A Preliminary Flight Investigation of Formation Flight for Drag Reduction on the C-17 Aircraft

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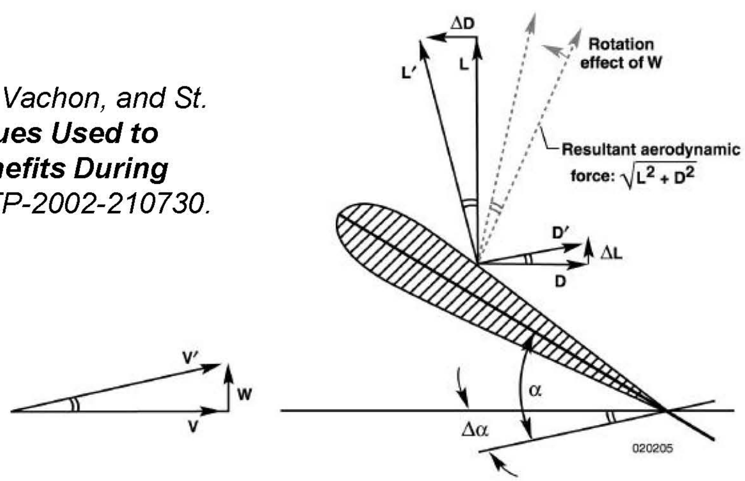
Air Force photo by Bobbi Zapka: http://www.edwards.af.mil/shared/media/photodb/photos/100916-F-9126Z-024.jpg

Why Investigate Formation Flight?

- **Primary benefit is reduced drag, resulting in fuel savings or longer range**
  - A 14% fuel savings demonstrated in flight for two F/A-18s in cruise configuration (2001 NASA/DFRC)
  - A 15% power reduction for two Dornier Do-28 (1995 Hummel)

- **If successful, the concept may be applied to existing A/C without external modifications**

*Figure from: Ray, Cobleigh, Vachon, and St. John, "**Flight Test Techniques Used to Evaluate Performance Benefits During Formation Flight**", NASA/TP-2002-210730.*



Background

- **Formation Flight is a very old concept …**
  - 1914 Wieselsberger
  - AIAA-1970-1337 FORMATION FLIGHT TECHNOLOGY
  - AIAA-1995-3898 AFF "A preliminary investigation into the application to civil operations"

- **With some very recent interest (particularly for transport-class vehicles)**
  - AIAA-2007-4163 Formation Flying of Commercial Aircraft, Variations in Relative Size and Spacing - Induced effects and control
  - AIAA-2009-3615 Formation Geometries and Route Optimization for Commercial Formation Flight
  - 2010 DARPA - Formation Flight for Aerodynamic Benefit program
  - AIAA-2010-1240 Aerodynamic Performance of Extended Formation Flight

There are technical, economic, and regulatory issues that must be addressed before formation flight would be considered a viable option

CAPFIRE

Cargo Aircraft Precision Formations for Increased Range and Efficiency

- Gather qualitative flight data and pilot comments with trail vehicle in the area of influence from the lead vehicle's vortex

- Use the C-17 FFS and auto-flight system to stabilize at pre-determined trail locations with predicted drag reduction (non-optimized)

- Use production fuel flow instrumentation and off-line thrust model (driven with flight data) to estimate drag reduction

Flight Test Approach

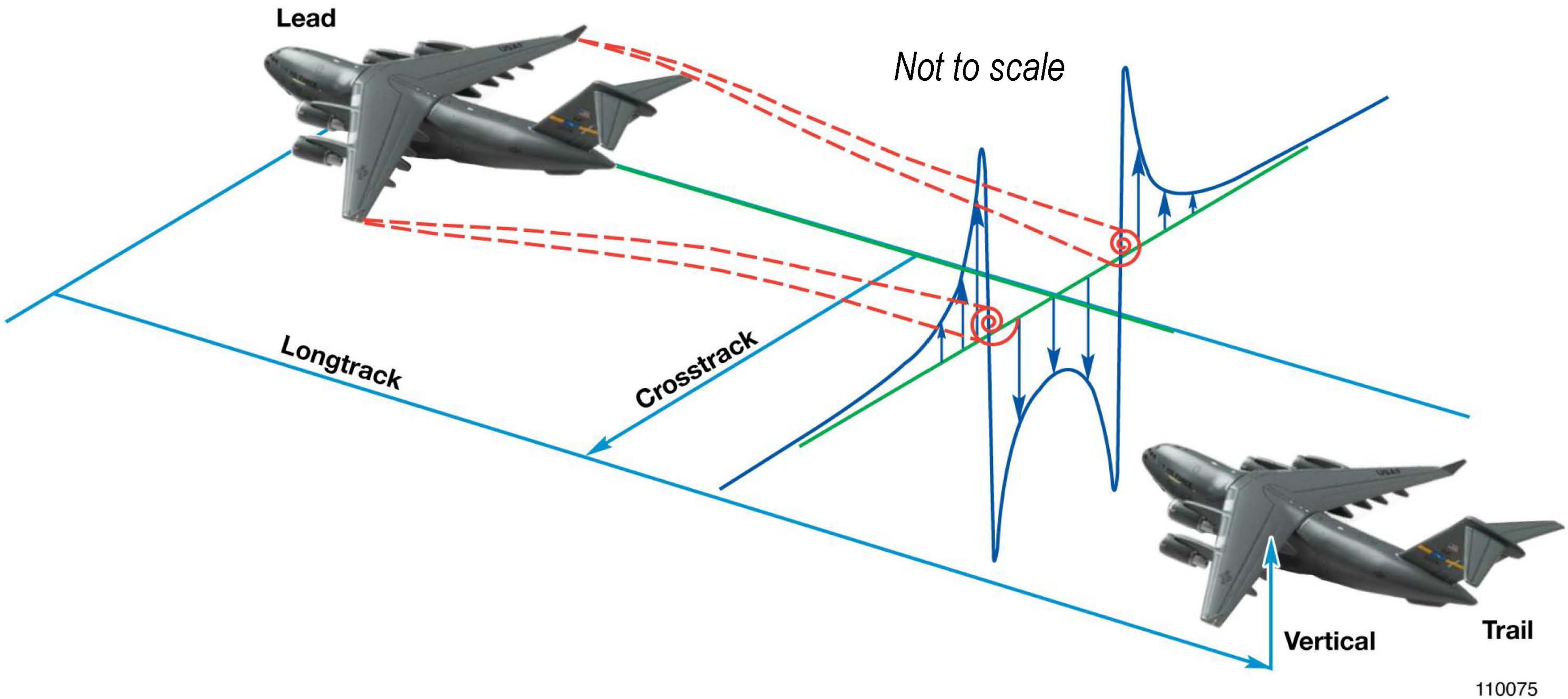
- NASA partnered with USAF/AFFTC as a product of the NASA Aviation Safety Research Test and Integration Plan
  - Production C-17 aircraft used in test
  - USAF AFFTC engineering staff assisted in safety assessment, test documentation, flight preparation, and flight test
  - NASA engineering staff on board for real-time data assessment and safety monitoring during test.
  - Flight data obtained through the C-17 Advanced Wireless Open Data System (AWODS)

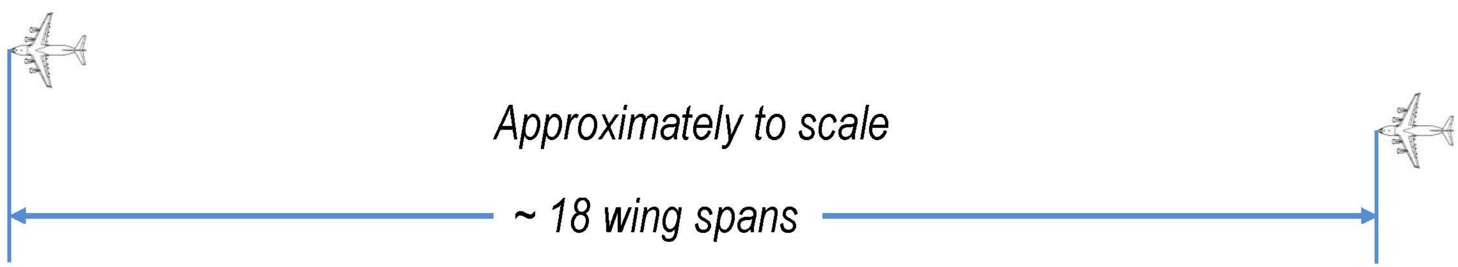
Flight Test Approach (cont.)

- **A similar (but simplified) flight test approach to the NASA Autonomous Formation Flight (AFF) program[1] was used**
  - **Stabilized Tare points outside of the vortex influence were flown before and after a horizontal or vertical test sequence**
  - **Step-wise horizontal profile co-altitude with lead vehicle**
    - **1000 ft in trail (flights 1 and 2)**
    - **3000 ft in trail (flight 3)**
  - **Step-wise vertical profile at one of the horizontal test points near the estimated vortex location**
  - **Automatic control of position using FFS was desired, but much of the flight data was pilot flown**

*1. Ray, Cobleigh, Vachon, and St. John, "**Flight Test Techniques Used to Evaluate Performance Benefits During Formation Flight**", NASA/TP-2002-210730.*

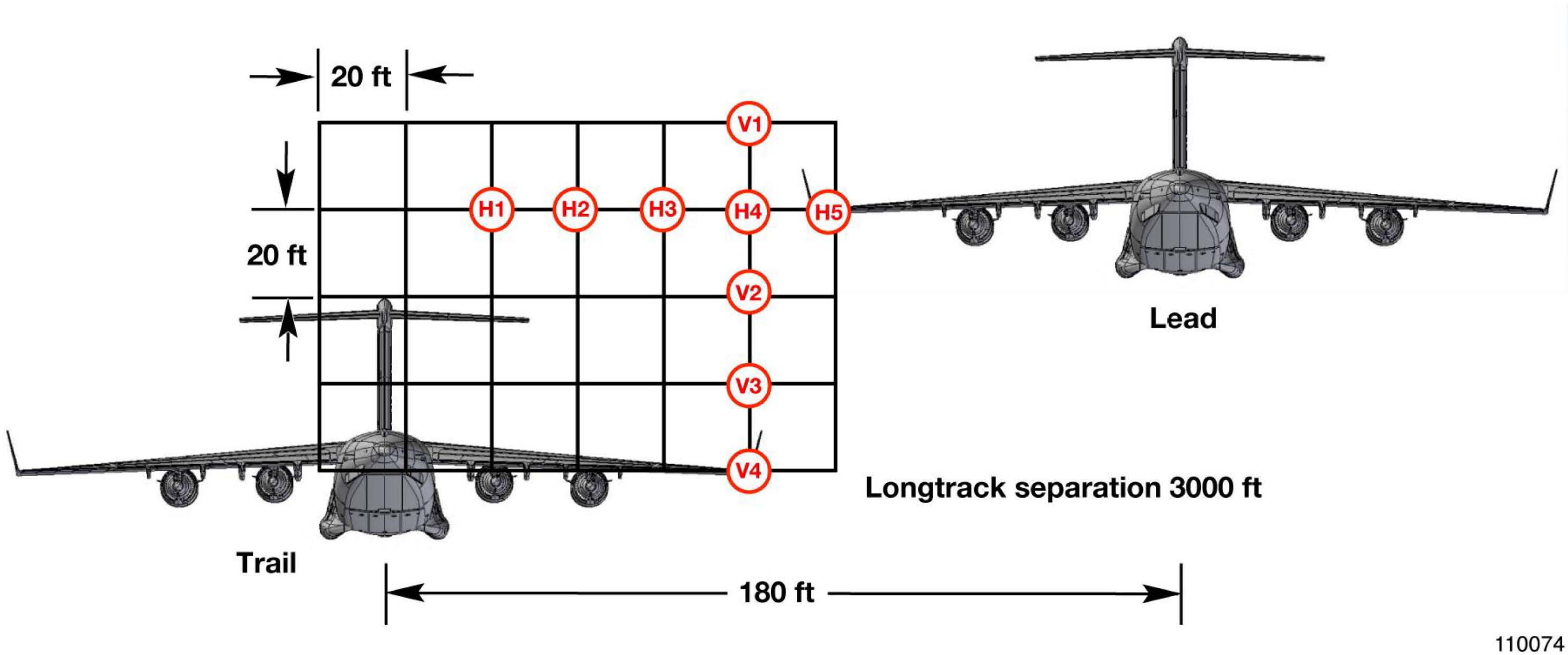
Formation Geometry





Test Point Sequence

- Utilize existing C-17 FFS, auto-flight system, and instrumentation
- Collect preliminary, qualitative results near estimated position of lead's vortex on both sides of the lead



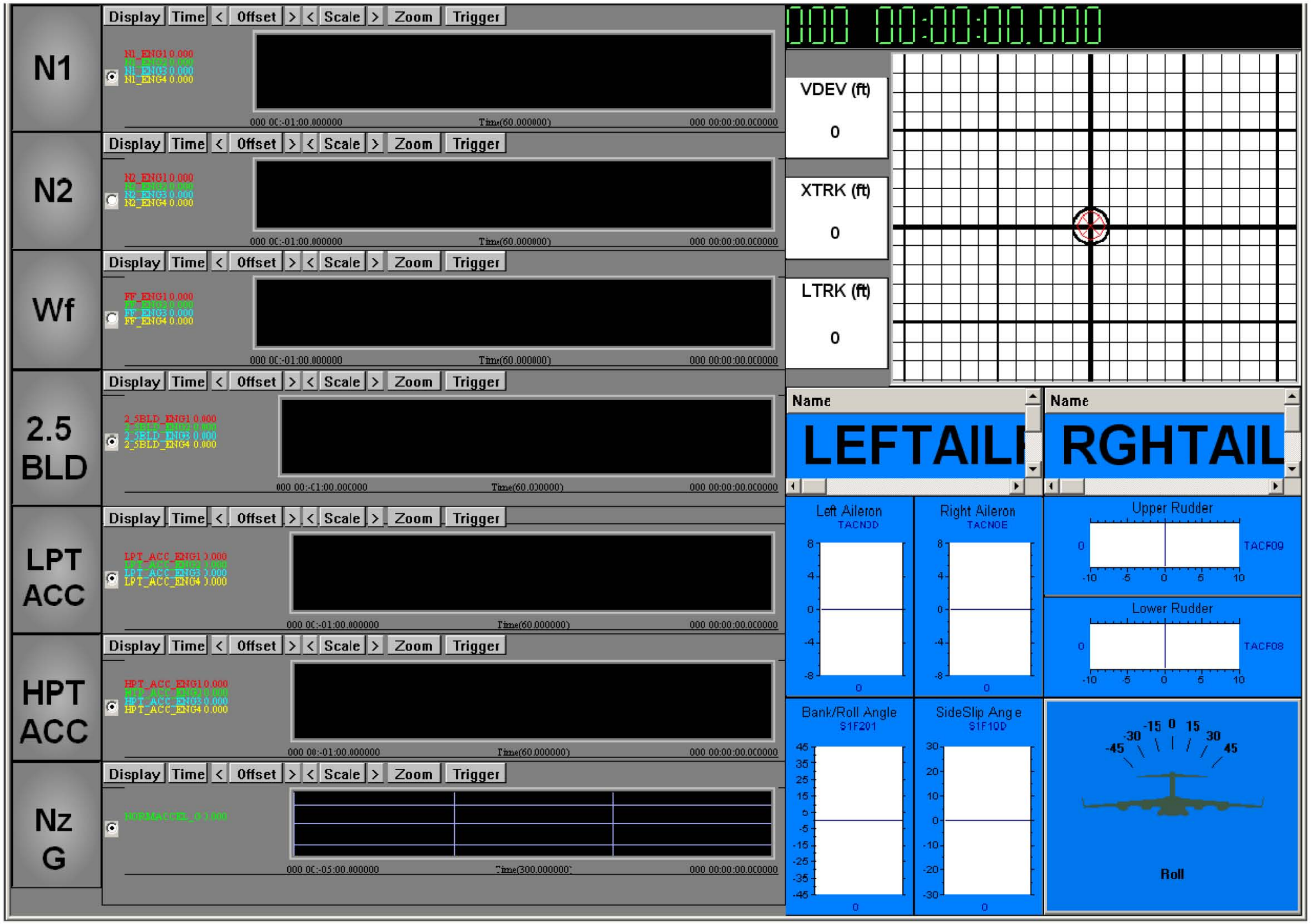
Test points for September flight (flight 3)

Test point	Cross track offset, ft	Vertical offset, ft	Note
T1	400	200	5 minute dwell after stabilized
H1	**240**	**0**	**3 minute dwell after stabilized**
H2	**220**	**0**	**3 minute dwell after stabilized**
H3	**200**	**0**	**3 minute dwell after stabilized**
H4	**180**	**0**	**3 minute dwell after stabilized**
H5	**160**	**0**	**3 minute dwell after stabilized**
T2	400	200	5 minute dwell after stabilized
V1	**180**	**20**	**3 minute dwell after stabilized**
V2	**180**	**-20**	**3 minute dwell after stabilized**
V3	**180**	**-40**	**3 minute dwell after stabilized**
V4	**180**	**-60**	**3 minute dwell after stabilized**
T3	400	200	5 minute dwell after stabilized

NASA Real-time Display

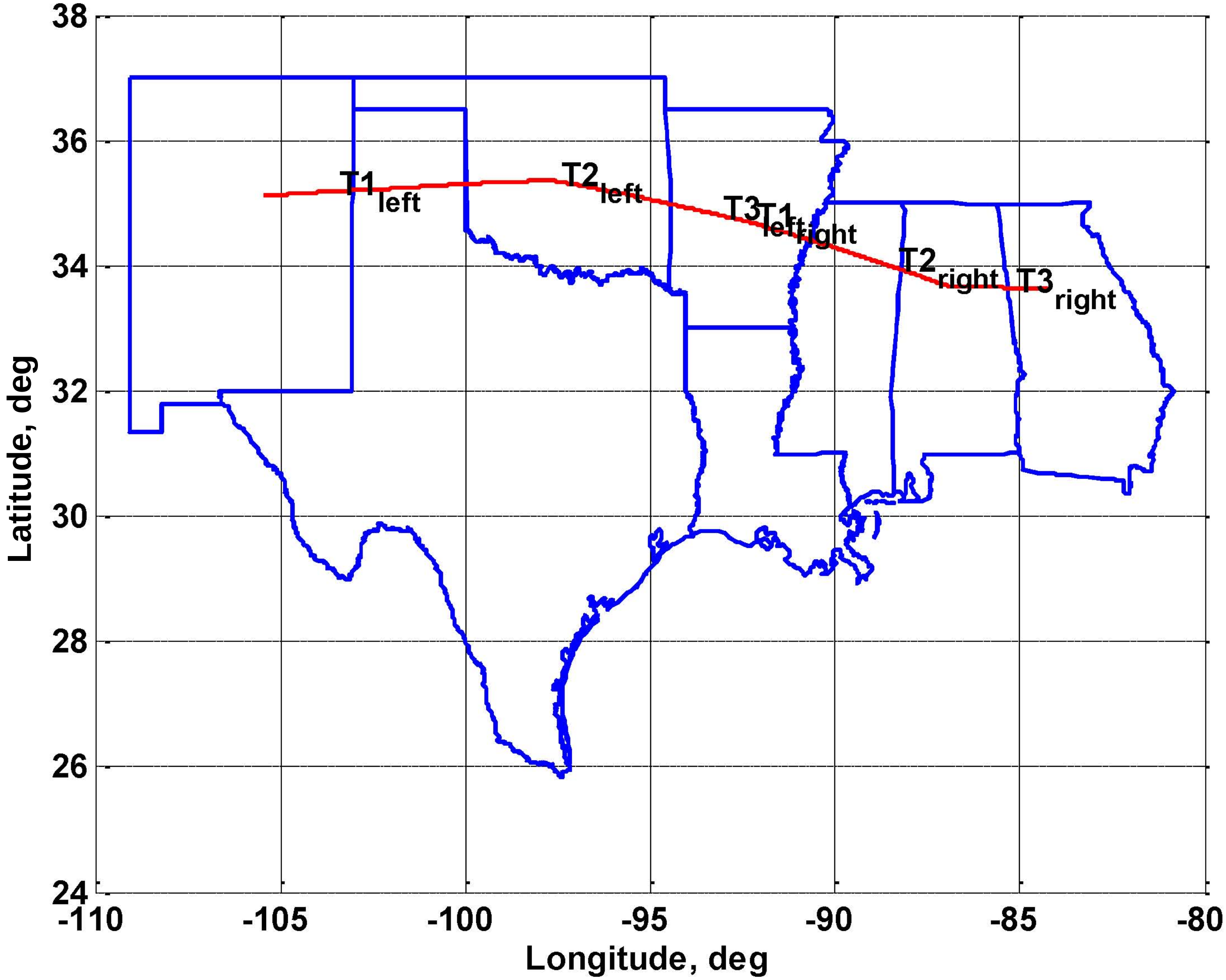
Trail Position

Engine parameters



Control Surfaces

Test Point Locations During Flight 3



Steady State Data Analysis

- Stabilizing at test point with existing pilot visual aids did not yield sufficient steady-state data for detailed analysis

- An alternate flight data analysis technique was developed
  - "steady-state" criteria over a period of 10 s
  - criteria was applied across all test points with proximity to the estimated vortex position

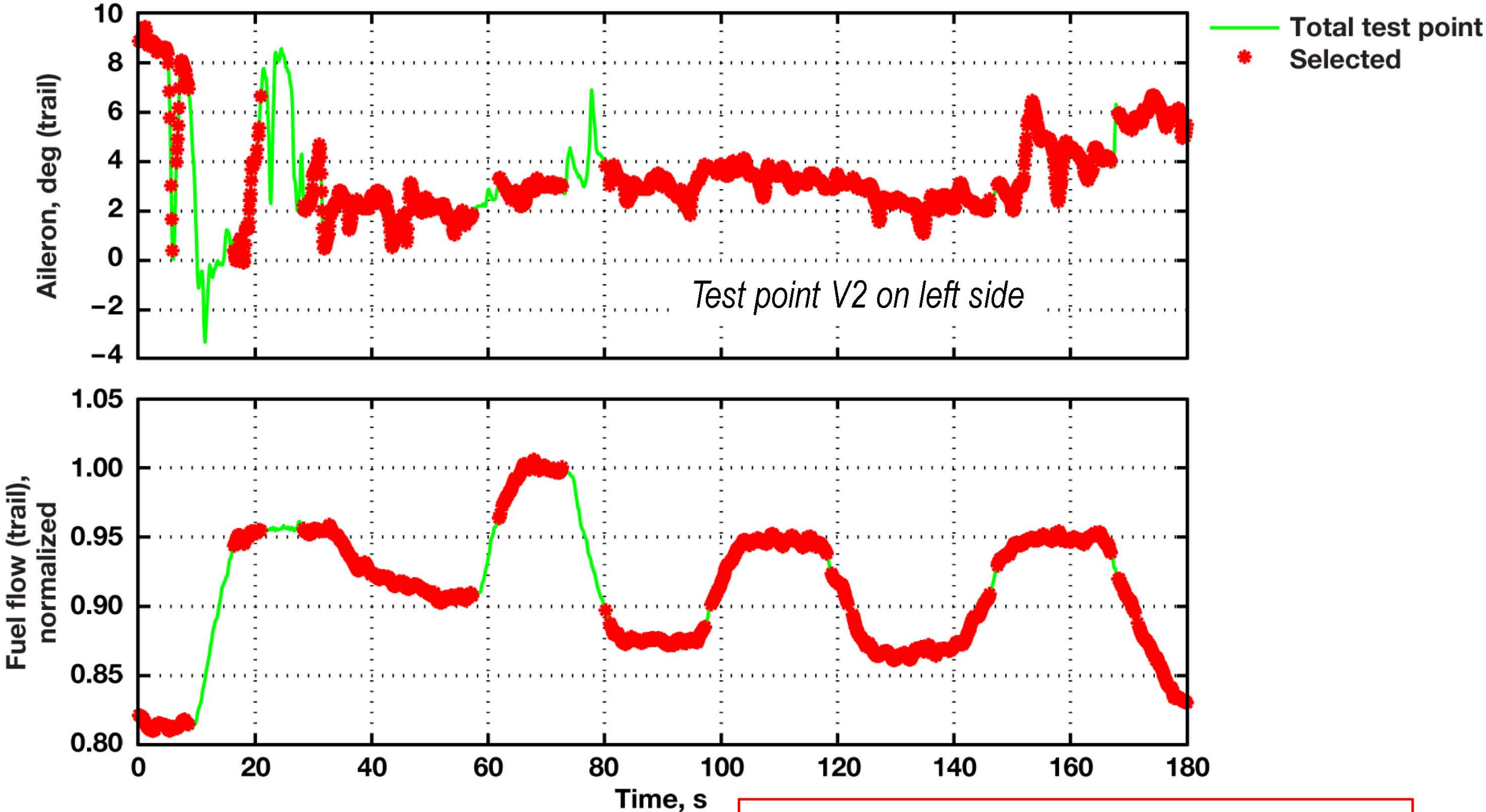
$$\text{Flight Condition: } 273\,\text{KCAS} < V < 277\,\text{KCAS and } |\dot{V}| < 4\,\text{knots/s}$$

$$\text{Test Point: } \left|\dot{Z}_{\text{offset}}\right| < 4\,\text{ft/s and } \left|\dot{Y}_{\text{offset}}\right| < 4\,\text{ft/s}$$

$$\text{Engine: } \left|\sum_{i=1}^{4} \dot{N2}_i\right| < 2\,\frac{\%}{s} \text{ and } \left|\sum_{i=1}^{4} \dot{F}_i\right| < 400\,\text{lb/s and } \left|\sum_{i=1}^{4} \dot{W}_{f_i}\right| < 200\,\frac{\text{pph}}{s}$$

$$\text{Control Surfaces: } \left|\delta_a\right| < 16^\circ \text{ and } \left|\dot{\delta}_a\right| < 10^\circ/\text{s and } \left|\delta_s\right| < 2^\circ$$

Example of Steady-State Criteria

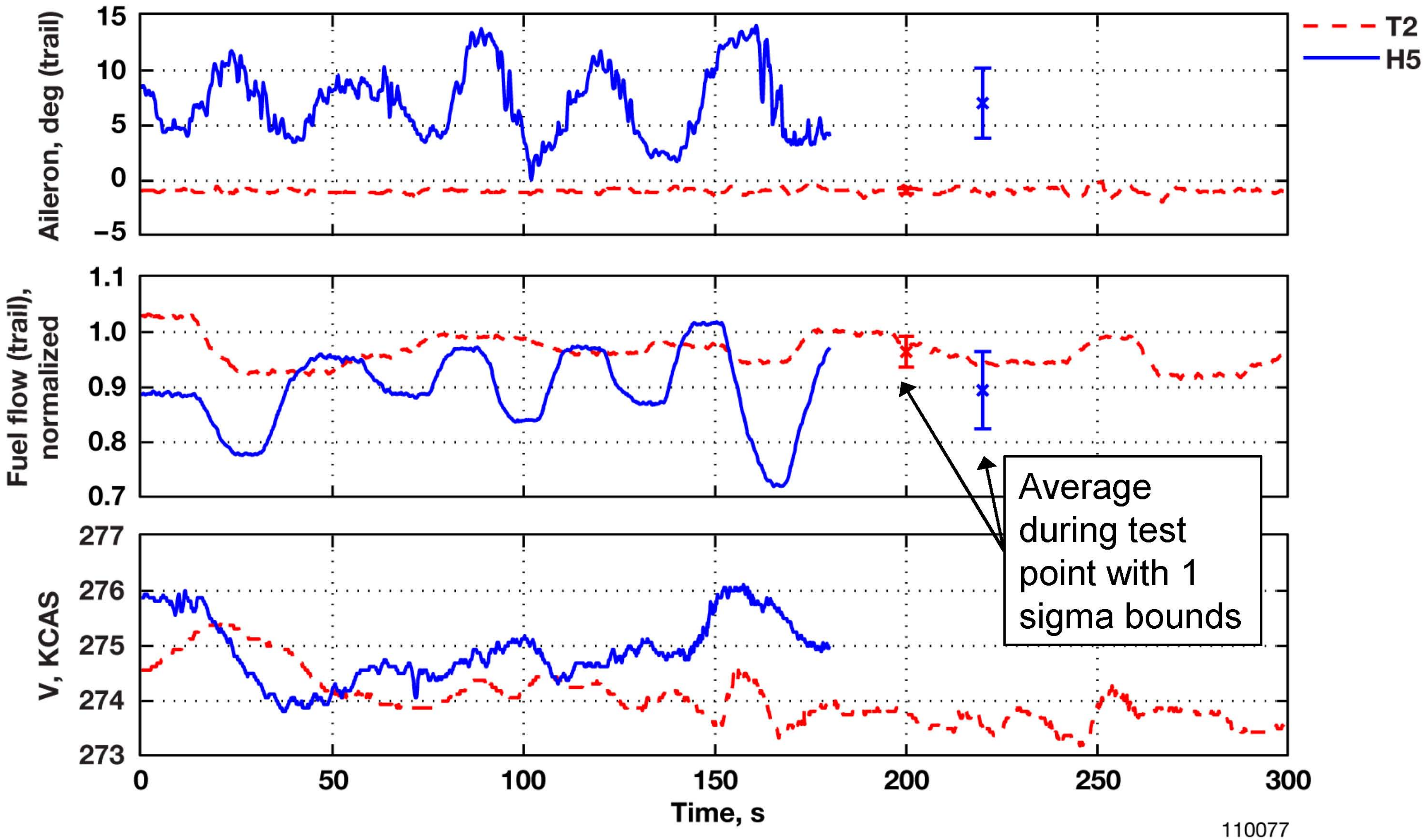


Red data points meet "steady state" criteria

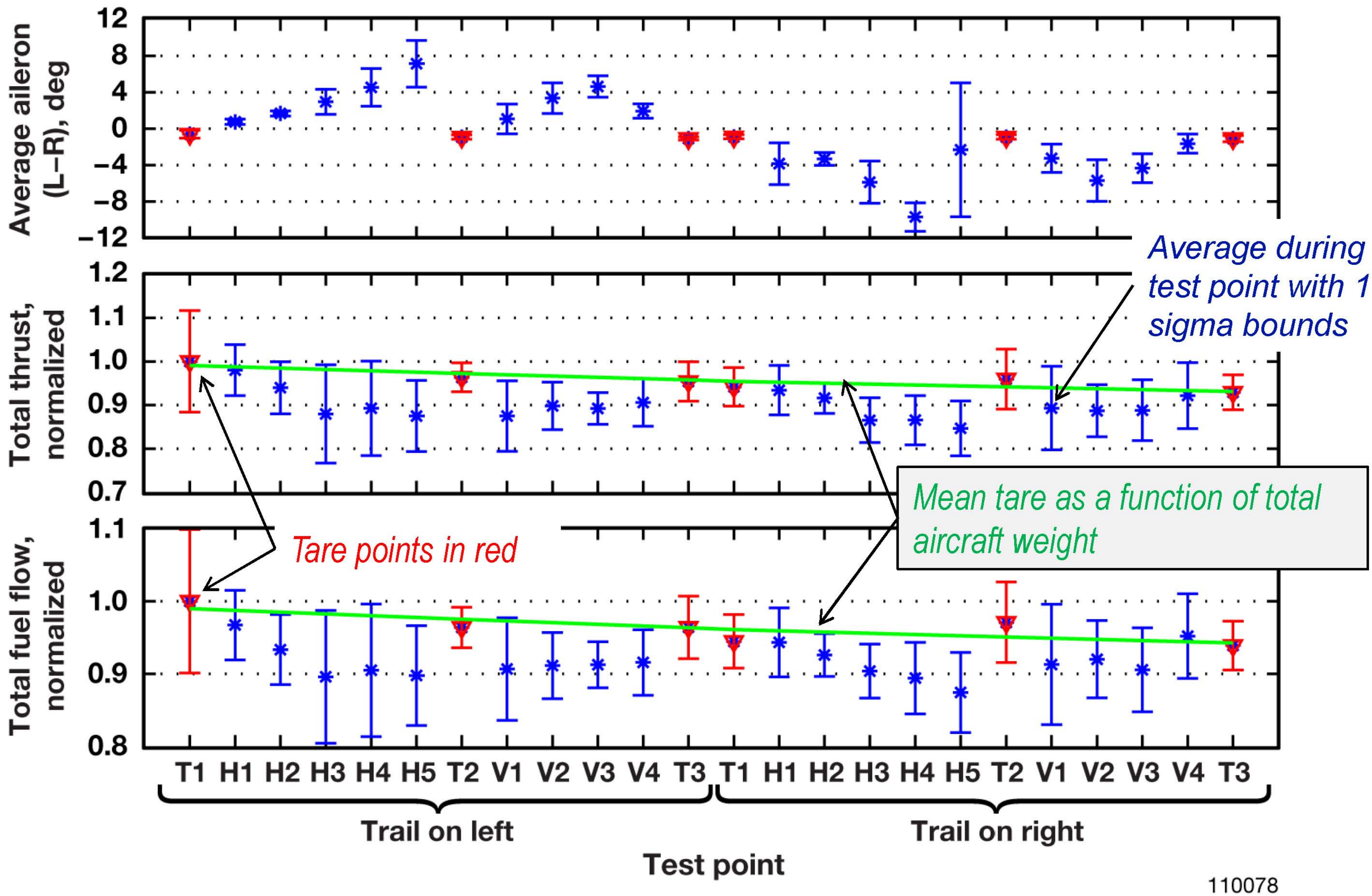
Initial Data Assessment (flight 3)

- Engaged FFS at 3000 ft trail in flight at 275 knots
  - Most test points in the area of influence of the vortex were pilot flown
  - Identical points repeated on the either side of the lead aircraft. Some asymmetry was noted, with H5 on the right side likely on the "downwash" side of the vortex
- Very difficult precision task for pilot to fly
  - Pilot noted that effort was similar to Aerial Refueling, but somewhat easier since it was not all 3 axes. Task was "not operationally representative" for the C-17.
- A reduction in estimated thrust and fuel flow is clearly evident
  - The benefit got larger as the trail vehicle got closer to the "wingtip overlap" point. This occurred on both the left and right sides.
  - Average aileron required for trim also increased as the trail vehicle moved closer to the "wingtip overlap" point

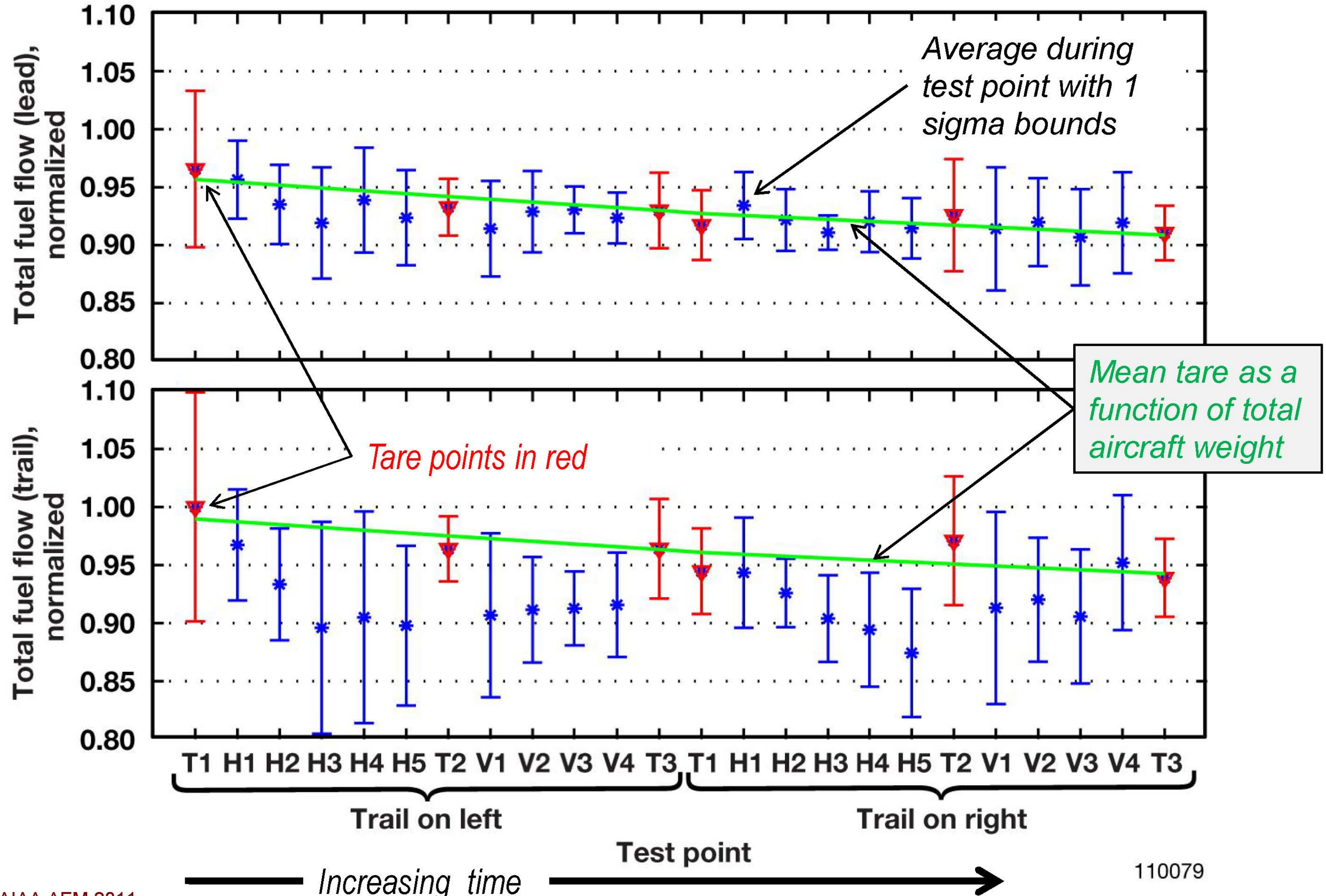
Comparison of Tare With Test Point



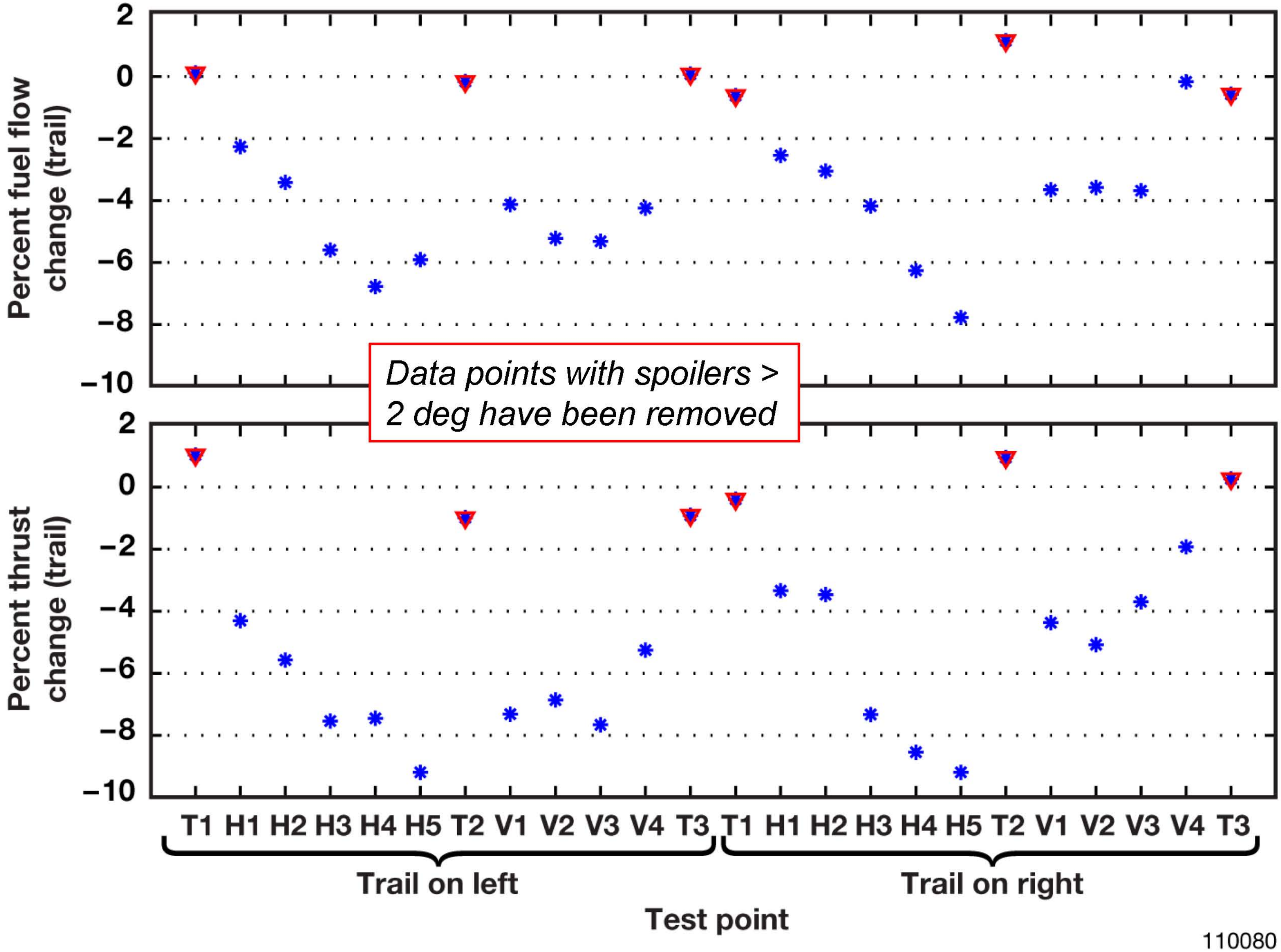
Summary of Test Points (trail)



Comparison of Lead and Trail Fuel Flow



Percent Change Corrected For Lead



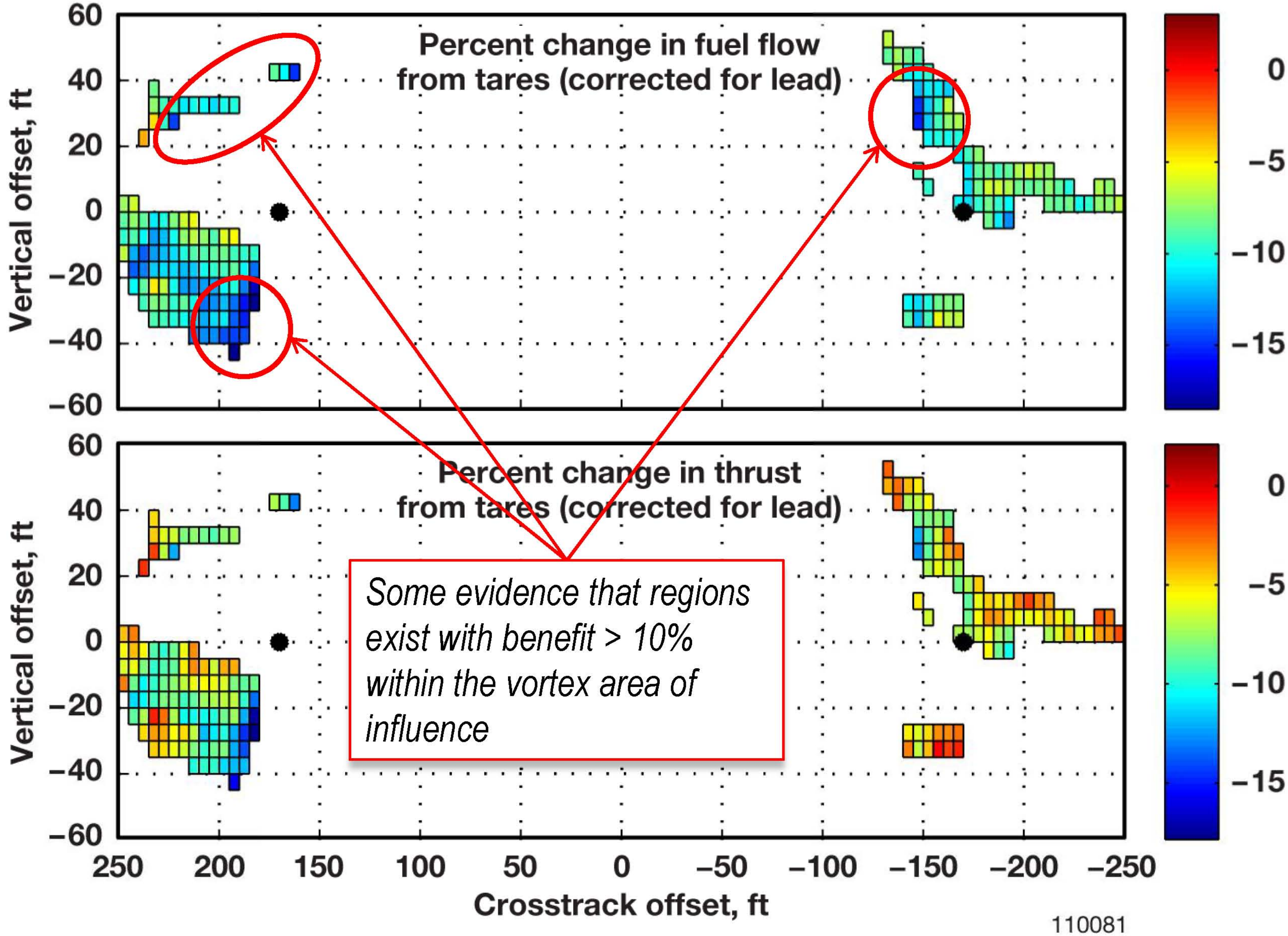
Sample Pilot and Crew Comments

- T1 – Left side “Pilot noted that position is maintaining very well” – NASA engineer
- H3 – Left side "I can hand fly this point no problem" – pilot
- H4 - Left side “Pilot holding steady right stick, no rudder, 2-3 lbs right stick” – FTE
- V2 – Left side “Position right on and ride feels very stable and smooth” – NASA engineer
- V3 – Left side “Rough ride with large aileron movements” - NASA engineer
- H2 - Right side “Like balancing on the head of a pin” – pilot
- H5 – Right side “by far the most difficult point to fly” – pilot
  - Hard to maintain, applying hard left – FTE
- V2 – Right side “A bit bumpy” - pilot

Comments taken from notes written by FTE and research engineers during test points.

All comments must be taken in context of the exploratory, research focus of the tests.

Percent Change in Fuel Flow and Thrust



Test Data Summary

- **Most test points flown in the vortex showed a reduction in average fuel flow and thrust compared to the tare test points**
  - **Test point data averaged over a 3 min “stabilized” period, tares averaged over a 5 minute period**
  - **In general, the greater the reduction in average fuel flow and estimated thrust, the greater the average aileron trim required to hold position**

- **The maximum *average* fuel flow reduction was approximately 7-8% (compared to the tare points before and after). This was during test point H4 and H5 on both the left and right side.**
  - **Average fuel flow reduction during both vertical profiles was 4-5%**
  - **Although benefit “maps” are incomplete, data suggests that regions with fuel flow and thrust reduction greater than 10% compared to the tare test points exist within the vortex area of influence**

Conclusions

- Qualitative flight data and comments were gathered during several two-ship, C-17 formation flights at a single flight condition (275 knots, 25,000 ft)
  - The C-17 FFS and auto-flight systems were used to stabilize the aircraft at some trail locations with predicted drag reduction
  - The pilot was able to fly test points, but the workload was high
- Production fuel flow and inputs to an estimated thrust measurement from the C-17 instrumentation system were of sufficient data quality for this initial experiment
- Predicting the maximum benefit location, or “sweet spot” for the trail aircraft was significantly hampered by the lack of knowledge regarding the actual location, size, and velocity profile of the wake vortex

CAPFIRE – Potential Development Path

- ***Address safety concerns and technical risks early***
- ***Integrate with future airspace concept developments***
- ***Leverage partnerships***

Commercial Passenger

Commercial Cargo

Military Transports

Increased Economic and Environmental Benefit

Photo by Mike Venti
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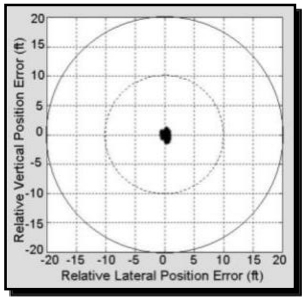
Historical: NASA Autonomous Formation Flight Program

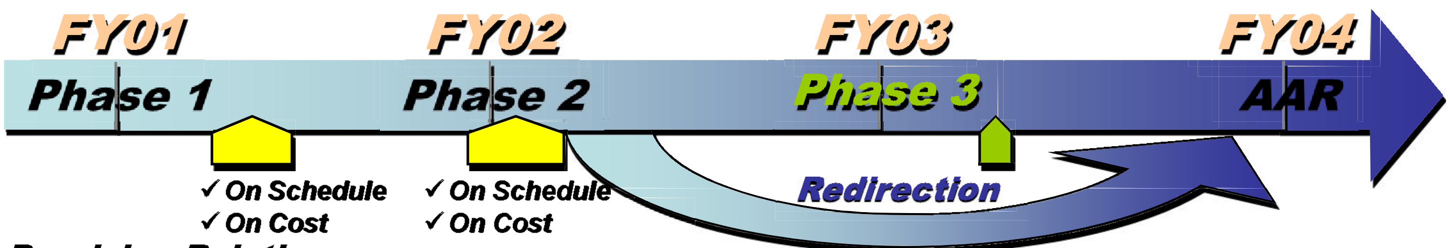
Autonomous Precision Station Keeping Demo



2-Minute Tracking Task

Autonomous Drag Reduction Demo

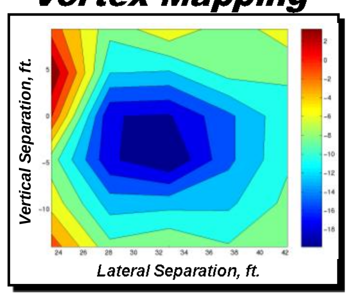
Potential Follow-on



Precision Relative Positioning

Achieved ~1ft Accuracy

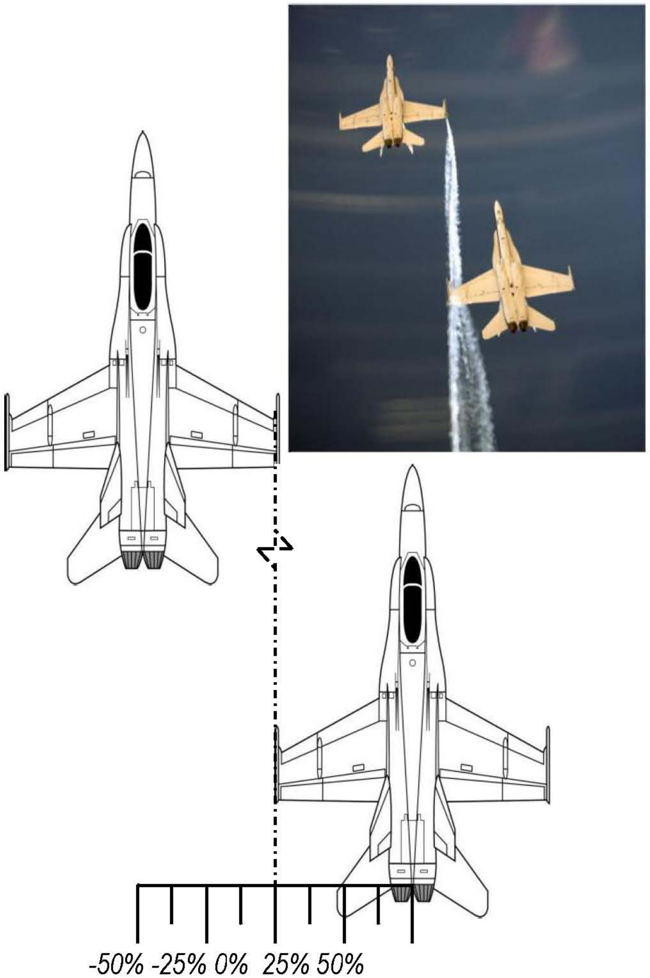
Vortex Mapping



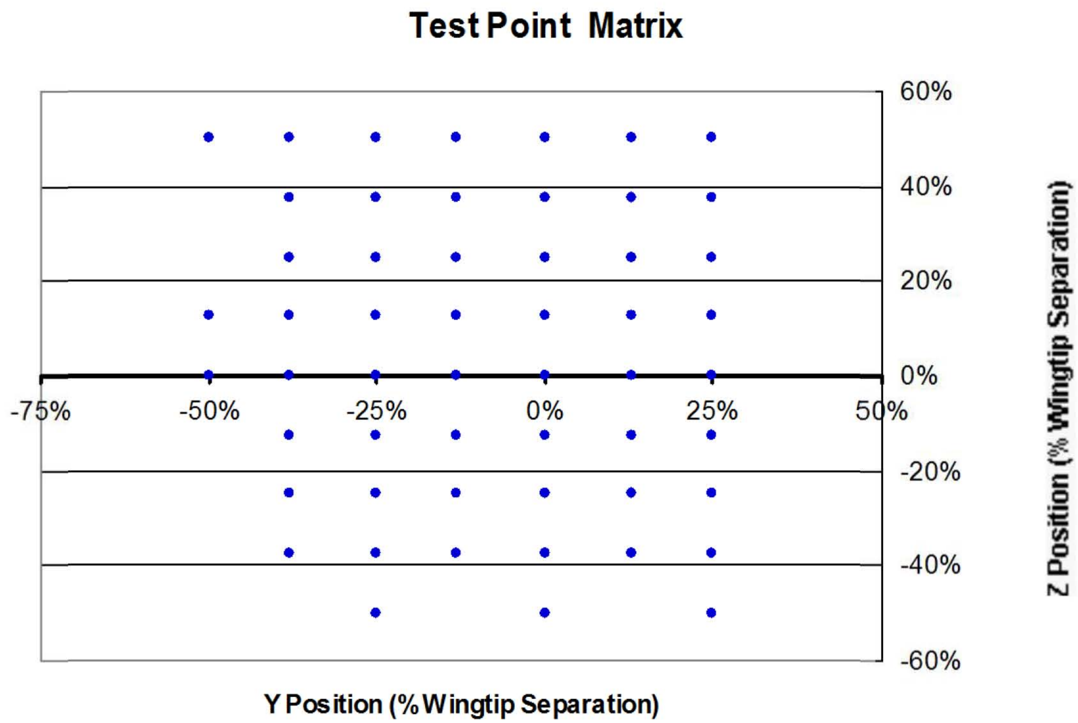
>20% Drag Reduction, 0.56M, 25Kft

Project emphasized systematic risk reduction approach

NASA AFF Phase 2: Vortex Mapping
Test Point Matrix



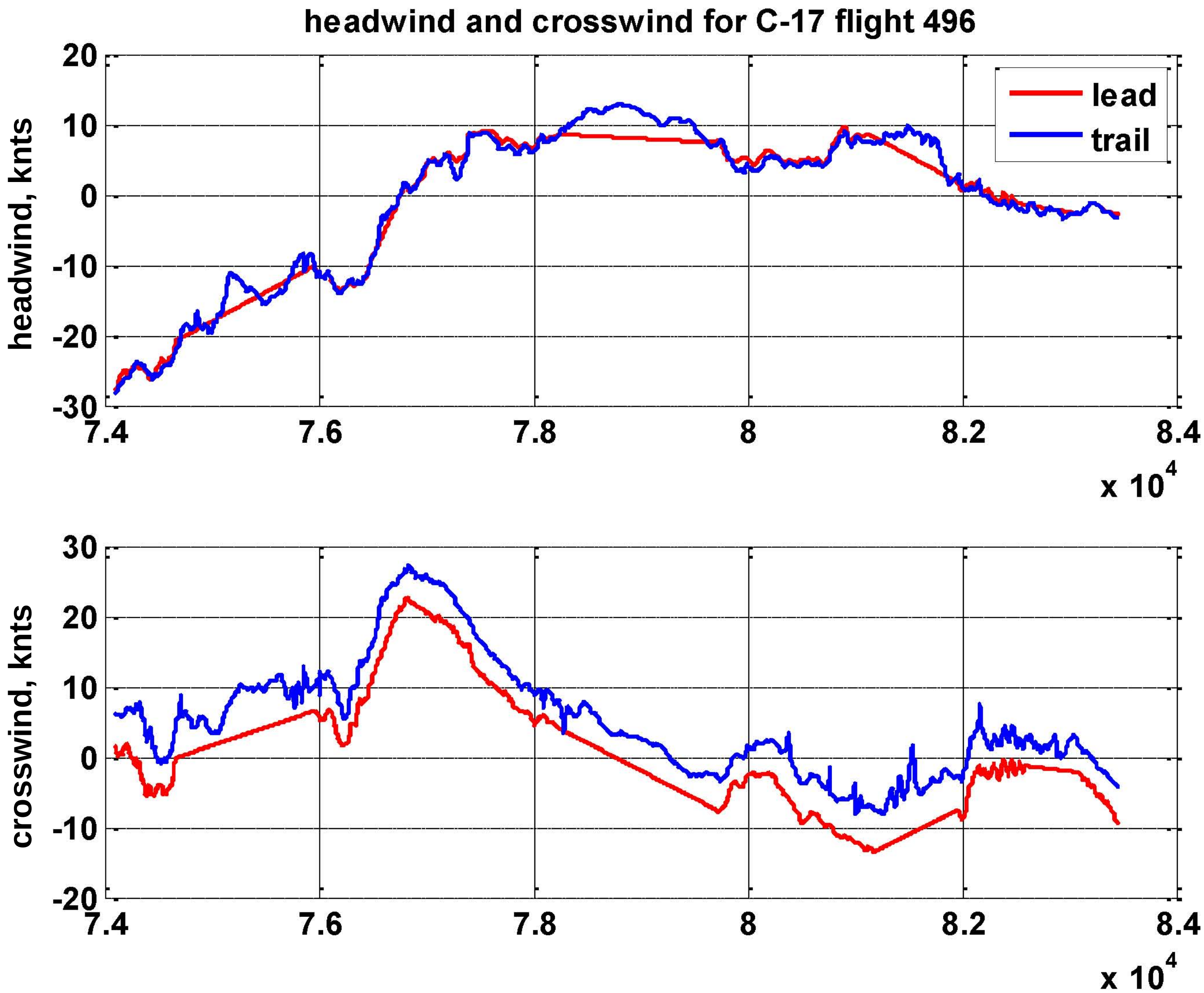
(% Wingtip Separation)



M=0.56 & 0.86
Nose to tail separation: 20, 55, 110, 190 feet

Note: Wingtip Separation = - Wingtip Overlap

Winds



headwind and crosswind for C-17 flight 496
headwind, knts
20
10
0
-10
-20
-30
7.4
7.6
7.8
8
8.2
8.4
x 10^4
lead
trail
crosswind, knts
30
20
10
0
-10
-20
7.4
7.6
7.8
8
8.2
8.4
x 10^4

Executive Summary

- Qualitative flight data and comments were gathered during several two-ship, C-17 formation flights (targeted at drag reduction) at a single flight condition (275 knots, 25,000 ft)
- The C-17 FFS and auto-flight systems were used to stabilize the aircraft at some trail locations with predicted drag reduction
  - The pilot was able to fly FFS test points, but the workload was high
- For this limited set of tests, the maximum *average* fuel flow reduction was approximately 7-8% (compared to the tare points before and after).
  - There is some evidence that regions with fuel flow and thrust reduction greater than 10% compared to the tare test points exist within the vortex area of influence