Wake-Surfing:
Automated Cooperative Trajectories

May 2017
Nelson Brown
Center Overview

NASA Armstrong Flight Research Center

May 2017
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

**NASA Program Funds**

- Science: 31%
- Space Technology: 35%
- Aeronautics: 25%
- Exploration Systems: 1%
- Education: 4%

**Armstrong**

~$287.3 million budget

538 civil servants

579 contractors

126 student interns

**AFRC Program Funds**

- Science: 36%
- Space Technology: 6%
- Aeronautics: 6%
- Exploration Systems: 36%
- Space Operations: 49%
- Education: 6%
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
Armstrong Vision
To Separate the Real from the Imagined Through Flight
To Separate the Real from the Imagined Through Flight

Armstrong Vision

X-56A
Dream Chaser
D8
Prandtl
X-57
Towed Glider
Air-Launch System
F-15 Quiet Spike
Supersonic Aircraft
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

Armstrong Flight Research Center
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.
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
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
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 (T³) 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

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NASA Armstrong Contributions
to Formation Flying for Improved Efficiency

F-18 AFF
1998-2001

F-18 / DC-8 SURF
2003

C-17 CAPFIRE
2010

G-III ACT
2016 (planned)

1. Initial propulsion charge = 12 minutes
2. All planes locate thermals within 10 minutes
3. Max altitude > 7,000 ft
4. End task due to low altitude
5. Min altitude = 1,600 ft after 80 minutes

Simulation Studies

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

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

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

2013c: 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
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

NASA G-III UAVSAR Aircraft
with Automated Cooperative Trajectory Systems

- Pilot Throttle and Wake Displays
- NASA ADS-B Enabled Autopilot Interface Computer
- Aileron and Rudder Actuator Displacement
- Fuel Flow Instrumentation
- Passenger Ride Quality and Cabin Noise Sensors

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

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.

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.
Automated Cooperative Trajectories
Throttle and Wake Display Pilot Evaluation

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

German Institute for Fluid Mechanics

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

NASA Dryden Flight Research Center

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

US Air Force Test Pilot School

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

NASA DFRC / USAF FTC

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

DARPA / AFRL / Boeing

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

Path To Commercially-Viable Automated Meta-Aircraft Operations

- 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

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

Path To Commercially-Viable Automated Meta-Aircraft Operations

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

Close Formation Flight Research

Extended Formation Flight Research

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

2013 - 2017

2014

2018 - 2020

2015

2016 - 2017

2001

2001

2010

2012 - 2013

2018 - 2020

2018 - 2020
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

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
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

\[ \xi = \psi - Gt \]

Parallel ground tracks

Estimated Vortex Formation Axis

Actual Lead Ground track

ADS-B Reported Lead Position

Estimated Lead Ground Track

Trail Ground track

Gt

We
ACT G-III HIL Systems Development Lab

G-III real-time simulation

- Flight Director
- G-III autopilot
- Pilot Model
- Aero + EOM
- AIM
- Vortex model
- Lead A/C playback

Existing G-III sim
Existing UAVSAR components
Interfaces
New ACT components

- A/D
- CAN bus
- Ethernet
- Analog outputs
- Serial
- ADS-B in
- ADS-B out
- ADS-B Roof antenna
- Attenuator
- RF cable link
- Lead A/C trajectory
- GPS Roof antenna
- Ethernet to Serial
- ADS-B in
- CT controller
- Autopilot Interface Computer

Operator station laptop

- ADS-B Roof antenna
- Attenuator
- RF cable link
- Lead A/C trajectory
G-III SIL Video
Flight Test Photos

2016-2017
Selected References

**Flight Demonstrations**


**Operational Analyses**


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 induced drag, scaled with relative aircraft sizes
  - Based on $4.22 per gallon fuel costs

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