Design, Development, and Flight Evaluation of Pilot Displays and Long-Track Control for Wake Surfing Applications

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NASA G-III Wake Surfing Flight Experiment

In 2016, NASA Armstrong equipped a G-III test aircraft with an ADS-B enabled research autopilot. The Automated Cooperative Trajectories (ACT) flight experiment had 3 main objectives:

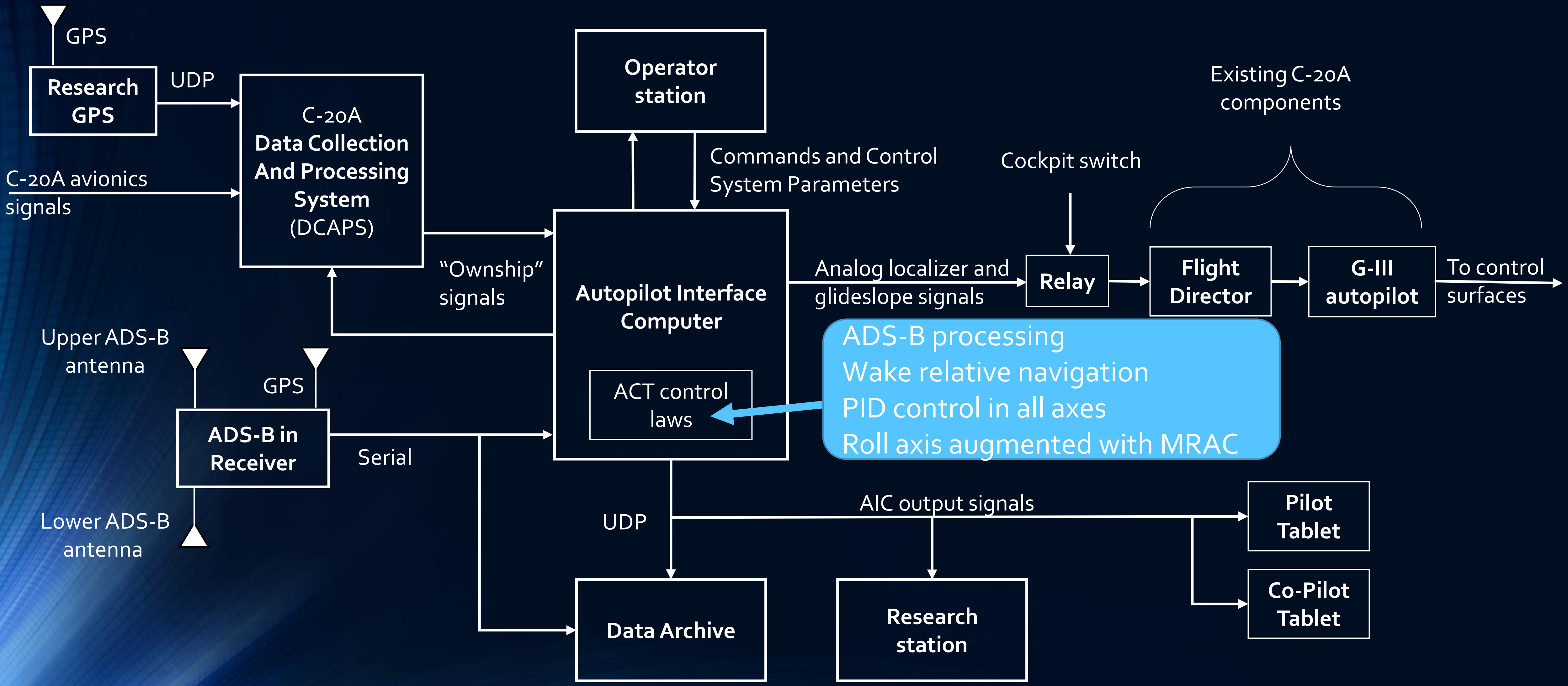
1. Gather data to help characterize the benefits and impacts of wake surfing for civil transport aircraft.
2. Evaluate the suitability of ADS-B as a data link for autonomous, cooperative flight procedures.
3. Advance the state of the art in tools, algorithms, and methods for wake surfing guidance and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

The lead - vortex-generating - aircraft was an unmodified G-III equipped with a certified 1090 MHz ES ADS-B transmitter.

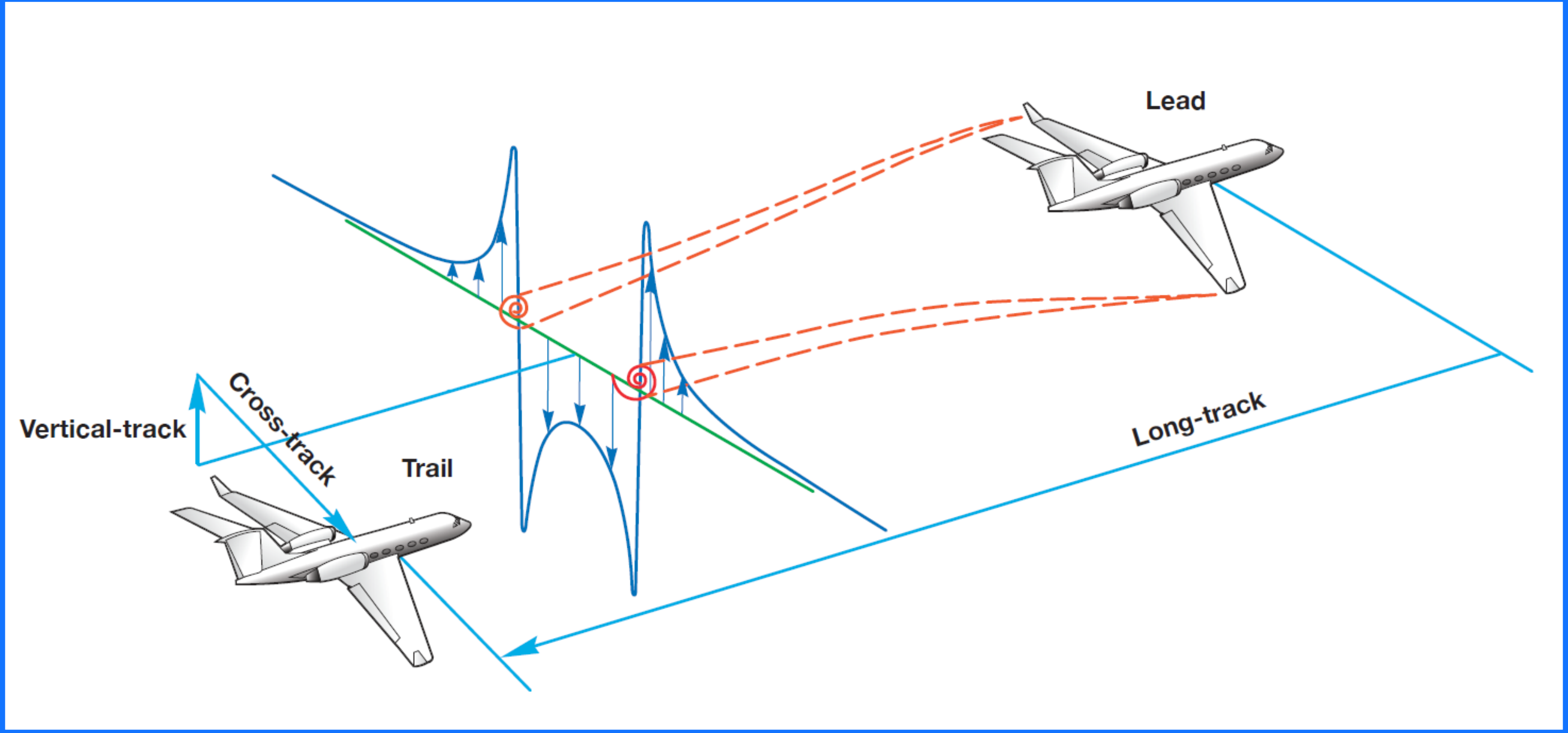
- 4,000 ft in trail
- Cruise flight condition: M0.7, 35,000 ft
- Straight-and-level flight, 30+ minute legs
- Autopilot control of wake-relative cross-track and vertical-track position
- Pilot control of long-track spacing

Flights were completed in May, 2017.

System Components



Wake-Relative Positions



(+) Cross-track to the right of the wake

(+) Vertical-track above the wake

(+) Long-track from the center of the lead aircraft to the center of the trail aircraft

Need for Wake Surfing Pilot Displays

A wake vortex situational awareness display was required to:

1. Provide situational awareness of an estimate of the wake vortex location.
2. Evaluate the performance of the ACT controller maintaining a commanded cross-track and vertical-track position.
3. Provide a target position for the pilots to set up at when engaging the ACT controller at a safe distance away from the wake vortex.

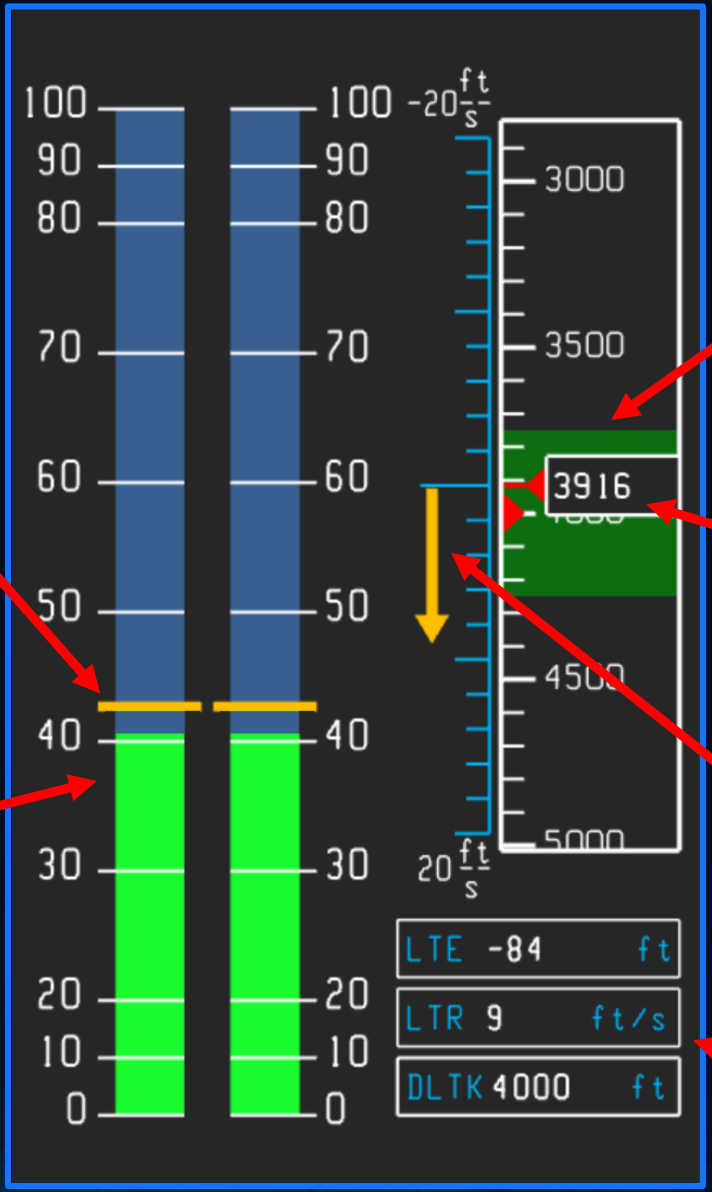
A throttle cue and long-track situational awareness display was required to:

1. Provide throttle cues for Pilot-in-the-loop throttle control required to maintain precise long-track position.
   - This is due to the G-III not having an auto-throttle capability.
2. Provide situational awareness of the relative separation distance between the lead and trail aircraft.

Long-track and Throttle Display

PLA Command in percentage throttle

Current PLA position in percentage throttle



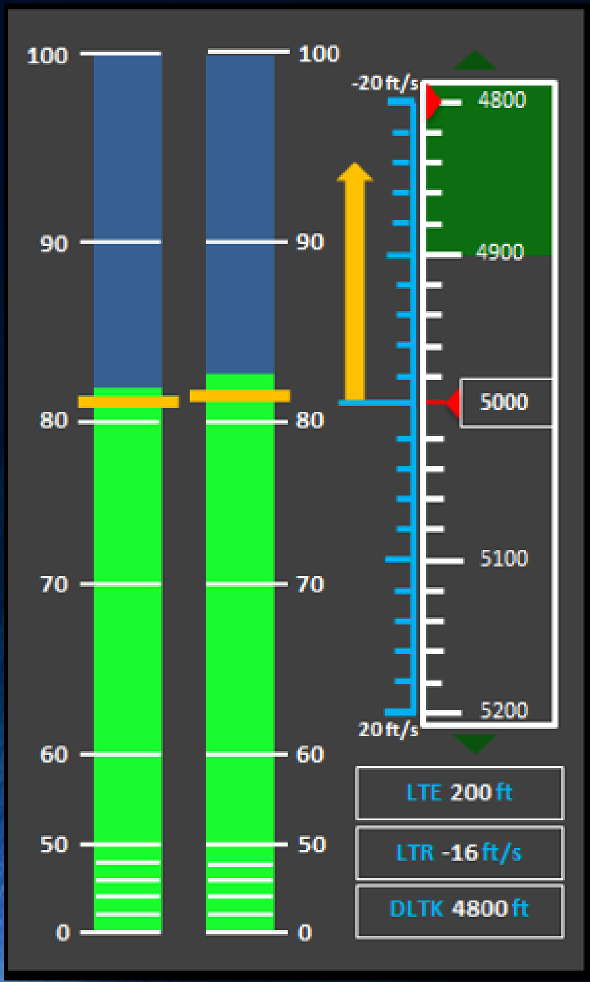
Desired long-track position in feet with +/- 250 foot tolerance box

Current long-track position in feet

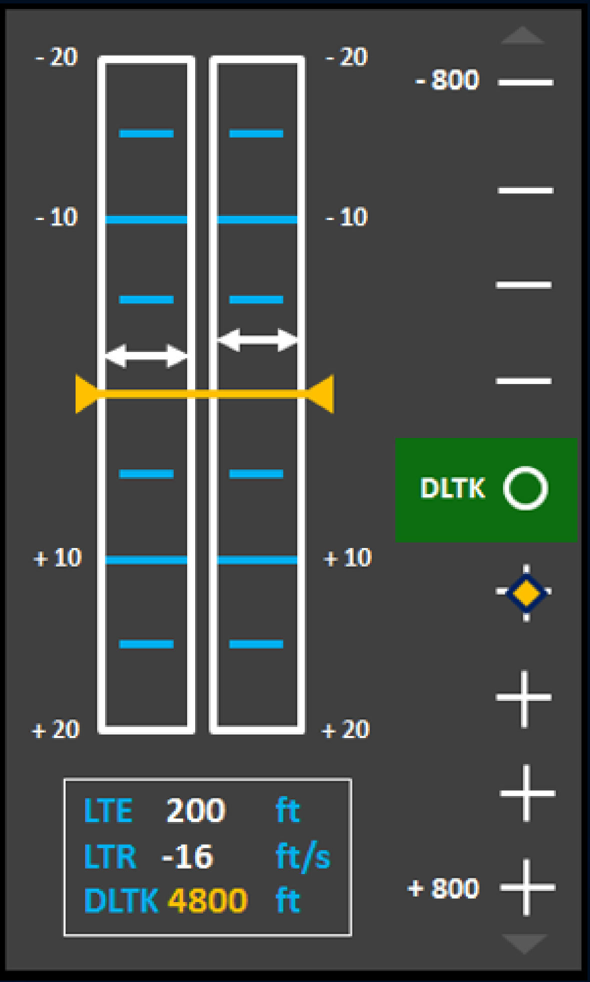
Long-track rate indicator in feet per second

Long-track error, long-track rate and desired long-track

Long-track and Throttle Candidate Displays



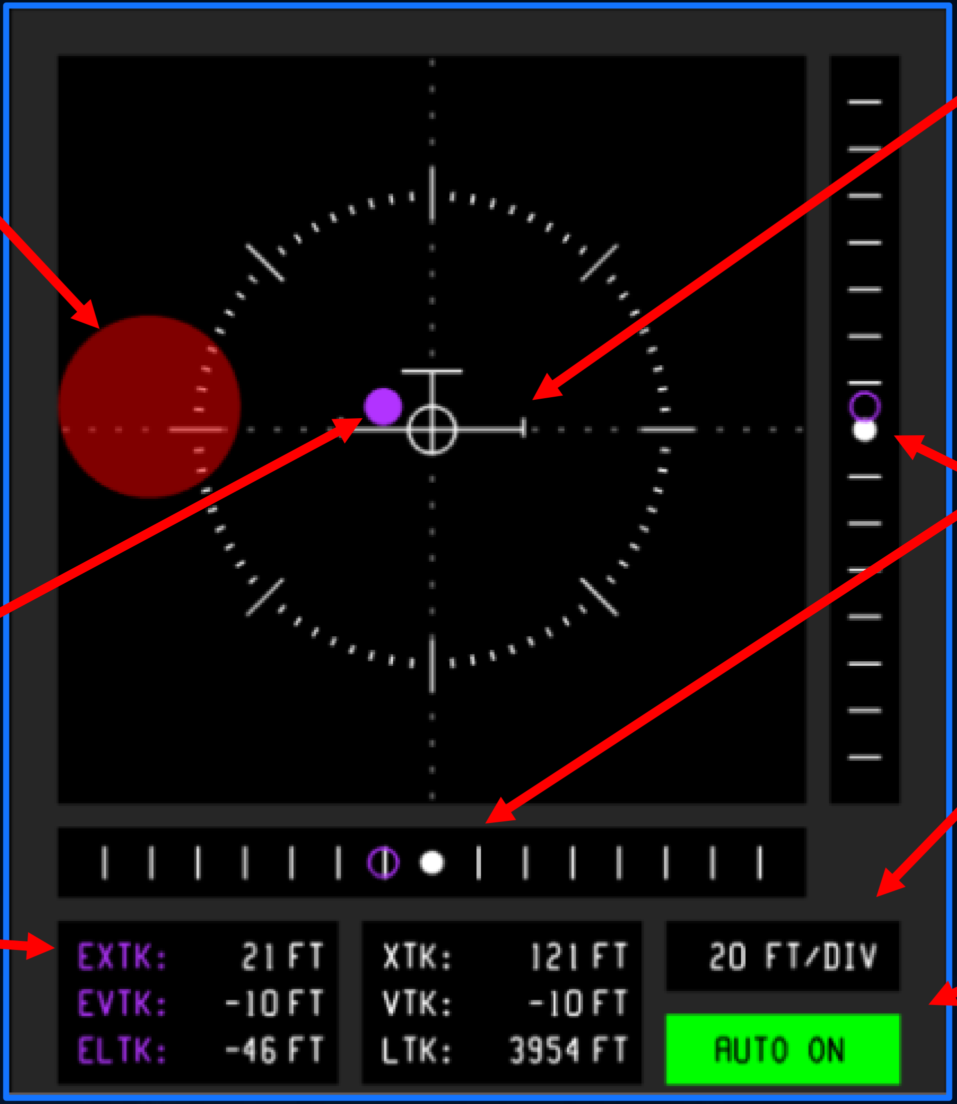
Total Command Display



Delta Command Display

- Candidate displays were developed with feedback from NASA test pilots using the displays in the G-III wake surfing simulation.
- The delta command display was found to be too sensitive which resulted in higher amounts of throttle activity.
- The long-track position and rate indicators were used by the pilots to anticipate upcoming throttle motion.

Wake Awareness Display



Estimated wake vortex position indicator (Red chevron when off screen)

Desired position indicator (purple chevron when off screen)

Current relative positions and errors in feet

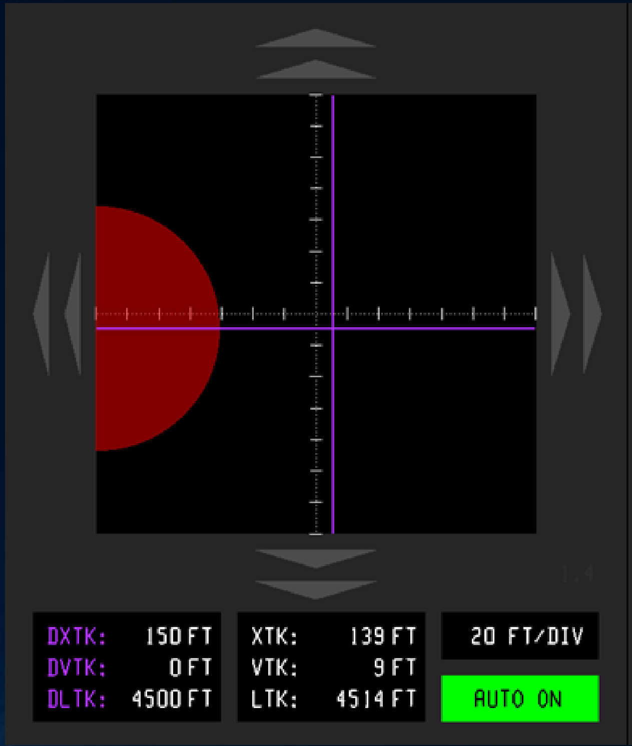
Trail Aircraft Indicator

Aircraft position and desired position tapes

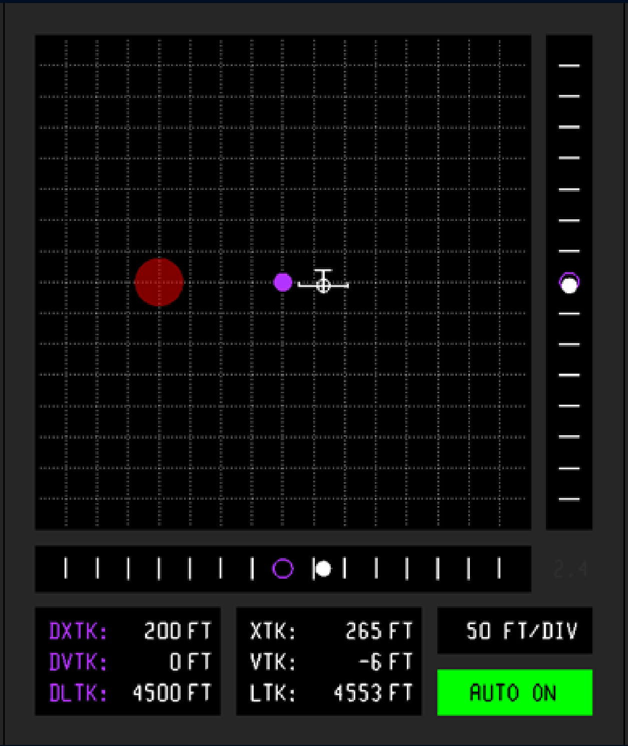
Display scale

Programmable autopilot engaged

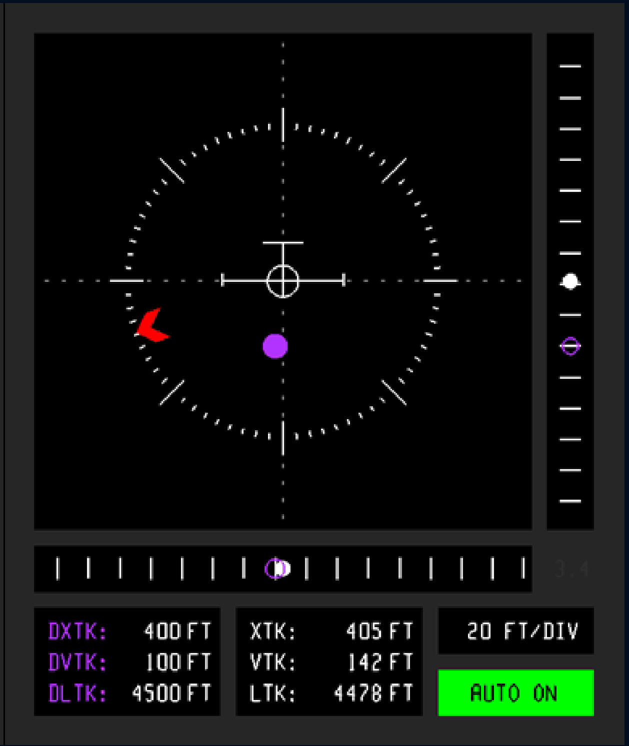
Wake Awareness Candidate Displays



ILS Display



Auto-scaling Display



Chase View Display

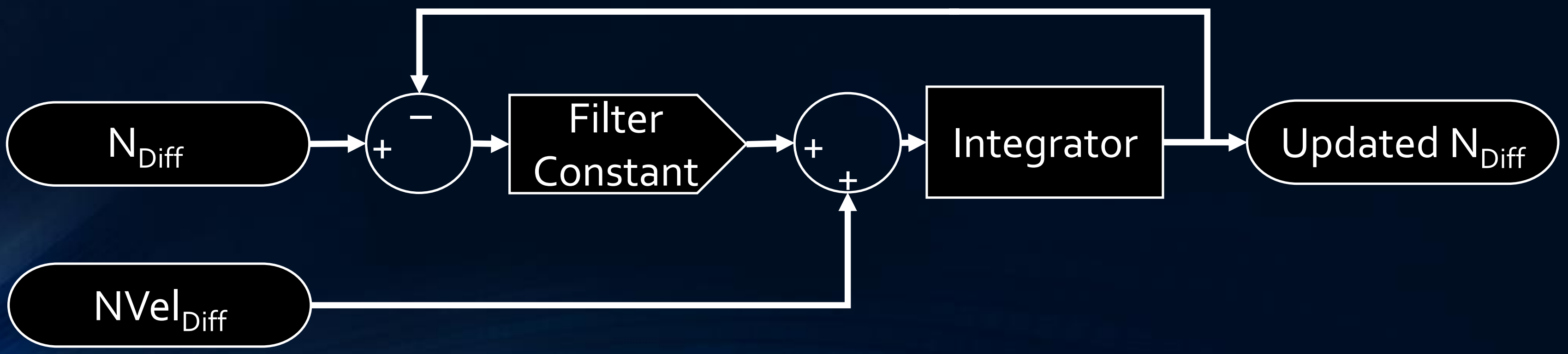
- Overall, the chase view display was most preferred by the pilots, providing more clarity than the ILS display.
- Auto-scaling display allowed the pilots to discern rate information, but would often cause confusion when the scale changed while the formation was in an unusual geometry or the pilot looked away from the display.
- Numerical error information was preferred over desired command values as they could be used by the pilots to determine the closure rates.

Long-track Calculation and Complimentary Filter

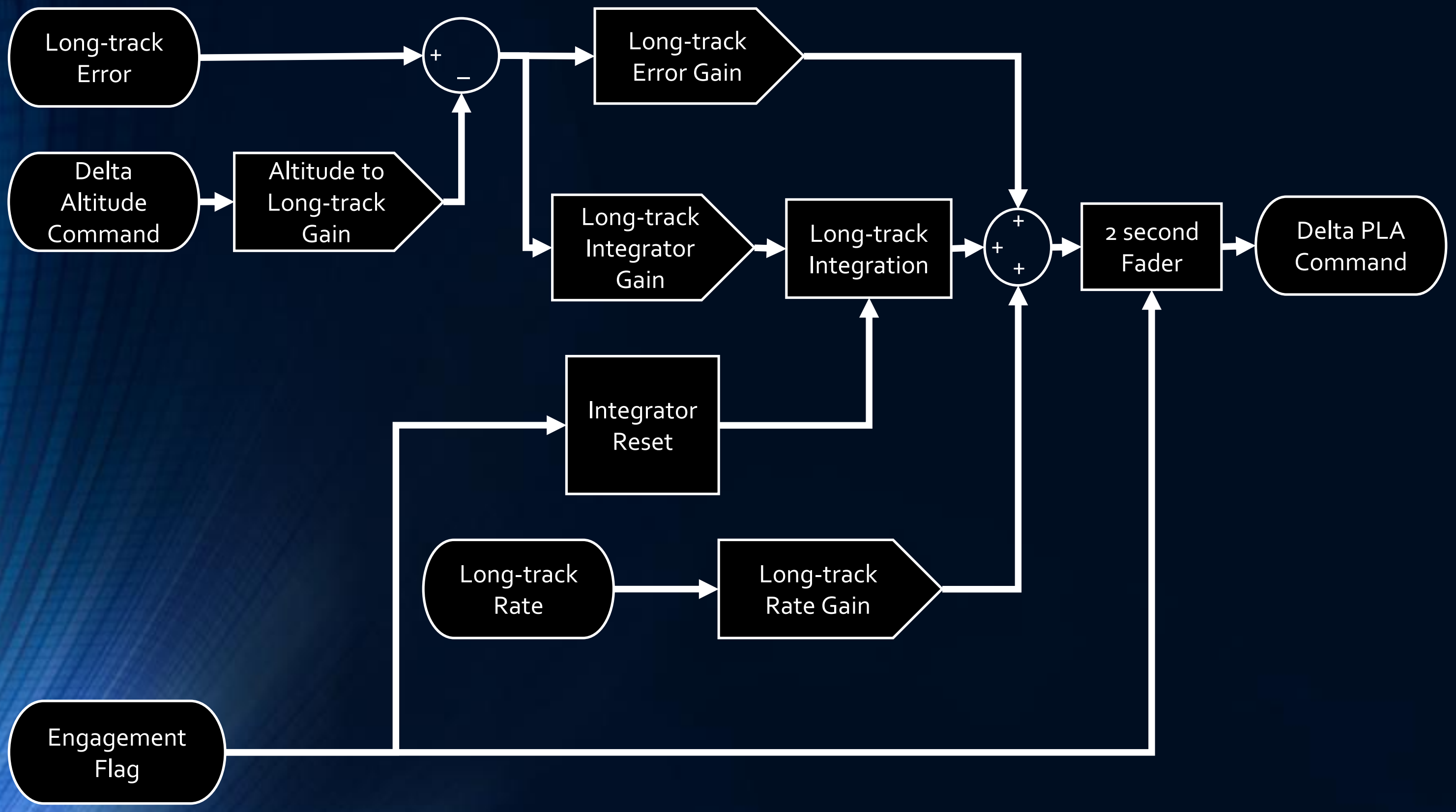
$$\text{Long-track}_{Est} = -\left(N_{Diff} * \cos(\text{LeadGroundTrackAngle}) + E_{Diff} * \sin(\text{LeadGroundTrackAngle})\right)$$

North and East position differences derived from coordinate transformation of ADS-B lead and trail GPS latitude, longitude, and altitude messages.

Due to difference in ADS-B and trail GPS data rates, a complimentary filter was required to smooth out and correct the N_{Diff} and E_{Diff} signals using the velocity difference between the lead and trail aircraft as a correcting term.



Long-track PLA Control



The long-track controller consists of a delta PLA command summed with a referenced PLA position for a total PLA command.

- The delta PLA controller is a PID controller with an additional delta altitude compensation term.
- The referenced PLA (not shown) is a slowly filtered average of the indicated PLA position.
  - Provides additional control authority when attempting gross acquisition of a long-track position.

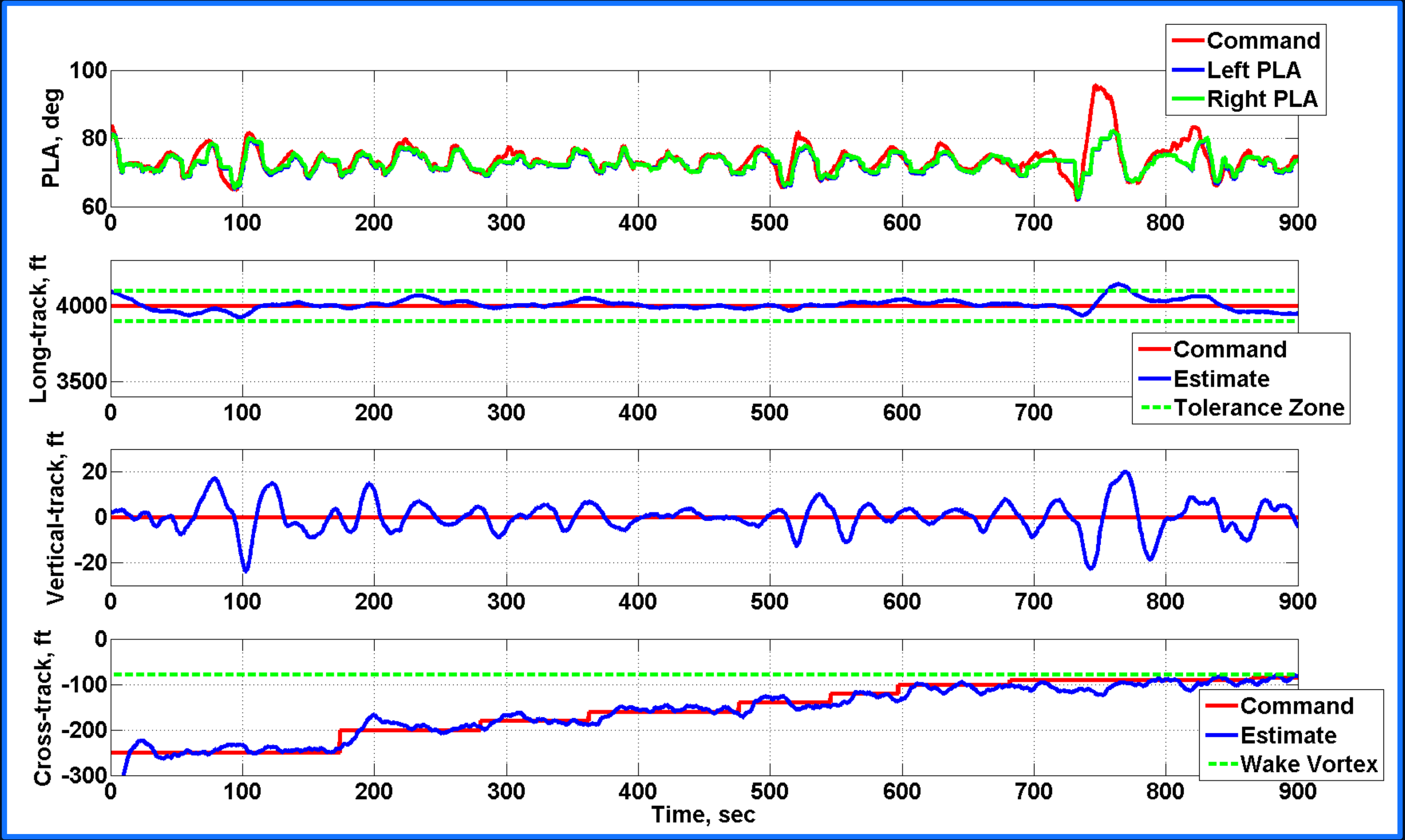
Flight Testing

- Completed 10 flights (8/16-5/17)
  - 6 system checkout and development flights
  - 4 flights in wake
- All testing was done in US Navy Special Use Airspace W-291 over the Pacific for 30+ minute test legs.
- 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 point out of wake effects
  3. Wake Mapping
  4. Performance Dwells of 3-5 minutes
  5. 5-minute Tare point

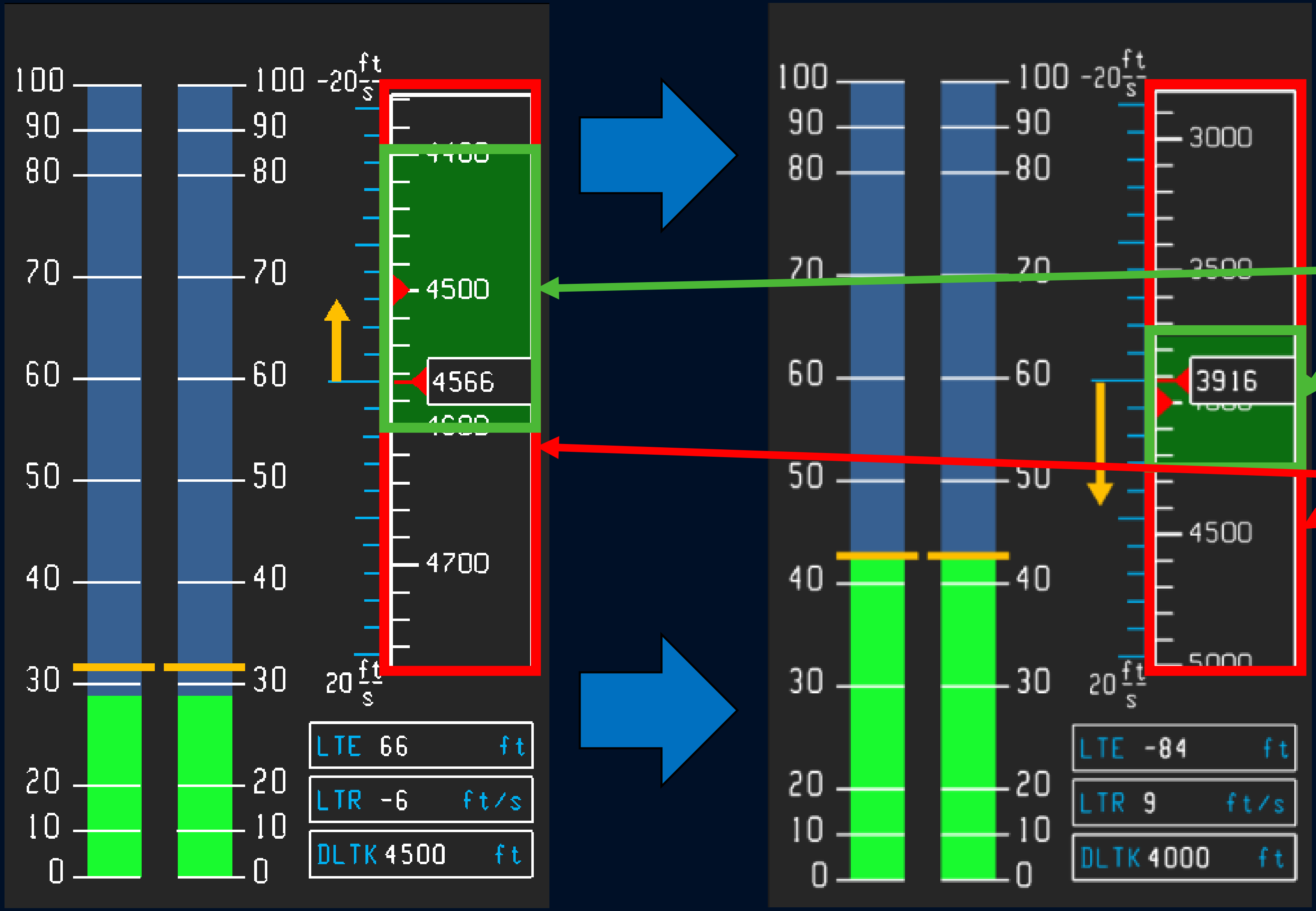
Wake Surfing

Flight 8 Throttle Response

- Throttle motion was high frequency with little damping, often requiring the pilots to constantly monitor the throttle display and position throughout the flight.
  - Any lapse in following the throttle command resulted in significant effort to regain longtrack position.
- Overactive throttles had a negative impact on vertical-track performance, causing constant oscillations in the vertical axis.
- Impossible to determine fuel savings due to dynamic throttle motion affecting the fuel flow measurements.



Changes to Long-track Display



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

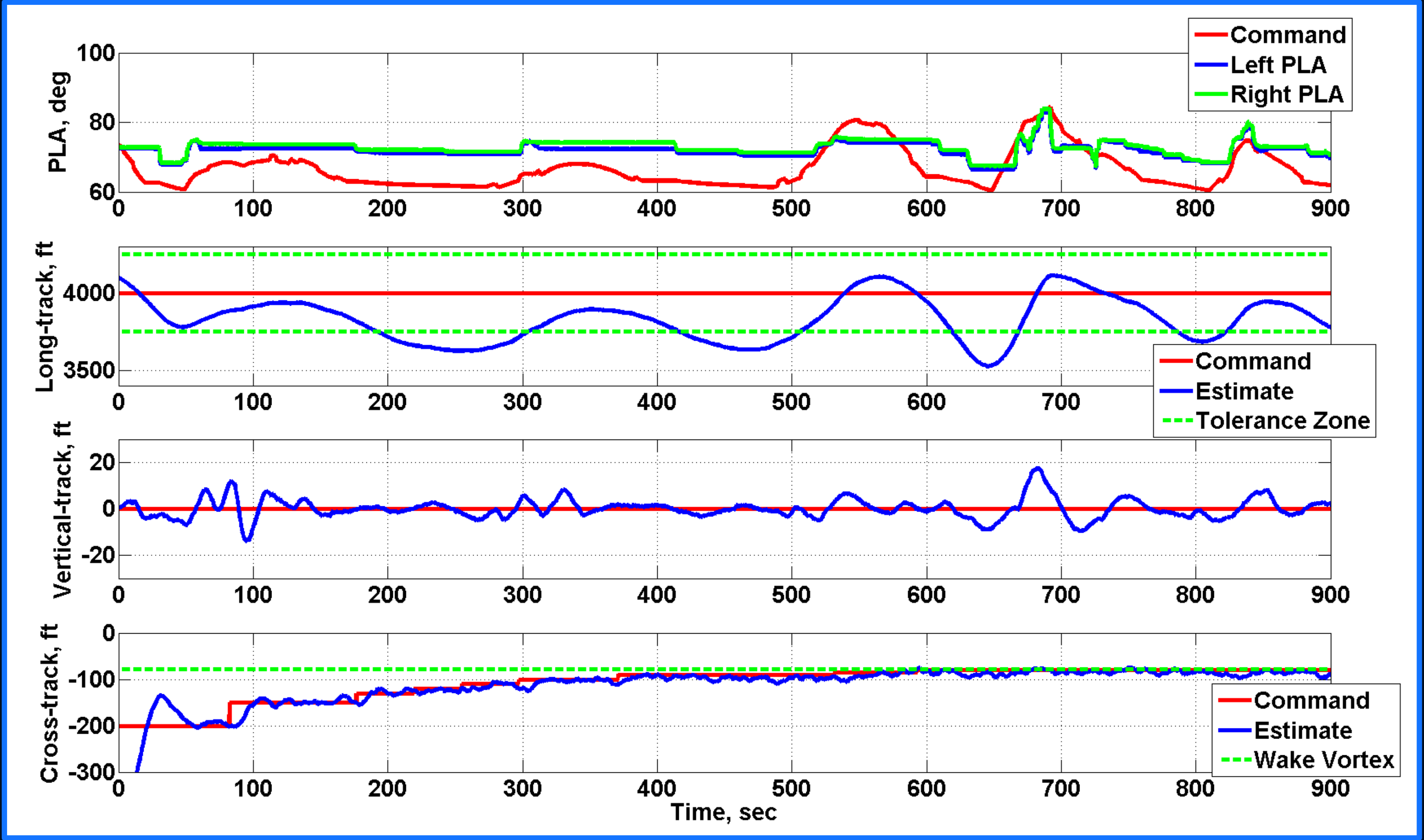
Increased the long-track tolerance box from +/- 100 ft to +/- 250 ft

Increased the long-track view range from +/- 200 ft to +/- 1100 ft.

Allow pilots to maintain long-track position without following throttle cues.

Flight 10 Throttle Response

- Significantly reduced the amount of throttle motion required by the pilot.
  - Pilots would often leave the throttles untouched for minutes at a time.
- Vertical-track motion due to throttle dynamics is significantly reduced.
- Long-track position error significantly increased with less throttle activity.
  - The cross-track and vertical-track controllers were able to hold the commanded positions even with large long-track error.
- Throttle dynamics were stable enough to determine fuel savings of greater than 8% in the effects of the wake.

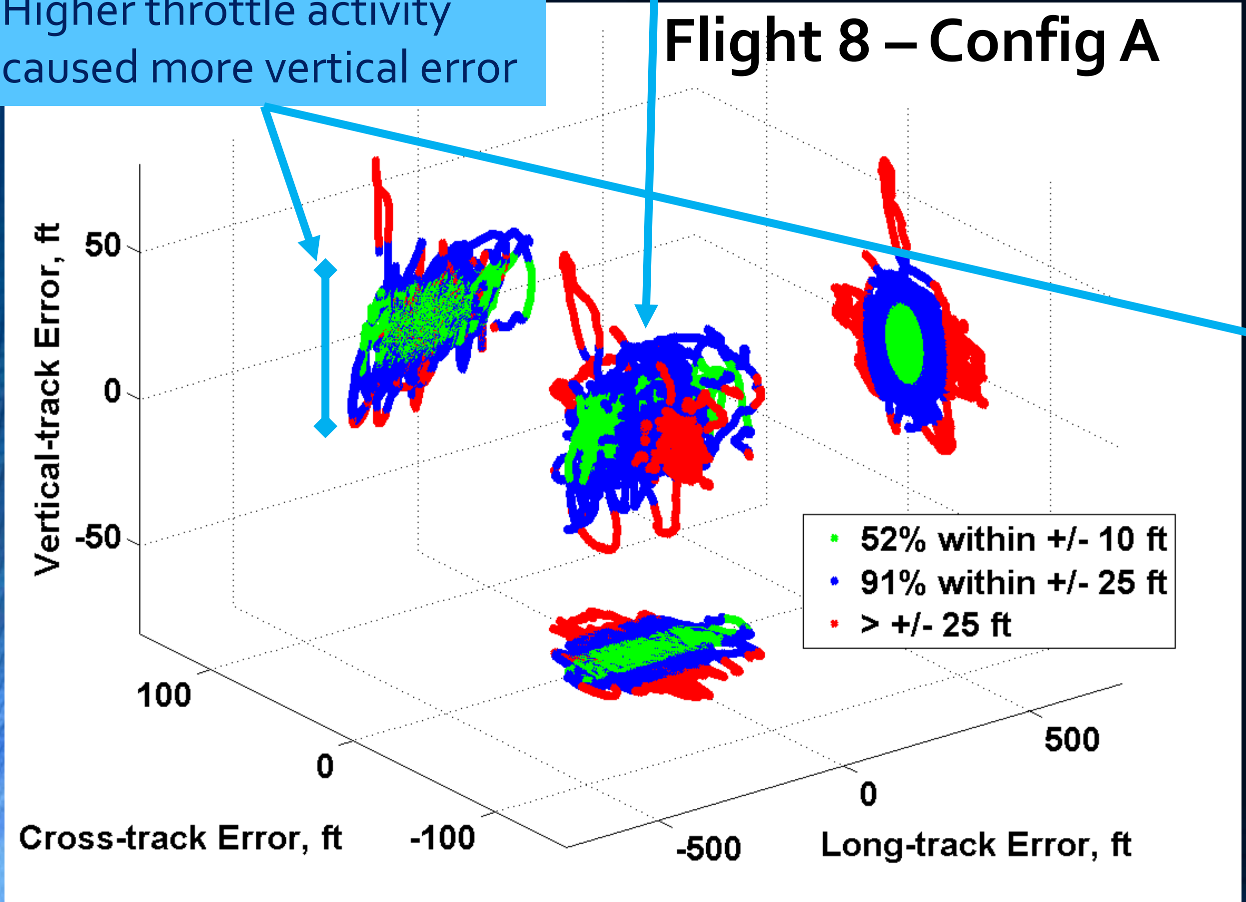


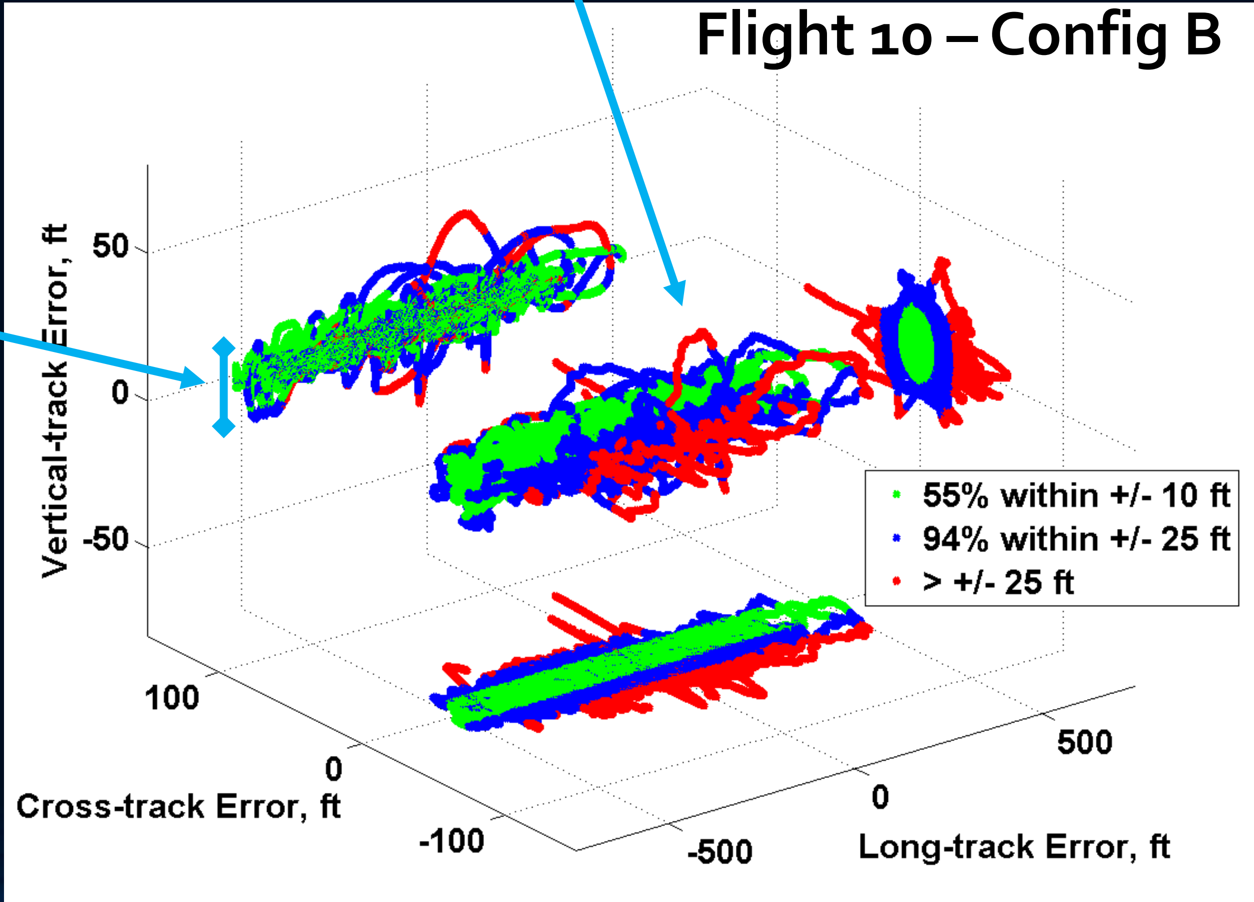
Pilot Throttle Cue – 3-Axis Results

Higher throttle activity used to keep the trail A/C Ltrk err < +/- 100 ft

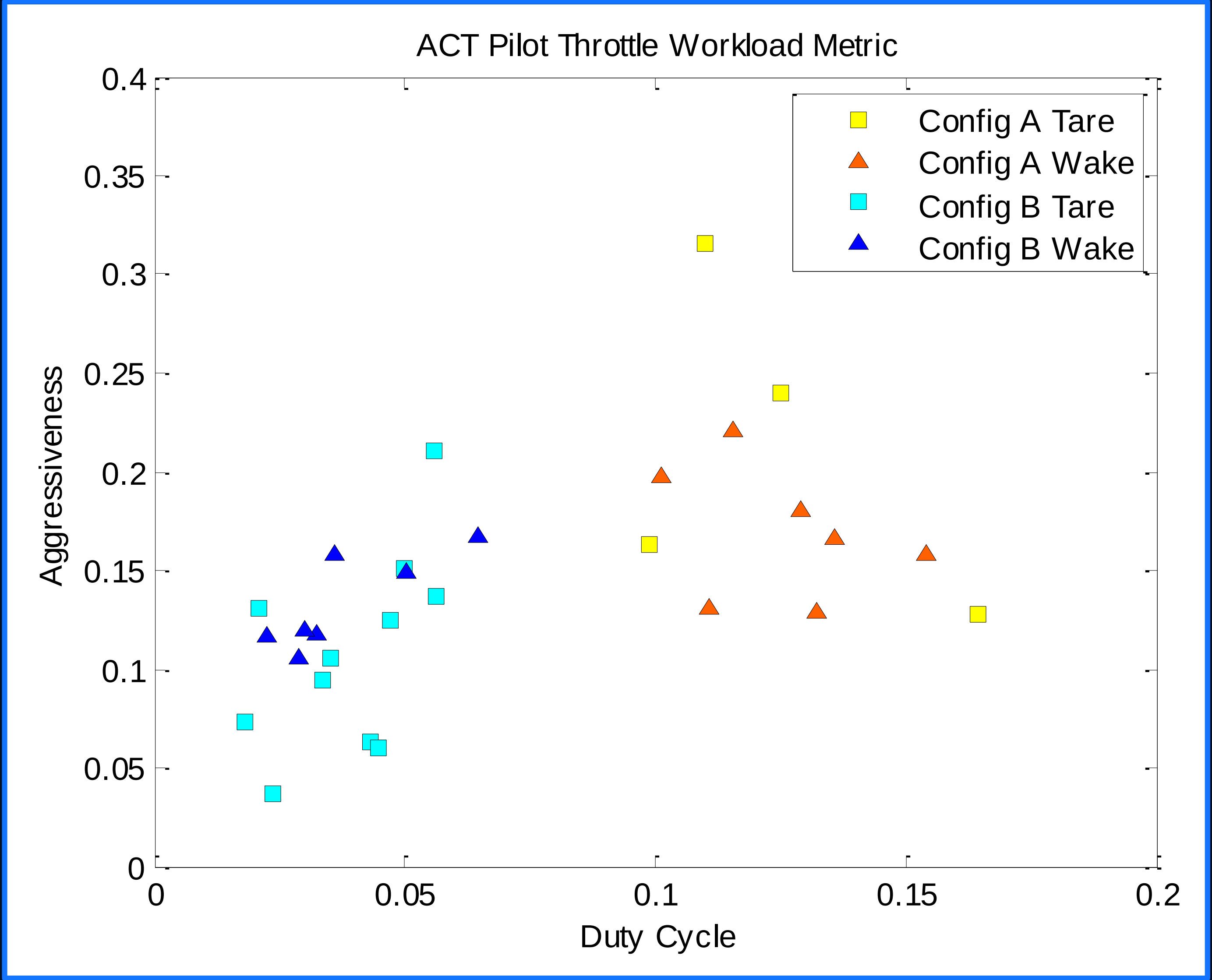
Lower throttle activity required to keep the trail A/C Ltrk err < +/- 250 ft

Higher throttle activity caused more vertical error





Pilot Throttle Cue and Wake Display



- The modified display reduced pilot workload to "Satisfactory" and improved post-flight calculations of fuel flow savings.
- The "Aggressiveness" metric measures the size of the throttle inputs the pilots used to maintain position.
  - There is a slight decrease in aggressiveness of pilot inputs from flight 8 to flight 10.
- Duty cycle is a measure of frequency at which the pilots adjusted the throttles.
  - The technique used during flight 10 resulted in a 67% decrease in duty cycle compared to flight 8.

Summary

- The wake awareness display was a success in flight. Pilots maintained situational awareness of the wake vortex and the research controller performance.
- Automatic throttle control is a necessity for maintain precise long-track position. Manual control of throttles aided by displays is likely unacceptable for long duration missions.
  - Accurate engine models are crucial in designing a throttle control system. Differences between flight testing and simulation testing made improving the long-track controller difficult in the middle of a flight test campaign.
- By giving the pilots the freedom to manage throttles without following cues, a technique was developed that minimized throttle motion and provided the clearest data for determining fuel savings.

Questions?