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BACK UP VELOCITY ESTIMATE FOLLOWING AIR DATA SYSTEM FAILURE (PROJECT HAVE VEST)

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FINAL TECHNICAL INFORMATION MEMORANDUM

Approved for public release; distribution is unlimited.

AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIAL COMMAND
UNITED STATES AIR FORCE

This Technical Information Memorandum (AFFTC-TIM-07-09, Limited Evaluation of a back up velocity estimate following air data system failure (Have VEST) was prepared and submitted under Job Order Number M07C0700 by the Have VEST test team, US Air Force Test Pilot School (USAFTPS), Edwards Air Force Base, CA 93524-6485.

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14. ABSTRACT
This report presents the results of Project Have VEST, a limited evaluation of a back up velocity estimate following air data system failure. This test program demonstrated the potential of the VEST algorithm to provide an airspeed estimate using aircraft last known state and flight control computer accelerations and rates. The USAF Test Pilot School (TPS), Class 07A, conducted six flight tests totaling 11.3 hours at Edwards AFB, California, from 9 to 21 Sep 2007. All test objectives were met.

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Have VEST Velocity Estimation Calspan Variable Stability Learjet Learjet N101VS In-flight Simulator Flight Test Ground Test Gain Scheduling Air Data System Failure Matlab® Simulink®

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EXECUTIVE SUMMARY

This final technical information memorandum presents the test procedures and results for the Have VEST Test Management Project (TMP). The Have VEST (Velocity Estimate) Test Team performed flight tests to characterize the performance of a velocity estimator algorithm developed as part of an Air Force Institute of Technology (AFIT) Master's Thesis. The Commandant of USAF Test Pilot School (TPS) directed this program at the request of the Department of Aeronautics and Astronautics (ENY), Air Force Institute of Technology (AFIT). All testing was accomplished under TPS Job Order Number M07C0700 using the Calspan Variable Stability Learjet (N101VS) aircraft. A total of 11.3 hours of flight test were flown during 6 test sorties in the R-2508 complex during September 2007 to accomplish the test objectives.

Following air data system failure, all sensors providing airspeed, altitude, temperature, angle of attack, and pressure readings would be unavailable for use by aircraft systems. Currently, flight control system operation following air data system failure is accomplished using standby gain settings. While standby gains provide necessary information for continued safe flight in recovering the aircraft, they do not provide an optimal gain schedule to allow continuation of the mission. The VEST algorithm was used to continuously estimate true airspeed following a complete air data system failure. The algorithm provided an estimate of the lost air data information. The algorithm estimated flight conditions were used to schedule stick command gain and to display airspeed and altitude information in the cockpit.

The true and calibrated airspeed error profiles were determined to be independent of aircraft maneuvers or speeds. Individual error profiles were variable with time, but magnitudes of error were less than the current standby gain scheduling that assumes constant airspeeds. The average true airspeed error was on the order of 12 knots (21 feet per second), non-divergent and minimally variable. Similarly the average calibrated airspeed error was on the order of 10 knots (17 feet per second). The results of this test demonstrate the potential of this type of airspeed estimation as a back up system following air data failures, and warrants continued research.

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INTRODUCTION

Background

Development of the Velocity Estimate (VEST) algorithm was proposed as a student thesis research topic at the Air Force Institute of Technology. Highly augmented high performance aircraft vary control system gains as flight conditions change to preserve good handling qualities and to avoid undesirable aircraft responses. In the event of a complete air data system failure, the flight control system loses its ability to schedule gains based on changing flight conditions. In order to ensure continued safe controlled flight, standby gains are fed to the flight control computer. Typical standby gains are made up of a single airspeed and altitude value that while not optimized for current conditions, will ensure continued safe flight. The VEST algorithm was designed to provide an estimate of the lost air data information to continue optimized flight control system gain scheduling based on current flight conditions prior to necessitating the use of standby gains. The only known values available from the aircraft following the air data system failure would be the last known aircraft state prior to failure, flight control computer body axis accelerometer outputs, and flight control computer rate gyro outputs. Using this information, the estimated true airspeed would then be available for flight control system gain scheduling and for determining calibrated airspeed for display in the cockpit. Modeling and simulation to test algorithm performance was performed using facilities and resources made available by the Air Force Institute of Technology Advanced Navigation Technology Center and the Air Force Research Lab T-38 simulator at Wright Patterson Air Force Base, Ohio.

Program Chronology

The test program was initiated on 1 May 2007. Modification of the aircraft began on 4 June 2007 and was completed on 13 July 2007. 11.3 hours of flight testing were conducted from 9 to 21 Sep 2007. A total of two ground test and six test flights were flown as shown in table 1. A detailed summary of the test points flown is presented in appendix D.

Table 1 - Summary of Test Flights

Ground /Flight	**Description**
1	Ground Power-up
2	Stick Force per Stick Deflection Mapping / Taxi Test
1	Calibration Flight / Algorithm Performance Characterization
2	Algorithm Performance Characterization
3	Algorithm Performance Characterization
4	Algorithm Performance Characterization / Operational Utility Evaluation
5	Algorithm Performance Characterization / Operational Utility Evaluation
6	Algorithm Performance Characterization / Operational Utility Evaluation

Test Item Description

VEST algorithm: The purpose of the VEST algorithm was to continuously estimate true airspeed following a complete air data system failure. The complete air data system failure meant that all sensors providing airspeed, altitude, temperature, angle of attack, and pressure readings were no longer available. The algorithm had three parts. The first part used available information to estimate the inertial position, velocity, and attitude. The pieces of available information were flight control computer accelerometer and rate gyro outputs, and last known position, velocity, attitude, and temperature. The algorithm used accelerometer and rate gyro outputs to propagate the last known state forward to the current state. The current state was inertial position, velocity, and attitude. The second part of the algorithm used the inertial information to continuously estimate the wind velocity. The wind was determined by the difference between the inertial track and the inertial heading to current nose position. Angle of attack and sideslip were estimated and included in the wind estimate. Finally, the true airspeed was determined by combining the inertial airspeed estimate and the wind estimate. The third part of the algorithm continuously estimated calibrated airspeed. Current temperature was estimated using a standard lapse rate based on inertial altitude deviation from last known altitude and temperature. The current temperature estimate was used to determine current pressure and density for use in converting true airspeed to calibrated airspeed. Figure 1 displays the VEST algorithm integration into the aircraft and required data inputs.

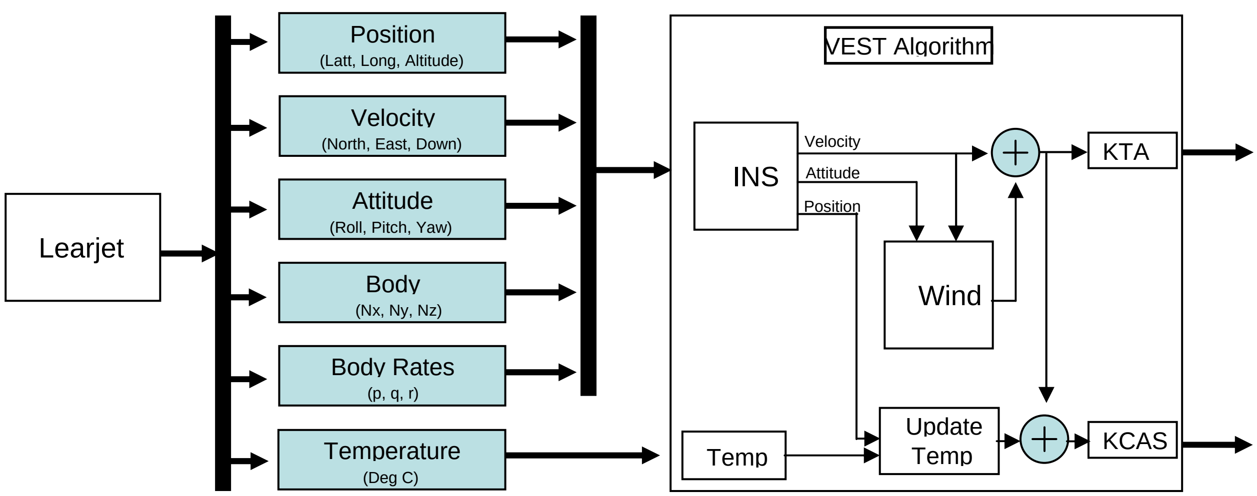

Figure 1 - VEST Algorithm Integration into Test Aircraft

Test Aircraft

Testing was accomplished on the Calspan VSS Learjet, N101VS incorporating a variable stability system (VSS). The modified Learjet provided in-flight simulator capability to test the VEST algorithm. The VEST algorithm was integrated onto the VSS using Matlab® Simulink®. The algorithm was developed as a Simulink® model, and converted into an executable file to be used on the VSS. The unique characteristics of the VSS made possible real time integration of the VEST algorithm and use of its estimated airspeed for gain scheduling. The left seat occupied by the safety pilot had basic Learjet controls and the right seat occupied by the evaluation pilot had fly-by-wire variable stability controls. If at any time the VEST algorithm produced unusable airspeed information or information that would result in an unsafe aircraft response, the VSS would disengage and give basic Learjet control back to the safety pilot. A full description of the Calspan Learjet N101VS is located in appendix A.

Test Objectives

The overall test objective was to evaluate the potential of the VEST algorithm in the event of a complete air data system failure. Additionally, results from testing were used to consider future VEST related tests. The specific test objectives were:

- Observe the Integration of the VEST Algorithm in a Ground Test
- Determine the Accuracy of the VEST Algorithm Inertial Speed During Taxi
- Determine the Airborne Accuracy of the VEST Algorithm Inertial Estimate
- Determine the Airborne Accuracy of the VEST Algorithm Wind Estimate
- Observe the Utility of the VEST Algorithm in Operational Maneuvers
- Determine the Airborne Accuracy of the VEST Algorithm Airspeed Estimate

All test objectives were met.

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TEST AND EVALUATION

General

Data were collected and analyzed in accordance with the procedures outlined in appendix B. The flight test matrix for the test points used in data analysis can be found in appendix H.

Integration of Velocity Estimate (VEST) Algorithm in a Ground Test

The purpose of the ground test was two fold. The first task was to check the integration of VEST algorithm with the Learjet Variable Stability System (VSS) to produce required outputs. The second task was to obtain a longitudinal stick force versus control surface deflection mapping for a FCS gain schedule which could be used during the flight tests.

Three power ups of the VEST algorithm implemented on the VSS from the complete power off condition were performed. VSS operation and VEST algorithm specific parameters were monitored throughout. The ground test was performed prior to first taxi.

To test the utility of the VEST algorithm, a gain schedule was set up in the VSS to change the command gain. The command gain schedule fed back calibrated airspeed to set the appropriate gain. There were three possible sources of fed back calibrated airspeed: Learjet air data, VEST, and a constant value to simulate standby gains. The command gain was multiplied by the actual air data value of calibrated airspeed, referred to as a "V^4 control law", then normalized by one of the three sources of fed back calibrated airspeed, referred to as a "V^4/V^4 control law". In this way, the command gain on the stick would be increased or decreased based on the value of calibrated airspeed from one of the three sources. If one of the sources provided a calibrated airspeed value that was different from the actual value, then the command gain on the stick would increase or decrease. If the fed back calibrated airspeed was the same as the actual value, then a constant command gain would result. The amount of change that would be noticeable by the pilot was set during the calibration portion of the first flight. The idea was that maneuvers would be flown in sequence using each of the three calibrated airspeed sources and compare the handling qualities observed while accomplishing specific tasks. Magnitude of airspeed errors would be perceived as changes in stick sensitivity while variations in airspeed errors would result in unpredictable aircraft responses. Figure 2 shows the implementation of this concept into the VSS.

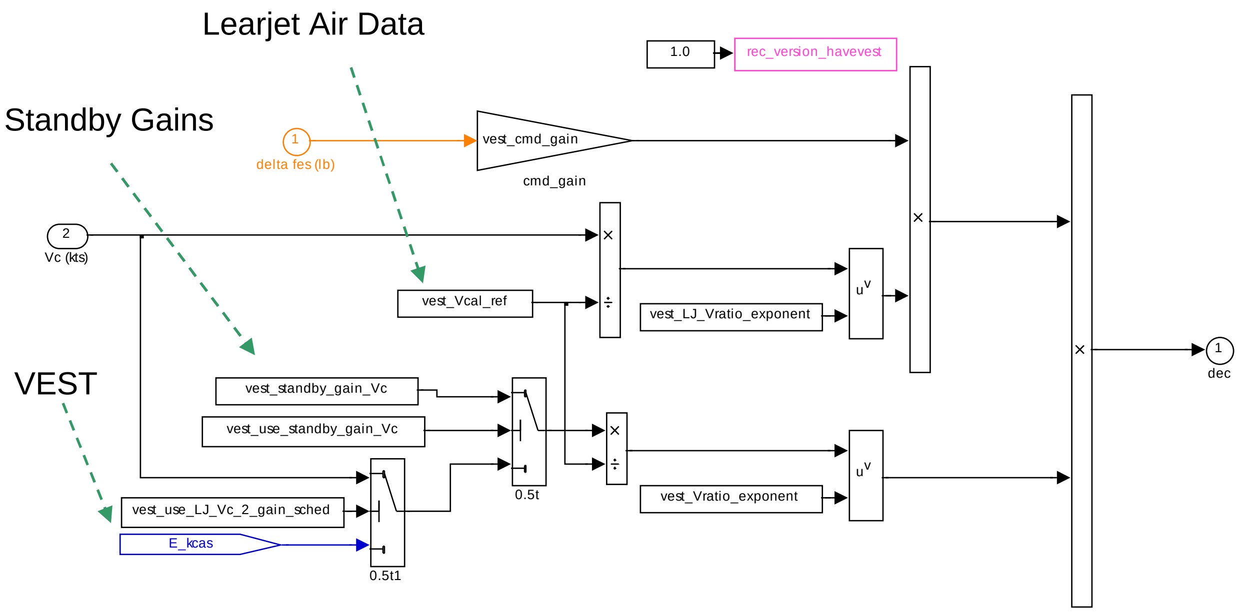


Figure 2 - Implementation of Gain Schedule

Stick forces (Fs) and deflections were measured before and after the calibration flight. The flight itself was performed at 15,000 feet and airspeeds of 200 to 300 KCAS to effectively calibrate the feel system for the gain scheduler. Pitch doublets, pitch captures, and rollercoaster maneuvers were performed at 220, 250, and 280 KCAS for familiarization of the basic Learjet control laws. Next a constant stick force per g (V^4/V^4) was flown for pilot familiarization. Initial tests at 220 KCAS indicated a Fs/g of 4 pounds per g with a command path gain of -0.5. The gain was decreased to -0.25 and the resultant stick force per g was approximately 8 pounds per g. At that point, maneuvers were flown at varying airspeeds using the V^4/V^4 control law to investigate the resulting Fs/g. The intent was to ensure the control laws were properly implemented to increase stick sensitivity as airspeed increased from 250 KCAS and became less sensitive at airspeeds less than 250 KCAS. At 250 KCAS the baseline performance as determined in the previous step was verified.

All indications of system functionality prior to engine start were positive and no system errors were encountered. Normal checklist procedures required the VSS be shut-down during engine start. Once engines were started, the VEST algorithm was observed to function properly with the VSS and no significant errors were noted.

Longitudinal Stick Force versus Control Surface Deflection Mapping: The plot of Fs per elevator deflection prior to and after the calibration flight is shown in figure 3 below. The slope of the plots before and after calibration matched as expected.

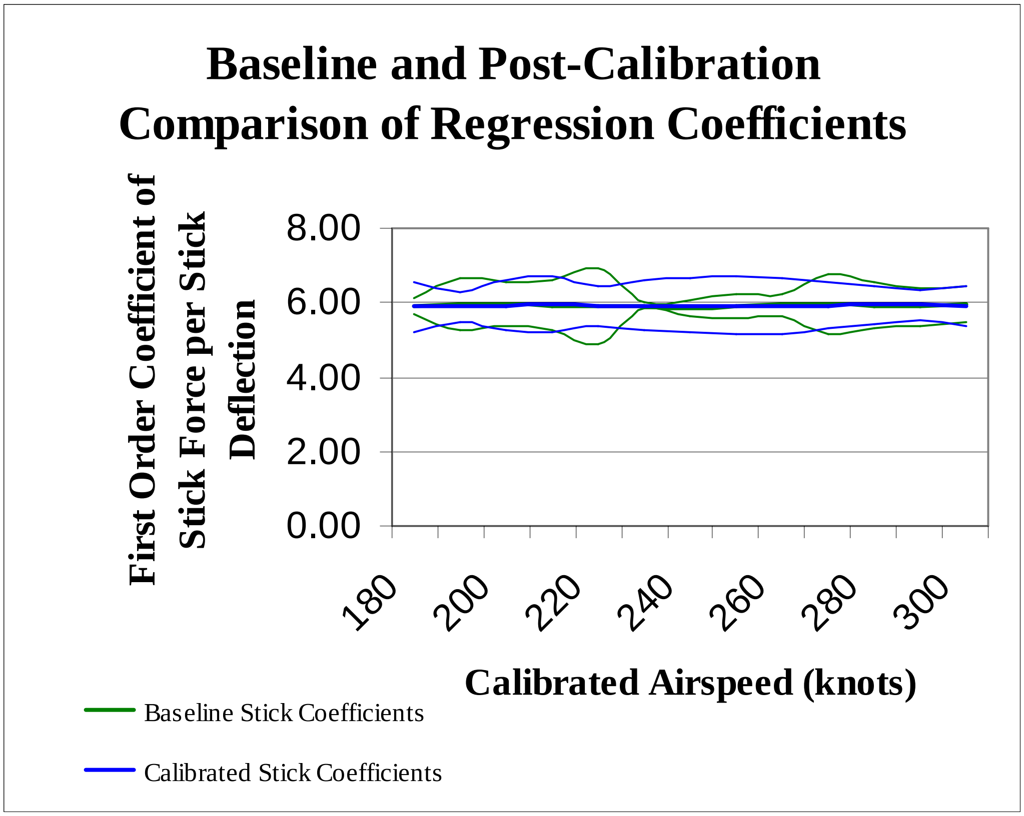


Figure 3 – Implementation of Test Team Gain Schedule

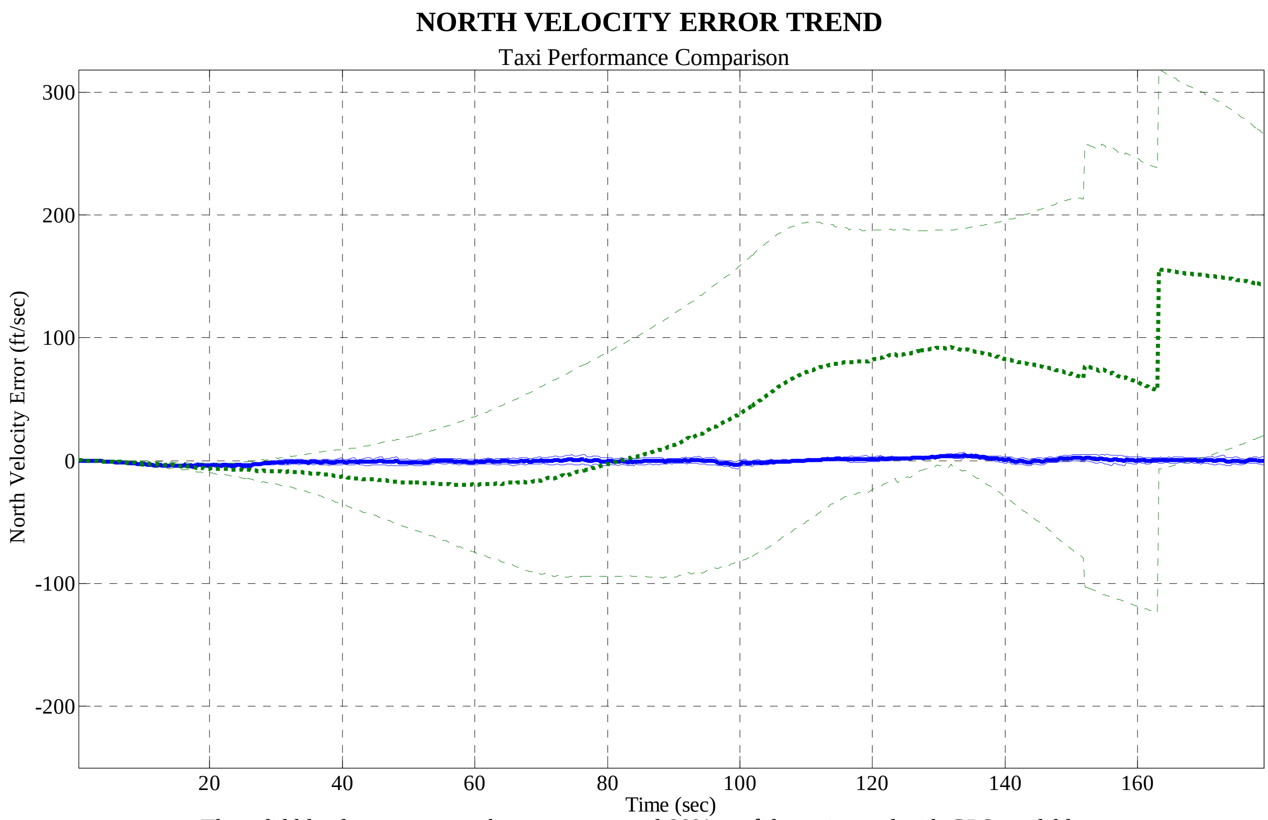
The system integration and functional check out of the VEST algorithm onto the VSS was accomplished during the ground test. Based on the longitudinal stick force versus control surface deflection mapping comparisons, the stick force gain schedule was determined to have been implemented correctly for use on subsequent flight test evaluations.

Accuracy of the VEST Algorithm Inertial Speed during Taxi

Based on the results of the system integration of the VEST algorithm onto the Learjet VSS, the taxi test investigation was initiated. The purpose of the taxi test was to determine the accuracy of the VEST algorithm inertial speed estimate.

The accuracy of the VEST algorithm inertial speed was determined during multiple taxi runs. The initial step performed for the taxi test was to apply tape to the Angle of Attack (Alpha) and side-slip (Beta) vanes ensuring the VSS did not trip due to excursions in Alpha and Beta during taxi. The aircraft GPS was used as the truth source for position and velocity. To verify the accuracy of the GPS, survey points along taxiway H were used as references for stationary aircraft position. The aircraft installed attitude and heading reference system (AHRS) was used as a truth source aircraft heading. The aircraft was taxied for 5 minutes and time histories of inertial speeds were recorded on the VSS for analysis. To calculate the accuracy of the VEST algorithm, inertial north, east, and down speeds were subtracted from the GPS speeds and plotted against time. This procedure was repeated both with and without GPS updates.

To evaluate the accuracy of the algorithm, north, east, and down velocity estimates were evaluated for all taxi tests with and without GPS updates. Results are presented in appendix E. Figure 4 is a sample time history plot of north velocity error with eighty percent confidence with and without GPS.



The solid blue line represents the mean error and 80% confidence interval with GPS available.
The dashed green line represents the mean error and 80% confidence interval without GPS available.

Figure 4 - North Velocity Error Trend with and without GPS

Post taxi test data analysis indicated that the VEST algorithm inertial speed estimate was properly integrated onboard the VSS. When GPS updates were not available, the VEST algorithm experienced drift in all three axes with no indication of correction to zero error. Results showed that the algorithm required GPS to provide an estimate to eliminate the effects of drift. Based on the error observed in the inertial speed estimate, test points without GPS updates were eliminated from flight test. **Improve algorithm performance in the absence of GPS updates. (R1[1])**

[1] Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

The VEST algorithm velocity errors with GPS updates were found to be on the order of 2 knots, minimally variable, and non-divergent. Therefore, follow-on airborne testing with GPS updates was justified.

Airborne Accuracy of the VEST Algorithm Inertial Estimate

The purpose of the inertial estimate portion of the VEST algorithm was two-fold. The inertial estimate itself was used for the calculation and display of flight information. Additionally, velocity and attitude outputs were used as inputs to the algorithm's wind estimator. The algorithm's true airspeed estimate was calculated using the inertial speed estimate and the wind estimate. Flight test techniques (FTTs) were set up to observe the accuracy of the inertial speed and heading estimates.

Four separate FTTs were developed. Three of the four FTTs included turning maneuvers to provide axis observability in inertial estimates. The fourth FTT was developed to evaluate the VEST algorithm's performance during straight and level, unaccelerated flight. An explanation and description of each of the four FTTs (J-Hook, Container, Sliceback, and Long Shot) can be found in appendix C.

Post flight data analysis from flights 1 and 2 indicated that the inertial estimate portion of VEST algorithm was not properly integrated with the Learjet VSS. Inertial estimates observed during flight (algorithm integration with VSS) did not match post-processed inertial estimates (algorithm integration with Simulink®). The disparity was investigated for the remainder of the flight test schedule, but was not resolved. Therefore, the airborne accuracy of the VEST algorithm's inertial estimate was determined by post-processing.

North and east velocity components of the inertial estimator were evaluated. Error trends for all of the FTTs in table B-1 were similar and the error was not a function of airspeed. Additionally it was observed that the magnitude of the errors were similar in both the north and east directions. Neither aircraft maneuvers nor airspeeds affected the VEST inertial estimate error profiles. Figure 5 is a representative plot of velocity error. Results for velocity errors are presented in appendix E.

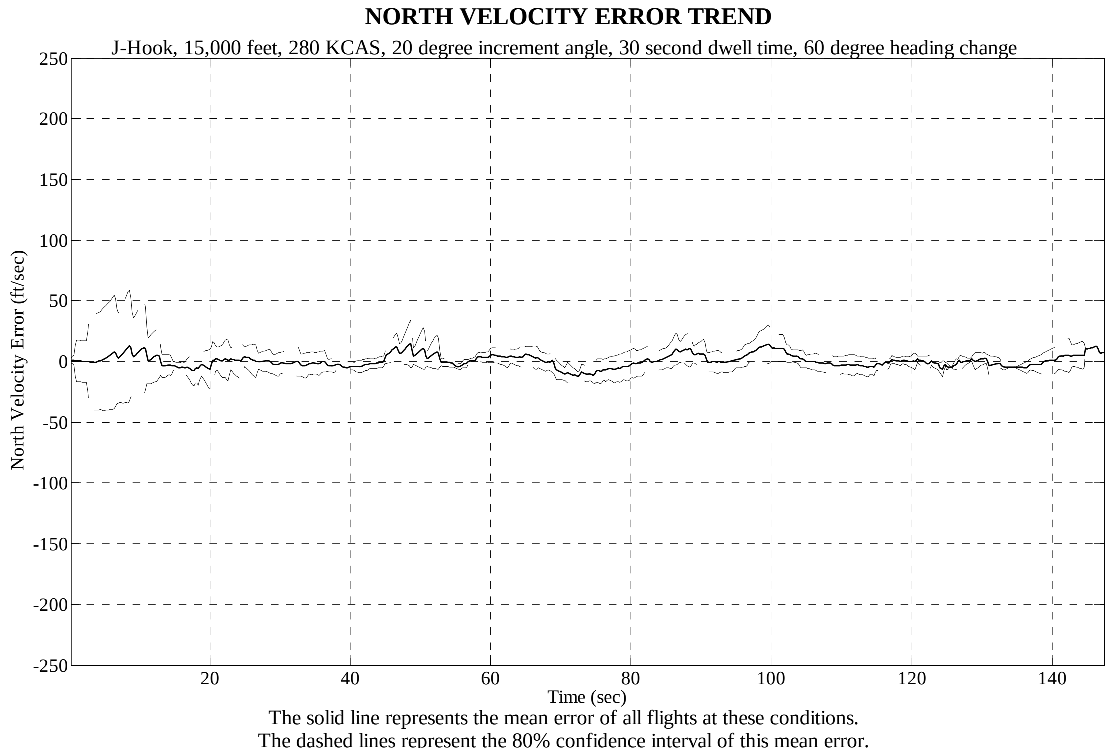


Figure 5 – North Velocity Error Trend during J-Hook

The VEST algorithm was updated by GPS every two seconds and as such the position errors were on the order of a thousandth of a degree. The magnitude of the north and east position errors remained relatively constant throughout all of the FTTs described in appendix B and was not a function of airspeed or maneuver. Figure 6 is a representative plot of position error. Results for position errors are presented in appendix E.

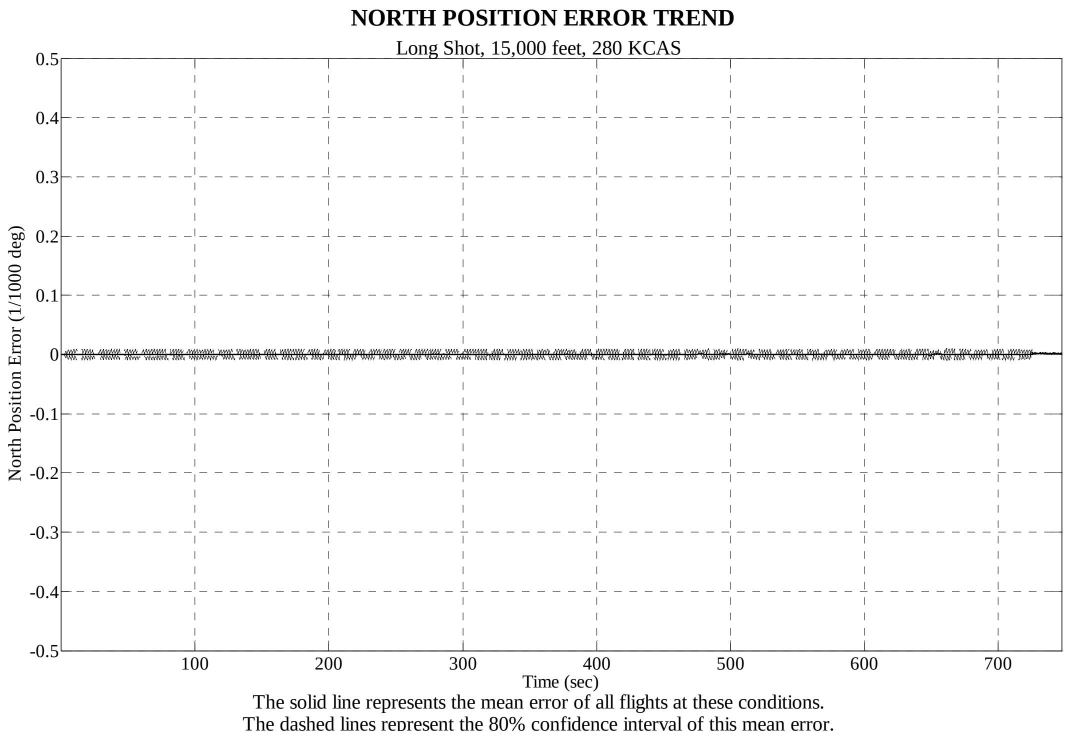


Figure 6 – North Position Error Trend during Long Shot Maneuver

The magnitude of heading errors from the VEST algorithm remained relatively constant for all of the FTTs in appendix B (as in figure 7) except for the Long Shot. The largest errors in heading of up to 150 degrees were noted during the Long Shot maneuvers. The inertial estimator was expected to drift similar to an actual INS due to the lack of aircraft accelerations in straight and level, un-accelerated flight. For all of the other FTTs, the heading error tended to zero with time, but with increasing variability. Airspeed was a significant factor in algorithm performance during the Sliceback maneuver. The higher speed test points resulted in a more desirable heading error profile (smaller magnitude and less variability). Results for heading errors are presented in appendix E.

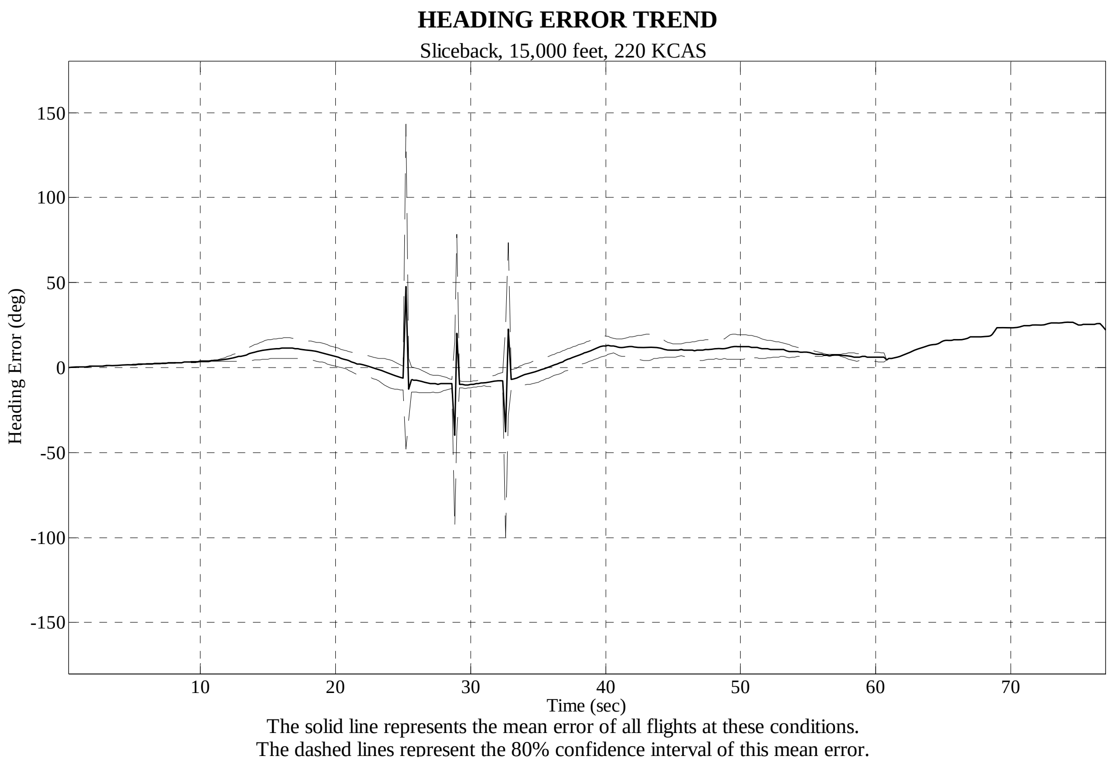


Figure 7 – Average Heading Error Trend for all Sliceback Maneuvers

The inertial estimate errors were determined to be acceptable to use as inputs into the rest of the VEST algorithm. Further, inertial estimates for the Long Shot FTT diverged as expected. Airspeed was a significant factor in heading determination (algorithm performance at higher airspeeds was improved).

Airborne Accuracy of the VEST Algorithm Wind Estimate

The VEST algorithm combined ground speed (from inertial estimates) and wind speed to determine true and calibrated airspeed. The accuracy of the VEST output wind magnitude and direction were determined during this portion of the evaluation. The same four FTTs used to determine the inertial estimate accuracies were used to evaluate the airborne accuracy of the VEST algorithm wind estimate.

The inputs used by the wind portion of the VEST algorithm to continuously estimate the current winds were aircraft north speed, east speed, and heading. The outputs were north and east wind components of the wind velocity. The north and east wind components were converted to magnitude (speed) and direction for comparison to Learjet provided wind truth source. A sample plot of the wind speed error trend during a J-Hook maneuver can be found in figure 8 below. The error trend plots for each of the remaining maneuvers flown can be found in appendix E.

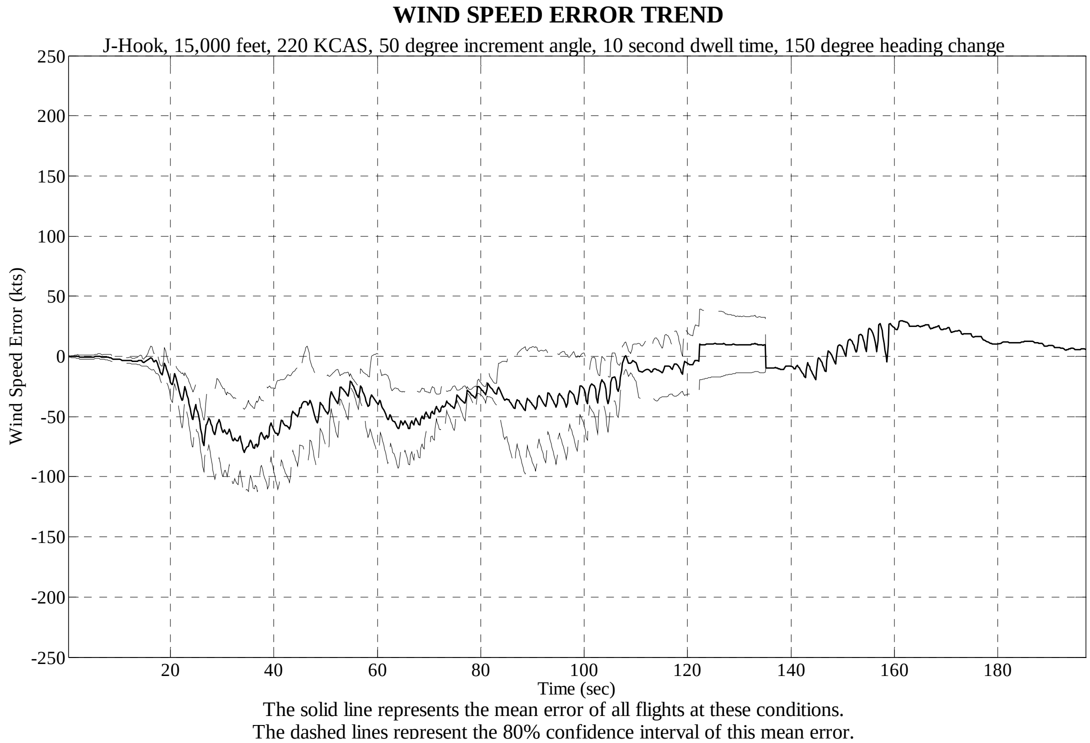


Figure 8 - Wind Error Time History during a J-Hook Maneuver

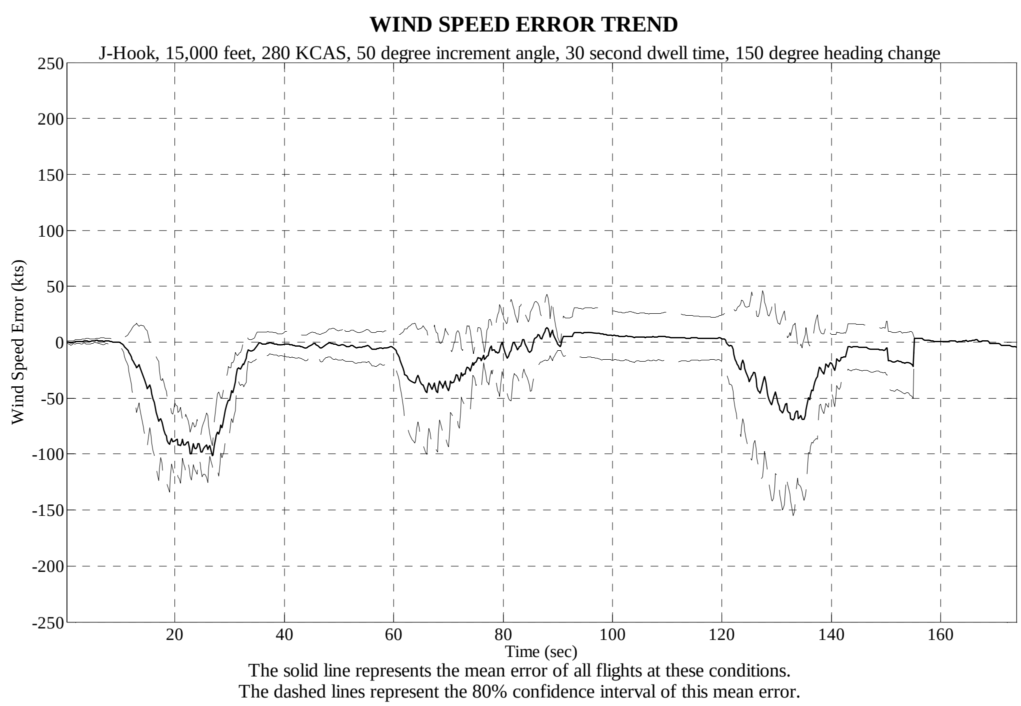


Figure 9 - Wind Error Time History during a J-Hook Maneuver

The wind speed error during the J-Hook maneuvers was found to be primarily a function of dwell time (time straight and level following a turn). Speed errors tended to increase during turns, but decrease once the turn was complete. Errors typically reduced to less than 10 knots during a 30 second dwell time. Similar maneuvers that reduced the dwell time from 30 to 10 seconds resulted in speed errors that stayed greater than 15 knots. During the short dwell time, the wind portion of the VEST algorithm did not have enough time to determine an accurate wind speed; thus the error remained high. This analysis was conducted by a graphical comparison of 10 and 30 second dwell time J-Hook time histories, as seen in figures 8 and 9. Increment angle and total heading change were found to not be significant to the wind speed error profile.

During the Long Shot maneuver, errors slowly increased with time. By graphical analysis of the Long Shot maneuvers, wind speed error divergence rate increased after approximately five minutes, see figure 10 for a representative plot.

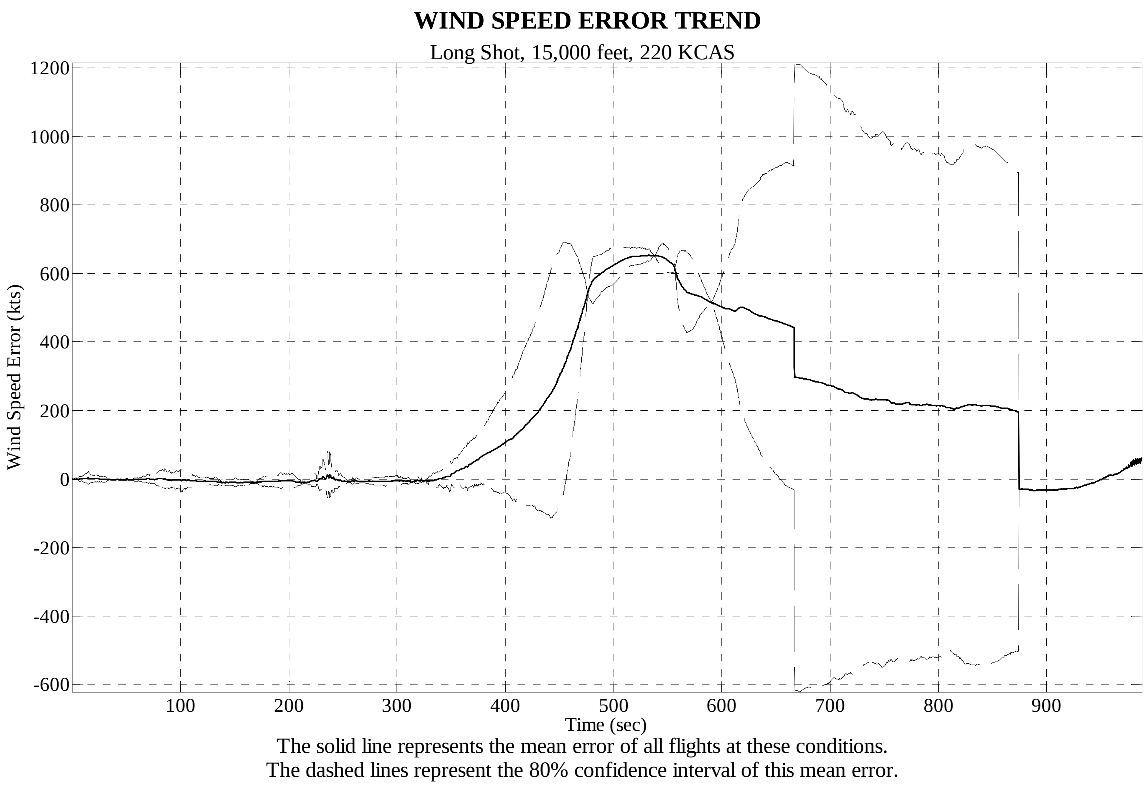


Figure 10 - Wind Direction Error Time History during a Long Shot Maneuver

The second portion of the wind analysis was to determine the wind direction. A sample plot of the wind direction error trend during a J-Hook maneuver can be found in figure 11 below. The error trend plots for each of the remaining maneuvers flown can be found in appendix E.

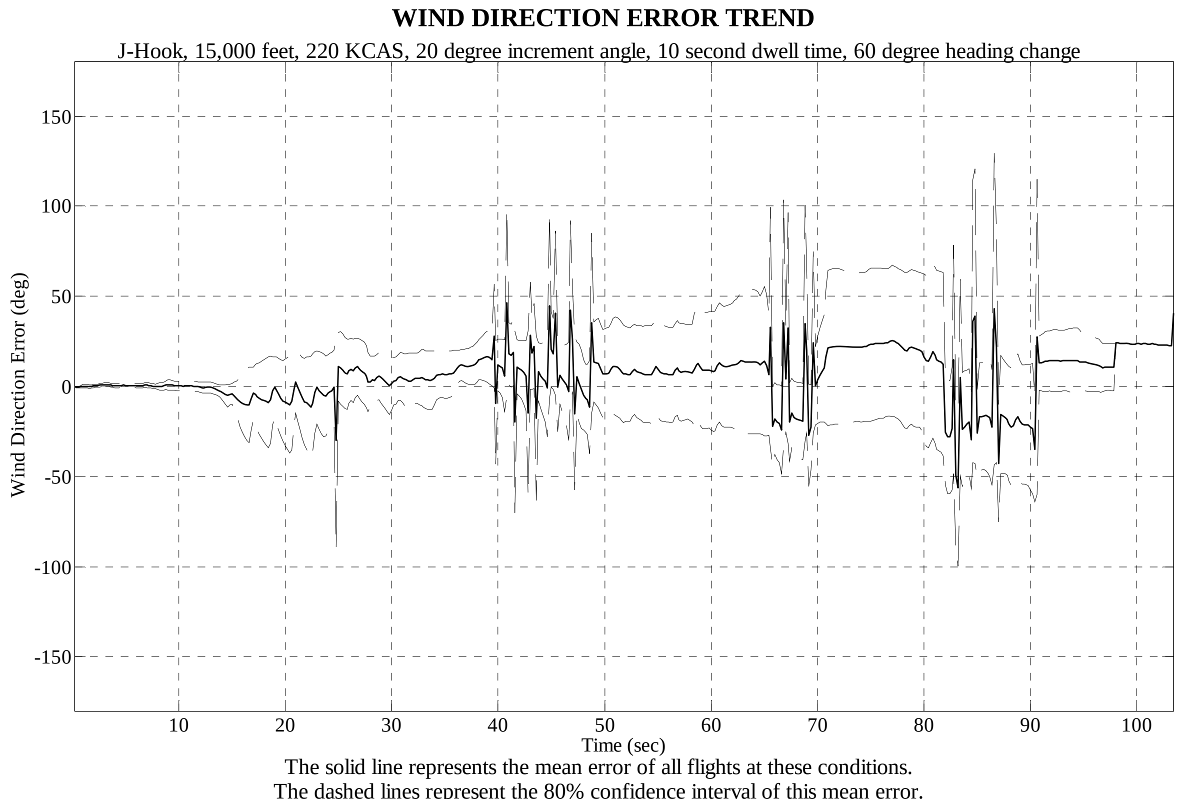


Figure 11 - Wind Direction Error Time History during a J-Hook Maneuver

The VEST wind direction estimate was least accurate during turns. Wind direction excursions during the turning portion of the J-Hook maneuvers reached approximately 150 degrees. Once returned to a wings level attitude, errors decreased to steady values. Wind direction errors following the first turn in figure 11 were on the order of 10 degrees. After the second turn, errors increased to 15 degrees, and after the third turn, errors increased to 20 degrees. This same trend continued for the majority of J-Hook maneuvers, this analysis was conducted by a graphical comparison of time histories, as seen in figure 11. Airspeed was a significant factor in algorithm performance during the J-Hook maneuver. The higher speed test points resulted in a more desirable wind direction error profile (smaller magnitude and less variability). Similar to the Long Shot wind speed error results, the wind direction errors increased to values in excess of 90 degrees after the five minute point.

The VEST wind estimate was most accurate in the wings level attitude. Estimates during turns produced unreliable values, but errors tended to decrease once the aircraft was returned to a wings level attitude. The VEST algorithm was determined invalid for providing accurate speed and direction estimates after approximately five minutes of non-maneuvering flight. Airspeed was a significant factor in wind direction determination and non-maneuver dwell time was a significant factor in wind speed determination. Algorithm performance was enhanced with non-maneuver dwell times and higher airspeeds.

Utility of the VEST Algorithm in Operational Maneuvers

The utility of the VEST Algorithm was observed during the following operationally representative maneuvers: air refueling, air-to-air and air-to-ground tracking. This was achieved by flying each of these maneuvers with three different gain schedules and comparing the corresponding aircraft response. Three gain schedules were created using fed back calibrated airspeed values from the Learjet air data system (ADS), the VEST algorithm, and 250 knots for standby gains in the V^4/V^4 control law. Pilot comments were noted during each of the maneuvers and pilot ratings were recorded on the analog scale found in appendix D.

As outlined above, the inertial estimate of the VEST algorithm was not correctly integrated onto the VSS. Outputs from the inertial estimate were key parameters in the VEST algorithm and the stick command gain schedule was based on the corresponding VEST output airspeed. Therefore, it was determined that GPS speed and AHRS heading information would feed the wind estimator portion of VEST algorithm for these real time evaluations. The post-processed average inertial speed errors were less than 5 knots of the input GPS ground speed and the heading error was less than 3 degrees of input AHRS heading.

A plot showing the time history error of the difference between GPS ground speed and post processed ground speed for test point 16 on flight 5 is shown in figure 12. The near zero error profile justified the use of GPS inertial information as the inputs for the wind estimator.

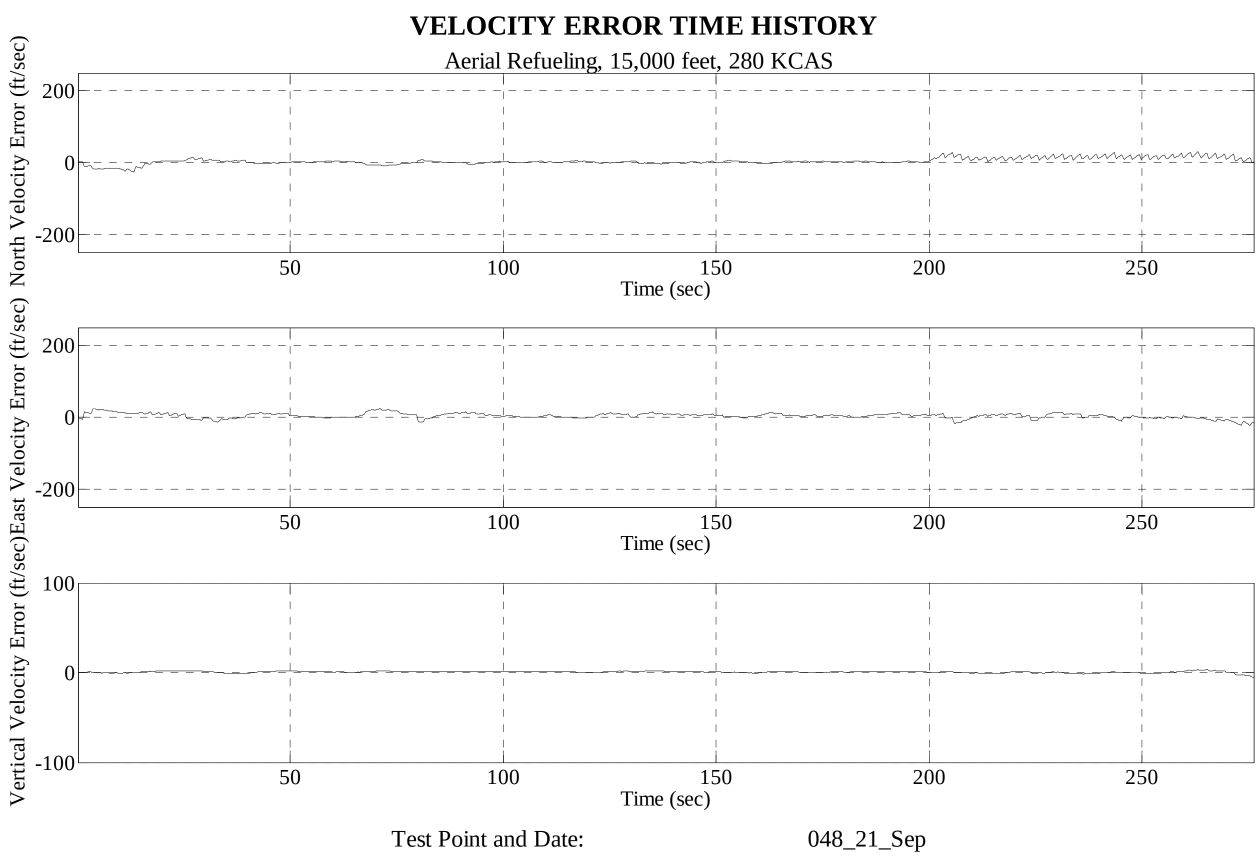


Figure 12 – Velocity Error Time History

<u>Air Refueling</u>: The maneuver started with the target stabilized on conditions (15,000 feet pressure altitude, 220/280 KCAS) and the test aircraft at a simulated observation position. The first task was to maneuver to the pre-contact position approximately 100 feet in trail. After stabilizing for 30 seconds, the test aircraft closed into the contact position, 50 feet in trail. After stabilizing for 30 seconds straight and level, the target was tracked through 90 deg of turn with 15 deg bank.

ADS Gain Schedule: The control force required to produce a desired pitch response was higher than expected, but predictable. There was no delay in the pitch response. Further there was no tendency to overshoot or undershoot and typically minimal workload was encountered to obtain desired performance throughout the refueling task. No undesirable motions were noticed (Pilot in Loop Oscillation Rating (PIOR) 1). Refer to appendix G for the PIO rating scale. This performance met expectations as the V^4/V^4 control law with ADS airspeed fed back was a constant stick force per g throughout the maneuver.

VEST Gain Schedule: The control force required to produce a desired pitch response was less than the ADS gain schedule and the higher stick sensitivity was apparent. There was no noticeable delay in the pitch response and some unpredictability was noticeable during precise maneuvers in contact position. There was a mild tendency to overshoot and typically tolerable workload was encountered to obtain adequate performance throughout the refueling task. Due to the sensitivity and predictability, there was a tendency for undesirable motion to be induced easily (PIOR 3). Stick sensitivity resulted when the fed back airspeed was different from truth values. A larger error created a greater change in stick sensitivity. Unpredictability resulted from variability of error in the fed back airspeed.

Standby Gain Schedule: The control force required to produce a desired pitch response was higher as compared to the previous case and the higher stick sensitivity was apparent. There was no noticeable delay in the pitch response and it was predictable. The higher control forces increase the workload and this led to task saturation. Typically high workload was encountered to obtain adequate performance throughout the refueling task. Due to the stick forces, there was a tendency for undesirable motion to be induced easily (PIOR 3). The high stick sensitivity was due to the large and fixed error in fed back airspeed. There was no variability in the fed back airspeed (due to the constant airspeed standby gain) and the aircraft response was predictable.

<u>Air-to-Air Tracking</u>: The Learjet was equipped with an optical sight that was used during air-to-air tracking. The test aircraft set up 3000 feet in trail and 1000 feet below the target. The first task was to capture the jet nozzle of the target T-38 with the upper mark of the sight. Once the capture task was complete and the aircraft were co-altitude, the next task was to track the target's canopy through 180 degrees with the target using 50 degrees of bank. During the turn the target varied pitch so as to maintain altitude within 1000 feet of the starting altitude.

ADS Gain Schedule: The control force required to produce a desired pitch response was marginally high but not objectionable. There was no noticeable delay in the pitch response and it was predictable. There was no tendency to overshoot or undershoot and typically minimal workload was encountered to obtain desired performance throughout the tracking task. No undesirable motions were noticed (PIOR 1).

VEST Gain Schedule: The control force required to produce a desired pitch response was less than as compared to the previous case and the higher stick sensitivity was apparent. There was no noticeable delay in the pitch response but predictably remained in question. In one of the tracking tasks the response was highly predictable in the first 90 degrees of turn. Subsequently there was a change in the stick forces and the response became unpredictable. Despite this unpredictability, adequate performance was achieved at the cost of extensive workload. Due to the sensitivity and predictability, there was a tendency for undesirable motion to be induced easily (PIOR 3).

Standby Gain Schedule: The control force required to produce a desired pitch response was higher as compared to the previous case and the higher stick sensitivity was apparent. There was no noticeable delay in the pitch response and it was predictable. The higher control forces increased the workload and this led to task saturation. Typically high workload was encountered to obtain adequate performance throughout the refueling task. Due to the stick forces, there was a tendency for undesirable motion to be induced easily (PIOR 3).

Air-to-ground tracking: The Learjet's optical sight was used during air-to-ground tracking. Operationally representative ground attack maneuvers were conducted 220 and 280 KCAS for a descent of 4,000 feet. Since 20 degree dives resulted in speeds rapidly approaching 300 KCAS at idle power, shallower dive angles were used. Test points 70, 72, 74, 76, 78, and 80 were conducted by a simulated ramp delivery (straight ahead push) at the dive angle required to maintain speed. The dives were shallow, so the pilot attempted to evaluate the gain schedules by rapidly changing aim points in the dive. Recovery was conducted with a 2g level pull with mild heading changes during the climb. The control inputs required to complete these shallow angle dives were all small. The inputs were so small in fact that the pilot noticed very little difference among the three gain schedules. Minimal calibrated airspeed error was observed during the VEST test points thereby showing the ADS and VEST gain schedules to perform similarly (indistinguishable). With the standby gain schedule, flying faster than the reference airspeed (250 knots) resulted in increased stick sensitivity, while flying at lower speeds resulted in less objectionable stick sensitivity. Test points 71, 73, 75, 77, 79, and 81 were conducted by selecting a simulated target area that had multiple targets separated by approximately one mile. The test aircraft was then flown to a point roughly perpendicular to the attack axis at 200 KCAS. An aggressive roll (over bank to approximately 120 degrees) and pull (2.0g) was accomplished to aggressively capture a target on the near side of the target area. Power was reduced to idle. As airspeed increased through 220 KCAS, the aim-point was shifted to the far side of the target area (stabilizing the airspeed). Then the dive angle was aggressively steepened to a third aim-point. As airspeed increased through 280 KCAS, a fourth target on the far side of the target area was tracked until 300 KCAS was achieved. A wings level pull to 2.0 g was used to recover followed by a heading change of approximately 90 degrees. This technique highlighted the gain schedule differences as airspeeds changed during the task of ground attack. Once again, the calibrated airspeed error observed with VEST gain scheduling was small (approximately 10 knots) and the ADS and VEST gain schedules were both assessed as desirable. The standby gain schedule, however, was not as predictable or desirable. At the slow speed roll in, the aircraft was very sluggish and difficult to change pitch attitude. At the higher speed tracking and recovery, the aircraft was extremely sensitive resulting in a stair-stepped pitch response. The tracking task became more difficult as the feel of the aircraft changed through the dive.

A sample time history plot for erratic wind errors resulting from VEST gain schedule is shown in figure 13 below.

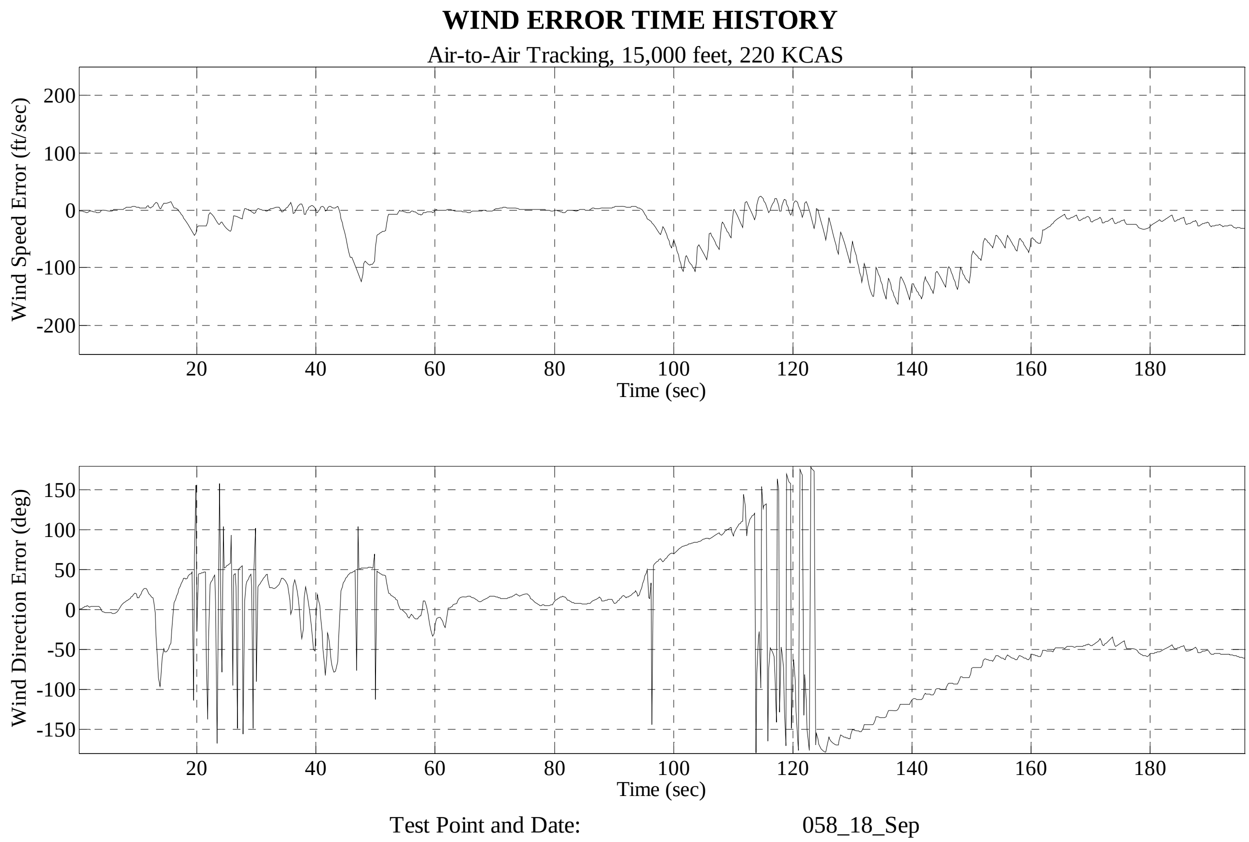


Figure 13 – Wind Error Time History during Air-to-Air Tracking

The wind components directly contributed to changes in calibrated airspeed, which in turn contributed to the unpredictability in control forces based on the gain schedule. This was due to the nature of the implemented gain scheduling wherein the slope of the force change with estimation error was deliberately chosen to be steep to enable the pilot to feel small speed variations.

The three operational tasks performed highlighted the capabilities and limitations of the VEST algorithm. Large errors in airspeed magnitude (more common in fed back standby gain airspeeds) resulted in stick sensitivities which adversely affected handling qualities. Large errors in airspeed variability (more common in fed back VEST airspeeds) resulted in unpredictable aircraft response which adversely affected handling qualities.

Aircraft flying these operational maneuvers would typically be fighters with a speed range in excess of 600 knots. Due to the VSS envelope, the standby gain schedule was tested over a 30 knot speed range with increased stick sensitivity to simulate a wider speed range. The increased stick sensitivity was used to highlight the effect of VEST algorithm errors. The VEST algorithm demonstrated the capability to reduce the magnitude of airspeed error over standby gains (to reduce sensitivity effect) at the cost of inducing variability. The effect of the variability was exaggerated due to the implemented gain schedule. The value of reduced sensitivity could not be evaluated. **Investigate VEST algorithm performance in a less exaggerated gain schedule over wider speed envelopes. (R2)**

Airborne Accuracy of the VEST Algorithm Airspeed Estimate

The accuracy of the VEST algorithm airspeed estimate was determined from airspeed errors between the VEST algorithm calibrated airspeed estimate and the VSS calibrated airspeed. Airspeed data from each maneuver tested were used in the analysis. VEST and VSS calibrated airspeed parameters were recorded for each maneuver. A time history of mean calibrated airspeed error bounded by its 80 percent confidence interval was plotted for each maneuver. A similar process was used to determine the accuracy of true airspeed

In the inertial portion of the VEST algorithm, the inertial speed estimate (or ground speed estimate) was broken into north, east, and vertical components. The north and east speed components, along with the inertial heading, were forwarded to the wind portion of the estimator to determine the current wind speed. The north and east components of the wind speed estimate were then subtracted from the inertial speed components to satisfy the following equation for true airspeed:

$$V_T = V_G - V_W .$$

V_T is the true velocity, V_G is the ground velocity from the inertial estimate, and V_W is the wind velocity. The true airspeed was then determined from the magnitude of the resulting true velocity vector. The calibrated airspeed was determined from the true airspeed and the current flight conditions from the VEST algorithm.

The time history error plots for the J-Hook, Long Shot, Container, landing, and operational maneuvers were determined using post processed data. An example true airspeed error trend plot of the 220 knot J-Hook maneuver is shown in figure 14.

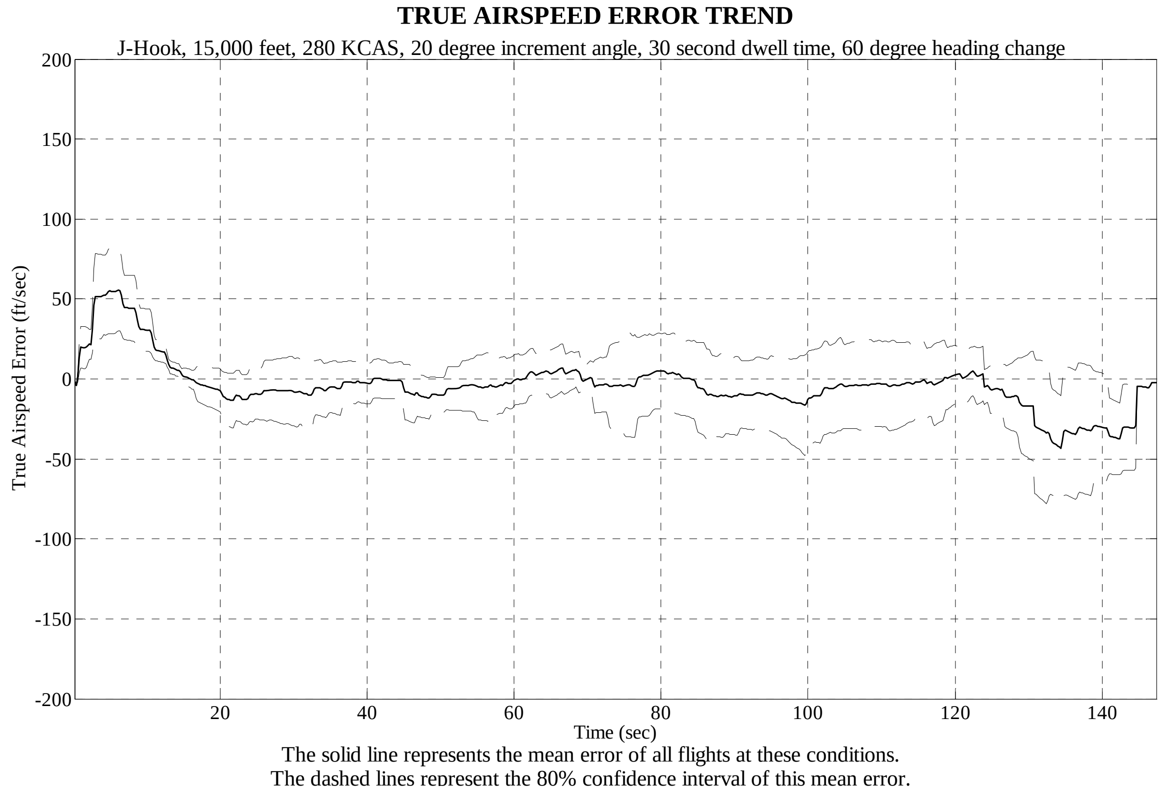


Figure 14 – True Airspeed Error Time History during a J-Hook Maneuver

Velocity error excursions were a combination of inertial and wind estimate errors. The errors were largest during the turning portion of the maneuvers, and decreased after the aircraft was returned to a wings level attitude. Error plots for the remaining maneuvers and test points can be found in appendix E. Table 2 summarizes the average errors calculated during each maneuver.

Table 2 – Average Airspeed Errors

Maneuver	Average TAS Error (ft/sec)	Standard Deviation	Average CAS Error (knots)	Standard Deviation
J-Hook	3.7	13.8	1.9	6.7
Long Shot	70.9	73.9	32.9	36.1
Sliceback	25.8	41.1	11.7	20.8
Container	15.4	22.7	7.3	11.5
Air to Air Tracking	17.4	19.7	9.7	10.1
Air Refueling	5.6	30.2	4.3	15.3
Air to Ground Tracking	21.2	22.4	10.2	11.4
Landing Approach	10.8	36.1	7.15	18.2

Individual airspeed excursions during turning portions of the maneuvers were typically in excess of the average errors shown above. The excursions were a function of both inertial and wind estimate errors, with the wind estimate providing the largest portion of the error.

The largest average error determined was during the Long Shot maneuver. The primary source of error during this maneuver occurred after five minutes of non-maneuvering flight. Ground and wind velocity estimates during the turns were as much as 150 ft per second after 15 minutes. The large errors were due to the design of the VEST algorithm. The algorithm was set up to provide airspeed estimates before and after turning maneuvers, not during the maneuvers. Non-maneuvering flight was expected to challenge the algorithm outputs.

The lowest average true airspeed error occurred during the J-Hook maneuvers. However, there was no correlation determined between maneuver type and airspeed error. The less dynamic maneuvers flown and short maneuver durations during the J-Hooks resulted in a lower overall airspeed solution estimation than during straight and level or continuous turning maneuvers. While the J-Hook maneuvers had the smallest airspeed errors, the J-Hooks also had the shortest maneuver duration. Figure 15 shows the comparison of calibrated airspeed error trends between J-Hook maneuvers and the first 90 seconds of Long shot maneuvers.

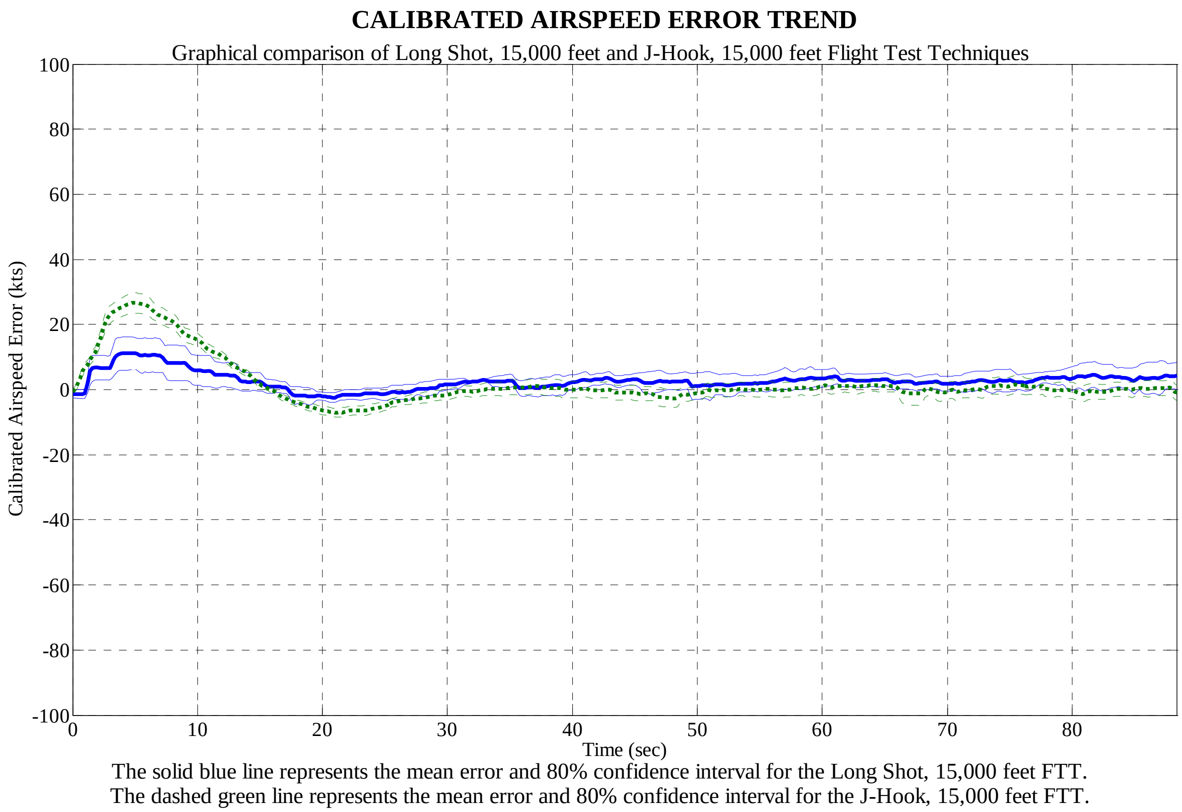


Figure 15 – Calibrated Airspeed Error for a Long Shot and J-Hook Maneuver

Calibrated airspeed errors shown above are both below 5 knots. For the J-Hook maneuvers, this error was for the duration of the maneuvers whereas the Long Shot maneuvers had yet to be completed.

The airborne accuracy of the VEST algorithm was determined. The average true airspeed accuracy was 12 knots (21 feet per second). The average calibrated airspeed was 10 knots (17 feet per second). The VEST airspeed estimate accuracy was independent of maneuver type.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of the Velocity Estimate (VEST) algorithm was to continuously estimate true airspeed following a complete air data system failure. Following air data system failure, all sensors providing airspeed, altitude, temperature, angle of attack, and pressure readings would be unavailable for use by aircraft systems. VEST provided an estimate of the lost air data information to supplement traditional standby gains with air data to schedule gains appropriate to the estimated flight condition. VEST estimated actual airspeed and flight conditions to schedule stick command gain and to display airspeed and altitude information in the cockpit. The average true airspeed error was 21 feet per second and the average calibrated airspeed error was 10 knots. The results of this test demonstrate the potential of this type of airspeed estimation as a back up system following air data failures, and warrants continued research. The results of the testing accomplished during this program are summarized below.

Integration of VEST Algorithm in a Ground Test

The system integration and functional check out of the VEST algorithm onto the Variable Stability System (VSS) was accomplished during the ground test. The stick force (Fs) gain schedule was determined to have been implemented correctly for use on subsequent flight test evaluations.

Accuracy of the VEST Algorithm Inertial Speed during Taxi

The VEST algorithm with GPS updates was found to be sufficiently accurate to continue with airborne testing. However, without GPS updates the algorithm’s inertial performance was inadequate.

R1: Improve algorithm performance in the absence of GPS updates.

Airborne Accuracy of the VEST Algorithm Inertial Estimate

The inertial estimate errors were determined to be acceptable to use as inputs into the rest of the VEST algorithm. Further, inertial estimates during long duration straight and level flight diverged as expected. Airspeed was a significant factor in heading determination (algorithm performance at higher airspeeds was improved).

Airborne Accuracy of the VEST Algorithm Wind Estimate

The VEST wind estimate was most accurate in the wings level attitude. Estimates during turns produced unreliable values, but errors tended to decrease once the aircraft was returned to a wings level attitude. The VEST algorithm was determined invalid for providing accurate speed and direction estimates after approximately five minutes of non-maneuvering flight. Airspeed was a significant factor in wind direction determination and non-maneuver dwell time was a significant factor in wind speed determination. Algorithm performance was enhanced with non-maneuver dwell times and higher airspeeds.

Utility of the VEST Algorithm in Operational Maneuvers

Three operational tasks highlighted the capabilities and limitations of the VEST algorithm. Large airspeed magnitude errors (more common in fed back standby gain airspeeds) resulted in stick sensitivities which adversely affected handling qualities. Large airspeed variability errors (more common in fed back VEST airspeeds) resulted in unpredictable aircraft response which adversely affected handling qualities. Aircraft flying these operational maneuvers would typically be fighters with a speed range in excess of 600 knots. Due to the VSS envelope, the standby gain schedule was tested over a 30 knot speed range with increased stick sensitivity to simulate a wider speed range. The increased stick sensitivity was used to highlight the effect of VEST algorithm errors. The VEST algorithm demonstrated the capability to reduce the magnitude of airspeed error over standby gains (to reduce sensitivity effect) at the cost of inducing variability. The effect of the variability was exaggerated due to the implemented gain schedule.

R2: Investigate VEST algorithm performance in a less exaggerated gain schedule over wider speed envelopes.

Airborne Accuracy of the VEST Algorithm Airspeed Estimate

The airborne accuracy of the VEST algorithm was determined. The average true airspeed accuracy was 12 knots (21 feet per second). The average calibrated airspeed was 10 knots (17 feet per second). The VEST airspeed estimate accuracy was independent of maneuver type. The airspeed error magnitude and variability affect the handling qualities of a highly augmented aircraft. The VEST algorithm has been demonstrated to reduce the error magnitude over standby gains, but increase the error variability (increase unpredictability). Potential exists for future applications with VEST.

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3. McLaren, S.A. (2008). *Airspeed Estimate Following Air Data System Failure.* Air Force University Press, Maxwell AFB, AL.
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APPENDIX A – DETAILED TEST ARTICLE DESCRIPTION

Figure A-1 – Learjet N101VS

The Calspan Learjet LJ-24, N101VS was used exclusively for this test program (reference 4).

Variable Stability Learjet N101VS: The Calspan Variable Stability Learjet was a modified Learjet designed to serve as a three axis in-flight simulator, where normal operations included the use of a safety pilot and an evaluation pilot. The safety pilot's controls (left seat) were standard, but the evaluation pilot's controls (right seat) were replaced with components of fly-by-wire, response feedback, variable stability, and variable control systems. The response feedback flight control system used the Learjet control surfaces to augment the stability characteristics of the basic Learjet.

Variable Stability System (VSS): The VSS was divided into two independent parts, a variable feel system and a response feedback system. The variable feel system provided the evaluation pilot with the stick and rudder pedal forces, gradients, and displacements, while the response feedback flight control system augmented the normal Learjet dynamics to represent those of the vehicle being simulated. The evaluation pilot's inputs were fed into the flight control system through the feel system, and the resulting control surface movements produced the aircraft response. The loop was closed by sensing the aircraft's motions and feeding back signals proportional to these motions, thus modifying the response to the pilot's inputs. Angle of attack vanes, sideslip vanes, rate and attitude gyros, and air data information were all used as the sensor elements. The VSS flight control modes were as follows:

VSS MODE: For purposes of this test, this was set to the basic aircraft parameters. A modified stick-command gain was scheduled in the speed range between 200 and 300 knots, in order to highlight estimated airspeed errors. Existing safety trips were not affected and remained in place.

EMERGENCY FLY BY WIRE (FBW) MODE: In the event the safety pilot becomes incapacitated or certain control cable failures occurred, the evaluation pilot can fly the aircraft as a normal Learjet using the FBW mode. All basic Learjet systems (gear, flaps, spoilers, brakes, etc.) were available. The handling characteristics were those of the basic aircraft with the yaw damper on. All safety trips were disabled and no feedback loops were used except rudder deflection per sideslip rate for yaw damping.

EVALUATION PILOT MANUAL DISENGAGE MODE: The evaluation pilot had the ability to electrically disengage the VSS and return control of the aircraft to the safety pilot. A disengage switch was located on the right seat center stick.

SAFETY PILOT MANUAL DISENGAGE MODE: The safety pilot had the ability to disengage the VSS by depressing any of the following: wheel master switch, glare shield disengage switch, or throttle quadrant disengage switch.

FORCE DISENGAGE MODE: A large force input by the safety pilot to the normal Learjet wheel/column will cause the VSS to disengage.

APPENDIX B – TECHNICAL DATA ANALYSIS

For each test point, eleven performance variables were analyzed. Position errors were determined in the north, east, and vertical direction. North and east position errors were determined in degrees while the vertical position error was determined in feet. This decision was made based on the precision of the recorded data in the north and east directions. Positions were available to the nearest thousandth of a degree corresponding to 364.56 feet. Velocity errors were determined in the north, east, and vertical directions and were determined in feet per second. Heading and wind direction errors were determined in degrees and presented between -180 and +180 degrees. Calibrated airspeed and wind speed errors were determined in knots. Finally, true airspeed was determined in feet per second. All errors were calculated by subtracting the Learjet variable value (truth source) from the Velocity Estimate (VEST) algorithm variable value (estimate).

Appendix E presents the time history of error for each of the eleven variables for each completed test point. Data were smoothed using a sliding average technique. Data were collected every 20 milliseconds. A single data point consisted of the average estimated value minus the truth source value over 400 milliseconds plotted at the midpoint of time. Figure B-1 illustrates the process. For each plot, the x-axis of time in seconds has been adjusted to allow the maneuver to span the entire plot. The y-axis scale was selected as a compromise between showing appropriate detail and attempting to maintain constant scaling for all plots. Figure B-2 is a representative airspeed and heading error time history plot.

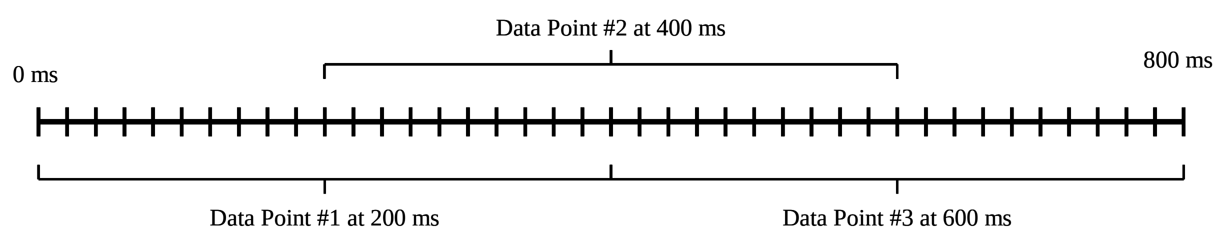

Figure B-1 – Sliding Average Method

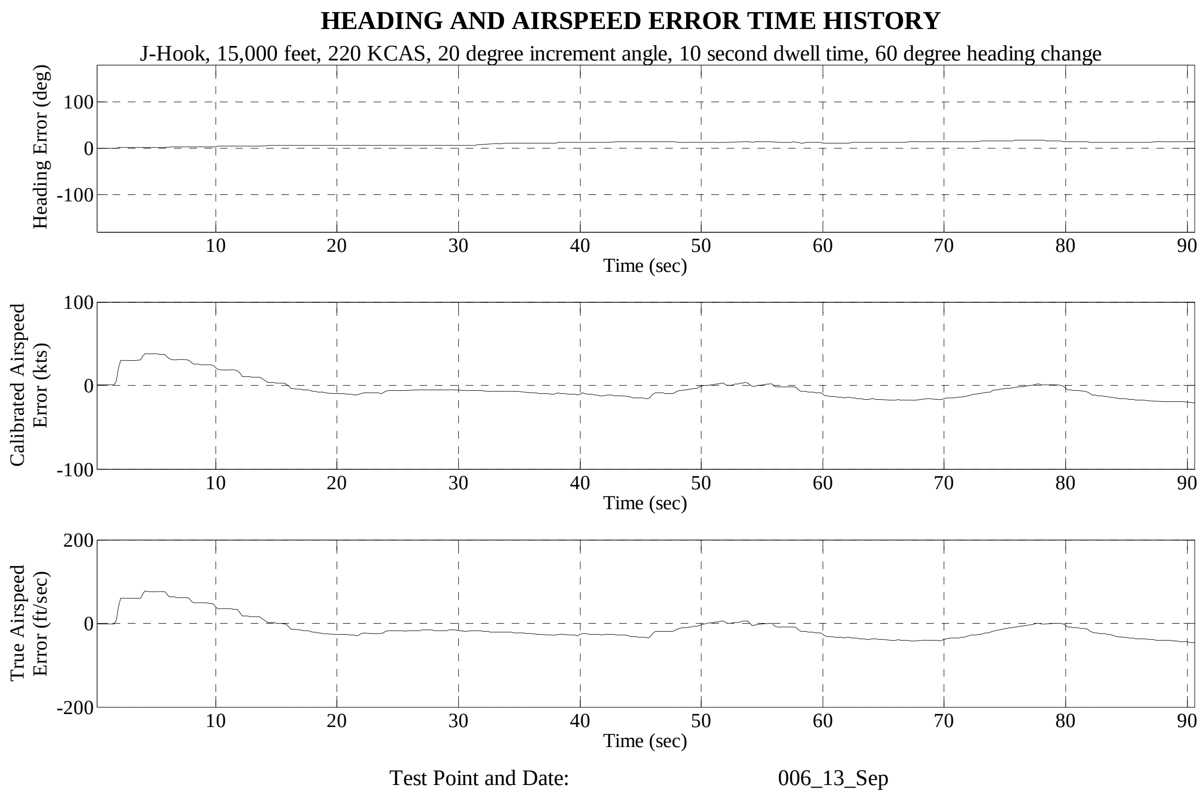

Figure B-2 – Representative Time History Plot

Appendix E presents the mean error time history for each of the eleven variables. Means were calculated by taking the average of each time history within a given treatment (combination of aircraft parameters). Additionally, an 80 percent confidence bound on this mean is presented. The 80 percent confidence bounds terminate if only one test point was available for a given period of time. Table B-1 shows the twenty-two treatments investigated and figure B-3 shows a sample mean error time history for calibrated airspeed error during a J-Hook maneuver. These specific maneuvers are described in detail in appendix C.

Table B-1 – Treatment Summary

Treatment Name	Description	Flight Test Points
LS	Long Shot FTT, 220 KIAS	1,2
LS_a	Long Shot FTT, 280 KIAS	3,4
J	J-Hook FTT, 220 KIAS, 10 second dwell time, 20 degree increment angle, 60 degree heading change	5,6,7,8
J_ad	J-Hook FTT, 280 KIAS, 10 second dwell time, 20 degree increment angle, 150 degree heading change	9,10,11,12
J_bd	J-Hook FTT, 220 KIAS, 30 second dwell time, 20 degree increment angle, 150 degree heading change	13,14,15,16
J_ab	J-Hook FTT, 280 KIAS, 30 second dwell time, 20 degree increment angle, 60 degree heading change	17,18,19,20
J_cd	J-Hook FTT, 220 KIAS, 10 second dwell time, 50 degree increment angle, 150 degree heading change	21,22,23,24
J_ac	J-Hook FTT, 280 KIAS, 10 second dwell time, 50 degree increment angle, 60 degree heading change	25,26,27,28
J_bc	J-Hook FTT, 220 KIAS, 30 second dwell time, 50 degree increment angle, 60 degree heading change	29,30,31,32
J_abcd	J-Hook FTT, 280 KIAS, 30 second dwell time, 50 degree increment angle, 150 degree heading change	33,34,35,36
Contain	Container FTT, 200 KIAS	37,38,39
Slice	Sliceback FTT, 220 KIAS	40,41,42
Slice_a	Sliceback FTT, 280 KIAS	43,44,45
AAR	Aerial Refueling Operational Maneuvering, 220 KIAS	46,47
AAR_a	Aerial Refueling Operational Maneuvering, 280 KIAS	48,49
AA	Air to Air Tracking Operational Maneuvering, 220 KIAS	58,59
AA_a	Air to Air Tracking Operational Maneuvering, 280 KIAS	60,61
GA	Ground Attack Operational Maneuvering, 220 KIAS	70,71
GA_a	Ground Attack Operational Maneuvering, 280 KIAS	72,73
APC	Approach to Landing	83,84,85,86,87
Treatment Name	**Description**	**Ground Test Points**
Grnd	Ground Taxi	14,15,16,17,18,19
Grnd_noGPS	Ground Taxi without GPS update	24,25,26,27

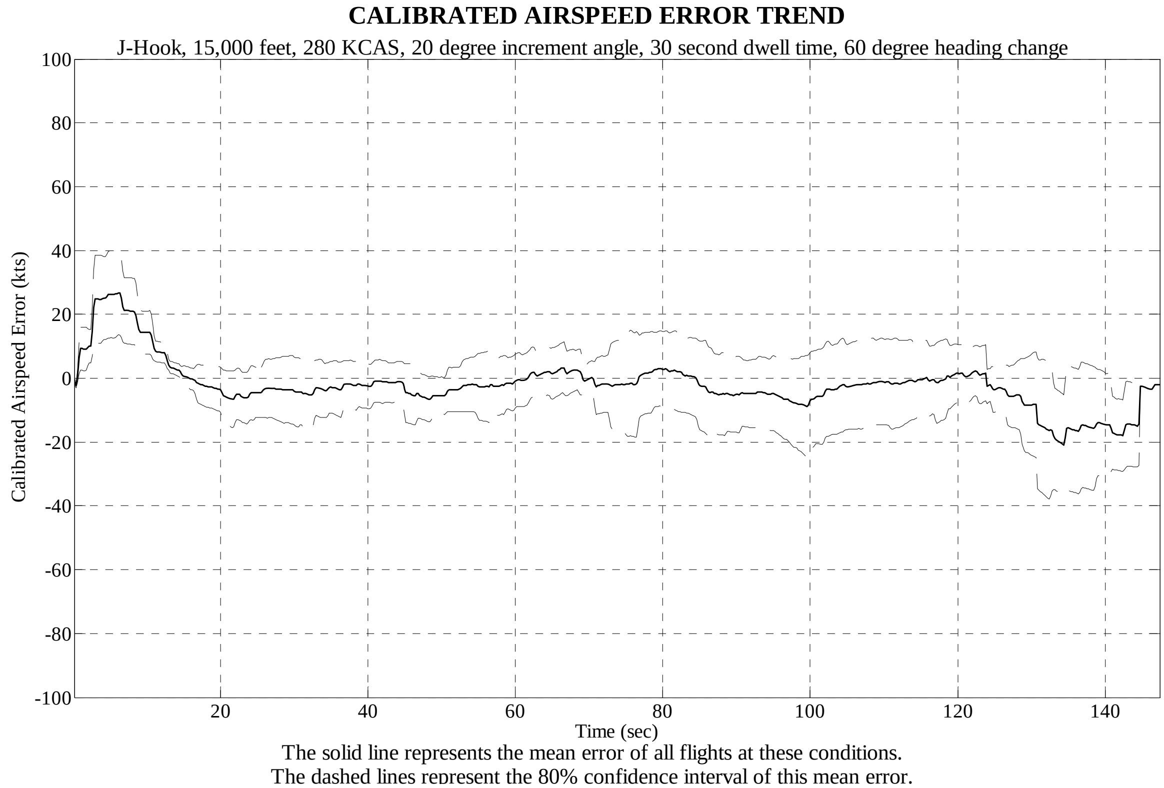

Figure B-3 – Representative Mean Error Time History

Appendix E shows the treatment mean time history plotted with its Haar wavelet approximation (reference 2) at various resolution levels. A sample treatment mean time history plot with Haar wavelet approximations is shown in figure B-4 for calibrated airspeed error during a J-Hook maneuver.

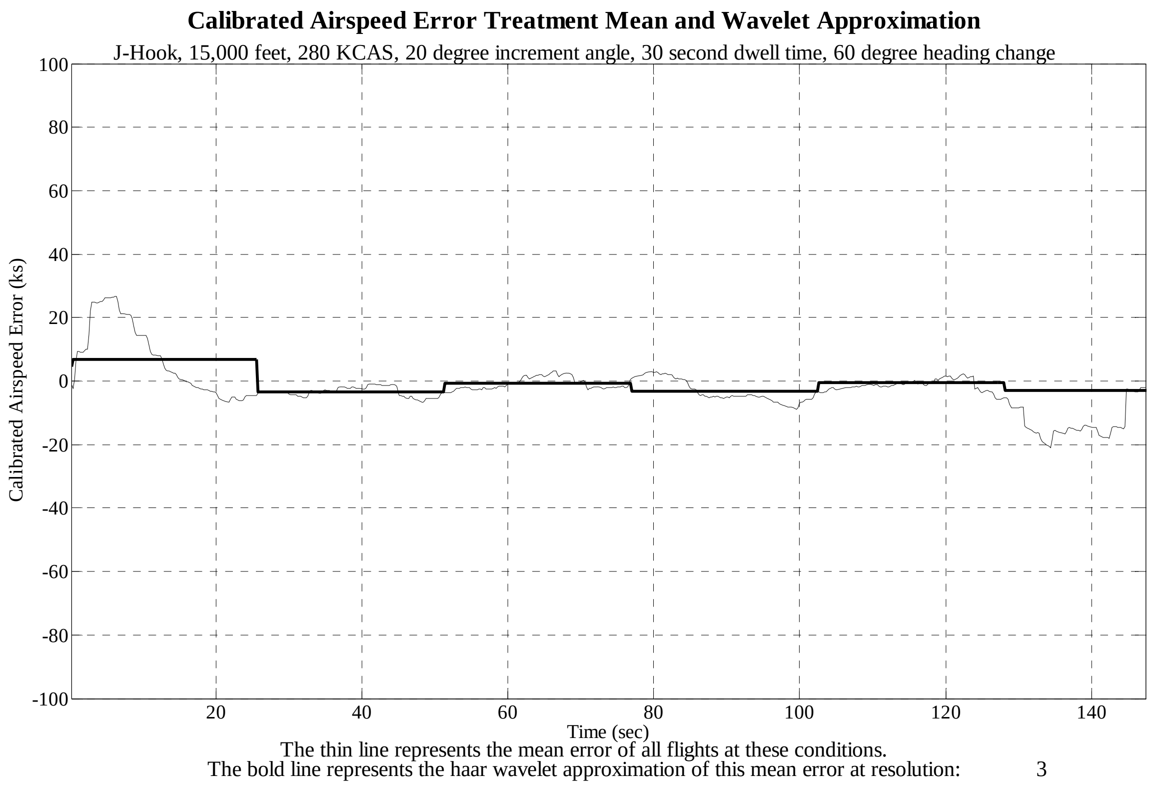

Figure B-4 – Representative Mean Error Time History

Haar wavelet analysis was selected in order to determine whether the performance of the VEST algorithm was significantly different under any of the four factors listed in table B-1 (airspeed, dwell time, increment angle, or heading change) during J-Hook maneuvers. The purpose of wavelet analysis is to select and interpret a subset of coefficient terms that contain the majority of information about profile data or a time dependent function. In concept, Haar wavelet analysis is similar to Fourier analysis except a function is broken into the sum of terms as shown in figure B-5 vice sine and cosine terms.

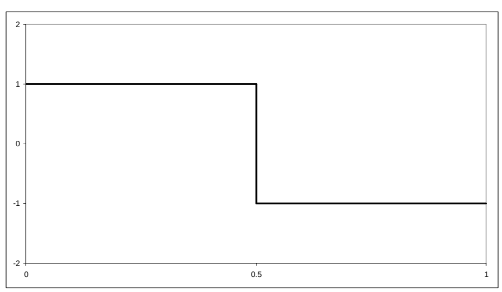

Figure B-5 – Haar Wavelet

The mean time history for each treatment was approximated using varying resolution. Each resolution of a Haar wavelet analysis adds 2^{n-1} waveforms as shown in figure B-6. The influence each resolution has on the approximation is determined by the corresponding wavelet coefficient value, similar to Fourier analysis. Large coefficient values at lower resolution are indicative of a global characteristic of the profile or the long term performance of the algorithm. A large coefficient value within the higher resolution is indicated by of a local change or spike.

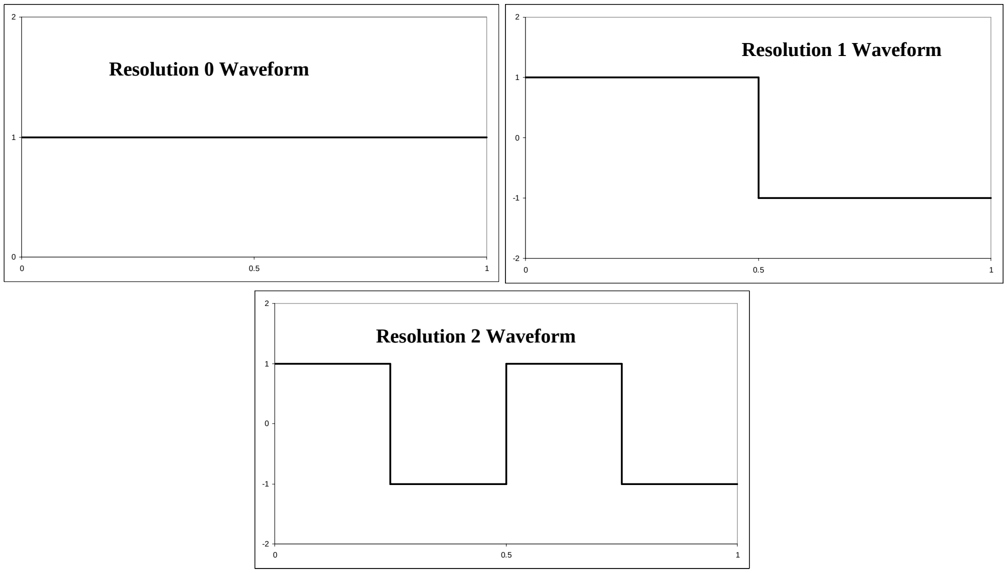

Figure B-6 – Haar Wavelet Resolution

The advantages of Haar wavelet analysis include its ability to assess local changes in profile data where standard test statistics lose power. Haar wavelet analysis also has the ability to de-correlate data that experiences auto-correlation, as was suspected in the error performance of the algorithm outputs. Most importantly for the VEST algorithm assessment, Haar wavelet analysis allowed time-frequency localization which prevented large error spikes (noisy data) from inappropriately biasing the Fourier coefficients.

The J-Hook Flight Test Technique (FTT) was tested using a 2^{4-1} fractional factorial design (reference 1). The main effects of airspeed, dwell time, increment angle, and heading change were compared for significant differences in global and local wavelet coefficients. Resolutions up to level 4 were considered global coefficients. Algorithm performance expectation was that the global trend would tend toward zero error. Any global deviations from zero error would be consistently non-zero in these low resolutions and expected to be the result of a normal error distribution. Therefore, these low resolution coefficients were tested for difference using a normal probability plot. These results are presented in appendix E and a sample normal probability plot is presented in figure B-7. If a main effect was consistently off the line of normality (2 of 3 plots), it was identified on the plot and considered a significant effect on algorithm performance.

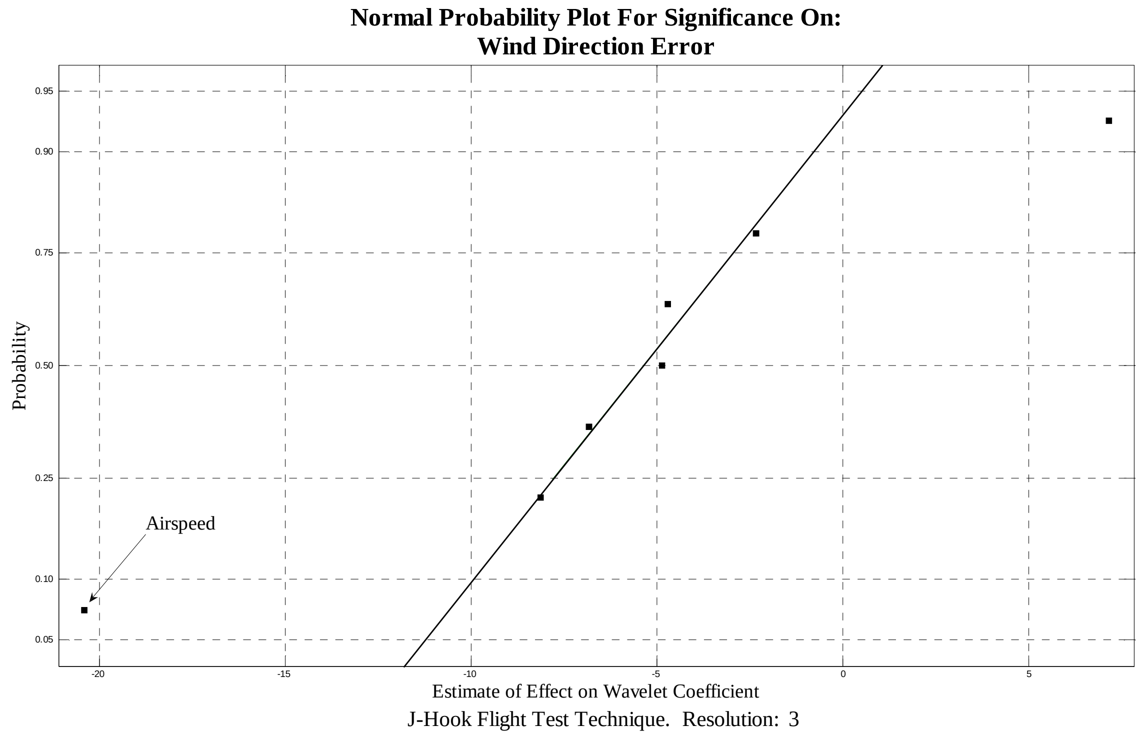

Figure B-7 – Representative Normal Probability Plot of J-Hook Coefficient Effect Estimate

Resolutions above level 4 were considered for local coefficients. Algorithm performance expectation was that error performance would have minimal localization, that is, few deviations representative of noise. This expectation would manifest itself with relatively constant higher resolution coefficients. If unexpected error performance was seen, a large number of coefficients would have disproportionately high values. The analysis for the higher resolution performance was conducted by determining the percentage of time the mean profiles were significantly different. That is, if the confidence bounds did not overlap at a given time, then the local coefficient values were considered significantly different. Figure B-8 shows a representative comparison of profiles and table B-2 summarizes the results for the J-Hook maneuvers. These results are presented in appendix E.

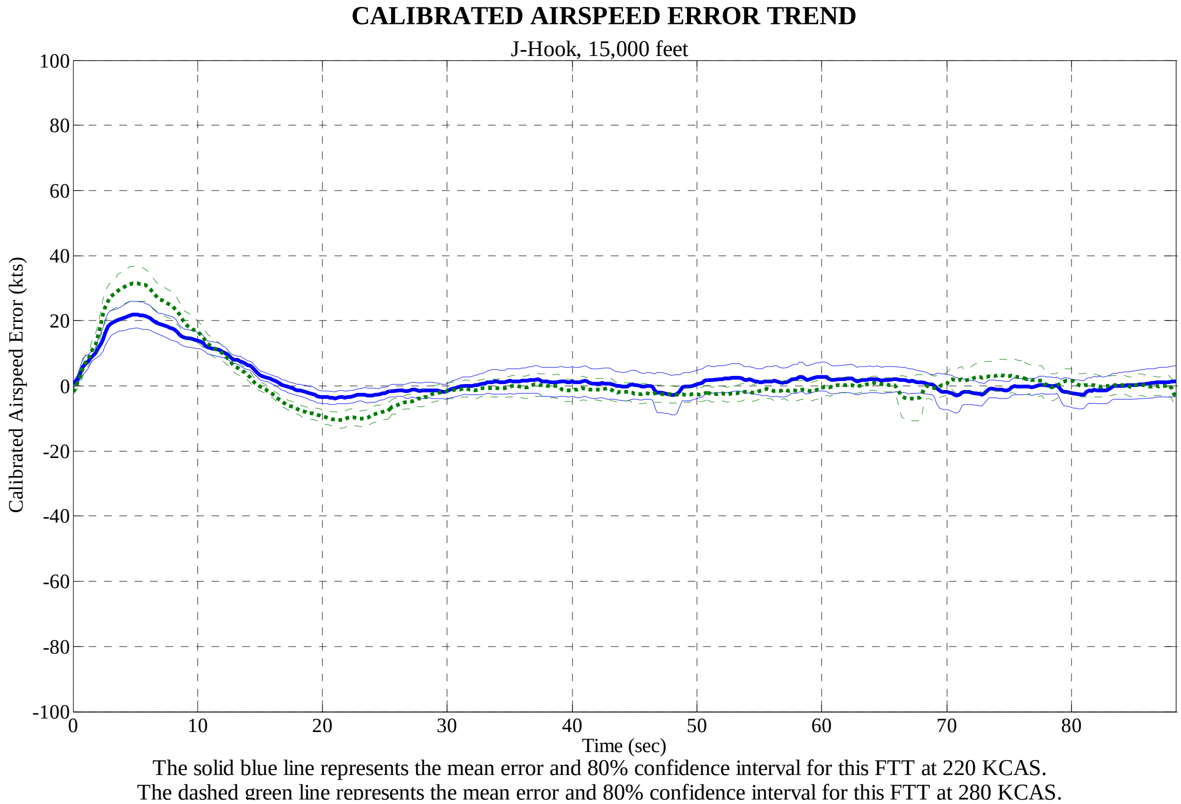

Figure B-8 – Representative Comparison of Profile Means

Table B-2 – Representative Percentage Difference Table (J-Hook Airspeed)

Error	**North Position**	**East Position**	**Vertical Position**	**North Velocity**	**East Velocity**	**Vertical Velocity**
	0 %	0 %	0%	4.5%	0.7%	0.5%
Error	**Heading**	**Calibrated Airspeed**	**True Airspeed**	**Wind Speed**	**Wind Direction**	
	0%	18.5%	9.9%	6.1%	7.7%	

Similar analysis was conducted for the factorial designs for treatments not associated with the J-Hook FTT. These treatments were investigated for airspeed effects only. Additionally, FTTs were compared for significance. Due to the single factor, only the mean comparison techniques were conducted (figure B-8 and table B-2). These results are presented in appendix E.

Table B-3 provides a summary of significant effects observed for the VEST algorithm.

Table B-3 – Summary of Significant Factors

Significant Factor	**Flight Test Technique**	**Error Affected**	**Factor Level for Best Error Profile**
Airspeed	J-Hook	Wind Direction	280 KCAS
Airspeed	Sliceback	Heading	280 KCAS
Airspeed	Air-to-Air Tracking	Calibrated Airspeed	280 KCAS

APPENDIX C – FLIGHT TEST MANEUVER DESCRIPTIONS

The J-Hook maneuver was flown as the primary maneuver to determine algorithm performance. The maneuver was a combination of level flight durations and incremental heading changes. The test aircraft was trimmed at the flight condition (A) dictated by the test matrix using the Learjet air data system. The maneuver began with the Velocity Estimate (VEST) algorithm providing its estimate to the Variable Stability System (VSS) feel system. The aircraft was flown straight and level for the dwell time (B) and then heading was incrementally changed (C) as dictated by the test matrix. This combination of straight flight and heading change was continued until a total turn (D) was completed. The maneuver terminated after the last level flight duration elapsed. The J-Hook Flight Test Technique (FTT) is graphically depicted in figure C-1.

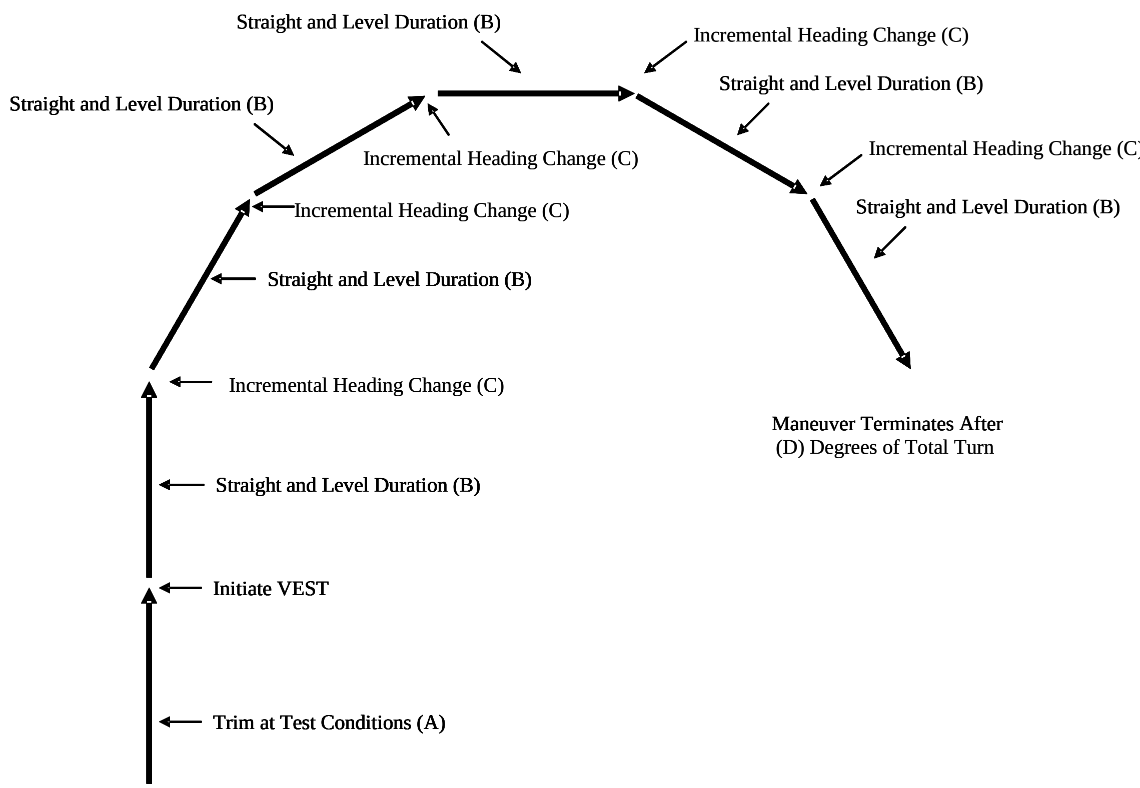

Figure C-1 – J-Hook Flight Test Technique

The Container maneuver was flown as the build-up to approach to landing test points and determined algorithm performance in the landing phase. The Container maneuver was conducted at the flight conditions (A) defined in the test matrix. The test aircraft established a constant heading to simulate a downwind leg of a landing approach. The maneuver began with the VEST algorithm providing its estimate to the VSS feel system. The test aircraft delayed for 10 seconds and turned 90 degrees to configure with gear and flaps for a normal approach. The test aircraft then turned 90 degrees in the same direction and began an 800-1000 feet/minute descent for 2000 feet. The Container FTT is graphically depicted in figure C-2.

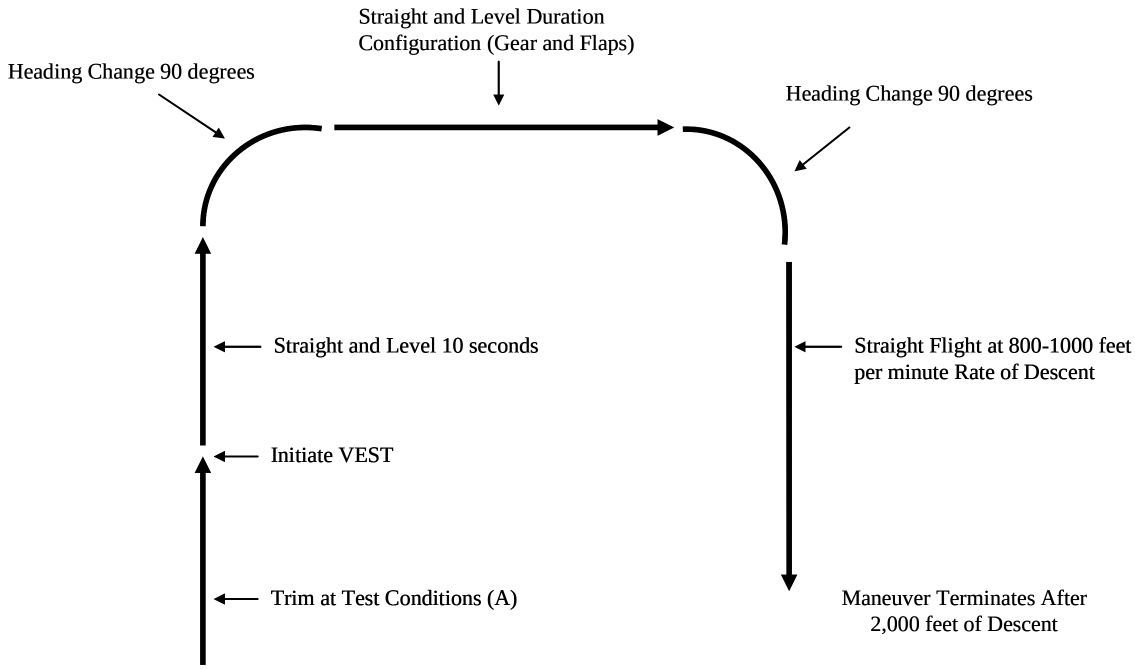

Figure C-2 – Container Flight Test Technique

The Sliceback maneuver was flown as the primary maneuver to determine algorithm performance during dynamic flight conditions. The maneuver was a combination of altitude, angle of bank, and normal acceleration changes. The test aircraft was trimmed at the flight conditions (A) dictated by the test matrix using the Learjet air data system. The maneuver began with the VEST algorithm providing its estimate to the VSS feel system. The pilot delayed for 10 seconds and then increased angle of bank to 60-70 degrees. Once in the bank angle, the pilot increased normal acceleration to 2g. The maneuver terminated when 10 seconds of level flight after 180 degrees of heading change was achieved. The Sliceback FTT is graphically depicted in figure C-3.

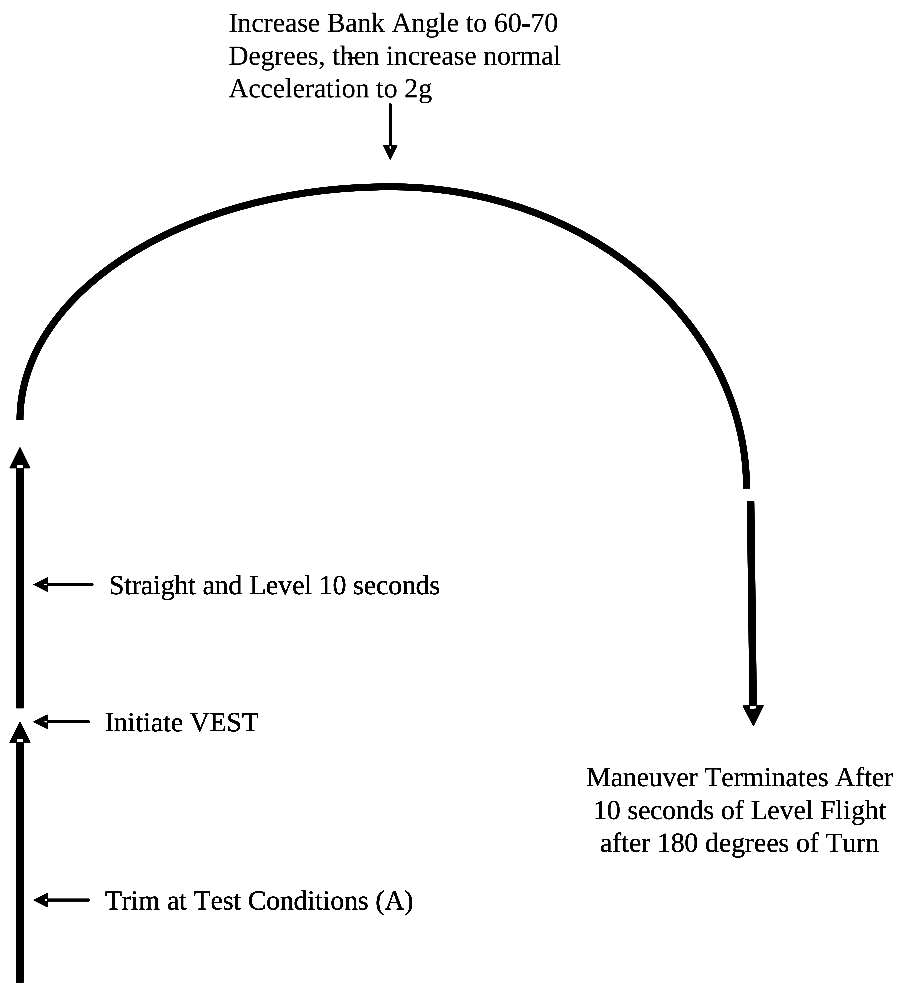

Figure C-3 – Sliceback Flight Test Technique

The Long Shot maneuver was flown as the primary maneuver to determine algorithm performance during straight and level, un-accelerated flight conditions. The test aircraft was trimmed at the flight condition dictated by the test matrix using the Learjet air data system. The maneuver began with the VEST algorithm providing its estimate to the VSS feel system. The test aircraft established a constant heading at the altitude and airspeed delineated in the test matrix. The test aircraft then flew straight and level maintaining a constant heading and airspeed for 70 nautical miles or until it was determined that in-flight VEST algorithm errors had grown to a maximum value.

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APPENDIX D – PILOT COMMENT ANALOG SCALE

Analog Scales for Air-to-Air, Air-to-Ground and Air Refueling Tasks:

Initial Delay in Pitch Response:

None —————— | —————— Gross Delay

Onset of Pitch Response:

Very Smooth —————— | —————— Too Abrupt

Sensitivity of Pitch Response:

Extremely Sensitive —————— | —————— Extremely Sluggish

Tendency to initially o.s./u.s. pitch:

No Undershoots —————— 2-3 deg —————— Overshoots (>5 deg)

Stabilize on new pitch att. Rapidly:

Very Easy —————— 2-3 O.S. —————— Overshoots (>5 O.S.)

Analog Scales for Landing Task:

Initial Delay in N, or Flight Path Response:

None | Gross Delay

Onset of N, or Flight Path Response:

Very Smooth | Too Abrupt

Tendency to initially o.s./u.s. Flight Path or N:

No Undershoots | 2-3 deg | Overshoots (>5 deg)

Stabilize N, or Flight Path Rapidly?

Very Easy | 2-3 O.S. | Overshoots (>5 O.S.)

APPENDIX E – PLOTS OF RESULTS

A data CD was provided to the customer at the time of publishing. See SF-298 for contact information.

The data presented in this memorandum can be located on this CD with the following organization:

- Have_VEST_Reduced_Data
  - 01_Time_Histories
    - This folder contains the time history of each determined error for each test point flown.
  - 02_Long_Shot_Means
    - This folder contains the mean error and 80% confidence interval of each determined error for each treatment of the Long Shot FTT (table B-1).
  - 03_J_Hook_Means
    - This folder contains the mean error and 80% confidence interval of each determined error for each treatment of the J-Hook FTT (table B-1).
  - 04_Container_Means
    - This folder contains the mean error and 80% confidence interval of each determined error for the Container FTT (table B-1).
  - 05_Sliceback_Means
    - This folder contains the mean error and 80% confidence interval of each determined error for each treatment of the Sliceback FTT (table B-1).
  - 06_Operational_Maneuver_Means
    - This folder contains the mean error and 80% confidence interval of each determined error for each treatment of the Operational Maneuvers (table B-1).
  - 07_Approach_Means
    - This folder contains the mean error and 80% confidence interval of each determined error for approach to landing test points (table B-1).
  - 08_Ground_Taxi_Means
    - This folder contains the mean error and 80% confidence interval of each determined error for taxi tests (table B-1).

- 09_Ground_Taxi_noGPS_Means
  - This folder contains the mean error and 80% confidence interval of each determined error for taxi tests without GPS (table B-1).

- 10_Flight_Test_Techniques
  - This folder contains the 1:1 graphical comparisons of each determined error for all FTTs.

- 11_Ground_Taxi_Comparison
  - This folder contains the 1:1 graphical comparisons of each determined error for all taxi tests.

- 12_J_Hook_Factors
  - This folder contains the 1:1 graphical comparisons of each determined error for all four factors of the J-Hook FTT.

- 13_Summary_Statistics
  - This folder contains the tabulated data for airspeed mean error and factor significance. Additionally,
  - J_Hook_Norm_Prob_Plots
    - This folder contains the normal probability plots for significance for the J-Hook FTT

APPENDIX F – LIST OF ACRONYMS

ADS	Air Data System
AFFTC	Air Force Flight Test Center
AFIT/ENY	Air Force Institute of Technology, Department of Aeronautics
AHRS	Attitude and Heading Reference System
AOA	Angle of Attack
ASTE	Aircraft and Systems Testing Establishment
CS	Curriculum Standards
EDT	Department of Test Management
FBW	Fly-by-Wire
Fs	Stick Force
FTT	Flight Test Technique
g	Normal Acceleration
GPS	Global Positioning System
IAF	Indian Air Force
KCAS	Knots, Calibrated Airspeed
KTAS	Knots, True Airspeed
PIO/PIOR	Pilot in Loop Oscillation / Pilot in the Loop Oscillation Rating
TIM	Technical Information Memorandum
TMP	Test Management Project
TPS	Test Pilot School
USAF	United States Air Force
USMC	United States Marine Corp
VEST	Velocity Estimate
VSS	Variable Stability System
WPAFB	Wright Patterson Air Force Base

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APPENDIX G – PILOT IN LOOP OSCILLATION (PIO) RATING SCALE

PIO RATING SCALE

Did I experience a PIO?
- No
  - Did I experience undesirable motion?
    - No 1
    - Yes
      - Did undesirable motion *tend to occur?* 2
      - Was undesirable motion *easily induced?* 3
- Yes
  - While attempting maneuvers or tight control?
    - Was the PIO *bounded*?........................ 4
    - Was the PIO *divergent*?....................... 5
  - While exercising normal control*?*.................... 6

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APPENDIX H – LESSONS LEARNED

1. 1 Aug 07 announcement of unusable algorithm format from Calspan – The algorithm was developed using Simulink® and was set up in a format that called Matlab® scripts to execute the algorithm. Following the news from Calspan that the existing format would not compile in Real Time Workshop, the algorithm had to be completely converted from called Matlab® script blocks to embedded Matlab® script blocks in Simulink®. This fix was completed by 16 Aug 07. However, this format would also not compile on Real Time Workshop. At this point every line of code had to be converted to Simulink® blocks (no embedded scripts). By no less than a heroic effort on the part of Have VEST (Velocity Esitmate) team, Calspan, and members of the TPS 07A class, this modification was accomplished by 25 Aug 07. All primary function blocks except inertial estimator blocks were verified by 31 Aug 07. Further block integration and run time errors were not verified until 9 Sep 07.

In effect, the 1 Aug 07 identification of integration incompatibility slipped the effective program timeline a total of 40 days. However, the timeline that the aircraft was available at Edwards AFB for ground and flight tests did not slip with this 40 day program slip. Efforts from Have VEST team and contractor team were then focused on getting a working algorithm on the Calspan Learjet N101VS within the time the aircraft would be available for testing. All efforts for flight preparation (including pacing, test conductor aircraft familiarization, FTT coordination, etc) were made secondary to the algorithm effort. This preparation was then accomplished simultaneously with fight testing, and was not finalized until flight 4. Conclusion – the entire program timeline (including flight test) needed to slip until a working algorithm was available for use on the N101VS. The TPS curriculum did not allow for such a slip. Less than optimal configuration control resulted.

Data analysis was also impacted. If flights were flown according to the original schedule, there would have been at least one day between data sorties to analyze data. Due to the slip, most data could not be analyzed until days following the actual flights. Since flights were accomplished up to the last day of aircraft availability, data analysis on portions of the missions was not accomplished until after the aircraft had departed Edwards. There was no opportunity to identify data quality until the aircraft had already departed Edwards. In summary, allow more time prior to flight testing for software integration.

2. The delay in getting a usable algorithm to test caused fluctuations in the TPS student non-TMP flying schedule. The N101VS was a dedicated TMP asset and could be available to fly on any schedule. However, the TPS student schedules were continuing to follow TPS syllabus flows, and were significantly impacted by aircraft delays. TPS scheduling office was flexible but stressed by the Have VEST TMP delays.

3. The program manager was intensely involved with algorithm conversion. Since the conversion continued until the last flight, the program direction tended to wander. Other team members were instrumental in piecing together plans and keeping the project moving.

4. A Learjet calculated wind estimate was used as a truth source comparison for the VEST wind estimate. The estimate was unusable during turns. Other wind sources (weather balloon data or chase aircraft) could have been used to get a more accurate and continuous wind truth source.

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