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

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From April to May 2017, the National Aeronautics and Space Administration Armstrong Flight Research Center completed a series of flights with a trail C-20A airplane surfing in the wake of a Gulfstream III airplane using a commercially available datalink as the primary communication between the two aircraft. The purpose of this test was to characterize the aerodynamic benefits received by the trail airplane flying in the upwash portion of the wake generated from the lead airplane. Lateral and vertical relative position to the wake were automatically controlled through an experimental programmable autopilot on the C-20A airplane. Long-track, the separation distance between the two aircraft, was maintained by test pilots managing throttle position using customized cockpit displays. These displays provided the pilots with throttle cues for maintaining long-track position and situational awareness of the wake vortex relative to the position of the trail airplane. Flight testing demonstrated the ability of the pilots to use these displays to maintain a safe long-track distance, but found there to be trades between tracking performance and the frequency of throttle motion. The wake awareness display provided the pilots with adequate situational awareness of the wake vortex during the flight experiment. This paper presents a summary of the design, development, and flight evaluation of the pilot displays and long-track control.

I. Nomenclature

ACT	=	automated cooperative trajectories
AIC	=	autopilot interface computer
ADS-B	=	Automatic Dependent Surveillance-Broadcast
DCAPS	=	Data Collection and Processing System
E_{Diff}	=	east position difference between lead and trail aircraft
FAA	=	Federal Aviation Administration
G-III	=	Gulfstream III airplane
GPS	=	global positioning system
$GndTrkAng_{Lead}$	=	lead airplane ground-track angle
HIL	=	hardware-in-the-loop
ILS	=	instrument landing system
INS	=	inertial navigation system
LtrackEst	=	estimated long-track position
NASA	=	National Aeronautics and Space Administration
NED	=	north, east, down
N_{Diff}	=	north position difference between lead and trail aircraft
$NVEL_{Diff}$	=	north velocity difference between lead and trail aircraft
PID	=	proportional-integral-derivative

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PLA = power lever angle

II. Introduction

Automated cooperative trajectories (ACT) is a multi-aircraft operational concept proposed for use in the en-route cruise portion of flight. ACT operations involve two or more aircraft in continuous data-link communication using automatic control of their relative positions to maintain positive separation and to coordinate their flight paths.

One advanced concept proposed for ACT operations is wake surfing, where one airplane flies in the upwash portion of the wake vortex system generated by another airplane. By doing so, the trail airplane extracts energy from the wake of the lead airplane, reducing fuel flow and combustion-related emissions. Wake vortex systems move with the atmosphere, and typically descend because of their own convection. In most atmospheric conditions, the wake vortex generated by an airplane is invisible to the naked eye. Because wakes can exist in the atmosphere for several minutes, energy extraction while wake surfing is feasible even with significant horizontal separation between the lead and trail aircraft; if the position of the wake can be properly identified at that separation distance. To surf the wake, a trail airplane must “fly in formation” with the wake generated by the lead airplane. The trajectories required for wake surfing are essentially parallel ground tracks, approximately co-altitude, with the trail airplane flying with as little as a wingspan of lateral spacing between the airplane and the center of the wake vortex system generated by the lead airplane. Safe separation between aircraft is ensured by maintaining nose-to-tail separation along the parallel trajectories between 0.5-2 nautical miles, or 5-15 seconds of time separation at typical cruise speeds which is significantly closer than the current five nautical-mile separation requirement used in the national airspace. Because the position of the trail airplane relative to the wake must be precisely maintained for long periods of time, automating the control of relative position (in all 3 axes) is desired for a production system.

Maintaining precise separation distance through throttle control has been a topic of formation flight for over 20 years. In 1992, Walsh found that a step degradation of handling qualities occurred with throttle time delay in formation flight applications [1]. In 2014, through the use of simulation, Sanders found that significant fuel savings can be achieved by maintaining accurate position in extended formation flight through the use of dynamic throttling, despite inefficient engine operations [2].

Pilot displays with wake vortex information have been in development for more than a decade. In 2003, Holforty developed and flight-tested a perspective-view flight deck display that used a prediction algorithm to predict the location of the wake from a lead airplane and display that information to the flight crew in the trail airplane [3]. In 2014, Bauer et al described displays that were used in flight tests to avoid predicted wake vortices using state information from the trail airplane in addition to meteorological data [4].

Wake surfing has been demonstrated in flight using straight-wing aircraft [5], fighter aircraft [6, 7], and large military transports [8, 9]. In 2016-2017, the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (Edwards, California) conducted a series of flight experiments with a prototype ACT system designed to explore the feasibility of wake surfing at extended distances, greater than 50 wingspans, using business jet class aircraft. NASA researchers found there to be fuel savings on the order of 8 percent when surfing in the wake [10].

A limitation of the trail airplane for this particular application is the lack of an auto-throttle capability. In order to aid the flight crew in controlling the separation distance between the aircraft, a pilot throttle display driven by a long-track controller was developed. Additionally, for situational awareness of the flight crew, a display was developed to illustrate the vertical and lateral position of the trail airplane relative to the predicted location of the wake vortex from the lead airplane.

This paper describes the design and development of the long-track and wake awareness displays used during the NASA wake surfing flights, the design of the controller used to drive the long-track display, and the flight-test results using the long-track controller and pilot displays to track and station-keep at the desired location near and eventually within the wake vortex generated by the lead airplane. The wake prediction and navigation algorithms, along with the vertical- and cross-track controller design are not discussed, as these topics are outside the scope of this paper.

III. Flight-System Description

The research flights were conducted with a Gulfstream Aerospace Corporation (Savannah, Georgia) C-20A airplane performing wake surfing behind a Gulfstream G-III airplane. The test aircraft are shown in Fig. 1. A diagram of the long-track, cross-track, and vertical-track positions required for wake surfing is shown in Fig 2. Positive long-track, cross-track, and vertical-track are when the trail airplane is flying behind (or aft) of the lead airplane, to the right of the lead wake, and above the predicted wake position.

Fig. 1. NASA C-20A and G-III aircraft used for the wake surfing flight experiment.

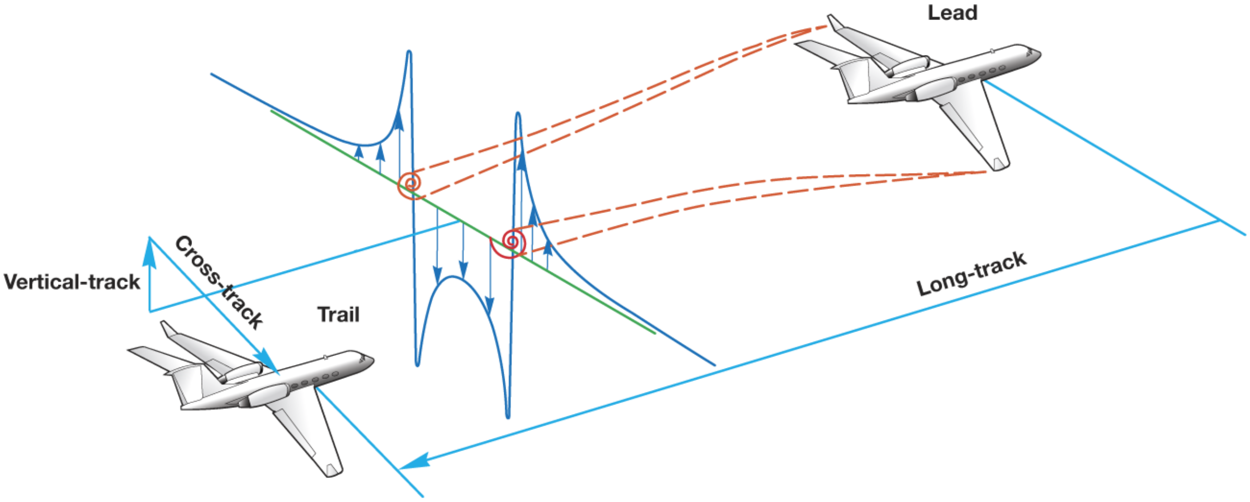


Fig. 2. Trail airplane position relative to the lead airplane.

Key components of an ACT system for wake surfing are a data-link between the aircraft; wake position prediction algorithms; relative navigation algorithms; and three-axis control of the vertical, lateral, and longitudinal axes. Automatic Dependent Surveillance - Broadcast (ADS-B) was selected as the datalink [11]. Because of the Federal Aviation Administration (FAA) mandate that all aircraft operating in Class A, B, and C airspace within the United States must be equipped with an ADS-B out data link by 2020 [12], ADS-B is the most readily available technology around which to build an ACT architecture. The lead NASA G-III airplane was recently equipped with an FAA certified ADS-B out installation.

The trail airplane (C-20A) was equipped with an experimental programmable autopilot that controlled the lateral and vertical position of the airplane relative to a prediction of the wake location. Using ADS-B as the ship-to-ship datalink, the programmable autopilot was designed to augment a typical autopilot (instrument landing system (ILS), or altitude/bank hold) in a manner similar to the Platform Precision Autopilot [13] developed for another NASA project. The programmable autopilot system architecture is shown in Fig. 3. Position and velocity of the lead airplane from the ADS-B in receiver, combined with real-time position, velocity, and wind information from the trail airplane is used to compute a localizer and glideslope command to the trail airplane flight director. The localizer and glideslope commands are based on the position of the trail airplane to the desired cross-track and vertical-track positions relative to the predicted location of the lead generated wake vortex system. The predicted wake position is calculated from the lead airplane position that is adjusted for wind drift and the descent rate of the wake vortex, which is a function of the lead fuel weight and wingspan. This information of the wake location relative to the trail airplane position is provided to the pilots via a wake awareness display.

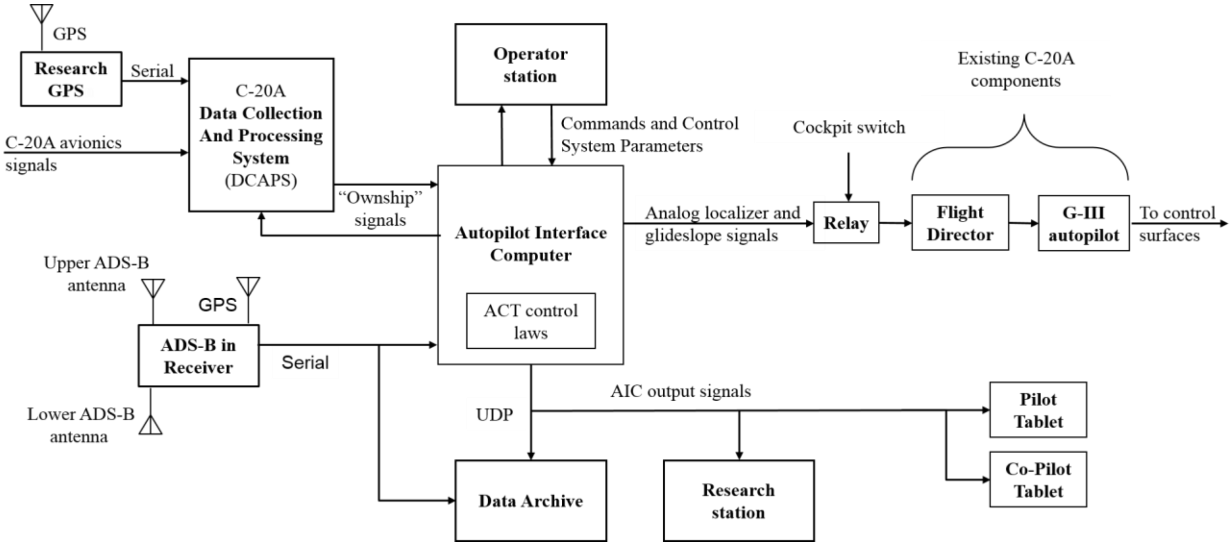


Fig. 3. Programmable autopilot system architecture.

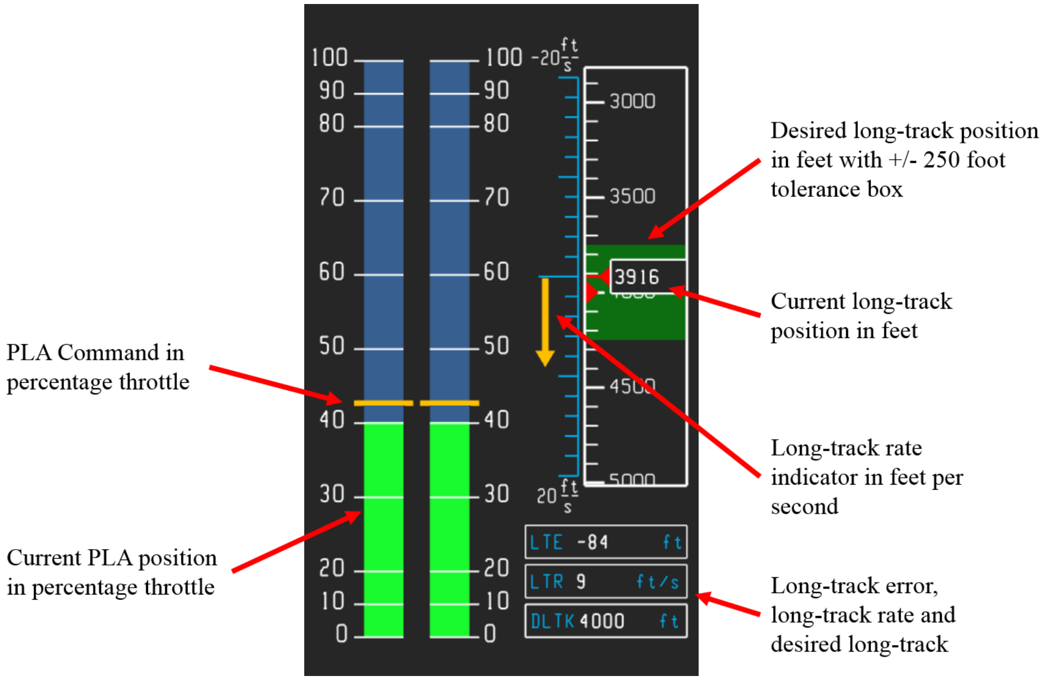
The programmable autopilot also generates a throttle position command based on the desired long-track position. Tablet displays mounted on the pilot's and co-pilot's yoke display these throttle command cues, long-track commands, range, and error.

IV. Long-track Position and Throttle Display

Due to the lack of an auto-throttle capability on the C-20A airplane, the NASA team developed a tablet display of throttle cues in order to assist the pilots in maintaining the desired long-track position. This section describes the finalized design of the long-track position and throttle display and the development process using pilot feedback from G-III wake surfing simulations to access the effectiveness of the two candidate displays.

A. Design

The display depicted in Fig. 4 is the design settled on after completion of piloted simulation sessions. The focal point of the display is the left side where the current throttle position is depicted in green, and the commanded throttle position is depicted by the orange horizontal bars. The pilot is tasked to match the green line to the orange bars closing the loop on the long-track controller to minimize long-track error and match the long-track rate between the lead and trail aircraft.



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

Current long-track position in feet

PLA Command in percentage throttle

Long-track rate indicator in feet per second

Current PLA position in percentage throttle

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

Fig. 4. Long-track display.

The right side of the display is meant to provide situational awareness about the actual long-track distance and the rates at which the trail airplane is either closing on or falling away from the lead airplane. The display is a sliding scale, where the current long-track position is fixed in the center box, and the desired long-track position slides along the scale depending on how far away the trail airplane is from that position. The desired long-track position is signified by the red arrow pointing right and is surrounded by a green box that represents the tolerance region for long-track error. The tolerance region was developed to give the pilots a margin for error when trying to maintain throttle position and reduce pilot workload by allowing them to leave the throttles untouched for longer periods of time while still remaining in the green region. Initially, this tolerance region was set to +/- 100 ft from the current long-track position, but was later set to +/- 250 ft after initial flight testing found that region to be overly restrictive.

Between the throttle display and the long-track position display is a yellow arrow indicating a long-track rate of change between the two aircraft. The long-track rate indicator was implemented to provide the pilots with additional information about how fast the trail airplane was closing or falling back from the lead airplane. The long-track rate is calculated such that a negative long-track rate indicates that the trail airplane is closing on the lead airplane, and a positive long-track rate indicates that the trail airplane is falling back from the lead airplane. In order to reduce the long-track rate, the pilots would move the throttles in the opposite direction of the indicator arrow, until the long-track rate was near 0 ft per second.

In the bottom right is a box of numerical values for long-track error, long-track rate, and the desired long-track position. The numerical values provide greater fidelity to the pilots, and provide additional rate information based on how quickly the numerical values are changing.

B. Development

Candidate displays were developed and presented to the pilots in a G-III wake surfing simulation. Pilots were selected with backgrounds in both fighter jets and commercial aircraft. The pilot simulation session setup can be seen in Fig. 5 with both the throttle display and the wake vortex display on the tablet to the left of the cockpit.

Fig. 5. Simulation display of the G-III airplane with the wake vortex model and pilot simulation setup.

The candidate displays fall into one of two categories based on how the throttle command was presented to the pilots, which is depicted in Fig. 6. In the first category, the current total throttle position and the commanded position were displayed on the same bar display, with the pilots tasked to match the current position to the commanded position. In the second category, delta throttle commands were presented to the pilots, which required movement of the throttles until the delta throttle command was set to zero by matching the moving white current position bars to the yellow delta power lever angle (PLA) command bars.

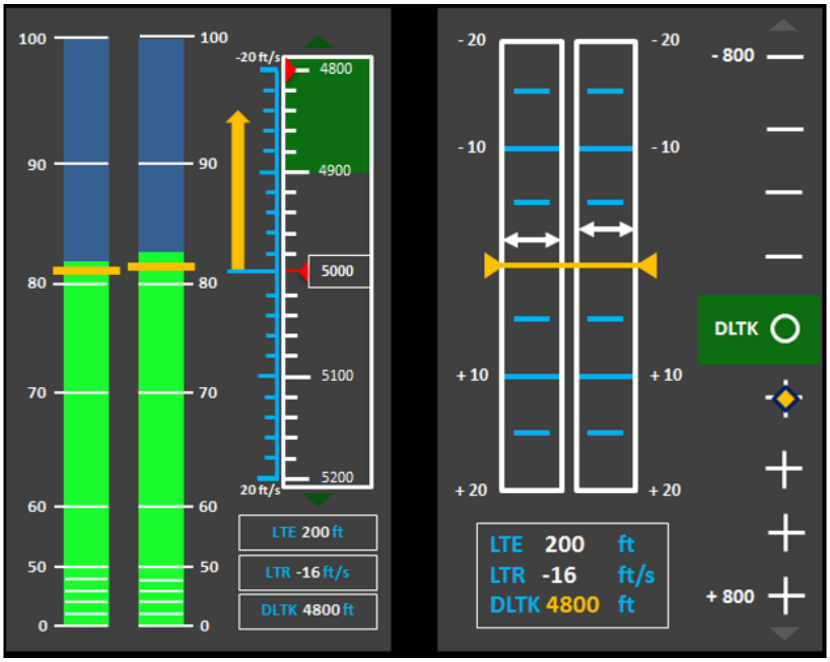


Fig. 6. Candidate long-track displays: (1) total command concept, and (2) delta command concept.

The primary goal of the piloted sim sessions was to receive pilot feedback on the effectiveness of the two different methods displaying throttle queues. Pilots found that trying to control the throttle position through delta PLA commands was too sensitive, and that it was difficult to minimize throttle motion, whereas displaying the total command and asking the pilots to match the throttles to this command was more intuitive and reduced throttle activity due to overcorrections. Even with the total throttle command display, the continuous throttle motion required to maintain the +/- 100-ft tolerance made the pilot task a medium to high workload.

Pilots were able to use the long-track rate indicator on the total PLA command display to reduce oscillations by damping the throttle motion faster than the long-track controller commanded. This indicator was more intuitive to the pilots, since a change in throttle position quickly correlated to a change in the long-track rate, whereas changes in the long-track position would often occur several seconds after a throttle change was inputted.

During the initial piloted sim sessions, the long-track controller had not been properly tuned, which caused the pilots to constantly overcorrect when following the throttle commands to maintain the desired long-track. This high frequency motion resulted in pilots tending to ignore the throttle commands and focus purely on maintaining position within the tolerance zone by relying heavily on the long-track distance display and the long-track rate indicator. The long-track controller was eventually tuned via changes to the gains and the addition of a complementary filter on the input position signals which solved the problem of the overactive throttle commands during simulation testing. However, due to differences between the sim engine model and the dynamics of the actual airplane engine, this behavior would re-emerge and required the development of new piloting techniques to maintain the long-track distance as discussed in the flight-test portion of this paper.

V. Wake Awareness Display

Wake awareness displays were developed to provide situational awareness of the wake vortex to the pilots for system monitoring during flight tests. The final design of the wake awareness display and the development process used to arrive at this design are described in this section.

A. Design

The final selected display is a two dimensional representation of the vertical and horizontal position of the trail airplane relative to the predicted wake vortex position as seen in Fig. 7. A line drawing of the trail airplane with a scaled C-20A wingspan is fixed at the center of the display. A filled purple circle indicates the desired position being commanded by the programmable autopilot. When the system is engaged, the trail airplane moves towards this purple indicator until they are stacked on top of each other. If the commanded position is off the scale of the display, the purple circle is instead a chevron pointing in the direction of the commanded position. Additionally, the commanded position is depicted by a hollow purple circle on the ticker tapes to the right and bottom of the display, representing the vertical and horizontal position respectively.

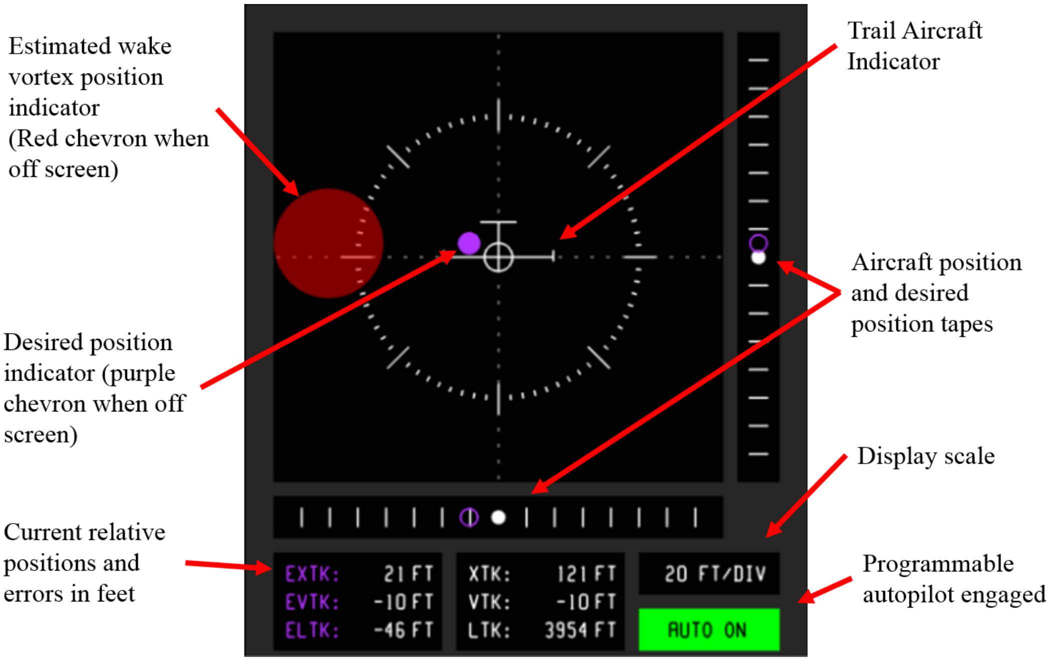
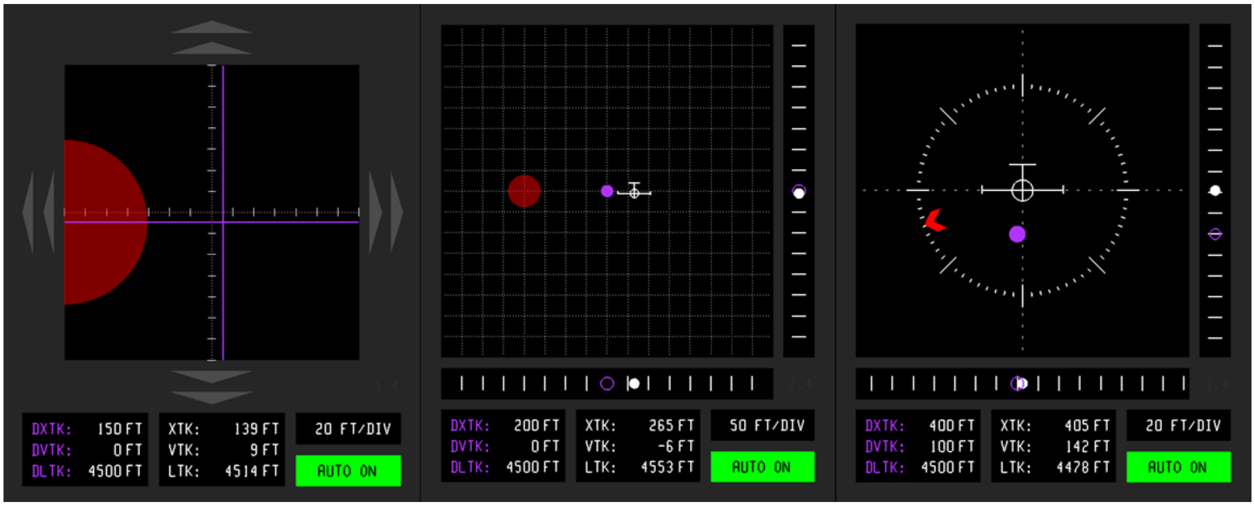


Fig. 7. Wake awareness display.

The predicted position of the wake vortex is depicted as a red circle indicator with a scaled width matching the wingspan of the lead airplane. Similar to the desired position indicator, when the wake vortex is off screen the red circle is depicted as a chevron pointing in the direction of the vortex. When both the desired position and the wake vortex are off scale in the same direction, the chevrons will stack in the order of whichever indicator is further away. Across the bottom of the display are numerical values for the desired relative positions, the current relative positions, the scale of the display, and an indication of the programmable autopilot being engaged or disengaged.

B. Development

The strengths and weakness of the three candidate displays were evaluated by NASA Armstrong pilots using the G-III flight simulator modified with the programmable autopilot control system. These candidate displays are depicted in Fig. 8. The first display used an ILS design where the trail airplane was a fixed crosshair at the center of the display on a static scale. The commanded position was a purple crosshair that would move around the display relative to the fixed airplane crosshair. The second display was centered on the commanded position and would auto scale to fit the airplane position, commanded position, and wake vortex zone on the screen. The third display was similar to the finalized design, with the trail airplane centered on the display as a line drawing of the C-20A airplane from a chase view, and the commanded position was a purple circle. The wake awareness displays were mounted on a side screen within the cockpit of the G-III simulator, in a setup identical to the configuration used for the long-track display evaluation seen in Fig. 5.


DXTK: 150 FT
DVTK: 0 FT
DLTK: 4500 FT
XTK: 139 FT
VTK: 9 FT
LTK: 4514 FT
20 FT/DIV
AUTO ON

DXTK: 200 FT
DVTK: 0 FT
DLTK: 4500 FT
XTK: 265 FT
VTK: -6 FT
LTK: 4553 FT
50 FT/DIV
AUTO ON

DXTK: 400 FT
DVTK: 100 FT
DLTK: 4500 FT
XTK: 405 FT
VTK: 142 FT
LTK: 4478 FT
20 FT/DIV
AUTO ON

Fig. 8. Candidate wake awareness displays: (1) ILS concept, (2) auto scale concept, and (3) chase view concept.

The pilots were given two tasks to familiarize them with the wake vortex dynamics and the displays. First, the pilots were given the opportunity to fly the system manually with the wake awareness displays providing guidance cues to the pilot, and with an out-the-window visible model of the vortex turned on. The visual vortex model is depicted in Fig. 5, where the white tubes represent the vortex cores, and the red ellipses display the vortex area of influence. This task was done to allow the pilots to gauge the difficulty of maintaining position near the vortex with the ability to see the wake, and then compare that task to an autonomous system controlling the airplane with pilot system monitoring.

Next, the pilots were taken through scenarios with the programmable autopilot control laws automatically controlling the airplane, and the out-the-window vortex displays disabled so that the pilots would rely on the wake awareness displays for situation awareness. The initial trail airplane location was varied between display evaluation runs in order to eliminate familiarity with the trajectories, such that the pilots could evaluate each display without being able to predict what the airplane was going to do based on prior runs. After the completion of the second run, general feedback on the displays and pilot preferences were collected. Example questions asked of the pilots were:

- Did the displays offer enough situational awareness for the wake surfing task?
- Was there any information that was missing from the display?
- Did the color scheme adequately indicate the different objects on the screen?

Several common strings of feedback became apparent during the course of the pilot evaluation experiment. The most common of which was the necessity for a yoke mounted display. It was exceedingly difficult to use the display (mounted off to the left) for system monitoring while being able to maintain out-the-window line of sight of the lead airplane. The pilots would occasionally fail to notice a wake crossing or a vertical- and cross-track command change from the programmable autopilot until several seconds after the event occurred. Several pilots recommended a flashing indication on the display to alert when these events occurred.

It was also noted that absolute position values were not as useful as error values for the cross-track and vertical-track calculations. With the error values, pilots were able to develop a better sense of how well the system was performing at a glance, instead of trying to calculate errors in the middle of a test. The yoke mounted display, flashing command indications, and error values were incorporated into the final design of the display.

There was also a desire to include attitude information, such as the bank and pitch of the trail airplane. The pilots mentally adjusted to the inconsistency of the airplane appearing to move closer to the wake while the airplane display icon would remain straight and level. Once the pilots became more comfortable with the display, they ended up monitoring yoke movements driven by the autopilot and using the airplane avionics to sense changes in bank and pitch from the programmable autopilot commanded maneuvers.

On the candidate displays without auto scaling, when the wake vortex indicator or the commanded position went off screen, the pilots had little rate information on how quickly the trail airplane was approaching the commanded value. This lack of off-screen rate information could be remedied either by the error values being displayed over the arrows and chevrons, or by including a scaling function (either manual or automatic) that would keep the objects on the display as needed. The auto-scaling feature was ultimately not implemented due to the complexity of adding auto scaling that would work correctly for all scenarios. By using smaller commands during the flight experiment, the static scale of the displays was large enough for the pilots to determine the desired rate information.

Pilots suggested putting a tolerance circle around the commanded position dot to let the pilots get a better idea of system performance. An indication of fuel economy when near the wake was also suggested as a way of judging whether or not the system had found the sweet spot for fuel savings. The research team did not have a method to determine real-time fuel economy in flight, and found that displaying error information gave enough insight into system performance such that the former suggestion was not necessary.

VI. Long-track Controller

The long-track controller generates a delta PLA command sent to the yoke-mounted pilot displays such that the pilots can maintain the desired long-track position from the lead airplane by following the PLA commands. The total PLA command displayed on the pilot tablet is the sum of the reference PLA and a delta PLA command that is computed by the programmable autopilot controller in order to maintain the desired long-track.

The estimated long-track position is calculated from north and east position differences between the lead and trail aircraft and the lead ground-track angle, as show in Eq.(1). The equation is summed together such that a positive long-track estimate corresponds to a positive distance behind the lead airplane.

$$LtrackEst = -(N_{Diff} * \cos(GndTrkAng_{Lead}) + E_{Diff} * \sin(GndTrkAng_{Lead})) \tag{1}$$

The north and east position differences are corrected by the differences in north and east velocities between the two aircraft via a complimentary filter of the form shown in Fig. 9. The difference in north and east positions are calculated via a coordinate transformation of the latitude, longitude, and altitude of each airplane to north, east, down (NED) coordinates. The lead airplane positions and velocities were provided by ADS-B, while the trail airplane positions and velocities were provided from either the aircraft intertial navigation systems (INS) or an independent global positioning system (GPS).

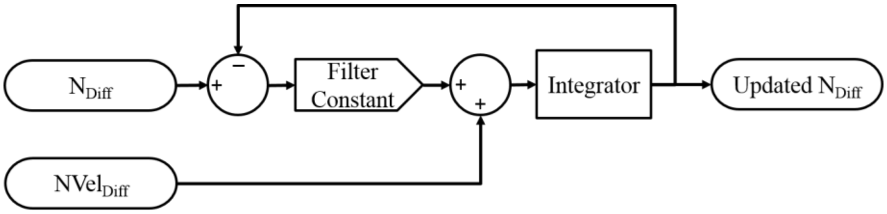


Fig. 9. Example of a complimentary filter.

The delta PLA controller is a proportional-integral-derivative (PID) design which uses long-track error as the signal for proportional and integral control, and long-track rate for derivative control. A simplified block diagram of the throttle PID controller is depicted in Fig. 10. The input error signal is limited to +/- 250 ft of long-track error to control the maximum rate at which the delta PLA commands will attempt to capture the desired long-track position. The limited long-track error includes a potential vertical energy compensation term based off of the delta altitude command from the vertical-track controller to provide compensation for large changes in the vertical-track command. The integrator is reset whenever the programmable autopilot control system is disengaged to prevent transients due to a large integrator built up from previous engagements, and has a saturation limit of +/- 20 percent of the total PLA range. The derivative loop uses the long-track rate between the lead and trail aircraft as the input signal. The long-track rate signal is limited to +/- 20 ft per second.

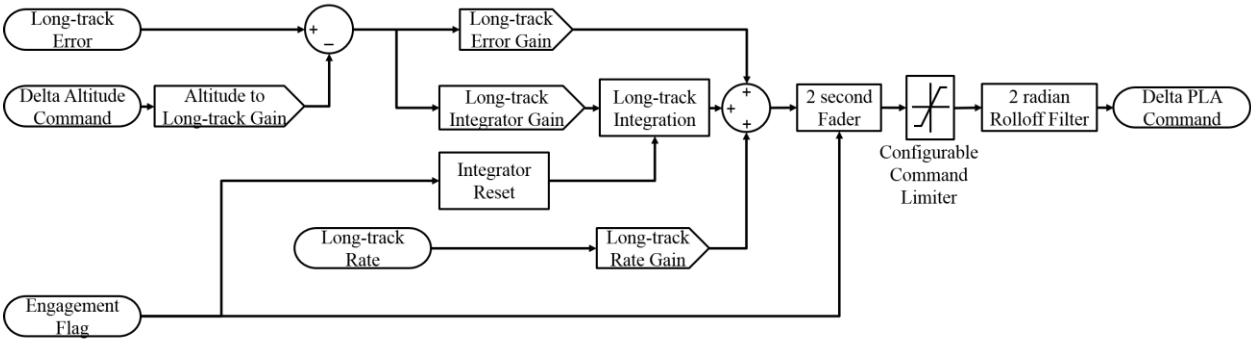


Fig. 10. Block diagram of a throttle PID controller.

The total delta PLA command is limited by a variable limiter that was defaulted to +/- 25 percent of the total PLA range from the reference PLA position. There is a two-second fader that is active when the programmable autopilot is engaged or disengaged to minimize transients when the control laws are enabled or disabled. The delta PLA command is filtered through a two radian roll off filter to provide a smoother command to the pilot displays.

The gains and the command limiter used in the delta PLA controller are configurable in flight via commands sent from the operator’s station. For each configurable gain, there is a range of valid inputs that the controller will accept. If an entered gain exceeds this range, the input will be ignored and the last valid gain will be used instead.

The reference PLA is a filtered average of the current left and right indicated aircraft PLA. A simplified block diagram of the reference PLA calculation is depicted in Fig. 11. The purpose of the filtered average is to slowly update the PLA referenced position to allow for more control authority when the throttle position is consistently increasing or decreasing.

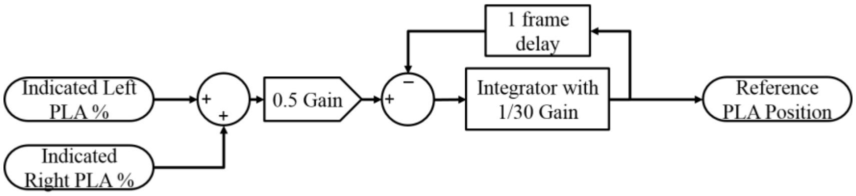


Fig. 11. Block diagram of a reference PLA calculation.

VII. Flight Evaluation

The NASA Armstrong test team completed several flights from April 2017 to May 2017 that included extended surfing of the lead airplane wake vortex using the long-track and wake awareness displays to provide situational awareness of the experiment to the pilots and the research team. Figure 12 shows a representative engagement during the flight experiment. The trail C-20A airplane is controlled by the programmable autopilot controller in the vertical and lateral axis while the pilots maintain the long-track position following the cues from the pilot displays.

Fig. 12. Chase photo of the NASA C-20A airplane in formation with the wake contrails of the NASA G-III airplane.

The display tablets used in the flight experiments have a screen size of 10.1 inches and are mounted on both the pilot and co-pilot yokes. Due to these limitations on position and screen size, the displays were stacked vertically, with the long-track display on the upper half of the screen and the wake awareness display on the bottom half. The long-track display is on the top half of the tablet screen to provide the best viewing angle to the pilots. Maintaining the long-track position was a mission critical function, giving the long-track display the higher priority. A photo of the tablet display being used by the pilots in the airplane cockpit is shown in Fig. 13.

Fig. 13. Long-track and wake awareness display mounted on yokes, providing throttle cues to the pilot.

The pilot displays were developed using OpenGL in Visual Studio (Microsoft Corporation, Redmond, Washington) and are designed to run on both Microsoft Windows 8.1 and Windows 10 operating systems. The display is fed position and throttle information from an Ethernet connection to the autopilot interface computer (AIC) at the back of the airplane. To verify that valid and current information is being sent to the display, a blinking green indicator is included in the top right of the display. When the indicator is no longer blinking, the display software has frozen and requires a restart. When the indicator changes from green to orange, no valid data packets from the AIC have been received in the last five seconds. The display software running on the pilot tablets in flight is shown in Fig. 14.

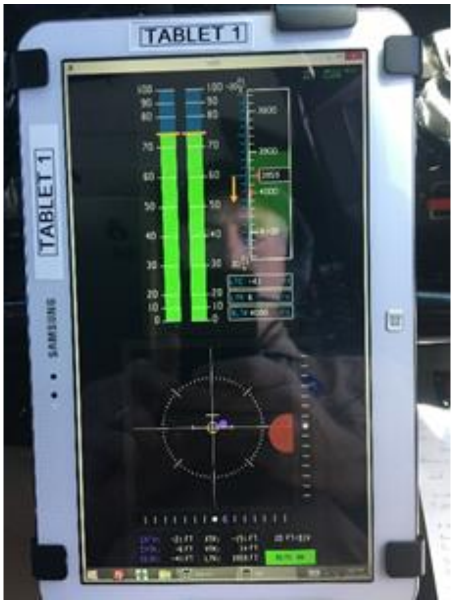


Fig. 14. Long-track and wake awareness display running on pilot tablets during a wake surfing experiment.

Two additional tablets were positioned in the cabin of the airplane to provide the same situational awareness to the research team. An example of this display is seen in Fig. 15, where the display is mounted above strip charts displaying the programmable autopilot performance data. The second display was mounted in the back of the airplane to provide additional awareness to test team members that did not have access to the strip chart displays.

Fig. 15. Long-track and wake awareness display mounted in the cabin of the trail airplane.

A. Long-track Display and Control

Over the course of the flight-test program, feedback from the test pilots stated that the throttle commands were too high frequency and resulted in pilot fatigue during the 4 to 5 hour flights. This problem is due to a mismatch between the engine model used in the G-III simulation, where the long-track controller was developed, and the actual airplane engine performance in flight.

As a first solution, the gains on the long-track controller were reduced in the proportional and derivative loops by 20 percent and 75 percent, respectively. According to pilot comments, this gain change did provide slight improvements to the throttle motion, but still resulted in pilot fatigue.

A second solution was developed where the pilots would ignore the throttle commands, and instead use the long-track portion of the display to stay within the green tolerance box. The tolerance box was expanded from +/- 100 ft to +/- 250 ft, and the scale on the long-track tape was changed to +/- 1000 ft to provide a wider perspective on the long-track position.

Figs. 16 and 17 depict the difference in performance in the three axes using the two different throttle techniques for controlling the long-track position. During flight 8, the long-track position was controlled by matching the throttle commands displayed on the throttle display as closely as possible. This method resulted in a much smaller long-track error, but due to the high-frequency throttle commands, the vertical performance was degraded with more vertical motion, greater than 10 ft from the commanded position. The flight 8 data set includes approximately 2 hours and 50 minutes of programmable autopilot engaged flight activity. For flight 10 (the final research flight), the pilots were tasked to maintain position within the +/- 250 ft long-track tolerance box and not to rigorously follow the throttle commands. The modified pilot technique used on flight 10 resulted in larger long-track errors, but vertical performance was generally closer to the commanded position than in flight 8. The flight 10 data set includes approximately 3 hours and 10 minutes of programmable autopilot engaged flight activity.

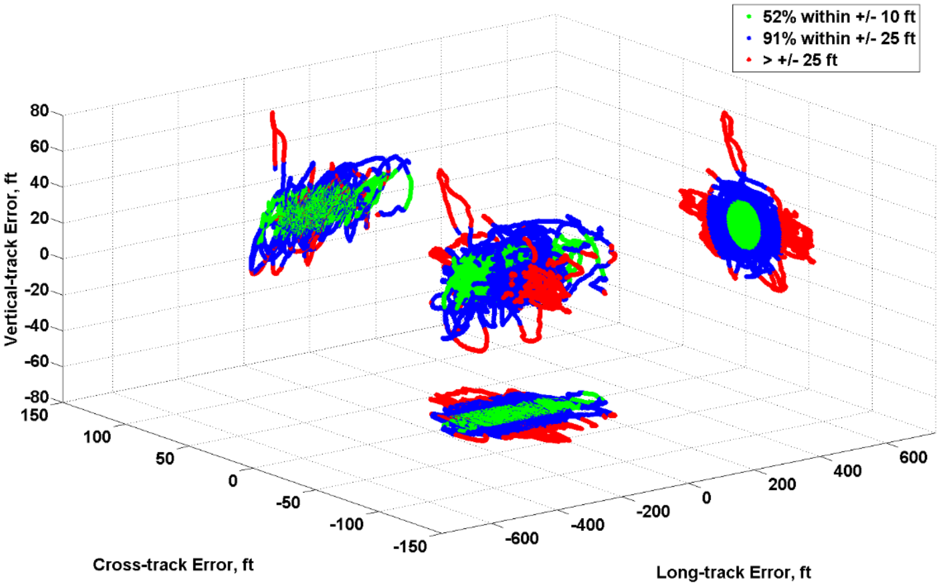


Fig. 16. Flight 8 performance with high throttle activity; 2-D projections included on each plane.

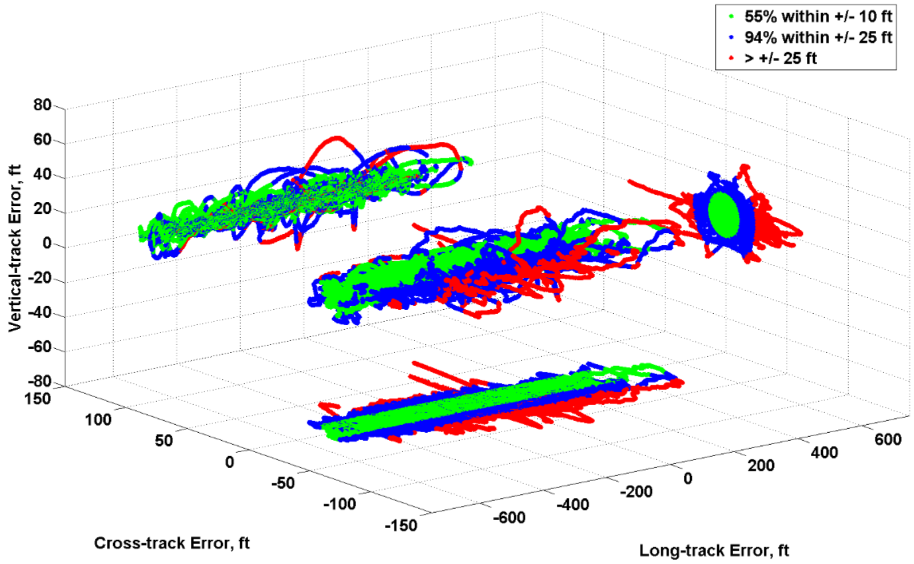


Fig. 17. Flight 10 performance with lower throttle activity; 2-D projections included on each plane.

A representative 15-minute engagement from flights 8 and 10 are depicted in Figs. 18 and 19, respectively. The first subplot in each of these figures demonstrates the difference in throttle techniques employed by the flight crew. Using the technique of closely following the PLA command in flight 8 results in significantly smaller long-track error, with the long-track position mostly contained within the +/- 100-ft tolerance zone. The cost of following the PLA command was consistent oscillations in the vertical-track position. These vertical oscillations grow slightly in size as the trail airplane moves closer to the wake.

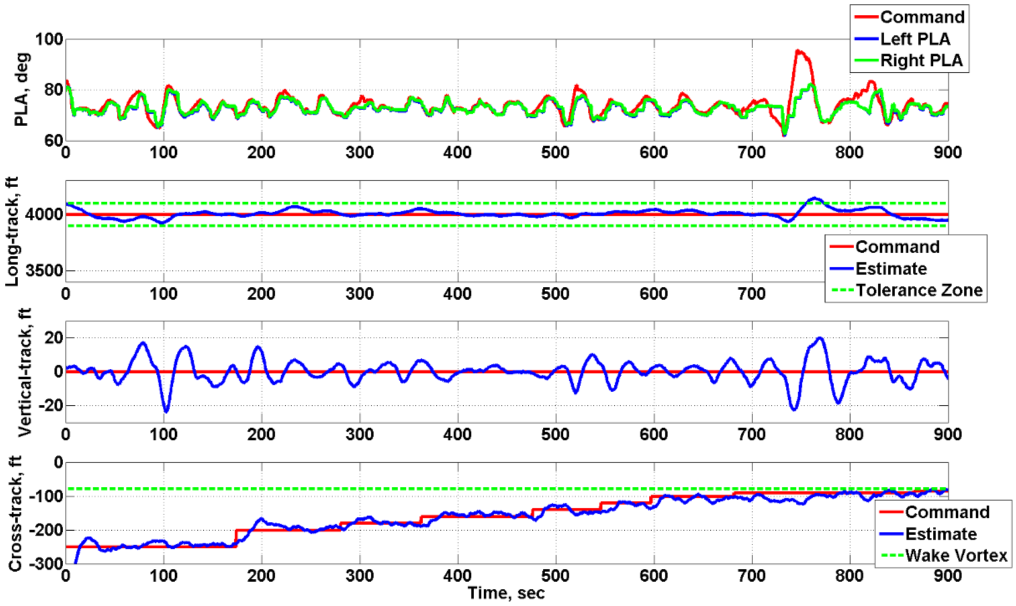


Fig. 18. Representative engagement of the programmable autopilot controller during flight 8.

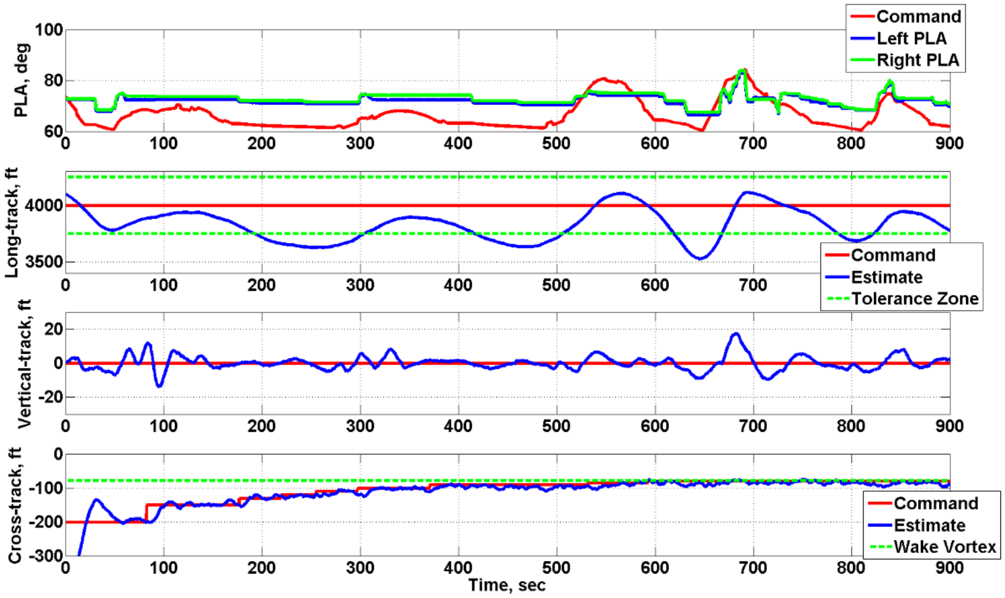


Fig. 19. Representative engagement of the programmable autopilot controller during flight 10.

During flight 10, when the pilots focused primarily on minimizing throttle motion, we see large excursions in the long-track position, which includes moving outside the +/- 250-ft tolerance in long-track position. However, these large long-track errors had minimal impact on the ability of the programmable autopilot controller to find and maintain vertical and lateral position on the edge of the wake. The vertical oscillations in flight 10 were significantly more dampened compared to the performance in flight 8, suggesting there is a relationship between throttle movement and vertical movement.

In order to quantify the differences in throttle techniques from a pilot workload perspective, a metric was adapted from a previously developed metric for measuring pilot workload in adaptive controllers [14]. The difference in pilot workload between flights 8 and 10 is depicted in Fig. 20 where pilot aggressiveness is plotted against the pilot duty cycle for tare points outside of the wake and for mapping points within the wake. Duty cycle is a measure of how frequently the pilot significantly adjusts the throttles in order to maintain the long-track position. Following the PLA commands closely resulted in an average duty cycle over three times as large as when the pilots maintained the long-track position using minimal PLA inputs. Aggressiveness is the integral of the magnitude of deviation in the pilot throttle position from the time-averaged position, normalized as a percentage of the maximum PLA range.

There appears to be a trend between the duty cycle and aggressiveness based on the throttle technique being used in flight 10. When the pilots were tasked with minimizing PLA inputs, a higher duty cycle generally corresponded with an increase in the aggressiveness of the pilot commands. This correlation suggests that when the pilots would input aggressive commands, the airplane would move from one end of the tolerance box to the other at higher rate, requiring another aggressive input to correct the long-track error. When using smaller PLA inputs, the rate at which the airplane traverses the tolerance zone is reduced, resulting in more time between required throttle corrections. This trend does not hold true for flight 8, when the pilots were closely following the throttle cues. It is also of note that the presence of wake effects did not seem to have a noticeable effect on either the duty cycle or aggressiveness for both flights 8 and 10.

From a qualitative perspective, the pilots vastly preferred the technique of managing long-track distance through minimal throttle movements to the technique of closely matching throttle cues to minimize long-track error. After flight 8, the pilots referred to the long-track control as “unsatisfactory” and that even at low long-track errors the cues would call for huge corrections that would cause large oscillations, as corroborated in Fig. 18. After flight 10, pilot feedback was much more positive, as they commented that “workload is low on long-track and easy to do” and that when timing their throttle movements, they often would not move the throttle for a minute at a time.

The technique of minimizing throttle motion was also a key contributor to estimating the fuel savings while wake surfing. Hanson found fuel savings estimates were best gathered from periods of constant throttle settings of 60 seconds or more [6], where these time segments were used to correct the fuel flow measurements for non-zero airspeed rates. The fuel flow data gathered from earlier flights such as flight 8 were found to be too dynamic to make estimations of fuel savings due to the high-frequency throttle motion.

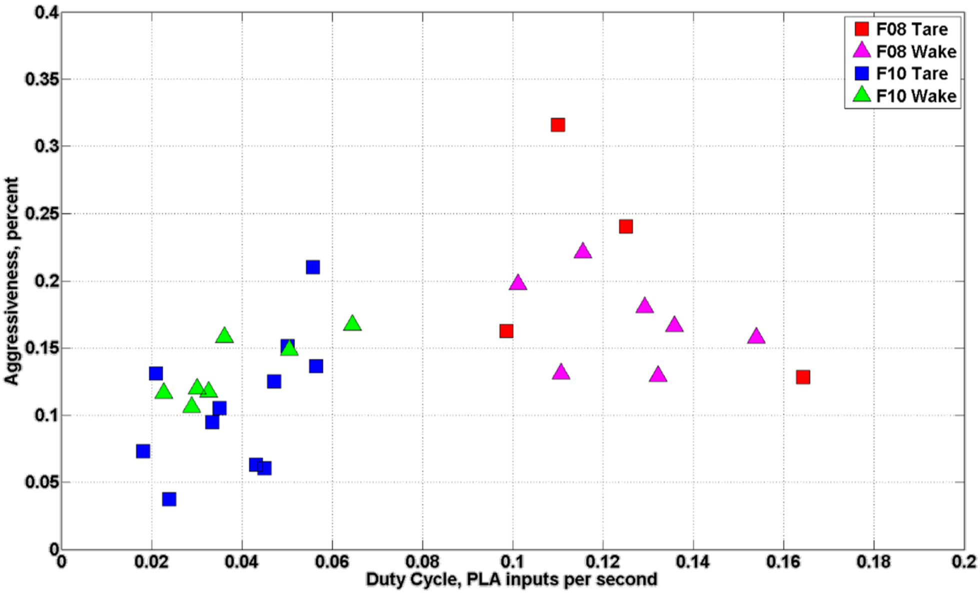


Fig. 20. Pilot throttle workload metric.

B. Wake Awareness Display

The wake awareness display worked well in flight and remained unchanged throughout the flight-test phase. According to pilot comments the red wake vortex indicator matched closely to when the pilots would begin to feel the wake effects, and was useful as an early warning for when a wake crossing would occur. In a post-flight debrief, one pilot characterized the display as “just seemed to work.” During later flights, the pilots used the wake vortex indicator to maneuver away from the wake when they felt the potential for a wake crossing. A frequent comment was to keep the wake awareness display active, even when the programmable autopilot was disabled, because once the control system was disengaged, the red wake vortex indicator would disappear causing a loss of situational awareness during the maneuvers away from the wake vortex.

Another limiting factor with this display was that it would only be as good as the wake prediction being computed within the programmable autopilot controller. During the first several flights, high winds would create large errors in the wake prediction, which would then propagate to the wake awareness display and give incorrect information to the pilots. As the wake prediction algorithms improved throughout the flight campaign, the pilot confidence in the wake awareness display increased as well.

The display worked well as a tool for setting up a flight engagement at a stabilized point outside wake effects. The scale was large enough that the pilots were able to consistently maneuver and stabilize the airplane within 50 ft of the desired engage position with minimal vertical- and cross-track rates, which lead to smooth engage transients.

VIII. Conclusion

The National Aeronautics and Space Administration Armstrong Flight Research Center performed a series of flights with a trail C-20A airplane flying in an automated cooperative trajectory with a G-III airplane to characterize the aerodynamic benefits of flying in the wake upwash of the lead airplane. In order to aid the flight crew in maintaining long-track separation between the two aircraft, a long-track control and corresponding throttle cue display were developed along with a wake awareness display for situational awareness.

The most prominent problem with the long-track controller and the throttle display was high-frequency throttle cues causing pilot fatigue over the course of the five-hour flight tests. This problem was further compounded by the lack of an accurate simulation model of the G-III engines, making it difficult to test the impact of changes to the long-track controller prior to flight. A potential solution to this problem would be an improvement on the engine models which in turn would lead to changes and potential improvements to the long-track controller.

The wake awareness display was a success in flight by helping the pilots maintain situational awareness of the wake vortex. Pilots found it simple to interpret and understand the workings of the display with minimal simulation training. Throughout the flight-test campaign, the pilots used the display to both maintain situational awareness of the wake vortex and as a tool for efficiently setting up in desired engage conditions. The long-track distance tape also clearly displayed to the pilots how well they were maintaining the desired position. When using only the long-track tape to keep position, the pilots often exceeded the +/-250-ft tolerance box, but did minimize throttle motion and reduced vertical oscillations.

There were also lessons learned on how best to incorporate the use of pilots in controlling long-track distance. When the pilots were asked to perform the task of following the throttle commands precisely, they found the task to be a high workload and caused untenable levels of strain and fatigue. When the pilots were given a desired long-track range and the freedom to figure out how to manage the throttles to stay within that range, both the throttle motion and the workload decreased dramatically.

For future wake surfing or wake avoidance applications, a combination of the two displays combined with an auto-throttle would be the most effective use of the developed displays. Combining the wake awareness display with the long-track position graphic would provide the pilots with the situational awareness of the wake position and the distance between the two aircraft in one intuitive display. Incorporating an auto-throttle into the programmable autopilot control loop would allow the pilots to be completely hands off during engagement, and potentially provide more precise long-track control.

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