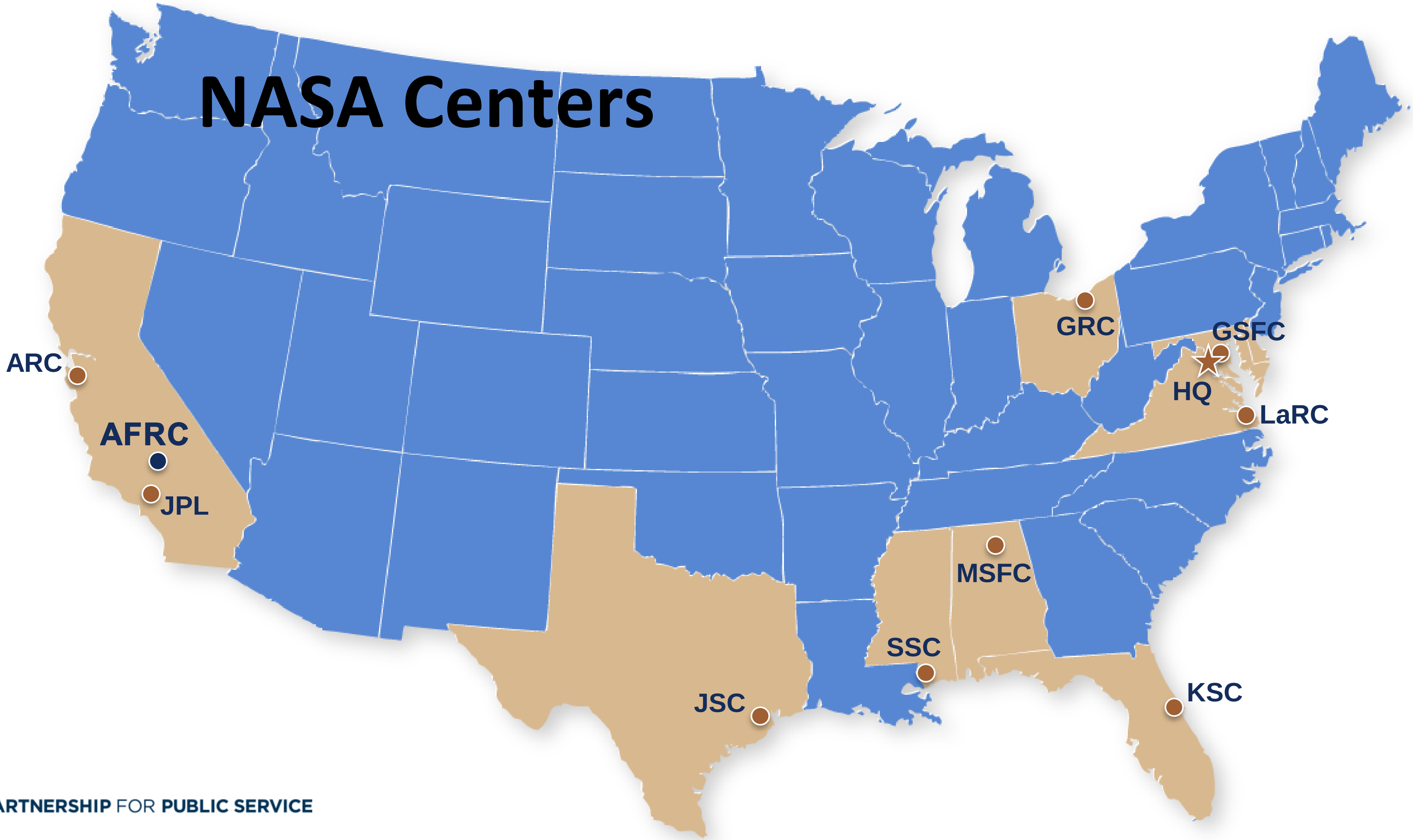
Civilian Transport Wake Surfing

NASA Automated Cooperative Trajectories & Programmable Autopilot

Curt Hanson & Nelson Brown

NASA Armstrong Flight Research Center (USA)

NASA Centers



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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)

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**

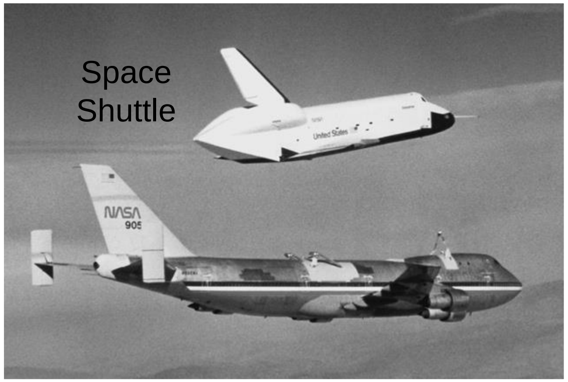
3. **Conduct airborne remote sensing and science observations**

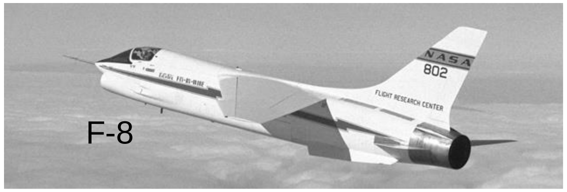
Ikhana MQ-9 Predator B Unmanned Aircraft System

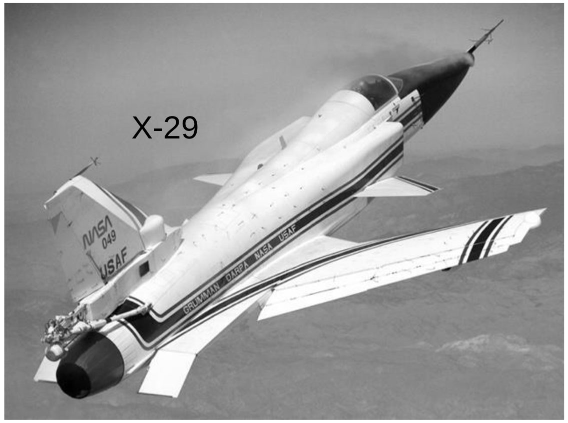
Stratospheric Observatory for Infrared Astronomy (SOFIA)

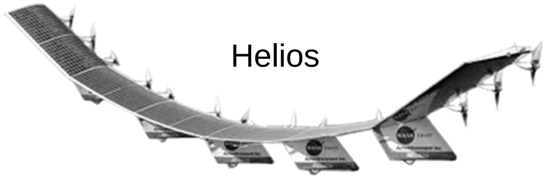
X-56 Multi-Utility Technology Testbed

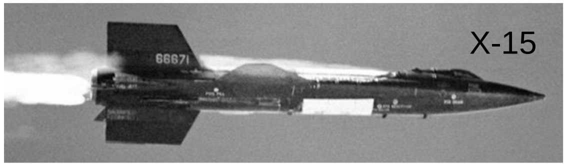
To Separate the Real from the Imagined Through Flight











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**

Civilian Transport Wake Surfing

Prior Wake-Surfing Flight Research

1986 — 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

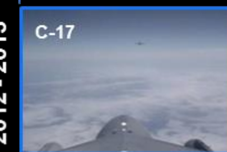
2003 — NASA Dryden Flight Research Center

- Manually flown
- No data link or autopilot
- 29% fuel savings
- Promising dissimilar aircraft test

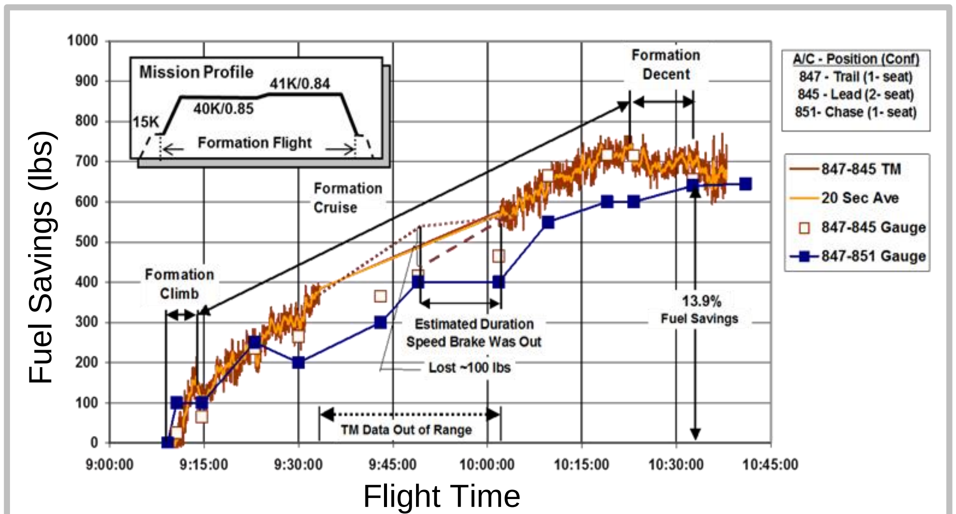
2010 — NASA DFRC / USAF FTC

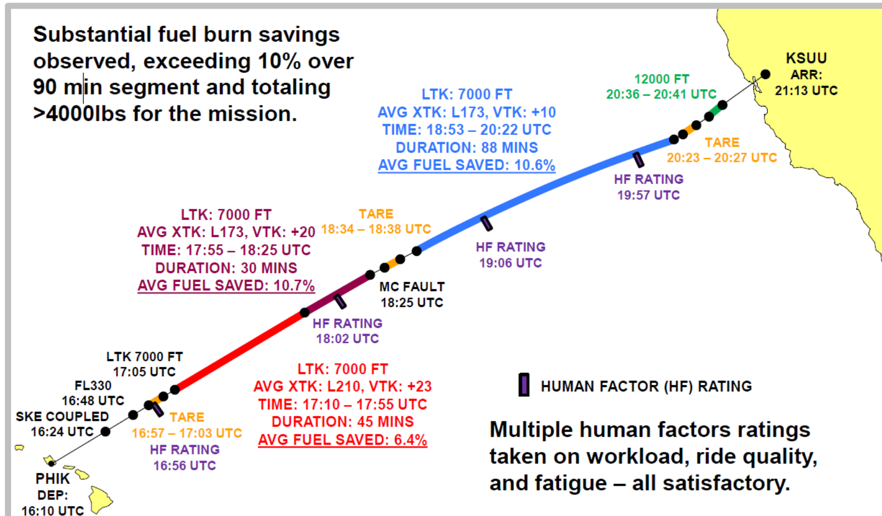
- Proof of extended formation concept
- Production military data link and autopilot
- 7-8% fuel savings (manual)

2012 - 2013 — DARPA / AFRL / Boeing



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





Wake-Surfing Experiment Overview

Automated Cooperative Trajectories (ACT) 3 main objectives:

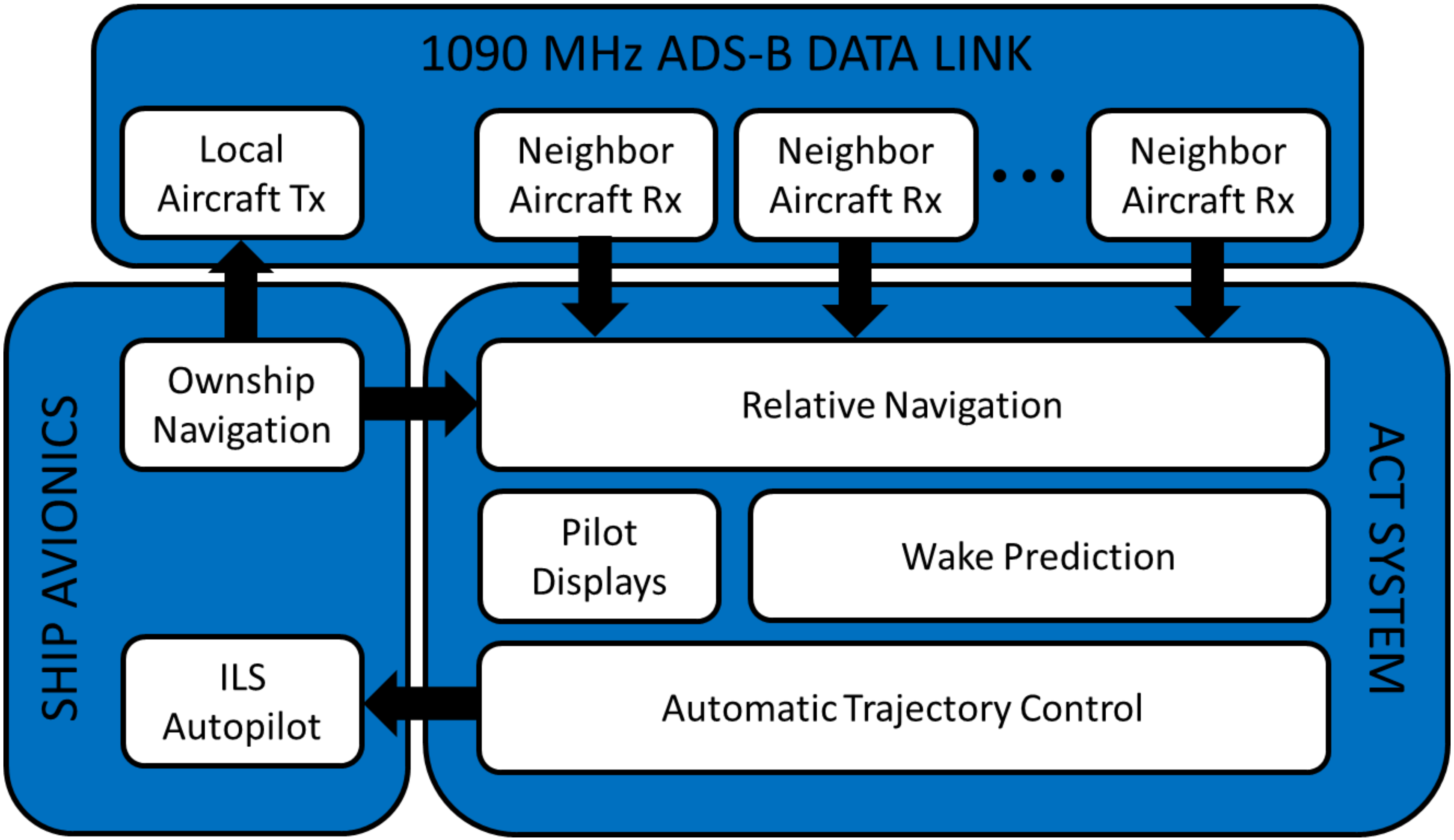
1. **Gather data to help characterize the benefits and impacts of wake surfing for civil transport aircraft.**
2. **Evaluate the suitability of ADS-B as a data link for autonomous, cooperative flight procedures.**
3. **Advance the state of the art in tools, algorithms, and methods for wake surfing guidance and control.**

Test conditions:

- **4,000 ft in trail**
- **Cruise flight: M0.7, 35,000 ft**
- **Straight-and-level flight**
- **30+ minute legs**
- **Autopilot control of wake-relative cross-track and vertical-track position**
- **Pilot control of along-track spacing**

Flights completed in May 2017

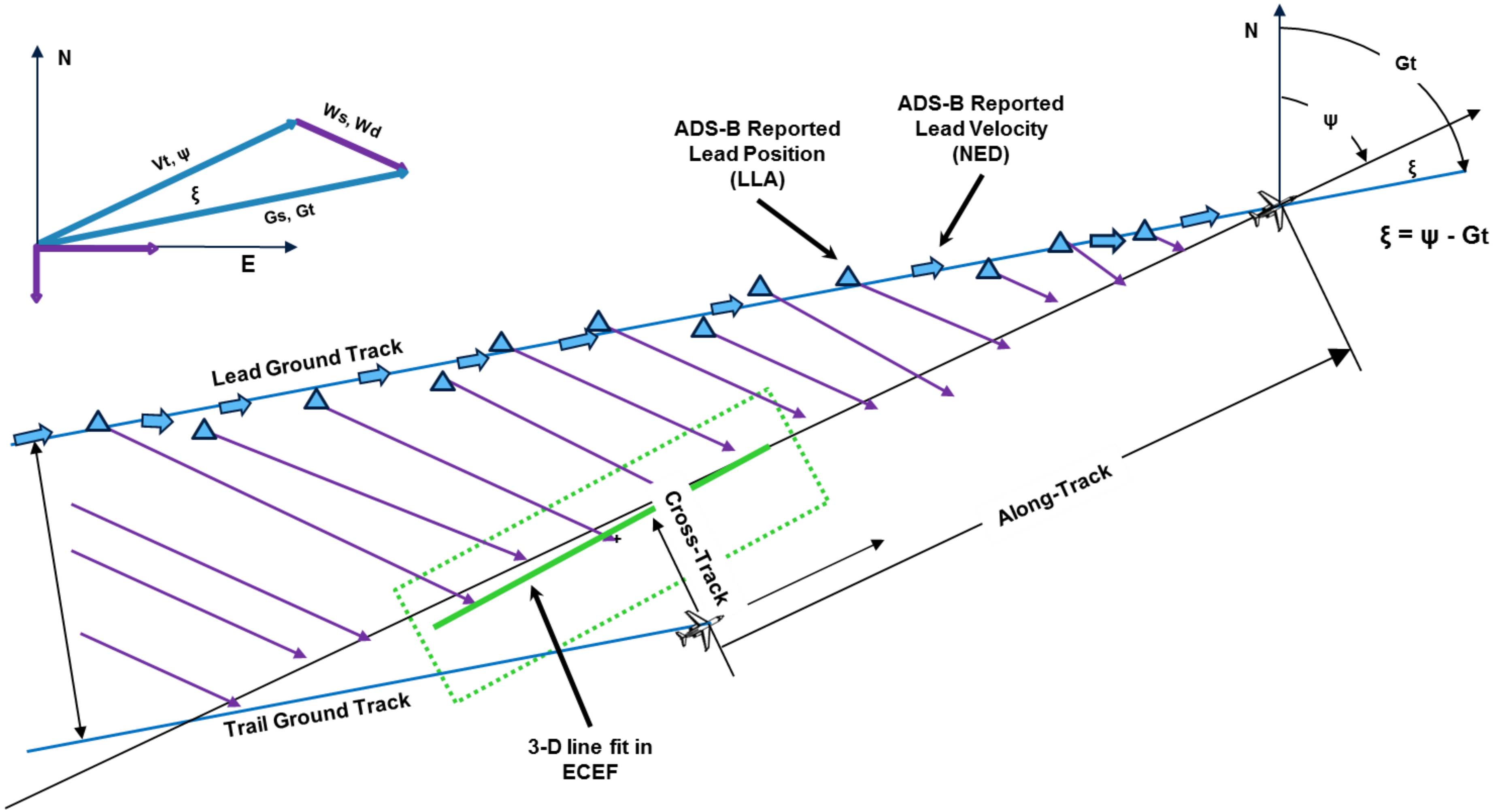
ADS-B Enabled Experimental Autopilot



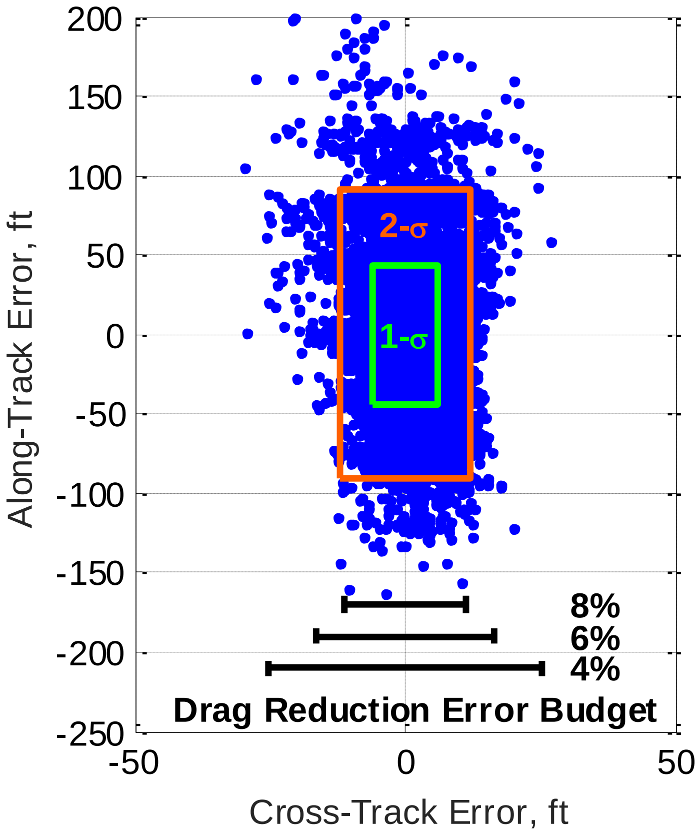
Experimental Autopilot Interfaces

- **Inputs**
  - ADS-B In (1090 MHz ES)
  - Trail aircraft navigation and state data
  - Throttle and control surface positions
- **Control Paths**
  - Analog localizer and glideslope commands to the ILS autopilot
  - Along-track and throttle cues to a custom pilot tablet display, yoke-mounted
- **Instrumentation**
  - Autopilot data
  - ADS-B traffic
  - Fuel flow gages
  - Flight director data (lead + trail)
  - Independent GPS (lead + trail)
  - Ride quality sensors (lead + trail)
- **Operator Interfaces**
  - Lead aircraft selection (virtual / real)
  - Controller gains and parameters
  - 3-axis position relative to the wake
  - Arm / engage / disengage

Relative Navigation & Wake Prediction



ADS-B Uncertainty



Timing uncertainty in ADS-B message data results in larger errors in along-track as compared to cross-track.

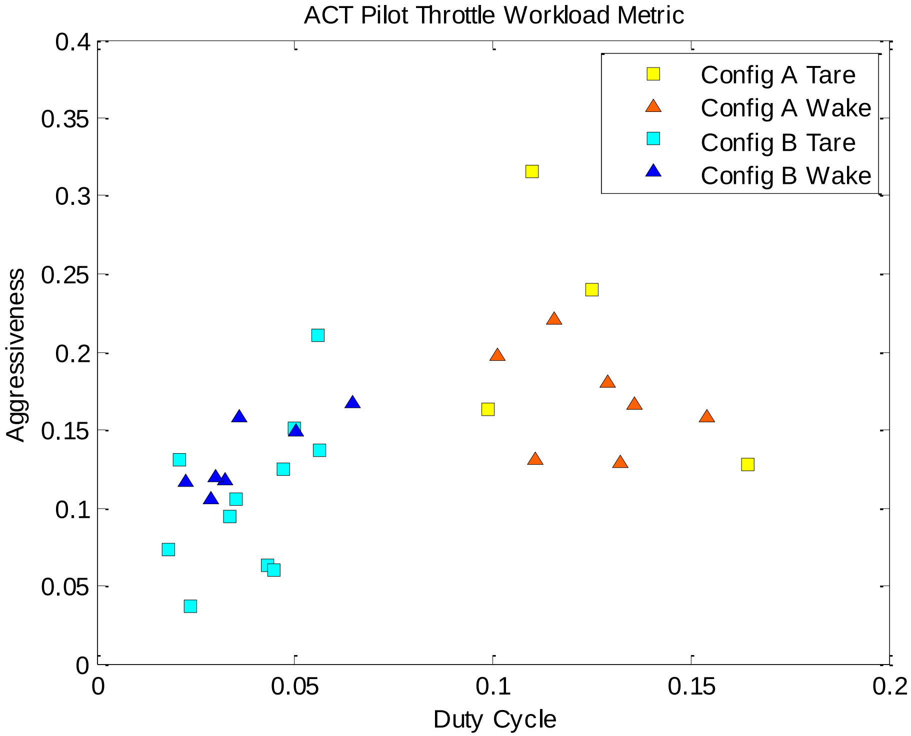
Each knot of error in cross-track wind speed adds another 10 ft of error in the predicted wake location.

Pilot Throttle Cue & Wake Display

Despite good results in the piloted sim, the pilots initially found the throttle cues “Unsatisfactory” in flight.

For the final flight, the pilot along-track error cue was re-designed with an increased range of view, and a relaxed acceptable error criteria.

Display Changes Assessment

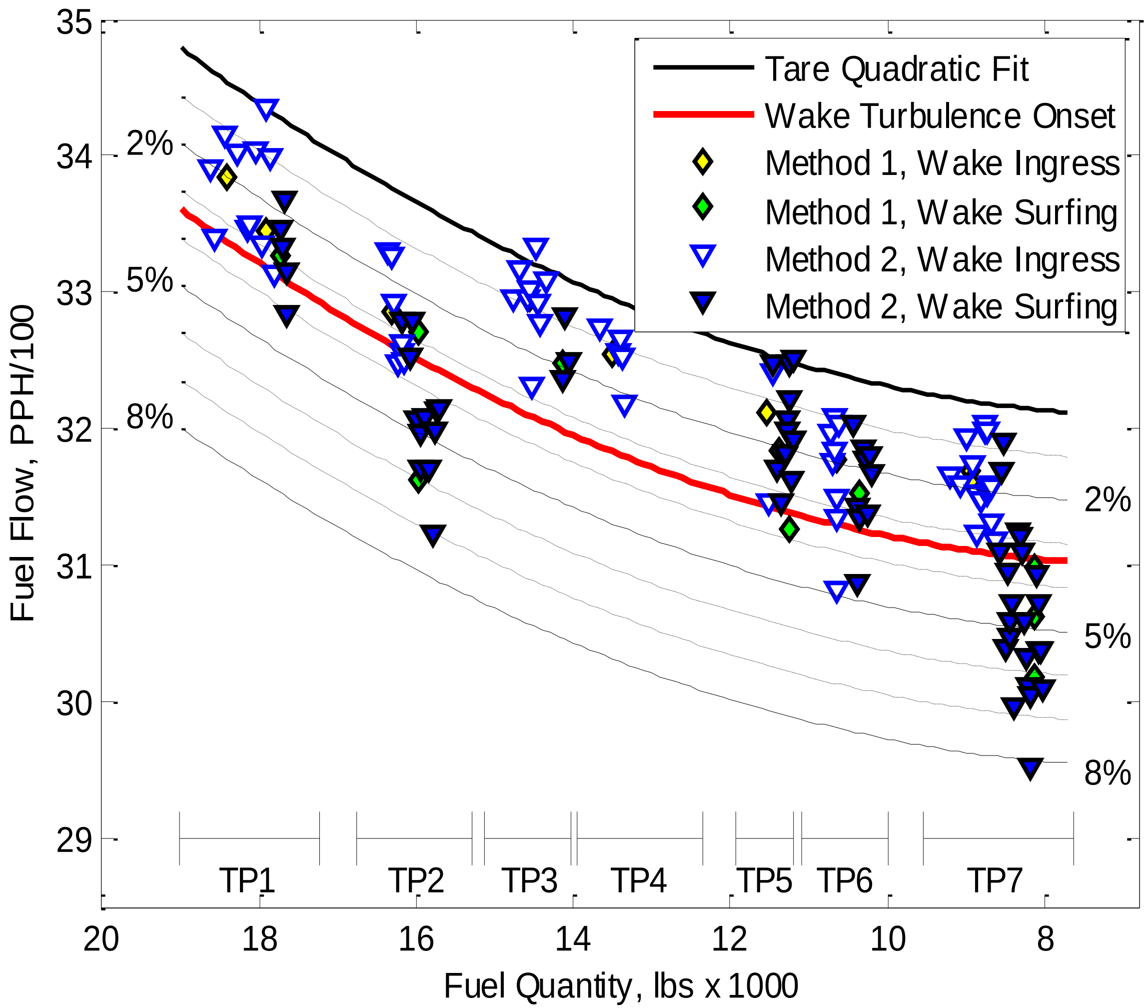


The modified display reduced the pilot workload to "Satisfactory" and improved post-flight calculation of fuel flow savings.

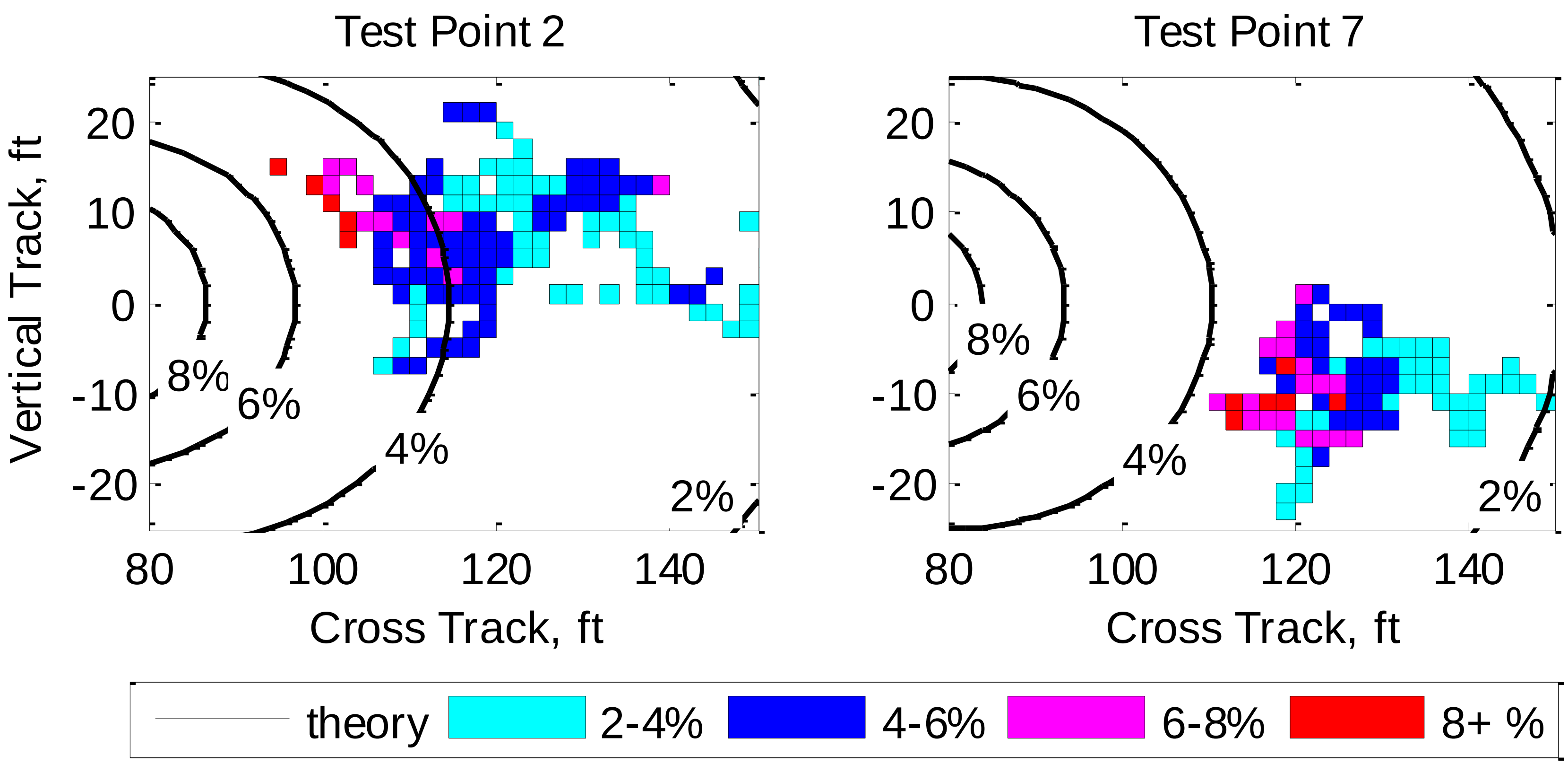
Fuel Flow Reduction

Flight Test Technique:

1. **Engage in straight-and-level flight**
    - 4,000 feet aft of the lead
    - 400 feet outboard
    - 150 feet below
2. **5-minute tare points**
3. **Wake mapping**
    - Command incrementally deeper into wake effects
    - Discontinue Mapping when wake effects (rumbling) were felt / heard
4. **Performance dwells of 3-5 minutes**
5. **5-minute tare point**

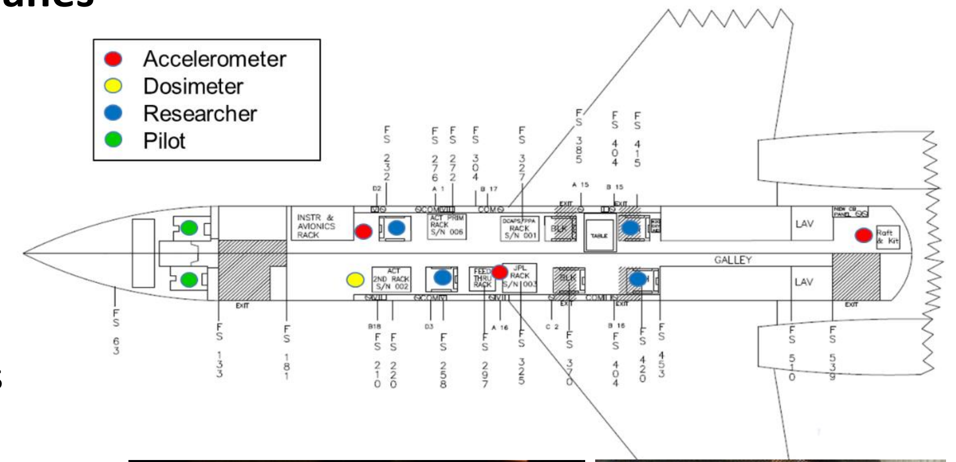


Fuel Flow Reduction



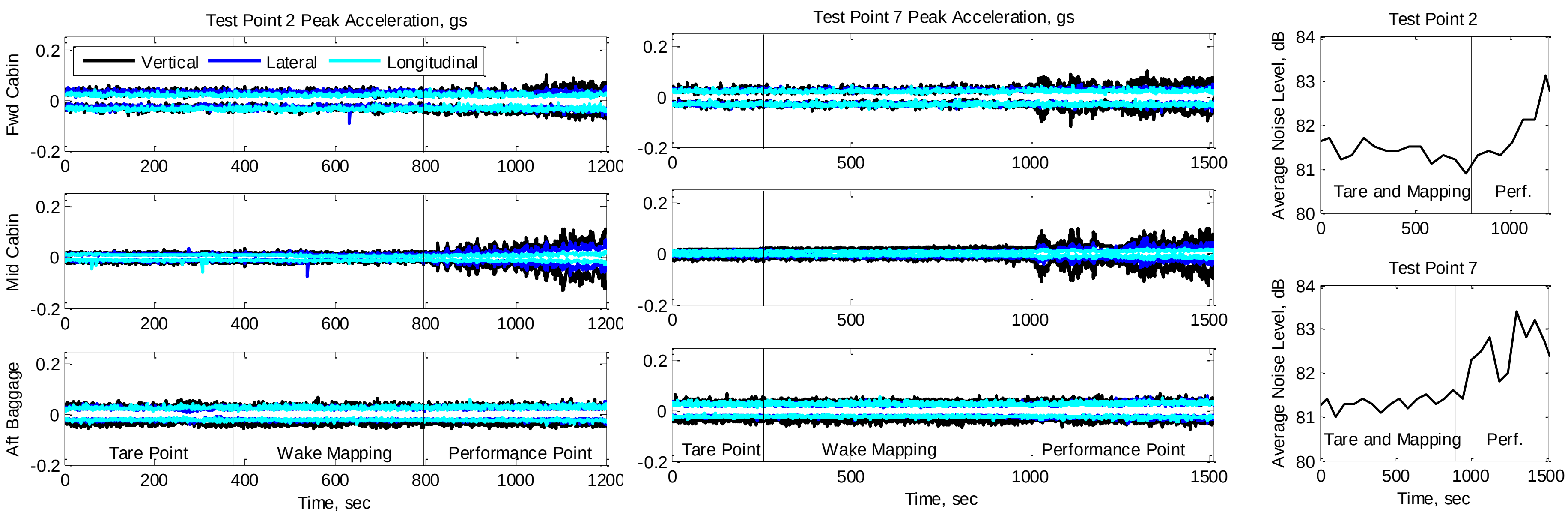
Passenger Ride Quality Instrumentation

- **Accelerometers on seat rails of both airplanes**
  - 3-axis accels sampled at 200 Hz
  - Separate accels for low and high frequency measurements
  - Internal data logging with time stamp
- **Sound dosimeter**
  - Mic at passenger ear location
  - Records 1-minute time-average sound levels
  - 100 Hz to 5 kHz, 40-140 dB
- **Pre-flight and post-flight surveys of pilots and research crew**
- **An additional accelerometer was mounted to the ceiling of the aft baggage compartments of both airplanes to measure tail buffeting**



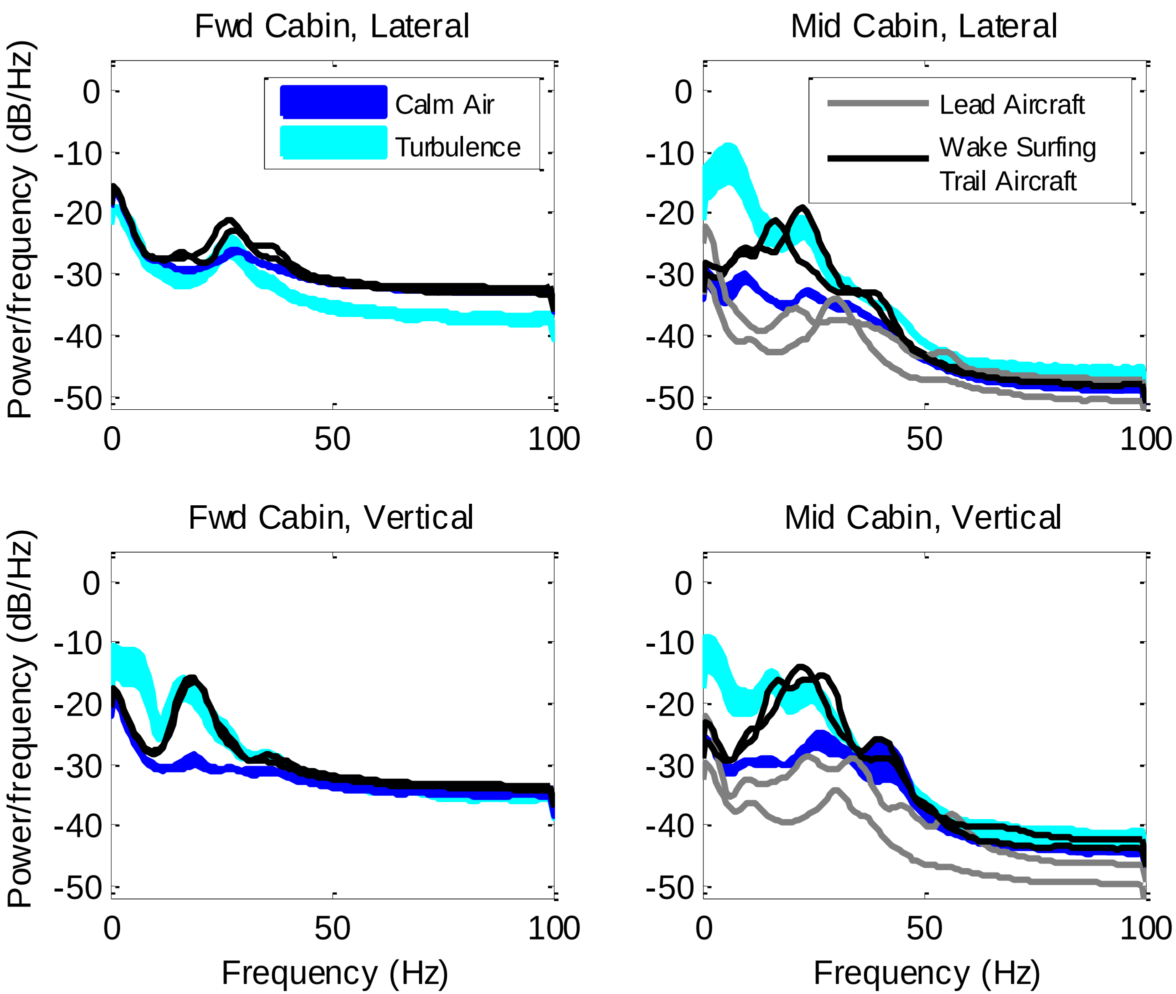
Passenger Ride Quality

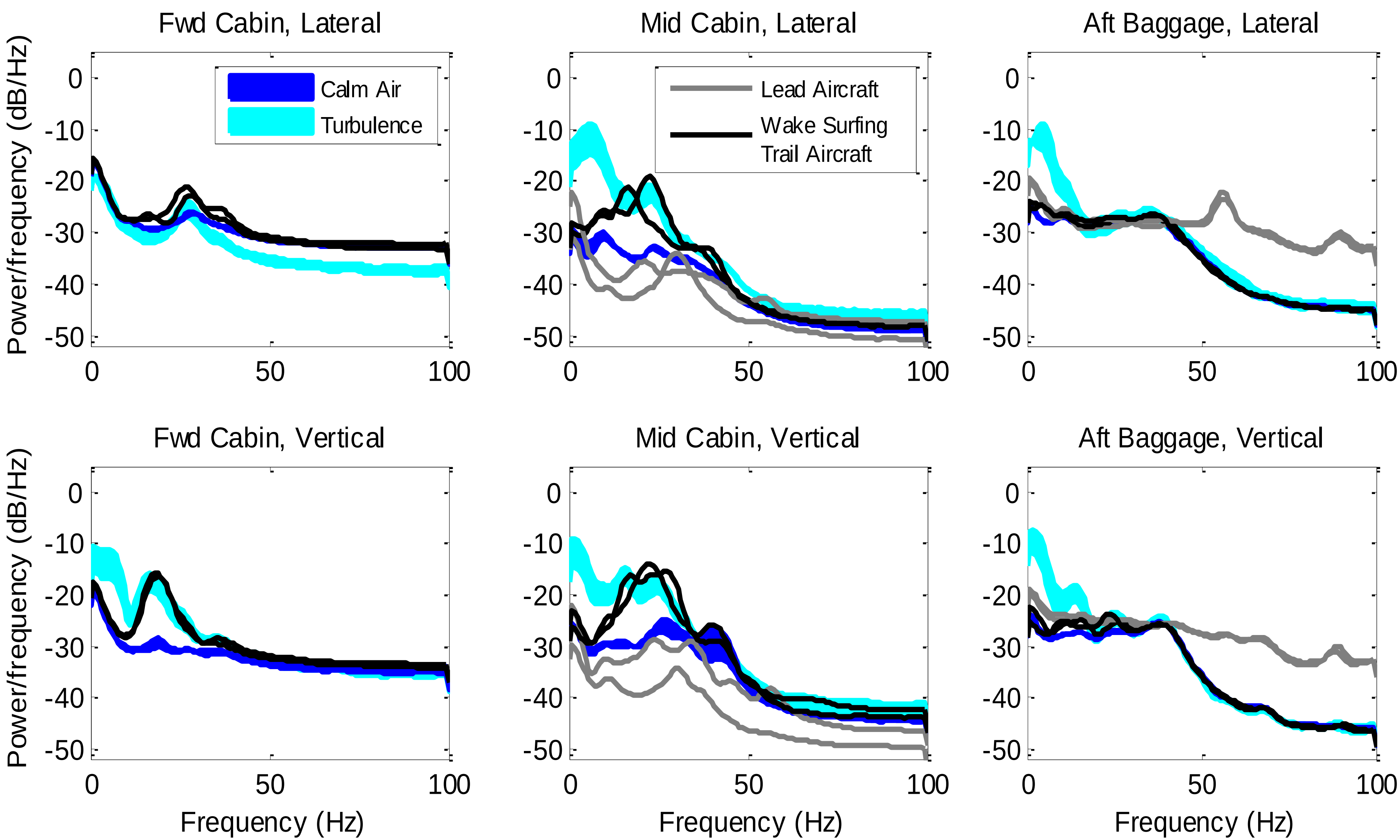
- Increased seat rail vibration levels recorded during two of the performance dwell test points
- Slight increases in cabin noise levels
- No change in vibration levels recorded in the aft baggage compartment



Passenger Ride Quality

- The forward cabin location experienced the least amount of wake-induced vibration, with almost no change in the lateral axis.
- The vertical-axis showed the largest increase in vibration.
- The peak vertical-axis vibration frequency ranged from 16 to 25 Hz. Peak lateral vibration occurred between 18 and 23 Hz.
- Mid-cabin effects had a slightly more narrow bandwidth than at the forward cabin location.




Fwd Cabin, Lateral
Mid Cabin, Lateral
Aft Baggage, Lateral
Calm Air
Turbulence
Lead Aircraft
Wake Surfing Trail Aircraft
Fwd Cabin, Vertical
Mid Cabin, Vertical
Aft Baggage, Vertical
Power/frequency (dB/Hz)
Frequency (Hz)
0
-10
-20
-30
-40
-50
0
50
100

Passenger Ride Quality Metrics (RQM)

In the 1970s, NASA LaRC conducted a series of studies to develop a criteria to predict passenger discomfort due to vibration and noise.

Vibration Tests

- 852 test subjects
- motion simulator fitted with six tourist-class aircraft seats
- 10 - 15 second excitations
- lateral, vertical, longitudinal, roll, and pitch vibrations
- rated as "comfortable" or "uncomfortable"

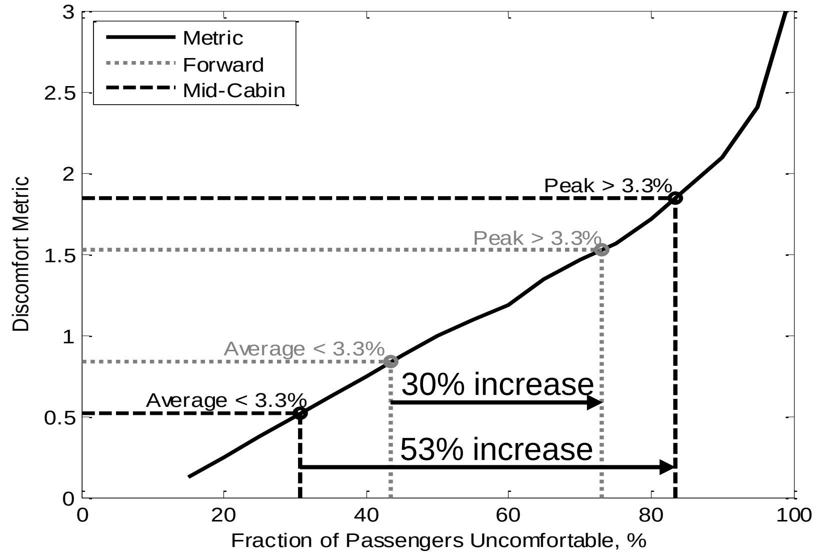
Noise and Vibration Tests

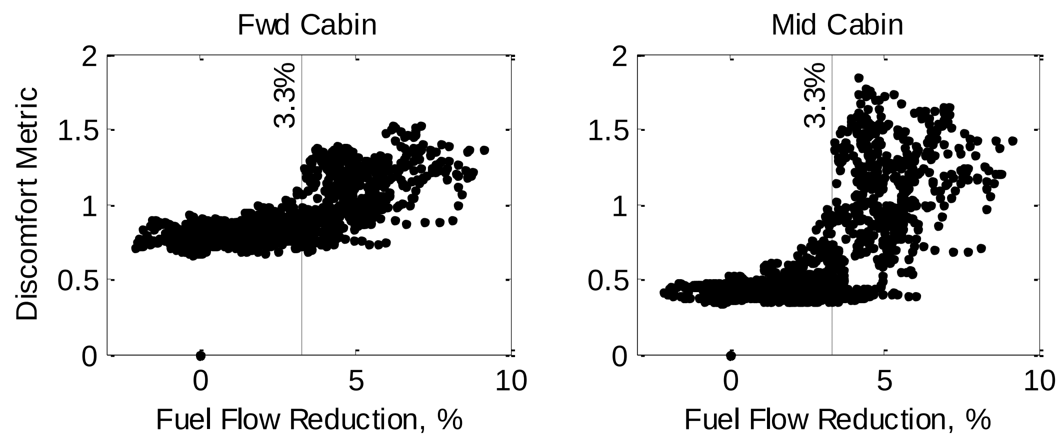
- 60 test subjects
- combinations of noise and vibration
- 4 sound levels, 6 octave bands

Applying NASA RQM

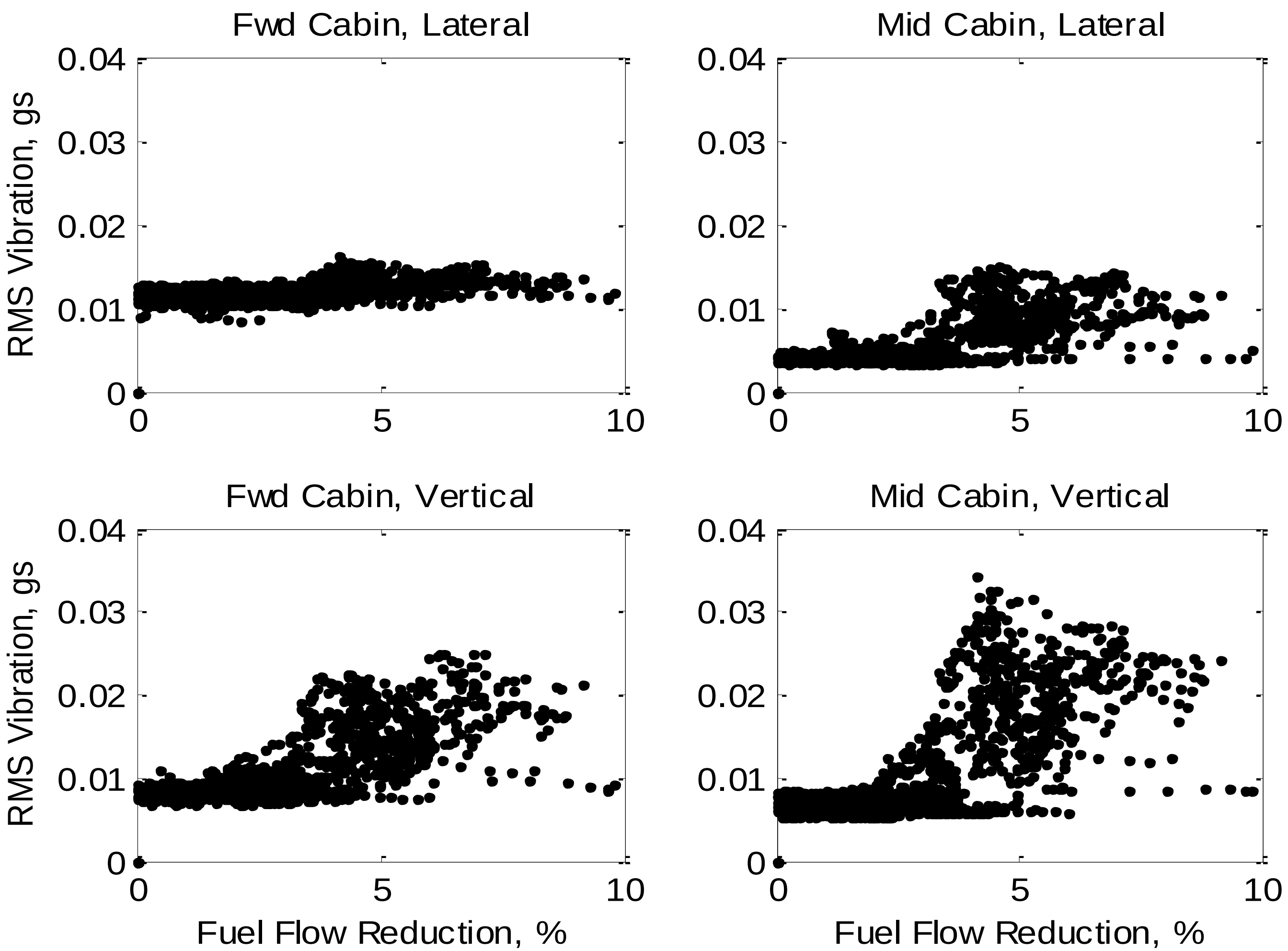
Applying the NASA RQM for vertical and lateral vibration and plotting against fuel flow reduction, the relationship shows a significant increase in discomfort metric above ~3.3% fuel flow savings.

Wake-induced noise contributions to the discomfort measure were found to be minor.





Cabin Seat Rail Accels vs. Fuel Flow Reduction due to Wake Surfing



Passenger Ride Quality Comments

Summary of the post-flight questionnaires:

- **9 participants (2 pilots, 6 engineers, 1 videographer); majority are frequent flyers**
- **Wake Surfing Comfort Response:**
  - "Comfortable": 45% (4 of 9)
  - "Neutral": 45% (4 of 9)
  - "Uncomfortable": 10% (1 of 9)
- **10% reported "Writing" would be difficult**
- **33% reported "Sleeping" would be difficult**

Comments:

- **"Similar to light turbulence"**
- **"Rhythmic, pulsing sound - not unpleasant but noticeable"**
- **"Like driving over a slightly-washboarded road"**
- **"I found the view of contrails outside my window unsettling"**
- **"The appearance of the wake was larger than I had originally imagined"**