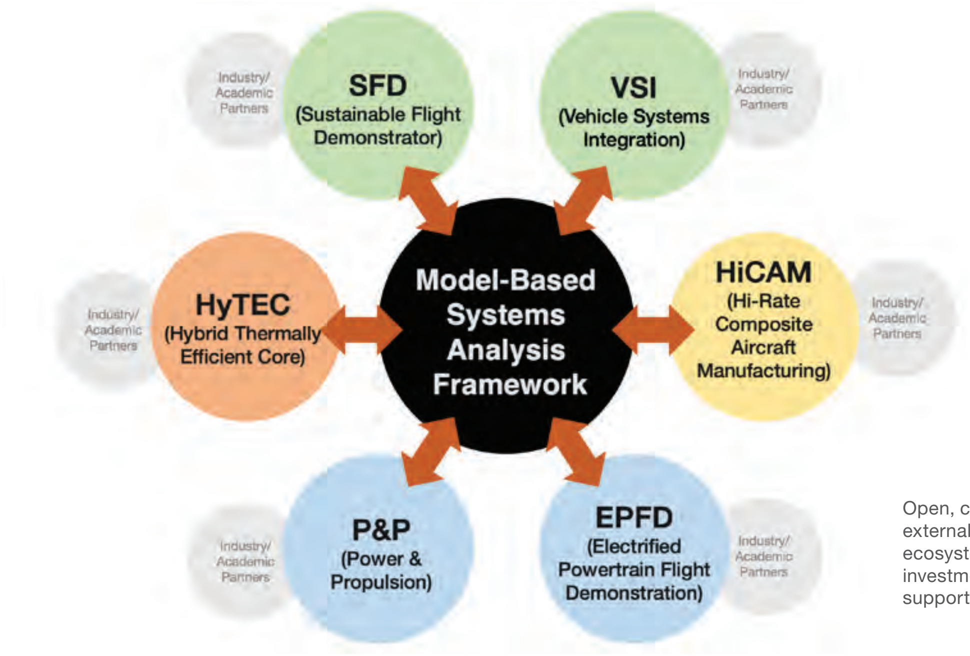
- **Enabling:** Provides reliable high-temperature measurements during ground and flight tests of re-entry vehicles and high-speed aerospace structures through a low-SWaP system
- **Efficient:** Significantly increases the return on investment of flight tests, collecting data to characterize vehicle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

Model-Based System Analysis & Engineering (MBSA&E) Framework



Open, cross-project/program/external-capable MBSA ecosystem building on ARMD investments and capabilities in support of the SFNP.

The MBSA&E framework is a multi-center NASA effort being developed in support of the Sustainable Flight National Partnership (SFNP). It will support NASA internal systems analysis workflows, tools, and expertise related to advanced subsonic transports. The digital framework is being created in the open multidisciplinary design analysis and optimization (OpenMDAO) open-source framework and will provide advanced capabilities for coupling existing tools and producing optimized, converged solutions. Phase I involves creating a unified MBSA&E ecosystem by developing necessary building blocks for critical disciplinary analyses, integrating these blocks into a coupled MBSA&E framework, testing the framework with various aircraft use cases, and advancing the integration between the MBSA/MDAO environment and the MBSE tools. Phase II focuses on conducting integrated system analysis studies to support the SFNP, encompassing common open reference vehicle models, vision vehicle models, and technology benefit assessments and sensitivity studies informed by SNFP demonstrations.

Work to date: Researchers at Armstrong are developing building blocks of key stability and controls (S&C) subdisciplinary component codes to integrate into the MBSA&E framework, serving as integral constraints for optimization-based analysis within OpenMDAO. The S&C building blocks include analytical methods for aircraft tail volume coefficients, control surface sizing, static and dynamic stability, and flying quality assessments. Integrating S&C into MBSA&E will mark an important step forward in enhancing aircraft optimization design analysis and ensuring a more thorough consideration of stability and control constrains to assess whether a given aircraft configuration is capable of overcoming the static and dynamic challenges within its flight envelope. To date, empennage design, control-surface sizing, static stability, and flying qualities component codes have been integrated into the MBSA framework. Some of these components have been tested for the analysis and design of an N+3 advanced conventional aircraft concept, and others will be tested in the optimization-based framework using the Transonic Truss-Braced Wing concept as the use case.

Looking ahead: Integration of stability augmentation and flight control design will be investigated to include additional constraints within the integrated vehicle optimization to quantify impact on vehicle sizing and mission performance. This will enhance the S&C subdisciplinary tools being integrated into MBSA to influence advanced vehicle designs during their optimization design process.

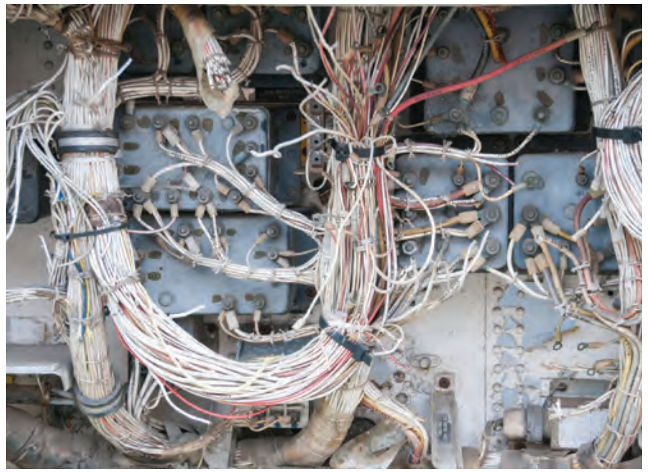
Partners: NASA's Langley Research Center, Glenn Research Center, and Ames Research Center

Benefits

- **Enabling:** Incorporates design objectives for flight dynamics and controls early in the process to allow for a more integrated design approach, leading to potential advantages in weight reduction and minimized drag for the aircraft
- **Advanced:** Aims to enhance NASA's understanding of potential benefits and challenges associated with incorporating flight dynamics and controls into the early aircraft design process
- **Innovative:** Offers the potential to help new transport-class aircraft designs advance toward integrated system-level benefit assessments of the SFNP vision vehicle concepts

PI: Felipe Valdez | 661-276-3330 | felipe.valdez@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 | 661-276-5708 | Matthew.Waldersen@nasa.gov

Deploying Unmanned Aircraft Systems (UAS) to Study Water Quality

Environmental water quality monitoring is currently performed with in-situ sensors and data collected manually and via satellite. This research project investigated how high- and medium-altitude, long-endurance UAS can complement existing measures to provide near real-time data involving environmental events such as industrial waste run-off and harmful algal blooms (HABs).

Work to date: With Center Innovation Fund (CIF) resources, NASA Armstrong researchers developed a proof-of-concept field campaign. The campaign utilizes large military grade UAS, small commercial off-the-shelf UAS, and sensing technologies to demonstrate a phased, deployable solution for water-quality monitoring. Researchers developed a concept of operations for a HAB monitoring mission and several mission scenarios detailing the deployment of systems to monitor HABs.

- Phase I: Mission planning, development, and systems integration
- Phase II: Systems checkout (calibration and familiarization flights) and data collection involving precursors of HAB events, validation of previous data sets/studies, creation of water maps, and digital elevation modeling
- Phase III: Data collection during HAB season
- Phase IV: Follow-on flights and future planning

Looking ahead: Adapting UAS and sensing technologies for environmental monitoring has high potential to spur innovation. With funding, these systems, processes, and techniques can be refined for transition to industry, state/local governments, and federal agencies.

Benefits

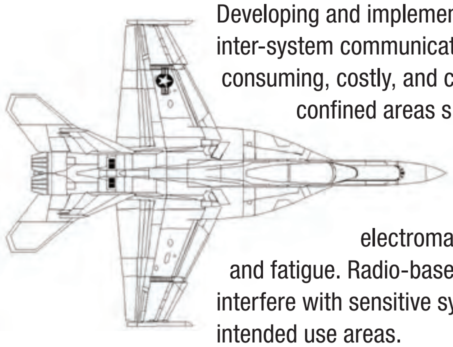
- **Effective:** Reduces environmental impact and costs due to water-quality events induced by climate change
- **Empowering:** Bolsters HAB detection and infrastructure monitoring for vulnerable communities enabling
- **Increases adoption:** Increases collaboration between organizations, technology/policy development, and standardization

Applications

- Water-quality monitoring
- Wildfire detection
- Flood surveillance and management

PI: Todd Jackson | 661-276-5822 | Todd.J.Jackson@nasa.gov

Inter-System Communications



Developing and implementing cable solutions for inter-system communication can be time-consuming, costly, and challenging – especially in confined areas such as aircraft bays. Cable systems also can be cumbersome to track and susceptible to electromagnetic interference (EMI) and fatigue. Radio-based wireless options can interfere with sensitive systems and “leak” out of intended use areas.

Innovators at NASA Armstrong are investigating the feasibility of using miniature visual light communication (VLC) technologies for inter-system communications, specifically between more than three systems simultaneously and between aircraft bays. If found practical and inexpensive to implement, VLC technologies could lead to significant cost and time savings on system-system integration, especially in small compartments and bays.

Work to date: VLC components are lightweight and robust and primarily consist of a light emitter transmitter and a photo-detector receiver. They work with ambient light and at short and medium communication distances. With Center Innovation Fund (CIF) resources, researchers leveraged commercially available LiFi (a form of VLC) modules to develop representative compartments and research systems to demonstrate VLC advantages in a laboratory. System-system communication tests were carried out within the representative compartments. Under most conditions, the systems performed at peak performance of 100+ megabits per second with both line-of-sight and compartment wall reflections. System-system communication in presence of daylight also showed strong performance levels. Systems were paired with batteries and modular operation was demonstrated.

Looking ahead: Armstrong innovators are extending their research to examine whether VLC technologies can be used for robust “drop-in” flight research systems. The team has selected an aircraft to integrate LiFi infrastructure into side and underbelly compartments for a real-world demonstration. Integration is in process and ground characterization tests are planned. Quick turnaround flight tests using multiple robust “drop-in” flight systems to demonstrate time savings is an eventual goal.

Benefits

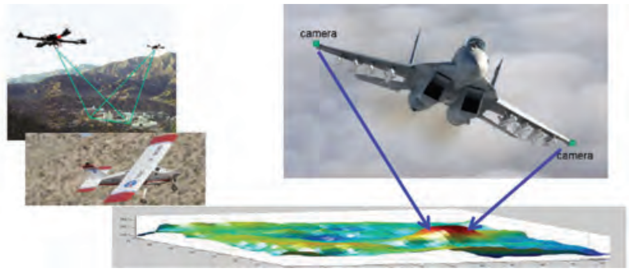
- **Economical:** Saves time and cost associated with planning, fabricating, and integrating wiring harnesses and tracking cable integrity – time savings could be weeks to months in engineering and aircraft down-time
- **Robust:** Mitigates data failures due to EMI or wire fatigue

Applications

- Aircraft internal system-system communication
- Fast turnaround drop-in research systems

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

Visual Radar Advances Aircraft Sensor Systems



Researchers at NASA Armstrong and NASA’s 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: VWith 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

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

Applications

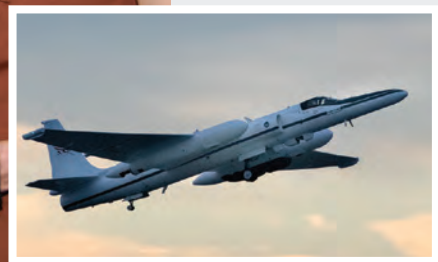
- Autonomous flight techniques
- Automatic collision avoidance technologies
- 3D modeling of terrain and structures
- Passive object detection
- In-flight measurements such as flutter or displacement

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

The X-59 team working on the aircraft’s wiring around the engine inlet prior to the engine being installed.
Credits: Lockheed Martin

Specialized Aircraft Support Worldwide Science Efforts

NASA's Armstrong Flight Research Center in 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 freshwater.



ER-2

The ER-2 high-altitude aircraft collects data that helps researchers understand the world's ecosystems. In 2023, it completed a five-year effort that included investigating Atlantic coast snowstorms and the dynamics of the summer stratosphere, with a total of more than 400 flight hours in 70 flights. Upcoming missions include supporting efforts to measure the microphysical properties of aerosols in Earth's atmosphere and a collaboration with Canadian researchers to compare atmospheric measurements with satellite observations.

DC-8

The DC-8 aircraft leverages a suite of advanced sensors and data systems to provide services that can be tailored to specific research missions. In 2023, it supported numerous atmospheric emissions campaigns. After more than 36 years supporting the Airborne ScienceProgram, the DC-8 aircraft will retire in 2024.

The view from the DC-8 flight deck.

C-20A

The C-20A is equipped with NASA's Jet Propulsion Laboratory's unmanned aerial vehicle synthetic aperture radar (UAVSAR) and an Armstrong-developed precision autopilot. In 2024, it will aid international partners in an airborne campaign to collect radar and field measurements of tropical forests, savannas, peatlands, and mangroves in the African continent.

SOFIA

Flying in the stratosphere at 38,000-45,000 feet put the Stratospheric Observatory for Infrared Astronomy (SOFIA) aircraft above 99% of Earth's infrared-blocking atmosphere, allowing astronomers to study the solar system and beyond in ways that are not possible with ground-based telescopes. A collaboration of NASA and the German Space Agency DLR, the SOFIA mission ended in 2022.

SOFIA returns to Armstrong on Aug. 11, 2022, after a productive month of science flights out of Christchurch International Airport in New Zealand.

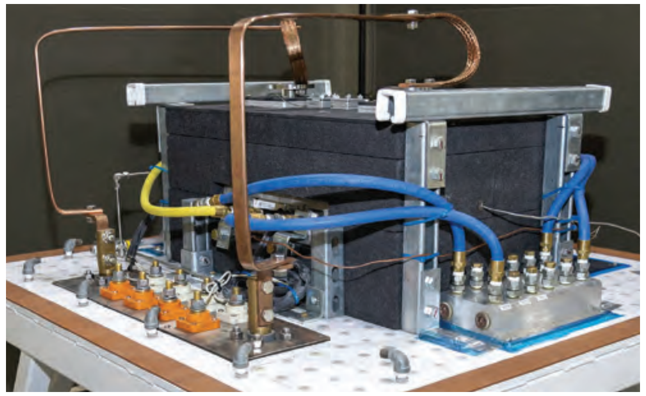
Space and Hypersonics Technologies

PROJECT SUMMARIES

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. Armstrong has a long history of pioneering research in this area.

Leading Edge Irradiation Assembly (LEIA)



Arc jets are critical test facilities for leading edges and other thermal protection system (TPS) components, but demand far exceeds national capacity. This can result in significant cost and schedule impacts for reentry and hypersonic flight programs at NASA and other agencies. The LEIA research project at NASA Armstrong seeks to develop a radiant thermal test methodology to complement those at arc jet facilities and to add a new ground test capability to impart thermal loads to leading edge and other TPS components. The LEIA research leverages Armstrong expertise in refractory materials, high-temperature instrumentation, and multimodal heat transfer analysis capabilities.

Work to date: With resources from the Center Innovation Fund (CIF), the team identified flight-relevant aerothermal profiles; completed literature reviews and analytical studies to evaluate potential configurations and system performance; designed, analyzed, and fabricated a prototype test setup; and completed a test series with the prototype setup.

The test series more than tripled the previous NASA Armstrong Flight Loads Lab record for radiant heat flux imparted to a flight-representative test article.

Looking ahead: Follow-on CIF work will integrate mechanical loading of test articles into LEIA test setups. A preliminary patent application is in process, and the team has submitted a New Technology Report (NTR). Armstrong researchers have secured additional funding to transition LEIA thermal testing to an operational state for future programs of record.

Benefits

- **Innovative:** Meets an urgent thermal testing need for the hot structures and high-speed flight community
- **Powerful:** Provides researchers and vehicle designers with an additional tool for thermal evaluation and risk reduction for new technologies

Applications

- Testing for TPS components and hot structures

PI: Jackson Winter | 661-276-5579 | Jackson.T.Winter@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 completed a store-separation analysis for the Crossflow Attenuated Natural Laminar Flow (CATNLF) test article that indicated that a safe separation would occur at a set jettison condition. The Armstrong team also provided store separation analysis for the Talon-A hypersonic testbed for Stratolaunch. The company has completed a successful inert drop test and is working toward first flight.

Armstrong's TGALS project benefitted from store separation analysis.

Looking ahead: As flight testing of the CATNLF test article approaches, the team will support the airworthiness process to ensure flight safety by reporting results of store separation analyses.

Benefits

- **Risk-quantifying:** Characterizes separation behaviors
- **Validating:** Corroborates mitigation techniques
- **Partnering with external companies:** Helps companies develop validated toolsets for store-separation analysis

Applications

- In-flight payload release

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

Magnetic Payload Separation Demonstration

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 connect and release components quickly and reliably. In the approach, magnets hold an object to another main body then, through a sequenced command, engage a release function 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: Center Innovation Fund (CIF) resources were instrumental in enabling design and testing activities. The team demonstrated in a laboratory that a cluster of patterned magnets successfully held and released payloads of up to 200 pounds. The magnetic release was tested in 2022 using a remotely piloted Carbon-Z® Cub aircraft with a small remotely piloted experimental Prandtl-M glider (Preliminary Research Aerodynamic Design to Land on Mars) affixed under it using the magnetic release mechanism. The mechanism provided an additional push to the separation of the Prandtl-M that was not provided by a previous mechanical pin design. The successful flights featured smooth separation and a small-scale validation of the concept.

The team also lab tested a series of space-anchoring mechanisms and developed a recapture device that incorporates four robotic arms with magnetic end-effectors for grappling and a camera system for tracking the trajectory and orientation of an incoming drone. In a parallel effort, the team designed a static magnetic release device rated at 500 pounds to study benefits and challenges when scaling to higher load masses.

Looking ahead: Efforts are focused on combining all functions into a single operation. The 500-pound-rated demonstrator will undergo load analysis and safety review prior to fabrication and lab demonstration.

Benefits

- **Potentially safer and more efficient:** Eliminates design time, costs, and safety measures associated with pyrotechnic separation events
- **Versatile:** Can be incorporated into a wide variety of surfaces and object shapes with minimal reconfiguration
- **Enabling:** Increases functionality of release 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

An engineer programs a machine to cut, rotate and turn a block of steel to form a jury strut adaptor for a 10-foot model of the Transonic Truss-Braced Wing.

Gas Giant Atmospheric Probe

Current probe designs for planetary exploration of gas giants are limited by how deep within the atmosphere a probe can descend before the orbiting space craft disappears over the radio horizon and is no longer in range. This research effort studied the suitability of using lifting body aircraft and wing shapes to design a new probe that offers more control in its descent rate.

Work to date: Leveraging Center Innovation Fund (CIF) resources, the research team – which included two teams of mentored students from Tufts University – conducted a literature review then formulated a design based on previous lifting body research, notably the HL-10 lifting body. Data on this vehicle are widely available and the team had access to an HL-10 on display at Armstrong.

The team designed and produced a carbon fiber test article in late 2023. An aerodynamically similar model was flown in free flight to verify CG placement and general stability ahead of test article free flights. The team exceeded its CIF project goals and has a clear path to validate the concept through flight.

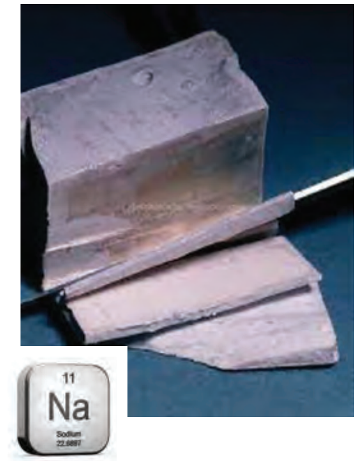
Looking ahead: Next steps to mature the technology are to build and flight test several subscale models. Using flight data and input from the planetary science community, the team will solicit funding for the next phase of the project, which will include a larger vehicle and testing in a more relevant environment.

Benefits

- **Informing:** Provides exploration platform for gas giant atmospheric research
- **Enables exploration:** Advances mission profiles that lead to previously unobtainable scientific information about the solar system and its formation

PI: John Bodylski | 661-276-3425 | John.K.Bodylski@nasa.gov

Climate Change Reversal Using Sodium as an Aircraft Fuel Additive



NASA researchers are investigating the feasibility of using an aviation fuel additive to reverse climate change via stratospheric aerosol injection (SAI). Also referred to as solar geoengineering, SAI is the concept of injecting particles into the stratosphere to reflect sunlight back into space and cool the planet. An ideal alternative fuel system would be readily produced by solar energy, burned efficiently to release energy, create an exhaust free of carbon dioxide, and result in reduced solar energy absorption to the atmosphere.

One possible solution could be the addition of sodium, as it produces sodium carbonate when burned with hydrocarbon fuel. In this concept, sodium carbonate would be released as a fine aerosol and, if released high enough in the atmosphere, could reduce absorption of sunlight in the atmosphere.

NASA Armstrong researchers are looking to partner with NASA's Glenn Research Center and Goddard Space Flight Center as they consider:

- How sodium, as a highly reactive metal, could be stored, transported, and fueled in an aircraft
- How sodium could be efficiently burned in an aircraft engine
- Whether the lower fuel energy density that the addition of sodium would present would be acceptable
- How to determine that the sodium carbonate produced does not contaminate areas where humans reside
- Whether society will accept geoengineering as a means to reverse climate change
- What particle size, density, and distribution in the atmosphere is needed to effectively reflect sunlight

Benefits

- **Environmentally impactful:** Potentially reduces global warming by reflecting sunlight out of the atmosphere
- **Efficient:** Burning sodium in transport aircraft could create an essentially "carbon negative" transport system

Applications

- Transport aircraft
- Specially designed geoengineering aircraft

PI: Timothy Risch | 661-276-6720 | Timothy.K.Risch@nasa.gov

Quest Mission

Engine Integration Activities Pass Key Milestones
Paul Dees | Paul.M.Dees@nasa.gov | 661-276-3433

Air Data Neural Network Research Pinpoints Key Flight Parameters
Kurt Long | Kurtis.R.Long@nasa.gov | 661-276-2258

Piloted Simulations and Flying Qualities Analysis Support Flight Readiness
Timothy Cox | 661-276-2126 | Timothy.H.Cox@nasa.gov

Researchers Analyze Structural Test Results to Prepare for First Flights
Ivan Chavez | Ivan.S.Chavez@nasa.gov | 661-276-5893

Ground Vibration Test Measures X-59 Modal Parameters
Natalie Spivey | 661-276-2790 | Natalie.D.Spivey@nasa.gov
Shun-fat Lung | 661-276-2969 | Shun-Fat.Lung-1@nasa.gov
Ben Park | 661-276-5406 | Benjamin.C.Park@nasa.gov

Control Surface Freeplay Testing Conducted to Assist in X-59 Aeroelastic and Aeroservoelastic Airworthiness
Natalie Spivey | 661-276-2790 | Natalie.D.Spivey@nasa.gov
John Atherley | 661-276-5269 | John.Atherley@nasa.gov

Trajectory Modeling Software to Aid Community Boom Exposure Tests
Forrest Carpenter | Forrest.L.Carpenter@nasa.gov | 661-276-7559

Electrified Aircraft Technologies

Flight-Qualified Cruise Motor Controllers (CMCs) Guide Future Electric Powertrain Component Development
Jacob Terry | Jacob.R.Terry@nasa.gov | 661-276-2231

X-57 Cruise Motor / Cruise Motor Controller Vibration Testing Informs Standards for Next-Gen Electric Aircraft
Keerti Bhamidipati | 661-276-7305 | keerti.k.bhamidipati@nasa.gov

Integration Yields Electromagnetic Interference Solution
Kassidy McLaughlin | Kassidy.McLaughlin@nasa.gov | 661-276-6209

Innovative Machine Interfaces Enable Electric System Monitoring Tools and Safety Mitigation
James Reynolds | James.R.Reynolds@nasa.gov | 661-276-6017

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

Supersonics Technologies

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

Instrumentation System Demonstrates Readiness to Support Supersonic Aircraft Test Flights
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

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

Enhanced ADS-B System for Supersonic Aircraft
Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov
- A Provisional and a non-provisional NASA patent was filed on April 6th, 2023, titled: "Automatic Dependent Surveillance Broadcast (Ads-B) Collision Avoidance Method And System For Aircraft That Can Exceed The Speed Of Sound"

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

Minimum Fuel Supersonic Test Trajectories
Matt Boucher | 661-276-2562 | Matthew.J.Boucher@nasa.gov

CarpetDIEM Phase III flight campaign team

NASA research pilot Scott "Jelly" Howe tested specialized retinal movement tracking glasses at Sikorsky Memorial Airport in Bridgeport, Connecticut on June 27, 2023. The glasses will help researchers working to design air taxis understand how a pilot visually experiences the cockpit and interacts with flight navigation tools.

Autonomous Systems

Enhancing Precision and Safety on High-Altitude Aircraft
Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov

Advanced Air Mobility (AAM) National Campaign
Cheng Moua | 661-341-8488 | Cheng.M.Moua@nasa.gov

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

Advanced Exploration of Reliable Operation at Low Altitudes: Meteorology, Simulation, and Technology (AEROcAST)
Luke Bard | 661-276-2756 | Luke.J.Bard@nasa.gov

Machine Learning Enables Virtual Windsock
Luke Bard | 661-276-2756 | Luke.J.Bard@nasa.gov

Enhanced Detect and Avoid Optical Sensing for Urban Air Mobility (UAM)
Ricardo Arteaga | 661-276-2296 | Ricardo.A.Arteaga@nasa.gov

Subscale Research Vehicles to Advance Flight Research
Jinu Idicula | Jinu.T.Idicula@nasa.gov | 661-276-2892

Flight Loads Laboratory

Coincident Heating and Loading Technique Supports Structural Tests
Chris Kostyk | 661-276-5443 | Chris.B.Kostyk@nasa.gov

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

Wing Store Structural Dynamics Airworthiness Clearance
Samson Truong | 661-276-2998 | Samson.S.Truong@nasa.gov
Natalie Spivey | 661-276-2790 | Natalie.D.Spivey@nasa.gov
Shun-fat Lung | 661-276-2969 | Shun-Fat.Lung-1@nasa.gov
Benjamin Park | 661-276-5406 | Benjamin.C.Park@nasa.gov

Structural Digital Twin Generation Tool
Chan-gi Pak | 661-276-5698 | Chan-Gi.Pak-1@nasa.gov
- Pak, C.-G., "Finite Element Model Tuning Using Analytical Sensitivity Values," *Journal of Aircraft*, Vol. 60, No. 4, 2023, pp. 1105–1117. https://doi.org/10.2514/1.C037178

Geometrically Nonlinear Structural Deformation Computation
Chan-gi Pak | 661-276-5698 | Chan-Gi.Pak-1@nasa.gov
- Pak, C.-G., "Linear and Geometrically Nonlinear Structural Shape Sensing from Strain Data," *AIAA Journal*, Vol. 61, No. 2, 2023, pp. 907–922. https://doi.org/10.2514/1.J062165

Improving Aerospace Vehicle Efficiency

New Propeller/Fan Reduces Noise and Improves Efficiency
Jason Lechniak | 661-276-2620 | Jason.A.Lechniak@nasa.gov

CFD Analysis of Swept Wings with Bell-Shaped Lift Distribution
Seung (Paul) Yoo | 661-276-5247 | Seung.Y.Yoo@nasa.gov
Trong Bui | 661-276-2645 | Trong.Bui-1@nasa.gov

Investigating Laminar Flow
CATNLF Lead: Mike Frederick | 661-276-2274 | Mike.Frederick-1@nasa.gov
CLIP Flow Rake PI: Aliyah Ali | 661-276-5533 | Aliyah.N.Ali@nasa.gov
CATNLF PI: Michelle Banchy | 757-864-9097 | Michelle.N.Banchy@nasa.gov (NASA Langley)

Prandtl Flying Wing
Jason Lechniak | 661-276-2620 | Jason.A.Lechniak@nasa.gov
David Berger | 202-358-2473 | Dave.E.Berger@nasa.gov

Glider Swarm Sensor Distribution
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
Jeffrey Ouellette | 661-276-2152 | Jeffrey.A.Ouellette@nasa.gov

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

Fiber Optic Sensing System (FOSS)

Fiber Optic Technology Aids Wing Calibration Tests
Francisco Pena | 661-276-2622 | Francisco.Pena@nasa.gov

NASA's 'Rocket Box' FOSS Flies on Launch Vehicles
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

Next-Generation Laser to Boost Testing Capabilities
Patrick Chan | 661.276.6170 | Hon.Chan@nasa.gov

FOSS Aims to Advance Hypersonic Research
Patrick Chan | 661.276.6170 | Hon.Chan@nasa.gov

Avionics and Instrumentation Technologies

Aeronautics Research Mission Directorate
(ARMD) Test Data Portal (ATDP)
Minh Luu | 661-276-7006 | minh.v.luu@nasa.gov

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

SonicSonde for Atmospheric Sensing
Kimberly Bestul | 661-276-3315 | Kimberly.A.Bestul@nasa.gov

Adaptable Radiometric Measurement System (ARMS)
Chris Kostyk | 661-276-5443 | Chris.B.Kostyk@nasa.gov

Model-Based System Analysis &
Engineering (MBSA&E) Framework
Felipe Valdez | 661-276-3330 | felipe.valdez@nasa.gov

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

Deploying Unmanned Aircraft Systems
(UAS) to Study Water Quality
Todd Jackson | 661-276-5822 | Todd.J.Jackson@nasa.gov

Inter-System Communications
Paul Bean | 661-276-2451 | Paul.Bean@nasa.gov

Visual Radar Advances Aircraft Sensor Systems
Matthew Versteeg | 661-276-3902 | Matthew.L.Versteeg@nasa.gov

Space and Hypersonics Technologies

Leading Edge Irradiation Assembly (LEIA)
Jackson Winter | 661-276-5579 | Jackson.T.Winter@nasa.gov

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

Magnetic Payload Separation Demonstration
Paul Bean | 661-276-2451 | Paul.Bean@nasa.gov

Gas Giant Atmospheric Probe
John Bodylski | 661-276-3425 | John.K.Bodylski@nasa.gov

Climate Change Reversal Using Sodium
as an Aircraft Fuel Additive
Timothy Risch | 661-276-6720 | Timothy.K.Risch@nasa.gov

Awards and Special Features

ECI Update: Enhancing Parachutes by
Instrumenting the Canopy (EPIC)
Erick Rossi De La Fuente | 661-276-2651 |Erick.R.Rossidelafuente@nasa.gov
L. J. Hantsche | 662-276-2199 | L.J.Hantsche@nasa.gov

ECI Update: CryoMag Coupler: A Magnetic Cryogenic
Dust-Tolerant Coupler for Space Applications
Shideh Naderi | 661-276-3106 | Shideh.Naderi@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

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) NASA's X-59 research aircraft moves from its construction site to the flight line at Lockheed Martin Skunk Works in Palmdale, California, on June 16, 2023. This milestone kicks off a series of ground tests to ensure the X-59 is safe and ready to fly. Credits: Lockheed Martin

(back cover) NASA's C-20 aircraft departs NASA Armstrong for a Soil Moisture Active Passive Validation Experiment (SMAPVEX) flight campaign.

NASA/SP-20240003091