Wake-Surfing:
Automated Cooperative Trajectories

May 2017

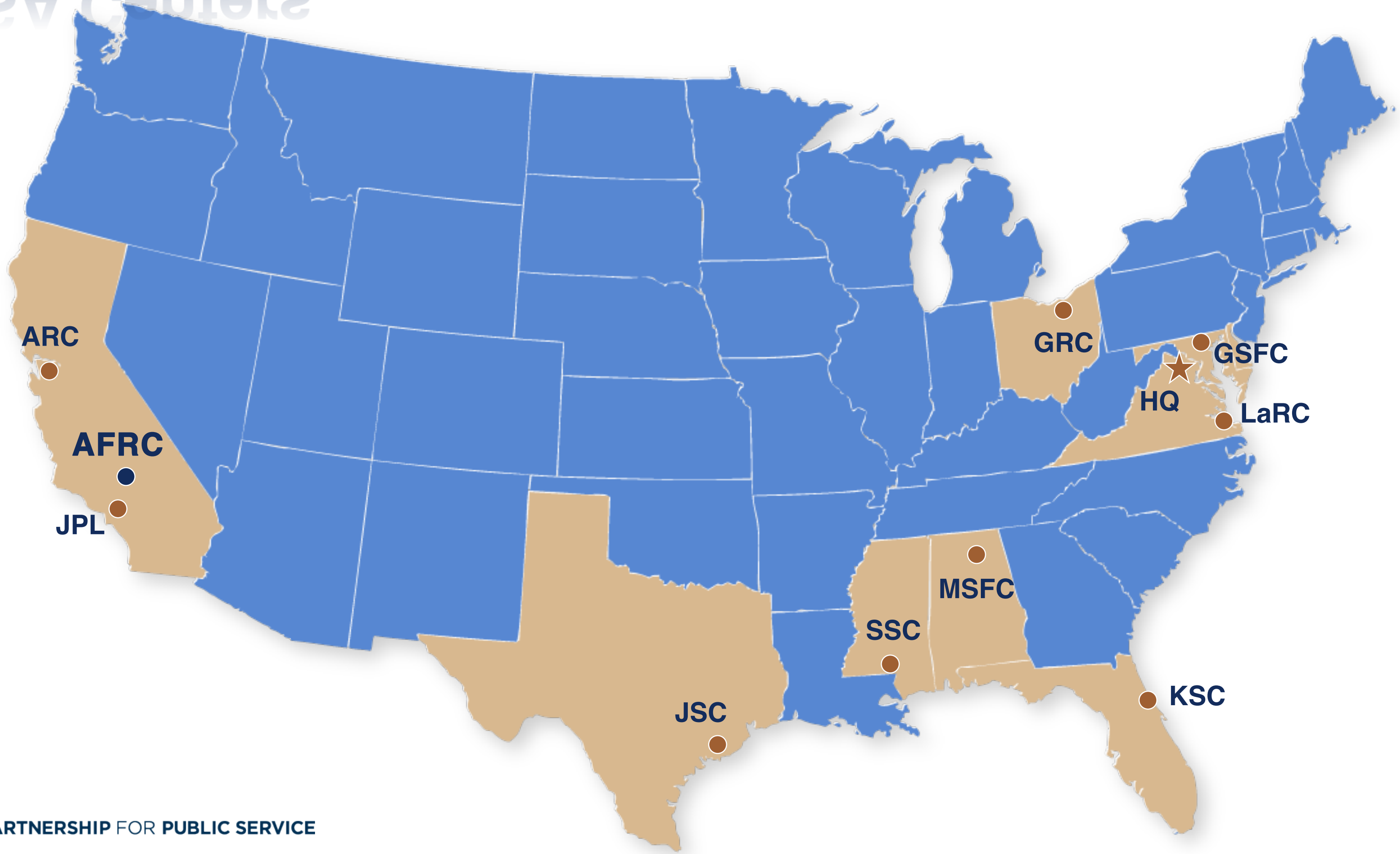
Nelson Brown

Center Overview

NASA Armstrong Flight Research Center

May 2017

NASA Centers



PARTNERSHIP FOR PUBLIC SERVICE

THE BEST PLACES TO WORK in the Federal Government®

NASA rated #1 Large Agency five years running!

Fiscal Year (FY) 2016 Budget

NASA

~$19.3 billion budget

17,220 civil servants

40,000 contractors

Armstrong

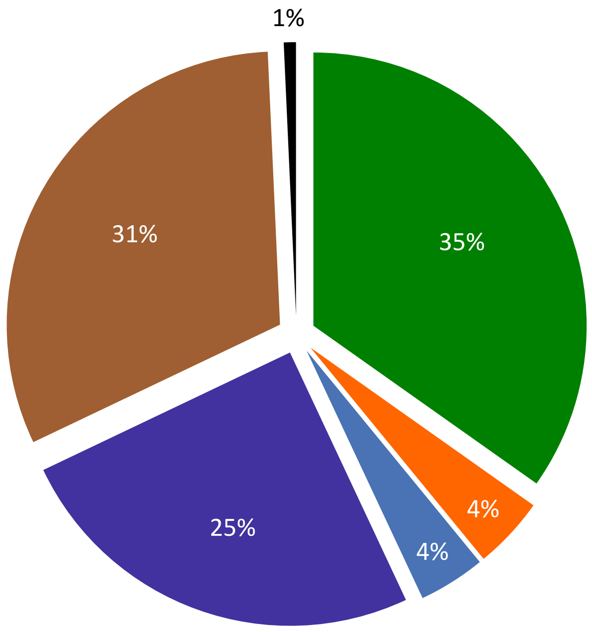
~$287.3 million budget

538 civil servants

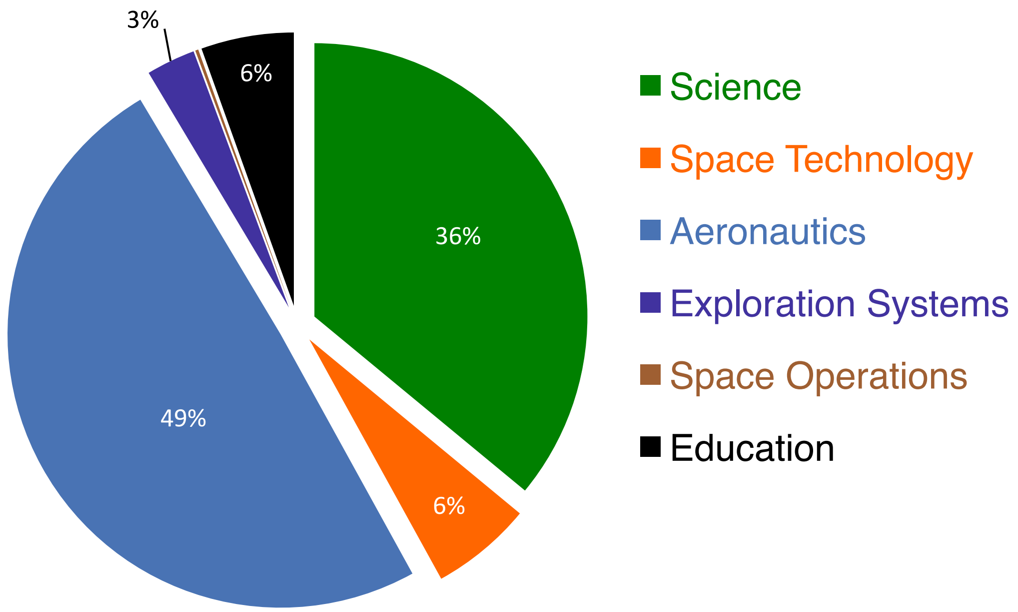
579 contractors

126 student interns

NASA Program Funds



AFRC Program Funds



Neil A. Armstrong Flight Research Center

Neil A. Armstrong

Research Test Pilot (1955-1962)

Command Pilot of Gemini 8 (1966)

Commander of Apollo 11 (1969)

Mystery creates wonder and wonder is the basis of man’s desire to understand.

– **Neil A. Armstrong**

Armstrong Mission

Advancing Technology and Science Through Flight

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

2 Validate space exploration concepts

3 Conduct airborne remote sensing and science observations

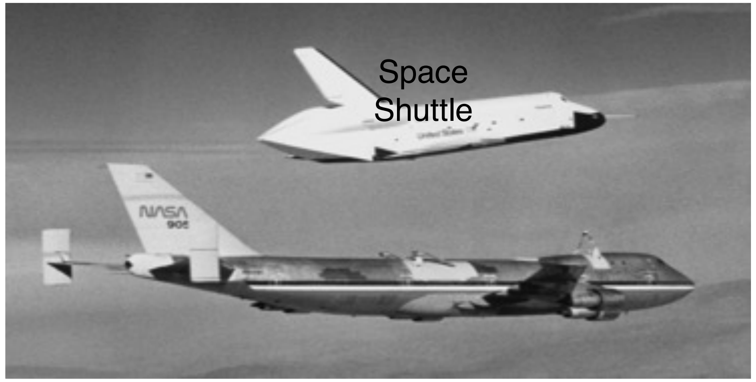
Ikhana MQ-9 Predator B Unmanned Aircraft System

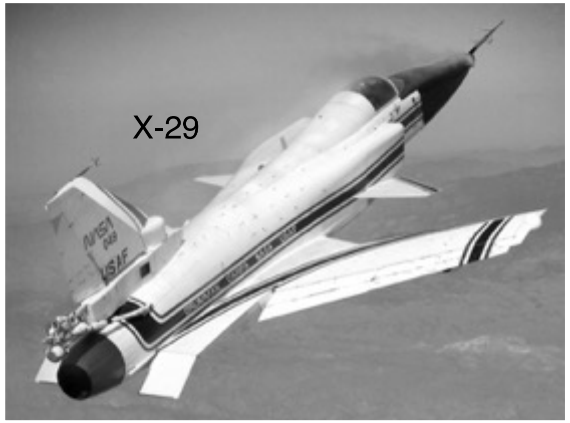
Stratospheric Observatory for Infrared Astronomy (SOFIA)

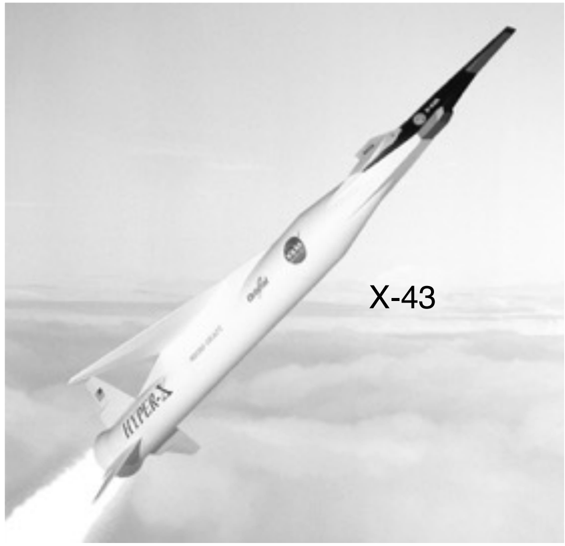
X-56 Multi-Utility Technology Testbed

Armstrong Vision

To Separate the Real from the Imagined Through Flight

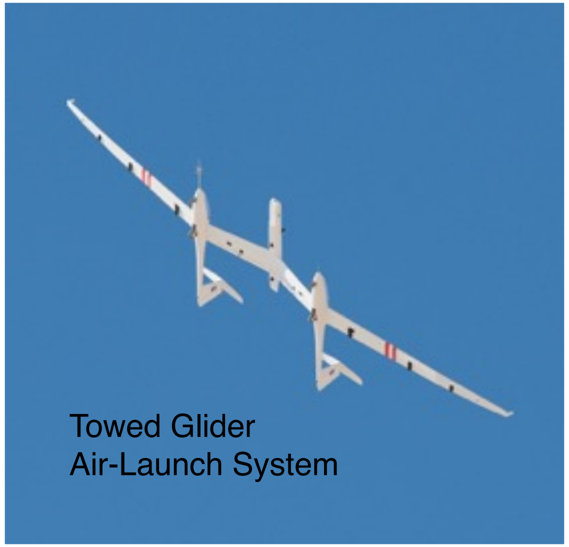






Armstrong Vision

To Separate the Real from the Imagined Through Flight




F-15 Quiet Spike

Armstrong Flight Research Center

Edwards AFB, California,
main campus:

- Year-round flying weather
- 301,000 acres remote area
- Varied topography
- 350 testable days per year
- Extensive range airspace
- 29,000 feet of concrete runways
- 68 miles of lakebed runways
- Supersonic corridor
- U.S. Air Force Alliance

NASA Armstrong Science Operations Building 703

Palmdale, California

Home to

- Stratospheric Observatory for Infrared Astronomy (SOFIA) – Astrophysics
- Earth Science – Airborne Science

Aeronautics

NASA is With You When You Fly

Ensure the right balance among physics-based analysis, simulation, ground testing, and flight research.

NASA is With You When You Fly

Every U.S. aircraft and U.S. air traffic control tower has NASA-developed technology on board.

NASA Armstrong is committed to transforming aviation by

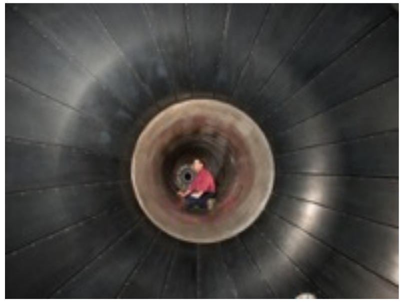
- Dramatically reducing its environmental impact
- Maintaining safety in more crowded skies
- Paving the way to revolutionary aircraft shapes and propulsion

What is NASA Aeronautics Working On?

Research Activities Reflect NASA's Vision to Ultimately Transform Aviation

- Air traffic management tools to reduce delays and save fuel
- Aircraft shapes that reduce aviation's impact on the environment
- Data that reveals the real impacts of alternative jet fuels
- Tests of new technologies that increase autonomy in the aviation system
- Technologies that lower the effects of sonic booms
- Ground tests on ways to detect and prevent engine icing in jet engines



Six Aeronautics Research Strategic Thrusts

What Led to This Strategic Direction?

The World Wants to Travel More …

1. Safe, Efficient Growth in Global Operations
2. Innovation in Commercial Supersonic Aircraft

While Being Fuel Efficient and Reducing Environmental Impacts …

3. Ultra-Efficient Commercial Vehicles
4. Transition to Low-Carbon Propulsion

And Taking Advantage of the New Technologies

5. Real-Time System-Wide Safety Assurance
6. Assured Autonomy for Aviation Transformation

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

Automated Cooperative Trajectories

FOR A MORE EFFICIENT AND RESPONSIVE AIR TRANSPORTATION SYSTEM

CURT HANSON
NASA ARMSTRONG FLIGHT RESEARCH CENTER

Automated Cooperative Trajectories

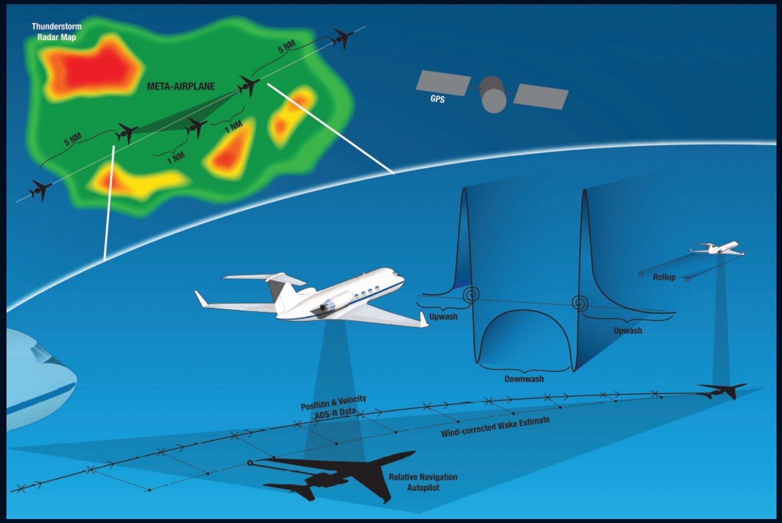
Project Overview

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

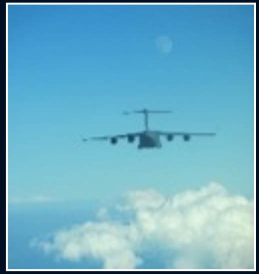
NASA Armstrong Contributions
to Formation Flying for Improved Efficiency

Flight Experiments

F-18 AFF
1998-2001

F-18 / DC-8 SURF
2003

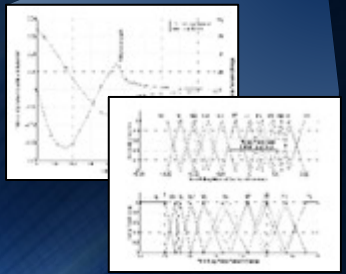
C-17 CAPFIRE
2010



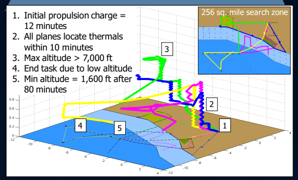
G-III ACT
2016 *(planned)*

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

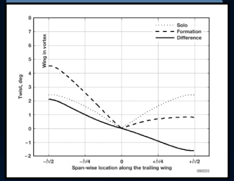
Simulation Studies



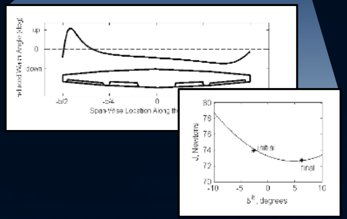
Fuzzy Wake Estimator
2003-2004



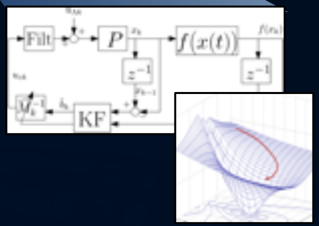
Small UAV Flocking for Energy Efficeincy
2005-2006



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)

Automated Cooperative Trajectories

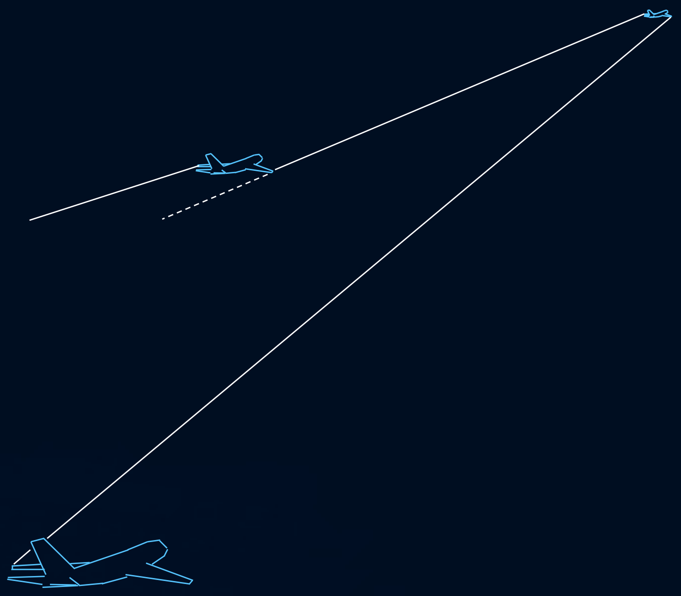
Update from Spring 2015

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



Automated Cooperative Trajectories

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.

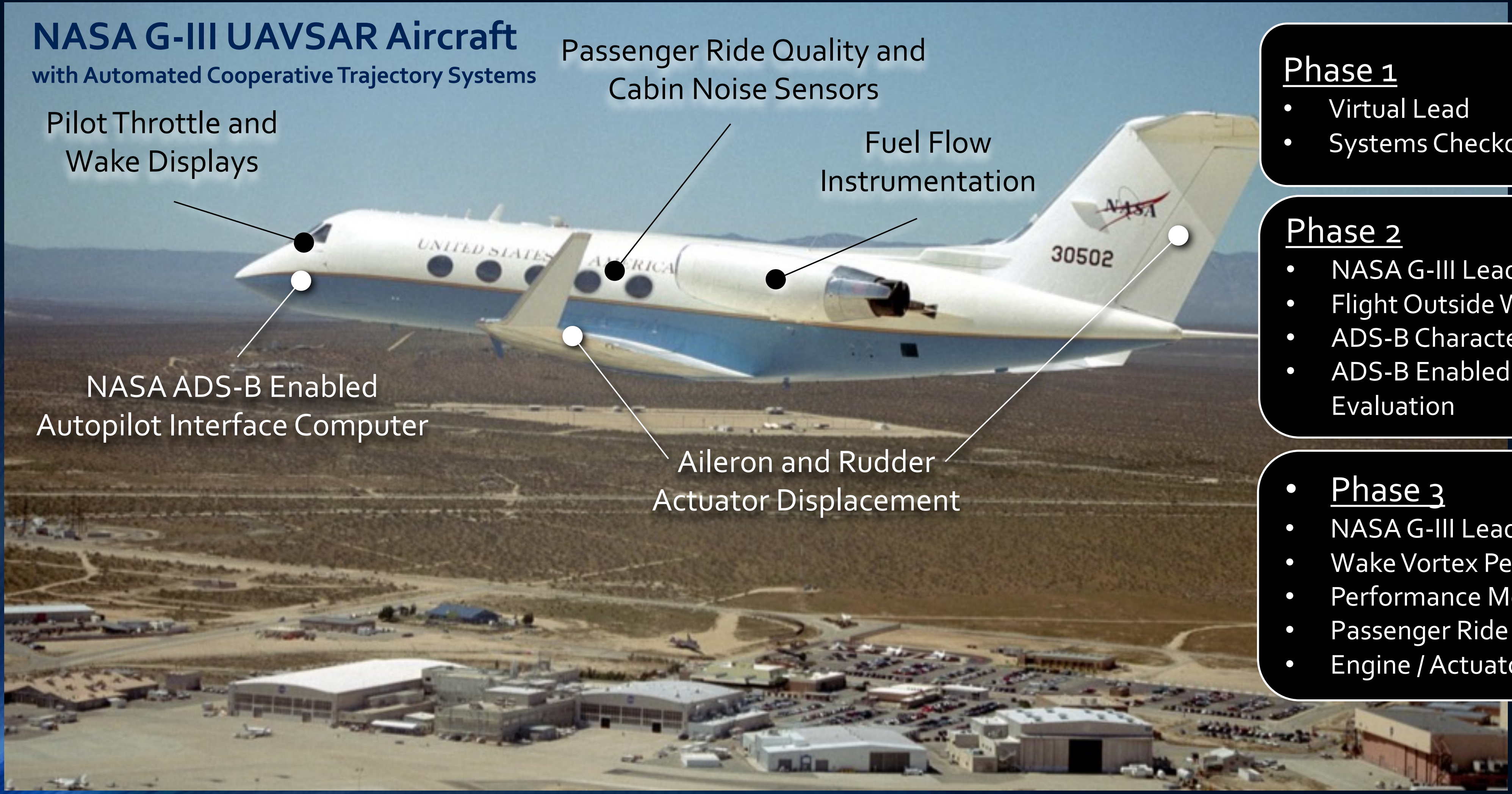
Automated Cooperative Trajectories

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.

Automated Cooperative Trajectories

2016 G-III Flight Test - Approach



Phase 1
- Virtual Lead
- Systems Checkout

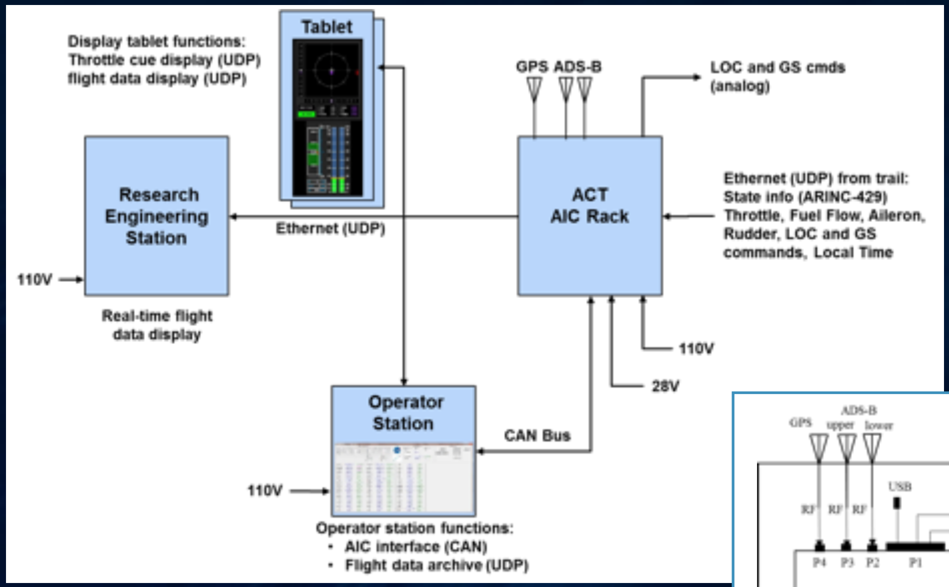
Phase 2
- NASA G-III Lead Aircraft
- Flight Outside Wake Influence
- ADS-B Characterization
- ADS-B Enabled Autopilot Evaluation

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

Automated Cooperative Trajectories

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.

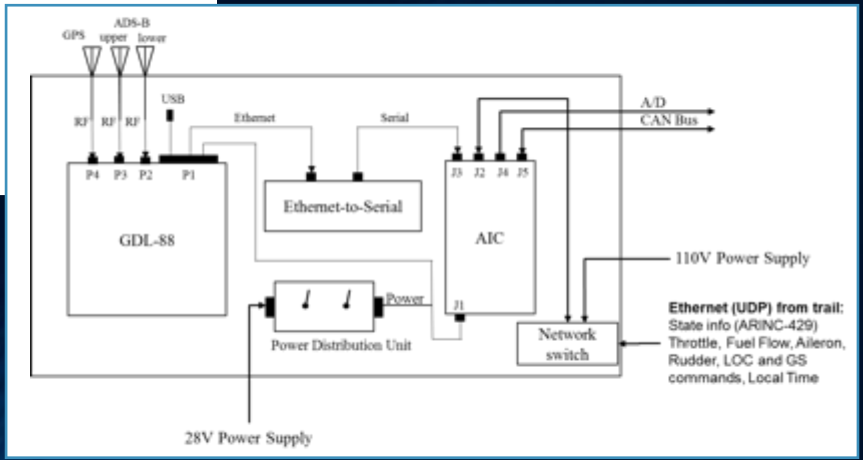


Inputs

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

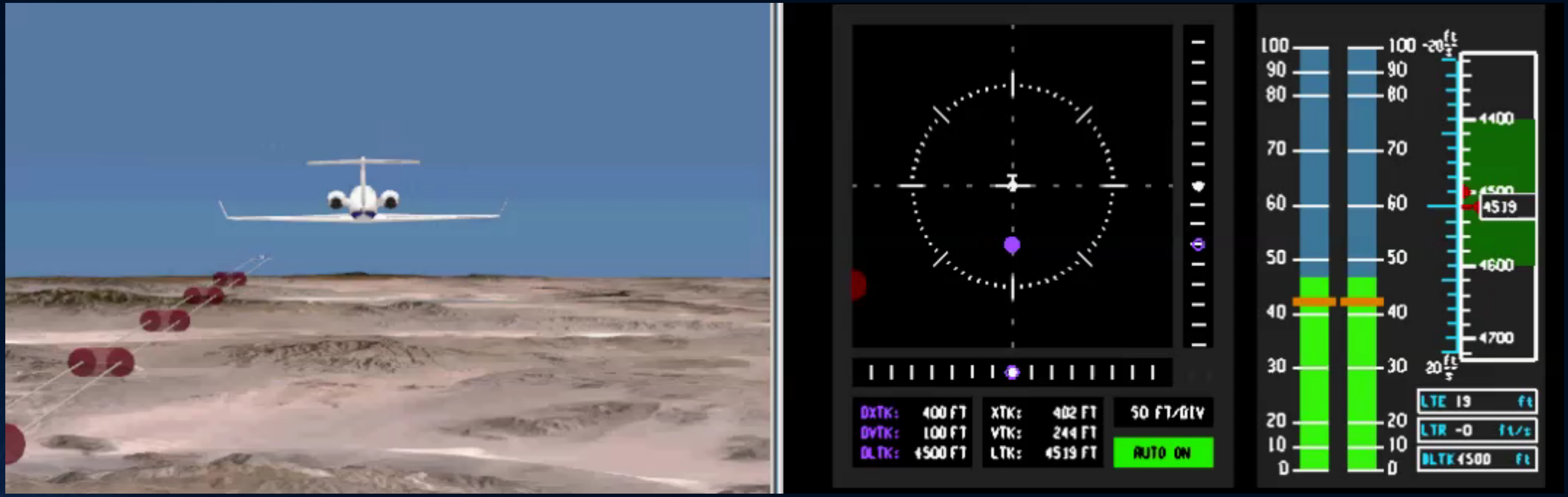
Outputs

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



Automated Cooperative Trajectories

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.

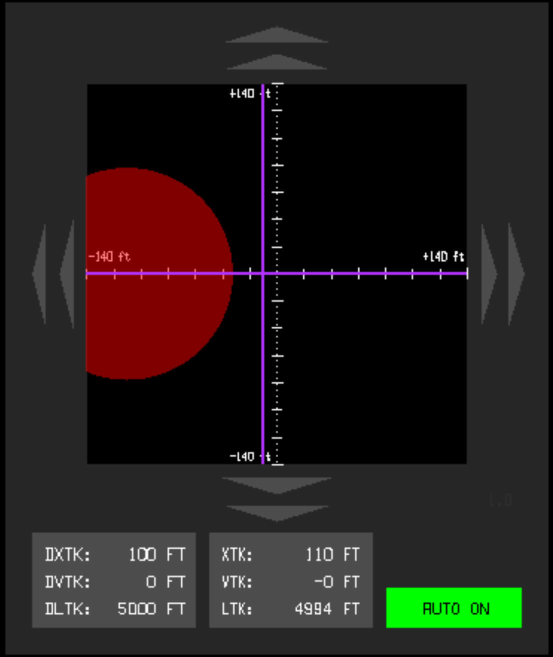
The NASA G-III does not have an autothrottle, so the AIC will give the pilot throttle cues via a tablet display mounted on the yoke.

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

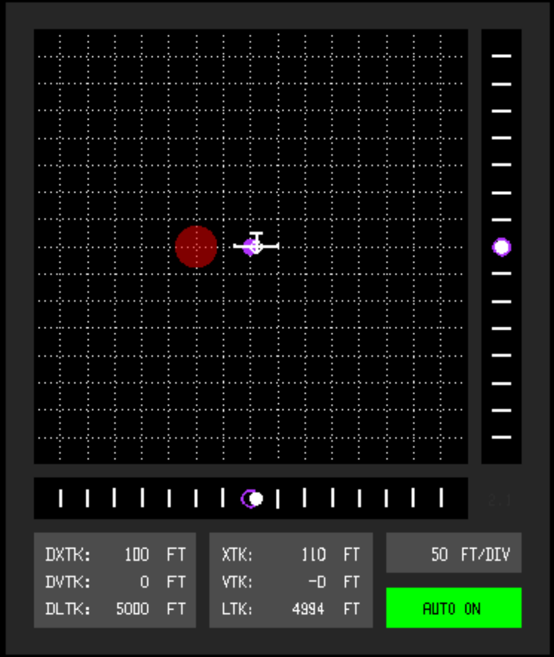
Automated Cooperative Trajectories

Throttle and Wake Display Pilot Evaluation

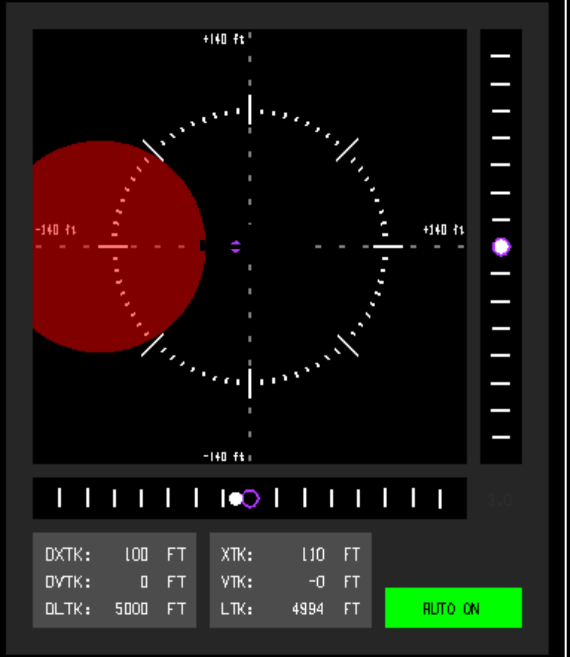
ILS Style Design



Chase View – Auto-Scale



Chase View – Fixed Scale



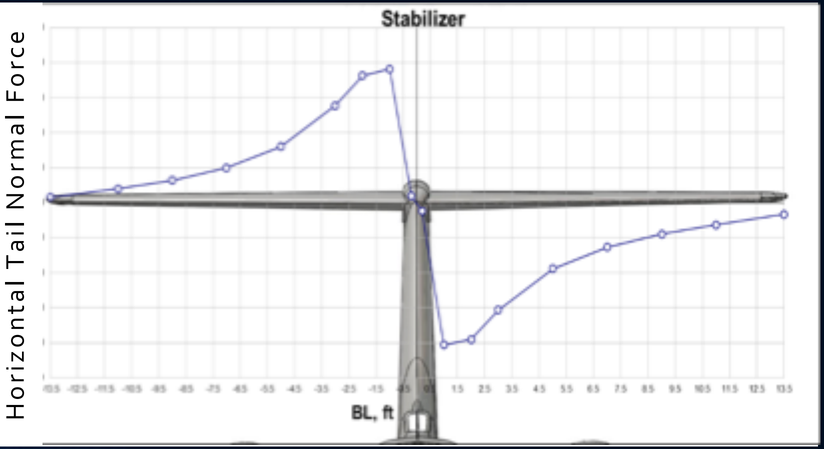
The project designed three wake displays and asked NASA test pilots to evaluate them in the G-III piloted simulation.

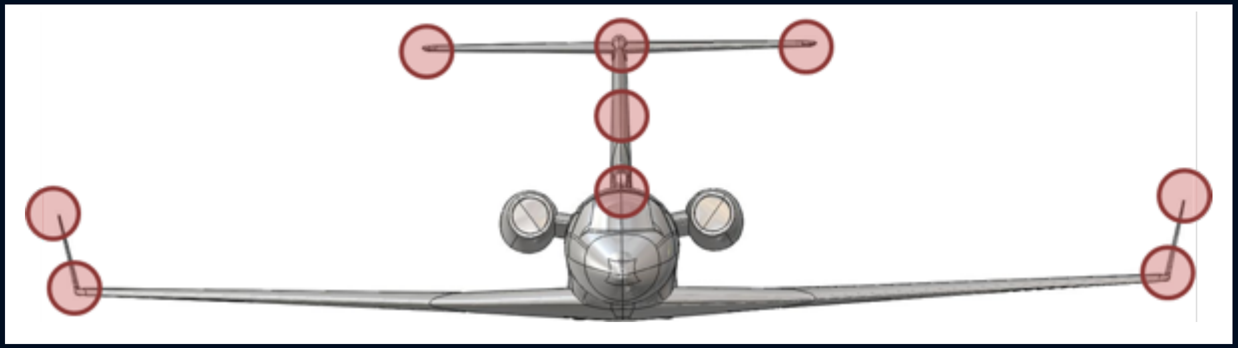
Piloted Simulation Evaluation

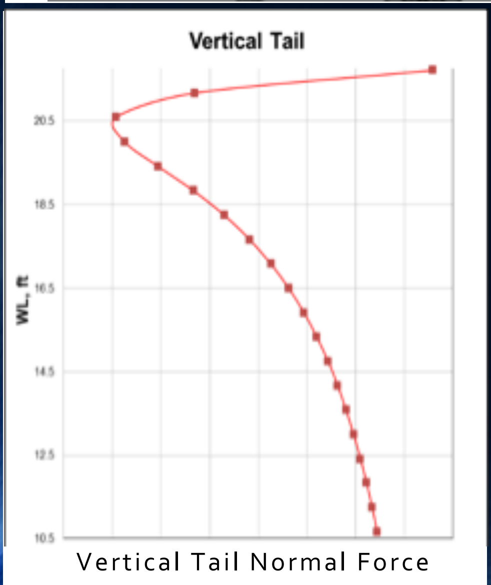
- Four NASA Test Pilots
  - Three G-III Test Pilots
  - One Pilot with C-17 FFS Experience and NASA F-18 AFF Experience
- One NASA Engineer
  - Civilian Pilot
  - Designed the Pilot Displays for the G-III UAVSAR
- Initial Feedback
  - Pilots generally found the displays useful
  - No concensus on the 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.

Automated Cooperative Trajectories

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

Technology Validation Roadmap

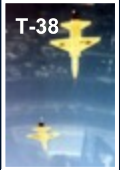
1995 — *German Institute for Fluid Mechanics*

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

2001 — *NASA Dryden Flight Research Center*

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

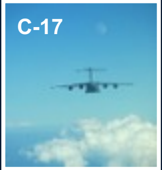
2001 — *US Air Force Test Pilot School*



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

Close Formation Flight Research

2010 — *NASA DFRC / USAF FTC*



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

2012 - 2013 — *DARPA / AFRL / Boeing*

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

Extended Formation Flight Research

2013 - 2017 — *Partnership between NASA AFRC, ARC, GRC, and LaRC (proposed)*

- 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

2018 - 2020 — *Operational Demonstration with Industry Partners (to be determined)*

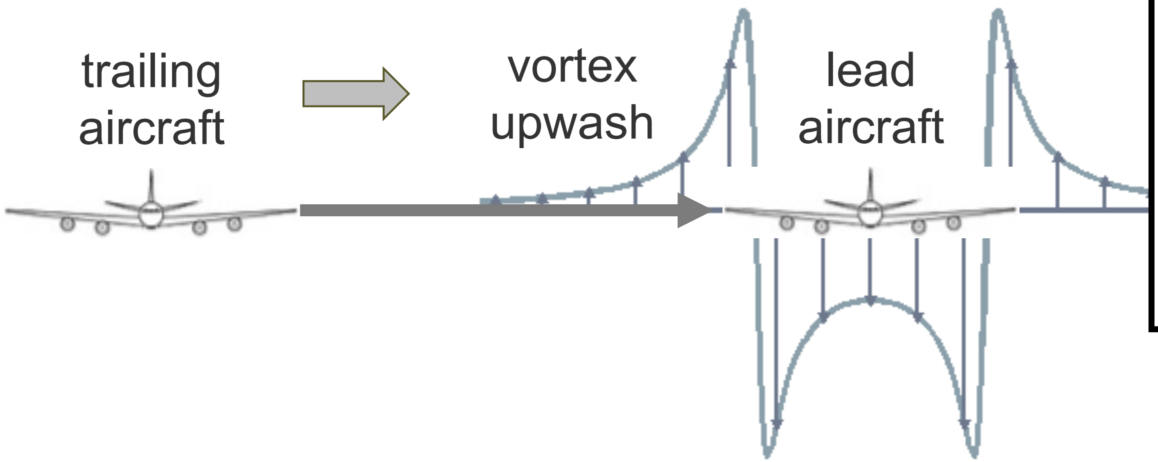
- Commercial Data Link (1090 MHz ADS-B In and Out)
- Meta-Aircraft functionality integrated with commercial avionics
- FAA participation (in the US NAS)
- Pilot / ATC displays and procedures
- Demonstrate scheduling / routing tools
- Commercial transport class aircraft

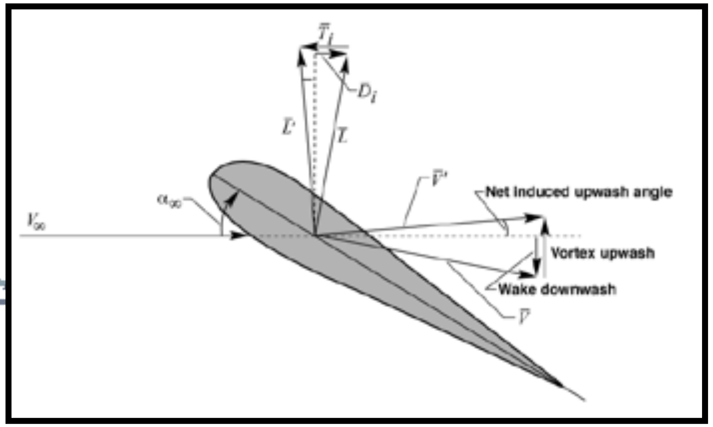
Path To Commercially-Viable Automated Meta-Aircraft Operations

The Aerodynamics of Cooperative Trajectories

In cruise flight, an aircraft produces a wake that retains its structure and strength for several miles. The wake is characterized by the following:

- An area of downwash in the center of the wake
- Twin regions of upwash outboard of the vortex cores





Two NASA aircraft in close formation flight (2001)

Sustained flight within the upwash produces two primary effects on the trail aircraft:

- A forward rotation of the lift vector, lowering induced drag → 10-15% fuel flow reduction for the trail airplane
- An asymmetric span-wise lift distribution results in a roll trim imbalance → highly non-linear, requiring automated station keeping

C-17s in Formation Flight

Military Formation Flight systems already exist!

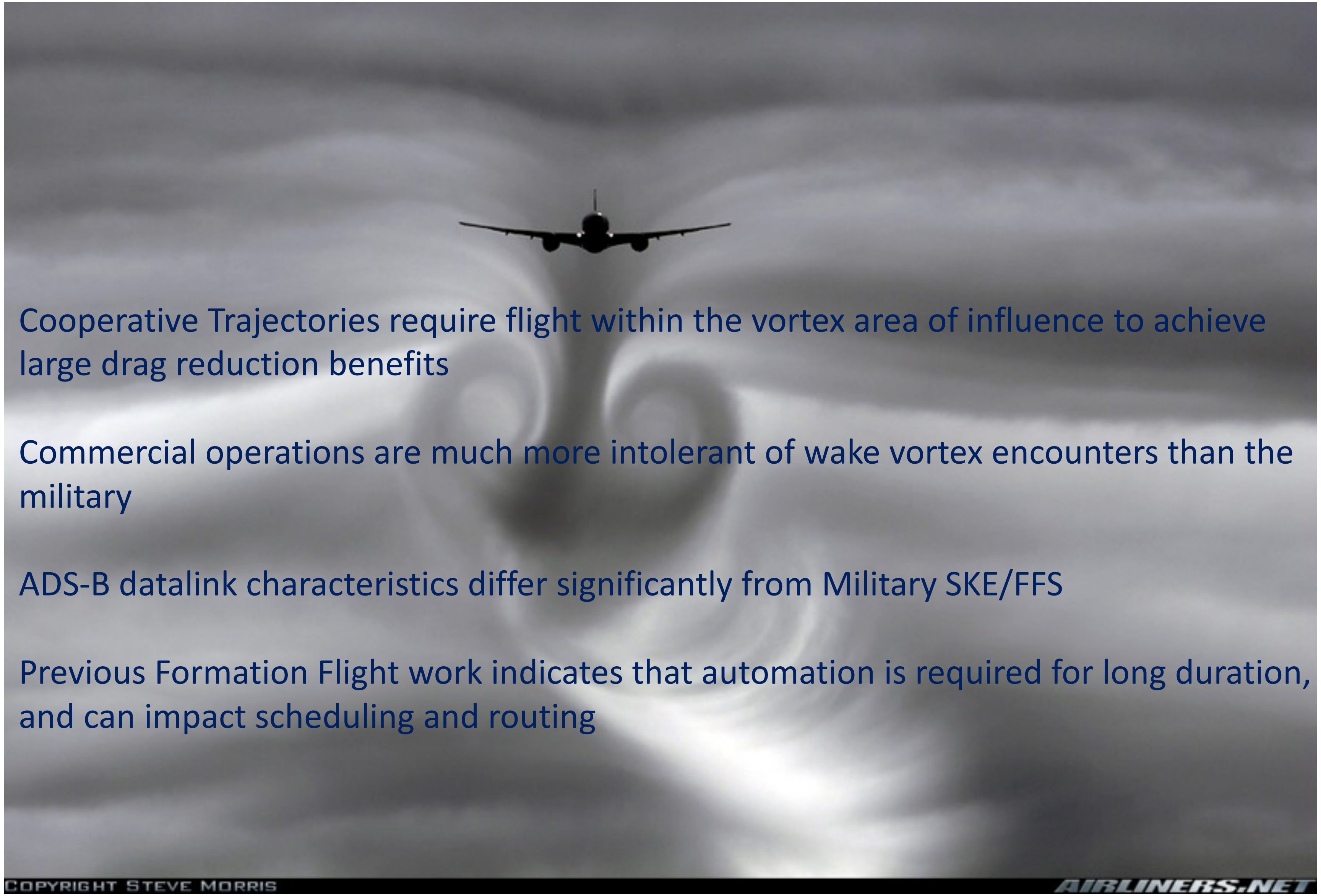
NASA partnered with USAF/AFTC in 2010 to explore drag reduction.
7-8% fuel flow reduction (partially automated)

Production C-17 aircraft used in test

Boeing/AFRL conducted flight tests in 2012-2013 under the SAVE program (Surfing Aircraft Vortices for Efficiency)

For extended durations > 90 minutes, fuel burn savings for SAVE exceeded 10% and were accomplished fully automated

Air Force photo by Bobbi Zapka:
http://www.edwards.af.mil/shared/media/photodb/photos/100916-F-9126Z-024.jpg



Cooperative Trajectories require flight within the vortex area of influence to achieve large drag reduction benefits

Commercial operations are much more intolerant of wake vortex encounters than the military

ADS-B datalink characteristics differ significantly from Military SKE/FFS

Previous Formation Flight work indicates that automation is required for long duration, and can impact scheduling and routing

Technological and Operational Challenges

Air-to-Air Relative Navigation and Autopilot Control

- 1090 MHz ADS-B provides only coarse Lat / Lon / Alt resolution (±15 ft. horizontal, ±25 ft. vertical) for pilot display. NASA is developing:
  - Wake estimation algorithms to combine ADS-B reported information, probabilistic wake model predictions, and measured steady-state wake effects
  - Wake avoidance algorithms to prevent wake crossings
  - Integration with existing heading and altitude hold autopilot modes

Integration into the NAS

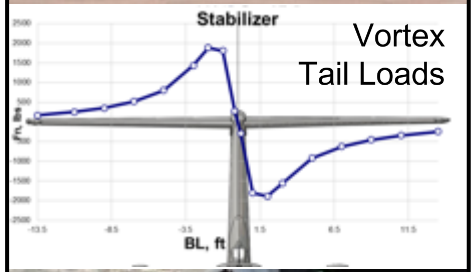
- ACT requires modification of the current FAA minimum separation standards
  - Cooperative trajectories are already used in the NAS – MARSA (Military Assumes Responsibility for Separation of Aircraft)
  - Cooperative trajectory operations are well-aligned with a new FAA initiative for operations from closely-spaced parallel runways

Potential Adverse Impacts

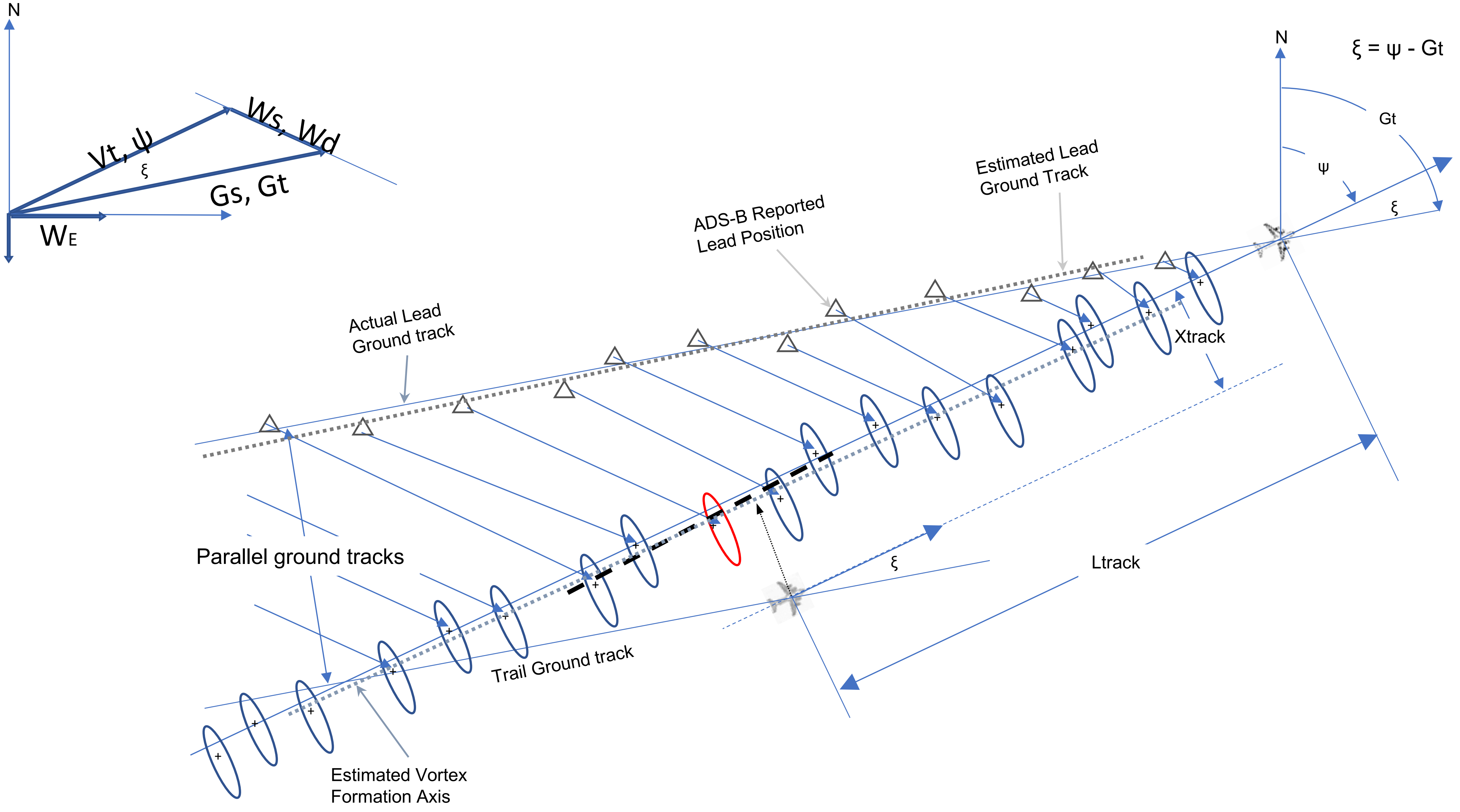
- Loads and fatigue
- Duty cycles on aileron actuators
- Passenger ride quality

Operations

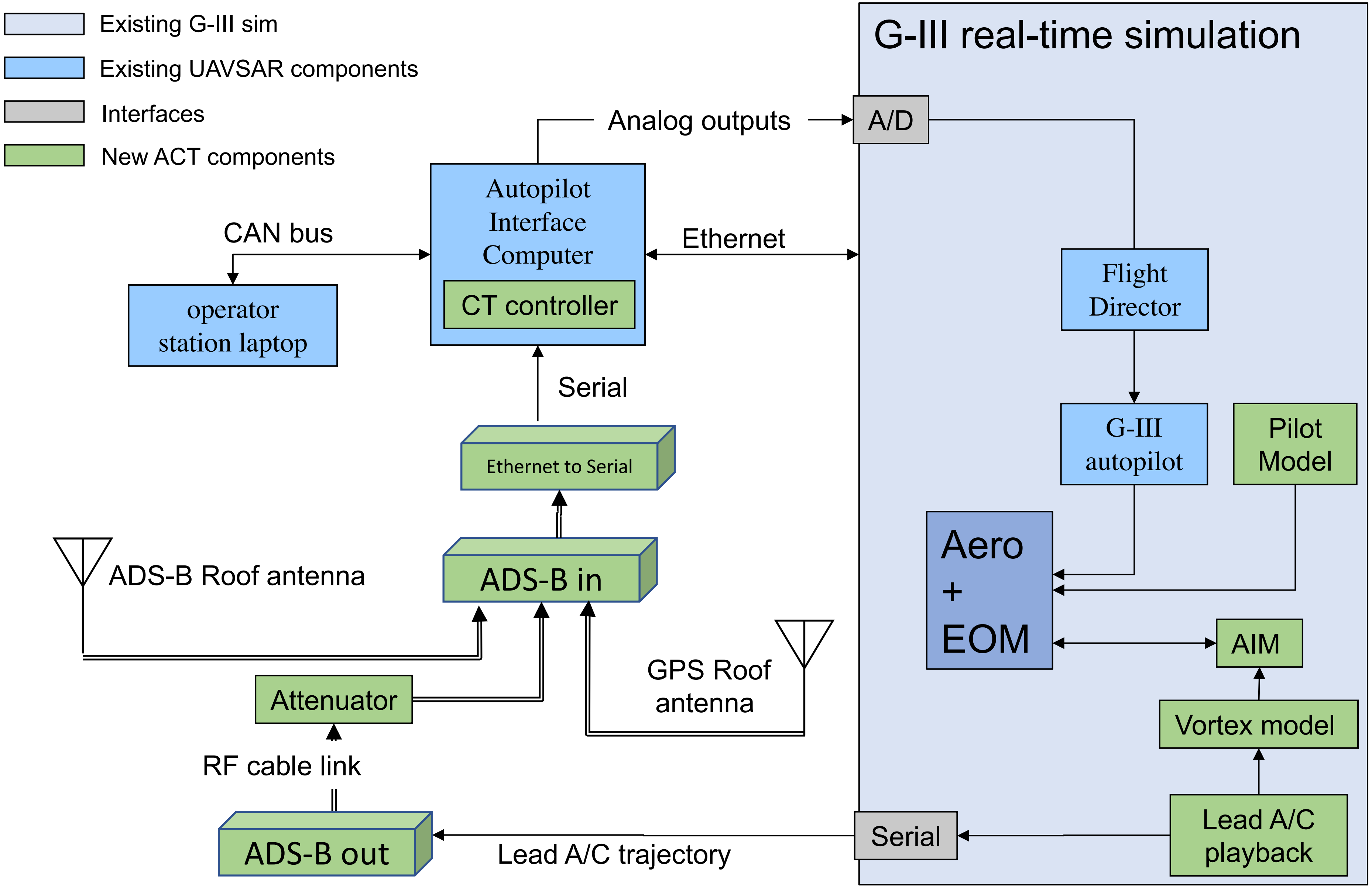
- Pilot training and cockpit displays
- Integration into cargo and passenger operations



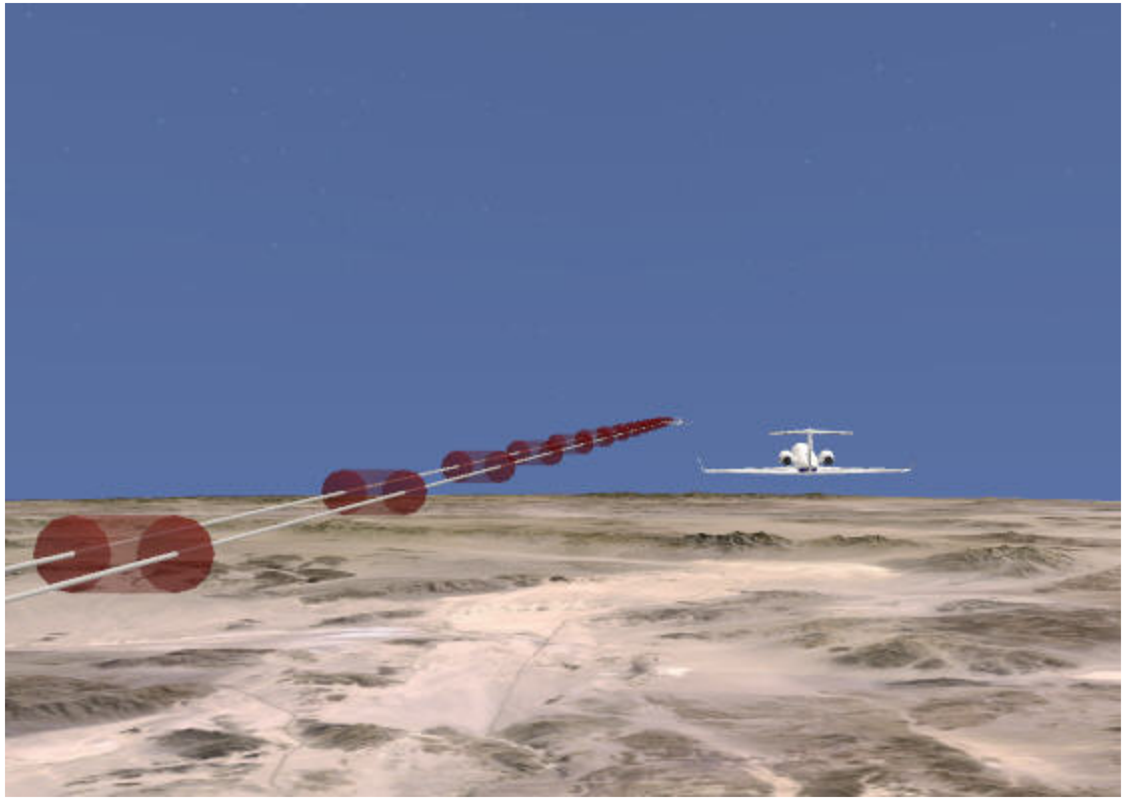
Simplified Wake Location Prediction



ACT G-III HIL Systems Development Lab



G-III SIL Video



Flight Test Photos

2016-2017


BOSE


N808NA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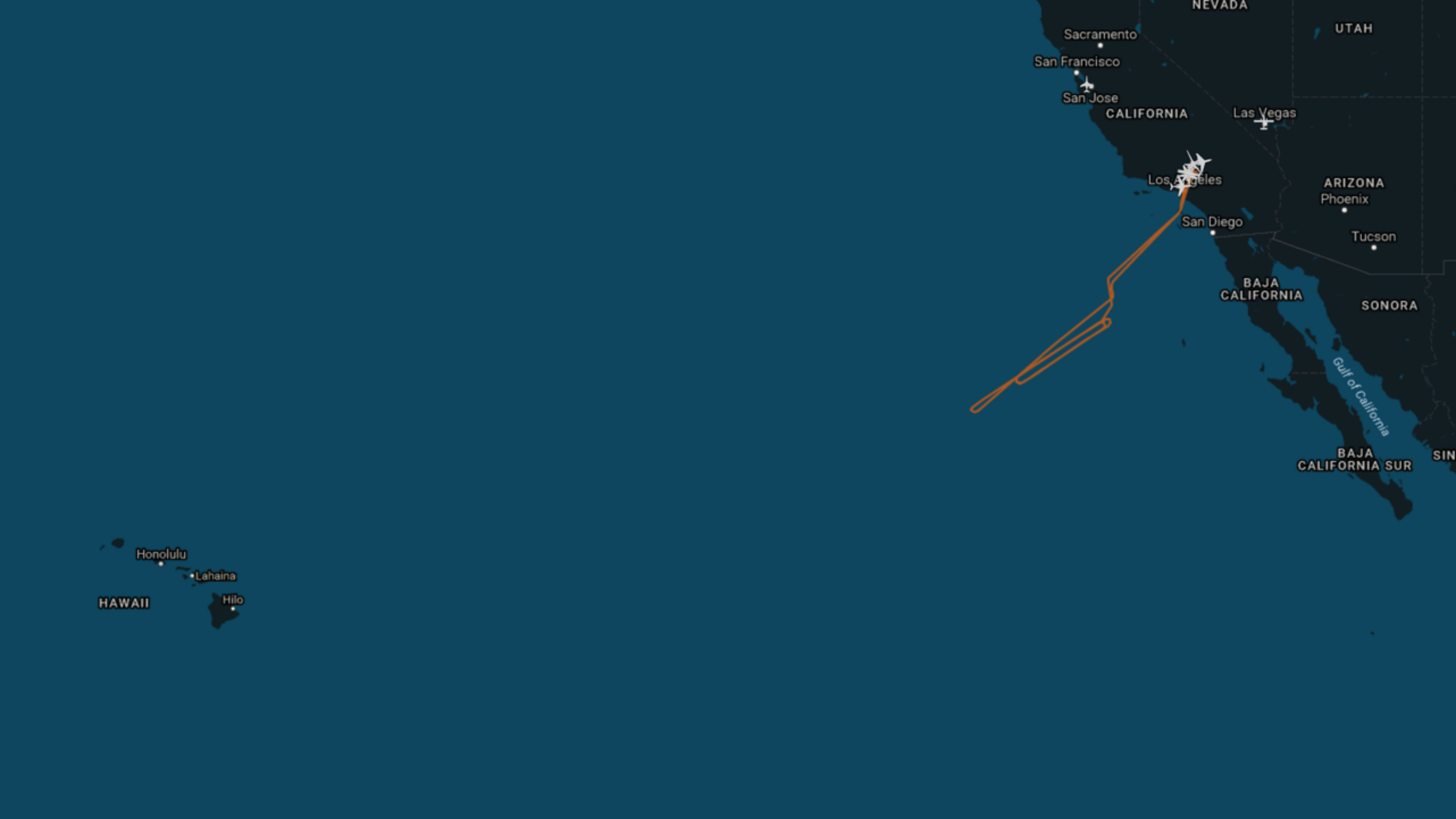
808


UNITED STATES OF AMERICA


NEVADA
UTAH
Sacramento
San Francisco
San Jose
CALIFORNIA
Las Vegas
ARIZONA
Phoenix
San Diego
Tucson
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SONORA
Gulf of California
BAJA CALIFORNIA SUR
Honolulu
Lahaina
HAWAII
Hilo


NASA
ARMSTRONG
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UNITED STATES OF AMERICA

Selected References

Flight Demonstrations

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Vachon, J., Ray, R., Walsh, K., and Ennix, K., "F/A-18 Aircraft Performance Benefits Measured During the Autonomous Formation Flight Project," AIAA 2002-4491, Proceedings of the AIAA Atmospheric Flight Mechanics Conference and Exhibit, 2002.

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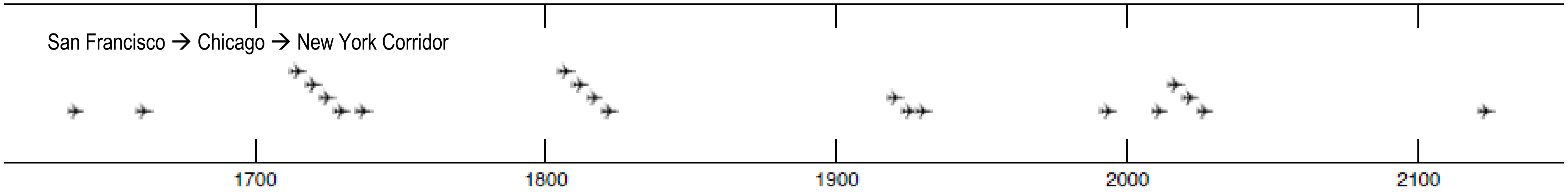
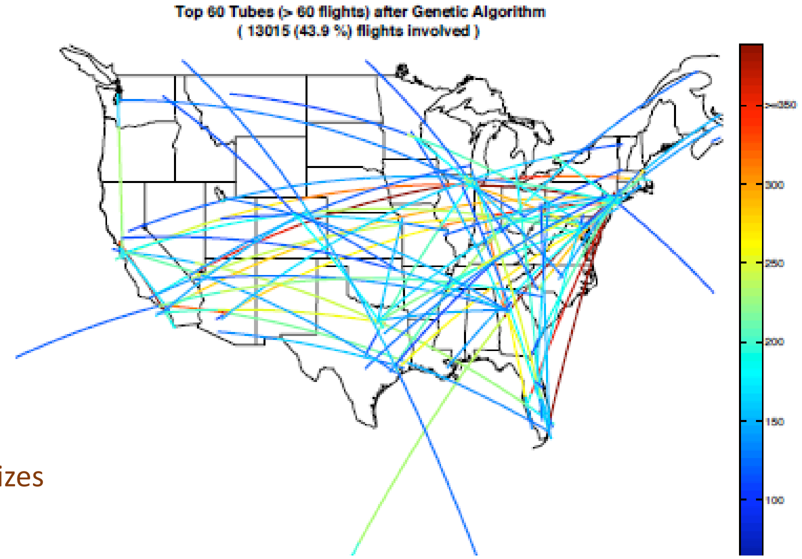
Cooperative Trajectories in the Airspace



One Application: Corridor-in-the-Sky Formations (Xue and Hornby, 2012):

- ♦ Maximum of 4 aircraft in formation
- ♦ Merge aircraft within 50 nm
- ♦ Trailing airplane accelerates to merge with leader
- ♦ Top-Ten Corridors:
  - 20% of aircraft participate in formations
  - $320M - $600M annual savings
  - Assumes ~25% reduction in <u>induced</u> drag, scaled with relative aircraft sizes
  - Based on $4.22 per gallon fuel costs



Figures from Xue and Hornby, 2012

Other Potential Airspace Operations Applications for Air-to-Air Relative Navigation and Control

- ♦ Closely-Spaced Parallel Runways
  - Wake turbulence mitigated arrivals
  - Timed paired departures
- ♦ Precision Departure Release capability
- ♦ Interval Management
- ♦ Trajectory based operations
- ♦ Efficient Descent Advisor
- ♦ Synthetic wake imaging displays

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