NATO ET-145 Formation Flying for Improved Efficiency
October 12-16, 2015

Automated Cooperative Trajectories

FOR A MORE EFFICIENT AND RESPONSIVE AIR TRANSPORTATION SYSTEM

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Automated Cooperative Trajectories

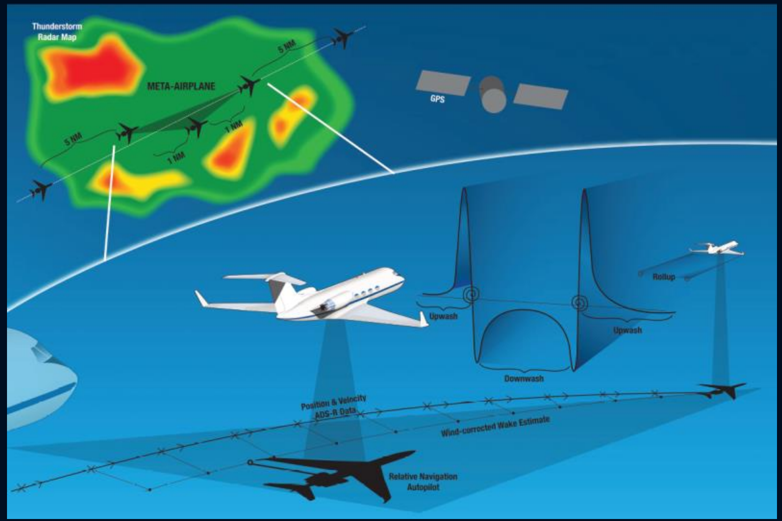
Project Overview

The NASA Automated Cooperative Trajectories (ACT) project is advancing ADS-B enabled autopilot capabilities to improve airspace throughput and vehicle efficiency.

- Meta-Aircraft Operations for safe, reduced separation and decreased air traffic control workload
- Formation Wake Surfing for fuel savings

The ACT project is run out of the NASA Armstrong Flight Research Center in Edwards, CA

- NASA's Transformative Tools and Technologies (T^3) and Flight Demonstrations and Concepts (FDC) Projects
- ACT is a small project (1-3 researchers) that started following C-17 CAPFIRE flight experiment* in June 2010
- Next Milestone: 2016 Dual G-III Flight Experiment



Meta-Aircraft Concept

*Pahle, J., et al., "An Initial Flight Investigation of Formation Flight for Drag Reduction on the C-17 Aircraft," AIAA 2012-4802

NASA Armstrong Contributions

to Formation Flying for Improved Efficiency

Flight Experiments

F-18 AFF
1998-2001

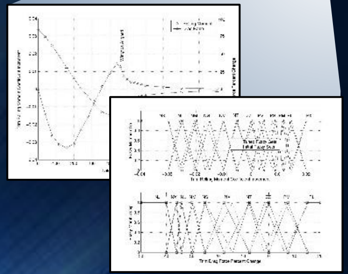
F-18 / DC-8 SURF
2003

C-17 CAPFIRE
2010

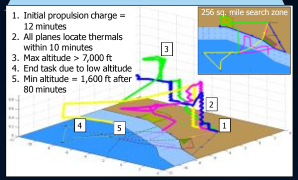
G-III ACT
2016 *(planned)*

2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011[a] 2012[b] 2013[c] 2014 2015 2016

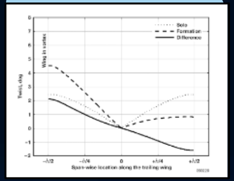
Simulation Studies



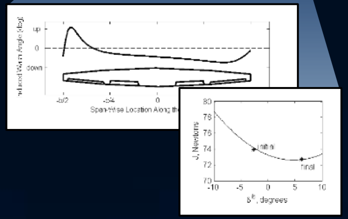
Fuzzy Wake Estimator
2003-2004



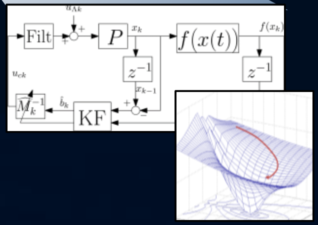
Small UAV Flocking
for Energy Efficiency
2005-2006



Static Aeroelastic
Effects of FF
2007-2008



Spanwise Lift Distribution
Optimization
2010-2011



Peak-Seeking Drag
Optimization
2011-2012

2011[a]: Analysis of Trim and Compressibility Effects
Kless, Aftosmis, Ning
(NASA ARC)

2012[b]: Airspace Corridors for Formation Flying
Hornby and Xue
(NASA ARC)

2013[c]: Formation Flight Dispatch Strategy
Hange (NASA ARC)

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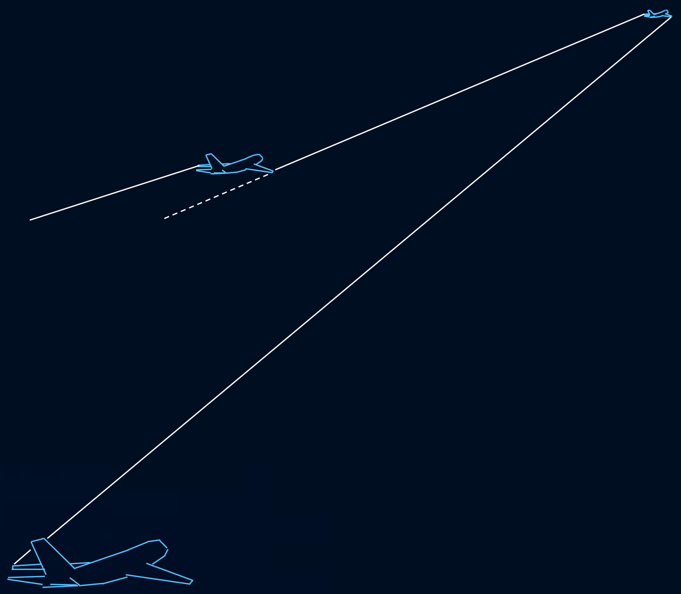
Update from Spring 2015

Advocacy and Collaboration

Apr. 8-9: Spring WakeNet USA Meetings, Chicago, USA
Apr. 20-24: Spring NATO Meetings, Rzeszow, POL
Apr. 28: Convergent Aeronautics Solutions (CAS) Proposal Briefing, NASA HQ, Washington DC, USA
Jun. 3-4: RTCA Global Aviation Symposium, Washington DC, USA
Jun. 10: USAF AMC, Scott AFB, Belleville, USA
Oct. 12-16: Fall NATO Meetings, Prague, CZE
Nov. 10-11: Fall WakeNet USA Meetings, Hampton, USA

Technical Status Updates

1. ADS-B Enabled Autopilot Hardware-in-the-Loop Simulation
2. Throttle and Wake Display Piloted Simulation Evaluation
3. G-III Wake Encounter Structural Analysis
4. Flight Test Planning for '16 Flight Research Campaign



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2016 G-III Flight Test - Motivation

Wake surfing for fuel efficiency has been demonstrated in flight.

1995, German Institute for Fluid Mechanics

- 1st In-Flight Demonstration of the Technique
- Peak-Seeking Lateral Control
- 10% Power Reduction

2001, NASA Autonomous Formation Flight

- Independent Confirmation of German Results
- Vortex Mapping
- Manual Control Only
- 14% Fuel Savings

2010, NASA-USAF C-17 CAPFIRE

- 1st Demonstration of Extended Formation Flight
- Primarily Manual Control
- 7-8% Fuel Flow Reduction

2012, DARPA-USAF-Boeing C-17 $AVE

- 1st Fully Automatic Demonstration
- Prototype to a Production System
- 10% Fuel Flow Reduction

Commercial cargo and passenger operators remain skeptical that these fuel savings can be safely and affordably achieved with civilian airframes and avionics, without aircrew and passenger discomfort.

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2016 G-III Flight Test - Objectives

1. Data-Driven Characterization of the Benefits and Impacts to Commercial Transports
   A. Mature wake surfing performance modeling for commercial transport airframes
   B. Assess passenger ride quality for commercial transport wake surfing
   C. Advance understanding of the effects of commercial transport wake surfing on engines and actuators

2. Suitability Assessment of ADS-B for Cooperative Autonomy
   A. Evaluate a meta-aircraft system architecture based on commercial off-the-shelf civilian data-link technology and autopilot systems.
   B. Characterize the 1090 MHz ADS-B data link for cooperative trajectory procedures.
   C. Characterize the 1090 MHz ADS-B data link for wake surfing applications.

3. Tools and Methods to Support Wake Surfing Technology
   A. Evaluate relative navigation, guidance, and control strategies for wake surfing applications.
   B. Gather pilot comments on wake displays.

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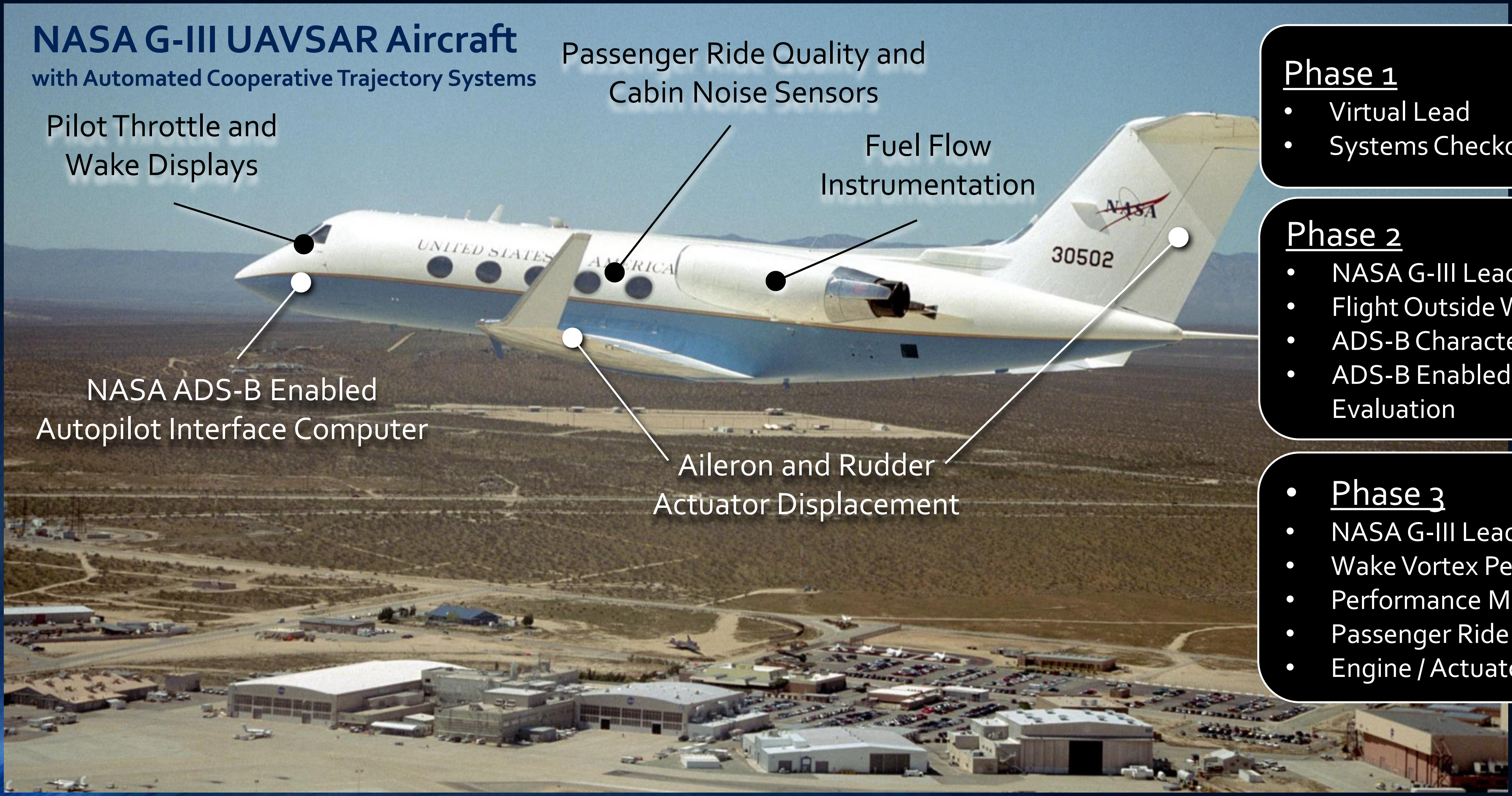
2016 G-III Flight Test - Approach



Phase 1
- Virtual Lead
- Systems Checkout

Phase 2
- NASA G-III Lead Aircraft
- Flight Outside Wake Influence
- ADS-B Characterization
- ADS-B Enabled Autopilot Evaluation

- **Phase 3**
- NASA G-III Lead Aircraft
- Wake Vortex Penetration
- Performance Measurements
- Passenger Ride Quality
- Engine / Actuator Impacts

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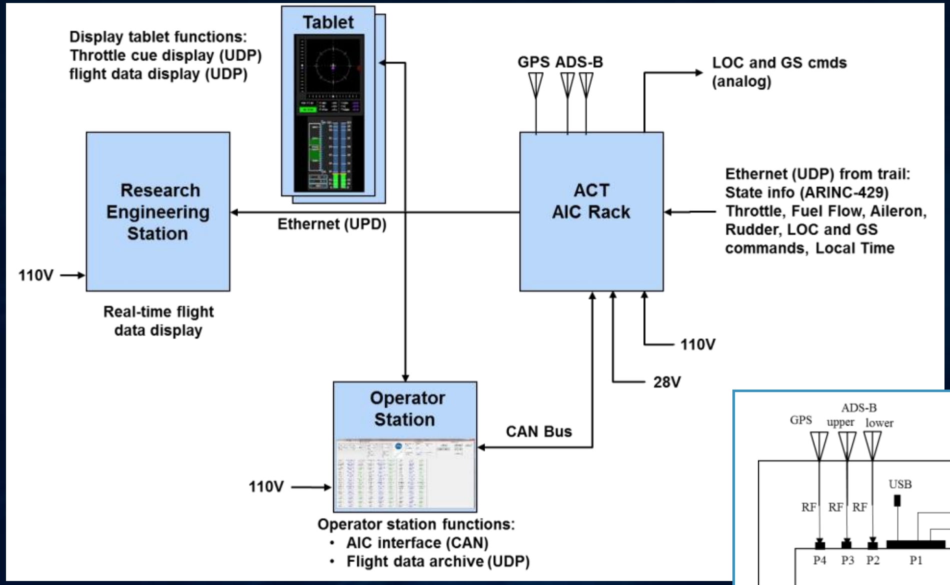
ADS-B Hardware-in-the-Loop Simulation

The Autopilot Interface Computer (AIC) provides a programmable ADS-B enabled autopilot capability for the G-III test aircraft.

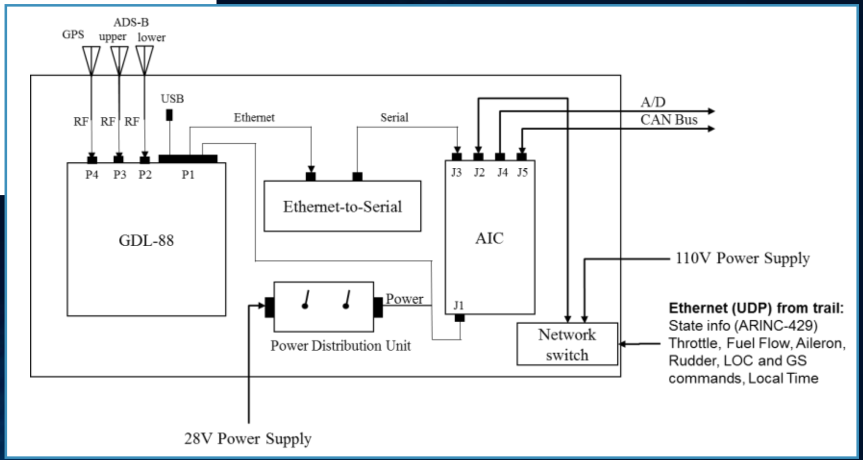


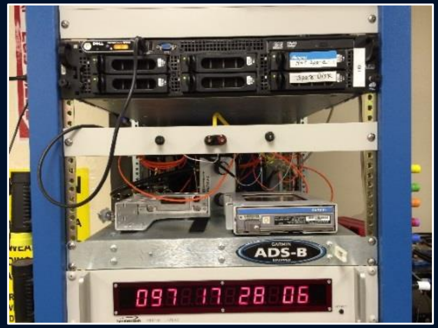
Inputs

- ADS-B In Messages from the Lead Airplane
- Local Aircraft Data
- Researcher Trajectory Commands
- Researcher-Selectable GNC Gains

Outputs

- Analog ILS Localizer and Glideslope Commands
- Pilot Throttle Cues and Wake Display Data





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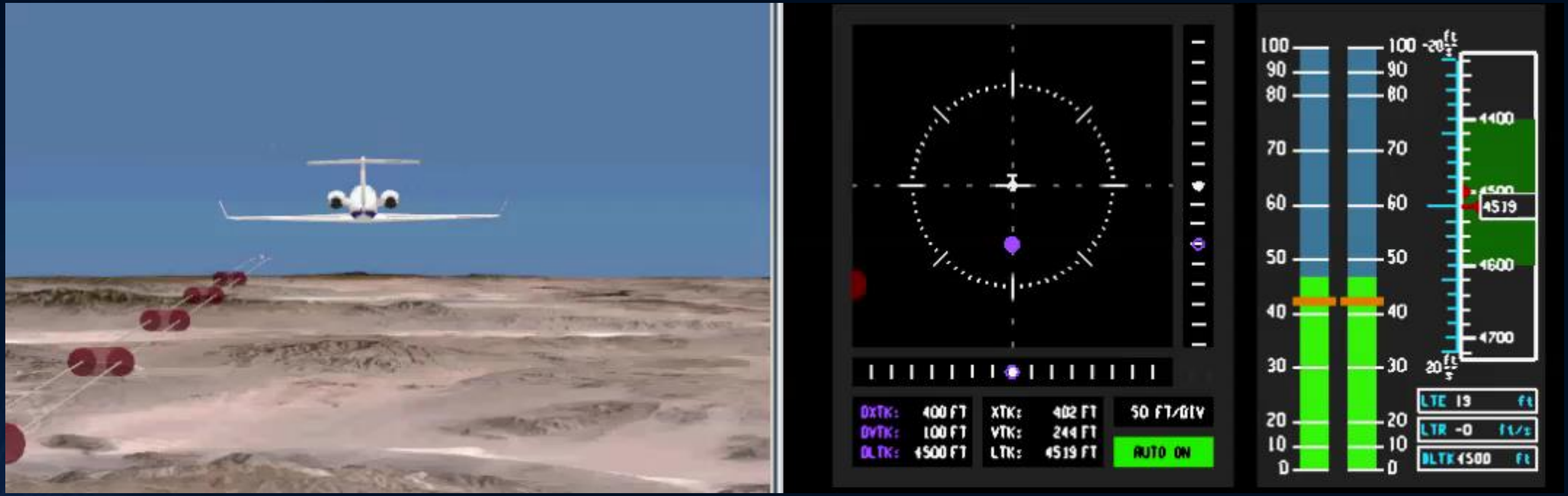
Throttle and Wake Display Pilot Evaluation



Aggressive throttle motion caused by a combination of errors in ADS-B message handling (since fixed) and high gains in the throttle cueing logic.

Excessive engine cycling will degrade fuel savings from wake surfing. Throttle commands also cause pitch transients.

The NASA G-III does not have an autothrottle, so the AIC will give the pilot throttle cues via a tablet display mounted on the yoke.

For situational awareness, a wake display will also be included on the tablet for flight evaluation.

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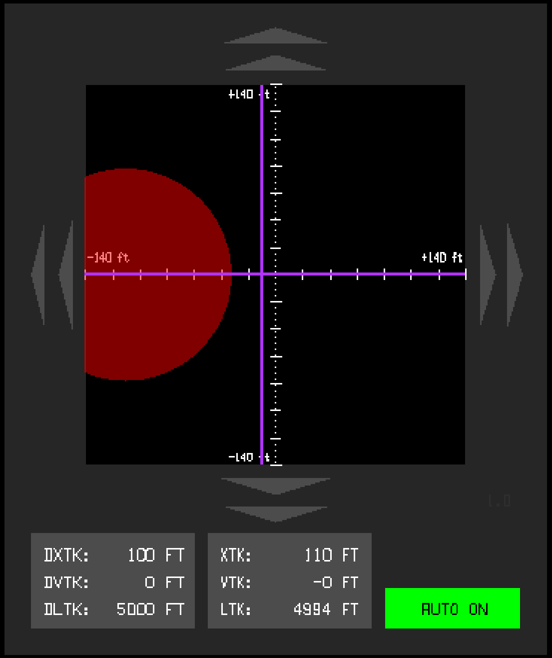
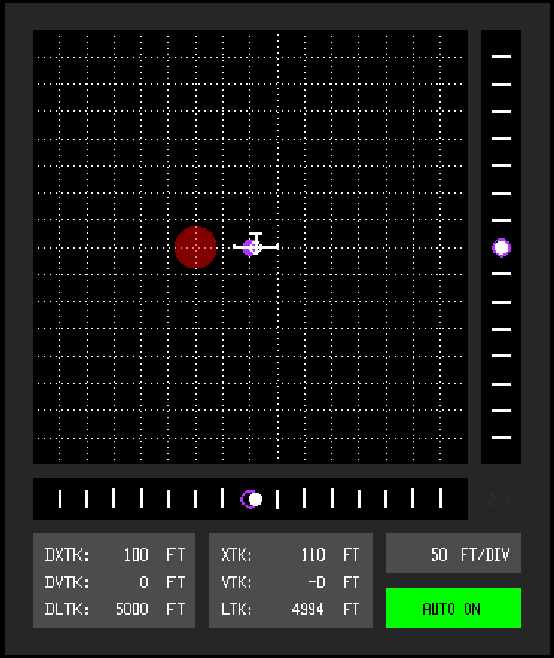
Throttle and Wake Display Pilot Evaluation

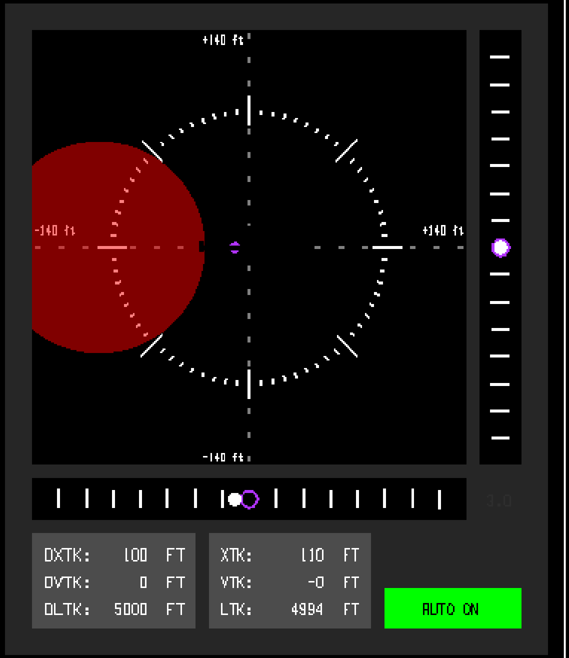
ILS Style Design



Chase View – Auto-Scale



Chase View – Fixed Scale



The project designed three wake displays and asked NASA test pilots to evaluate them in the G-III piloted simulation.

<u>Piloted Simulation Evaluation</u>

- Four NASA Test Pilots
  - Three G-III Test Pilots
  - One Pilot with C-17 FFS Experience and NASA F-18 AFF Experience
- One NASA Engineer
  - Civilian Pilot
  - Designed the Pilot Displays for the G-III UAVSAR
- Initial Feedback
  - Pilots generally found the displays useful
  - No concensus on the best design out of the three
  - Pilots requested rate cues during formation join-up
  - None of the pilots wanted uncertainty information on the wake position estimate – interesting to see if this holds during flight tests.

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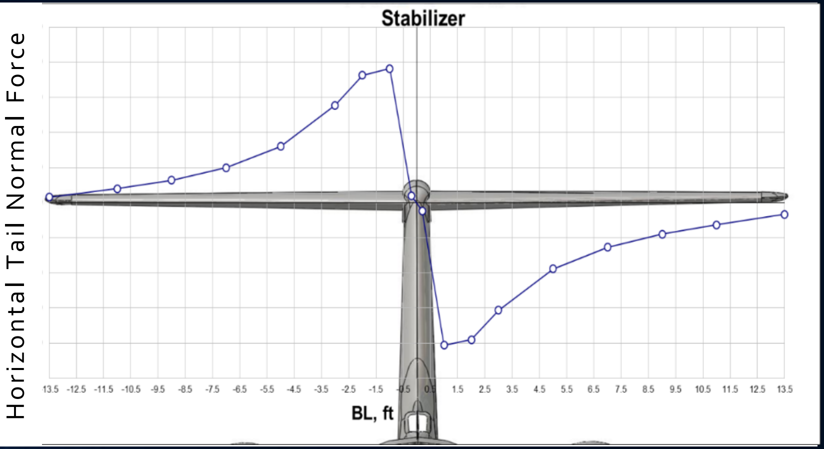
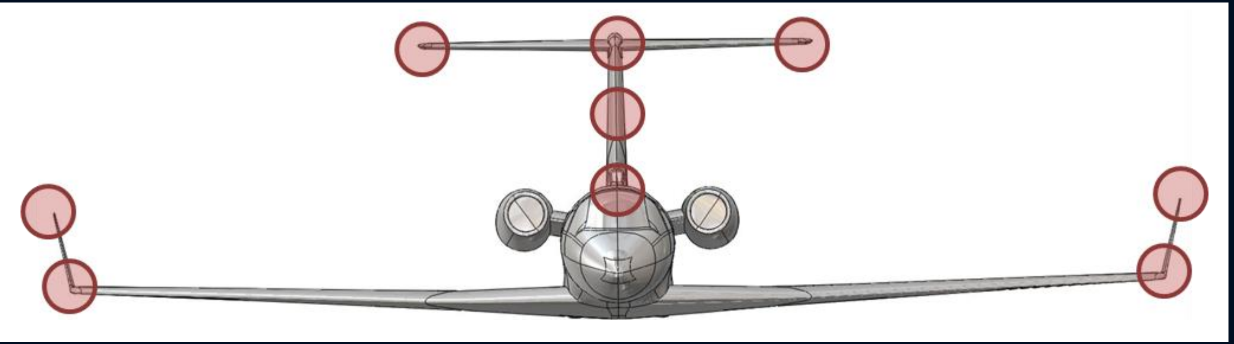
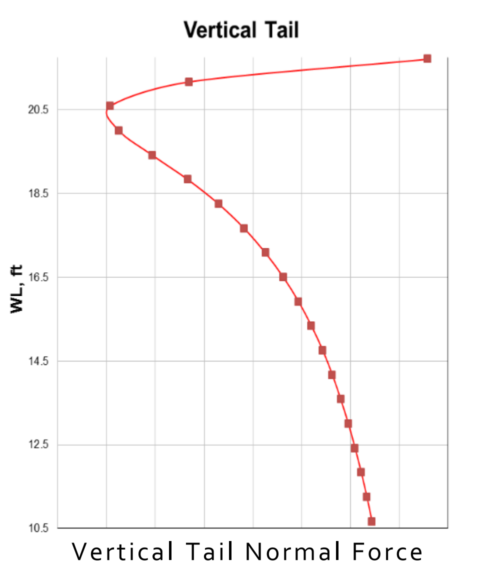
G-III Wake Encounter Structural Analysis





The G-III airframe was analyzed for vortex impingement at multiple locations. Critical points are the winglets and the intersection of the vertical and horizontal tail.



Predicted loads are within NASA safety margins for testing without instrumentation and active loads monitoring.

- Medium lead aircraft weights
- One nautical mile in trail
- Altitudes at 30,000 feet and above
- Mach numbers at 0.75 and below

NATO ET-145: Formation Flying for Improved Efficiency

Technology Pillars

1. Operations, Logistics, and Policy

A. Impacts to Trailing Airplane

This area covers loads, fatigue and aeroelastic effects on the trailing aircraft, as well as potential adverse impacts to the engines and control effector actuators due to continuous, long-duration flight in the wake. This topic also covers aircrew and passenger ride quality concerns, as well as the possibility for structural overload during inadvertent wake crossings.

B. Routing and Scheduling Constraints

Novel scheduling/routing tools and procedures are needed for homogeneous formations and for the more complex problem of mixed groupings of transports, tankers, fighters, and unmanned aircraft. Some nations operate small numbers of large transports and have a particular interest in heterogeneous formations. Work under this topic must also support interoperability among aircraft from partner nations participating in coalition operations.

Challenges include the problem of formations composed of aircraft with different departure and/or destination airfields as well as performance characteristics. This topic may also address special considerations applicable to formations of future combat aircraft. In the longer term, we may consider mixed formations of military and civilian aircraft. However there will be some sensitivities to resolve.

C. Regulations and Policy

Regulatory agencies, such as the FAA and EASA / Eurocontrol, present challenges related to separation requirements, aircraft and avionics certification, and impacts to airspace control. This topic will also cover any special requirements for pilot training.

2. Onboard Equipment

A. Applicability to Current Aircraft

To help expedite the application of this technology to the current generation of aircraft while maintaining an acceptable retrofit/upgrade cost, system architecture studies must be undertaken for likely candidate aircraft. Also taken into account should be synergy with other technologies, such as automated aerial refueling systems, which share many of the same requirements as formation flight systems.

B. Data Links and Sensors

Data link requirements for automated formation flight include message content, timing, and encoding resolution, as well as availability, integrity, and reliability. Existing data link technologies, such as 1090 MHz ADS-B, may not be able to meet these requirements without modification.

Flight within the wake has the potential to corrupt onboard wind estimates and control system feedback paths by altering the readings of air data sensors such as angle of attack and sideslip. This topic may also address novel onboard sensors, such as LIDAR, for wake detection.

C. Avionics and Flight Deck Design

Requirements for autopilot systems include trim authority and bandwidth. Special modifications to engine control and inner-loop flight control systems may also be required to maintain precise, stable formation flight despite wake disturbance effects. Other avionics, such as IFF and TCAS, might be affected by formation operations. This topic also includes pilot displays for situational awareness and pilot throttle cueing for aircraft without auto-throttle capability.

3. Algorithms and Optimization

A. Wake Detection and Crossing Prevention

In situ measurements from onboard sensors combined with information transmitted by other aircraft in the formation can be used to improve estimates of the location and strength of the wake. Additionally, knowledge of the wake location and the performance characteristics of the trailing airplane can be used to develop algorithms to minimize the potential for inadvertent wake crossings, especially during formation maneuvering and data link communication anomalies.

B. Performance Optimization

The position of the trailing airplane within the wake can be optimized for minimum fuel flow under the constraints of maintaining acceptable aircraft handling characteristics, ride quality, impact to the airframe, and risk of inadvertent wake crossing. Additionally, real-time manipulation of the aircraft trim schedule, to include some or all of the wing and tail aerodynamic effectors and possibly differential thrust, to account for the wake's asymmetric upwash field can lower trim drag and improve formation flight efficiency.

C. Wake Modeling

Simulation and analysis tools require appropriate and computationally efficient models of wake propagation through the atmosphere and aerodynamic influence effects on the trailing vehicles, possibly including the special applications of turboprop airplanes, rotorcraft and small UAVs. Onboard formation flight systems will require real-time wake propagation algorithms for predicting the size, strength and location of the wake based on information transmitted from the lead.

D. Formation Control

Advanced methods are required for control of large (3 or more airplanes) formations to ensure maximum performance, minimum maneuvering requirements and string stability.

Automated Cooperative Trajectories

Relation to ET-145 Technology Pillars

1. Operations, Logistics, and Policy
   - A. Impacts to Trailing Airplane

     [redacted]

     Passenger Ride Quality

     Engine / Actuator Impacts

   - B. Routing and Scheduling Constraints

     [redacted]

     Interaction with the WakeNet USA Community

     Discussions with NASA Airspace Modeling and Control Groups

   - C. Regulations and Policy

     [redacted]

     Discussions with FAA and RTCA

2. Onboard Equipment
   - A. Applicability to Current Aircraft

     [redacted]

     ILS Autopilot Interface

   - B. Data Links and Sensors

     [redacted]

     ADS-B Characterization and Evaluation

   - C. Avionics and Flight Deck Design

     [redacted]

     ILS Autopilot Interface

     Pilot Throttle and Wake Displays

3. Algorithms and Optimization
   - A. Wake Detection and Crossing Prevention

     [redacted]

     Wake Prediction and Estimation

     Wake Avoidance

   - B. Performance Optimization

     [redacted]

     Trajectory Optimization

     Trim Optimization

   - C. Wake Modeling

     [redacted]

     Prediction-to-Flight Comparisons for 60k lbs Class Airplane

   - D. Formation Control

     [redacted]

     Relative Guidance and Control

Questions?

Technology Validation Roadmap

German Institute for Fluid Mechanics

1995

- Proof of concept
- No data link
- 10% power reduction
- Rudimentary peak-seeking control

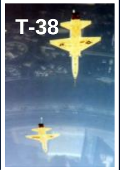
NASA Dryden Flight Research Center

2001

- Research data link and autopilot
- 14% fuel savings (manual)
- Validated system requirements
- Detailed wake effect mapping

US Air Force Test Pilot School

2001

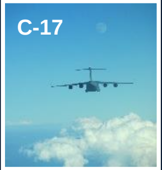


- Manually flown
- No data link or autopilot
- 9% fuel savings (2-ship)
- Inconclusive 3-ship evaluation

Close Formation Flight Research

NASA DFRC / USAF FTC

2010



- Proof of extended formation concept
- Production military data link and autopilot
- 7-8% fuel savings (manual)

DARPA / AFRL / Boeing

2012 - 2013

- Modified C-17 autopilot
- Production military data link
- 10% fuel savings (autopilot)
- Wake avoidance algorithms

Extended Formation Flight Research

Partnership between NASA AFRC, ARC, GRC, and LaRC (proposed)

2013 - 2017

- Airspace simulation study
- Hardware-in-the-loop multi-vehicle simulation
- Flight research

Optimal Scheduling and Real-Time Routing Tools

Wake Estimation and Avoidance, Performance Optimization

Suitability of ADS-B for Wake Surfing

Flight Data: Performance and Ride Quality

Operational Demonstration with Industry Partners (to be determined)

2018 - 2020

- Commercial Data Link (1090 MHz ADS-B In and Out)
- Meta-Aircraft functionality integrated with commercial avionics
- FAA participation (in the US NAS)
- Pilot / ATC displays and procedures
- Demonstrate scheduling / routing tools
- Commercial transport class aircraft

Path To Commercially-Viable Automated Meta-Aircraft Operations